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Drought Risk Analysis using Remote Sensing and GIS in the Oshikoto Region of Namibia.

by

FC Persendt

Submitted in partial fulfilment of the academic requirements for the degree of
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“Come, let us sing of drought,

Drought – the hate of the Sun; ...”,

“Naked is the veld, scorched and naked,

Charred is its coat, once brave and green;

Naked to the Sun’s lash it quivers –

A victim defenceless.

Silent are the streams, sad and silent;

Drought has sucked their Shining souls away;

The stars have slipped from their fingers

The moon has escaped them...”

Extracts from the anthology “Drought: A South African Parable” by Francis Carey Slates, a South African poet, writing under the pseudodonym of Jan von Avond.

Preface

The research work described in this mini-dissertation was carried out in the Centre for Environment, Agriculture and Development, University of KwaZulu – Natal, Pietermaritzburg, from January 2005 to December 2008, under the supervision of Dr Denis Rugege and Prof Onisimo Mutanga.

I, Frans Carel Persendt, hereby declare that this mini-dissertation is my own original work and that all sources have been accurately reported and acknowledged. This mini-dissertation has not been previously in its entirety or in part been submitted at any university in order to obtain an academic qualification.

....

FC Persendt (Candidate) Date

....

Dr. Dennis Rugege Date

....

Prof Onisimo Mutanga Date

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Abstract

Drought is a recurrent climatic process that occurs with uneven temporal and spatial characteristics over broad areas and over an extended period of time. Therefore, detecting drought onsets and ends as well as assessing drought severity using satellite-derived information is essential. This should be especially the case in an arid country like Namibia where drought is part of Namibia's climatology. It is believed that proper planning and research using near real-time data can curb the devastating environmental and socio-economic impacts of drought. Weather data used currently are often from a very sparse meteorological network, incomplete and/or not always available in good time to enable delineating accurately and timely, regional- and local-scale droughts. Consequently, the detection and monitoring efforts are hampered to provide timely and unbiased information to decision makers for accurate drought relief allocation and for land reform purposes.

Furthermore, even though, data obtained from satellite-based sensors such as the Advanced Very High Resolution Radiometer (AVHRR) have been studied as a tool for drought monitoring for many years and provides an extensive temporal record for comparison, its coarse spatial resolution limits its effectiveness at detecting local scale variability where severe droughts might go undetected due to these data constraints.

The objective of this study was to evaluate satellite-based and meteorological drought indices for the spatial and temporal detection, assessment and monitoring of drought condition to accurately delineate drought characteristics of drought prone areas.

The study computed the Vegetation Condition Index (VCI) and Normalized Difference Vegetation Index (NDVI) from the 250m resolution NDVI data obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor and one- and three-months Standardized Precipitation Index (SPI) data from rainfall stations in the study area.

Detailed analyses of spatial and temporal drought dynamics during three seasons (2005/6 - wet, 2006/7 - normal and 2007/8 - dry) have been carried out through index maps generated in a Geographic Information Systems (GIS) environment from the mentioned data. Analysis and interpretation of these maps, which give different drought scenarios, reveal that remotely-sensed drought indices can accurately detect and map the local and regional drought spatial occurrence. Moreover, statistical analysis found strong correlations between the regional crop production data and the remotely-sensed data. However, the results showed that the local and regional drought occurrences detected were not reflected in national crop production data, confirming the suspicion that important local spatial variations are only detected if higher spatial resolution data are used. The study concluded that fine spatial resolution satellite data should be used to aid decision makers in monitoring and detecting drought which will also aid the allocation of millions of dollars in drought relief funds.

Table of Contents

Preface **3**
Acknowledgements **4**
Abstract **5**
List of Figures **7**
List of Tables **7**
List of Equations **7**
List of Abbreviations **8**
Chapter 1: Introduction **9**
1.1 General Background 9
1.2 Importance of drought risk analysis 10
1.3 Traditional methods used to assess drought and their problems 11
1.4 Remote Sensing in drought risk mapping 13
1.5 Gaps in the utilization of Remote Sensing in drought risk mapping 15
1.6 Problem Statement 17
1.7 Research Questions 18
1.8 Main Objectives of the study 18
1.9 The hypotheses of the study 18
2.0 Structure of the dissertation 19
Chapter 2: Literature Review **20**
2.1 Introduction 20
2.2 Drought Risk Analysis Methodologies 22
2.3 Drought Analysis 24
2.3.1 Introduction 24
2.3.2 GIS methods to study drought risk analysis 25
2.3.3 Drought Indices 26
2.4 Potential of GIS, SPI and NDVI for drought risk mapping 31
2.5 Gaps in mapping drought risk areas using Remote Sensing 34
2.6 Conclusion 36
Chapter 3: Study Area **38**
3.1 Introduction 38
3.2 Location and Extent of study area 40
3.3 Landscapes and Topography 41
3.4 Drainage and Water supplies 42
3.5 Climate 43
3.6 Vegetation and Soils 44
3.7 Demography and Household economics 44
3.8 Land tenure, governance and farming 45
3.9 Agro-ecological Zoning 46
Chapter 4: Materials and Methods **48**
4.1 Data characteristics and acquisition 48
4.1.1 Satellite data 48
4.1.2 Meteorological Data 49
4.1.3 Agricultural Data and Ancillary data 51
4.2 Software Used 51
4.3 Methodology 51
4.3.1 Conceptual Framework for the research approach 52
4.3.2 Pre – Fieldwork 54
4.3.3 Fieldwork 54
4.3.4 Post Field work 55
Chapter 5: Results and Discussion **57**
5.1 Crop production analysis 57
5.2 Satellite-based indices 60
5.3 Standardized Precipitation Index (SPI) 69
5.4 Statistical Analysis 71
Chapter 6: Conclusions and Scope for Future Research **75**
6.1 Introduction 75
6.2 Conclusions 76
6.3 Problems and limitations 77
6.4 Future work 78
References: **79**
Appendix A **104**

List of Figures

Figure 1.1: The spatial and temporal characteristics of commonly used remote sensing systems and their sensors. 16
Figure 2.1: Relationship between various types of drought and duration of drought events. 21
Figure 2.2: Drought Risk Analysis Framework. 23
Figure 3.1: Location and extent of the Study Area.....38
Figure 3.2: The Study Area. 39
Figure 3.3: The Study Area and part of the surrounding northern NCAs. 40
Figure 3.4: Agro-ecological Zones.....46
Figure 4.1: MODIS Sinusoidal Tiling System 49
Figure 4.2: Oshikoto Region: 2007/08 season rainfall performance compared to normal averages. 50
Figure 4.3: Oshikoto Region: 2004/05 seasonal rainfall performance compared to normal means. 51
Figure 4.4: A schematic presentation of the methodology. 52
Figure 4.3: Conceptual Framework for the research approach.....53
Figure 5.1: Cereal production (tonnes) in Namibia from 1996 to 2008. 58
Figure 5.2: Oshikoto Region: coarse production trends. 59
Figure 5.3: Seasonal averages for NDVI and VCI. 61
Figure 5.4: Multi-year NDVI mean with minimum and maximum values for all three seasons.....62
Figure 5.5: Multi-year VCI mean.....64
Figure 5.6: NDVI drought risk maps for the early and main season of all three seasons.....65
Figure 5.7: VCI drought risk maps for the early and main seasons of all three seasons. 66
Figure 5.8: The total drought areas identified by NDVI and VCI.....68
Figure 5.9: Multi-year $NDVI_{DEV}$ from the Mean. 68
Figure 5.10: SPI values for 5 study sites. 70
Figure 5.11: Monthly 1-month and 3-months SPI values. 73
Figure 5.12: Linear correlation and regression analysis of the NDVI and VCI indices with long-term rainfall averages.....74

List of Tables

Table 1.1: Summary of studies using drought indices to delineate drought prone areas.....14
Table 2.1: Drought classification scheme using drought indices. 27
Table 2.2: Remote sensing data, indices and thresholds relevant to drought analysis. 29
Table 3.1: Summary evaluation of potential per agro-ecological zone. 47
Table 3.2: Evaluation of cropping potential for individual agro-ecological zones.....47
Table 4.1: Available monthly rainfall data per station. 50
Table 5.1: Classify the three seasons into different types of seasons. 60

List of Equations

Equation 1: 26
Equation 2: 28
Equation 3: 30
Equation 4: 31
Equation 5: 55
Equation 6: 55
Equation 7: 56
Equation 8: 56
Equation 9: 56
Equation 10: 56

List of Abbreviations

AEZ: Agro-ecological Zones
AVHRR: Advanced Very High Resolution Radiometer
BMDI: Bhalme and Mooly Drought Index
BRDF: bi-directional reflectance
CBS: Central Bureau of Statistics
CMI: Crop moisture index
CWSI: Crop Water Stress Index
DSI: Drought Severity Index
EDI: Effective Drought Index
EMU: Emergency Management Unit
EOS: Earth observing system
EVI: Enhanced Vegetation Index
GIS: Geographic Information Systems
HDF: Hierarchical Data Format
ILWIS: Integrated Land and Water Information System
LST: Land surface temperature (Ts)
MAWRD: Ministry of Agriculture, Water and Rural Development
MODIS: Moderate Resolution Imaging Spectrometer
MVC: maximum value composite
NCA: Northern Communal Area
NDPS: National Drought Policy and Strategy
NDTF: Namibian Drought Task Force
NDVI: Normalised Difference Condition Index
$NDVI_{DEV}$: Normalised Difference Condition Index – Deviation
NDWI: Normalised Difference Water Index
NEWFIU: Namibia Early Warning Food Information Unit
NIR: Near infrared
NOAA: National Oceanic and Atmospheric Administration
NPC: National Planning Commission
NPOESS: National polar Orbiting Operational Environmental Satellite System
PDSI: Palmer Drought Severity Index
PNR: Percent of Normal Rainfall
RAI: Rainfall Anomaly Index
RDI: Reconnaissance Drought Index
RI: Rainfall Index
SPI: Standardized Precipitation Index
SPOT: Système Probatoire d'Observation de la Terra
TCI: Temperature Condition Index
VCF: Veterinary Cordon Fence
VCI: Vegetation Condition Index
VHI: Vegetation Health Index
VPI: Vegetation Production Index
WMO: World Meteorological Organisation

Chapter 1: Introduction

1.1 General Background

Throughout southern Africa, drought frequency and severity has become a major climate disaster (Unganai and Kogan, 1998). Droughts affected the region during 1982/1984, 1991/1992 and 1994/1995, with devastating impacts on agriculture, water resources, national economies, industry and the environment.

In sub-Saharan Africa, for example, the droughts of the early to mid 1980's are reported to have adversely affected more than 40 million people (Office of Foreign Disaster Assistance, 1990). The 1991/2 drought which was by far the worst drought in southern Africa affected 20 million people and resulted in a deficit of cereal supplies of more than 6.7 million tonnes (SADC, 1992).

Up to 70% of Namibia's population depends on subsistence farming which is compounded by the fact that Namibia is the driest country in southern Africa. Hence, the immediate impacts of the most recent (EMU, 2007) and particularly the well documented 1991/2 drought, namely food shortage for people and scarcity of grazing for livestock and wildlife, affected at least part of all 13 regions of the country and approximately 625 000 of Namibia's population of 1.4 million (National Drought Policy and Strategy, 1997; Sweet, 1999).

It is against this background that Wilhite *et al.*, (2000a) have concluded that vulnerability to drought has increased globally and particularly in developing countries where the primary concerns are centred largely on issues of food security and meeting the nutritional needs of the population, environmental degradation, and a retardation of the development process. Hence, greater attention must be directed to reducing risks associated with its occurrence through the introduction of planning to improve operational capabilities and mitigation measures that are aimed at reducing drought impacts.

Consequently, many governments have introduced drought policies and preparedness plans that aim to move societies away from the traditional approach of crisis management, which is reactive in nature, to a more pro-active, risk management approach. Hence, the goal of risk analysis is to promote the adoption of preventative or risk-reducing measures and strategies that will mitigate the impacts of future drought events, thus reducing societal vulnerability.

Drought policies are usually based on drought risk analysis methodologies which comprise of two components for this study; drought risk assessment and management and can further be subdivided into hazard analysis and vulnerability analysis (Figure 2.2; Hayes *et al.*, 2004).

Essentially drought risk analysis is centred on a hazard which represents the probability of occurrence or frequency of droughts and vulnerability which represents the broadest concept of biophysical and social vulnerability in a region. Therefore, to reduce drought risk, there must be an understanding of the hazard using climatology, improved operational monitoring, an analysis of vulnerability to understand what people and sectors may be most affected by drought, why these impacts occur, and if these relationships are changing over time.

This study primarily focused on the first stage of Drought Risk Analysis methodology, namely drought (drought is a natural hazard) analysis which apply spatially and temporally consistent indices for the detection, assessment and monitoring of drought conditions at different scales. These indices will give information on the spatial extent, frequency, intensity and the duration of a drought period that will allow for an improved evaluation of the impact of a drought on natural ecosystems and agriculture. This will also enhance the prediction capabilities of early warning systems for current and future drought risk.

Ultimately, this study seeks to delineate areas that are prone to vegetative (agricultural) and meteorological droughts by using medium spatial resolution satellite based indices that can map local variability for the former and meteorological based indices for the latter.

1.2 Importance of drought risk analysis

Drought risk analysis is important, in general, and for Namibia in particular, firstly, because drought seriously threatens poverty reduction efforts in Namibia. Secondly, drought risk analysis can help in reducing the risk to agricultural and rural development from droughts. Thirdly, it can help to map, monitor and reduce the environmental degradation that droughts are cause. Fourthly, it can improve water resource management as well as enabling countries achieve sustainable development and, sixthly, it can enable decision makers to distribute and allocate drought relief subsidies on the basis of biophysical criteria and not on a subjective and emotive manner. Lastly, in addition to crisis assessment and mitigation, delineating drought risk prone areas are also essential for fair and efficient land reform when land is distributed to the vulnerable and poor majorities.

Therefore, decisions on how to identify and then address drought risks need to be done by managers of and other stakeholders in development and to do this effectively, they have to understand the actual harm of past droughts and the potential threats posed by imminent droughts. This is done through drought risk analysis methodology that emphasizes proactive management of drought risk through reduction of both prospective and accumulated risks.

1.3 Traditional methods used to assess drought and their problems

Drought is a complex natural disaster that causes serious environmental, social, and economic consequences in arid, semi-arid, and other marginal areas (Wilhite *et al.*, 2000). Drought is also difficult to detect and monitor. However, the complex drought phenomenon can be simplified into a drought index, which is a single number assimilating a large amount of data. The index allows scientists to quantify climate anomalies in terms of intensity, duration, frequency and spatial extent, making it easier to communicate the information to diverse users (Wilhite *et al.*, 2000a). These indices can also be used to describe all types of droughts such as meteorological drought, agricultural drought, hydrological and socioeconomic drought.

Traditional methods that are predominantly based on meteorological data have rainfall-only variables, they do not express much local spatial detail, and they are only valid for a single point location (Brown *et al.*, 2002).

The most popular traditional drought indices include the Palmer Drought Severity Index (PDSI), the Standard Precipitation Index (SPI), the Percent of Normal Rainfall (PNR), the method of Deciles, and others (Hayes, 2004; Keyantash and Dracup, 2002).

The PDSI (Palmer, 1965; Alley, 1984) provides a measure of the departure from normal of the moisture supply. Its strengths are that it is the first comprehensive drought index used widely and it is very effective for agricultural drought since it includes soil moisture. Weaknesses include that it may lag emerging droughts, it’s less well suited for areas of frequent climatic extremes, and have complex categories that are not necessarily consistent, in terms of probability of occurrence, spatially or temporally.

The *Standard Precipitation Index* (SPI; McKee *et al.*, 1993 and 1995) is a simple calculation solely based on rainfall with a temporal flexibility that is theoretically much better suited to the quicker responses in vegetation detected by satellite imagery. It is a statistical measure on the surplus or lack of precipitation during a given period as a function of the long-term average precipitation.

Its strengths, amongst others, are that it is used by many drought planners, and it computes droughts for different time scales and hence provides early warning of drought. It also helps assess drought severity. Its weaknesses are that its values are based on preliminary data that may change and that precipitation is the only parameter used. It also cannot account for water deficit caused by evapotranspiration, deep percolation and runoff.

The '*Percent of Normal Rainfall'* is one of the simplest indices of precipitation anomaly. It is calculated by dividing actual precipitation by normal precipitation, typically considered to be a 30 year mean, and multiplied by 100% (Hayes, 1999). This can be calculated for a variety of time scales ranging from a single month to an annual or water year. Analysis using the percentage of normal is very effective when used for a single region or a single season, but can be easily misunderstood and can give different indications of conditions, depending on the location and season. Other weaknesses are that precipitation does not have a normal distribution and values depend on location and season.

The '*Percentile Method*' indicates the severity of a given value of a meteorological element that can be drawn from the percentile value determined from the cumulative frequency of the value. The 'Deciles of Precipitation' method which groups monthly precipitation occurrences into deciles, so 'much lower than normal' weather cannot occur more often than 20% of the time (Hayes, 1999). Its strengths are accurate statistical measurement and simple calculation. It also provides uniformity in drought classifications while its weakness is that accurate calculations require a long climatic data record that is not usually available, as mentioned earlier.

Other traditional indices include, the 'Surface Water Supply Index', the 'Poisson Process', the 'Palfai Drought Index' (Tate and Gustard, 2000), the 'Foley Drought Index', the Reconnaissance Drought Index (RDI) (Tsakiris, 2004).

Lastly, recent research have shown that the SPI has many advantages over other indices in that it is relatively simple, spatially consistent, and temporally flexible, thus allowing observation of water deficits at different scales (Guttman, 1998, 1999; Hayes *et al.*, 2000; Hayes *et al.*, 1999; Szalai and Szinell, 2000). Since the SPI is more reliable for detecting emerging drought, it has become an increasingly important tool for assessing moisture condition and initiating mitigation and response actions (Wilhite *et al.*, 2000b).

1.4 Remote Sensing in drought risk mapping

Existing drought monitoring and declaration procedures in Namibia lag behind the development of methods that accurately detect and delineate drought events, since most of them are based on traditional methods of drought assessment and monitoring that rely heavily on rainfall data only (NEWFIU, 2004, 2005, 2006, 2007, 2008 and 2009). They are limited to a region, often inaccurate and, most importantly, difficult to obtain in real-time. In contrast, the satellite sensor data are consistently available and can be used to detect the onset of drought, its duration and magnitude more effectively and efficiently. Satellite-based data, in combination with meteorological indices, are widely used in southern Africa for national, regional and international drought and food early warning systems, hence inappropriate at a district and/or local scale.

More than fifty vegetation indices are in use today (Jensen, 2000). Amongst them are the Normalized Difference Vegetation Index (NDVI) and Vegetation Condition Index (VCI).

The NDVI takes advantage of the reflective and absorptive characteristics of plants in the red and near-infrared portions of the electromagnetic spectrum and has been used in research on vegetation yield and productivity, vegetation monitoring and drought detection and mapping. The ability to use satellite data in drought detection and mapping is based upon the fact that moisture-stressed vegetation has a higher reflectance than green, healthy and photosynthetically active vegetation in the red band and a lower reflectance in the near-infrared band. Additionally, no other surface exhibits higher NDVI values than vegetated surfaces and when vegetation vigour changes due to the nature of the vegetation growth and development cycle or environmental induced stress such as drought, the NDVI also changes.

Numerous studies (Table 1.1) have been carried out for several parts of the world that showed the potential of satellite-based data in drought monitoring and risk assessment.

In Africa, the vegetation monitoring has been carried out for more than ten years (Tucker *et al.*, 1985; Justice *et al.*, 1985; Townshend and Justice, 1986). Theoretically studies showed, NDVI can be considered as a climatic recorder, and in the Tropics, mainly a rainfall recorder. Also, NDVI can be used as a good proxy for the study of inter-annual climate variability, as shown by its correlation with the Southern Oscillation index, over East Africa or Botswana (Anyamba *et al.*, 1998).

Table 1.1: Summary of studies using drought indices to delineate drought prone areas.

Author's Name	Year	Year Studied	Method	Region
Bayarjargal *et al.*,	2006	1982 - 1999	NDVI/VCI/NDVIA/TCI/LST	Mongolia
Bhuiyan *et al.*,	2006	1984 -2003	NDVI/VCI/TCI/ VHI/GIS	India
du Pisani *et al.*,	1998	-	Met Drought	South Africa
Filella *et al.*,	2004	1999 – 2002	NDVI and PRI	Spain
Fox *et al.*,	2005	1985 - 2001	NDVI	South Africa
Gu *et al.*,	2007		NDVI and NDWI	Central Great Plains, USA
Hartmann *et al.*,	2003	2001	NDVI – lsd	Argentina – South East Buenos Aires
Hayes	2000	1885 - 1985	SPI	USA
Ji and Peters	2003b	1989 - 2000	NDVI and SPI	Northern Great Plains, USA
Jury	1997	1981 - 1994	NDVI	Southern Africa
Kassa	1999	1982 – 1993	NDVI integrated	Sudan
Liu and Juarez	2001	1981 – 1993	NDVI (ENSO)	North Eastern Brazil
Liu and Kogan	1996	1985 - 1992	NDVI/VCI/Rainfall	South America
McVicar and Bierwirth	2001	1997	Ts / NDVI	Papua New Guinea
Peters *et al.*,	1993	1988 – 1989	NDVI, PDSI and CMI	New Mexico
Ramesh *et al.*,	2003	1985 - 1996	NDVI/VCI/TCI	India
Seiler *et al.*,	1998	Jan – Feb	VCI / TCI and corn yield	Argentina
Song *et al.*,	2004	1997 – 1999	NDVI (lsd)	East South East Asia
Unganai and Kogan	1998	1985 – 1995	VCI / NDVI	South Africa / Zimbabwe
Viau and Beaudin	2000	1987 - 1993	NDVI/VCI/SPI	Spain
Washington-Allen *et al.*,	1998	1986 – 1987	TNDVI	Bolivian Altiplano

Furthermore, several other studies have also shown the utility of satellite measurements for observing and monitoring drought. For example, Kogan (1991; 1995) have analyzed droughts in the United States using AVHRR data. In this research, several derivations of the NDVI

were developed, in order to improve the ability to extract drought information from a time-series of satellite composite data. One index, the Vegetation Condition Index (VCI), which is a ratio of the NDVI collected in a given period compared to its historical range (maximum minus minimum) derived over several years of record. Building on this research, Kogan and others (Liu and Kogan, 1996; Kogan, 1997; Unganai and Kogan, 1998) have demonstrated the utility of the VCI in Africa, South America, and Asia (Table 1.1). Song *et al.,* (2004) for example used the changes of up-to-date and normal NDVI from NOAA/AVHRR data, to develop an early detection system for drought.

Although a number of previous studies have indicated a strong relationship between, especially AVHRR – NDVI and precipitation, this relationship is far more complex (Ji and Peters, 2003b) than what can be represented by simple linear correlation between two variables. Studies have found that the relationship is influenced, amongst other factors, by the temporal and spatial scale of the data (Eklundh, 1998).

1.5 Gaps in the utilization of Remote Sensing in drought risk mapping

Figure 1.1 illustrates the spatial and temporal characteristics of commonly used remote sensing systems and their sensors (Jensen and Cowen, 1999). Spatial resolution refers to the size of object that can be resolved and the most usual measure is the pixel size while temporal resolution, or repeat cycle, describes the frequency with which images are collected for the same area (Longley *et al.,* 2005; Jensen and Cowen, 1999). These researchers also defined a fine spatial resolution as pixel sizes between 0.2m to approximately 100m (e.g. Quickbird, SPOT 5, etc), medium spatial resolution as pixel sizes between 100m and approximately 500m (e.g. MODIS) while coarse/large spatial resolution as pixel sizes between 500m to 10km (e.g. AVHRR, SPOT 4 vegetation, METEOSAT, etc) (Figure 1.1).

The above mentioned studies (Table 1.1) have predominantly used coarse spatial resolution data from the Advanced Very High Resolution Radiometer (AVHRR) aboard the National Oceanic and Atmospheric Administration (NOAA) series of polar-orbiting meteorological satellites. Many organisations and researchers, especially in the southern African region, also use this sensor because of its extended time-series of spatially coarse NDVI data (Figure 1.1). In Namibia, for example, a national study on rangeland resources assessment used NOAA/AVHRR-derived satellite imagery (NDVI) as an operational tool for national planning (Ganzin *et al.,* 2005). This study used 17 years of AVHRR and SPOT VEGETATION coarse satellite data over Namibia to estimate seasonal biomass production using a simple but

operational vegetation production model. The output, amongst others, is the identification of areas with very low biomass production that can therefore be classified as drought prone areas.

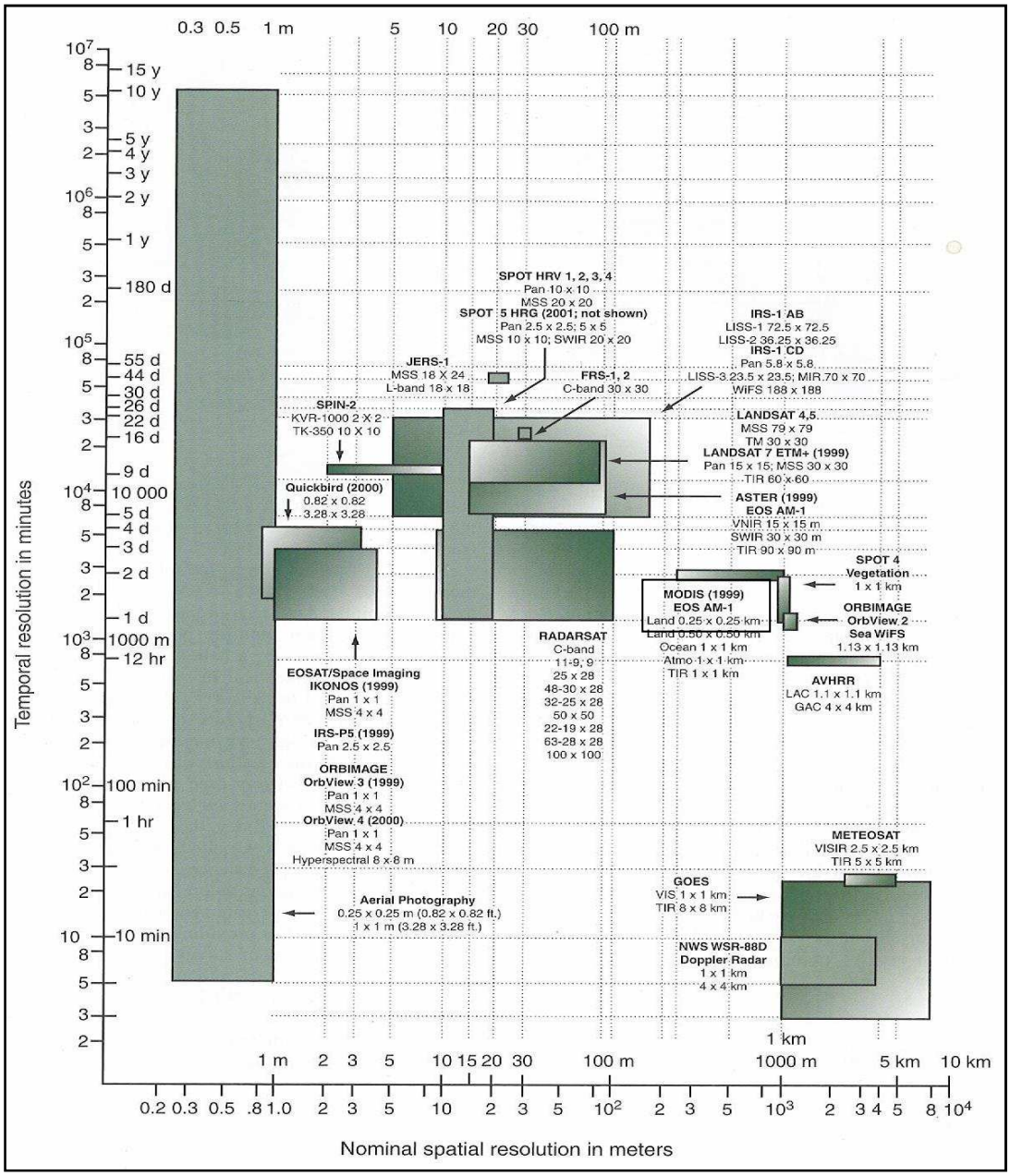

Figure 1.1: The spatial and temporal characteristics of commonly used remote sensing systems and their sensors. **Source: After Jensen and Cowen, (1999)**

Although the AVHRR and other coarse spatial resolution sensors provide an extensive temporal record for comparison, the coarse spatial resolution of these data limits their effectiveness at detecting local scale variability that is needed for drought relief and land allocation for the rural poor and other vulnerable groups.

Therefore, in addition to the moderate spatial resolution, Justice *et al.*, (2002) in a review of the new MODIS products (Figure 1.1) reported that they allow the land research community to move beyond dependence on the NOAA/AVHRR NDVI.

Hence, this study intends to delineate drought risk areas facing vegetative as well as meteorological drought by using temporal images from MODIS NDVI (250m) and meteorological based Standardized Precipitation Index (SPI).

1.6 Problem Statement

The Namibian National Drought Policy and Strategy (NDPS, 1997) emphasize the paradigm shifts from crisis management to risk management in assisting with crisis (drought) mitigation. This policy requires decisions that can be made at community level which can be of great benefit to the vulnerable rural communities as well as to the commercial farmers if the decisions are based on scientific rational. Hence, these decisions must be based on unbiased and up-to-date information on the forage resources over the entire country. Consequently, the Government is in need of both near real-time information on agro-meteorological situation of the ongoing season for crisis assessment and mitigation, and general information on the drought prone areas that need urgent attention in the different parts of Namibia. This information is also needed for fair and efficient land reform and drought relief allocation.

The NDPS (1997) specifically indicates that one of its key objectives is to provide an adequate definition of drought so that drought declaration is determined by a more scientific process rather than the *ad hoc* manner as is the case. However, the drought assessment used by the policy is based on a meteorological threshold assessment that have numerous shortcomings amongst them: (i) drought is a complex phenomenon whose impacts have different time scales and for this reason, the computation of precipitation deficit alone is not sufficient for the evaluation of possible drought conditions, (ii) it is possible to record agricultural droughts several times in a given season even when neither meteorological nor hydrological droughts can be said to have occurred at the end of the season (Usman *et al.*, 2005), (iii) the assumption that the water related activities in a region should be in harmony with the amount of water which would normally be available (Zucchinni and Adamson, 1984) and (iv) it further assumes that the vegetation that occurs naturally within a particular region is adapted to the average climatic variability (du Pisani *et al.*, 1998).

Drought is inherent to Namibia's climate due to its location and other climatic conditions. Therefore, despite the huge amount of money that is spent recently and in the past (EMU, 2007) defining drought scientifically remains a challenge. Consequently, this study designed a methodology that will not only define drought appropriately but will also address the spatial resolution challenge, mentioned earlier. In fact, many researchers (du Pisani *et al.*, 1998) and policy makers have also argued that these deficiencies should warrant that decisions relating to drought assistance should not be based on meteorological indices only, as in the case of the NDPS (1997).

1.7 Research Questions

- Can vegetative and meteorological indices derived from medium spatial resolution satellite data detect local drought risk variability?
- Can the analysis of regional crop production data detect local drought risk variability?
- Can local variability in drought risk better be evaluated by combining satellite, meteorological and crop production data?

1.8 Main Objectives of the study

To identify and delineate vegetative and meteorological drought risk areas by using temporal images from MODIS NDVI and SPI values based on meteorological point data.

Specific objectives:

- To establish an accurate, scientific and operational definition for the different types of droughts.
- To determine the local variability in vegetative drought risk maps by analysing vegetation indices derived from medium spatial resolution MODIS NDVI satellite data.
- To determine the one and three month SPI for selected rainfall stations that might indicate meteorological drought risk.
- To produce vegetative drought risk maps from MODIS NDVI satellite data that delineate local variability for effective and targeted interventions.

1.9 The hypotheses of the study

The hypothesis of this study is that local variability in drought risk can be better evaluated by combining and using medium spatial resolution satellite and meteorological data.

2.0 Structure of the dissertation

This thesis comprises of different chapters.

Chapter 1: It gives a general background, explains the importance of drought risk analysis, examines traditional methods used to assess drought risk and their problems, investigates the use of remote sensing in drought risk mapping and identifies gaps on the utilization of remote sensing in drought risk mapping. Lastly, it covers the problem statement, research question, specific objectives and structure of the dissertation.

In chapter 2: A detailed literature review has been done on drought risk methodologies, GIS methods used to study drought risk, drought indices and lastly, the potential of GIS, SPI and NDVI for drought risk analysis.

Chapter 3: It describes the geographic setting of study area, landscapes and topography, drainage and water supplies, growing and agro-ecological zones, climatic conditions, land tenure, governance and farming, soils and vegetation, and lastly, demography and household economies.

Chapter 4: It gives an overview about the data used for the present study, which includes satellite data preparation from EOS- data gateway, meteorological and agricultural data collection from various organisations during field work. In addition to this it explained how drought indices were calculated and the methodology for this study.

Chapter 5: This chapter presents the results of this study, which gives a critical observation for different drought indices and their relationships. It gives a brief discussion based on the results achieved and the analysis carried out.

Chapter 6: Conclusions and recommendations draw some conclusions from the study results obtained and proposing some recommendations and opportunities for further research.

Chapter 2: Literature Review

2.1 Introduction

Due to its nature as a complex phenomenon, defining drought can be very difficult. There is no universal definition of drought since its perception depends on the impact of the water deficit. However, drought definitions can be categorized as conceptual or operational (Wilhite and Glantz, 1985). Conceptual definitions are formulated in general terms, to identify the boundaries of the concept of drought. They also provide little guidance to those who wish to apply them to current (for example, near real-time) drought assessments. Common conceptual drought definitions include, amongst others, "*insufficient water to meet needs*" (Redmond, 2002) and a period of abnormally dry weather which results in a change in vegetation cover, a definition widely use by the remote sensing community (Bayarjargal *et al.*, 2006; Heim, 2002 and Tucker and Choudhury, 1987).

While operational definitions attempt to identify the precise characteristics and thresholds that define the onset, severity, and termination of drought episodes, they can also be used to analyze drought frequency, severity, and duration for a given historical period. They are the foundation of an effective drought early warning system.

Conceptually operational drought definitions can be clustered into four types (Figure 2.1; Wilhite and Glantz, 1985):
Meteorological drought is expressed solely on the basis of the degree of dryness (often in comparison to some normal or average amount) and the duration of the dry period. *Agricultural drought*, according to Wilhite and Glantz, (1985) links various characteristics of meteorological drought to agricultural impacts. *Hydrological drought* is associated with the effects of periods of precipitation shortfall on surface or subsurface water supply (i.e stream flow, reservoir and dam levels, and groundwater) rather than with precipitation shortfalls (Dracup *et al.*, 1980, Klemes, 1987). *Socio-economic drought*s associate the supply and demand of some economic goods or services with elements of meteorological, hydrological, and agricultural droughts. Sanford (1979) suggested that drought could be defined as occurring when the demand for goods exceeds supply as a result of a weather related shortfall. Lastly, *famine drought* is often regarded as an extreme form of agricultural drought which destroys food security to the point where large numbers of people become unable to maintain an active healthy life (Smith, 2001).

Hence, from Fig. 2.1 precipitation deficiency defines a meteorological drought, therefore the study will used rainfall and SPI to analyze meteorological drought characteristics while agricultural (vegetative) drought is defined by a reduced biomass (vegetation cover) and yield. The latter was analyzed using vegetative drought indices such as NDVI, $NDVI_{DEV}$ and VCI.

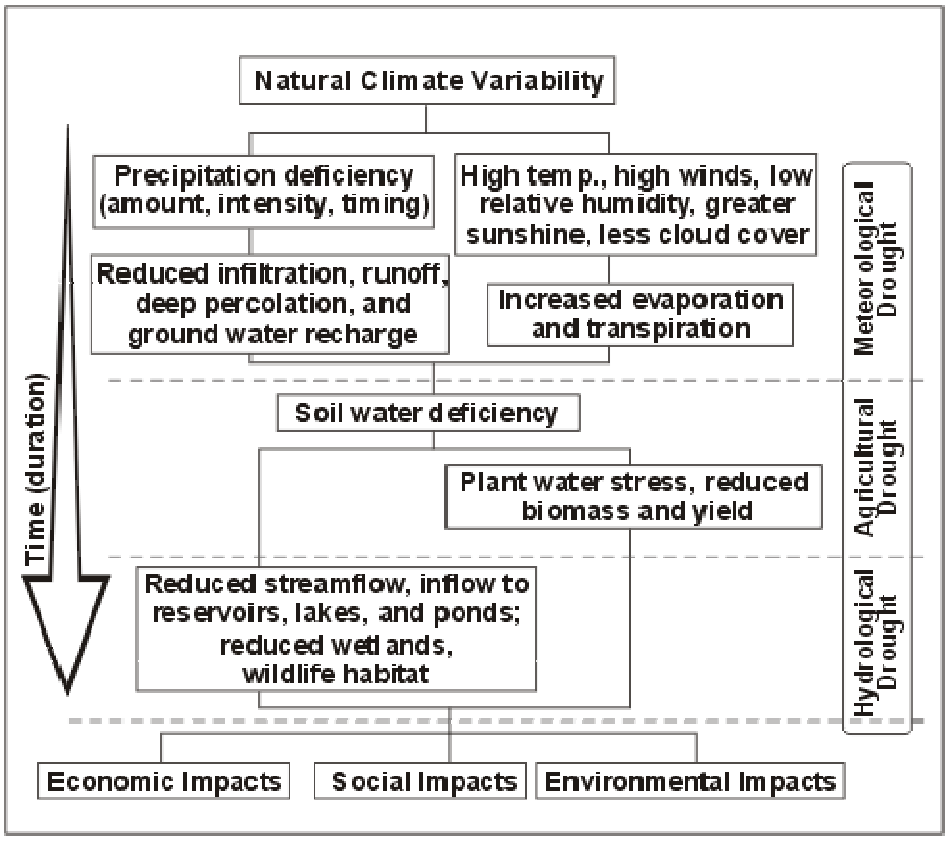

Figure 2.1: Relationship between various types of drought and duration of drought events. **Source: National Drought Mitigation Centre http://www.drought.unl.edu/)**

The major causes of these types of droughts (Figure 2.1) are anomalies in the weather or climate that leads to less precipitation than normal for meeting water demands. Amongst them are ocean-atmosphere system, sea surface temperature anomalies, high temperatures of the soil during drought and the increase in fine particles in the air, high albedo in dry areas and solar-weather relationship (Redmond, 2002; Sanford, 1977; Wilhite, 2000a and Wilhite and Glantz, 1985).

Furthermore, Figure 2.1 shows that drought produces a complex web of impacts. These impacts might be *economic impacts* that occur in agriculture and related sectors, including forestry and fisheries, because of the reliance of these sectors on surface and subsurface water supplies or *environmental impacts* that are the result of damages to plant and animal species, wildlife habitat, air and water quality, forest and range fires, degradation of landscape quality,

loss of biodiversity, and soil erosion. And lastly, *social impacts* that involve public safety, health, conflicts between water users, reduced quality of life, and inequities in the distribution of impacts and disaster relief.

Given the consequences and pervasiveness of drought, it is important to quantify droughts using the major drought characteristics such as severity, frequency, intensity, duration, and spatial extent. Therefore, the complex nature of the drought phenomenon asks for the combined analysis of meteorological and satellite-based indices in order to adequately characterize the event.

2.2 Drought Risk Analysis Methodologies

Many options exist to study drought. These include: forecasting the occurrence of drought prior to the beginning of an agricultural production or rainfall season and monitoring the current season as it progresses, providing early warning of impending drought and assessing drought impact.

This study followed the latter that formed part of a drought risk analysis methodology which provided a holistic approach to drought studies and that can also help countries develop drought strategies (Hayes *et al.*, 2004). This Drought Risk Analysis (DRA) methodology (Fig. 2.2) balances many of the scientific concepts in the risk literature and is consistent with the interactions of drought specialists and other stakeholders around the World (Hayes *et al.*, 2004).

Figure 2.2 illustrates this methodology showing the two major components; risk assessment and management. Risk assessment can further be subdivided into hazard (drought) and vulnerability analyze. Risk assessment is the relation between hazard, vulnerability and risk (Mileti, 1999). Therefore, any effective strategy to manage drought risk must begin with an identification of the types of droughts and what is vulnerable to them. This requires information on the nature and extent of risk that characterizes a particular location. It includes information on the nature of the particular physical droughts that can be obtained through hazard analysis, while vulnerability analysis gathered information and data on the degree of exposure of a population and its built environment to such droughts.

Conceptually, drought is a complex concept, as was discussed earlier, involving the supply and demand of water resources, and therefore both physical and social characteristics. Hence,

a conceptual approach to risk assessment can be broken down into a combination of the hazard and vulnerability.

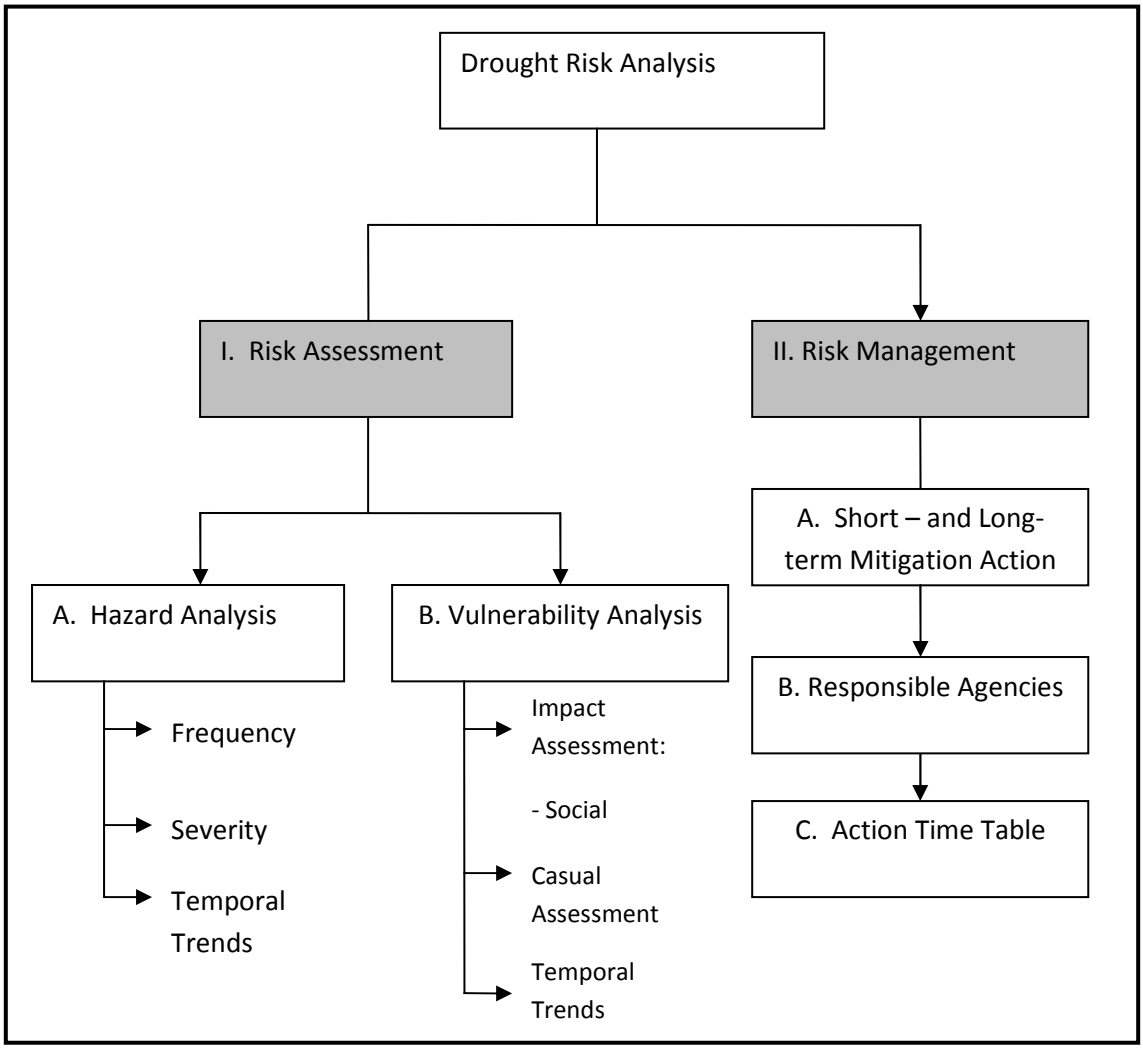

Figure 2.2: Drought Risk Analysis Framework. (After: Hayes *et al.*, 2004)

Blaikie *et al.*, (1994) originally represented risk as the sum of the hazard plus vulnerability (risk = hazard + vulnerability). More recently, risk has been represented as the product of the hazard and vulnerability (risk = hazard *x* vulnerability) (Knutson *et al.*, 1998; Downing *et al.*, 1999; Downing and Bakker 2000; Wilhite, 2000a).

Hazard in the study represents the probability of occurrence or frequency of droughts; vulnerability (defined differently) represents the broadest concept of biophysical and social vulnerability in a region. Therefore, to reduce drought risk, there must be an understanding of the risk using its climatology, improved operational monitoring, an analysis of vulnerability to understand what people and sectors may be most affected by drought, why these impacts occur, and if these relationships are changing over time.

This study will focused on drought analysis with the aim of defining drought precisely using a combination of meteorological and satellite-based indices.

2.3 Drought Analysis

2.3.1 Introduction

Numerous drought indices, using diverse variables for drought quantification, were developed during the 20th century (du Pisani *et al.,* 1998; Heim, 2000 and 2002; and WMO, 1975).

Meteorological and satellite-based drought indices are commonly used to identify and quantify drought's magnitude, duration, intensity and spatial extent, and to improve techniques for drought early warning and management (Wilhite *et al.,* 2000b). Meteorological drought risk analyses are predominantly based on precipitation using point data sets that are site-specific or applicable to small areas. They have many advantages such as that their measurability and their extensive historic records enable the application of numerous statistical techniques (Oladipo, 1985; Guttman, 1998; Keyantash and Dracup, 2002). Hence, the most robust and effective meteorological drought index is the Standardized Precipitation Index (SPI), developed by McKee *et al.,* (1993).

Satellite-based drought indices are chosen above point-based indices because of their accurate assessment of the occurrence, extent, and severity of drought and their excellent vantage/synoptic/bird's eye view of the drought situation. Combined with meteorological data, satellite-based indices give a correct picture of the spatial and temporal distribution of a number of meteorological and agricultural variables. NDVI is amongst the most widely used satellite based drought index, consequently, this study used NDVI data derived from the MODIS sensor as opposed to the coarse resolution AVHRR/NOAA sensors. The advantages of MODIS compared to NOAA/AVHRR form the crux of this study and will be discussed in Section 2.5.

Lastly, the used of GIS for integrating these data sets that were from different sources was used in this study and was found essential in many other drought studies (Lourens, 1995; Chang *et al.,* 1997; De Jager *et al.,* 1997; Ghosh, 1997; Reed, 1993; Thiruvengadachari and Gopalkrishna, 1993; Matthews *et al.,* 1994).

2.3.2 GIS methods to study drought risk analysis

GIS has an important role to play in drought analysis because of the following advantages over traditional methods such as maps (Wadge *et al.,* 1991): spatial modelling and map creation can be done on the same computer; a variety of models can be created and displayed to reflect different drought scenarios and in a format other than the traditional map; and the implications of drought in terms of risk and planning can be made understandable to planners.

Two commonly used techniques in studying drought risk analysis with GIS are deductive (or deterministic) and inductive (or empirical) techniques (Wadge *et al.,* 1991). In this study the *empirical approach* was used that is also widely used by many researchers in drought risk analysis. It used spatial and/or temporal characteristics of previous drought events to infer the ambient hazardous states of a number of environmental variables and forecast the liability to drought in the future. In this approach, after the spatial locations of past drought events are identified they are overlaid with a number of environmental variable coverages. Values of the variables at the drought sites are analyzed using some form of multivariate statistical techniques to derive global functions, which are then applied to produce a map of the drought potential (Wadge *et al.,* 1991).

Statistical techniques especially the empirical approach was used. It comprises linear regression (Jibson *et al.,* 1989), logistic regression (Bernknopf *et al.,* 1988) and discriminant analysis (Carrara *et al., 1991*).

In addition to the above techniques that are based on the physical environment, Rejeski (1993) proposed a new paradigm that integrates the “technical rationality” of the scientists, or the “cultural rationality” displayed by the public. This paradigm also echoes the concepts advocated by the Drought Risk Analysis methodology (Fig 2.2) discussed earlier and calls for models that integrate these subcultures such as the binary (nominal) models, weighted (ordinal) models and the quantitative (interval/ratio) models.

2.3.3 Drought Indices

2.3.3.1 Meteorological Indices

The traditional methods used to assess drought include most of the meteorological indices that are based on the meteorological parameters as recorded at meteorological stations. Therefore, they rely on the interpolation of rainfall and other variables in order to give a spatially distributed picture of the situation. Furthermore, they measure the climatic deviation from the "normal" and do not necessarily give a clear picture of the impact of the water deficit (Unganai and Kogan, 1998; Usman *et al.*, 2005).

Some of the well known meteorological drought indices, amongst others, are: Percent of Normal also known as Precipitation and Accumulated Precipitation Departure (Willeke *et al.*, 1994), Deciles (Gibbs and Maher 1967), Palmer Drought Severity Index (PDSI; Palmer, 1965), Standardized Precipitation Index (SPI; McKee *et al*., 1993), statistical rainfall Z-Score or standard score, Rainfall Anomaly Index (RAI; van Rooy, 1965), Crop Moisture Index (CMI; Palmer, 1965), Reconnaissance Drought Index (RDI, Tsakiris, 2004), National Rainfall Index (RI; Gommes and Petrassi, 1994), Effective Drought Index (EDI; Byun and Wilhite, 1999) and the Bhalme and Mooly Drought Index (BMDI; Bhalme and Mooly, 1980).

The advantages and disadvantages of a few commonly used indices were discussed in Chapter 1. For comprehensive reviews of meteorological and other drought indices see: Byun and Wilhite, 1999; Hayes, 2004; Heim, 2002; Keyantash *et al.*, 2002; Smakhtin and Hughes, 2004; Tate and Gustard, 2000, and Tsakiris *et al.*, 2004.

2.3.3.1 (i) Standard Precipitation Index (SPI) as an indicator of meteorological drought

The SPI is based on the probability of precipitation for any desired time scale and spatially invariant indicator of drought (Guttman, 1998, 1999). It involves fitting a gamma probability density function to a given frequency distribution of precipitation totals for a station (Edward and McKee, 1997). The SPI is computed by dividing the difference between the normalized seasonal precipitation and its long-term seasonal mean by the standard deviation.

Thus,

Equation 1: $$SPI = \frac{X_{ij} - X_{im}}{\sigma}$$

where, $X_{i\,j}$ is the seasonal precipitation at the *i*-th raingauge station and *j*-th observation, X_{im} the long-term seasonal mean and σ is its standard deviation. McKee *et al.*, (1993) proposed a seven-category classification for the SPI, this study will use the modified five drought classification scheme by Bhuiyan *et al.*, (2006):

Table 2.1: Drought classification scheme using drought indices.
(Modified after: Bhuiyan *et al.*, 2006; McKee *et al.*, 1993 and Kogan, 1995, 1998, 2002; Liu and Kogan, 1996)

	SPI	**VCI**	**NDVI**
No drought	> 0.0	>40	> 0.4
Mild drought	< 0.0	<40	< 0.4
Moderate drought	< -1.0	<30	< 0.3
Severe drought	< -1.5	<20	< 0.2
Extreme drought	< -2.0	<10	< 0.1

In this study, the SPI was calculated and analyzed using a one- and three – month time periods. It was calculated as follows, the precipitation total of the current month and previous *i* months (*i* = 1, 2, 3,. . .) were used to compute the (*i* + 1) - month scale of the SPI. For example, the one-month SPI of May utilized only the precipitation of May; the three-month SPI of May used the precipitation totals of May, April, and March. Hence, the SPI required different interpretations according to its time scale. For example, the one-month SPI reflects short-term conditions, and its application can be related closely to soil moisture and the three-month SPI provides a seasonal estimation of precipitation. (National Drought Mitigation Centre, http://www.enso.unl.edu/ndmc/). The one- and three-month periods was used for this study.

2.3.3.2 *Satellite-based Vegetative Drought Indices*

This study utilized the Normalized Difference Vegetation Index (NDVI) that uses the ratio of the reflectance of one band to that of another, the red and the near infrared. The use of NDVI-based indices for monitoring and detecting drought is justified because vegetation vigour is closely related to moisture condition and can easily be recorded by satellite sensors in real time.

Furthermore, the mitigation of the effects of severe droughts requires relevant information regarding droughts in near real time and the possible prediction and monitoring of droughts requires rapid and continuous data.

Moreover, satellite or remote sensing techniques can be used to monitor the current situation, before, during or after the drought which is more advantageous than conventional methods for collecting data on such phenomena that varied hugely in terms of spatial and temporal distribution. Hence, satellite sensors have the capability to retrieve surface parameters with various spatial and temporal resolutions over large areas that can provide a comprehensive view of the situation.

Numerous satellite based drought indices are used within Africa and world-wide. They can generally be subdivided into three groups (Bayarjargal *et al.*, 2006). The first group of the drought-indices are based on vegetation state derived from the reflective channels. This group includes the Normalized Difference Vegetation Index (NDVI; Tucker, 1979; Tucker and Choudhury, 1987; Ji and Peters, 2003b), Anomaly of Normalized Difference Vegetation Index (NDVIA; Anyamba *et al.*, 2001), Standardized Vegetation Index (SVI; Liu and Negron-Juarez, 2001; Peters *et al.*, 2002), Vegetation Productivity Index (VPI; Sannier *et al.*, 1998), Enhanced Vegetation Index (EVI; Huete *et al.*, 1994; Huete, *et al.*, 1997) and Vegetation Condition Index (VCI; Kogan, 1990a,b, 1995, 1997, 2000). The second group is based on surface brightness temperature derived from the thermal channel and includes the Temperature Condition Index (TCI; Kogan, 1997, 2000). The third group is based on combinations of the reflective and thermal channels and includes the ratio between Land Surface Temperature (LST) and NDVI (LST/NDVI; Lambin and Ehrlich, 1996; McVicar and Bierwirth, 2001; Karnieli and Dall'Olmo, 2003), the Vegetation Health Index (VHI; Kogan, 1997, 2000; Kogan *et al.*, 2004), and the Drought Severity Index (DSI; Bayarjargal *et al.*, 2000).

2.3.3.2 (i) Normalized Difference Vegetation Index (NDVI)

NDVI was first suggested by Tucker (1979) as an index of vegetation health and density (Thenkabail *et al.*, 2004).

Equation 2: $$\text{NDVI} = \frac{NIR - VIS)}{(NIR + VIS)}$$

where *NIR* and *VIS* are the reflectance in the near infrared (NIR) and visible (VIS - red) bands respectively. NDVI varies in a range of -1 to +1, but in practice it is well within these limits (Table 2.2). The healthy and dense vegetation show large NDVI values. In contrast, clouds, water and snow have larger visible reflectance than those of the near-infrared (NIR), hence, these features yield negative index values. Because of the above properties, NDVI has become a primary tool for mapping changes in vegetation cover (see Section 2.1 for drought definition) and is the most commonly used index (Jensen, 1996).

Table 2.2: Remote sensing data, indices and thresholds relevant to drought analysis.
(Modified after: Thenkabail *et al*., 2004)

Drought Index	Bands or index used to compute the index		Range	Normal Condition	Severe drought	Healthy vegetation
	AVHRR	MODIS				
1. NDVI	Band 1 (0.58 - 0.68 μm) Band 2 (0.73 - 1.10 μm)	Band 1 (0.62 - 0.67 μm) Band 2 (0.84 - 0.87 μm)	-1 to +1	Depends on the location	-1	+1
2. Drought Severity Index ($NDVI_{DEV}$)	NDVI NDVI long-term mean	NDVI NDVI long-term mean	-1 to +1	0	-1	+1
3. VCI	NDVI NDVI long-term minimum NDVI long-term maximum	NDVI NDVI long-term minimum NDVI long-term maximum	0 to 100%	50 %	0%	100%

Vegetation only shows signs of water stress after the available soil water have been depleted to the level that the water supply is less than the evapotranspiration loss. Since NDVI is a good indicator of vegetation greenness, a rainfall shortage can only be detected by NDVI after the leaves show the signs of greenness loss. Therefore, the NDVI correlates well with the rainfall amount required to maintain plant greenness and consequently, it can be properly used to infer drought as a result of rainfall shortage (also see Fig 2.1). Since rainfall data collected by surface observation stations often possess poor spatial resolution, especially in remote regions with difficult access, NDVI data may provide a valuable source of information for drought monitoring.

The severity of a drought (or the extent of wetness – on the other end of the spectrum) can be defined as NDVI deviation from its long-term mean ($NDVI_{DEV}$). This deviation is calculated

as the difference between the NDVI for the current time step and a long-term mean NDVI for that month for each pixel:

Equation 3: $NDVI_{DEV} = NDVI_i - NDVI_{mean,m}$

where $NDVI_i$ is the NDVI value for month i and $NDVI_{mean,m}$ is the long-term mean NDVI for the same month m. When $NDVI_{DEV}$ (Table 2.2) is negative, it indicates the below-normal vegetation condition/health and therefore points to the prevailing drought situation. The greater the negative departure, the greater is the magnitude of a drought. In general, the departure from the long-term mean NDVI is effectively more than just a drought indicator, as it would reflect the conditions of healthy vegetation in normal and wet months/years. This indicator is widely used in drought studies (Song *et al.*, 2004). Its limitation is that the deviation from the mean does not take into account the standard deviation and hence can be misinterpreted when the variability in vegetation conditions in a region is very high in any one given year.

NDVI's role in drought monitoring and assessment has been described by several authors during the last decades (Kogan, 1991, 1995; Yang *et al.*, 1998; McViar and Bierwirth, 2001; Ji and Peters, 2003b; Wan *et al.*, 2004). Most of these efforts were based on NDVI calculated from data collected by the Advanced Very High Resolution Radiometer (AVHRR) sensor. In contrast, this study used the successor to the AVHRR sensor, the MODIS terra sensor. Many studies (Gu *et al.*, 2007) have also used MODIS NDVI for vegetation cover analysis and drought monitoring.

However, despite the potential application of the NDVI, numerous shortcomings have also been revealed: (a) uses only two bands and is not very sensitive to influences of soil background reflectance at low vegetation cover, (b) has a lagged response to drought (Reed, 1993; Rundquist and Harrington, 2000; Wang *et al.*, 2001) due to a lagged vegetation response to developing rainfall deficits, and (c) for heterogeneous land cover, the NDVI is normally higher in areas with more favourable climate and soil and more productive ecosystems (forest) than in areas with less favourable environmental conditions. The development of the VCI provides an answer to the above challenges by primarily assessing the changes in NDVI (stratified vegetation type) signal through time due to weather conditions, by reducing the influence of geographic or eco-systems and by not using NDVI as the primary tool to detect drought.

2.3.3.2 (ii) Vegetation Condition Index (VCI) (Table 2.2)

Except, for its shortcomings NDVI generally provides a broad overview of the vegetation condition and spatial vegetation distribution in a study area. Vegetative drought is closely related with weather impacts. In NDVI, the weather component gets subdued by strong ecological component. VCI separates the short-term weather-related NDVI fluctuations from the long-term ecosystem changes (Kogan, 1990b, 1995). Therefore, while NDVI shows seasonal vegetation dynamics, VCI rescales vegetation dynamics in between 0 and 100% to reflect relative changes in the vegetation condition from extremely bad to optimal (Kogan, 1995). Therefore, the VCI is an indicator of the status of the vegetation cover as a function of the NDVI minima and maxima encountered for a given ecosystem over many years.

Equation 4: $$VCI = \frac{(NDVI - NDVI_{min})}{(NDVI_{max} - NDVI_{min})} * 100$$

where $NDVI_{max}$ and $NDVI_{min}$ are calculated from the long-term record for that month (or 16-day period) index of the current month. NDVI values are calculated using Equation 4 above. The condition/health of the ground vegetation presented by VCI is measured in percent. The VCI values around 50% reflect a fair vegetation conditions. The VCI values between 50 to 100 % indicate optimal or above-normal conditions. At the VCI value of 100% the NDVI value for this month (or week) is equal to $NDVI_{max}$. Different degrees of a drought severity are indicated by VCI values below 50% depending on the study area, however 36% were used for this study (Kogan 1998). The VCI value close to zero percent reflects an extremely dry month, when NDVI value is close to its long-term minimum. Consistently low VCI values over several consecutive time intervals may point to drought development/presence.

2.4 Potential of GIS, SPI and NDVI for drought risk mapping

Studies on drought delineation using the different drought indices span many regions, continents and decades and are summarized in Table 1.1 below. It illustrates the extensive nature of the usage and potential of, especially NDVI-based, drought indices in studying drought risk mapping. These studies are predominantly based on coarse spatial resolution (Figure 1.1) AVHRR NDVI except Gu *et al., (*2007) which used MODIS NDVI.

The utilization and potential of satellite-based indices for drought delineation are particularly highlighted by the following studies; Bhuiyan *et al.,* (2006) monitored drought dynamics in

the Aravalli region of India using NDVI, VCI, SPI and other drought indices. Their study produced numerous vegetative and meteorological drought maps which were analyzed, correlated and compared. The study concluded that a deficient rainfall as per the SPI index does not always correspond to vegetative drought. Bayarjargal *et al.,* (2006) compared the spatial occurrences of droughts detected by remotely sensed drought indices amongst them NDVI, VCI and DSI. The study concluded that it is difficult to point out the most reliable drought index but that the combination of satellite derived drought indices can identify wider drought-occurred areas. Viau *et al.,* (2000) used VCI and SPI at different scales for the spatial and temporal detection, assessment and monitoring of drought conditions in Spain. Song *et al.,* (2004) designed an early detection system for drought mapping in East Asia using NDVI from NOAA/AVHRR. They calculated standard NDVI and up-to-date NDVI to derive difference NDVI ($NDVI_{DEV}$) image, which enabled them to detect drought intensity and agricultural damaged areas.

Gu *et al.,* (2007) analyzed a five year history of MODIS NDVI and Normalized Difference Water Index (NDWI) data for grassland drought assessment within central USA. The results showed strong relationships among NDVI, NDWI and drought conditions. They also produced a new drought index, the normalized difference drought index (NDDI) that showed a stronger response to drought conditions than NDVI while others combined the drought indices with GIS and other data to create models. Mongkolsawat *et al.,* (2001) in Northeast Thailand modelled drought risk areas by using three different types of droughts i.e. meteorological, hydrological and physical drought which were calculated using an overlay matrix operation to yield the areas which faced drought risk. Prathumchai *et al.,* (2001) used weighted linear combination to identify drought risk areas.

Lastly, Nawa (2000) used Meteosat and NDVI data to monitor drought in Zambia and Rabab (2002) used NDVI for delineating drought vulnerable areas in Pakistan.

Many studies used the binary and weighted models for drought risk analysis in GIS. They include Reed (1993), Thiruvengadachari and Gopalkrishna (1993), Matthews *et al.,* (1994), Wilhelmi and Wilhite (2002), Mongkolsawat *et al.,* (2001) and Prathumchai *et al.,* (2001).

GIS also has the capability to generate an improved agricultural drought monitoring system that integrates various factors that contribute to drought impacts, and that will present the results in a timely and appropriate manner for policy makers (Lourens *et al.,* 1995, de Jager *et al.,* 1998).

Even though several researchers have attempted to combine as many variables (Figure 2.1; rainfall, temperature, evaporation, soil type, etc) as possible, some studies (Alley, 1984; Oladipo, 1985) have found that multivariable indicators do not do any better than measures based entirely on rainfall. Furthermore, timely operational availability of information on all these variables may also be an important hindrance in using multivariable indices (Usman *et al.,* 2005).

As indicated earlier, SPI is more reliable for detecting emerging drought than other meteorological indices. It has become an increasingly important tool for assessing moisture condition and initiating mitigation and response actions (Wilhite *et al.,* 2000).

Although, SPI is a recent index, it was used in Turkey (Komuscu, 1999), Argentina (Seiler *et al.,* 2002), Canada (Anctil *et al.,* 2002), Spain (Lana *et al.,* 2002), Korea (Min *et al.,,* 2003), Hungary (Domonkos, 2003), China (Wu *et al.,* 2001) and Europe (Lloyd-Hughes and Saunders, 2002) for near real-time monitoring or respective analysis of droughts. SPI have also been used extensively in the USA to monitor, especially, the 1996 drought and for continuous drought monitoring (Hayes *et al.,* 1999; Brown *et al.,* 2002).

Numerous studies in southern Africa (Rouault and Richard, 2003; Smakhtin *et al.,* 2006; South African Weather Service (2009); Monnik, 2000; Usman *et al.,* 2005) have used SPI at national scale to determine and monitor the intensity and spatial extension of droughts at different time scales.

Furthermore, many studies have used SPI to monitor and delineate drought area such as Ji *et al.,* (2003b) who undertook a study to assess vegetation response in the northern Great Plains using NDVI (vegetation) and SPI (drought index). Vicente – Serrano *et al.,* (2007) determined the spatial differences in the effects of drought on the natural vegetation and agricultural crops by means of the joint use of NDVI, SPI, and GIS. Loukas and Vasiliades, (2004) used SPI to investigate the temporal and spatial characteristics of meteorological drought to provide a framework for sustainable water resources management. Mishra and Desai, (2005) used SPI to forecast droughts in the planning and management of water resource systems in India. Agnew (2000) and Komuscu (1999) used SPI to identify meteorological droughts. Bhuiyan *et al.,* (2004) used various drought indices (SPI, NDVI and others) to monitor drought conditions in India. Smakhtin *et al.,* (2004) reviewed existing drought indices to analysis their applicability for drought detection/prediction and management in south Asia. Keyantash and Dracup, (2002) evaluate drought indices for the quantification of drought. Lastly, Edwards

and McKee, (1997) used SPI to provide the means to analyze drought and wet periods at different time scales to characterize drought in the USA.

2.5 Gaps in mapping drought risk areas using Remote Sensing

When choosing a data source in remote sensing for drought risk analysis, sensor resolution is an important issue. The coarse spatial resolution (Figure 1.1) of the satellite data used in the above mentioned studies (Table 1.1), limits their effectiveness at detecting local scale variability. High spatial resolution satellites, however, have relatively long revisit times, and, given inevitable weather or technical problems, it can be difficult to obtain sufficient images to incorporate adequate phenology information for a large area. Hence, the 16-day revisit time of the Landsat 4, 5 and 7 satellites (Figure 1.1), and the high likelihood that clouds would obscure parts of one or more scenes, make it likely that images could not be acquired during the desired times. In contrast, medium spatial resolution sensors such as MODIS provide daily coverage of the earth, and so weather events are much less of an obstacle.

Much of the research in the southern Africa region has focused on using the extended time-series of NDVI derived from the Advanced Very High Resolution Radiometer (AVHRR) aboard the National Oceanic and Atmospheric Administration (NOAA) series of polar-orbiting meteorological satellites. As the AVHRR sensor was not originally designed to monitor vegetation, studies have revealed some disadvantages in the payload of the AVHRR platforms regarding the design of the channel 1 and 2 when formulating NDVI (King, 1999).

Furthermore, the low spatial resolution of the NOAA-AVHRR data and the large errors inherent in the NDVI time series data sets (poor sensor calibration, poor pixel location, insufficient cloud screening and variable acquisition geometry) seriously impede their utilization for vegetation cover studies (Ferreira *et al.*, 2007, Goward *et al.*, 1991, Moody and Strahler 1994).

Built on this knowledge, new and improved generation of Earth Observing data have emerged, including the polar orbiting Moderate Resolution Imaging Spectroradiometre (MODIS) sensor aboard the National Aeronautics and Space Administration's (NASA) TERRA and AQUA platforms.

King (1999) stated that the MODIS vegetation indices are envisioned as improvements over the current NOAA-AVHRR NDVI as a result of both improved instrument design and characterization and the significant amount of vegetation indices research conducted over the

last decade. The new indices are based on improved knowledge of atmospheric effects, soil effects, sun- and view-angle effects, surface anisotropy, and canopy radiant transfer models. Improved vegetation sensitivity was achieved with improved MODIS sensor characteristics and from the optimal utilization of MODIS sensor wavebands (King 1999). The new MODIS VI will: 1) increase sensitivity to vegetation; 2) further normalize internal and external noise influences, thus improving the vegetation signal-to-noise ratio (external-, internal-, and sensor caused); and 3) provide new, unique information for vegetation analysis. External variations was minimized through atmospheric correction algorithms, an atmospherically- resistant NDVI equation, and a level 3 compositing algorithm which incorporates the anisotropic reflectance behaviour of vegetated surfaces utilizing directional MISR data. Furthermore, MODIS' attractiveness is also from a data continuity perspective, as a follow-on to AVHRR and its record of acquisition from 2000 to present is becoming long enough to provide homogeneous time-series information. Moreover, MODIS data continuity from Terra and Aqua satellites is guaranteed over time with successor satellite and sensor systems already planned and assured, at least, until 2018, with National Polar-Orbiting Operational Environmental Satellite System (NPOESS) series of satellites (Justice and Townshend 2002). Lastly, its 2,000-km swath is easily applied to daily global coverage needs, and MODIS data specifications ensure improved accuracy over previous satellite sensors.

Even though MODIS NDVI data are the most suitable for the current study, other operational users have identified barriers that must be overcome to assimilate MODIS products in their work. Standard MODIS products have been designed to accommodate the needs of science investigators, but several elements of the product specifications limit their relevance and use in decision support systems. First, the standard MODIS VI products are composited on a 16-day interval, reducing the temporal sensitivity often needed in vegetation monitoring applications. Second, the standard product tiles are cast on a Sinusoidal mapping grid and are available as HDF-EOS format, both of which present barriers to the ready assimilation of data into modelling and monitoring frameworks. Third, and perhaps most importantly, the standard products are not generated, delivered, and made available quickly enough to support monitoring requirements in near-real time. While the positive characteristics of MODIS represent a valuable extension of the global AVHRR record, many operational users continue to find difficulty overcoming the aforementioned barriers to effectively detect, monitor, and model change on an abbreviated time scale. Most of the aforementioned challenges were overcome as was explained in Chapter 4 – Materials and Methods.

It is against this background that MODIS NDVI is rarely used to delineate drought prone areas. Those that use it, for example, Richters (2005), used 1 km x 1 km spatial resolution data and did not attempt to map drought areas but rather develop a vulnerability model for the evaluation of environmental changes in northwest Namibia. This model mapped biomass changes and degradation areas while other studies such as Klintenberg and Seeley, (2004) developed a degradation risk model using AVHRR NDVI at 1km x 1km data with other data. Their results include land degradation maps at national scale for two selected locations in Namibia. A study by Sannier *et al.,* (1998) creates a new vegetation index that is highly correlated to rainfall hence enabling the identification of drought affected areas. The study used coarse resolution AVHRR NDVI to produce the vegetation production index (VPI).

A study by du Plessis (1999) established a linear regression relationship between NDVI, vegetation cover and rainfall in Etosha National Park, Namibia. The current study is located next to Etosha National Park, hence the results of this study can help to confirm the positive correlation between rainfall vs NDVI and MVC, even though the sensor used was AVHRR. Another study using NDVI was by Sannier *et al.,* (2002) estimated biomass production for the assessment of fire risk. Lastly, a comprehensive study on the 1992/3 drought in Namibia was done by Moorsom *et al.,* (1995) who analyzed meteorological drought indices at a national scale.

2.6 Conclusion

In the first part of this chapter drought was described as an insidious hazard of nature. Even though it has scores of definitions and it originates from a deficiency of precipitation over an extended period of time, usually a season or more. It can be classified as conceptual or operational. Four types of operational drought definitions were discussed: meteorological, agricultural, socio-economic and famine. Figure 2.1 summarized these drought types and their impacts.

Drought is one (others might include floods and fires) of the many natural hazards of nature. Hence, the chapter also discussed the Drought Risk Analysis (Hayes *et al.,* 2004) methodology which provided a holistic approach to drought studies. The study specifically focused on hazard analysis and since the hazard studied here is drought, the term hazard was replaced with drought.

Two types of drought indices were discussed namely, meteorological and satellite-based. Table 2.1 classified the SPI, VCI and NDVI into different drought categories while Table 2.2 gave a summary of the different bands these indices used and their characteristics pertaining to thresholds relevant to drought analysis. Table 1.1 summarized the studies that used these drought indices and their potential for this study.

Lastly, the last part of this chapter discussed the gaps in mapping drought risk areas and highlighted the coarse spatial resolution of these studies in Table 1.1 had used compare to the medium spatial resolution this study used.

Chapter 3: Study Area

3.1 Introduction

Namibia is situated in the south west of the continent of Africa, bordered by the Atlantic Ocean on the west, Angola and Zambia to the north, Botswana to the east and the Republic of South Africa to the south (Fig. 3.1). The total land area is 824, 269 km^2, which can be divided into three main topographic regions. The first is the western coastal plain of the Namib Desert, occupying 12% of the total, and the second is the central plateau stretching from the southern to the northern border and covering more than half the country, and the third is the semi-arid Kalahari zone lying along most of the eastern portion of the country (Isaacson, 1995).

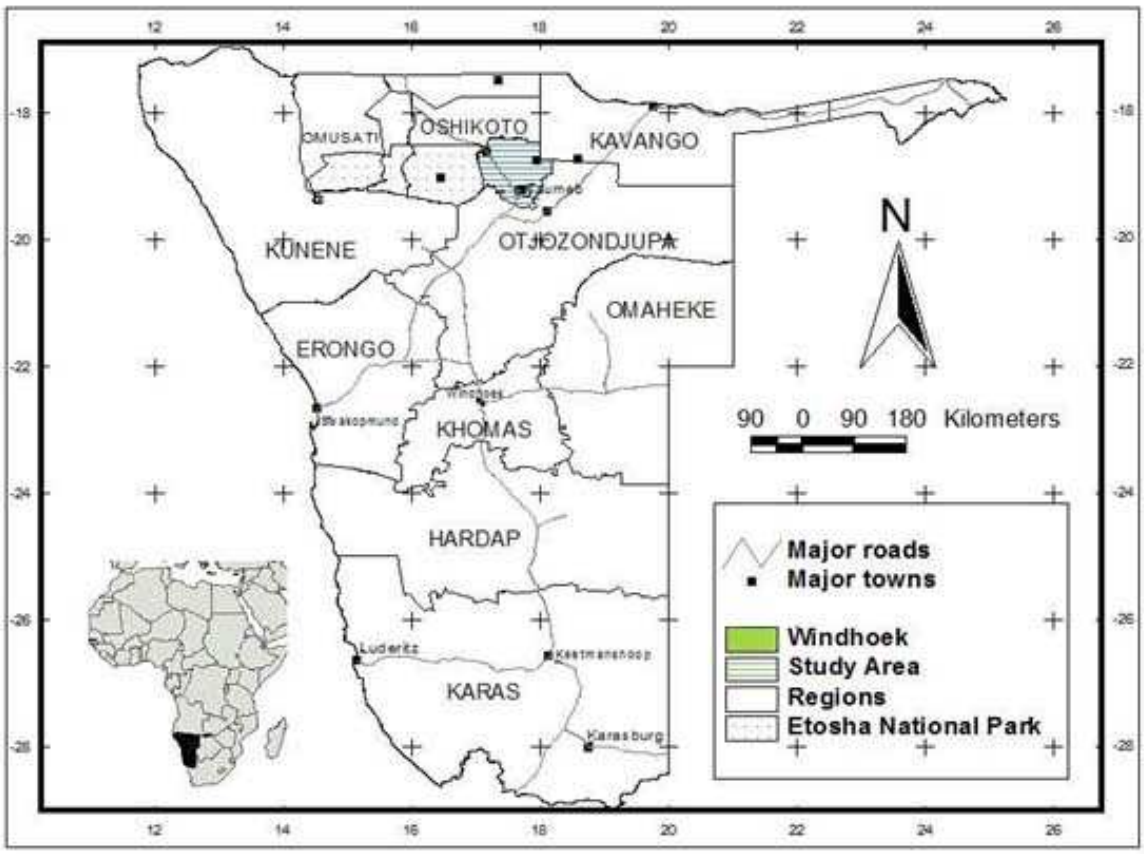

Figure 3.1: Location and extent of the Study Area

The mean annual rainfall of Namibia is approximately 270 mm, consequently it is rated to have the driest climate in sub-Saharan Africa (NDTF, 1997a). Furthermore, there is a wide regional variation in annual rainfall, from less than 20 mm in the western Namib and coastal zones to more than 700 mm at the eastern end of the Caprivi Strip. Namibia has a medium to

low potential for rain-fed and irrigated crop production, partly because some 97% of the country's soils have a clay content of less than 5%. As a result, this potential represent only about 1% of the land surface, or 820 000 hectares considering soils and rainfall (NDTF, 1997a).

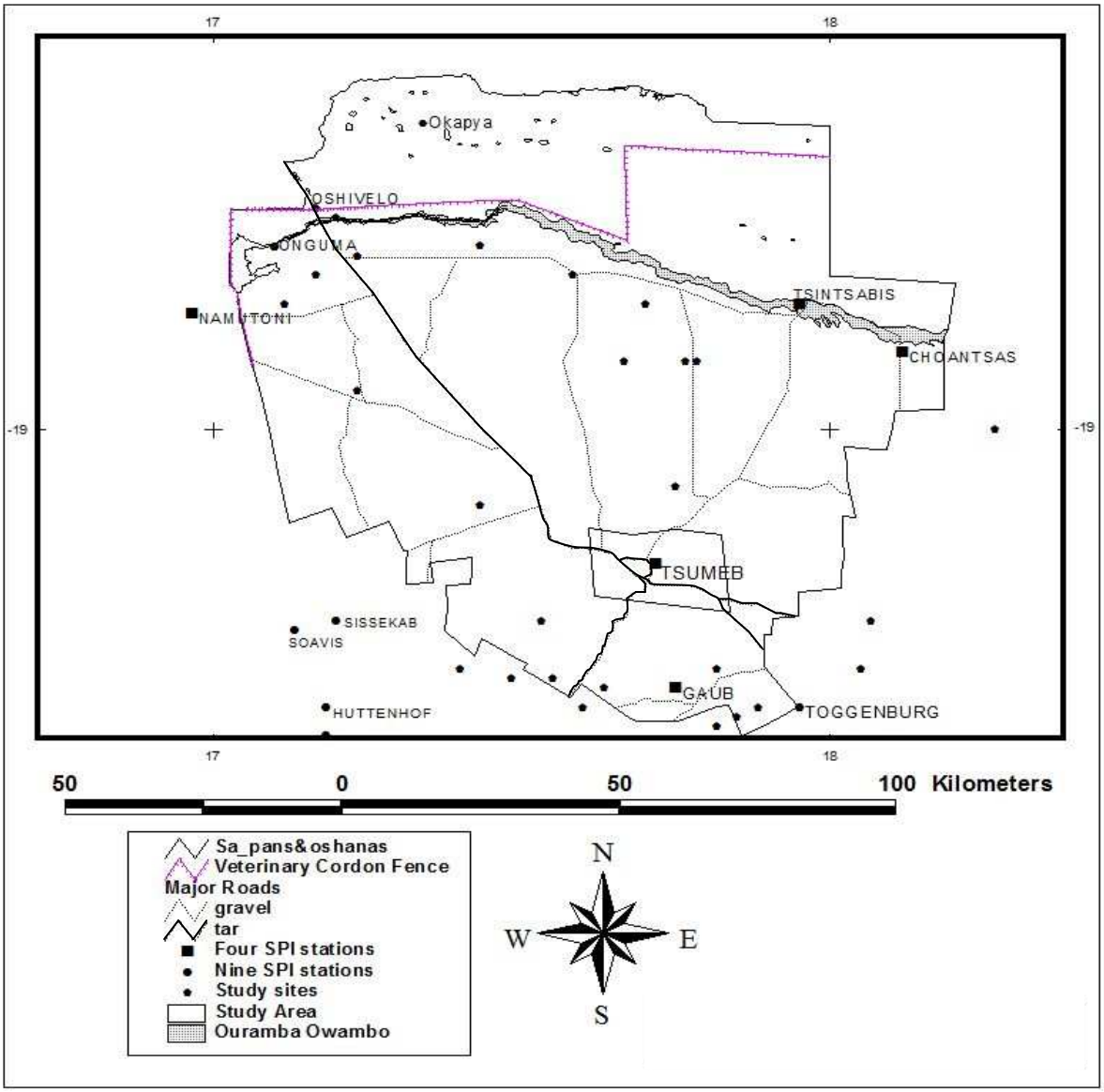

Figure 3.2: The Study Area.

3.2 Location and Extent of study area

The Oshikoto region is part of thirteen political regions of Namibia (Figure 3.1). The region is also located within the Northern Communal Areas that consist, amongst others, of the Omusati, Oshana, Ohangwena and Oshikoto regions. The Northern Communal Area (NCA) is predominantly for subsistence farming purposes and is characterized by very low and even declining productivity due to a combination of low and uneven rainfall and poor soils. Furthermore, the NCA, in general are also burdened with conditions of extreme income inequality and poverty, under-nutrition, out-migration of labour and high population growth rates (Sweet, 1999).

The northern part (Fig 3.2 and 3.3 - north of the Omuramba Owambo) of the study area forms part of the NCA, while the rest forms part of commercial and resettlement farms.

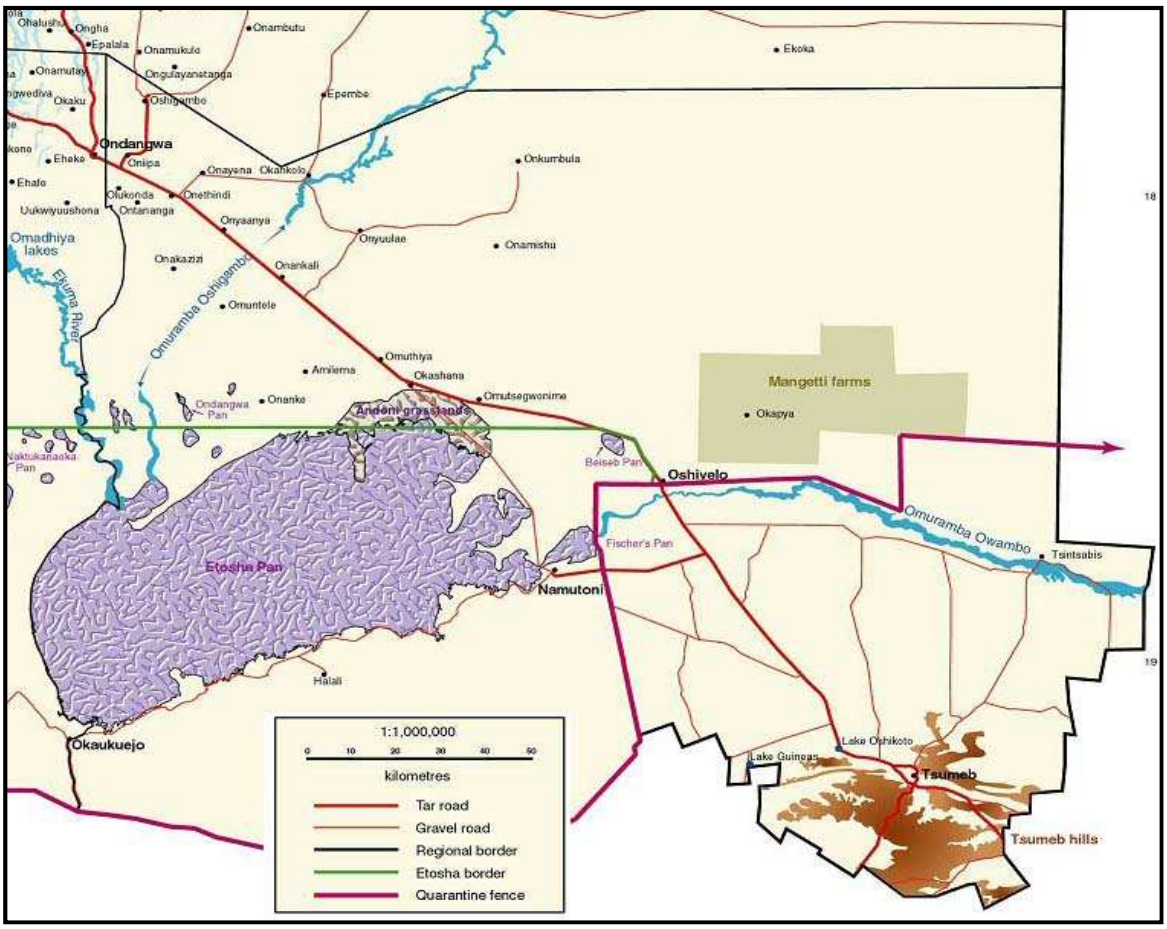

Figure 3.3: The Study Area and part of the surrounding northern NCAs. (Source: Adapted from Mendelshon *et al.*, 2000)

Namibia's NCAs occupy an area of about 170,000 square kilometres to the north of the country's only active Veterinary Cordon Fence (VCF; Fig. 3.2 and 3.3), which runs approximately along the 19th parallel. The VCF restricts the movement of livestock and livestock products from the north to south. Moreover, the VCF has been successful in preventing the introduction of diseases into the commercial farming areas from where the bulk of the country's meat exports emanate. According to Vigne and Whiteside (1997) nearly 50 percent of the country's population lives here, in most farming communities that is mainly for subsistence and is based on agro-pastoral farming systems. These systems are characterized by strong crop-livestock production linkages and in some regions, pastoralism based on seasonal grazing areas. Land in the NCAs is owned by the State and administered by traditional authorities in a variety of ways, including in some areas the de facto sale of land to wealthy individuals.

The administrative capital of the Oshikoto region is Tsumeb and it is also the only urban centre as well as one of the constituencies that forms part of the study area (Fig 3.2). Regions are divided into constituencies, the study area made up of two; Tsumeb and Guinas. Tsumeb also forms part of Namibia's maize triangle that includes towns such as Otavi and Grootfontein, where commercial maize production is practiced under irrigation. Maize can either be planted in August/September or December/January. It can then be harvested in February/March or June/July, respectively.

The study area, therefore, also comprise of commercial farms which are located to the south of the VCF and communal areas to the north, making it an interesting and appropriate area to study due to its diversity in land use, land tenure, natural resources and other biophysical features.

3.3 Landscapes and Topography

Generally, the study area is flat except for the southern part which forms part of the Otavi Highlands (Fig. 3.3 - Tsumeb hills). The altitude of the study area ranges from over 1500m at Guab to less than 1095m at Namutoni and Onguma while it is between 1160 – 1170m at Choantsas. Hence, the Namutoni area is the lowest and it is also the extreme eastern extension of Etosha and the other salts pans (Fig. 3.3). The drainage direction is towards the world famous Etosha Pan located to the east of Namutoni.

The flat landscape has been produced by various depositions that have filled the Owambo Basin. Furthermore, the study area has four distinct landscapes that were created by the erosional and depositonal processes and the resultant differences in elevation, soil and vegetation.

These landscapes include, amongst others the Karsveld, Salt pans and surrounding plain and the Eastern Kalahari Woodlands.

The Karsveld is located to the south of the Omuramba Owambo and Namutoni. It lies on massive deposits of calcrete deposits and dolomite while the dolomites represent the remnants of the rim of the Owambo Basin folded upwards during the formation of Gondwanaland. The saltpans and surrounding plains are located as a tongue extending west-ward from Onguma to Namutoni (Fig. 3.3). It forms a distinct landscape represented by the well-known Etosha Pan. The pans are dry for most of the year and surrounded by treeless plains. Lastly, the Eastern Kalahari Woodlands is located north of the Omuramba Owambo (Fig. 3.3). It is dominated by a huge expanse of deep Kalahari sands and some parallel ridges of dunes running east to west. The pans, drainage lines and inter-dune valleys are the only places in this landscape type where crops can be grown because their soils are more clayey. The southern boundary is marked by the Omuramba Owambo, which appears to prevent the spread of Kalahari sands to the south of the study area (Mendelsohn *et al.*, 2000).

3.4 Drainage and Water supplies

The most prominent river that drains the study area is the Omuramba Owambo that forms part of the Cuvelai system. The river provides water to Etosha Pan through Fischer's Pan (Figure 3.3) when good rains are received in the eastern part of the study area. This river originates from the east unlike the Cuvelai system that originates in Angola. This system brings both water and fish into the northern part of the study area when it flows. This usually only happens when a medium or high flow or *efundja* occurs, which is in about four out of every ten years on average according to Mendelsohn *et al.*, (2000). Surface water is heavily relied upon in this part of the study area (north of the Omuramba Owambo) which forms as a result of local rainfall and is also found in the many pans. Additionally, people depend entirely on water drawn from shallow wells during dry periods in this part of the study area. Many lakes and pans occur within the study area, such as the Lake Oshikoto and Guinas and the other small ones near Okapya (Fig. 3.2).

Throughout the study area boreholes are reliable sources of water since water is supplied by underground aquifers that hold water that has accumulated over a long time. These boreholes can yield groundwater at 1 – 5 cubic metres per day which is enough to supply a village and can be found almost everywhere in the region (Mendelsohn *et al.*, 2000).

One of such aquifers in the study area is the Otavi Dolomite Aquifer, which is associated with karstveld reserves in the Tsumeb area. It typically yields fresh water, often in large quantities, and is used to supply the town of Tsumeb and the crop (maize) irrigation schemes in the surrounding areas. Huge dams are rare in the study area and their absence can be attributed to the study area's gently sloping landscape and high evaporation rates (Mendelsohn *et al.*, 2000).

3.5 Climate

The study area can be classified as semi-arid with rains falling in the summer months when temperatures are highest. The annual average rainfall varies from 600mm at Guab and Toggenburg to 450mm in the Namutoni (Fig. 3.2). There is a general decrease in rainfall towards the west and north-west and an increase towards the south and north-east. Most of the moist, rain-carrying air blows in from the north-eastern and north, so these areas not only receive rain first, they receive more of it, thus leaving less moisture available to fall further south and west. The zone of higher rainfall around Tsumeb is the result of the hills forcing incoming air upwards where it cools, condensing the water vapour and producing greater falls of rain in that area (Mendelsohn *et al.*, 2000).

On average, 96% of all rain falls during the six months from November to April. In fact, most rain is concentrated in January, February and March, when an average of two-thirds of the year's rain falls. These are usually the only productive months with enough rain for crop and pasture growth (Mendelsohn *et al.*, 2000).

The average daily temperatures rise from about 17° Celsius in June and July to about 25° Celsius in October, November and December. These three months and September also have the highest maximum temperatures for the year of between 30° and 35° Celsius. The summer months that follow are generally cooler due to the effects of cooling rain and greater cloud cover. Average minimum winter temperatures drop to about 7° or 8° Celsius and very few days with temperatures close to zero are encountered. Frost may occur very occasionally further south in the study area (Mendelsohn *et al.*, 2002).

On average, about 2500 millimetres of water evaporates each year, against an average amount of rain of 400 – 500 mm per year, five to six times more water evaporates than falls. Hence, it is this difference between low rainfall and high evaporation rate that produces the region's arid environment (Mendelsohn *et al.,* 2002).

3.6 Vegetation and Soils

Nine major types of soils are found in the study area and are largely dominated by sands and clays, which have been reworked and mixed by the action of water and wind. They are silts, sodic sands, deep Kalahari sands, loams and clays, loams, clayey sodic sands, sands and loams, clayey sands and dolomite sands. Their potential for crop cultivation is low in most areas for several reasons: poor water holding capacity, low nutrient content, high salt content and hard layers of clay below the surface (Mendelsohn *et al.,* 2000).

Most plants characteristically grow on certain types of soils, so those in the eastern Kalahari sands are quite different from those in other landscapes (Section 3.3).

In areas north of the Omuramba-Owambo, Mopane and various older trees provide important sources of wood. Fruit and many other products are harvested, which are of greatest value to the poorest people. Grasses and shrubs feed large numbers of domestic stock and have resulted in a reduction in the availability and quality of pastures. More farmers are changing land use, especially in the Tsumeb area, as many farms have become badly encroached by dense thickets, making the farms much less productive for cattle ranching than they were before (Mendelsohn *et al.,* 2000).

3.7 Demography and Household economics

The estimated number of people in the Oshikoto region is about 151, 900 for the year 2000 (Mendelsohn *et al.,* 2000) whereas the total population enumerated by the Namibian Central Bureau of Statistics (CBS) in 2001 is 161,007 (NPC, 2004). The growth rate is 2.2% lower than the national average (NPC, 2004). The study area is predominantly rural based while only the Tsumeb area is urban. The literacy rate is up from 78% in 1991 to 84% in 2001. The housing conditions particularly safe water access, increased from 19% in 1991 to 88% in 2001 while the main source of household income is farming with 56%, followed by wages and salaries with 21% and pension with 11% (NPC, 2004).

The structure of the population is skewed by high rural-to-urban migration rates, particularly of working-age people to towns elsewhere in Namibia. Fertility rates have decreased in recent years and death rates are expected to increase dramatically because about one in four people now carry HIV, the virus that causes AIDS (Mendelsohn *et al.*, 2002).

A vibrant economy based on mining collapsed due to the closing and now downscaling of mining activities in Tsumeb a few years ago. In the northern part of the study area, there are large disparities in wealth between households: big households with many family members are much wealthier than small ones. Large households have also a greater diversity of incomes, more labour, more livestock, bigger fields and more access to cash than poor homes. Hence, they are exposed to less risk in the event of mishap or disaster, nevertheless they also consume far more natural resources than anyone else does (Mendelsohn *et al.*, 2000).

3.8 Land tenure, governance and farming

Agriculture represents most of the region's land use. The agricultural land use can be subdivided into small scale farming, communal grazing, large farms in the Tsumeb area, the Mangetti farmers and people that were relocated to resettlement farms.

The cultivation of rain fed crops in Namibia are mainly confined to the northern communal areas apart from a small but significant area of commercial maize production in the so-called maize triangle between Grootfontein, Tsumeb and Otavi (Sweet, 1998b). Pearl millet is the most widely grown cereal in the northern part of the study area, and maize (some irrigated – Maize triangle) in the commercial areas. Wheat is only grown in the commercial areas and under irrigation. Maize is widely preferred as the staple food in the communal areas, but millet and sorghum are more reliable crops except in the highest rainfall zones (Sweet, 1998a; Vigne and Whiteside, 1997) with the study area.

Except for the commercial farming area, farming contributes very little to the cash incomes of the majority of households because few farm products are sold. However, farm products are a vital source of food for poor households, while farming serves only as an investment for wealthier households.

Low levels of agricultural productivity and aggregate production, particularly in the communal areas, north of the Omuramba-Owambo, pose the major constraints to agricultural and rural development (Isaacson, 1995).

3.9 Agro-ecological Zoning

Agro-ecological zones (AEZ) are considered to be land entities that are sufficiently uniform in terms of climatic, landform and soil features for broad planning objectives and are unique by the specific combinations of these land attributes (De Pauw *et al.*, 1998). Figure 3.4 shows the nine AEZs that are present in the study area.

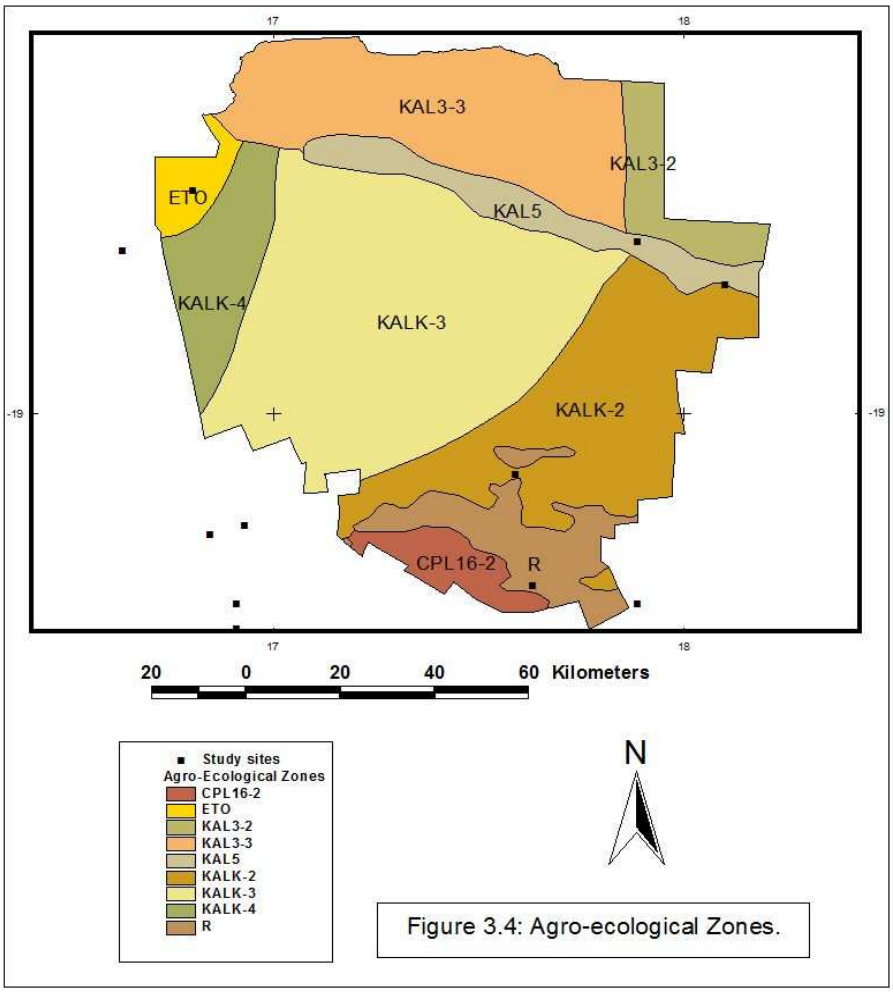

Figure 3.4: Agro-ecological Zones.

Table 3.1 shows a summary of the evaluation of the potential per agro-ecological zones in the study area. The growing period refers to the time during a growing season when air temperature, soil temperature and soil moisture permit crop growth. A Growing Period Zone (GPZ) defines climatically comparable zones, while at the same time incorporating temporal variability (Coetzee, 2000). According to De Pauw *et al.*, (1998), Namibia can be divided into 11 GPZs. Zone 1 represents all year humid periods while zone 11 represents all year very dry

periods. The study area has a relative sub-humid climate according to the GPZ ranking of 2, 3, and 3 (Table 3.1), although it is not suitable for crop farming due to shallow soils.

Table 3.1: Summary evaluation of potential per agro-ecological zone.
(Source: de Pauw *et al*., 1998).

Growing Period Zone ranking	Suitability	AEZ's
2	Large stock grazing	CPL16-2, KAL3-2, KAL8, KALK-2
3	Large stock grazing	KAL3-3, KAL4, KAL9-3, KAL5
4		ETO, KALK-4
	N.A.	R

Table 3.2 evaluates the cropping potential for individual agro-ecological zones and indicate that most AEZs are not suitable for crop farming but excellent for grazing. The only zone that is suitable for crop farming is CPL16-2 (Figure 3.4).

In general, the growing period analysis confirmed that only a small part of Namibia receives sufficient rainfall to make crop production feasible. Even where feasible, cropping remains risky and often unproductive, owing to variable rainfall and low moisture retention capacity of the predominantly sandy soils (Coetzee, 2000).

Table 3.2: Evaluation of cropping potential for individual agro-ecological zones.
(Source: de Pauw *et al*., 1998).

Rank	AEZ	Evaluation of cropping potential
2	CPL16-2	Mainly sandy and loamy soils, often shallow; usually underlain by calcrete. Dependable growing period can be adequate for crop growing, provided soils are deep and have a good moisture retention capacity.
	KAL3-2	Mainly deep sandy soils; dependable growing period marginal even for drought-resistant crops, owing to the low moisture retention and fertility status of the soils.
	KALK-2	Not suitable for cropping due to predominance of shallow soils on calcrete. Good grazing areas.
	KAL3-3, KAL4	Unsuitable for crop production due to low dependable growing period, combined with sandy soils.
3	KALK-3	Unsuitable for crop production due to low dependable growing period, combined with shallow soils.

Chapter 4: Materials and Methods

In this chapter the different data sets and their sources that were used in a systematic methodology, comprising of phases, such as pre-fieldwork, fieldwork and post-fieldwork and their sources are presented.

4.1 Data characteristics and acquisition

This study used four sets of data to achieve its objectives. These include MODIS NDVI, meteorological data, agricultural data and data collected through fieldwork.

4.1.1 Satellite data

The satellite based data that was used is derived from the MODIS sensor, a successor of AVHRR. MODIS is the primary sensor for monitoring the terrestrial ecosystems for the NASA Earth Observing Systems (EOS) program (Justice *et al.,* 2002). According to Heute *et al.,* (2002) the MODIS is more sensitive to changes in vegetation dynamics and was found to be more accurate and versatile instrument to monitor the global vegetation conditions than the AVHRR (Gitelson and Kaufman, 1998 – see also Section 2.5).

The MODIS sensor acquires data in 36 spectral bands, in variable spatial resolution of 250-1000 meters, in narrow bandwidths and in 12-bits. The 36 MODIS bands are a compromise of atmospheric, land and ocean studies of which seven bands are considered optimal for land applications (Justice *et al.,* 2002). MODIS data have a temporal resolution of 8 days and are available since 2000 till 2009 (present). The 8-day, 7-band data are made available by USGS EROS DAAC (similar to the pre-processed AVHRR reflectance data by NOAA GSFC), after corrections for molecular scattering, ozone absorption and aerosols. The data are also adjusted to nadir and standard sun angles with the use of bi-directional reflectance (BRDF) models (Vermote *et al.,* 2002, Justice *et al.,* 2002). The seven bands have waveband centres at 648 nm, 858 nm, 470 nm, 555 nm, 1240 nm, 1640 nm, and 2130 nm respectively. All MODIS data are directly downloadable free of charge from the USGS EROS data centre (http://edcdaac.usgs.gov).

Many products are available from the Moderate Resolution Imaging Spectroradiometer (MODIS), amongst them the vegetation indices (VI) products. They are designed to provide consistent, spatial, and temporal comparisons of global vegetation conditions that can be used to monitor photosynthetic activity according to Huete *et al.,* (2002), Justice *et al.,* (1998) and Running *et al.,* (1994). Two MODIS vegetation indices are available, the normalized

difference vegetation index (NDVI) and enhanced vegetation index (EVI), the study used the former. These VIs are produced globally over land at 250 m, 500 m and 1 km resolutions and 16 and 32 – day composing periods.

Most of the standard MODIS data use the Sinusoidal grid tiling system, tiled at 10 degrees by 10 degrees (Fig. 4.1) at the equator and the products are processed at different processing levels from Level 2 to 4.

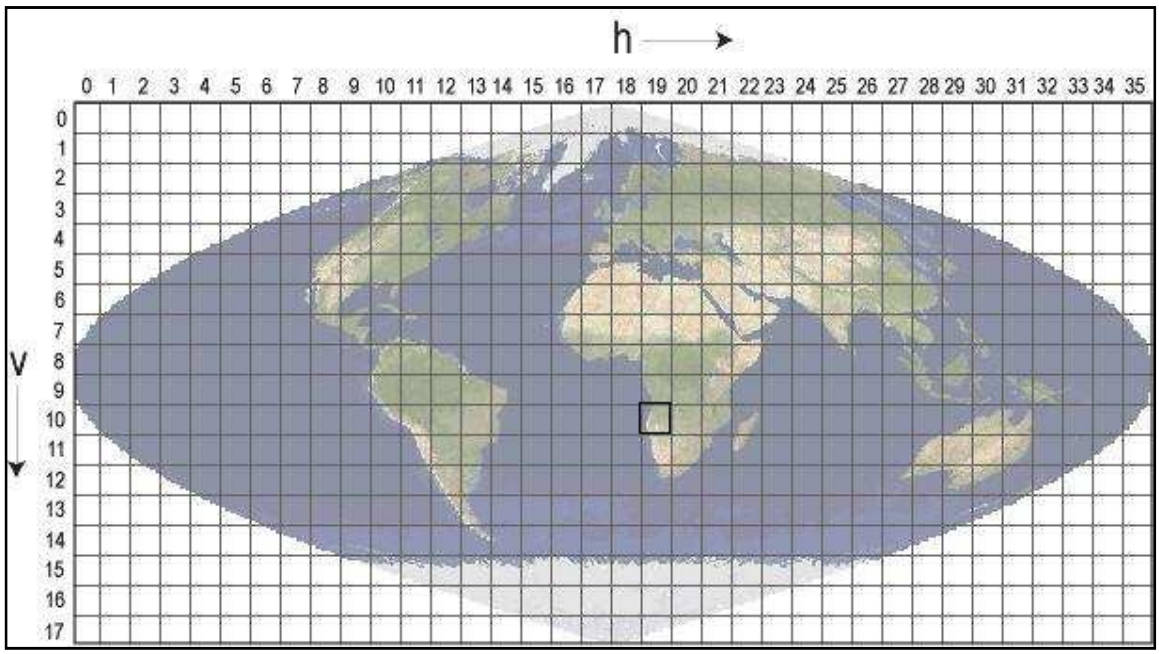

Figure 4.1: MODIS Sinusoidal Tiling System. (**Source:** lpdaac.usgs.gov/lpdaac/products/modis_overview)

Tile h19v10 (Fig 4.1) was downloaded for the period September 2005 to 22 March 2008. Season 2005/6, 2006/7 and 2007/8 were used in the study hence one season's data set will contain data of two years (2006 and 2007 for the season 2006/7). For each season fourteen 16-day composites were downloaded, except for season 2006/7 where only eleven images were available from the MODIS server. The tiles were subset for the study area that cover a geographic area of 17.00^{o} E, 18.29^{o} S and 18.26^{o} E and 19.56^{o} S.

4.1.2 Meteorological Data

Numerous shortcomings of meteorological data were discussed earlier in Chapter 1 and 2. These shortcomings included, amongst others, unavailability and incompleteness of rainfall data for selected rainfall stations (Table 4.1). Attempts were made by numerous researchers to update the data sets that are incomplete, as is the case in a study by Namibia Resource Consultants (1999) in collaboration with the Namibian Ministry of Agriculture. They

interpolated and analyzed vast sets of meteorological data nationally to increase the quality and completeness of data sets for a period from the early 1960s to late 1990s. This attempted did not completely solve the problem since data are still missing for a few stations.

Hence, this study had used three datasets for meteorological data analysis, (1) four (the fifth one, Namutoni, is outside the study area) rainfall stations that have data sets for the years 2005 to 2007, since no data is available for 2008 (Figure 3.2 and Table 4.1); (2) nine rainfall stations (Choantsas, Gaub, Namutoni, Okapya, Onguma, Oshivelo, Toggenburg, Tsintsabis and Tsumeb; Figure 3.2) that have monthly average for 35 years and (3) averaged seasonal rainfall data for seasons 2004/5 and 2007/8 (Fig 4.2 and 4.3) from the Agriculture Development Centres within the Ministry of Agriculture.

Table 4.1: Available monthly rainfall data per station.

	2005		2006		2007		2008
	J F M A	**O N D**	**J F M A**	**O N D**	**J F M A**	**O N D**	**J F M A**
Choantsas		O N D	J F M A	O N D	J F M A	O N D	
Gaub	J F M		J F M A	O			
Namutoni	J F M A		J F M A	O N D	J F M	O N D	
Tsumeb			J F M A	O N D	J F M A	N D	
Tsintsabis	F M A	O N D	J F M A	O N D	J F M A	O N D	
		2005/6		2006/7		2007/8	

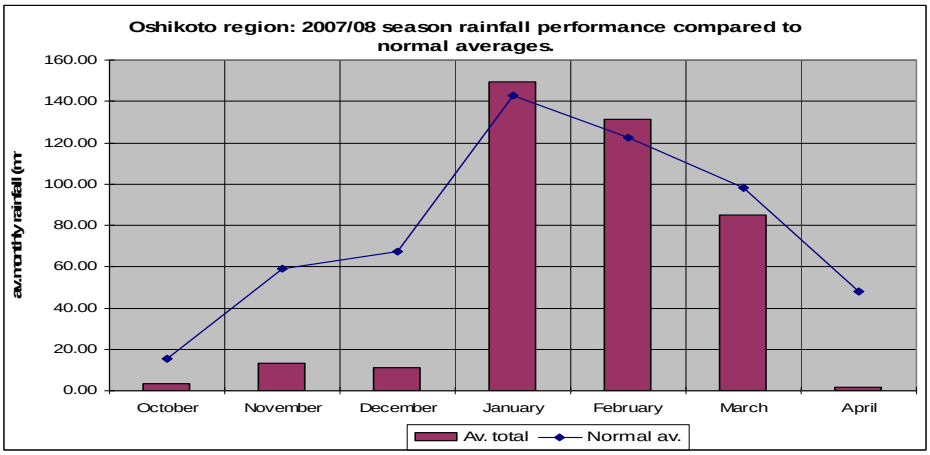

Figure 4.2: Oshikoto Region: 2007/08 season rainfall performance compared to normal averages.

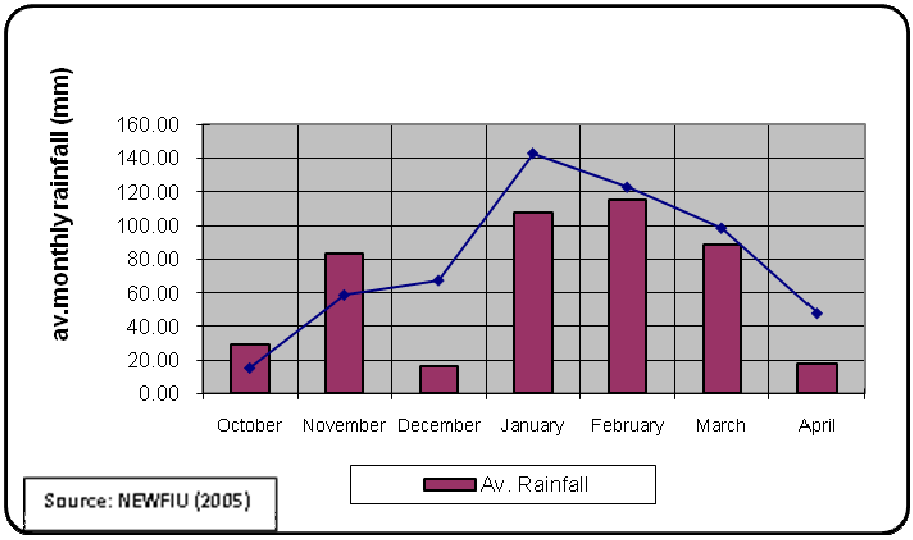

Figure 4.3: Oshikoto Region: 2004/05 seasonal rainfall performance compared to normal means.

4.1.3 Agricultural Data and Ancillary data

The National Early Warning and Food Information Unit (NEWFIU) of the Directorate of Planning within the Ministry of Agriculture provide bi-annual reports on the crop and food security situation in Namibia. Reports for 2005, 2006, 2007 and 2008 were used to extract data yields of agricultural crops. These graphs were used to identify dry, normal and wet seasons using the annual crop production data. Because the time periods for the crop production figures, NDVI and rainfall do not match, no statistical analysis could be performed for example crop production vs NDVI.

4.2 Software Used

The study used software packages such as ILWIS 3.3 (2007), ESRI ArcView 3.3 (1996), ESRI ArcGIS 9.2 (2008), and ENVI 3.4 (2008) which were the main image processing and analyzing software used. The Standardized Precipitation Index (SPI) program to calculate the SPI index from rainfall data were downloaded from the US National Drought Mitigation Centre (http://www.drought.unl.edu/monitor/spi/program/spi_program.htm).

4.3 Methodology

The section will systematically explain the analysis used in this study. MODIS NDVI data were downloaded, and then subset, and geo-referenced. Thereafter the VCI and $NDVI_{DEV}$ were computed. Furthermore, rainfall stations were used to extract NDVI and VCI values for the appropriate rainfall stations (points). The SPI was calculated from the point data and then

statistically compared with the extracted NDVI and VCI data. Lastly, maps indicating drought risk were created from the NDVI and VCI.

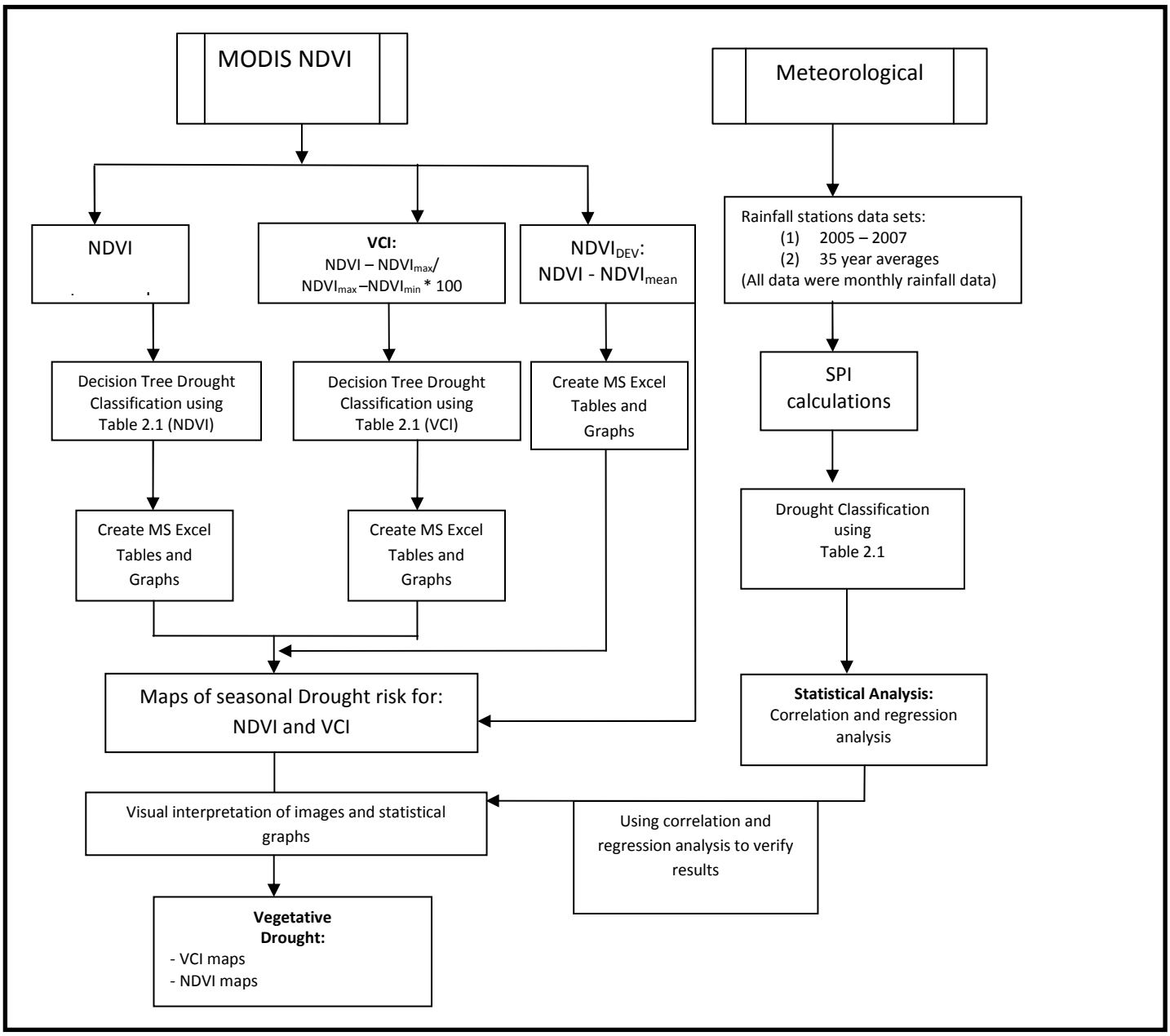

Figure 4.4: A schematic presentation of the methodology.

4.3.1 Conceptual Framework for the research approach

This framework (Figure 4.5) consists of three phases namely: pre-field work, field work and post-field work.

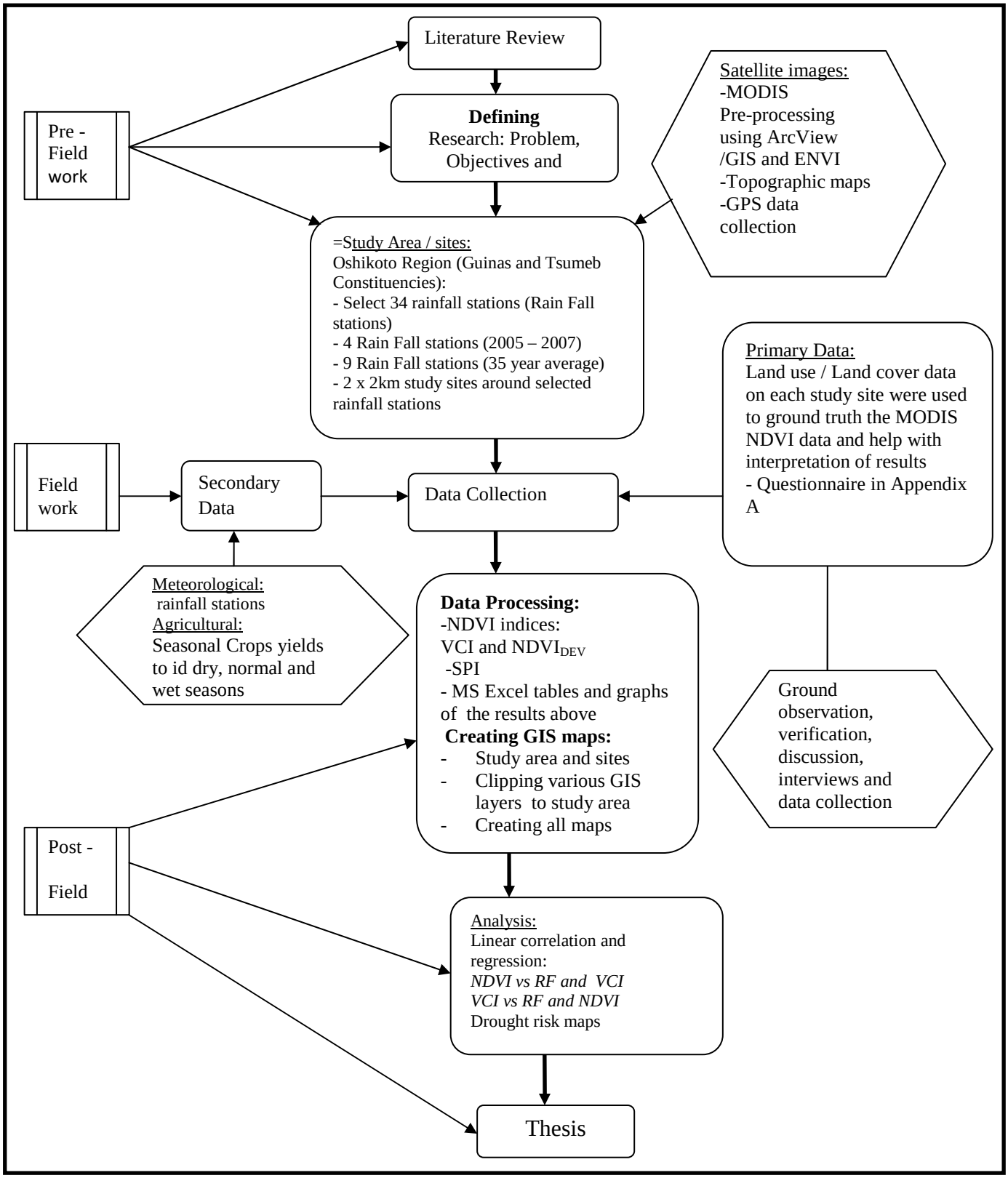

Figure 4.5: Conceptual Framework for the research approach

4.3.2 Pre – Fieldwork (Figure 4.5)

The pre-fieldwork mostly entailed the following: orientate and locate the study area and the data collection process in the field and to map features with a GPS for geo-referencing and image reference information ("ground truth") purposes. The following resources were used aerial photography, orthophotos and topographic maps data.

Furthermore, these resources were also used to demarcate a buffer of approximately 2 km round the rainfall stations or study sites to collect land use land cover data.

Most of the pre-processing for the MODIS satellite image data was done such as sub-setting and geo-referencing were performed on the downloaded MODIS granules.

4.3.3 Fieldwork (Figure 4.5)

The fieldwork comprised of two phases; primary and secondary data collection. The first phase was conducted through field trips to the study area during December 2006 for 2 weeks and in August 2008 to verify the processed satellite images, for one week. The first trip was during a wet period while the second trip was during a dry period. These field trips help will the interpretation of the satellite images for the different seasons but did not influenced the results.

The national (tar) and district (gravel) road systems were used to create transects that crosses most of the study sites (Figure 3.2 and Section 4.1.2). At each study site data was collected at an interval of 1 km along the road-transect. Hence, each study site had at least three questionnaires filled detailing the land cover / use at that location. The modified land use land cover mapping questionnaire used as a tool, was developed by the Ministry of Agriculture, Water and Rural Development – Agro-ecological Zone Unit (MAWRD - AEZ) (Appendix A).

Secondary data collection phase mostly entailed the collection of meteorological data to identify rainfall stations. Stations were chosen depending on whether complete data sets were available and whether they were continuous temporally. No rainfall stations are situated in the north section of the study area (north of the Orumba-Owambo River – Figure 3.2) because it is communal area. Interpolation could not be performed due to the sparsely distributed stations in that part to supplement rainfall data for the study area.

Rangeland is the most suited land-use for the study area, as can be deducted from the agro-ecological zones (Tables 3.1 and 3.2), although rain-fed crops are also possible but at great risk.

4.3.4 Post Field work (Figure 4.5)

During this phase data processing for this study was explained in detail such as analysis to produce the SPI data for the four and nine rainfall stations. Also analysis on NDVI images to produce drought risk maps of the study area were also performed (Fig. 4.2 and 4.3).

The SPI Index (rainfall data) was computed separately for each rain station located within and around the study area. Since drought is a regional phenomenon, SPI values of the rainfall stations should have been interpolated using *Spline* interpretation techniques in ESRI Arcview 3.3 (2006) and/or ESRI ArcGIS 9.2 (2008) to demarcate its spatial extent. But due to the incompleteness and unavailability of the data was not possible.

4.3.4.1 Calculation of vegetation Indices (Figure 4.4)

One advantage of the MODIS images were that vegetation indices calculations are already calculated and a quality assurance is given on most data sets downloaded. The MODIS VIs are at 250 m resolution and 16 – day compositing periods, which minimize cloud contamination, hence most images downloaded had less than 10% cloud cover, hence the data is cloud free.

The following were calculated:

Firstly, average NDVI for each season (2005/6) was computed by using the following expression:

Equation 5: **Average NDVIy = ($NDVI_1$ + $NDVI_2$ + $NDVI_3$)/ 3**

Where, averageNDVIy is NDVI across a season thus, $NDVI_1$ (30/09/05 – 2005/6), $NDVI_2$…(30/09/06 – 2006/7) + $NDVI_3$ (30/09/07 – 2007/8) equal to the averageNDVI of that particular 16-day composite.

Secondly, seasonal NDVI was then computed by using the following expression:

Equation 6: **Seasonal NDVI = ($NDVI_1$+ $NDVI_2$+……..+ $NDVI_y$)/7**

Where, $NDVI_1$(30/09) + $NDVI_2$(16/10) + $NDVI_1$(01/11)…….. $NDVI_7$ (22/04) stands for the 16-day composite NDVI values for 7 images (16-composites) for that season.

Thirdly, to derive NDVI maximum NDVI for each season; 2005/6, 2006/7 and 2007/8 have been computed using the following formula:

Equation 7: **NDVI max i = (NDVI $_1$, NDVI $_2$ …….NDVI$_n$)**

Where, NDVI max *i* is maximum NDVI in *i*th 16-day composite and $NDVI_1$(30/09/05 – 2005/6) ... $NDVI_2$ (30/09/06 – 2006/7)... $NDVI_1$(30/09/07 – 2007/8) = $NDVI_{max}$ for that month / 16-day composite.

Fourthly, to derive NDVI minimum for each season; 2005/6, 2006/7 and 2007/8 have been computed using the following formula:

Equation 8: **NDVI min *i* = (NDVI $_1$, NDVI $_2$ …….NDVI$_n$)**

Where, NDVI max *i* is maximum NDVI in *i*th 16-day composite and $NDVI_1$(30/09/05 – 2005/6) ... $NDVI_2$ (30/09/06 – 2006/7)... $NDVI_1$(30/09/07 – 2007/8) = $NDVI_{min}$ for that month / 16-day composite.

Fifthly, after computing NDVI max and NDVI min across 16-day composites, the VCI was computed as:

Equation 9: **VCI $_i$ = (NDVIi, – NDVI min)/ (NDVI max - NDVI min)*100**

Where, VCI_i is VCI for *i* th year and 16-day composite, $NDVI_{max}$ is long-term maximum NDVI (over three seasons) and $NDVI_{min}$ is the long-term NDVI minimum.

Sixthly, after calculating the average NDVI, the $NDVI_{DEV}$ was calculated now as follows:

Equation 10: **$NDVI_{DEV}$ = (NDVI $_i$ - averageNDVI$_n$)**

Where, $NDVI_i$ is the NDVI value for the month month/16-day composite and averageNDVI is the long-term NDVI for the three seasons.

Chapter 5: Results and Discussion

The main objective of this study is to identify and delineate the temporal and spatial characteristics (frequency, duration, extend, intensity and severity) of drought using finer spatial resolution satellite data (Figure 1.1) in the study area, located within the Oshikoto region of Namibia. Numerous studies have indicated that drought can be detected, tracked and mapped using a combination of satellite and meteorological based drought indices. Furthermore, studies also indicate that once satellite data is calibrated with ground truth, using climatic and crop data, it can be used to monitor the onset of drought, the vegetation's response to the drought and its recovery from the resulting stress.

However, most of these studies (see Table 2.2) used coarse spatial resolution satellite data from the NOAA AVHRR sensor which failed to detect the local variability of drought essential for drought relief and land reform purposes. Hence, this study opted for a medium spatial and new generation MODIS data to delineate areas that might experience drought that are not adequately detected by coarse spatial resolution data.

A common trend among these studies on drought is to identify a dry, wet or normal season using *in situ* data such as crop production and/or rainfall data. Consequently, this study used national and regional crop production data to classify the three seasons (2005/6, 2006/7 and 2007/8).

Most of the image pre-processing was already done on the 39 NDVI MODIS images hence images were only geo-referenced and subseted. The 39 NDVI images were used to calculate: (a) the long-term minimum, maximum and average NDVI values across the 16-day composite (eg. images 09/09/2005, 09/09/2006 and 09/09/07); (b) the VCI and DEV_{NDVI} and lastly, (c) the average for the early and main seasons (eg. 05/06, 06/07 and 07/08) for all 16-day composites of that season for the NDVI, VCI and DEV_{NDVI}. Tree classification analyses were performed on NDVI and VCI.

5.1 Crop production analysis

Figure 5.1 (NEWFIU, 2006) shows the national analysis of cereal production data which was used to classify the seasons as dry, normal or wet. It classified season 2005/6 as a very *wet* (productive) season because the yield exceeded 180,000 tonnes, season 2006/7 can be classified as *dry* since it has the lowest yield figure of below 120,000 tonnes, while season 2007/8 has yields just above 120,000 tonnes which is typical of an average / *normal* season,

nationally. Hence, the threshold value for a dry season was 114,135 tons, for a normal season was 121,3009 tons and for a wet season 188,742 tons, for this study.

Furthermore, the 12 year crop production yield time series (Figure 5.1) clearly illustrate that season 2001/2 and 2002/3 had the lowest yields followed by 1997/8 and 1999/2000 while the season with the highest is the season 2005/6 which are part of this study.

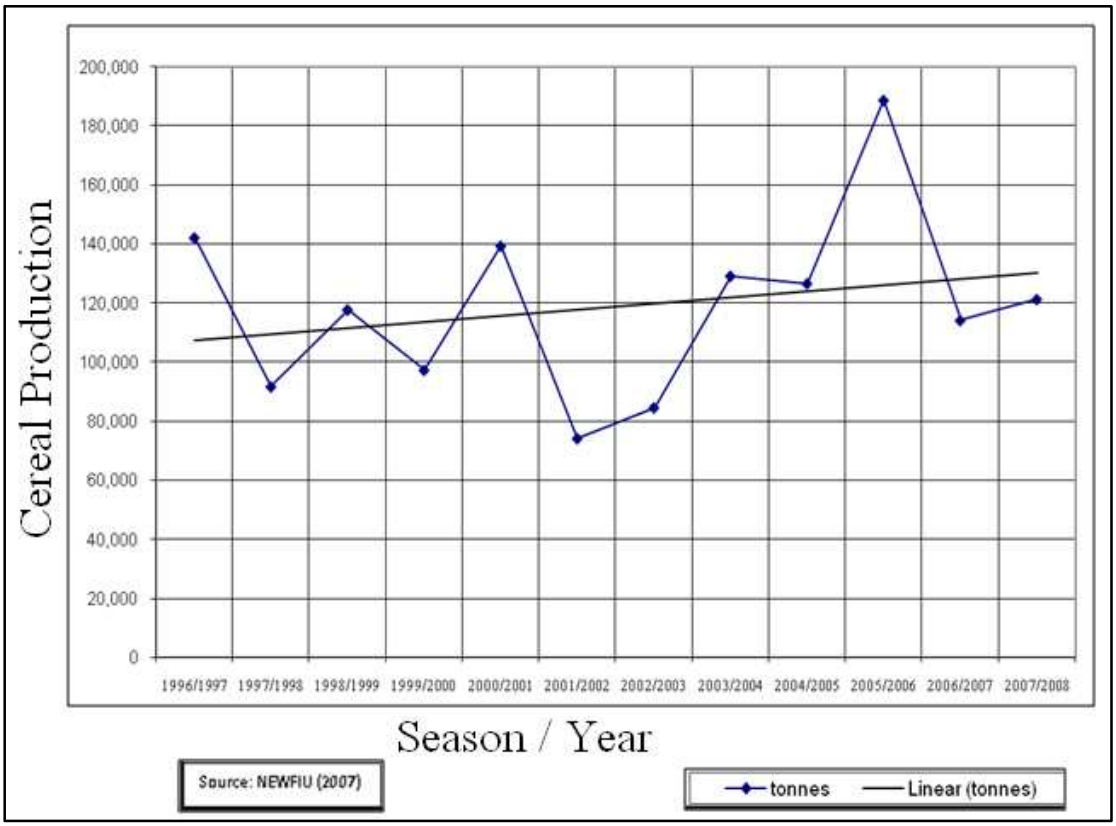

Figure 5.1: Cereal production (tonnes) in Namibia from 1996 to 2008.

Figure 5.2 shows the regional analysis for the Oshikoto region and clearly illustrate that 2007/8 has the lowest yields (dry season), followed by 2006/7 (normal) while season 2005/6 (wet) has the highest. Hence, there is a good correlation for the wet season 2005/6 both regionally and nationally, while seasons 2006/7 and 2007/8 were different on a regional and national scale. Reasons for this apparent contradiction will follow shortly.

As indicated earlier season 2005/6 (Fig 5.1, 5.2 and Table 5.1) was generally very wet (bumper harvest) with most parts of Namibia receiving above average rainfall, nationally and regionally (NEWFIU, 2006).

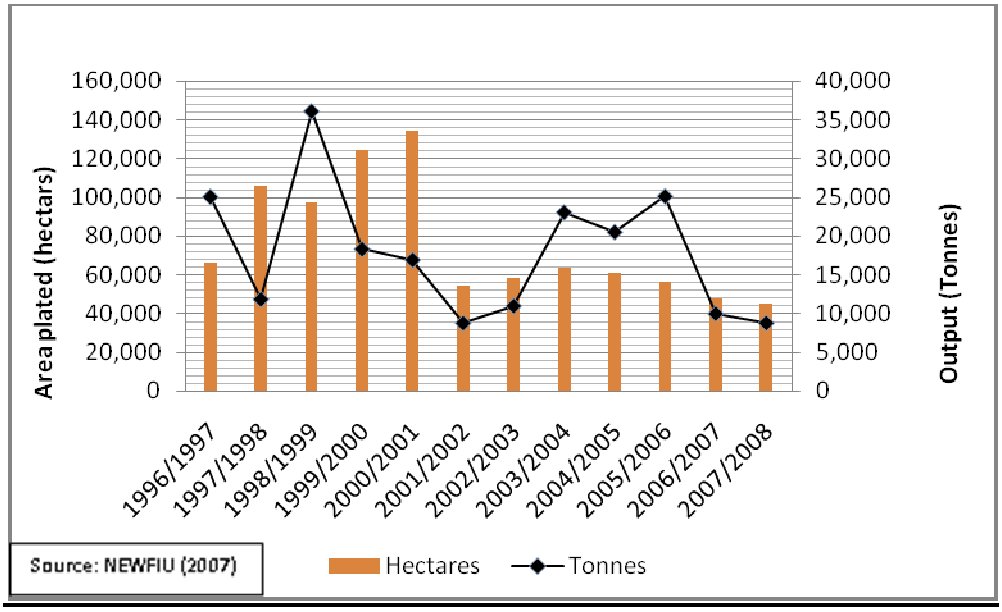

Figure 5.2: Oshikoto Region: coarse production trends.

During the 2006/7 season the country received good rains during the first half of the rainy season (October to December 2006 – Table 5.1), but experienced long dry spells, floods and a persistence of swarms of red-billed quellea birds during the second half of the season (January to March 2007 – Table 5.1) which has subsequently lead to poor harvest, nationally, even though a good harvest was expected (NEWFIU, 2007). The national cereal production figures (Fig 5.1) indicate that nationally this season was the driest (yields) season amongst the three seasons for this study. However, on a regional level the aforementioned factors were not so prominent hence the harvest represents a normal season (Fig. 5.2 and Table 5.1).

The NEWFIU (2008) crop report attributes the poor harvest for the 2007/8 season to an unfavourable rainy season characterized by heavy and flood rains. Furthermore, it also points to the fact that the rainfall ended prematurely at the end of March 2008 (Figure 4.2 and Table 5.1) and hence, a combination of the said factors were experienced during critical stages of crop development and consequently led to depressed yields for the 2007/8 crop season, nationally and regionally. Even though Figure 5.1 illustrates a higher production yield for 2007/8 compared to season 2006/7, the NEWFIU (2007) report attribute this higher production yields to the merging of commercial and communal crop yield data to get the national data. Commercial farmers enjoy irrigation farming throughout the year and are not influenced much by the variability in rainfall.

Table 5.1 summarizes the NEWFIU crop reports for the years from 2005 to 2008. The NEWFIU crop production reports has utilized rainfall data collected from their agricultural extension services at the Agricultural Development Centres (ADC). These data are used in their reports to classify the season as dry, normal or wet. However, these rainfall data are not available for all reports especially for seasons 2005/6 and 2006/7 for the study area.

Table 5.1 (row 1) indicates the normal calendar years to explain how the months are divided into the three seasons for this study. Table 5.1 (2) shows the early and main rainy seasons that consist of October, November and December and January, February March and April respectively while Table 5.1 (3) explains the summarized classification of the NEWIU reports. Lastly, Table 5.1 (4 and 5) gives the final seasons and their drought classes, based on the ADC's rainfall data and the regional crop production data (Fig 5.2) while (6) gives the supporting figures for the drought classes.

Table 5.1: Classify the three seasons into different types of seasons.

(1)	2005		2006		2007		2008
(2)	Jan Feb Mar Apr	Oct Nov Dec	Jan Feb Mar Apr	Oct Nov Dec	Jan Feb Mar Apr	Oct Nov Dec	Jan Feb / Mar Apr
(3)	Wet/ Dry (Fig. 4)	Wet	Wet	Wet	Dry	Dry (Fig 3)	Wet / Dry
(4)		2005/6		2006/7		2007/8	
(5)		Wet		Normal		Dry	
(6)	Fig 4.3	Fig.5. 2, 5.3, 5.4, 5.3		Fig. 5.3 (NDVI)		Fig 5.2, 5.3 (NDVI)	

Legend: (1) calendar years; (2) months used for the seasons; (3) seasons as summarized after NEWFIU; (4) seasons this study will use; (5) seasons classified for comparison in this study; (6) figures supporting classifications.

It is against this background that the next section will discuss the results of the satellite-based indices namely NDVI, VCI and $NDVI_{DEV}$ using Table 5.1 (5) for comparison.

5.2 Satellite based indices

Figure 5.3 shows the averages for all months/16-day composites for the three seasons for both the NDVI and VCI. The NDVI values (Fig. 5.3 – line) are in agreement with the findings in Table 5.1 that classify season 2005/6 as wet, season 2006/7 as normal and season 2007/8 as dry. The VCI values indicate 2006/7 as dry and season 2007/8 as normal. All the methods indicate 2005/6 as the wettest season. The VCI therefore correlate well with the national crop production figures while the NDVI with the regional figures. Thresholds of 36% for VCI and 0.26 for NDVI based on research (Liu and Kogan, 1996) to delineate drought areas was used for this study.

It is clear that neither these seasons can be classified as drought stricken since their values are above the critical average values for all three seasons used in this study. Only season 2006/7 represent a dry season with an average VCI value of 38% (Figure 5.4). The next section will take an in-depth look at each season using the 16-day composites as a temporal time scale.

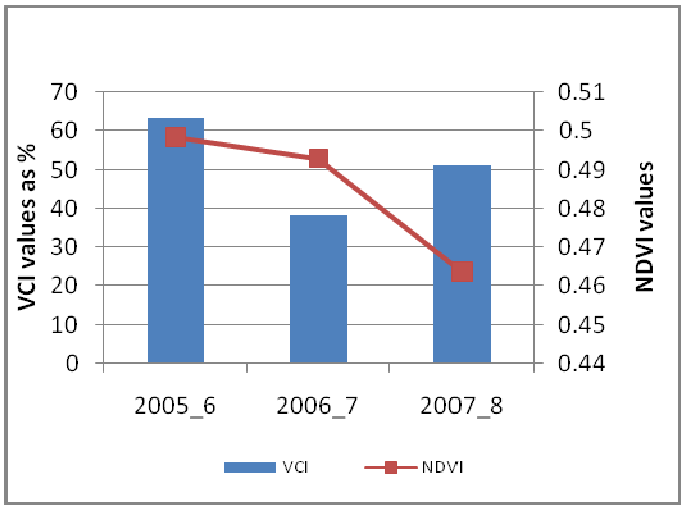

Figure 5.3: Seasonal averages for NDVI and VCI.

The NDVI plots (Fig 5.4) for the three seasons from 30 September 2005 to 23 April 2008 (excluding the bi-weekly (16-day composite) images identified by their starting dates 01 November, 17 November and 03 December 2006 for each 16-day composite of a year/season are shown in Figure 5.4. The multi-year minimum and maximum NDVI is also plotted, they represent the highest and lowest NDVI values during the three seasons for each 16-day composite average across each season and for each pixel. The maximum and minimum NDVI have been used as the criteria for estimating the upper (favourable weather) and the lower (unfavourable weather) limits of ecosystem resources (Kogan *et al.*, 1998 and Liu and Kogan, 1996).

The plots in Figure 5.4 generally represent the seasonal fluctuation between the early rainy season (October, November and December - OND) and the main rainy season (January, February, March and April - JFMA). They clearly show that the first half of the rainy season (early season – OND) is generally dry while the second half (JFMA) is usually wet (Olszewshi and Moorsom, 1995).

The 2005/6 season classified as wet using the crop production figures, started with very unfavourable conditions during the period 30 September to 17 November 2005, this may be

due to the preceding dry 2004/5 season especially the second half (JFMA). It represents a moderate drought (Fig. 5.4 and 5.6a) using the NDVI (0.2 – 0.3) drought categories (Chapter 2). This category is within the long-term threshold (average) NDVI value of 0.26 (Fig. 5.4 - threshold) for the whole study area over the three seasons. Figure 5.6a illustrates the spatial distribution of this drought category and others. Studies (Kogan *et al.*, 1998 and Liu and Kogan, 1996) suggest that values below the threshold indicate relatively bad conditions, although the conditions for the study area do not warrant drought warning due to the very good preceding seasons. Furthermore, the NDVI values of this season (2005/6) correspond to the crop production figures for the national and regional data, especially in the latter part of this season.

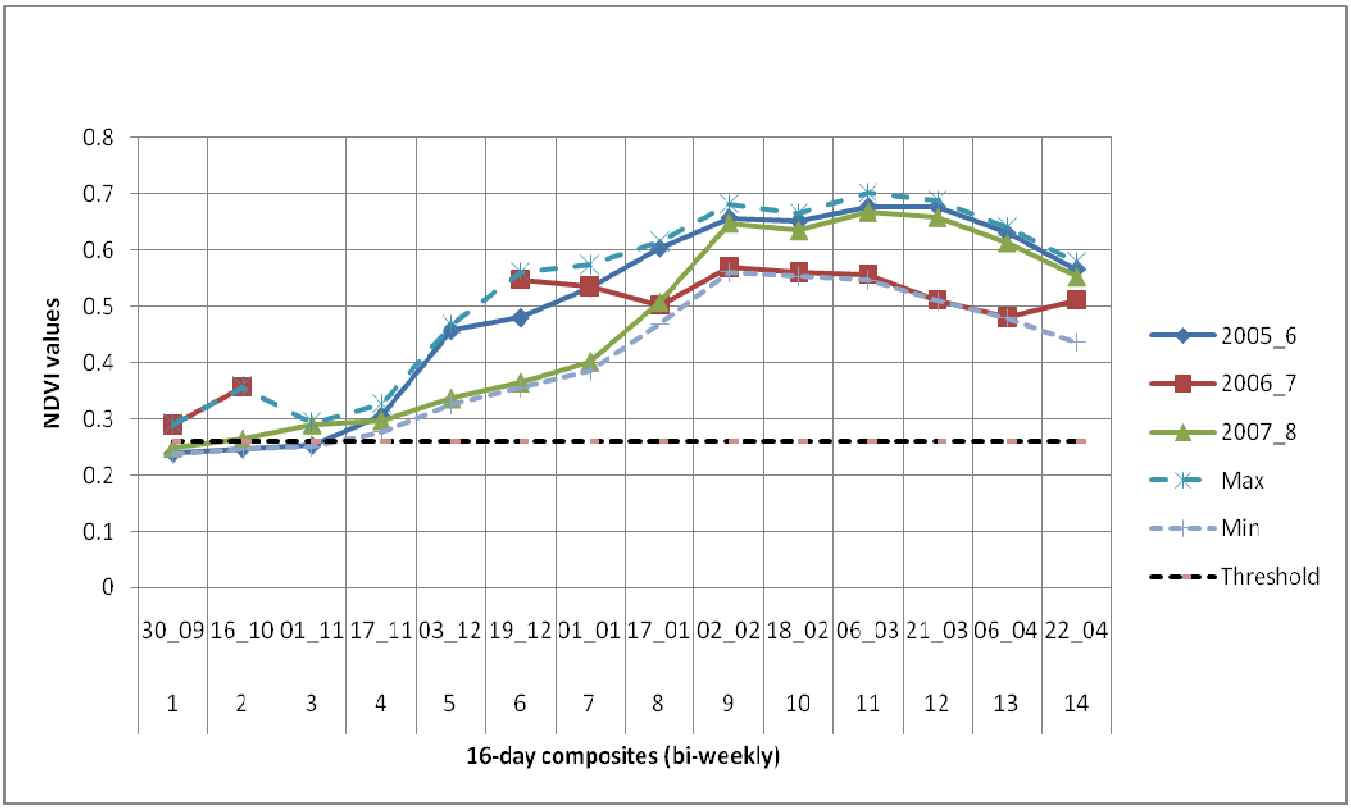

Figure 5.4: Multi-year NDVI mean with minimum and maximum values for all three seasons.

In Figure 5.4, season 2006/7 started with very favourable conditions during the early season and overlap with the maximum line but ends with very unfavourable conditions on the minimum plot during the main rainy season. Figure 5.4 shows that the early and main season for 2006/7 is above the threshold line, especially the main season, even though it represents unfavourable conditions. This concurs with Table 5.1 which indicate that season 2006/7 had a

wet early season (OND) and a dry main season (JFMA, see Fig. 5.5), therefore contradicting the national crop production figures (Fig. 5.1) that indicate that the 2006/7 season represent a normal season.

The plot for season 2007/8 (Fig. 5.4) started with average minimal conditions in the early season (Fig. 5.5 and 5.6e), but responded well to the good rains (Fig 5.3) after January 2008. This season is classified as a dry season but indicate good and favourable conditions between January and March as indicated by the rainfall (Fig. 5.3) and NDVI (Fig 5.4, 5.5 and 5.6f). Reasons for the poor yield might be because the pre-season (OND – Fig. 5.3) was very dry due to below average rainfall that were received, making the planting of crops difficult to almost impossible and also delaying the eventual planting and later harvesting.

Figure 5.5 shows the mean for the three seasons for the VCI values for the study area. Many studies have shown that vegetative drought is closely related with weather impacts. In NDVI, strong ecological component (soils, vegetation types, etc) subdues the weather component (rainfall, temperature, etc). Hence, the utilization of Vegetation Condition Index (VCI) will separate the short-term weather-related NDVI fluctuations from the long-term ecosystem changes (Kogan, 1990 and 1995). Therefore, while NDVI shows seasonal vegetation dynamics, VCI varies in the range 0 and 100% reflecting relative changes in the vegetation condition from extremely bad to optimal (Kogan, 1995, Kogan *et al.*, 2003 and Liu and Kogan, 1996). Consequently, VCI will accentuate the fluctuation that NDVI showed concentrating on the changes in the local weather conditions. Liu and Kogan, (1996) further suggested that the value of 36% which is almost less than one third of its historical maximum VCI should be used as a threshold for VCI, indicating drought.

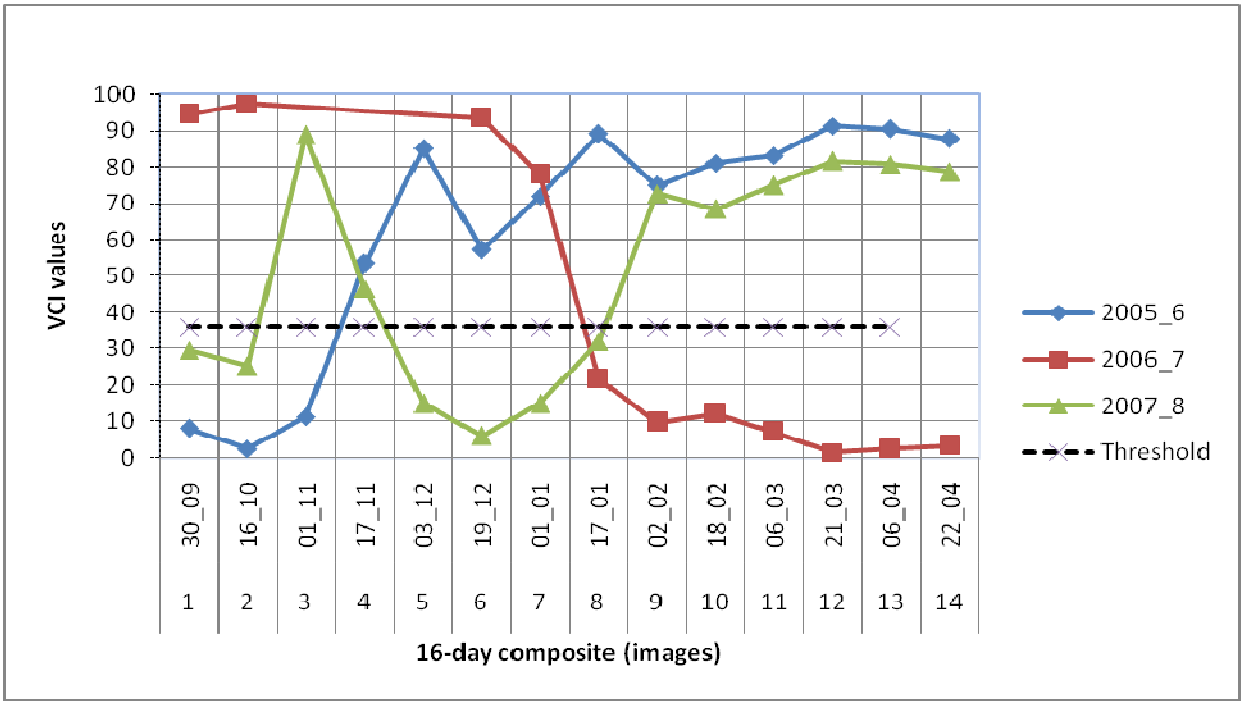

Figure 5.5: Multi-year VCI mean.

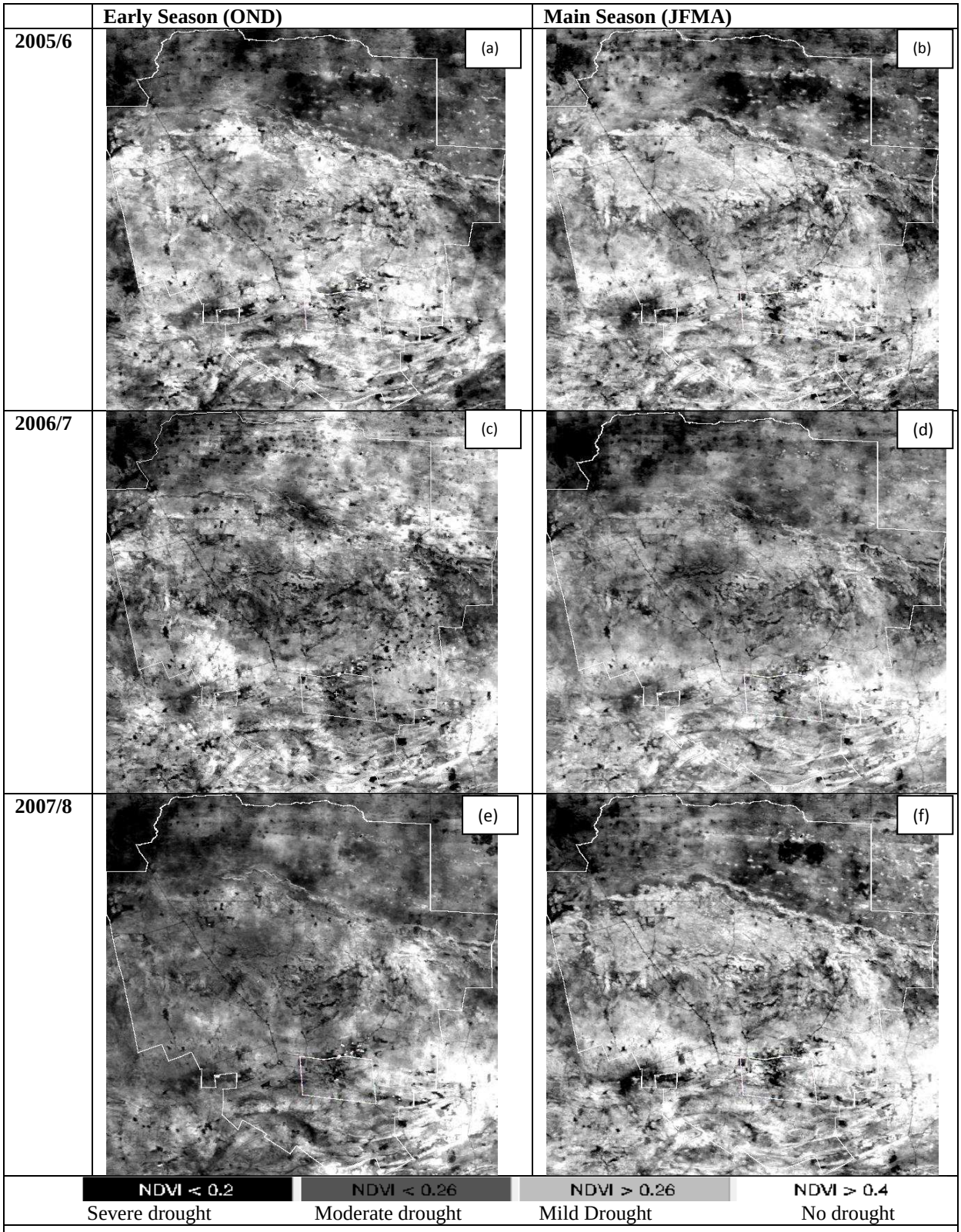

Figure 5.6: NDVI drought risk maps for the early and main season of all three seasons.

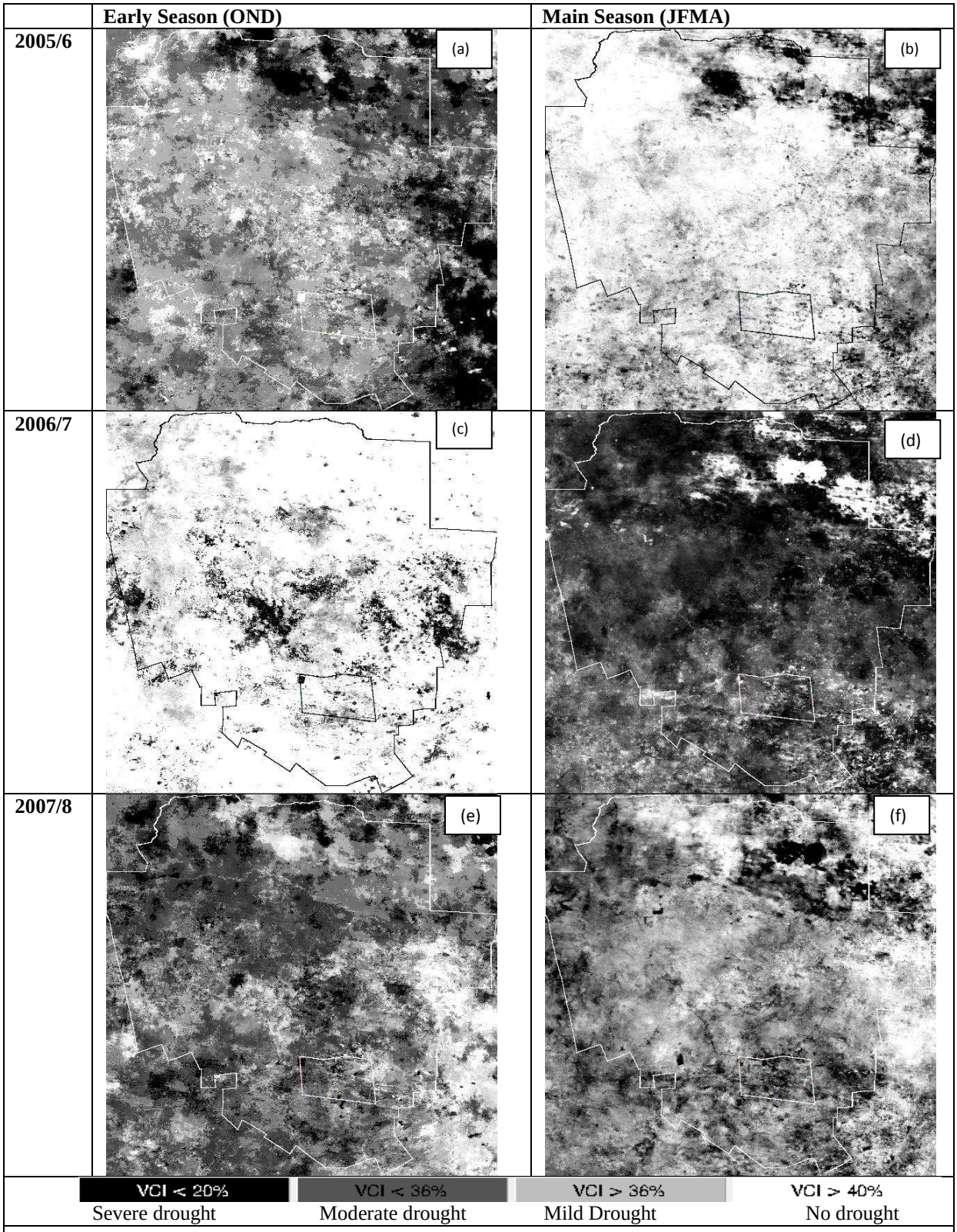

Figure 5.7: VCI drought risk maps for the early and main seasons of all three seasons.

Figure 5.5 shows the VCI plots for the three seasons which show heightened drought conditions compared to the NDVI plots (Fig 5.4). Using the threshold average of 36%, Figure 5.5 shows severe drought conditions for the following periods: 30 September to 01 November for season 2005/6 (Fig. 5.7a); 17 January to the end of the main rainy season 22 April for season 2006/7(Fig. 5.7d); and two periods for season 2007/8 namely, 30 September to 01 November and 03 December to 17 January 2008 (Fig. 5.7e). The first period can be seen on Figure 5.7a in the south eastern corner and the northern part. The second dry period is detected and spatially shown in Figure 5.7d and occupy predominantly the middle and northern part of the study area while the last dry period is shown in patches across Figure 5.7e-f.

During season 2006/7, both the NDVI and VCI are in agreement, although the VCI amplify both the first half and second part of the season's values. Extreme dry conditions were experienced after the 17 January 2007 as explained in Table 5.1 despite a very wet season with floods preceding the 2006/7 season. The dry conditions from the 2006/7 season continue into season 2007/8. This is illustrated by the low VCI values of around 30% at the start of the 2007/8 season. An unexpected sharp increase in values from 25% (30 September) to 88% (01 November) occurs which is followed by a sharp drop to 45% (17 November). This is exceptional since the rainfall for that period is below the average (Fig 5.3). Thereafter, VCI values drops to a low of 5% (19 December) and increase drastically due to good rains in January to 71%, where it continues as expected.

Figure 5.5 as well as Figure 5.8 illustrates VCI's sensitivity to detect severe drought across all seasons. The severe drought areas (Fig 5.8) detected by VCI cover; 31% for the 2005/6 season, 57% for the 2006/7 season and 38% for 2007/8 of the study area while the NDVI areas classified as severe drought areas are zero. This demonstrates VCI excellent ability to detect and map droughts.

Figure 5.8 illustrate that NDVI predominantly detects favourable conditions of more than 50% of the study area for all three seasons while NDVI indicate moderate drought conditions for season 2007/8 (28%) and 2005/6 (22%) of the study area. Furthermore, NDVI (Fig 5.8) also indicate areas covering a mild drought of between 13 – 18% for the combined three seasons. Only 3% of the area is mild and moderate drought according to VCI.

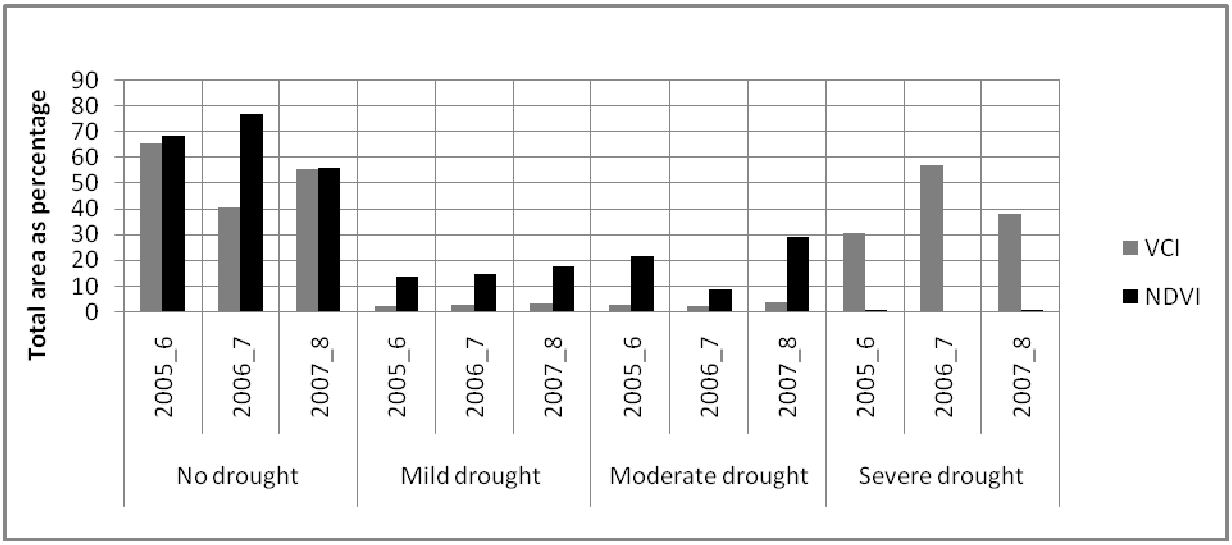

Figure 5.8: The total drought areas identified by NDVI and VCI.

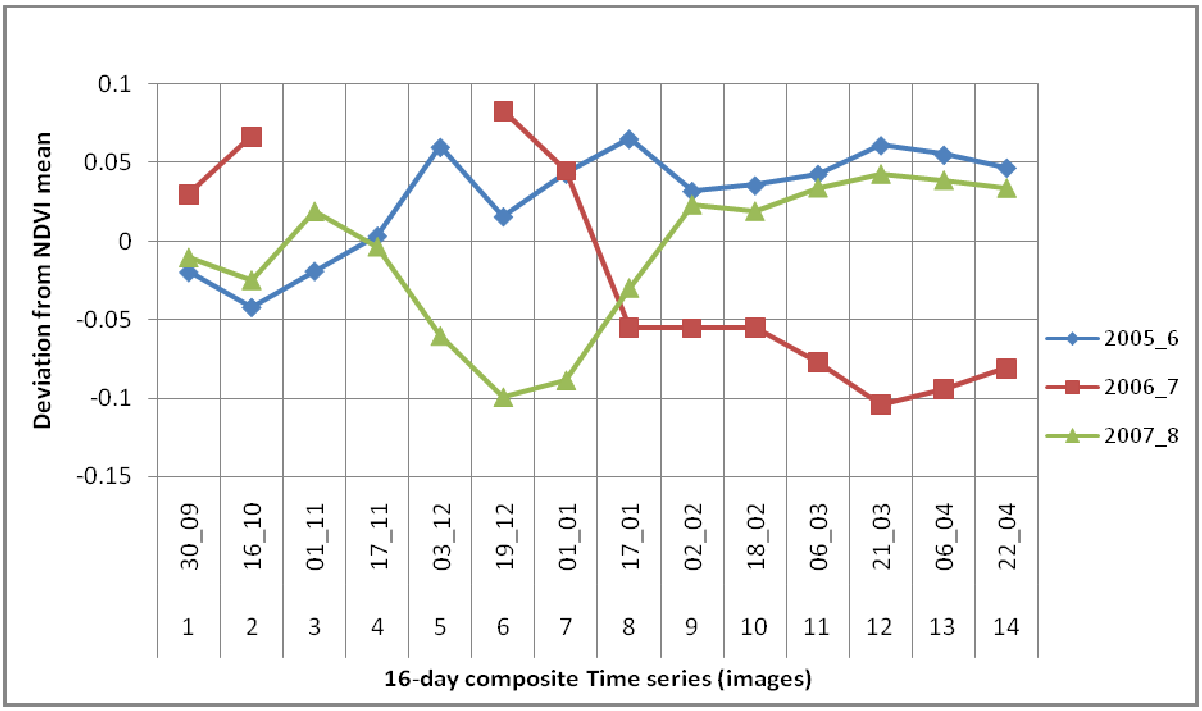

Figure 5.9: Multi-year $NDVI_{DEV}$ from the Mean.

Another popular satellite-based drought index that is regularly used in literature is the NDVI difference / deviation index ($NDVI_{DEV}$). Song *et al.*, (2004) suggested that with the deviation of NDVI, it is also possible to detect the area and intensity of drought damage. They suggested that the negative NDVI image's ($NDVI_{DEV}$) pixels (< -0.1) are listed as drought areas and the bigger the negative values (< -0.25) of $NDVI_{DEV}$ image's pixels, the more

intense the drought will be. They produced drought risk maps using the $NDVI_{DEV}$ image's pixels values, especially where the negative values are the biggest, to indicate the highest drought risk. This study will use this index to assess and validate the accuracy of the preceding drought indices (NDVI and VCI).

When comparing the general patterns of Figures 5.5 and 5.9, a clear match can be seen. It therefore confirmed the findings of the VCI drought index that emphasized the seasonal fluctuations and also for detecting the different drought categories more accurately. The $NDVI_{DEV}$ (Fig. 5.9) also detects the most intense drought during the main rainy 2006/7 season where the negative pixel values reach values smaller than -0.1 while the 2007/8 season recorded a drought intensity of -0.09 (19/12). This index again illustrates that the last half of the 2006/7 season (JFMA) had an intense drought while the 2007/8 season had a drought only for periods from 03 December to 17 January 2008.

5.3 Standardized Precipitation Index (SPI)

Standardized Precipitation Index (SPI) is a relative new index (McKee *et al.*, 1993) and is used to quantify the precipitation deficit for multiple time scales (one-month and three-months) for this study. These time scales reflect the impact of drought on the availability of different water resources. The one-month SPI reflects short-term conditions and its application can be closely related to soil moisture while the three-month SPI, on the other hand, provides a seasonal estimation of precipitation which can be used to detect different categories of drought as explained in Chapter 2.

Table 4.1 highlighted some of the disadvantages that point data have. These disadvantages include very sparse meteorological network, incomplete and/or unavailable data which later on influence the accuracy and timeliness to detect, track and map droughts efficiently and effectively. Moreover, these methods do not express much local spatial detail, and they are only valid for a single point location.

It is against this background that the study initially identified 34 study sites (9 study sites located outside study area for interpolation purposes) to minimize incompleteness and unavailability of data. However, Table 4.1 also shows that from the initial study sites (rainfall stations) only five sites have sufficient data to enable analysis to be performed. From the five rainfall stations one falls outside the study (it was chosen for interpolation purposes – Fig 3.2) and hence only four sites could be used to do the SPI analysis. The blank gaps in Table 5.2

indicate the months for which monthly data is unavailable. Nine stations encompassed monthly long-term rainfall for 35 years were used separately from four study sites. These four study sites were used to extract data from the satellite-based drought indices and also to perform statistical analysis.

Figure 5.10 summarize the mean yearly SPI values for the five study sites (including Namutoni is not within the study area) for the one-month and the three-month SPI from 2004 to 2007. As expected the SPI three-month results detect drought more accurately (Lei and Peters, 2003). It indicated mild droughts in 2006 for stations Tsumeb, Gaub and Namutoni. It also detects a mild drought in 2005 at station Choantsas while the one-month SPI detect mild droughts at Guab in 2007 and Tsumeb in 2006. A mild drought also occurs when the SPI values are less than -1.0.

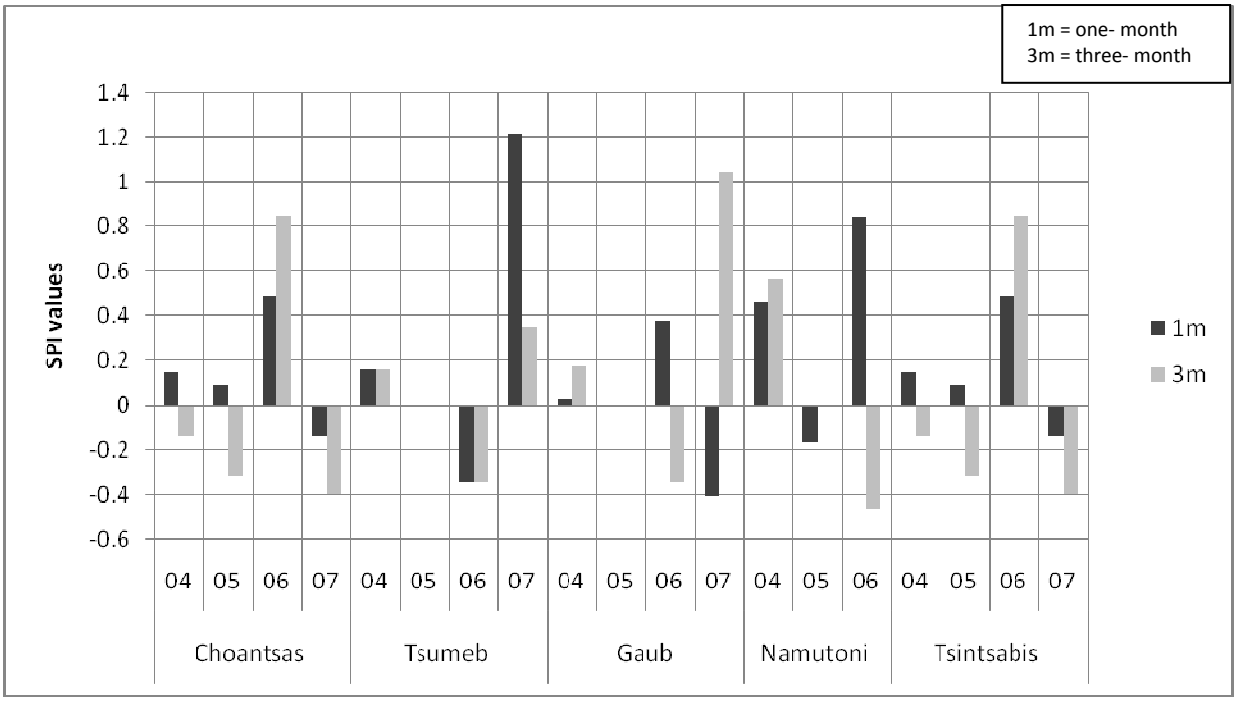

Figure 5.10: SPI values for 5 study sites.

In Figure 5.11, SPI three-month for Gaub detects a mild drought for the period January, March and March 2005 and Namutoni for February 2005 which coincides with the dry season preceding the 2005/6 season. SPI at Namutoni also detect a mild drought in February 2005, at two stations mild droughts were also identified in 2006, Gaub and Choantsas for May and April, respectively. In 2007, SPI detects mild to moderate droughts for stations Tsumeb, Choantsas, and Namutoni. The most intense drought for the whole study area across all three

seasons was detected by the one-month SPI from February, March and April 2007 for Choantsas while a moderate drought was also detect for November 2007 for Namutoni at -1.62. Most of these droughts are in agreement with the dry period (Table 5.1 – JFMA 2007).

SPI did not detect drought as well as expected, due to the data constraints mentioned earlier, limited datasets, the lack of appropriate and up-to-date long-term monthly data sets (Lei and Peters, 2003).

5.4 Statistical Analysis

Due to the many constrains with the study sites (rainfall stations) interpolation of the study sites using the SPI values could not be performed. The intention was to interpolate the SPI values for the different study sites and produce a rasterized map of SPI one – and three months values.

However, statistical analysis was performed on the four study sites. Firstly, NDVI and VCI values were extracted from the early and main season images. These data were then tabulated and used in conjunction with the SPI one – and three month data to perform correlation and regression analysis. Correlation analyses was mainly based on NDVI vs rainfall, SPI one--month and three-month and VCI vs rainfall, SPI one-month and three-month.

As expected the strongest correlation was between NDVI vs SPI three-month, followed by NDVI vs rainfall and rainfall vs SPI. The other correlation combination gives correlation values ranging from 0.01 to 0.2. The regression analysis was also performed on the same combinations mentioned above and reveal that again the strong correlation is between NDVI/SPI three-month with a value of $r^2 = 0.94$ while the other regression analysis values range from 0.01 to 0.62 (rainfall vs SPI three month).

Namibia Resource Consultants (1999) compiled monthly averages for 35 years for 275 rainfall stations in Namibia. From this data set nine rainfall stations monthly average data were used. Seasonal averages were compiled for the early and main season and the correlation and regression analysis were performed. Figure 5.12 shows the mean NDVI and VCI values for the early and main season versus the long-term average monthly rainfall.

Generally, the results show poor correlation between the NDVI and VCI vs the seasonal rainfall for the rainfall stations. Figure 5.12 (a) shows that an increase in rainfall slightly increases the VCI during the average main season while Fig 5.12 (b) shows an increase in the

correlation between rainfall and VCI where the coefficient of determination is 0.51 and the seasonal mean VCI increase as the long-term rainfall increase. For the NDVI, Figure 5.12 (c) and (d) show that the correlation is better than the VCI even though it is still weak. An increase in rainfall causes a slight increase in NDVI. The regression analysis shows that rainfall does not result in an increase in NDVI and VCI, hence with a regression coefficient of between 0.01 and 0.22 rainfall cannot strongly predict NDVI and VCI. The weak correlation can be attributed to data averaging and also because appropriate monthly data for the corresponding months were not used.

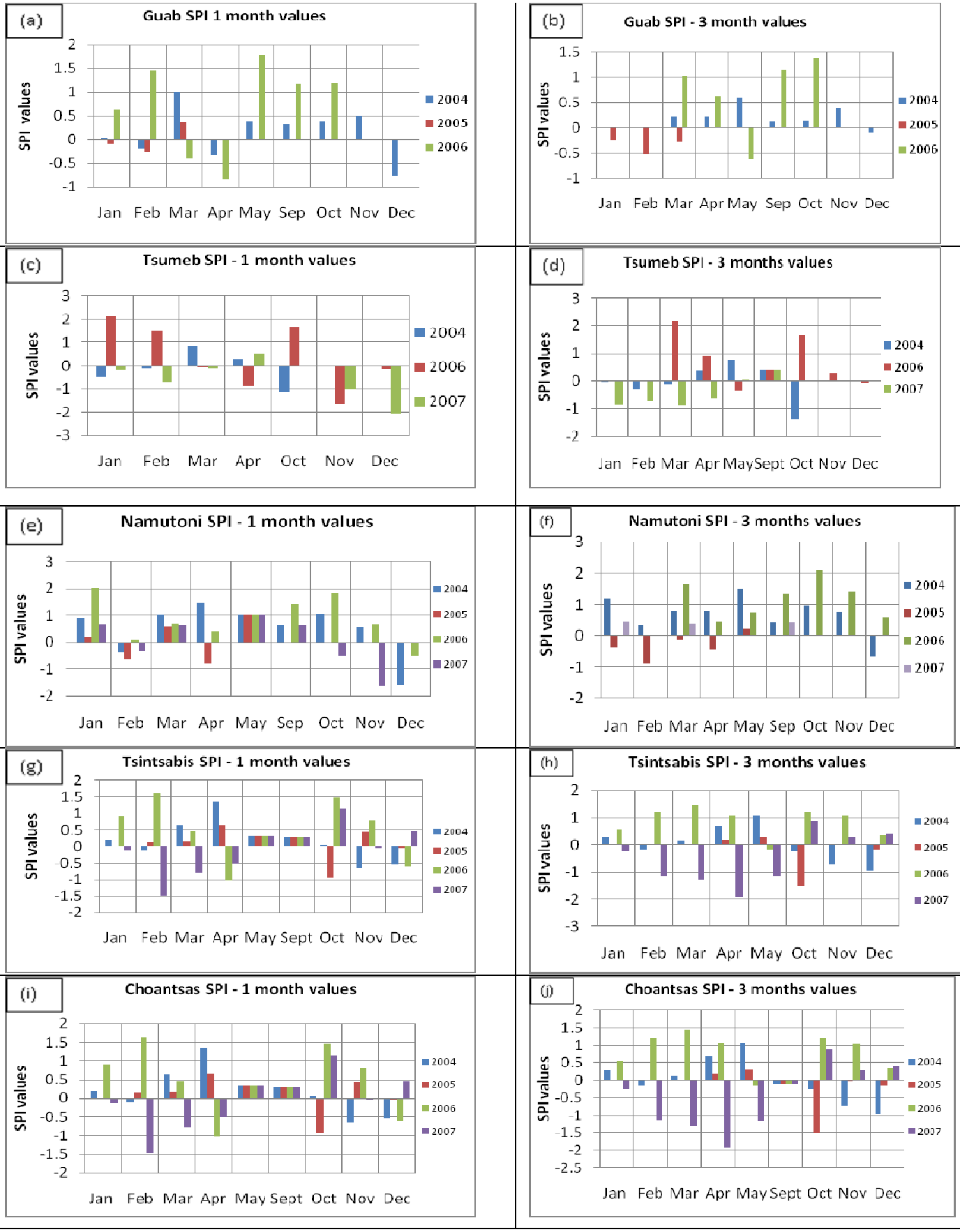

Figure 5.11: Monthly SPI 1-month and 3-months values.

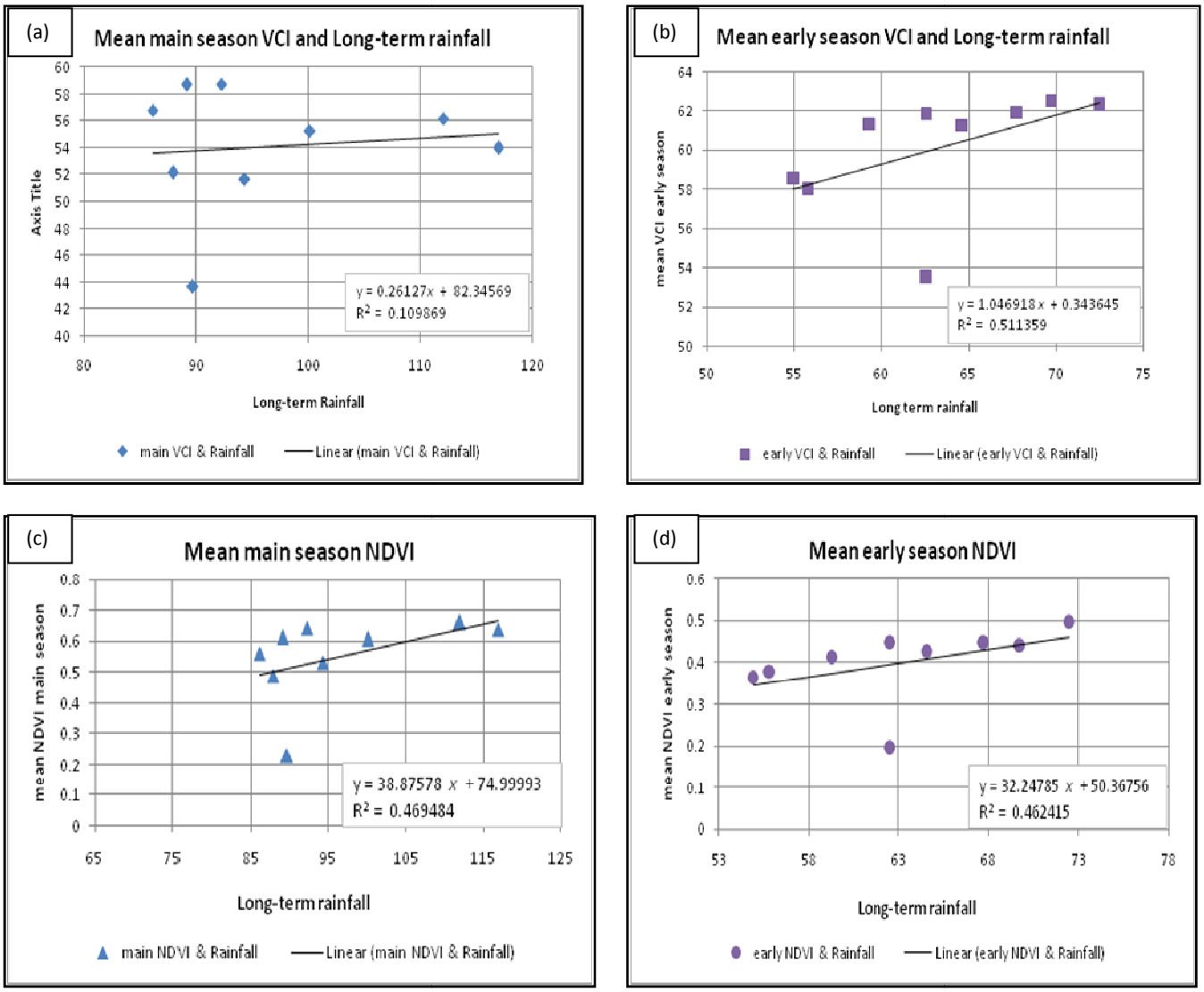

Figure 5.12: Linear correlation and regression analysis of the NDVI and VCI indices with long-term rainfall averages

Chapter 6: Conclusions and Scope for Future Research

6.1 Introduction

In recent decades, the impacts of drought have escalated in response to increasing population growth, misdirected or non-sustainable government policies and programs, environmental degradation, new technologies and fragmented government authority in water and natural resources management (Wilhite, 2000b).

These escalating impacts have increasingly drawn the attention of both the scientific and policy community, not only because of the frequency and severity of recent droughts in both developing and developed countries, but also because of the complexity of economic impacts associated with the phenomenon and their far reaching social costs and environment damages.

In response to the above, this study had contributed modestly in designing a methodology to detect risk areas by using temporal images from MODIS NDVI and meteorological-based SPI. Eklundh (1998) has found that, amongst others, the temporal and spatial scale influence the NDVI values, especially at the coarse spatial resolution of the AVHRR sensor, hence the study opted for the MODIS sensor. Hence, the gaps within the remote sensing community to use finer spatial resolution data, such as the MODIS sensor, to detect drought's complex characteristics formed the essence of the study. Because drought by its nature is localized in small pockets and so is the distribution of rainfall, hence averaging them to arrive at a generalized assumption, create more problems to the resource-less poor majority who depends absolutely on rainfall to curve out a living. Hence, the usage of coarse spatial resolution and/or generalized crop production data, for example, does not help to identify those people who suffer due to climatic phenomena. Consequently, further research in refining this operational methodology to identify and delineate drought prone areas should be encouraged.

This methodology also solved the problems/challenges the Namibia National Drought Policy posed in terms of defining drought scientifically in order to guide other policies that depend on it such as the Land Distribution and Drought Relief policies.

6.2 Conclusions

Even though only part of the objectives of this study were achieved, the results presented earlier, are consistent with findings elsewhere. For example, Ji *et al.*, (2003b) most important finding was that NDVI and its derivative (VCI) are effective indicators of vegetation-moisture condition since the three-month SPI is highly correlated with NDVI. Furthermore, Kogan (1998, 2000) found that VCI is a better vegetative drought index than others including NDVI, due to the fact that NDVI's weather component is subdued by strong ecological components while VCI separate short-term and long-term ecosystem changes (see Fig. 5.4 and 5.5).

Furthermore, Bhuiyan *et al.*, (2006) found that the SPI one-month data is weak and there is no correlation with NDVI and VCI (Section 5.4). They explained that it is due to the fact that SPI one-month reflects short-term conditions and its application can be related closely to soil moisture while the three-month SPI provides a seasonal estimation of precipitation as explain in Section 2.3.3.1. Hence, the impact of precipitation on vegetation does not occur instantaneously but is cumulative.

It is against this background that the first research question asks whether vegetative and meteorological indices derived from medium spatial resolution satellite data can detect local drought risk variability better. Figures 5.6 and 5.7 clearly indicate the extent, intensity and spatial distribution of drought throughout the three seasons. The NDVI drought maps consistently identified the northern part of the study area as the most drought prone areas that need to be investigated further. These areas mostly comprise of communal farmers that needed drought relief aid urgently. The VCI (Figure 5.7) further identified distinct patches of intense drought occurrences which could help planning agencies to target their drought relief funds and aid more appropriately.

The second research question asks whether regional crop production data can detect local drought risk variability more efficiently than satellite based data. As expected these data sets failed to indicate neither the spatial distribution nor the local variability that exist where drought occurred.

The last question asks whether a combination of *in situ* and satellite data can delineate drought risk better and show local variability. The combination of the above clearly helps

with delineating drought risk. Especially since drought is scientifically defined using the mentioned methods (indices) and the *in situ* data were used to verify and confirm the accuracy and reliability of the methodology to delineate drought risk prone areas.

The functional and user-friendly maps produced, can help decision makers to make more informed decisions concerning challenging issues pertaining to drought relief, land reform and land use planning.

Lastly, from the drought risk maps it is also evident that the north-western corner has consistent NDVI values of less than 0.2. These values indicate the tongue extension of the salt pans from the Etosha Pan which also forms part of the northern section of the Omuramba-Owambo.

The VCI clearly indicate the 2006/7 main season has been the worst drought condition for the three seasons in the study area.

The overall outcome is that this methodology was cost effective and achieved its objective in defining vegetative and meteorological drought while using a finer spatial resolution MODIS sensor opposed to the coarse AVHRR sensor, used by most studies.

6.3 Problems and limitations

The following limitations were experienced:

- The unavailability, incompleteness and inconsistent formats of rainfall data
- MODIS HDF format created unique challenges since only a few image processing software programs (eg. ENVI) can properly handle this format.
- Time constraints since it would have been interesting to see how other seasons as defined by the national and regional crop production data would correlate with NDVI and VCI
- Insufficient rainfall data to interpolate SPI and precipitation data properly
- Unavailability of agricultural data on a monthly basis and also at a district/constituency level to create excellent time-series analysis on a more finer temporal scale

- Three seasons were inadequately short. This should have been extended to at least 5 years to get more significant correlations.
- The non-inclusion of the socio-economic and vulnerability data prevented the full application of the Drought Risk Methodology.

6.4 Future work

The conceptual framework used a drought risk analysis methodology to show the holistic approach demanded to study drought. Hence future research should include the following:

- Socio-economic aspects of drought since risk assessment without it are not significant enough. This will also enable vulnerability analysis to be performed (Fig. 2.2) and finally Risk management where policies are amended and created. This study however is the first phase of the said methodology.
- Other variables such as vegetation type, soils, temperature, evaporation rate, water availability and other biophysical variables that help to more accurately define a drought.
- To include an extended historic satellite data of at least 5 to 10 years.

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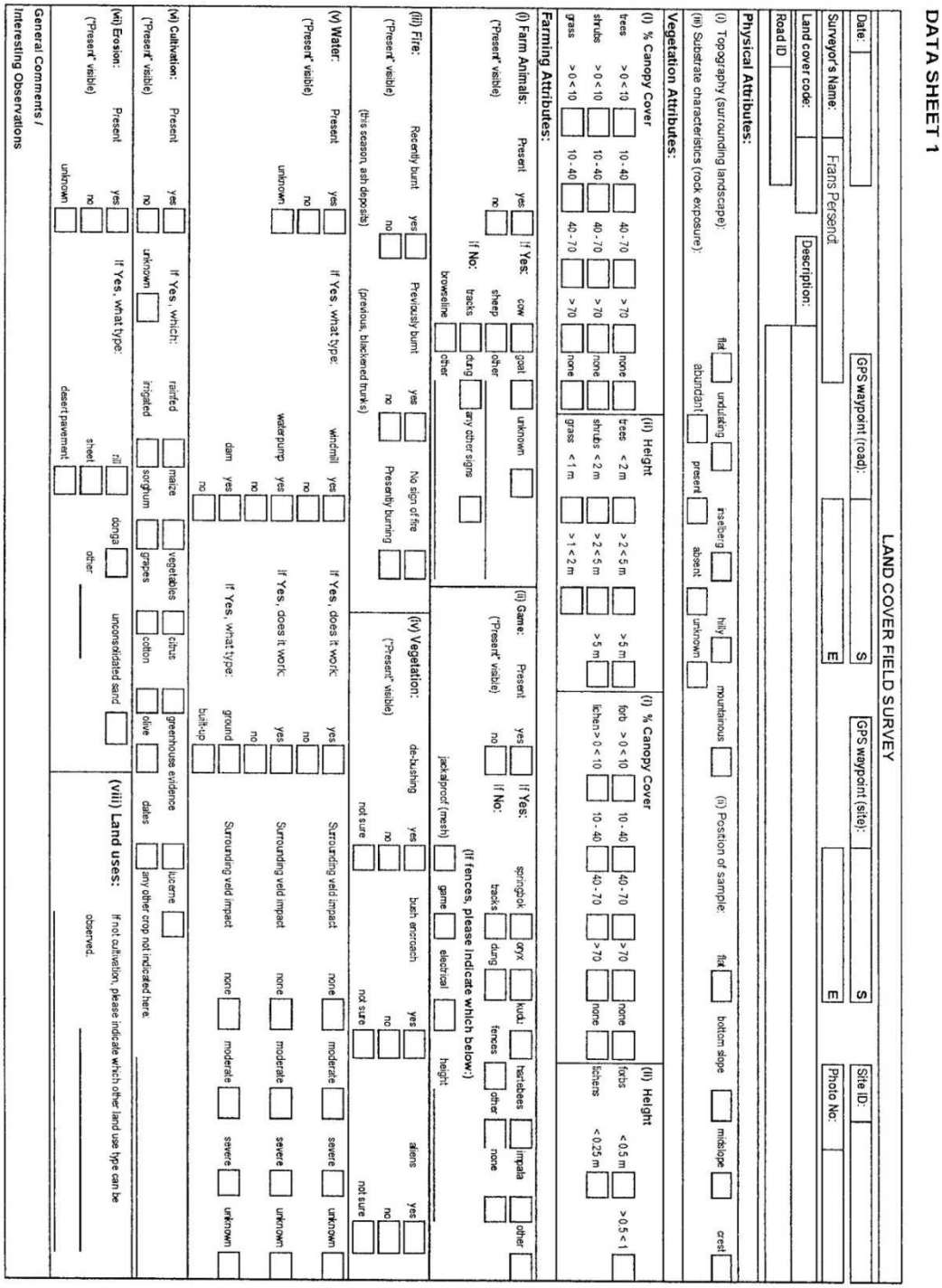
Appendix A

Appendix A: Land use Land cover Data Sheet



DATA SHEET 1

LAND COVER FIELD SURVEY

Date: | GPS waypoint (road): | S | GPS waypoint (site): | S | Site ID:

Surveyor's Name: Frans Persendt | E | E | Photo No:

Land cover code: | Description:

Road ID

Physical Attributes:

(i) Topography (surrounding landscape): flat | undulating | inselberg | hilly | mountainous | (ii) Position of sample: flat | bottom slope | midslope | crest

(iii) Substrate characteristics (rock exposure): abundant | present | absent | unknown

Vegetation Attributes:

(i) % Canopy Cover: trees > 0 < 10 | 10 - 40 | 40 - 70 | > 70 | none; shrubs > 0 < 10 | 10 - 40 | 40 - 70 | > 70 | none; grass > 0 < 10 | 10 - 40 | 40 - 70 | > 70 | none

(ii) Height: trees < 2 m | > 2 < 5 m | > 5 m; shrubs < 2 m | > 2 < 5 m | > 5 m; grass < 1 m | > 1 < 2 m

(i) % Canopy Cover: forb > 0 < 10 | 10 - 40 | 40 - 70 | > 70 | none; lichen > 0 < 10 | 10 - 40 | 40 - 70 | > 70 | none

(ii) Height: forbs < 0.5 m | > 0.5 < 1; lichens < 0.25 m

Farming Attributes:

(i) Farm Animals: ("Present" visible) Present: yes | no. If Yes: cow | goat | sheep | other | unknown. If No: tracks | dung | any other signs | browseline | other

(ii) Game: ("Present" visible) Present: yes | no. If Yes: springbok | oryx | kudu | hartebees | impala | other. If No: tracks | dung | fences | other | none. (If fences, please indicate which below:) jackalproof (mesh) | game | electrical | height

(iii) Fire: ("Present" visible) Recently burnt: yes | no. Previously burnt: yes | no. No sign of fire. Presently burning. (this season, ash deposits) (previous, blackened trunks)

(iv) Vegetation: ("Present" visible) de-bushing: yes | no | not sure. bush encroach: yes | no | not sure. aliens: yes | no | not sure

(v) Water: ("Present" visible) Present: yes | no | unknown. If Yes, what type: windmill | yes | no; waterpump | yes | no; dam | yes | no. If Yes, does it work: yes | no; yes | no; yes | no. If Yes, what type: built-up | ground. Surrounding veld impact: none | moderate | severe | unknown; none | moderate | severe | unknown; none | moderate | severe | unknown

(vi) Cultivation: ("Present" visible) Present: yes | no | unknown. If Yes, which: rainfed | maize | vegetables | irrigated | sorghum | grapes. If Yes, what type: rill | donga | sheet | other | desert pavement. (vii) Erosion: ("Present" visible) Present: yes | no | unknown. (viii) Land uses: citrus | greenhouse evidence | lucerne | cotton | olive | dates | unconsolidated sand | any other crop not indicated here: If not cultivation, please indicate which other land use type can be observed:

General Comments / Interesting Observations