

**ASSESSMENT OF SPATIAL-TEMPORAL OCCURRENCE
OF AGRICULTURAL DROUGHT FROM SATELLITES
AND METEOROLOGICAL DATA IN SOUTH
PHUTHIATSANA CATCHMENT, LESOTHO**

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**Master (Integrated water Resources Management) dissertation
University of Dar es Salaam
August, 2016**

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By

Nkeletseng Matsumunyane

**Dissertation submitted in partial fulfilment of the requirements for the Degree
of Master (Integrated Water Resources Management) of University of Dar es
Salaam**

**University of Dar es Salaam
August, 2015**

CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the University of Dar es Salaam a dissertation entitled: *Assessment of spatial-temporal occurrence of agricultural drought from satellites and meteorological data in South Phuthiatsana catchment, Lesotho* in (Partial) fulfilment of the requirements for the Degree of Master in Integrated Water Resources Management of the University of Dar es Salaam.

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DECLARATION AND COPYRIGHT

I, **Nkeletseng Matsumunyane**, declare that this thesis is my own original work and that it has not been presented and will not be presented to any other University for a similar or any other degree award.

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DEDICATION

This dissertation is dedicated to my mother Mrs 'MakeleboneMatsumunyane, my husband Mr SechabaMpesi, my sisters; Kelebone, 'Machaka, Keneuoe, Lindiwe and Lineo, and my two families at large: the family of Matsumunyane and Mpesi.

LIST OF ABBREVIATIONS

AET _M	Actual Evapotranspiration
AVHRR	Advanced Very High Resolution Radiometer
BOS	Bureau of Statistics
CWR	Crop Water Requirements
DEM	Digital Elevation Model
ET _C	Crop evapotranspiration
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GNP	Gross National Product
GIS	Geographic Information Systems
GWP	Global Water Partnership
IDWM	Inverse Distance Weighted Method
IFAD	International Fund for Agricultural Development
ILWIS	Integrated Land and Water Information System
IMF	International Monetary Fund
IPCC	International Panel of Climate Change
IWRM	Integrated Water Resources Management
LLWP	Lesotho Lowlands Water Project
MSI	Moisture Stress Index
MODIS	Moderate Resolution Imagery Spectrometer
NASA	National Aeronautics and Space Administration
NDMC	National Drought Mitigation Centre

NDVI	Normalised Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NSDP	National Strategic Development Plan
PRSP	Poverty Reduction Strategy Paper
PET _M	Potential Evapotranspiration
PRSP	Poverty Reduction Strategy Paper
SADCC	Southern African Development Coordination Conference
SEBAL	Surface Energy Balance Algorithm for Land
SEBS	Surface Energy Balance
SPI	Standardised Precipitation Index
SWC	Soil water content
TCI	Temperature Condition Index
U.S	United States
VCI	Vegetation Condition Index
VHI	Vegetation Health Index
WMO	World Meteorological Organization

ABSTRACT

Lesotho has been battling with food insecurity in the recent past years. This has been associated with a series of crop failures occurrences that the country has put a country in difficulty. The South Phuthiatsana catchment Lesotho, where this study is carried out, is no exception, and has been documented to have undergone severe drought situation in the recent past. This study has attempted to assess the spatial-temporal occurrence of agricultural drought in South Phuthiatsana catchment Lesotho, using ground based and remotely sensed indices. Standardized precipitation index (SPI), moisture stress index (MSI) and vegetation health indices (VHI) were used in the assessment. This is done in order to attain sustainable management in water for food security. The results from the SPI and VHI analysis indicate the western part of the catchment being affected/prone more than Eastern part of the catchment. Contrary conclusions are drawn from the SMI analysis that indicates the eastern part as the most affected. This contrary result is due to topography, the eastern part of the catchment is at high elevation and it is dominated by steep slopes. In terms of temporal occurrence there is minor difference per location throughout cropping season. The results from these 3 indices imply that not only rainfall is the cause of crop failure but some factors such as topography, soil fertility or types of seed might contribute to decline in maize production. Further studies are recommended and proper rainwater management for sustainable food production.

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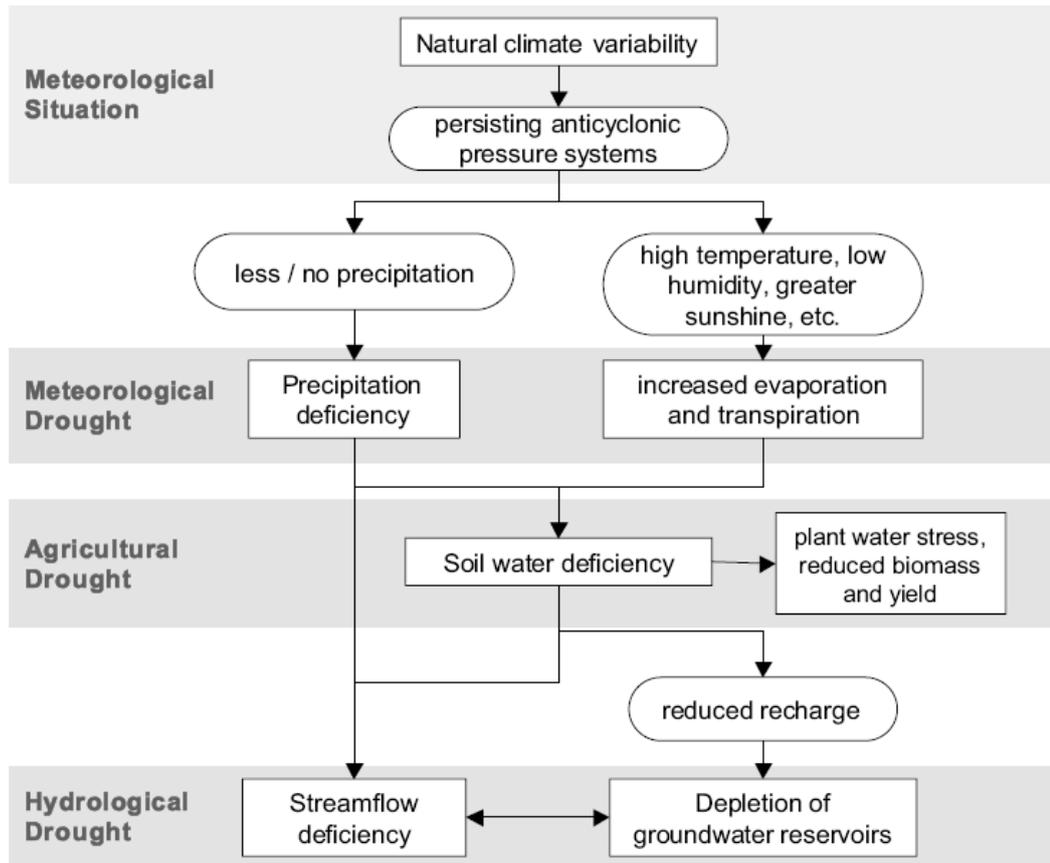
CHAPTER ONE

INTRODUCTION

1.0 General Introduction

Water is life, without it crops cannot survive. In water management, it is very important to take into account water for agriculture in order to attain sustainable agricultural water management. Absence of water for crops is known as agricultural drought. According to NOAA “Agricultural drought occurs as a result of meteorological drought and it also has a relationship with hydrological drought. It generally starts with precipitation shortage which leads to soil water deficits, and consequently reduced ground water or reservoir levels needed for irrigation, and so forth. Major source of water for soil is rainfall. However, how much rain is kept in the soil depends on several factors namely; soil type and conditions, intensity of rainfall and topography.

There are ultimately numbers of droughts which are interrelated and occur in sequence; normally it starts with rainfall shortage. Rainfall shortage is termed meteorological drought, it leads to soil moisture deficits which is known as Agricultural drought, and hence there is direct relationship between meteorological drought and agricultural drought. Figure 1.1 shows the occurrence and sequential relationships of different droughts. In many places of Africa, agriculture is rain dependent (rain fed), Lesotho is not an exception, meaning that without rain there is no crop production.



(Source: National Drought Mitigation Centre)

Figure 1.1 The sequence of drought impacts and occurrence

The agricultural drought is measured or described by farmers as insufficient soil moisture to support crop production. Insufficient soil moisture often occurs during dry, hot periods of low precipitation, it can also occur during periods of average precipitation when soil conditions or agricultural techniques require extra water. It is moreover described in terms of intensity, duration and spatial coverage. In terms of spatial-temporal occurrence drought may be defined as a deficit of water in time, space, or both, the variation is due to varying amount of rainfall in space and time,

variation of temperature or other factors that influence drought such as different physiographical, topographic and geological properties of the area.

Other factors like soil salinity, presence of other chemicals, lack of pest and disease control, poor soil management and limited water availability at the root zone may lead to variation of drought in space and time. Other factors that affect evapotranspiration which increase drought effect are groundcover and plant density. According to Brouwer et al (n.d) Cultivation practices used in this catchment can alter the microclimate, affect the crop characteristics or affect the wetting of the soil and crop surface. Hence more studies need to be done on the above aspects.

According to Oweis *et al* (2007) developing countries like Lesotho entirely depend on subsistence rain fed agriculture for food production and lately due to climate change and other unknown factors; food production is decreasing while demand for food due to increasing population is increasing. Facing the food and poverty crises in developing countries will require a new emphasis on small scale water management in rain fed agriculture involving the redirection of water policy and large new investments. Rain fed systems dominates world food production, but water investments in rain fed agriculture have been neglected over the past 50 years.

According to U.S Drought monitor the end of October 2015, drought conditions remained relatively constant, globally. Currently there is El Nino characterized as a strong event, similar in strength to the 1997-1998 events. In Africa, drought remains entrenched across the equatorial region and through much of the South. Lesotho as

one of the Southern countries is greatly affected by the effects of El Nino. The condition of 2015/2016 was as shown on appendix D.

According to 2nd International Conference global Food Security report, mankind is challenged by the fact that, they have to maximise food production in order to meet demand for growing population while they have to take into account the environment needs. It further emphasises that by 2050 at least 9 billion people will be in need of food which means the world has to ensure food security. Some factors such as increasing incomes and urbanisation will lead to dietary change. The report shows that food security challenge will progressively encompass the tripling of malnutrition (under nutrition), obesity and micronutrient deficiencies.

Oweis *et al* (2007) found that there is a close relationship between water, poverty and hunger. Areas that are affected by inadequate water are regions where poor people dwell, and these regions have challenges of food insecurity due to poor production of food caused by lack of water. For example; in the arid, semiarid, and dry sub humid regions of the world hunger and poverty are concentrated because, water is a key challenge for food production, due to the extreme unpredictability of rainfall, long dry seasons, and repeated droughts and dry spells. He further emphasises that these regions cover a large part of the world approximately 40% and the population is 40% of the world population. Moreover these regions are mainly rain fed. Increasing water availability and the water uptake capacity for crops is a challenge due to lack of water management skills and scarcity of water.

Scheierling *et al* (2011) found that Lesotho rainfall is roughly estimated to be between 500mm to 1000mm in the southern lowlands per year. It is characterised by short duration but high intensity rainfall. Intermediate frosts and hail storms are common but they occur in May and September. The cheapest way of agricultural water improvement is to harvest rain water in-situ and make sure it is stored in large quantities so that it is available over a longer time, (Scheierling & Anchor, 2011). However rain varies from year to year, this fluctuations affect plant growth.

Lesotho agricultural year for maize production runs from October to March with harvests for winter crops, wheat and peas occurring in the first half of the year while that of summer crops like maize, sorghum and beans in the second half. Agriculture output is erratic over time and has been declining as a share of national output due to various factors. Between the period 2003 and 2009 the share of agriculture to gross national product fell from 9.3% to 7.1%. In 2011 and 2012, it declined to 7.3% and remained constant for both years (Bureau of Statistics, 2012). In 2014, 2015 and 2016 the situation was worsened by ElNino as shown on appendix D.

However, Lesotho vision 2020 the aim is to improve and increase agricultural productivity so that it increases the contribution to country's Gross Domestic Product (GDP). Basically, an increase in maize yields and livestock output would increase contribution of agriculture to country's GDP by M70 million.

However due to terrible drought conditions which have negative impact to maize production and agricultural production as a whole, it means the country will fail to

achieve vision. It could only be overcome by practicing irrigation systems, which is also a problem in a country like Lesotho which lack machinery and techniques for irrigation. The research on irrigation failures was conducted by PalamangNtai; Irrigation farming in Lesotho in 2011. Present agricultural water management practices are failing; hence there is a need for paradigm shifting.

1.1 Problem statement

Lesotho has been battling with food insecurity in the recent past years because of agricultural drought. Food production in Lesotho has seen a terrific decrease and this has caused a country to import 70 per cent of food for its people, while at the same time prices are rising. According to the Lesotho Poverty Reduction Strategy Paper (PRSP) of 2012, developed by the International Monetary Fund (IMF), agriculture is the main sources of employment and income for most people in the country. However, the low performance of the sector continues to exacerbate poverty.

Agriculture output is erratic over time and has been declining as a share of national output due to various factors. Between the period 2003 and 2009 the share of agriculture to gross national product fell from 9.3% to 7.1%. In 2010 it increased again to 8.1% while in the next two years, 2011 and 2012, it declined to 7.3% and remained constant for both years (Bureau of Statistics, 2012).

Droughts have been a part of the climate change in Southern Africa. The frequency of drought, irregular rainfall, and abnormal temperature patterns in Lesotho have increased significantly over the past few years, this is due to its high elevation which

ranges from 1,333 - 3,482 meters above sea level- and it is positioned at the tip of Africa. Lesotho is seriously influenced by variety of opposing weather situations, leaving it disposed to natural disasters. According to Ministry of Agriculture (2013) it is more susceptible to drought and desertification.

The effects of the drought in Lesotho concern multiple sectors: food security and agriculture, water, health and nutrition as well as migration, protection and security. This presentation will give a brief overview over the situation in the most effected sectors.

From the United Nations report on www.unlesotho.org, website the following evidence was found “The impact of El Niño induced drought during the 2015/2016 planting season (Sep-Dec) is having enormous repercussions in Lesotho and neighbouring areas of South Africa, it has accounted to the dry spell experienced during the 2014/2015 agricultural season.

Lesotho is currently facing water scarcity and rain deficits which have led to delays or failure of the planting season and will certainly cause a sharp decline in food production. Water shortages in Lesotho do not only affect agricultural activities but also industrial production, access to basic services that are unable to function normally (e.g. health centres and schools) as well as household consumption patterns. The water scarcity severely endangers the water reserves in Lesotho’s dams and has already led to water rationing in many districts In the light of gravity of the situation.”

1.2 Research Objectives

1.2.1 Main Objective

The main objective of this study is to assess the spatial-temporal occurrence of agricultural drought using satellite derived and meteorological data.

1.2.2 Specific Objective

- Assessment of spatial and temporal occurrence of drought using standardised precipitation index (SPI) from 1993 to 2013 rainfall data.
- Assessment of agricultural drought from soil moisture condition using moisture stress index (MSI)
- Assessment of agricultural drought from the vegetation using vegetation health index (VHI).

1.3 Research questions

- How is drought condition due to rainfall variations in the catchment?
- How is the soil moisture condition and variation in the catchment?
- How is the vegetation health variation in the catchment?

1.4 Significance of Study

It is very important to study and understand agricultural drought in order to achieve sustainable management of water for food security, this kind of drought is generally soil water deficiency. The study is important in that it assesses drought, its magnitude, coverage and duration which makes it easy to simulate and warn farmers about current and future drought, so that mitigation measures can be taken. The unit

for defining drought in agriculture is soil moisture, greenness of vegetation. Moreover it is important in planning and allocation of land to industries, residential and agriculture, agriculture can be located where crop production is maximized in order to improve food security.

Integrated water resources management (IWRM) is concerned with efficient use of water resources without compromising the environment. Economic success should not be achieved or met at the expense of growing environmental risks by taking all the water for agricultural production and leaving none for environmental sustainability, also leading to ecological scarcities and social disparities (Opportunities, n.d.)

Since the water in the Phuthiatsana River is for environmental flow, alternative uses of water like rainwater harvesting should be used. This study area is downstream of Metolong Reservoir, which is vulnerable to reduced flows, and even if land users opt for irrigation they are constrained because the flows in the river are mainly for environment, therefore they are obliged to supplement it with rainwater harvesting. Phuthiatsana River is the only river in the downstream area which is perennial. This study is meant to generate useful information for policy makers and those dealing with food security issues in preparing for disaster and planning mitigation measures well in advance. In addition, the crop monitoring sectors may use the information to advise the farmers on areas that are less prone to droughts and to use of drought-prone or drought-resistant crops.

The previous studies carried out in this region do not show the spatial coverage, severity and the effects of drought on maize as the main grown crop in the catchment. Understanding and knowledge of concept and characteristics of drought, its difference from other natural hazards which is achieved by this study will help scientists and policy makers and planners. It will not only help them with knowledge and understanding but also with future scenarios, so that awareness and mitigation measures can be taken before hand in order to reduce vulnerability and stabilize favourable conditions for future generation.

1.5 Scope of Study

This study assessed the agricultural drought situation in terms of spatial coverage in the catchment and temporal occurrences that is which part of the catchment experienced drought and which years, it furthermore assess soil moisture conditions in the catchment as well as vegetation health. For these assessments the study used standardised precipitation index, soil moisture stress index and vegetation health index. Data used include remote sensed data, meteorological data and secondary data

CHAPTER TWO

LITERATURE REVIEW

2.1 Food Security

In studying agricultural drought which has a terrific ruthless on food production, it is important to know about food security because it is the main reason one would get concerned about agricultural drought. The following are the views of different writers on food security and how it is related to agricultural drought and its impact to people's lives.

According to Oweis *et al* (2007) the majority of poor people in the world are dependent on rain fed agriculture for food, incomes, and thus livelihood security. If rainfall fails, this means failure in agriculture hence food insecurity.

Mukhala & Hoefsloot(n.d.)found that two areas that define food security problems are access to food by both rural and urban people and poor food production due to shortage of rainfall.

According to World Bank (2008b)states that the prices of food has risen due to little food produced, hence there is a calling of improving food production by adapting better water management strategies. Food prices increased sharply in 2008 since and are expected to remain high forever. This rising is already showing deadly effects to

the growing world population. Therefore factors like poverty and malnutrition are overwhelming.

According to the reviewed writers food insecurity is dependent on failure of rainfall especially in countries like Lesotho which solely depend on rainfall for agriculture. Hence agricultural drought leads to decline in food production which means food insecurity. This shows that Lesotho is in great distress as its main source of employment is agriculture and importing food means taking out money which people do not have.

2.2 Lesotho Agriculture

According to the Lesotho Poverty Reduction Strategy Paper (PRSP) of 2012, developed by the International Monetary Fund (IMF), agriculture is the major source of employment and income in rural areas and some urban areas. However, the low performance of the sector continues to exacerbate rural poverty. This critical state of affairs has led the Government to prioritise agriculture and food security. Its goals in this regard are outlined in the Vision 2020 document as well as the National Strategic Development Plan (NSDP: 2012). However, the problem is overwhelming. This leads one to believe the approach used might be wrong. Most of the writers emphasise that current management practices are failing to support food production in some countries. This makes a sound for shifting from old management practices into new approach which is integrated water resources management (IWRM).

According to Mosenene, (1999) the contribution of the agriculture sector towards the GNP dropped from 50% in the seventies to 12% in 1994. however livestock

production was the one dominating by 50% and crops accounted for only 40%. He continued showing that since majority of the population depend on agriculture as a source of employment, this means many people were at jeopardy. He says normally Lesotho imports 25% of its food stuff but to 16% in 1994.

According to Ministry of Agriculture situation report (2012) The economy of Lesotho is mostly dependent on agriculture with a small industrial sector. The type of agriculture practiced is mainly subsistence with minimal commercial farming. Agriculture is practiced across ten districts of Lesotho and covers four ecological zones; the Lowland, Foothills, Mountain and Senqu River Valley. The lowland zone is most densely populated and intensively cultivated with relatively high chance of rainfall. The foothills zone as compared to lowland is less populated with less rainfall. The mountain zone is the largest zone of the country that is characterized by very cold winter with snow. Senqu River Valley is the smallest zone which runs from the east to the west across the districts of Thaba-Tseka, Qacha's Nek, Quthing and Molepolole along the Valley of Senqu River.

According to Opportunities (n.d.) The poor people are always the ones adversely affected by food security which declines due to climate change related problems which lead to unfavourable weather conditions this is because they solely depend on farming and nothing else. The effect of this unfavourable weather conditions do not only affect food security but also human health, ecosystem stability and water availability. He moreover emphasises that even though agriculture is the main source of employment in the country, its subsistence nature makes it to contribute little to

country's GDP, and it contributes little to poverty reduction because it does not meet households' food requirements

Current water management strategies in water for food security in rain fed production are expected to improve in order to improve food production to meet the current population and the growing population. The other detrimental factor leading to decline in food production is climate change which leads to reduced rainfall. Further Climate projections show that water resources will strongly be affected by climate change, hence there is a need to manage the little water the country gets from rainfall, in order to improve food production.

Agricultural productivity in rain fed areas depends critically on the temporal and spatial dynamics of precipitation, soil moisture and runoff and of course evaporation. According to IPCC (2008), Probable effects of climate change in many areas include changing precipitation patterns, intensity and extremes; reduced snow cover and widespread melting of ice; and changes in soil moisture and runoff, which needs to be sufficient to meet evaporative demands and associated soil moisture distribution. Arid and semi-arid regions are the most likely to be adversely affected since their rain fed agriculture is very vulnerable to climate change.

From the above writers the information grasped is that Lesotho solely depends on agriculture the same agriculture failing, and the situation is on-going. One would conclude that there are no good management practices in order to take care of their only means of survival. Even though drought disasters are natural and beyond human

abilities, more attention can be on agriculture improvements in order to sustain people during droughts like in order countries which invest more on agriculture.

2.3 Drought

NOAA, (2003) defines Drought as insufficiency of precipitation over a long period of time, normally a season or more, leading to water shortage in the soil, which affects vegetation, ecosystem, animals and people.

According to Hagman, (1984) Drought is said to be a very complex phenomenon, it is least understood of all natural hazards. It affects a large number of people than other hazards. For example, according to Office of Foreign Disaster Assistance (1990) in 1980s in Sub Saharan Africa drought adversely affected more than 40 million people while SADCC (1992) reported that 1991 to 1992 in Southern Africa 20 million were affected and this resulted in grains shortages such that they had to import. Moreover Riebsame et al. (1991) found that in United States in 1988 drought impact was amounting to US\$40 billion.

Droughts are one of the most costly hazards on a year-to-year basis and its impacts are significant and widespread such that many economic sectors and people can be affected at any one time. In addition, there are different indicators and indices to help define drought. From different reviewed literature on drought in both developing and developed countries, it seems it affects all regardless of the level of development.

This means that it is difficult to come up general and exact definition of drought. It has different meanings depending on the needs of people, location and time. For people who want water for crop production they define drought as lack of water to support their crops, for people who want water for drinking, they define it as lack of water to sustain their lives. Hence the information from different literatures reviewed is that drought is a very complex phenomenon.

Moreover from different literatures reviewed it was found that droughts are a normal part of the climate and they can occur in any climate region around the world, even deserts and rainforests. Droughts are also one of the most costly hazards on a year-to-year basis and its impacts are significant and widespread such that many economic sectors and people can be affected at any one time. Also, the area affected or hazard footprint for drought is typically quite large compared to many other hazards that are constrained to a floodplain, coastal region, storm track or fault zone.

It is also important to monitor or assess drought in order to come up with mitigation measures, preparedness, and prediction. But Wilhite (2000) says in drought management more especially when the focus is on drought management, scientists and policy makers are required to focus on both protection and recovery/rehabilitation. This is where the issue of sustainable agricultural water management can be practiced, for example use of rainwater harvesting in agricultural fields can bring about profitable use of little rain fall hence improvement of agricultural production.

2.3.1 Agricultural drought

Agricultural drought is absence of moisture in the soil's root zone to support crops growth; this is caused by several factors such as uneven distribution of precipitation both temporally and spatially, crop types, cropping systems, water requirements for different crops, different water supply condition. These all lead to decline in food production.

According to Wilhite (2000) Agricultural drought has a direct relationship to meteorological drought which occurs when there is rainfall shortage, high difference between potential evapotranspiration and actual evapotranspiration, this then leads to water deficit in the soil, plants water needs are then not met. Plants water demand is dependent on the weather conditions at that area, biological characteristics of the specific plant, its stage of growth, and the physical and biological properties of the soil. Definition of agricultural drought entails susceptibility of crops at different stages of growth. For example, shortage of soil moisture at early and very late stage of development has little impact to crop development, while at the flowering and ripening stage, if there is shortage of soil moisture that imposes a big threat to crops which eventually lead to reduced.

For agricultural drought assessment number of remotely sensed indices that are satellites derived are used, these are the normalized difference vegetation index (NDVI), vegetation health index (VHI), temperature indices such as the temperature condition index (TCI), and the vegetation condition index (VCI) which is the

combination of vegetation greenness and temperature indices. This is achieved by using AVHRR data at regional to global scales according to Brown et al (2008).

2.3.1.1 Water needs for crops (maize)

According to Brouwer, Heibloem, & Division,(n.d.)Crop water requirements for different crops means the total amount of water used in evapotranspiration and varies from crop to crop. FAO (1984)defined crop water requirements as ‘the depth of water needed to meet the water loss through evapotranspiration of a crop, in the condition where the crop is disease-free, soil conditions favourable and fertile, enough soil water, grown in large fields and production fully achieved.

Scientifically crop evapotranspiration ETC, is the loss of water by plant and soil under standard conditions where the soil and crops are disease free, well fertilized, under favourable climatic conditions. The values of crop evapotranspiration and evapotranspiration are identical when aforementioned conditions are maintained. But definitions are different ETcrefers to the amount of water lost through evapotranspiration and CWR refers to the amount of water that is needed to compensate for the loss.

From different writers, the information conveyed is that since the amount of water consumed by a crop equals the amount the crop transpires through the leaves and the amount of water the soil evaporates, knowledge of amount of water evaporated is very important in order to find out if crops are healthy or not healthy. If evapotranspiration is less that implies there is little water in the soil such that crops

absorb little. Therefore it is important to know the amount of water consumed by crops in the study of agricultural drought.

2.4 Previous drought studies in the country on food production

The studies carried out in the whole country show that extremely poor harvest outlook: Crop estimates (particularly area planted) and vegetation indexes show that, mainly in the lowlands and Senqu River Valley will be at historically poor levels, with a strong likelihood that they will be worse than those in 2012. Unlike in previous food insecurity crises where harvest suffered from irregular rainfalls in this occasion many subsistence farmers have not even been able to plant. In parts of Lesotho and central and south-eastern South Africa, the season is late, with delays of 50 days or more in many areas.

These delays reduce the chances of successful cropping due to the shortened period available for crops to reach maturity before the cessation of rains or the arrival of low temperatures and frosts. Farmers also tend not to plant or are hesitant to plant if they do not receive sufficient planting rains by specific cut-off dates, which differ by area. Even many of those having dared to plant encouraged by isolated rains have reported seeds not germinating due to the lack of moisture in the fields, insufficient rainfall subsequent to the plantation and high temperatures. In areas where planting took place such as the mountains and to a lesser extent in the foothills, crops have been under water and heat stress. Frost damage in the mountain areas in early November caused significant extensions of crops to be damaged. Besides the reduction of yields, the climatologically conditions have resulted in a reduction of

many on-farm labour opportunities (both in Lesotho and in South Africa) which are crucial contributions to the rural household's livelihood strategies.

2.5 Characteristics of Agricultural drought

Spatial and temporal occurrence of agricultural drought is described below.

According to World & Organization (1950), three essential elements distinguish droughts from one another: intensity, duration, and spatial extent. Intensity refers to the magnitude or extends of precipitation shortage, which varies from place to place and from time to time. While duration refers to how long it takes and spatial extent refers to area affected.

2.6 Assessment of Agricultural drought

The main factors related with agricultural drought are Climate in terms of evapotranspiration and precipitation, Soil in terms of its moisture content, Crops types and stage of development, Irrigation capacity in areas when irrigation is practised. In drought assessment, some of the above factors are assessed and the indices are discussed below.

According to Wilhite (2000) is studying detailed monitoring, collective climatologically data (e.g., temperature and precipitation) as well as stream flow, reservoir and groundwater levels, soil moisture, snowpack, and remotely sensed data from satellites should all be taken into consideration, because they entail all the necessary factors affecting crop yield. This information is useful in forecasts of agricultural and hydrological drought, monitoring and early warning techniques,

including the use of indices to track current drought conditions and to view them in a historical context so that farmers are warned well in advance.

2.6.1 Remote sensing of drought

According to Rojas, Vrieling, and Rembold (2011) currently the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR) are the sensors mostly use for land surface dynamics and environmental monitoring and they are very popular worldwide. According to Yagci et al. (2011) this sensors were used in Aegean of Turkey to monitor agricultural drought on grape field, it was used to monitor vegetation greenness in an adverse weather conditions then the results proved that MODIS and AVHRR sensors are suitable for monitoring agricultural drought.

Remotely sensed vegetation condition indices, include the normalized difference vegetation index (NDVI) and the vegetation condition index (VCI), the temperature condition index (TCI), and vegetation health index (VHI) that combines vegetation greenness and temperature indices. These have widely being used to identify agricultural droughts and to monitor vegetation canopy. In this study AVHRR data was used because of its availability and easily accessible.

2.6.1.1 Moisture Stress Index (MSI)

It is beyond doubt that the spatial and vertical properties of soils are important to water management, for it is the capacity of the soil to, absorb, retain and redistribute water that is a prime regulator of hydrological responses within a catchment in regard

to the generation of storm flow, base flow and peak discharge; and the soil is the medium in and through which many other hydrological processes operate. In agricultural drought the main interest is how much water is present in the soil (root zone).

In studying soil moisture the following are very important to understand, the soil's textural composition into percentages of clay, silt and sand, and the amount of water a soil of a given texture retains at specified/critical soil water conditions, at permanent wilting point (i.e. the soil water content constituting the lower limit of soil water available to the plant), at its drained upper limit (previously also termed "field capacity", i.e. the soil water content held by capillary forces is great enough to resist gravity after natural percolation from the soil until drainage ceases) and when the soil water content is at total porosity, i.e. at saturation (when all pore spaces are filled with water), in which case water retention may be increased when soil bulk density is decreased, for instance by tillage practices; furthermore, with soil properties which influence the depth and intensity of root ramification since these have a major effect on the water extraction pattern. Other factors may also operate, for example, in the capillary fringe just above the water table.

Soil moisture stress index is a measure of soil moisture condition, whether low or high. Low moisture implies drought conditions. Some writers talk about Palmer Z index as a measure of agricultural condition as measured by soil moisture. It is remotely sensed and monthly values are determined. The meteorological data is used

to monitor, it uses monthly mean temperatures and precipitation across major cropping regions.

In this study spatially distributed soil-water balance was implemented on the high-resolution WorldClim and CGIAR-CSI PET climate dataset using ArcAML (ESRI) as modelling tool. This model uses spatially distributed average values of monthly precipitation and monthly Potential Evapotranspiration and returns monthly Spatially-distributed values defining Actual Evapotranspiration (*AET*), Runoff (*R*) and Soil Water Content (*SWC*). The modelling is spatially explicit to represent varying climate conditions, while vegetation and soil properties are assumed as uniformly standard (characterized by crop coefficient equal to 1, rain interception coefficient equal to 0.15 and maximum SWC in the rooting zone equal to 350 mm). The results highlight specifically the climatic influence on hydrological dimensions regulating vegetation suitability. It takes into account; effective precipitation and actual evapotranspiration, which are discussed below.

Effective precipitation is calculated as the gross precipitation minus the precipitation intercepted by canopy cover and litter. Rain interception is the process by which precipitation trapped by vegetation canopy and litter before it falls on the ground. It is said to be subject to evaporation. It is included in the water budget because it reduces the amount of available precipitation and hence the amount of water in the soil. In order to get amount of effective precipitation, intercepted precipitation is subtracted from gross precipitation. The quantity of rain intercepted is proportional to the interception coefficient, calculated as a fraction of gross precipitation.

Actual Evapotranspiration is the amount of water that is removed from soil plus the amount removed from plants, they all go to the atmosphere. *AET* is dependent on the available atmospheric energy (*PET*), vegetation characteristics, some vegetation transpire more than others depending on the amount of water they take from the soil, quantity of water available in the soil and soil hydrological properties.

The vegetation coefficient (*Kveg*) used in this model is spatially standardized, assumed as reference crop ($Kveg = 1$, typical of agronomic crops at maturity and tree), in order to define results explicit just to climate conditions. The soil stress coefficient (*Ksoil*) represents a dimensional reduction factor resulting from the limit imposed by the monthly soil water content (*SWC_m*). The model uses a linear soil moisture stress function that is considered appropriate for monthly computation:

The maximum amount of soil water available for *ET* processes within the plant rooting depth zone ($SWC_{max} = 350$ mm) is equal to the *SWC* at field capacity minus the *SWC* a wilting point times the rooting depth. The Maximum Soil Water Content for evapotranspiration processes is assumed at a fixed spatial value of 350 mm, which corresponds to average soil texture for a plant rooting depth of 2 meters.

The *SWC* defines the monthly fraction of Soil Water Content available for evapotranspiration processes (as percentage of Maximum Soil Water Content). It is therefore a measure of soil stress, and equals to the soil water stress coefficient (*Ksoil*). This Priestley-Taylor alpha coefficient is generalized as the ratio

(dimensionless) of annual AET over annual PET. As alpha coefficient approaches 1, vegetation is uninfluenced by water stress. This variable may be effectively considered to describe overall aridity stress on vegetation, as it integrates monthly soil water availability for vegetation requirements through generalized soil water balance.

2.6.1.2 Vegetation Health Index (VHI)

According to Kogan, (1994) VHI is a composite index because it combines vegetation condition index (VCI) and the Temperature Condition Index (TCI). The VCI is derived from the Normalized Difference Vegetation Index (NDVI). It is widely used because it incorporates many aspects together. Vegetation Index is determined during the growing season, it indicates if a crop contains live green vegetation, which means crop has enough water. It uses the global vegetation index data, which is produced by mapping the 4 km daily radiance. Radiance measured in both the visible and near-infrared channels is used to calculate the NDVI. The NDVI measures greenness and vigor of vegetation over a 7-day period as a way of reducing cloud contamination.

2.6.2 Meteorological assessment of Agricultural drought

Meteorological assessment of agricultural drought is based on meteorological parameters. It assessed using the following index.

2.6.2.1 Standardised Precipitation Index (SPI)

It uses historical precipitation records. According to McKee et al. (1993), the Standardized Precipitation Index is an index based on precipitation historic data, it only uses precipitation, which is placed in severity classes called index. This index values represent standard deviation from mean. However he concludes that this index is one such index under investigation. Using precipitation data, the status of too low or high precipitations over the time periods can be monitored. SPI is based on probability (chance) of occurrence.

The rainfall received on the ground not only depends on the angle of incidence of the falling drops, shown by Schultz (1981) to be a function of wind speed and drop diameter, but also on the slope and aspect of the ground surface. Thus the discrepancy between "meteorological" rain catch (i.e. measured by a vertical rain gauge) and "hydrological" rain catch (i.e. with the rain gauge perpendicular to the slope face) may be as high as 4-11% on different aspects when rainfall is associated with storms moving.

According Edwards and McKee (1997) Standardized Precipitation Index (SPI) expresses the actual rainfall as a standardized departure with respect to rainfall probability distribution function. This makes this index important to assess drought, it compares drought over space and time. The calculation of SPI requires long term data on precipitation to determine the probability distribution function which is then transformed to a normal distribution with mean zero and standard deviation of one.

Thus, the values of SPI are expressed in standard deviations, positive SPI indicating greater than median precipitation and negative values indicating less than median precipitation

The understanding that a deficit of precipitation has different impacts on groundwater, reservoir storage, soil moisture, and snowpack and stream flow led American scientists McKee, Doesken and Kleist to develop the Standardized Precipitation Index (SPI) in 1993. (“Standardized Precipitation Index User Guide,” n.d.)

In this study precipitation related index (standardised precipitation index) is used because in the countries like Lesotho agriculture is mainly rain fed so it is important to understand and analyse precipitation hence why standardised precipitation index. This was also used at the following places according to the following writers and they found it effective.

Moreover according to WMO report (2013), because of the utility and flexibility of the SPI, the index can be calculated with data missing in the period of record for a location. Ideally, the time series should be as complete as possible, but the SPI calculations will provide a ‘null’ value if there are insufficient data to calculate a value, and the SPI will begin calculating output again as data becomes available. The SPI is typically calculated for timescales of up to 24 months, and the flexibility of the index allows for multiple applications addressing meteorological, agricultural and hydrological drought events.

It further more emphasises that, the ability of the SPI to be calculated at various timescales allows for multiple applications. Depending on drought impact in question, SPI values of three months or less might be useful for basic drought monitoring; values of six months or less for monitoring agricultural impacts; and values of 12 months or longer for hydrological impacts. This is why it was used in this study of agricultural drought analysis together with moisture stress index (MSI) and Vegetation Health Index (VHI). Three indices were used because according to the same WMO (2013) no single indicator or index can be used to determine appropriate actions for all types of droughts given the number and variety of sectors affected.

2.7 Maize yield reduction in the catchment

Maize is selected in this study because it is the most dominating crop produced in Lesotho as shown on the Figure 2.1. It is the staple food and also the pride of the country. From the research done by the ministry of agriculture it makes 70% and the remaining 30% is for other crops such as sorghum, beans, wheat and others as shown in Figure 2.1.

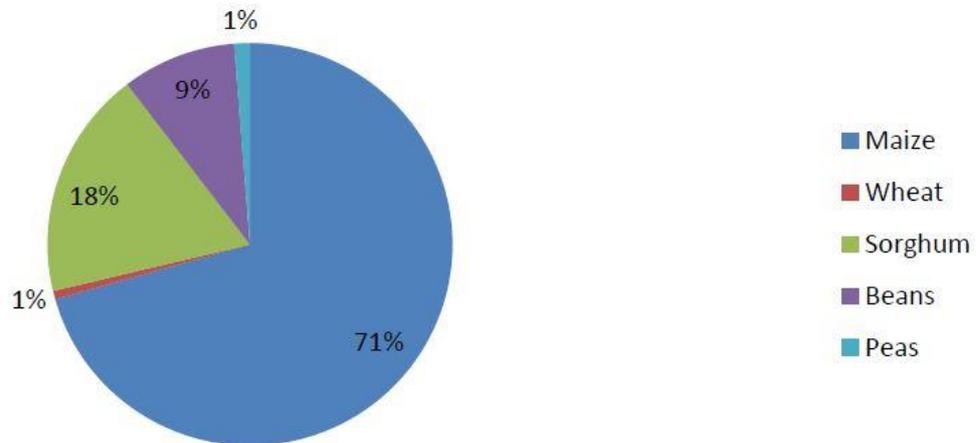


Figure 2.1 Crops produced in Lesotho

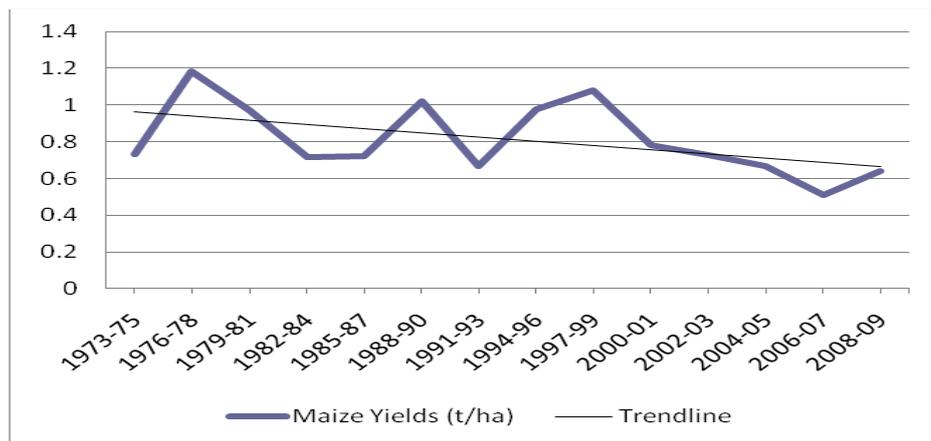
Source: Ministry of Agriculture and food security

Maize yield per hectare for 2013/2014 was 0.59mt/ha, showing a decrease of 28.0 percent compared to 0.82mt/ha of the previous year. Berea recorded the highest yield of 1.01mt/ha followed by Maseru with 0.92mt/ha. The lowest maize yield (0.18mt/ha) was observed in Mafeteng.

Trend of Maize Yield

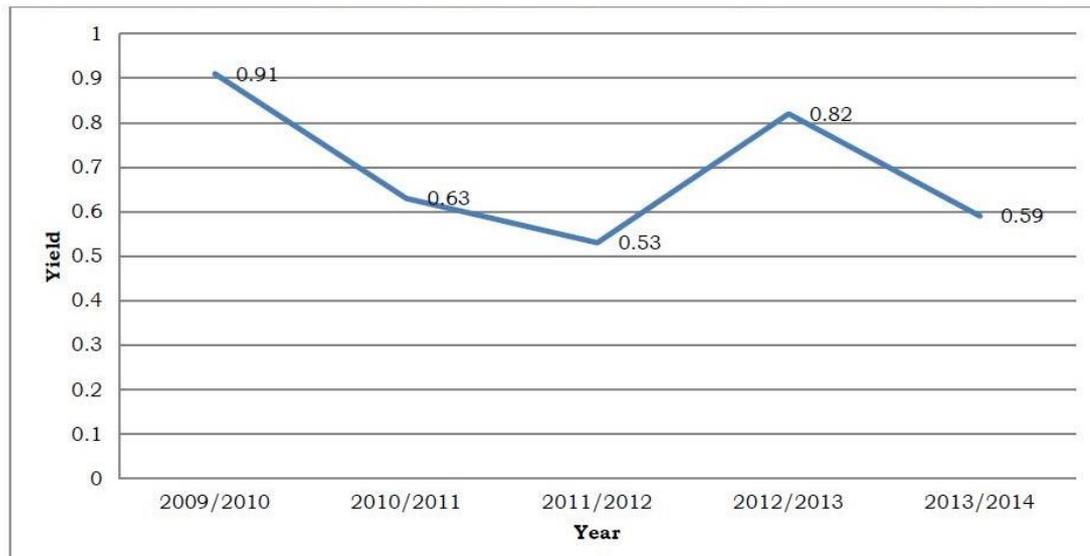
According to Crop forecasting Report (2014) Maize yield trend for a period of five consecutive years is covered in this section. Figure 2.3 illustrates maize yield per hectare from 2009/2010 to 2013/2014 Agricultural Years. From 2009/2010, yield decreased by 30.8 percent from 0.91mt/ha to 0.63mt/ha. Maize yield further decreased by 15.9 percent from 0.63mt/ha in 2010/2011 to 0.53mt/ha in 2011/2012. From 2011/2012 to 2012/2013, yield increased by 57.4 percent from 0.53mt/ha to 0.82mt/ha. Yield decreased by 28.0 percent from 0.82mt/ha in 2012/2013 to 0.59mt/ha in 2013/2014. Figure 2.2 shows a major decrease in maize production since 1973.

From 1993 to present maize production has shown a significant decrease, while population is increasing and hence the demand. This implies that demand surpasses the supply, this put a country in the threat of food insecurity. And the situation was worsened by ElNino in 2015 and 2016, in some areas of the catchment there was zero harvest.



Source: Ministry of Agriculture

Figure 2.2 Maize yield reductions in tonnes/ha



Source: Ministry of Agriculture

Figure 2.3 Maize yield reductions in tonnes per hectare

2.8 Previous studies done in the catchment

There are some hydrological studies that have been done in the catchment but study on spatial coverage of agricultural drought has not been done hence why this study attempted to analyse the spatial coverage of agricultural drought. Maliehe (2015) studied the water availability in the catchment and his findings are 26% of rainfall form base flow, 41% of total flow comes from base flow, while surface runoff accounts for 59%, 14% of precipitation percolates to shallow aquifers, 0.1% percolates to deep aquifers and 68% of precipitation is lost through evaporation Maliehe further concludes. From his findings evaporation is very high however he states that that “the models used shows uncertainties and this can be from different sources and the rainfall covariance show spatial variability of rainfall within the catchment’ runoff is also high, which means that the water from runoff can be harvested for crops. Soil water is not discussed in details by this writer.

Fobo (2009) studied duration and severity of meteorological drought. His findings are that the most important information which can be obtained from this study is that hydrological and meteorological droughts are persistent, can be severe and they are connected. Therefore knowledge about hydrological droughts and processes causing hydrological drought and its spatial variability is important for the management of these water resources in order to meet the demand of different users (Fleig, 2004) and for a sustainable management of water resources (Sabina et. al, 2004)

Moreover he concluded that SPI is suitable for hydrological drought he indicates that although hydrological droughts are defined by below long-term mean of annual flow, the cause is mainly below normal precipitation falling on the catchment.

Therefore one can conclude that Agricultural drought is more linked to meteorological drought than hydrological drought is to meteorological drought, hence why in this study SPI was confidently used to assess agricultural drought in this study. This is a sort of continuation from Fobo's study. Moreover as indicated in chapter 2, 6 months' time series SPI calculation can be used to assess agricultural drought, this conclusion was reached on the 2013 conference of WMO (World Meteorological Organization), GWP (Global Water Partnership) and NDMC (National Drought Mitigation Centre). Use of SPI was recommended for all countries.

Moreover in Lesotho there is lack of data, the only available reliable ground data is rainfall data, hence why it is used in this study, so that in addition to satellite data there is also ground based data.

In the same study area Mathafeng(2013) estimated evapotranspiration using SEBS (Surface Energy Balance) and SEBAL (Surface Energy Balance Algorithm Land models). His findings are in some area of the catchment 9mm/day evapotranspiration is experienced especially in November. He further suggested building of more meteorological stations for good quality data. This was because of extreme catchment characteristics heterogeneous land cover and elevation variations (Mathafeng, 2013).

And many other researchers who did water related studies in the catchment none came up with detailed study on agricultural drought and spatial coverage of agricultural drought. The common thing on their findings they all complain about lack of data and need for further studies in the catchment.

2.9 Sustainable water management for Agriculture

According to Kostas, (n.d) sustainable water management in agriculture aims to relate amount of water available to crops water need both in space and in time, with acceptable environment impact. It tries to find applicable techniques to improve water for agriculture taking into account social behaviour of rural communities, economic constrains, legal and institutional framework and agricultural practices.

In agricultural water demand management most attention has been given to irrigation scheduling (when to irrigate and how much water to apply) giving minor role to irrigation methods (how to apply the water in the field) and in the rain fed agriculture the attention is how to improve soil moisture, some writers put emphasis on rain harvesting. Many parameters like crop growth stage and its sensitivity to water stress, climatic conditions and water availability in the soil determine when to irrigate or when to maximize crop production, however it becomes difficult in rain fed areas where water stress is determined by precipitation. However rainfall harvesting can be the solution.

According to NOAA (2008) Human factors, such as high water demand and poor water management, can worsen the impact that drought has on a region. Even in the regions where there is less rain fall proper management of that rain water becomes profitable in that area, in countries like Lesotho there are improper or not at all, any good water management practices in agriculture, hence why drought is deteriorating foodproduction.

CHAPTER THREE

METHODOLOGY

3.1 Description of Study Area

3.1.1 Location

Lesotho is a small country surrounded by South Africa, its people mainly depend on rain fed subsistence agriculture and animal husbandry. That is many people entirely depend on agriculture. Failure for agriculture means failure for them to survive. Mean annual rainfall is 788 mm.

Lesotho is divided in to 4 regions, highlands (mountains), foothills, Senqu valley and lowlands. South Phuthiatsana catchment falls under lowlands part; it is situated in Maseru district. The Phuthiatsana River originates from Berea and drains into Caledon River which also drains into Senqu River. There is a big reservoir (Metolong dam) on the North of this Phuthiatsana River; this reservoir is for serving other parts of Maseru the capital city of Lesotho with domestic and industrial water. The catchment is located in the western part of Lesotho as shown in red colour in Figure 3.1.

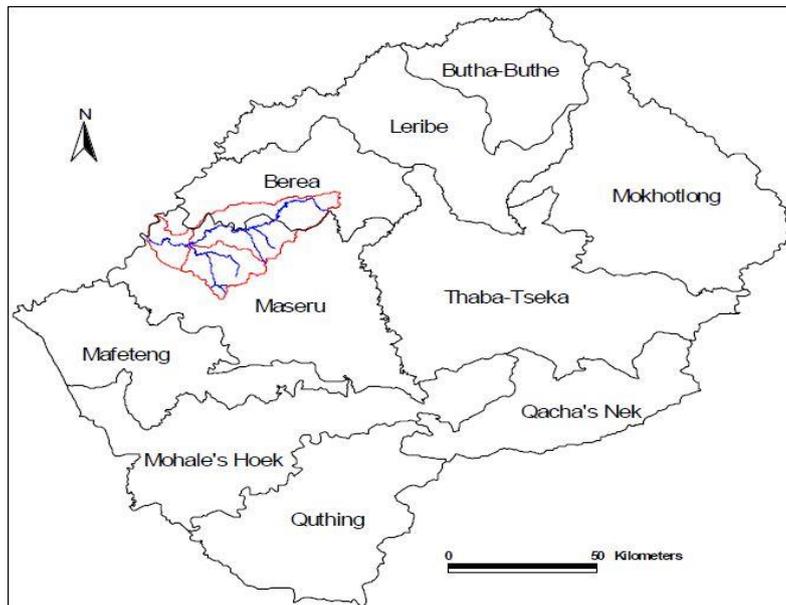


Figure 3.1 Location of south Phuthiatsana on the map of Lesotho

South Phuthiatsana is one of the catchments of Lesotho; it is approximately 1,116km². It is made up of perennial Phuthiatsana River, which covers some part of Maseru and Berea districts as shown on the map above. It originates from Pulane which is in Berea district and flows through Maseru into Mohokare (Caledon) river which then finds its way into orange SenquRiver.

It has about six rainfall stations, but for the purposes of this paper only three stations were used for analysis because of length and reliability of rainfall data. These selected stations are shown in Figure 3.2 and in Table 3.1.



Figure 3.2 Rainfall stations selected for analysis

Table 3.1 Selected rainfall stations

ID	STATION_NAME	LATITUDE	LONGITUDE
LESBER04	PULANE	-29.25	27.92
LESMAS27	MOSHOESHOE1	-29.45	27.57
LESMAS29	MASIANOKENG	-29.42	27.55

According to Engineering, (2009) South Phuthiatsana has the mean annual runoff (MAR) of 128.47 millin m³/year. The South Phuthiatsana River flows into the Mohokare/ Caledon River which is boundary between Lesotho and South Africa flows into the Orange/Senqu system (Botswana, Lesotho, Namibia, and South Africa). There are seven rainfall gauging stations and three runoff stations, with available data, in the catchment one runoff station at Masianokeng. There is a

proposed water supply scheme – Lesotho Lowlands Water Project (LLWP) which will supply water to Roma, Mazenod, Maseru and Teyateyaneng. The volume of the reservoir will be 52Mm³ and the direct abstraction will be 82MI/d and water release and downstream abstraction will be 92MI/d.”

3.1.2 Characteristics of the South Phuthiatsana catchment

3.1.2.1 Climate

According to the report of the government of Lesotho this catchment is characterised by high temperatures especially in summer, the melting of heavier snow which falls in winter, also has poor grass cover, experiences lower rainfall, frequent droughts, more intense rainstorms during the times of rainfall, strong winds. Mean annual rainfall is 788 mm.

The Metolong area which covers large area of the catchment according to the report of the government of Lesotho, ministry of natural resources experiences high evaporation and evapotranspiration rates during the summer months due to high temperatures while in winter it has the lowest evaporation rates. The evaporation rates average is 1700 mm/year while evapotranspiration rates are up to 1251mm/year, with the monthly mean and daily evapotranspiration rates ranging from 1.5 mm/day in June to 5.2 mm/day in December which is one of the hottest months.

3.1.2.2 Soils and geology

Siltstone, sandstone and basalt are main rock formation of the catchment according to government of Lesotho report. It further informs that basalt covers roughly greater than 70% the catchment. The soils in catchment are resultant of Karoo sedimentary rocks sequences and basalt overlay. This leads to formation of two soils which are lithosols and vertisols. According to Schmitz and Royani (1987), mountains soils are shallow in depth; however they are relatively more fertile than soils in flat lowlands. This is because of they have developed in temperate climatic environments where there is tall grass vegetation, this leads to high organic content. The soils of the lowlands have less than 2% organic matter (Schmitz & Royani 1987). Moreover Lithosols are resultant from granite, gneiss, schist or sandstone. They are also shallow escarpment soils with a rooting zone approximately 0.2m.

3.1.2.3 Land cover/use

The Catchment is characterized by a rural population which is very dense and dependent on agriculture, both crops growing and livestock. According to ESIA (2008) about 83.9 % of the inhabitants of this area own agricultural fields, therefore the dominating land use in the area is agriculture and some grasslands, plantation forest and wooded areas, and some few wetlands.

3.1.2.4 Water resources

The catchment comprises of perennial Phuthiatsana River and the Metolong part of catchment comprises of the drainage basin of the South Phuthiatsana-ea-Thaba-Bosiu River and its small tributaries that dry up in winter. The main tributaries of the

Phuthiatsana River are Thaba-Bosiu River, Pulane, Nkokobe, Monyameng and Pitsaneng which are at upstream part of the catchment. The Metolong part of the catchment which is in the upstream receives relatively low annual rainfall (700mm), while the rest of the catchment receives between this 700mm and 1000mm per year, the rainfall is in the form of short duration thunderstorm and characterized by bimodal distribution with high rainfalls occurring between October and April, which is the cropping season, accounting for 85% of the annual rainfall. Meaning that rainfall is seasonal in the catchment and this places constraints on livelihood activities in the catchment. SMEC (2003) found that monthly inflows for the upper part of the catchment and lower part of the catchment were estimated to be 45.96 MCM and were calculated from the flows in the Pulane and Masianokeng rivers which are well gauged.

Moreover the report states that there are a number of wetlands in the catchment, which are not protected and there is no plan of protecting them. The Department of Water Affairs as the responsible department just identified and mapped the wetland but they are degrading due to the fact that they are not protected and absence of management practices. Some animals graze on the wetlands, new agricultural fields are being made at the same wetland hence damaging them.

The kind of wetlands in this catchment comprises of small seepage zones and sponges, they are an important part of the Catchment landscape. They behave like natural sponges, storing water and slowly releasing it in hence adding to availability of water in the catchment even when it is not raining.

3.2 Data selection and preliminary analysis

The data for this study was collected from different government departments and from different satellites as shown on the Table 3.2.

3.2.1 Data collection

Table 3.2 Data collected, source and purpose

TYPE OF DATA	SOURCE/AGENCY RESPONSIBLE	PURPOSE/USE
VHI	http://www.star.nesdis.noaa.gov/smcd/emb/vci/vh/vh_browser.php	vegetation health analysis
MSI	CGIAR-CSI Global Soil-Water Balance Database	soil moisture analysis
rainfall	Lesotho meteorological services	spi calculation
shape files	ministry of forestry	catchment delineation
crops yield reports	ministry of agriculture and food security	maize yield reduction assessment
cropping calendar	department of crop services	-

3.3 Data Preparation and Processing

3.3.1 Rainfall preparation for SPI calculation

Daily rainfall was collected from Lesotho Meteorological Services from 6 rainfall stations namely Pulane, Thaba-bosiu, Metolong, Masianokeng, Roma and Moshoeshoe1 as shown in Figure 3.3. The length of rainfall data was different for these stations; this is as shown in Table 3.3.



Figure 3.3 Rainfall stations in South Phuthiatsana Catchment

Table 3.3 South Phuthiatsana Rainfall Stations

ID	STATION_ NAME	LATITUDE	LONGITUDE	LENGTH OF RAINFALL DATA
lesber04	Pulane	-29.25	27.92	20 years
lesmas08	Thaba-bosiu	-29.35	27.67	10 years
lesmas24	Roma	-29.45	27.33	11 years
lesmas27	Moshoeshoe1	-29.45	27.57	20 years
lesmas29	Masianokeng	-29.42	27.55	20 years
lesmas35	Metolong	-29.42	27.63	14 years

However for SPI calculation 3 stations were selected because of length of rainfall data since according to WMO (2013) The SPI can be calculated on as little data as 20 years, Selected stations are Pulane, Masianokeng and Moshoeshoe1as shown in Table 3.4, the data from these stations is of 20 years where other omitted station is below that, some have 14 years.

Table 3.4 Selected stations

ID	STATION_NAME	LATITUDE	LONGITUDE
LESBER04	PULANE	-29.25	27.92
LESMAS27	MOSHOESHOE1	-29.45	27.57
LESMAS29	MASIANOKENG	-29.42	27.55

SPI calculated using SPI calculator for 3 selected rainfall stations (Moshoeshoe1, Masianokeng, and Pulane) of South Phuthiatsana catchment, from 20 years (1993-2013) rainfall data. The program (SPI Calculator) calculates a time series of the Standardised Precipitation Index (SPI) at a given time interval from an input data file of precipitation is in monthly time series. In this paper, 6 months' time scale was used.

Monthly rainfall data for 1993 to 2013 was determined and then only cropping season data analysed using Standardised Precipitation index (SPI) , cropping season months are; October, November, December, January, February and March as shown in Appendix A . The SPI program calculates a time series of the Standardised Precipitation Index (SPI) at a given time interval, it calculates it from the input data file which contains precipitation in monthly time series. According to this program

the input files which is rainfall data for each station must follow 3-column format: Year, Month and Monthly Precipitation Value.

Edwards and McKee (1997) found that the SPI calculation for any given location that has rainfall data done on the long-term precipitation data for any desired period but not less than 20 years. This long term precipitation record is fitted to gamma probability distribution, and then transformed to normal distribution in order to make mean SPI zero, for any location and for desired period. Then it produces zero and positive and negative. Positive SPI values indicate greater than median precipitation which means wet periods and negative values indicate less than median precipitation which means dry periods.

3.3.3 Data processing

1. SPI (standardised precipitation index) calculation

SPI program was used to calculate SPI for 20 years per station.

6 months' time scale; October to March was used in this research which is the cropping season of maize in Lesotho. Input file is the file containing station rainfall data with cor extension. Output file is SPI results in dat extension.

Standardised precipitation index is based on the probability of precipitation for a given time period. Calculated as follows

$$G(x) = \int_0^x g(x) dx = \frac{1}{\hat{\beta}^{\hat{\alpha}} \Gamma(\hat{\alpha})} \int_0^x x^{\hat{\alpha}-1} e^{-x/\hat{\beta}} dx \quad \dots\dots\dots(3.1)$$

where

$G(x)$ = Cumulative probability

x = the precipitation amount >0

$\hat{\alpha}$ = a shape parameter (function of area)

β = a scale parameter

$\Gamma(\hat{\alpha})$ = a gamma function

Then the calculator:

- Uses probability distribution function to normalize precipitation, and then the SPI values seen as standard deviations from median.
- A normalised distribution gives negative and positive values which allow for estimation of dry and wet periods.
- Accumulated values are used to analyse drought magnitude
- Probability of observed precipitation is transferred into index.

2. MSI (moisture stress index) calculation

Data was downloaded from CGIAR-CSI Global Soil-Water Balance Database, which uses ArcAML (ESRI). It works as shown below

For each month, height of water in mm is determined in order to get monthly water balance budget. As shown below

$$\Delta SWC(m) = E Prec(m) - AET(m) - R(m) \dots\dots\dots (3. 2)$$

Where:

ΔSWC = change in soil water content for each month

$E Prec$ = effective precipitation for each month

AET =actual evapotranspiration

R = runoff, which contains both surface runoff and subsurface runoff.

The assumption is that SWC should not be above a maximum value, $\max SWC$ is the total maximum SWC available in the soil for evapotranspiration. All the monthly water input exceeding $\max SWC$ is accounted as runoff (R). The simulation has been repeated throughout several years, to achieve more realistic conditions of initial SWC .

Effective Precipitation is derived from subtracting intercepted precipitation from gross precipitation ($GPrec$). The intercepted precipitation is the one from canopy cover and litter.

$$E_{prec}(m) = GPrec - (GPrec \times K_{int}) = GPrec \times (1 - K_{int}) \dots\dots\dots (3.3)$$

Actual Evapotranspiration

$$AET(m) = PET(m) * K_{veg} * K_{soil} \dots\dots\dots (3.4)$$

Where

AET = Actual evapotranspiration

PET = Potential evapotranspiration

K_{veg} = vegetation coefficient which is dependent on vegetation characteristics (set to 1 as standard x this simulation)

K_{soil} = reduction factor which is dependent on volumetric soil moisture content (0-1)

To determine monthly PET , CGIAR-CSI PET (Hargreaves method) was used.

Hargreaves uses mean monthly temperature (T_{mean}), number of days in the month ($m N$), mean monthly temperature range ($m TD$) and extra-terrestrial radiation ($m RA$, radiation on top of atmosphere) to calculate monthly $m PET$:

$$PET(m) = 0.0023 * RA * (T_{mean} + 17.8) * TD * N \dots\dots\dots(3.5)$$

The vegetation coefficient (K_{veg}) used in this model is spatially standardized, assumed as reference crop ($K_{veg} = 1$, typical of agronomic crops at maturity and tree), in order to define results explicit just to climate conditions.

The soil stress coefficient (K_{soil}) shows dimensionless soil water reduction factor derived from limit imposed by monthly soil water content ($SWC_{monthly}$). This model used a linear soil moisture stress function which is believed to be appropriate for monthly calculations.

$$K_{soil}(m) = SWC(m)/SWC(max) \dots\dots\dots (3.6)$$

The maximum amount of soil water available for evapotranspiration (ET) processes within the plant rooting depth zone ($SWC_{max} = 350$ mm) is equal to the SWC at field capacity (SWC_{fc}) minus the SWC at wilting point (SWC_{wp}) multiplied by the rooting depth (RD).

$$SWC_{max} = RD * (SWC_{fc} - SWC_{wp}) \dots\dots\dots (3.7)$$

The Maximum Soil Water Content for evapotranspiration processes is supposed at 350 mm which is a fixed spatial value, which corresponds to average soil texture for a plant rooting depth of 2 meters. The SWC defines the monthly fraction of Soil

Water Content available for evapotranspiration processes (as percentage of Maximum Soil Water Content). It is therefore a measure of soil stress, and equals to the soil water stress coefficient (K_{soil}) as percentage (i.e. 0 - 100).

3. VHI (vegetation health index) calculation

AVHRR/VHP, http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_browse.php is

the website where data was taken from. It measures the greenness and vigor of vegetation. The resolution 4km, noised minimized by applying the time series smoothing techniques and corrections algorithms. Average VHI for cropping months was calculated in ILWIS using map statistics operation. Images were then analysed and classified in ArcGIS.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Standardised Precipitation Index (SPI)

Since Lesotho cropping season starts from October to March, SPI calculator was used to calculate standardised precipitation index for these months using 1993 to 2013 rainfall data, in order to get an overview of which part of the catchment is more prone to drought due to precipitation shortage. As mentioned before drought occurs when SPI is negative and reaches an intensity of -1.0 or less and wet periods are positive, as shown on Table 4.1.

Table 4.1 SPI Values

2.0+	Extremely wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately wet
-.99 to .99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 and less	Extremely Dry

From the SPI results the following graphs were created in Microsoft excel. From the graphs, Masianokeng and Moshoeshoe1 stations seem to experience same drought temporally, but differ in terms of severity while Pulane station experiences different drought in terms of temporal and severity.

Masianokeng rainfall station has experienced drought during the following years 1995, 1999, 2001, 2003, 2006, 2013. These are the years when SPI values were below -1 indicated by a green line on Figure 4.1.

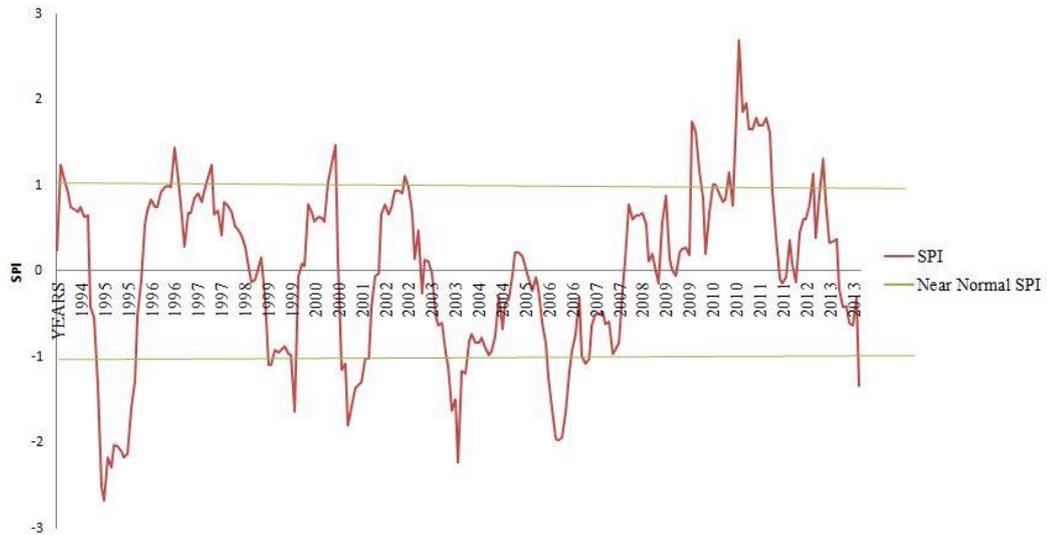


Figure 4.1 SPI values for Masianokeng station

Moshoeshoe rainfall station has experienced drought during the following years 1995, 1999, 2001, 2003, 2006 and 2013. These are the years when SPI values were below -1 indicated by a green line on Figure 4.2.

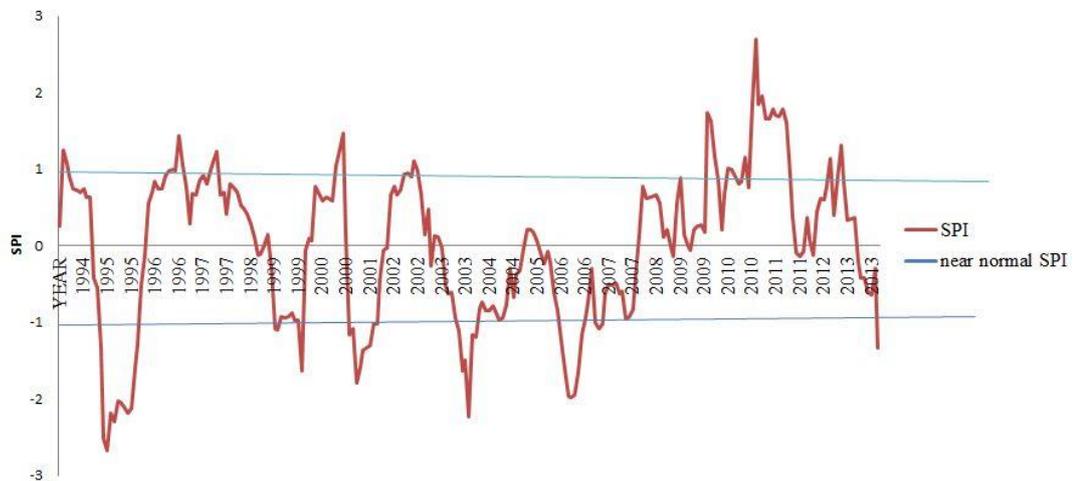


Figure 4.2 SPI values for Moshoeshoe 1 station

Pulanerainfall station has experienced drought during the following years 1995, 1997, 1999, 2003, 2004 and 2007. These are the years when SPI values were below -1 indicated by a green line on Figure 4.3.

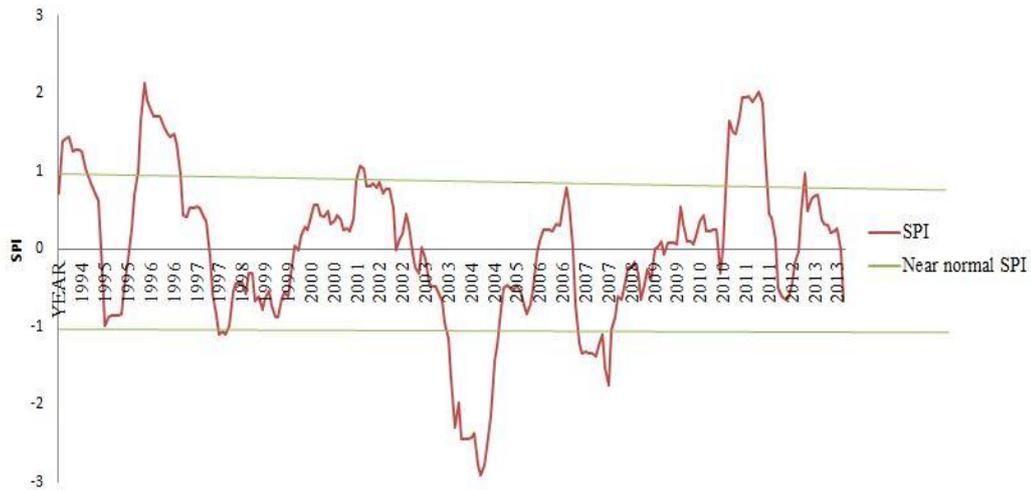


Figure 4.3 SPI value for Pulane station

Average SPI values for cropping season which entails; October, November, December, January, February and March months are mapped in order to get an overview of spatial distribution of drought in the catchment. The values were interpolated in ArcGIS, using IDWM technique. Then the following maps on Figure 4.4 were produced for different months of cropping season October to March.

Masianokeng and Moshoeshoe 1 which are in the western part of the catchment experience low values of SPI than Pulane station which is in the East part of the catchment. even though most of the months western part experiences -1 SPI which is moderately dry, while eastern part experience near normal values on average but for December the SPI values are the same, the catchment SPI is near normal. The

implication is that, western part of the catchment is more prone to drought than eastern part of the catchment when using SPI.

For October average SPI Pulane (eastern) part of the catchment has -0.4 which is near normal condition while Masianokeng and Moshoeshoe 1 (western) part of the catchment have -1 which is moderately dry, this is the same with November, February and March. Contrary December and January all stations have near normal values -0.4, -0.16 and -0.5.

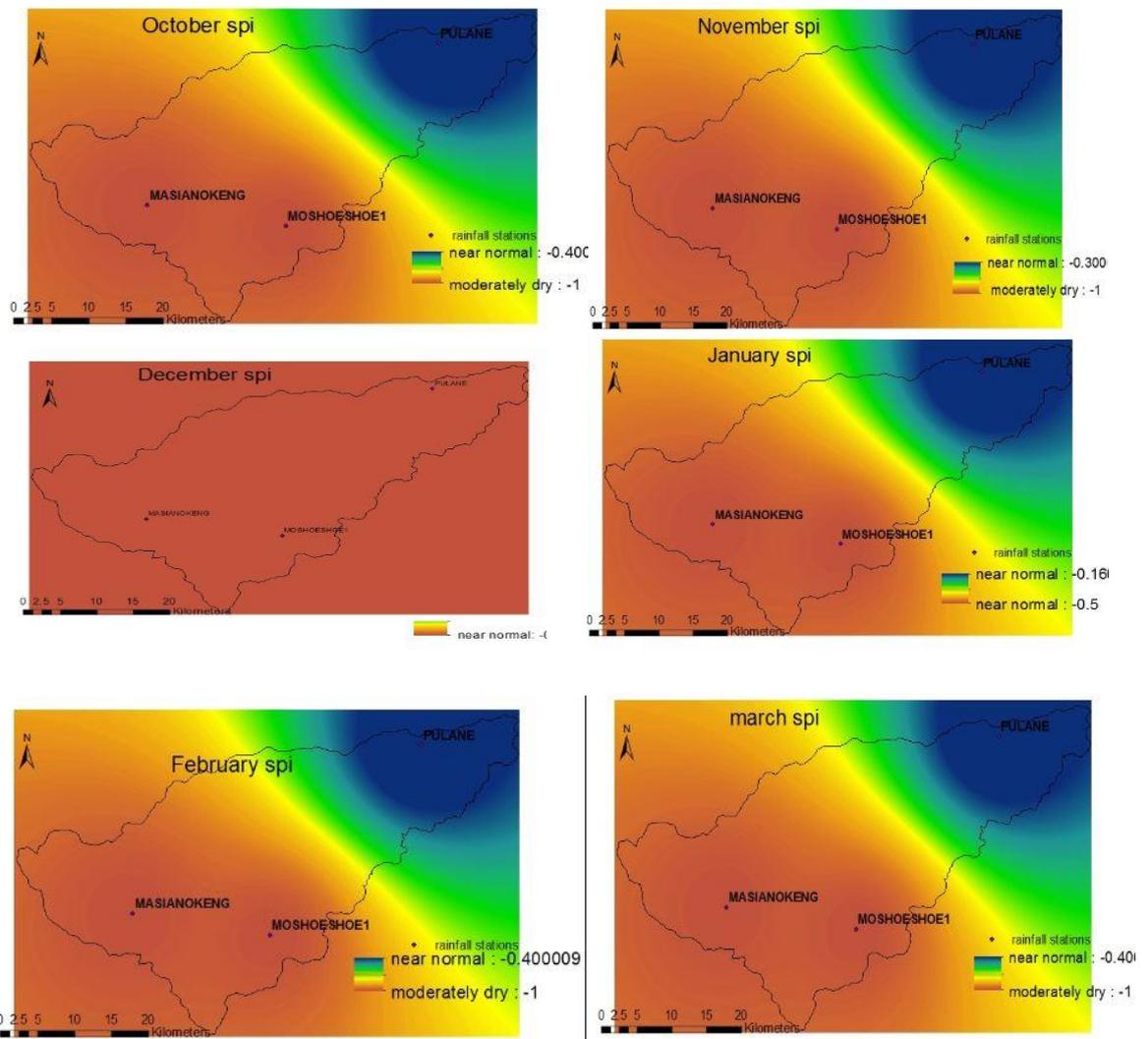


Figure 4.4 Average SPI for cropping season

4.2 Moisture Stress Index (MSI)

Worldclim and global potential evapotranspiration are used as primary inputs. And data was obtained from CGIAR-CSI Global Soil-Water Balance Database. This was for average over 1950-2000 periods. The results for cropping season months are selected, which are October, November, December, January, February and March. The results are according to MSI classifications. The classification of moisture stress values is shown on the Table 4.2.

Table 4.2 Moisture stress index values

MSI	Drought severity class
0 to 0.8	No stressed
0.8 to 1.60	Low stressed
1.60 to 2.40	Moderately stressed
2.40 to 3.20	Severe Stressed
3.20 to 4.00	Extremely stressed

The study area seems to fall only on category one and two which are no stressed and low stressed. This is illustrated on the maps in Figure 4.5, the values are in percentage. High values are for high water stress while low values are for low water stress. Pulane Station which is the eastern part of the catchment has high soil water stress than Masianokeng and Moshoeshoe1, however the values go as far as low stressed not beyond that.

Since crops rely on soil moisture for their survival, areas with stressed condition lead to low yield of agricultural production. Because soil moisture adversely affect crop

growth and, ultimately, crop yield. These results are due to topography and slopes of Pulane; this is shown in Appendix B, which is DEM of the catchment whereby Pulane is seen to be at high elevation than Masianokeng and Moshoeshoe1 and on Appendix C which is slope map of the catchment. One would conclude that due to these relief features of Pulane, soils cannot hold moisture like in the other parts of the catchment, hence why it appears to have high water stress than other parts of the catchment. Generally marked spatial differences in the hydrological processes occur within the catchment; these responses are associated with topography and different soil properties.

When there is water shortage at a certain growing period this will affect the yield depending on the stage of growth of a certain crop. Some stages of growth are more sensitive to water shortage than others; those stages which are sensitive to water deficit can cause a plant reach permanent wilting point hence affecting crop yield. The growing stages that is more sensitive to water deficit are flowering and early yield formation, they are more sensitive than early stage and late growth stage such as ripening. According to cropping calendar of Lesotho, the critical stage in maize production is in February and March this is when values of moisture stress are high compared to other times.

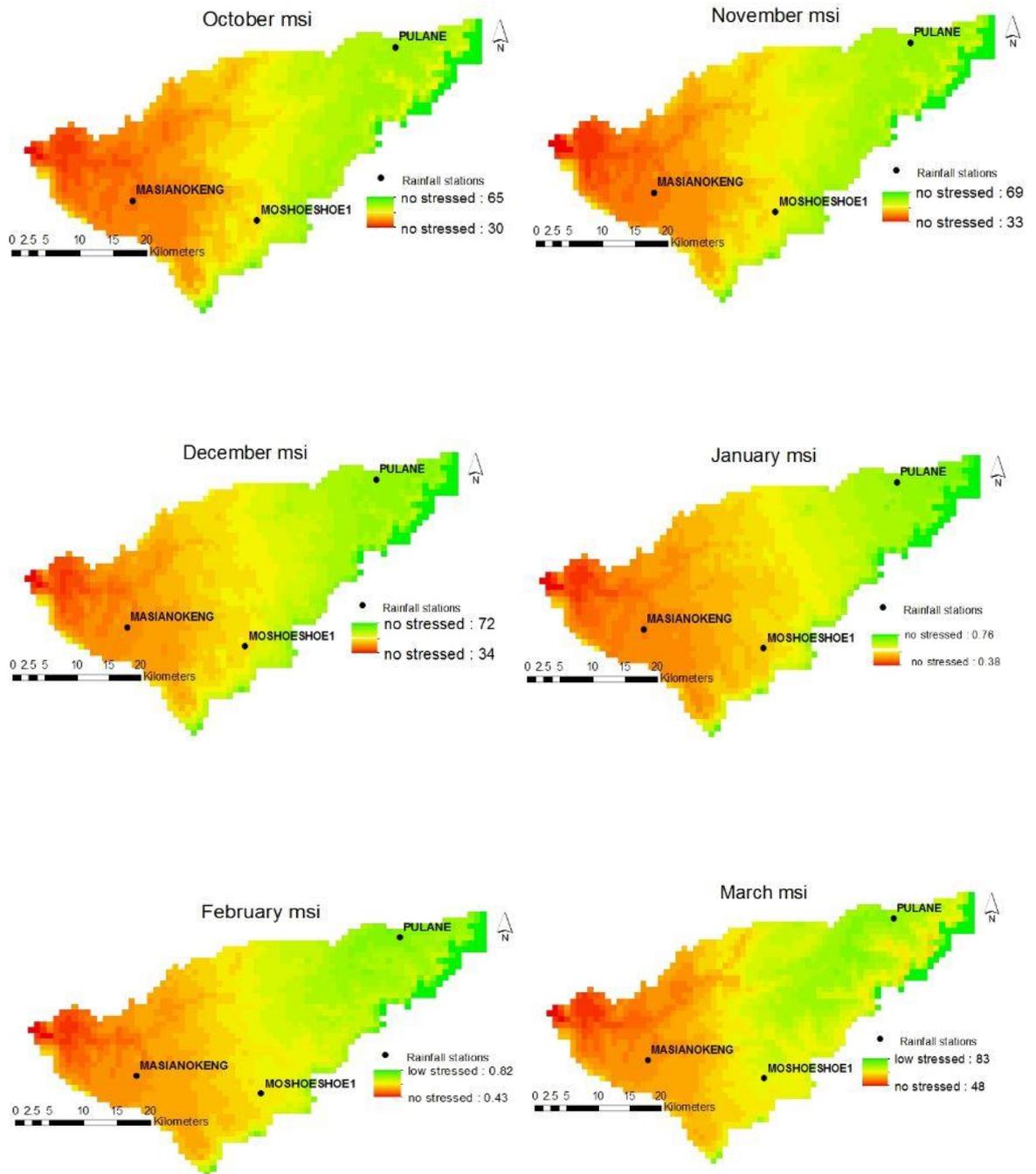


Figure 4.5 Average MSI for cropping season

4.3 Vegetation Health Index (VHI)

During the periods of prolonged soil water stress, plants physiological functions are affected negatively and that reduces the ability to transpire, also to respond

immediately when the stress is relieved through rainfall, it therefore loses its ability to photosynthesise, it reaches a wilting point where its greenness furnishes. The data is obtained from AVHRR Vegetation Health Product (AVHRR-VHP); it measures the greenness of vegetation. The greenness means the vegetation is healthy. This greenness is classified as vegetation health index as shown in Table 4.3.

Table 4.3 Vegetation Health index classification

Value (percentage)	Description
0 to 40	stressed
41 to 60	fair
61 to 100	favourable

Western part of the catchment which covers Masianokeng station has low values of vegetation health index throughout all the cropping season, which implies poor vegetation hence low crop production. Throughout the cropping season, on average Pulane convey better vegetation than Masianokeng and Moshoeshoe1. In terms of vegetation health index classification shown in Figure 4.6 Masianokeng's vegetation is stressed throughout. Pulane which is in the Eastern part of the catchment is much better, it experiences fair conditions.

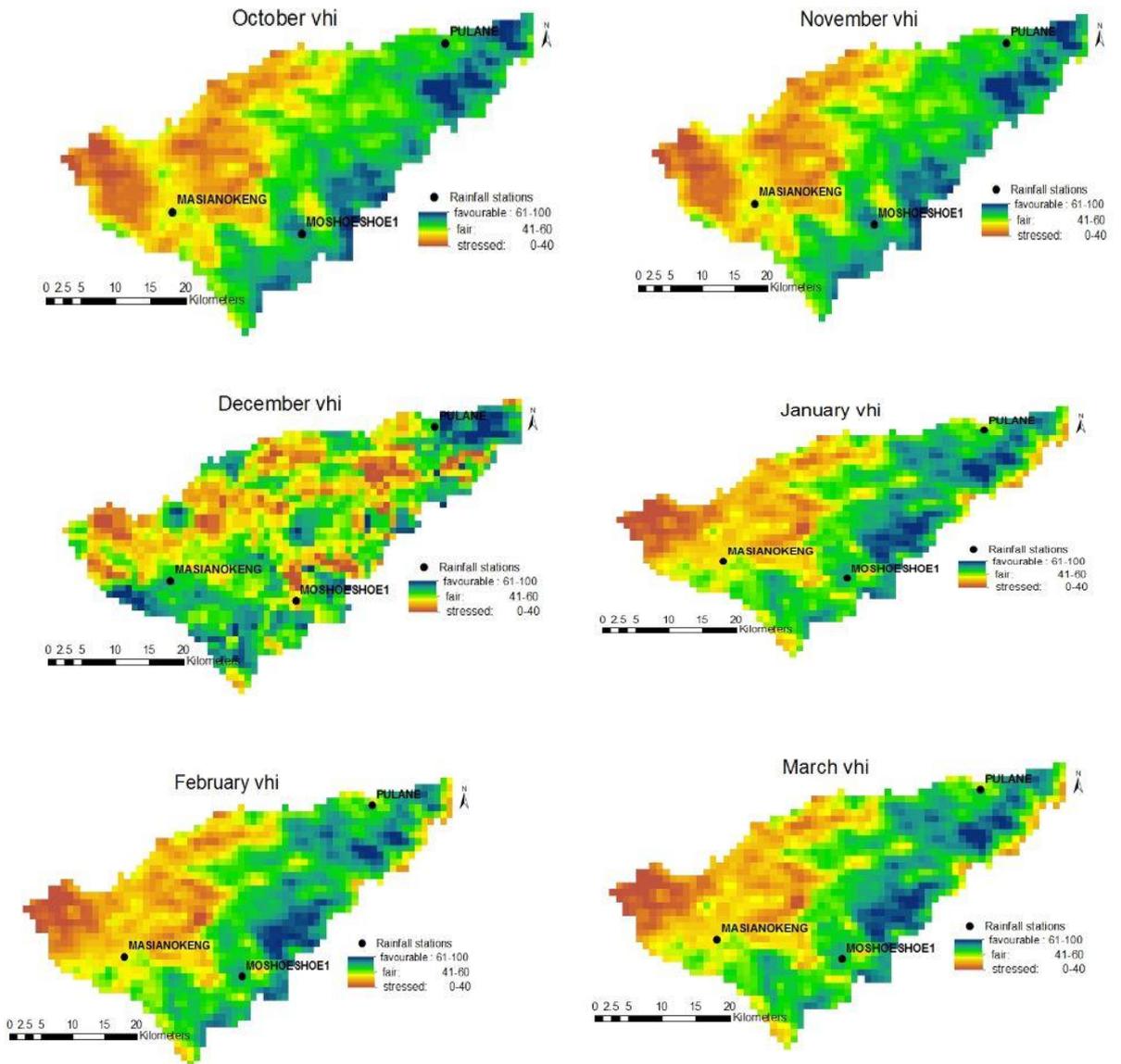


Figure 4.6 Average vegetation health index maps for the cropping season (Oct to Mar)

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

In terms of SPI and VHI, spatial occurrence of drought is in the west part of the catchment, in terms of MSI it is in the east part of the catchment. Pulane (east part) is on the high elevation of the catchment than western, this is shown by DEM on the appendix on the last page, this means that elevation has impact on soil water content, in the areas like those, most of rain water becomes runoff and less infiltrates. Moreover in terms of SPI and VHI temporal occurrence of drought is in December when SPI and VHI values are low. Generally, to assess drought, no single index is enough because they give different results which need a very critical analysis.

Since crops production is influenced by several factors such as Climate, Soil moisture condition, Rainfall and many more, it was found of importance to use indices based on the those factors. Also the methods and models use are limited by availability of data, especially SPI which in this study was calculated using very short data.

5.2 Recommendations

- Detailed study on soil types and water holding capacity in order to find causes for moisture variations in the catchment.

- In situ study of soil moisture should be done for verification of satellite derived soil moisture.
- Lesotho meteorological services must improve their long term rainfall data for SPI to be more reliable.
- Detailed study of the vegetation covers especially the natural one so that it does not disguise the VHI results.
- Rainfall harvesting is recommended, especially because rainfall in this catchment is characterised by high storms of rainfall. Large part of the world depends on rainfall for crop production, especially Africa. So improving this is very important, so as to increase and improve amount of water in the soil hence improving crop production. Rain water harvesting is recommended for eastern part of the catchment.

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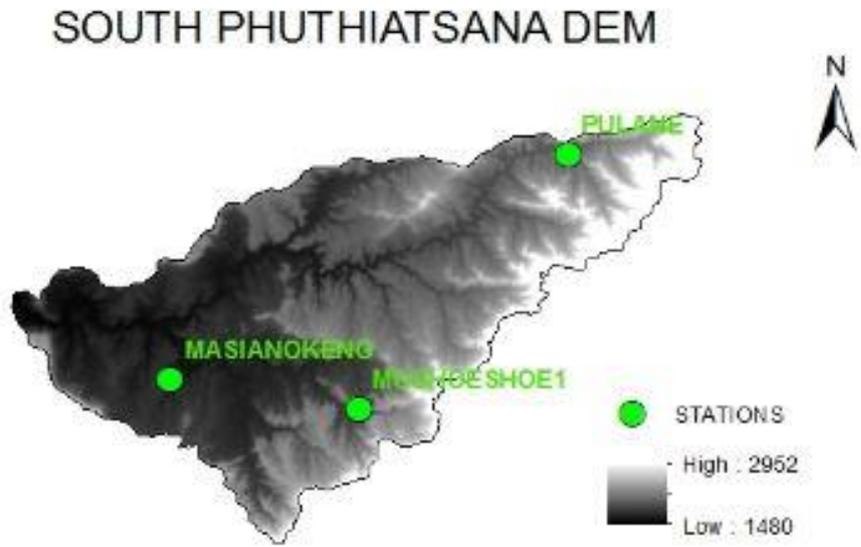
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APPENDICES

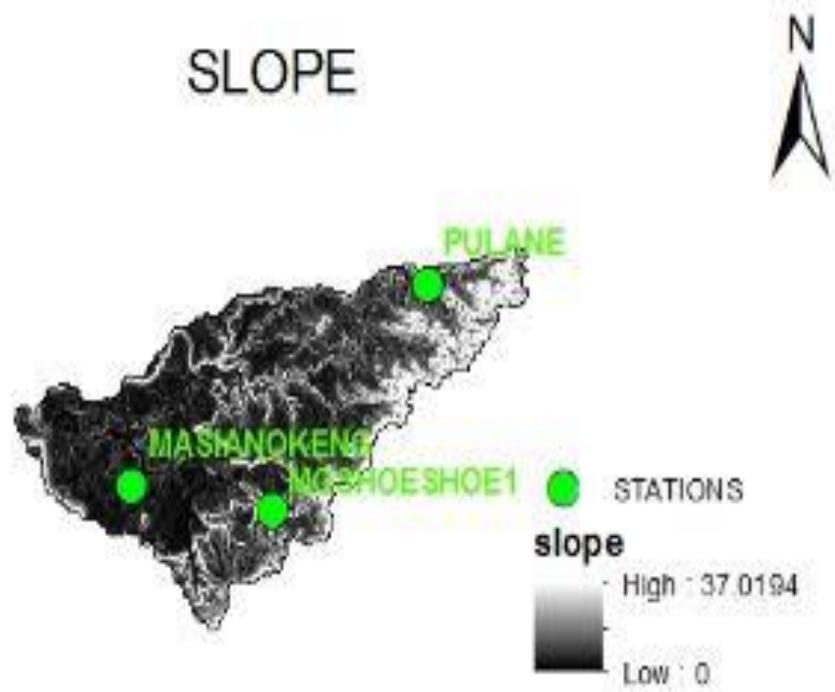
APPENDIX A: LESOTHO CROPPING GUIDES

CROP	VARIETIES	PLANTING DATE		
		LOWLANDS	FOOTHILLS	MOUNTAINS
GRAINS				
Maize	Hybrids:			
	Sensako(SNK):2969, , 2778			
	Pannar(PAN):6146,6363, 6043,6479,6730,4M19, 6017			
	Pionner PHB 32 A 05			
	RO: 413			
	Capstone			
	AgricolPanthera			
	Single Strains:			
Highland maize				
American White Flint	Oct.- Nov.	Sep.-15 Nov.	Sep.-Oct.	

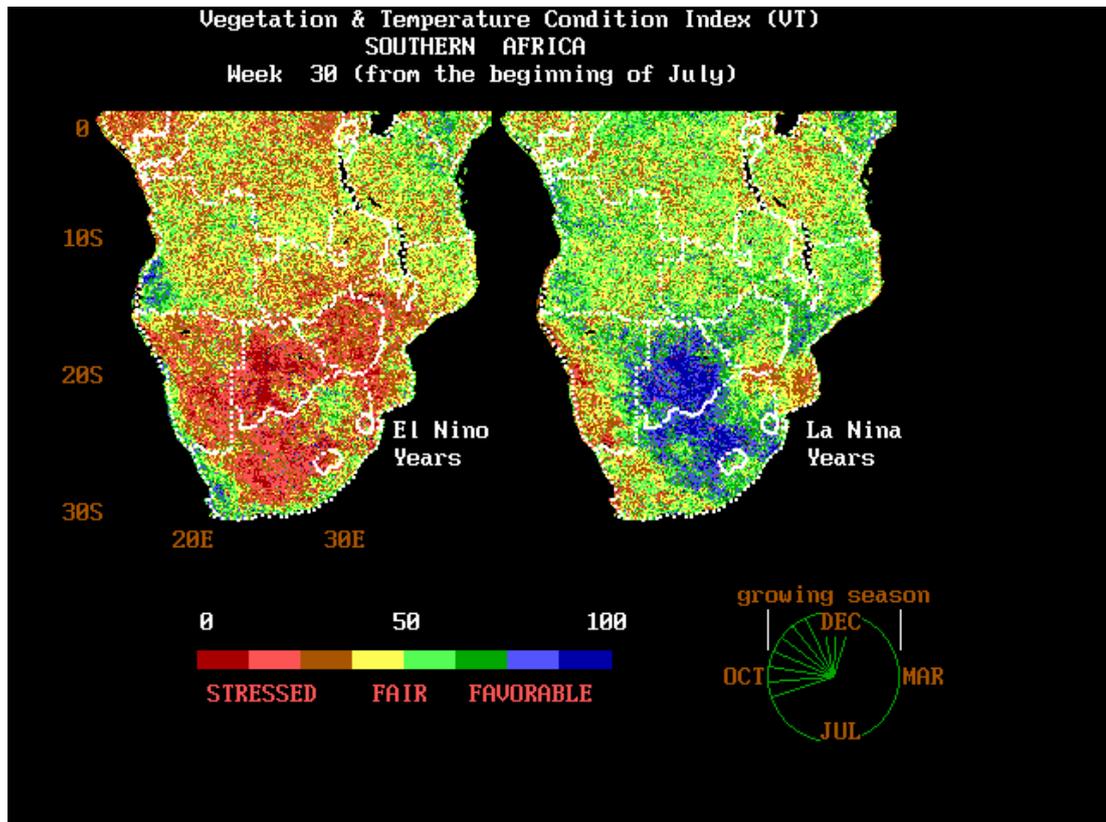
APPENDIX B: DEM OF SOUTH PHUTHIATSANA CATCHMENT



APPENDIX C: SLOPE OF SOUTH PHUTHIATSANA



**APPENDIX D: SOUTHERN AFRICA VEGETATION AND TEMPERATURE
CONDITIONS IN 2015/2016**



Source: NASA (2016)