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Sylvester Richard CHIKABVUMBWA

SPATIAL AND TEMPORAL DROUGHT CHARACTERIZATION IN VIEW OF THE BEST IRRIGATION PRACTICES IN CENTRAL MALAWI

Defended on 05/09/2019 Before the Following Committee:

Chair	Tirusew Asefa	Prof.	University of Tampa,Florida
Supervisor	Nasrin Salehnia	Prof.	Ferdowsi University
External Examiner	Boutaghene Hamouda	Dr.	University of Annaba
Internal Examiner	Debbal Zakaria	Dr.	University of Tlemcen

CERTIFICATION AND APPROVAL

SPATIAL AND TEMPORAL DROUGHT CHARACTERIZATION IN VIEW OF THE BEST IRRIGATION PRACTICES IN CENTRAL MALAWI: CASE OF KASUNGU ADD

Submitted by:

Sylvester Richard Chikabvumbwa	____________________	09/09/2019
Name of student	**Signature**	**Date**

Approved by Examining Board

____________________	____________________	____________
Name of examiner	**Signature**	**Date**

Thesis Supervisor

Prof. Nasrin Salehnia	____________________	12/09/2019
Name of supervisor	**Signature**	**Date**

Institute Dean

____________________	____________________	____________
Name of Dean	**Signature**	**Date**

Pan African University

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Name of Rector	**Signature**	**Date**

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DEDICATION

This dissertation is dedicated to all those who respond to the name "**Chikabvumbwa**". This is for you!

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ABSTRACT

Recently, in Kasungu Agricultural Development Division (ADD), agricultural production has been challenged by uneven rainfall distribution spatially and temporally leading to constant dry spells and droughts resulting in economic losses. This study sought to characterize the temporal and spatial variations of drought from 1977 to 2017 and relate it to climate smart irrigation technologies that can be promoted and drought resistant crops that can be grown in the area. The previous studies done in Malawi did not look into drought characterization and only used the Percentile Index such that other indices were not considered for drought analysis. This study bridged this gap by using different monitoring drought indices in DMAP software. It was found that the ADD experiences mild and moderate meteorological droughts, frequent moderate agricultural droughts and extreme hydrological droughts. Based on the results on crop water requirements in CropWAT software, this study found that cassava should be promoted in the region as a drought resistant crop. Furthermore, the study found out that surface irrigation systems with low efficiencies are commonly used and that climate smart irrigation technologies are not largely practiced in the ADD. This study recommends the promotion of rainwater harvesting technologies and the adoption of drip and micro-sprinklers irrigation systems in the ADD.

Keywords: Kasungu ADD, SPI, water resources, climate smart irrigation, Remote sensing.

ABBREVIATIONS AND ACRONYMS

CWR	Crop Water Requirements
DEM	Digital Elevation Model
ETc	Crop evapotranspiration
FAO	Food and Agriculture Organization
GIS	Geographic Information Systems
IDWM	Inverse Distance Weighted Method
IPCC	International Panel of Climate Change
MDGS	Malawi Growth and Development Strategy
NIP	National Irrigation Policy
SDG	Sustainable Development Goal
MoIWD	Ministry of Irrigation and Water Development
MoAFS	Ministry of Agriculture and Food Security
DMAP	Drought Monitoring and Prediction
SPEI	Standardised Precipitation Evapotranspiration Index
LPDI	Low Pressure Drip Irrigation
NIPS	National Irrigation Policy
NIPDS	National Irrigation Policy and Development Strategy

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

1. INTRODUCTION

Malawi has been experiencing different types of disasters which are increasing in frequency, duration and severity. Over the past 20 years, dry spells, seasonal droughts, flash floods have been so common. These have caused different havoc in agriculture production, water resources and the economy of the country (NAPA, 2006).

The geographical position of Malawi allows it to receive a considerable amount of rainfall. The Inter-Tropical Convergence Zone (ITCZ), Congo air and the south-easterly winds influence this considerable amount of precipitation received in Malawi (Kumambala, 2010). This precipitation is responsible for maintaining the water balance of most river basins in the country. However, the spatial-temporal climate variability has had a substantial impact on the amount, timing and frequency of rainfall resulting in recurring droughts (Chabvunguma et al., 2014). As if that was not enough, poor water use and water management practices and ever-growing population growth have created pressure on the already limited available water resources.

Although significant research has been done on disaster risk management in Malawi, research on drought characterization and characteristics is still limited for most watersheds in Malawi. For example, Kasungu ADD which has three watersheds continues to face dry spells and droughts. To make matters worse, droughts are becoming recurrent in Malawi due to climate change.

Drought is described to be a phenomenon which is complex, multidimensional and least understood yet has a lot of paramount effects on socio-economic and agricultural activities in most areas which are agri-based (Modarres, 2010). This agrees with Rossi (2000) who asserted that droughts are natural phenomena which are recurrent, extend over a long period of time and are associated with unavailability of water over a large area. Hagman (1984) further stated that drought conditions are not fully understood due to their complexity. Prediction of extreme events such as droughts can be complicated. Enhancing our ability to adapt to the adverse impacts of climate change is imperative for the management of effective solutions to future extreme events. This requires an accurate and in-depth assessment of the drought properties. Despite the difficulty to understand the drought conditions, it is possible to monitor and characterize droughts. For one to characterize a drought, long-term data of rainfall, temperature, evapotranspiration, land cover, soil moisture and river flows with appropriate spatial and temporal coverage is necessary. Aguilar et.al. (2005) cited in (Sheffield & Wood, 2007), observed that rainfall, streamflow, and soil moisture datasets are necessary to understand drought variations in a region. Of these parameters, rainfall is a key parameter for monitoring meteorological droughts(Wu, Hayes, Weiss, & Hu, 2001). Some studies recommended the SPI with long term monthly time series rainfall data for predicting future droughts or wet events (Jongman et al., 2015; Forsythe et al., 2012; De Sherbinin et al., 2015).

Different studies (Wilhite & Glantz, 1985; Hayes & Svoboda, 2000 ; Bhuyan-erhardt, 2018 ;Mckee et.al., 1993) agree that droughts can either be meteorological, agricultural, hydrological or socio-economic. Though termed differently, they are interrelated and consequential. All droughts share one thing in common and that is, they are as a result of deviations from normal conditions be it precipitation, soil moisture, stream flow or groundwater or aquifer recharge (Loukas & Vasiliades, 2004).

Simply put, these drought conditions are related such that a meteorological drought is followed by an agricultural drought then hydrological drought and finally a socioeconomic drought. Fig. 1 shows this relationship.

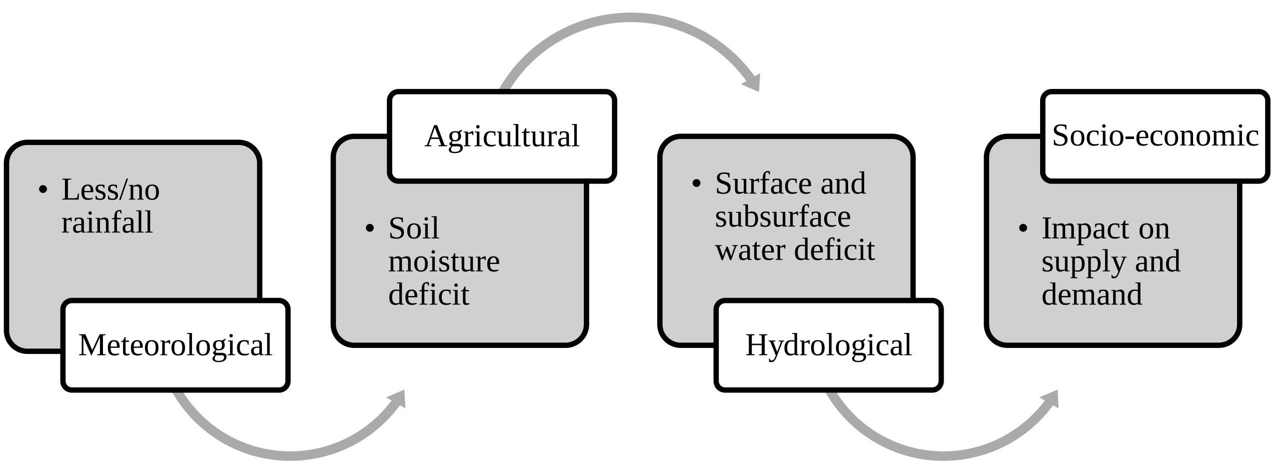


Figure 1: Relationship between types of drought conditions

Malawi depends on rainfall for their agricultural production. Most farmers in Malawi, about 90%, use rainfed agriculture for their livelihood (Khamis, 2006; Mkanda et al., 1995). This means that any reduction or insufficiency in rainfall leads to water insecurity and, this has negative direct impacts on agriculture production hence food security. As the effects of climate change continue growing, projections are that droughts will also continue increasing. With population growth, on the other hand, pressure on water resources will also continue to increase. Farmers are not certain as when to plant their crops, and which systems of irrigation to use in an event when disasters occur (Khamis, 2006). This then calls for a good management of water resources and effective planning taking into consideration drought management. One other requirement for the effective, efficient and sustainable management of water resources is a good understanding of droughts both at national, regional and basin level (Mutsotso, Sichangi, & Makokha, 2018).

Droughts are a threat to Sustainable Development Goals and Agenda 2063 as they adversely affect many sectors of economic development such as agriculture and food security, tourism, trade, hydropower generation and industry, human and animal health, livelihood security, personal security (for example, women walking long distances to fetch water) and access to education (for example, youths not attending school because of increased time spent on fetching water). Different studies (Mkanda, et al 1995; Malawi Government, 2006) concur with this assertion and state that agriculture is the most vulnerable sector. When droughts occur in agriculture dominant economies, their impacts are intense. Potop et al (2012) agree with Hunt et al (2014) that major losses in agriculture-based economies are caused by droughts.

Knowledge of which type of drought has occurred in an area is key on how to manage, monitor and remedy it. Having poor knowledge can easily make planners misguide one towards what type of risk management strategy to use in case one has occurred. Kasungu Agricultural Division (ADD) being an agricultural area has had droughts over the past years but knowledge of what type is not known. Whether there are trends in the drought conditions is also not known. This study, therefore seeks to characterize droughts in the ADD and relate on the best possible practices that can be promoted in the area according to the type of drought each area experienced. Furthermore, this study will help address the challenges of droughts in the region through the planning of water resource usages and conservation.

1.1 Problem Statement

Kasungu ADD lies on the Kasungu-Lilongwe plain which is the best area in Malawi for agricultural production. However, the region is currently facing water availability challenges due to the late onset of uneven rains and early recession of the same rainfall. This has often led to the decline of agricultural production which in turn leads to constant poverty levels of the people in the region. With reduced rainfall regimes which are uneven, high rates of deforestation leading to decrease in volumes of water reservoirs, high population rates, increased evapotranspiration, and varying weather patterns, pressure on water resources has worsened in the region making it more vulnerable to droughts. The Malawi Government concedes that the negative impacts of droughts are multispectral and normally affect sectors such as water supply, gender, fisheries, sanitation, public health, agriculture, and nutrition (NAPA, 2006).

Inadequate knowledge on drought characterization and distribution in relation to best crops to grow and the best ways of irrigation has led to poor choices of disaster risk management strategies in the ADD. Many drought indices to aid drought monitoring exist but the utilization of these indices in drought analysis in Malawian setting has necessarily not been done sufficiently.

Despite this vulnerability to drought conditions, no study has ever been done in the region to characterize droughts. This knowledge gap can be a barrier in drawing up an efficient and effective drought risk management plans which are essential for sustainable water resources management. Thus, there is a great need to study drought events at regional scales in different catchment areas.

As if that was not enough, disaster risk mitigation and management plans are normally effected at the national level. Same old theories and one-fits-all solutions are given without understanding the type of disaster at hand. The known plans and strategies which are applied normally deal with floods and less or none is known on droughts. Even though, Non –Governmental Organizations', government ministries and other stakeholders talk about droughts and their mitigation, there is still no clear documented research done at regional levels to characterize droughts.

1.2 Objectives of the Study

1.2.1 Main Objectives

The overall objective of this study is to characterize spatial and temporal drought conditions and characteristics in Kasungu ADD in Central Malawi.

1.2.2 Specific Objectives

- To assess the spatial and temporal occurrence of droughts using the DMAP indices from precipitation, potential evapotranspiration, stream flow and soil moisture data for 40 years.
- To analyze the characteristics of droughts in Kasungu ADD.
- To determine the rate of evapotranspiration and crop water requirements as crop choice and irrigation type planning tools for the region.
- To determine the best irrigation practices and drought risk management strategies in the region in accordance with the related type of drought.

1.3 Research Questions

Research questions include:

- How to assess meteorological, agricultural and hydrological drought?
- How to determine different characteristics of droughts?
- How to determine evapotranspiration and crop water requirements for Kasungu ADD?
- Which crops and irrigation systems can be used during drought conditions in Kasungu ADD?

CHAPTER TWO

2. LITERATURE REVIEW

Malawi has a predominantly agro-based economy with over 35 per cent of the country's Gross Domestic Product (GDP) generated from agriculture. Due to over-reliance on subsistence rain-fed agriculture, farmers are very vulnerable to droughts and floods, the most common disasters in Malawi (NAPA, 2006).The culmination of population growth, environmental degradation, poverty, rapid urbanization, lack of access to information and knowledge, cultural beliefs and customs, limited food diversity, weak buildings/infrastructure, and a lack of effective disaster risk reduction efforts have all increased the vulnerability of the population to natural disasters. Climate change further intensifies the frequency and severity of disasters in the country.

Out of the 407,862 hectares of potential irrigable land in Malawi, 74.34% remains unexploited. The limited area under irrigation leads to food deficits during periods of unpredictable rainfall patterns, dry spells, droughts and floods of which there has been increased frequency of occurrence due to climate change effects. The food deficits are heightened by population growth which the National Statistical Office projects to reach about 19.1 million by 2020. The National Irrigation Policy (NIP) is one of the tools developed for adapting to climate change which allows crop production during droughts and dry spells (DoI, 2016).

2.1 Definition of a Drought condition

The standard definition of drought is non-existent. Previous studies (Wilhite & Glantz, 1985; Ismael, 2016; Salehnia, 2018; Mutsotso et al., 2018; Wambua, Mutua, & Raude, 2015; Kang & Zhang, 2016) state that it is difficult to define a drought because it is normally hard to establish its beginning, end, and magnitude in different agro-ecological zones. Furthermore, the studies explain that the effects of droughts often increase slowly, spread over a very large area, over a very long period of time and do not have any structure. These parameters make it very hard to quantify the characteristics of the drought events.

Hydrological drought has not received much attention in Malawi despite the fact that agricultural activities mainly depend on surface and subsurface water resources. This called for this study to augment the study of hydrological droughts in Kasungu ADD. A hydrological drought is defined as the inadequate surface and subsurface water resources for established water uses of a given water resources management system (Mishra & Singh, 2010).

2.2 Drought Characterization Indices

WMO (2016) noted that elements of drought characterization include severity, location, duration and timing. Severity refers to the deviation from normal of an index. In an agricultural cycle, especially when a crop reaches a moisture sensitive period, a short drought with low severity, is more destructive on crop yield than a longer drought with high severity on a less sensitive crop stage. Based on a set threshold for an index, start and end of drought may be determined. Location refers to the geographic area experiencing drought conditions. The timing and duration are determined by the approximate dates of onset and cessation.

Knowledge of drought duration and magnitude is vital in the determination of water demand for people, crops and animals. It is also important to guide water planners on the best water storage options in an area, operational water management decisions and planning drought monitoring (Palmer, 1965). Recently, the PDSI is widely used for this purpose (Dalezios *et al.*, 2000; Kim *et al.*, 2003).

Drought characterization is normally done by the help of drought indices. Drought indices are tools which combine different datasets into a single number which aids decision making in water resources planning (Adnan, 2017). Different studies have used different indices to evaluate droughts. Some are satellite based whilst some are data driven. Data driven drought indices include Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Percentile Index (PI), Palmer Drought Severity Index (PDSI) , Surface Water Supply Index (SWSI), Crop Moisture Index (CMI),Soil Moisture Index (SMI) , Aggregated Drought Index (ADI), Reconnaissance Drought Index (RDI), Murger Index (MuI), Effective Drought Index (EDI), Agricultural Rainfall Index(ARI), Soil Moisture Deficit Index(SMDI), Evapotranspiration Deficit Index(ETDI), Surface Water Supply Index(SWSI), Streamflow Drought Index (SDI), Standardized Runoff Index (SRI), and Reclamation Drought Index (RDI).

Satellite based drought indices include the Vegetation Condition Index (VCI), Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Water Supply Vegetative Index (WSVI), and Normalized Difference Drought Index (NDDI) (Wambua et al., 2015); Garen (1993); Narasimhan and Srinivasan (2005); Nalbantis and Tsakiris(2009)).

SPI, SPEI and PDSI are normally used to characterize meteorological droughts. SMDI, ETDI and ARI are utilized to ascertain agricultural droughts whereas SWSI and SDI are calculated to classify hydrological droughts. These indices are not solely used on their own as each one of them has their own limitations. However, when used as a group, their multiplier effect reduces their limitations (Bhuiyan, 2004).

These indices are normally calculated on monthly time scales of 1, 3, 6, 9, 12 and 24. Short term indices, for time scales of 3 and 6 months, are generally used to classify meteorological and agricultural droughts; and long-term indices, for time scales above 6 months are normally used to classify hydrological and socio-economic droughts (Karavitis, Alexandris, Tsesmelis, & Athanasopoulos, 2011).

Investigation on drought characteristics such as severity, duration, and frequency is crucial for water resources planning and management in a river basin (Dodangeh, 2017).

2.3 Description of drought indices employed in this study

2.3.1 SPI

Due to its simplicity in terms of data availability, the SPI emerges to be the most accepted, most used and most powerful drought monitoring index (Hayes et al., 1999; Szalai and Szinell, 2000; Bordi and Sutera, 2001; Lloyd-Hughes and Saunders, 2002; Lana et al., 2001; Vicente-Serrano et al., 2004; Tsakiris and Vangelis, 2004).

This index to be effective for different time scales, long-term data which fits a parametric distribution is a need (Mckee et al., 1993). This drought analysis at various temporal scales enhances drought classification (Bagheri, 2016). This index is best used for meteorological drought analysis (Wu et al., 2001). The principle of SPI is to convert long term rainfall data to a gamma probability density function which is then transformed to a normal distribution with a mean of 0 and a standard deviation of 1.

The major advantage of this index is that it requires rainfall as the only input. The (World Meteorological Organization (WMO), 2013) recommends this index for meteorological drought analysis. It suggests that it is the best index for areas with data scarcity. However, the major disadvantage of this index is that it does not factor in other parameters that influence drought characteristics especially severity such as temperature and evapotranspiration (Stagge, Tallaksen, Xu, & Lanen, 2014).

2.3.2 SPEI

The SPEI is a modified version of the SPI. Instead of using only rainfall data, the SPEI integrates temperature hence it includes evapotranspiration parameters in a drought event. This integration of other parameters makes the index more reliable for climate change studies (Stagge et al., 2014). Just like SPI, this index is also more effective when the data under consideration is long-term (more than 30 years).

2.3.3 PDSI

This drought index was developed to measure the duration and magnitude of a drought (Guttman et al., 1992; Palmer, 1965). It incorporates rainfall, temperature and soil moisture data to determine the index. Since it comprises a larger data set, this index is a good fit for abnormally dry and wet conditions. The limitation of PDSI is that it is well suited to areas which have similar characteristics and at times the index values may holdup evolving droughts.

2.3.4 ETDI

ETDI is calculated based on water stress ratio. It is an index which measures the magnitude of agricultural drought. It is based on the evapotranspiration data. According to Narasimhan, et al. (2005), ETDI should respond to agricultural drought, should respond to all seasons and should be spatially comparable irrespective of climatic zones.

2.3.5 SWSI

This is a hydrological based index which is a complement to PDSI. It is mostly suited for analyzing a drought at a basin level. It is calculated using streamflow, rainfall, reservoir storage and snowpack. In areas where snowpack is not available, the value is equal to zero (Shafer and Dezman, 1982).

2.4 Previous studies on Droughts in Malawi

Recently, Malawi has recorded an increased number of drought-occurrences (National Disaster Risk Management, 2015). These occurrences are due to climate change (Syroka, 2010). These two consecutive droughts caused more harm to most people especially farmers, women, and children. Maize production reduced tremendously due to crop failures, poor sanitation and malnutrition conditions worsened due to the droughts (Khamis, 2006).

Nearly all droughts in Malawi are linked with El Nino (Pauw & Seventer, 2010). In Malawi, dry spells are common and when they are persistent (3 to 4 months), they become droughts. Save that, a drought is also said to have occurred if the seasonal rainfall is lower than 75% of the normal rainfall (Chabvunguma et al., 2014).

Munthali and Ogallo (1986) carried out a rainfall analysis where they found out rainfall irregularities in the time-series of 1897 to 1983. Kamdonyo (1993) classified droughts in Malawi based on percentiles where they considered rainfall data of 70 years (1922 to 1992) and they earmarked two most severe droughts i.e. 1948/49 and 1991/92.

Since then, no study has ever been carried in most parts of the country pertaining to drought characterization in view of water saving technologies and sustainable water resources development. The previous studies carried out in the country do not as well characterize the spatial and temporal drought conditions, magnitudes and the impacts of the drought on crop production and types of irrigation used in the country. Apart from these studies, the government of Malawi has concentrated more on flood and drought management. Nevertheless, the gap still exists (NAPA, 2006). However, understanding drought events, quantifying them, their characteristics, and their differences from other disasters which is achieved by this study will help agricultural planners, irrigation engineers, and policymakers to manage basin effectively, efficiently and integrated in a sustainable manner.

2.5 Best Irrigation systems in view of Drought Conditions

In Malawi, extensive and long periods of drought conditions and insufficient rainfall lead to food shortage problems contributing to food insecurity in the country. While it is very difficult to control droughts or insufficient rainfall, it is possible to lessen these problems by having mitigation and adaptation strategies. One such way is to develop and practice more efficient and effective water usage techniques.

Advanced irrigation techniques exist in Malawi but their usage is limited. Dominant irrigation systems in Kasungu ADD are surface irrigation systems predominantly basin and furrow. Most farmers use river diversion, treadle pumps and watering cans. Maximizing existing water resources efficiently in Kasungu ADD is of paramount importance since the available water resources are not enough to irrigate the entire cultivable area. Basin and furrow irrigation systems have low efficiencies and in times of droughts when temperatures and evapotranspiration are higher, the efficiencies get even lower, water is wasted, irrigation becomes laborious and yields reduce. In times of droughts, river diversion techniques become a problem as the rivers dry out.

Although some steps have been taken to improve water management in surface irrigation, the water use efficiency is not to the desired extent which has resulted in waterlogging and salinity in some areas (INCID, 1994). In view of the urgent need to maximise use of the available resources, it is imperative to effect utmost economy in water use by adopting advanced methods of irrigation like drip, sprinkler and piped systems. By introducing these advanced methods, more and more cultivated areas in the country can be brought under irrigation resulting in increased agriculture production in response to climatic shocks.

According to the Department of Irrigation (DOI) Annual Report for 2014, there has been an increase in hectarage for irrigation by smallholder farmers. In the smallholder irrigation schemes farmers are allocated land in the scheme through the scheme committees. The area allocated depends on the plots available. In upland areas, farmers have an average of 0.7 ha and here rainfed production is practiced. In irrigation schemes, farmers are generally allocated an average of 0.4 ha.

Average yields in most crops have remained below 1.5 tons per hectare for the past decades and below comparable potential. This has been due to over dependence on subsistence rainfed farming, low level of irrigation technologies development and mid-season dry spells leading to partial or complete crop failure.

The efficiencies are relatively low in gravity schemes where the canals are not lined due to seepage. The overall efficiency in most smallholder irrigation projects in Malawi is relatively low (<50%). The water use efficiency under the different technologies differs with watering cans being more efficient than other technologies (National Irrigation Master Plan, 2015).

In most irrigation projects, the following problems are unchangeably observed:

- The traditional approach of designing an irrigation system mainly for subsistence and not commercial production,
- The designed system not meeting the requirement of the modern climate smart agriculture systems based on drought resistant, water saving and high yielding crop varieties
- Water balance in the irrigated area is not considered nor the impact of irrigation on the ground water conditions ever studied at planning stage,
- Unscientific water management practices due to inadequate drainage, improper water application, non-matching of irrigation supplies and requirements,
- Probability of drought type and characteristics not considered during planning of the irrigation scheme
- Widespread variations in soil types within the irrigation scheme

Huge investments have been made in Malawi towards surface based irrigation development. Despite such huge investments, the growth in food production does not tally with the investments. The average productivity of irrigated land is below 2.0 t/ha while in selected locations it is proved to be much higher, up to 8 t/ha. Thus, there is a huge need for improving the efficiency in using irrigation water. Besides the improved levels of efficiency of the furrow and basin methods of irrigation, there is still a need for development of suitable technologies for improved methods of irrigation.

The modern methods of irrigation such as drip, sprinkler and piped systems from rainwater harvesting methods provide an answer to this problem. Essentially, these methods do not involve significant conveyance and percolation losses, besides providing good control on water application. Thus these methods perform far better than the traditional surface irrigation methods.

2.5.1 Low Pressure Drip irrigation (LPDI) system

Drip Irrigation is a climate smart technological innovation for increasing crop production in areas with inadequate water supply (INCID, 1994). It increases yield by 30% and saves water to the extent of 30-40%. It can be adopted for a wide range of crops particularly' for horticultural crops, flowers, vegetables etc. It may also be useful in the oilseeds such as groundnuts.

Drip irrigation is an advanced method of irrigation to achieve considerable saving of water through high water-use efficiency compared to surface irrigation methods where irrigation efficiency is low due to losses in the water distribution system and on the field. Researches in drip irrigation have shown that the system is well suited for water scarcity areas. The system involves applying water to crops in form of drops. Under this system, water is carried to the plant under low pressure, through small diameter plastic pipes (laterals) and delivered at the root zone, drop by drop through emitters. It is most suitable for horticulture crops, vegetables and drought resistant crops. It is a system which is also suitable in areas where groundwater is scarce and is essential in the optimization of limited water resources.

In recent years, low-pressure drip irrigation (LPDI) systems have been developed and are being promoted smallholder farmers. For many subsistence farmers, a standard drip system is costly, complex and requires much skill hence do not match their needs (Bustan, 2008).However, LPDI systems are appropriate for smallholder farmers as they are economical, do not require much expertise and are easy to use.

Fig. 2 shows the components of a typical LPDI system.

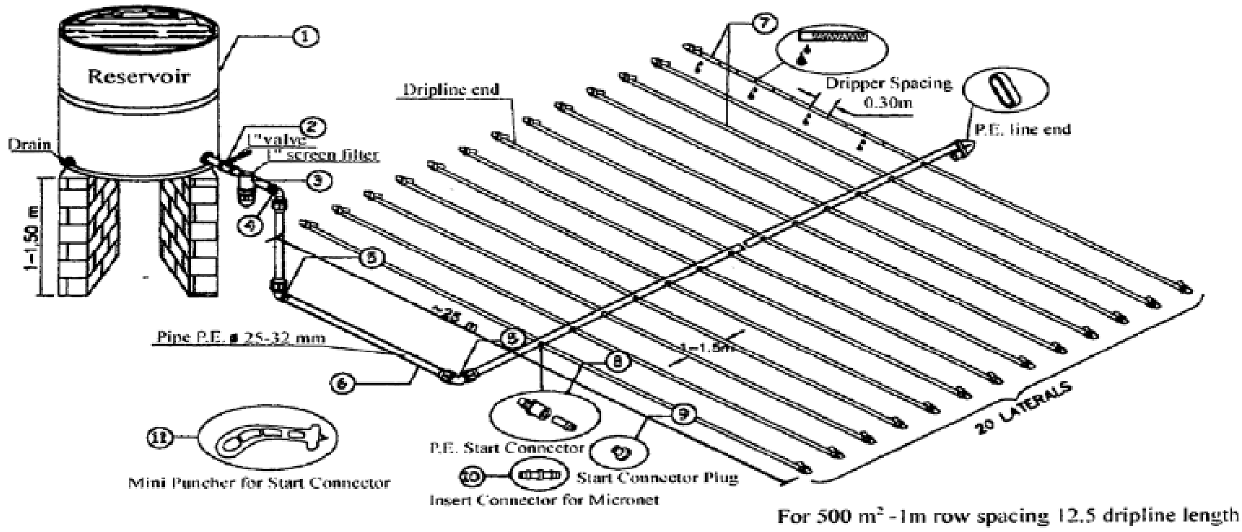


Figure 2: Diagram of the LPDI System [Source: Bustan (2008)]

2.5.2 Micro-sprinkler irrigation systems

Sprinkler Irrigation is a technique of applying irrigation water which is similar to rainfall. Water is distributed through a network of pipes usually by pumping. Water under pressure is pumped from the water source, conveyed in a pipeline system and distributed to the field through rising pipes (risers) with a rotating head at its end (sprinklers).

Source: https://www.jains.com/irrigation/popups%20and%20sprinklers/sprinklersystems.htm

Figure 3: Diagram of the Sprinkler System

2.6 DMAP (<u>Drought Monitor And Prediction)</u> software

Drought monitoring and prediction involves the computation of different types of indices. Drought indices are numerical values that describe drought intensities by integrating different data from one or several variables such as rainfall, soil moisture, stream flow and evapotranspiration into a single numerical value (Zargar et al. 2011). A drought index is reliable if it manages to tell when a drought can start and end, how often it can occur and how intense it can be. Such a drought index can be used for early warning systems and water resources planning and management (Wilhite 1993). To lessen drought damages, it is a necessity to monitor these events.

Whereas different tools have been developed to compute these indices such as DrinC, SPI Generator and RClimdex, these tools mostly calculate SPI only. DMAP surpasses all these tools in that it computes 19 different types of drought indices in three different types of droughts namely meteorological, agricultural, and hydrological. DMAP software is easy to use, comprehensive and time saving as it also aids in the determination of drought characteristics such as drought duration, drought frequency, and drought severity.

2.7 Rationale of the Study

In a bid to sustainably manage water resources and disasters, it is significant to analyze and understand different types of droughts in a region. This study is vital in Kasungu ADD in that it will characterize droughts by its type, severity, and duration. This will guide water resources engineers and district water planners to model, simulate and guide farmers and communities about the present and future drought conditions. This will ably guide the people on which mitigation measures can be taken to reduce the pressure on water resources. Furthermore, farmers will be guided on the best drought-resistant crops to grow in the region and what best irrigation techniques to be utilized. As if that was not enough, this research will also provide information for policymakers in preparing and strategizing on disaster risk management.

Concepts of integrated water resources management are not fully utilized in Kasungu ADD. With the persistent use of furrow irrigation in the ADD and reduced stream flows in different rivers in the ADD, this study will be of importance as it will guide on where to use rainwater harvesting technologies depending with drought conditions. Furthermore, this is the first study to be conducted in the region. This study will guide organizations and other stakeholders operating in the region to make use of the results in their disaster risk management plans.

CHAPTER THREE

3. METHODOLOGY

3.1 Description of Study Area

3.1.1 Location

Kasungu ADD is found in the Central region in Malawi and it comprises four districts namely Mchinji, Kasungu, Dowa and Ntchisi. The ADD lies within the Central Region Plateau. The western part is flat whilst the farthest eastern part is partly mountainous. The mountainous part is largely covered by Mchinji hills, Dowa Hills, Kongwe Mountain and Ntchisi hills.

Malawi is divided into water resource areas which are further divided into water resource units (WRU). Kasungu ADD is found in Bua catchment area which lies in WRU 5. Figure 1 below shows the location of Kasungu ADD in Malawi.

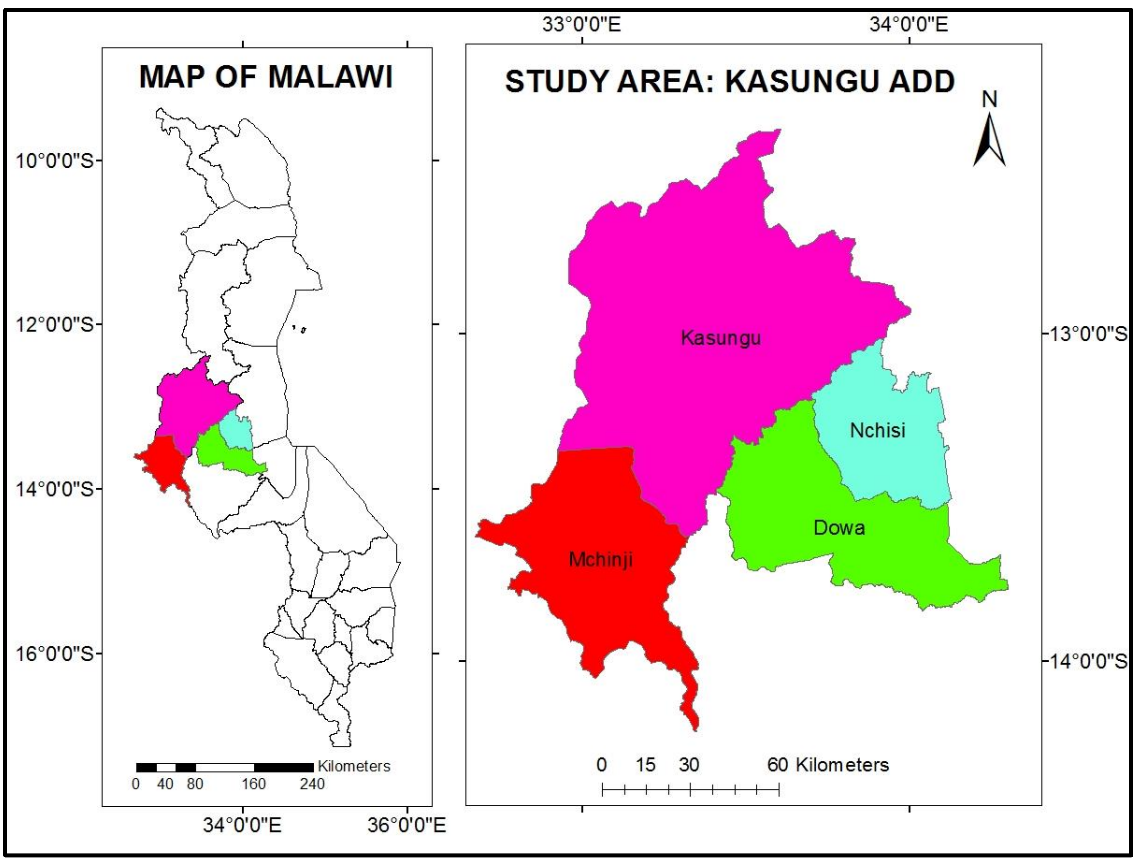


Figure 4: Location of Kasungu ADD on the map of Malawi

3.1.2 Topography

Kasungu ADD lies on the Kasungu-Lilongwe plain which is relatively flat. Fig.5 shows that over 80% of the study area ranges from 800 – 1200 metres above mean seal level. High lands within the range of 1500 -1700 metres above mean sea level lie on the southwestern part (Mchinji Mountains) and south eastern part (Dowa Hills). Main rivers originate from these high lands and have well-ordered profiles with several tributaries towards Lake Malawi.

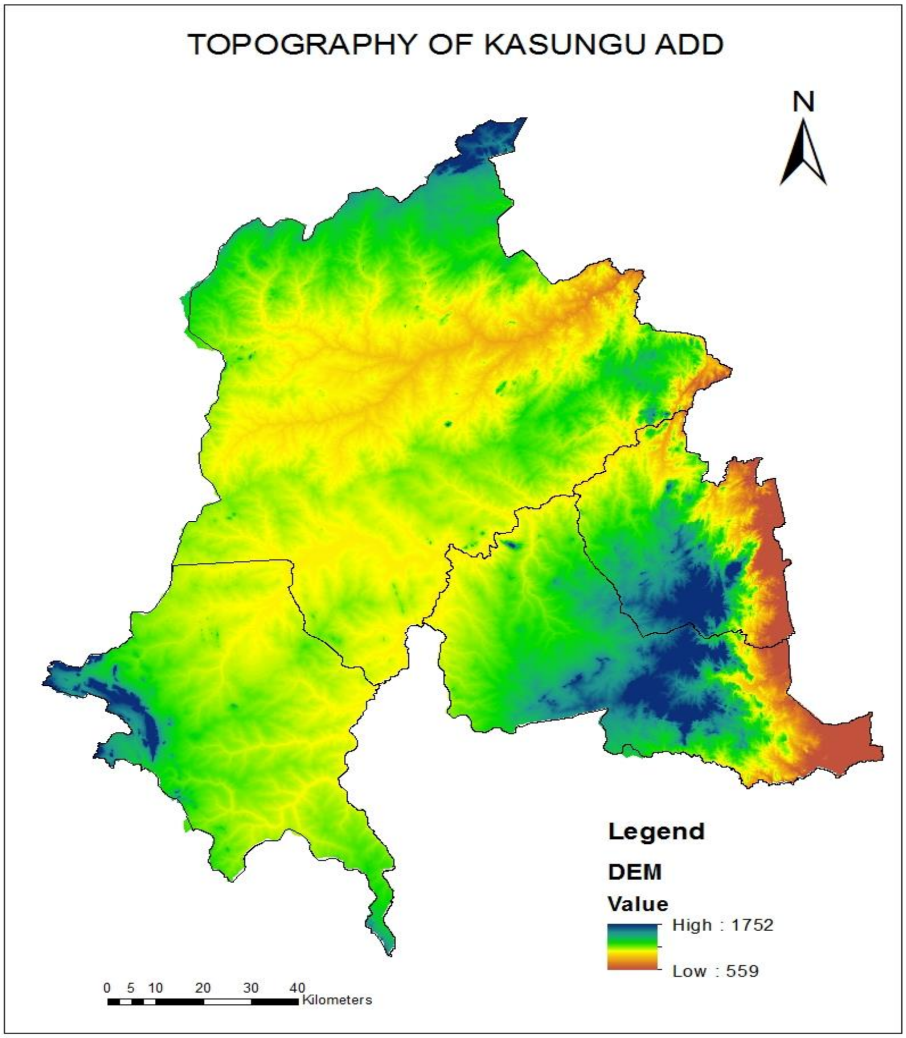


Figure 5: Topography of Kasungu ADD

3.1.3 Climate

The topography and migration of the Inter-Tropical Convergence zone are the main factors which influence the seasonal climate of the region. The peak cold months are May, June, and July while the rain season spans in an approximately normal distribution from mid-November to mid-March with huge rain downpours in February. The ADD has a tropical type of climate, which usually shifts from warm to hot during summer and cool to cold in winter. The winter season starts from May through September and summer runs from October to April. The eastern part of the ADD shares a boundary with a rift valley lying areas- Salima and Nkhotakota, which have hot to very hot types of climates in summer and cool to warm in winter. Western part lies in central highlands which are cold to warm in winter and warm to hot in summer. Fig. 6 shows the average temperatures in the ADD.

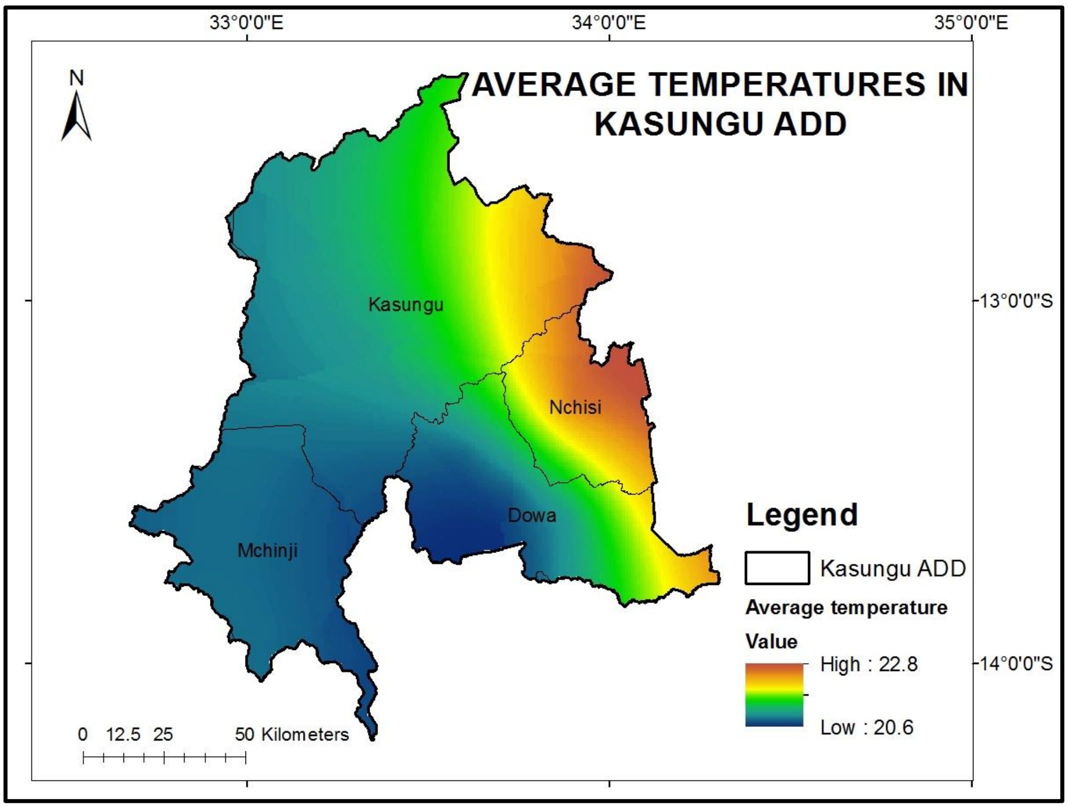


Figure 6: Average Temperatures of Kasungu ADD

The ADD has fewer operational stations for collecting climatic data following the closure of some Malawi Young Pioneer (MYP) bases which had some stations. For the available stations, data is either incomplete or inaccurate. The Department of Meteorology (2009) contends that most climatic stations in the basin have missing data or incomplete data sets ranging from rainfall, temperature, humidity, wind, and sunshine hours. This problem makes a computation of water requirements for irrigation a challenging task in the ADD.

Agriculture officers and/irrigation engineers can either overestimate or underestimate crop water requirements. The standard method has always been to use climatic data from neighboring stations such as Chipata and Lundazi in Zambia, Chitedze and Kamuzu International Airport in Lilongwe, Mzimba in the northern region of Malawi, Nkhotakota the north-western side of Malawi and Salima to compute approximate potential evaporation for the ADD. This method makes use of Kriging interpolation methods to estimate the characteristics of areas which do not have meteorological stations.

3.1.3.1 Rainfall Stations in Kasungu ADD

Table 1 shows the raingauge stations available around and in the ADD.

Table 1: Raingauge Stations in Kasungu ADD

Station Name	District	Latitude	Longitude	Years of data	Elevation
Dowa Boma	Dowa	-13.60	33.88	40	1351
Madisi	Dowa	-13.42	33.60	40	1115
Mponela	Dowa	-13.53	33.74	40	1208
Chitedze	Lilongwe	-13.98	33.63	40	1149
KIA	Lilongwe	-13.96	33.70	40	1136
Mwimba	Kasungu	-13.02	33.47	40	1084
Kasungu	Kasungu	-13.01	33.46	40	1015
Mchinji Boma	Mchinji	-13.80	32.89	40	1182
Tembwe	Mchinji	-13.90	33.06	40	1094
Mkanda	Mchinji	-13.50	32.99	32	1089
Ntchisi	Ntchisi	-13.28	33.89	39	1343

3.1.3.2 Average Rainfall in Central Malawi

Fig.7 shows the average annual rainfall from the meteorological stations found in Central Malawi.

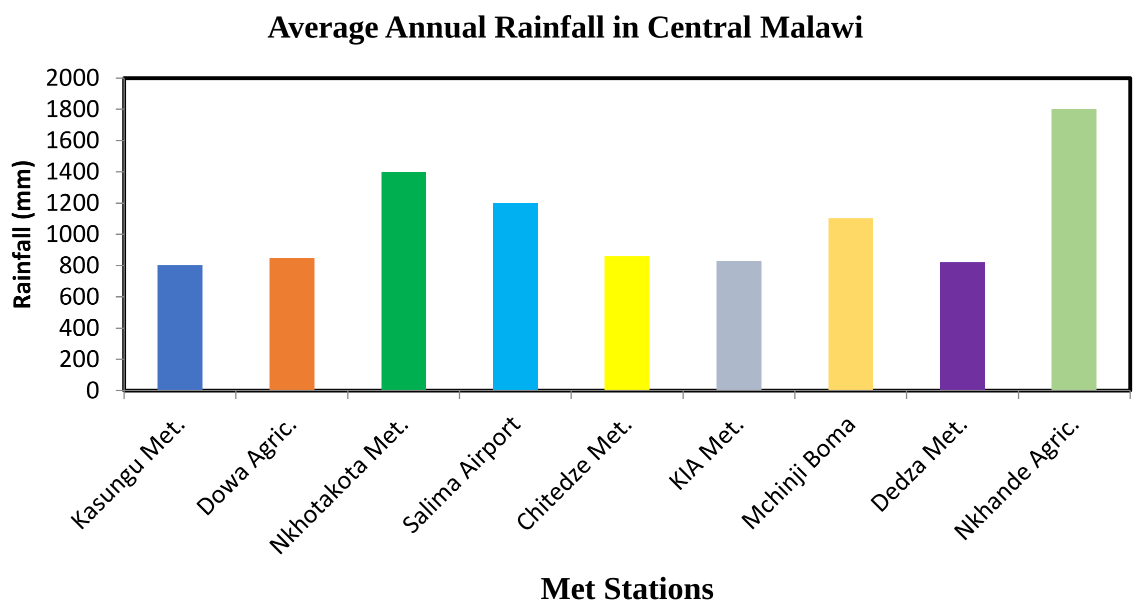


Figure 7: Average annual rainfall in Central Malawi

3.1.4 Soils and geology

The soils on the southwestern part (Mchinji Mountain) and southeastern part (Dowa Hills and Ntchisi Hills) are dominantly sticky laterites. On the part of the west central plain, the soils are a mixture of sand and clay. Erosion is more existent in the eastern part than the western part of the ADD. Generally, the area is comprised of the following kinds of soils: Weathered ferriticsoils / Latosols, Lithosols, and undifferentiated Lathosols, Alluvial soils, often calcimorphic soil, Lithosols, and Gleys. In simple terms, the most predominant type throughout the ADD is loamy sand followed by sandy loam with noticeable patches of sandy clay loam soils. The eastern part soils are generally shallow in-depth and fairly more fertile than western part soils in the ADD.

3.1.5 Land cover/use

Rainfed agriculture is the backbone of most economic activities of people in the ADD. Small-scale and large scale maize and tobacco production have led to massive deforestation of the natural deforestation. This has led to the opening of more land for farming in the ADD. The area has protected areas from Nkhotakota Game Reserve, Kasungu National Park, Mchinji Forest Reserve, Ngala Forest Reserve, and Dowa Hills Forest Reserve. Any agricultural threat, therefore, is significant in the lives of the people. There is annual flooding in the rainy season and alluvium is spread over the plain in the lower reach. Fig.8 shows the land cover in Kasungu ADD.

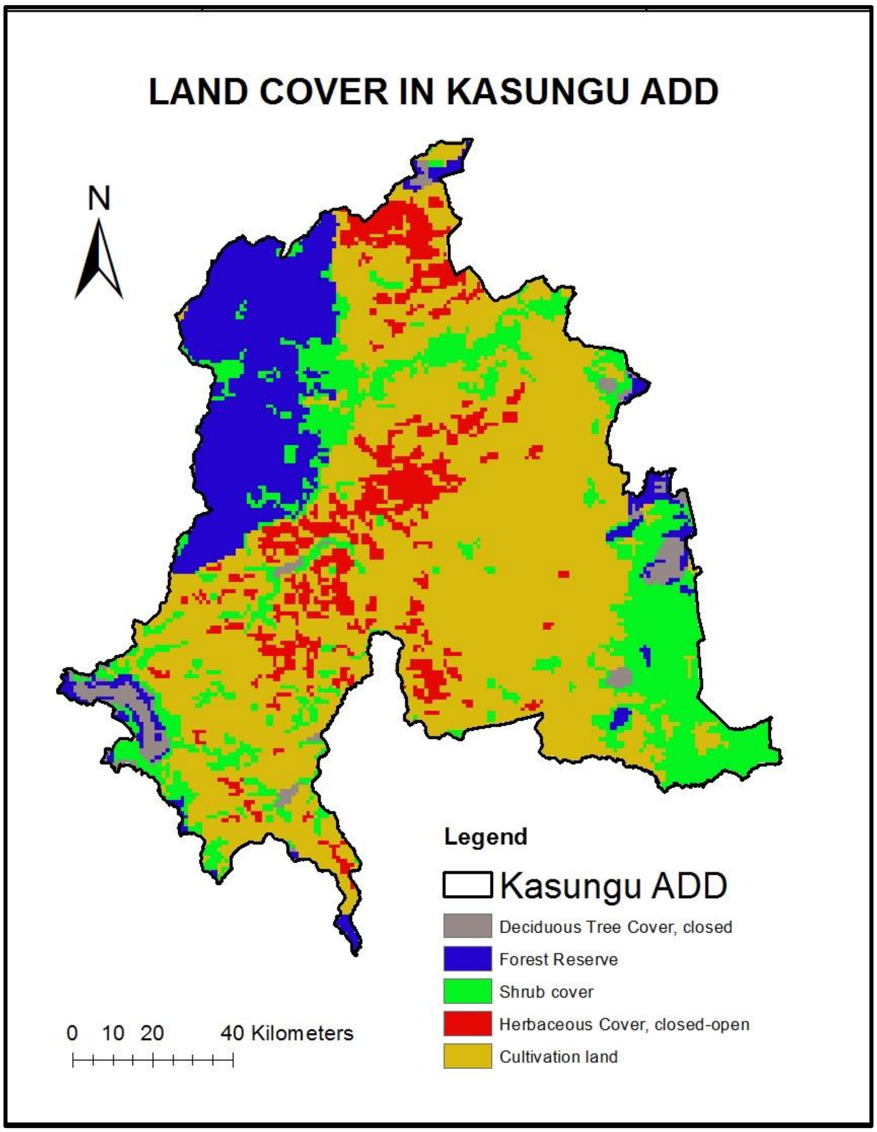


Figure 8: Land Cover in Kasungu ADD

3.1.6 Water resources in the ADD

The largest perennial river in the ADD is Bua River. River flows are collected from three main stations with the central station (5C1) at S53 Road Bridge. The main tributaries of the Bua River are Namitete, Kasangadzi, and Rusa. The other small tributaries are transient such that they dry up in winter. The ADD also has a rich network of wetlands which store water. Bua River is mainly used for irrigation and domestic water supply. Bua irrigation scheme abstracts almost 67% of the river flow. All other irrigation schemes belong to smallholder farmers and abstract smaller amounts of water. Fig. 9 shows water resources in Kasungu ADD.

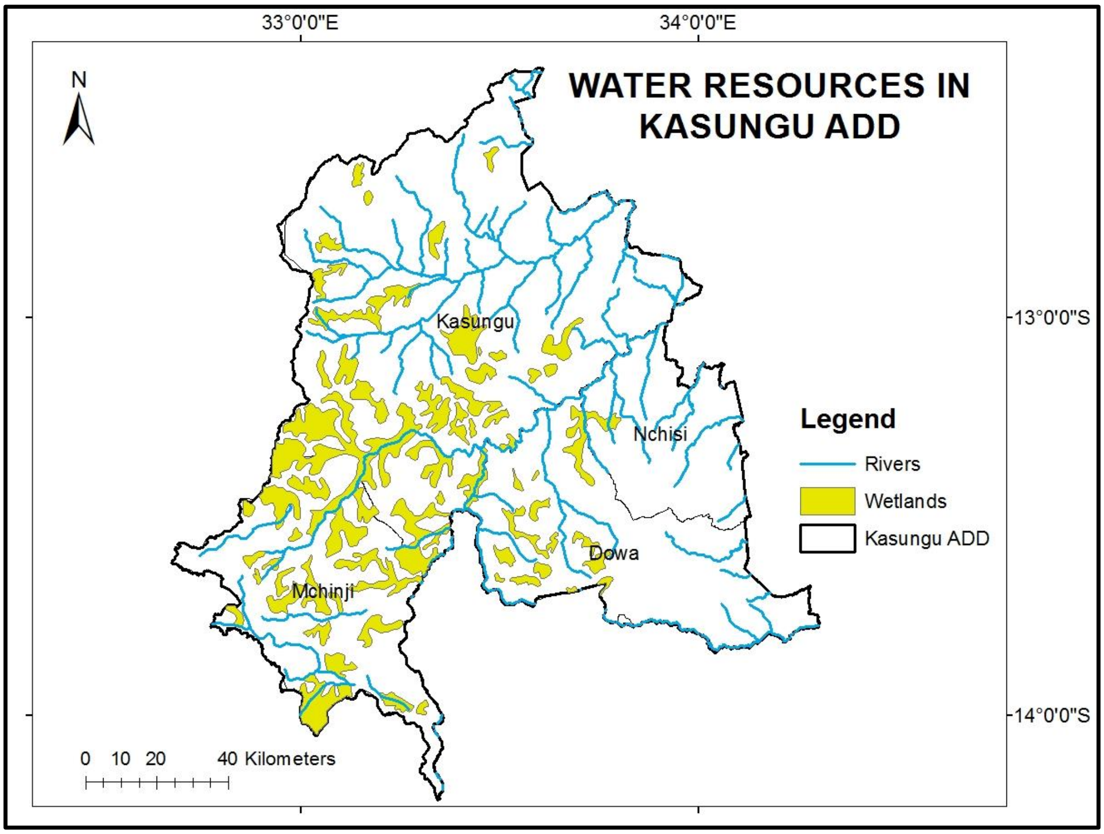


Figure 9: Water Resources in Kasungu ADD

3.2 Data selection and preliminary analysis

Table 2 shows different sources from which data for this research was obtained. Table 3 shows the types of drought indices which were calculated in this research.

Table 2: Data sources and uses

Type of data	Source	Purpose/use
DEM	http://srtm.csi.cgiar.	Elevation
Daily stream flows	Ministry of Irrigation and Water Development	Drought indices calculation
Monthly Rainfall	Department of Meteorological Services	Drought indices calculation
Monthly Temperature	Department of Meteorological Services	Drought indices calculation
Crop yields	Ministry of Agriculture-Statistics Department	Crop yields reduction assessment
Cropping calendar	Field surveys	Crop growth stage determination

Table 3: Types of drought indices calculated

Drought indices	Data needed	Category of use
SPI, SPEI and PDSI	Precipitation, Evapotranspiration	Meteorological, for monitoring and forecasting
ETDI and ARI	Precipitation, Temperature, Soil Moisture (Available Water Content)	Agricultural, effective in agriculture, used in historical analysis and risk analysis
SWSI and SDI	Precipitation, Stream flow	Hydrological

3.3 Data processing

3.3.1 Normality Tests for climatological, crop yields, and streamflow data for Kasungu ADD

In order to carry out parametric tests on both climatic and streamflow data, normality tests were carried out in Statistical Package for Social Scientists (SPSS) software. The null hypothesis for this normality test was that the data was normally distributed. The null hypothesis is rejected when the p-value is below 0.05. If p-value is above 0.05, then the null hypothesis is kept.

3.3.2 Statistical Analysis (Descriptive statistics and linear regression)

Monthly rainfall data from 1977 to 2017 for the districts in the study area were analyzed. The stations were chosen because data for the period was fairly accurate and did not have many missing data as compared to the other stations. Furthermore, the stations also represented the whole climatic scope of the ADD. Statistical analyses were performed to assess any significant differences among the four districts within the months and years under study.

The statistical analysis was used to establish the measures of central tendency (mean, range, maximum, etc.) and dispersion (R.C.I, S.D., CV, etc.). For identifying the trend in the rainfall data, the statistical analysis of linear regression was used. In order to calculate a trend of data in time series, linear regression is the easiest method. The equation of linear regression line is given by $Y = mX + \mathrm{c}$, where X is the independent variable and Y is the dependent variable.

The slope line is m and c is the intercept (value of Y when $X = 0$). The slope of regression describes the trend whether positive or negative. In this study dependent variable Y is rainfall and independent variable X is year. Linear regression requires the assumption of normal distribution. In this study, the null hypothesis is that the slope of the line is zero or there is no trend in the data. The significance of the slope is shown by the probability value (P value) of it. Microsoft Excel 2010 was used to calculate the lines and statistical values of linear regression analysis. The P-value from the analysis is the test for the significant level $\alpha = 0.05$.

The value of R-square (R^2) or the square of the correlation from the regression analysis was used to show how strong the correlation and relationship between the variables X and Y are. The value is a fraction between 0.0 and 1.0. A R^2 value of 1.0 means that the correlation becomes strong and all points lie on a straight line. On the other hand, a R^2 value of 0.0 means that there is no correlation, and no linear relationship between X and Y.

3.3.3 Drought Trends based on Mann-Kendall Tests

The Mann-Kendall test is a non-parametric technique which tests trends whether they are decreasing, increasing, or none. In this study, drought trends were analyzed using this test. Ordered time series is used to evaluate the data. The sum of increments and decrements gives a Mann-Kendall statistical trend value, S, calculated as follows:

$$S = \sum_{k=1}^{n-1} \left[\sum_{j=k+1}^{n} sign(x_i - x_k) \right] \tag{1}$$

The right hand side of the equation is simplified as:

$$sign(x_i - x_k) = \begin{Bmatrix} 1 \; if \; (x_i - x_k) > 0 \\ 0 \; if \; (x_i - x_k) = 0 \\ -1 \; if \; (x_i - x_k) < 0 \end{Bmatrix} \tag{2}$$

To determine the level of significance of the trend, the probability linked to S and selected n-data were established. The variance of the data sets VAR (S), and the normalized test statistic Z were both calculated using the equations (3) and (4) below:

$$VAR\ (S) = n(n-1)(2n+5) - \sum_t \frac{t(t-1)(2t+5)}{18} \tag{3}$$

$$Z = \begin{Bmatrix} \dfrac{S-1}{\sqrt{VAR(S)}} \; if \; S > 0 \\ 0 \; if \; S = 0 \\ \dfrac{S-1}{\sqrt{VAR(S)}} \; if \; S < 0 \end{Bmatrix} \tag{4}$$

Where VAR(S) is the variance of the data sets, and n is the number of data points. Drought trend qualification as decreasing, increasing or no trend was based on whether S < 0, S>0 and S=0 respectively. Significance level at 95% was used to determine whether the drought trend was significant or insignificant.

3.4 Drought Indices Calculation

All drought indices were calculated using AgriMetSoft Drought Monitoring And Prediction (DMAP) application. This software calculates meteorological, agricultural and hydrological indices. It was used due to its completeness, easiness, and comprehensiveness.

3.4.1 SPI

Standardized precipitation index (SPI) was calculated using monthly precipitation data. It is one of the easiest indices to calculate as the only input data needed is monthly rainfall. McKee et al. (1993, 1995) stated that SPI could be determined for different timescales e.g., 1, 3, 6, 12, 24 months and the characteristic values range from < -2 to > 2. SPI at different time scales i.e., monthly, 3-months, 6-months and 12-months was calculated to monitor droughts in the ADD. This index is based on the likelihood of precipitation for a given period.

In order to calculate the SPI, monthly precipitation data is normalized using the gamma probability distribution function. This normalization results in positive and negative values (standard deviations from the mean), allowing for the determination of wet and dry periods for a given area. The accumulation of these values is further used to estimate drought characteristics, especially drought magnitude.

The Standardized Precipitation Index (SPI) is a commonly used tool for defining and monitoring meteorological drought. It does not forecast or predict droughts.

Classification of SPI Values

Table 4 shows how SPI values are classified.

Table 4: SPI Classification

SPI Value	Drought/Wetness condition
≥ 2	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
≤ 2	Extremely dry

Mathematically, SPI is calculated as in the equation (5):

$$\mathrm{SPI} = \frac{\left(\mathrm{X_{ij}} - \mathrm{X_{im}}\right)}{\sigma} \tag{5}$$

Where X_{ij} is the seasonal rainfall at the *ith* station and *jth* observation, X_{im} is its longterm seasonal mean and σ is its standard deviation.

However, rainfall data is normally fitted by a Gamma distribution when considering SPI. Taking this probability density function of the Gamma distribution, SPI is calculated as:

$$\mathrm{g(x)} = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \mathrm{x}^{\alpha-1} \mathrm{e}^{\frac{-\mathrm{x}}{\beta}} \quad (\mathrm{x} > 0) \tag{6}$$

where $\Gamma(\alpha)$ is the Gamma function; x is the rainfall (mm); α is the shape parameter ($\alpha > 0$) and β is the scale parameter ($\beta > 0$) and:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{7}$$

$$\beta = \frac{\bar{\bar{x}}}{\alpha} \tag{8}$$

$$A = ln(\bar{\bar{x}}) - \frac{\sum \ln x}{n} \tag{9}$$

$$\Gamma(\alpha) = \int_{0}^{\Phi} y^{\alpha-1} e^{-y} dy \tag{10}$$

3.4.2 SPEI

The SPEI is a modified version of the SPI. Instead of using only rainfall data, the SPEI integrates temperature hence it includes evapotranspiration parameters in a drought event. This makes this index more reliable for climatic studies taking into consideration longer timeframes. The SPEI was also calculated at 3, 6, and 12-time scales.

Table 5 shows how SPEI values are classified.

Table 5: SPEI Classification

SPEI Value	Drought/Wetness condition
≥ 2	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
≤ 2	Extremely dry

SPEI considers cumulated anomalies of the climatic water balance. A simple status of the water balance is calculated as the difference between rainfall and potential evapotranspiration for the assessed month given by equation:

$$\mathrm{D_i} = \mathrm{P_i} - \mathrm{PET_i} \tag{11}$$

Monthly PET is given by Thornthwaite equation:

$$\mathrm{PET} = 16\mathrm{K}\left(\frac{10\mathrm{T_{avg}}}{\mathrm{I}}\right)^{\mathrm{m}} \tag{12}$$

Where *P* is monthly rainfall, PET is monthly potential evapotranspiration, *T* is average temperature and *I* is the heat index based on the total of 12 monthly index values, m is the heat index coefficient and *K* is a correction factor as a function of month and latitude. Thornthwaite equation is very helpful in areas where observed data is limited. The only data needed to compute it is mean temperature and latitude.

3.4.3 ETDI

The following steps are used in the computation of the index: The ETDI for time *I* month is calculated on incremental basis by Palmer (1965):

$$ETDI_j = 0.5ETDI_{j-1} + \frac{WSA_j}{50} \tag{13}$$

Where $ETDI_{j-1}$ represent the ETDI for initial month and WSA monthly water stress anomaly:

$$WSA_{i,j} = \frac{MWS_j - WS_{i,j}}{MWS_j - minWS_j} * 100 \qquad if\ (WS_{i,j} = MWS_j) \tag{14}$$

$$WSA_{i,j} = \frac{MWS_j - WS_{i,j}}{maxWS_j - MWS_j} * 100 \qquad if\ (WS_{i,j} > MWS_j) \tag{15}$$

Where MWS_j is the long-term mediain water stress of month j, $maxWS_j$ is the long-term maximum water stress of month j, $minWS_j$ is the long-term minimum water stress of month j. Normally, the water stress anomaly value ranges from -100 to +100 indicating very dry to very wet conditions respectively.

Water stress is given by,

$$WS = \frac{ET_o - ET}{ET_o} \tag{16}$$

Where ET_o is the reference evapotranspiration from Penman-Monteith equation and ET is the actual evapotranspiration derived from SEBS.

Table 6 shows how ETDI is categorized.

Table 6: ETDI Classification

ETDI Value	Drought/Wetness condition
≥ 2	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
≤ 2	Extremely dry

3.5 Drought Characteristics Analysis using Runs Theory

All droughts events emerge from the definition of drought indices based on SPI calculation. A drought is said to have occurred when the SPI is constantly below zero and reaches a threshold value of -0.99 or below and is said to have ended when the SPI becomes positive. During this drought occurrence, four drought characteristics or properties, namely duration, severity, intensity, and frequency, can be detected. Typically, runs theory is used to identify these drought properties. Fig.9 shows the drought characteristics using the run theory for a given set level.

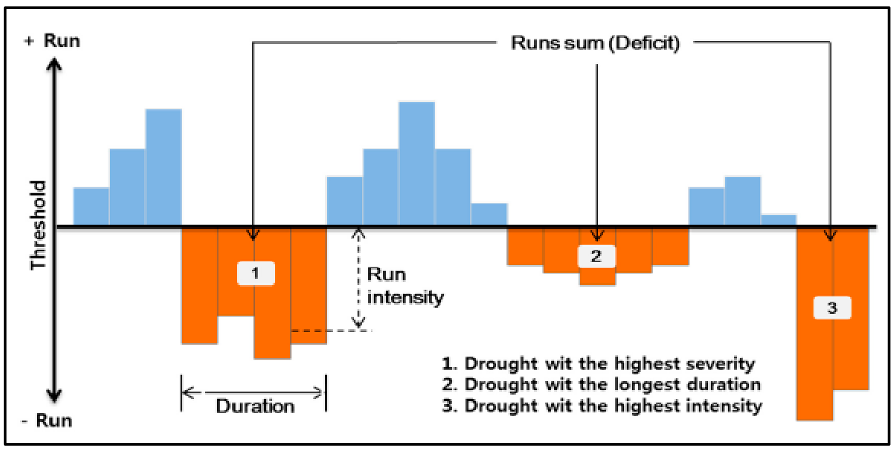


Figure 10: Drought characteristics using the run theory for a given threshold level [Source: Bae (2018)]

Duration of a drought event defines the number of months in drought conditions.

Severity defines the definite value of the sum of the index during a drought event. In other words, it is the sum of the integral area below zero of each drought event.

The intensity of drought is given by:

$$\text{Drought Intensity} = \frac{\text{Severity}}{\text{Duration}} \tag{17}$$

Frequency of a drought defines the number of drought events the occurred within a given period. Mathematically,

$$\text{Drought Frequency} = \frac{\text{Number of drought events}}{\text{Total number of years of study period}} \tag{18}$$

These properties of droughts are very critical in understanding water management in an area. However, most prolonged duration and high severity are central in agricultural-based economies such as Malawi.

3.6 Determination of Crop Water Requirements

Crop water requirements were determined in CROPWAT 8.0 software.

3.6.1 Description of CROPWAT 8.0 Software

CROPWAT 8.0 is FAO based software which calculates reference evapotranspiration, crop water requirements, irrigation scheduling, and irrigation water requirements. In order to compute the aforementioned parameters, the software takes into consideration local climatological data, soil types, and crop types. The software is based on differential equations and is very easy to use.

3.6.2 CROPWAT 8.0 Data Requirement

The software requires local climatological data, local rainfall data, local soil data, and local crop data. Locally climatological data for approximately forty years (1977-2017) was collected from the National Meteorological Department for the stations in the study area. The observed mean values for the data from the weather stations replaced those obtained from the CLIMWAT 2.0 for CROPWAT program.

The crop data for maize (corn), pulses, groundnuts, and cassava were taken from the FAO Manual 56. Planting dates were based on agricultural operations received from the Department of Extension Services.

The United States Department of Agriculture (USDA) soil conservation (S.C.) method was used in this study. The soil properties such as soil type, total available moisture content, initial moisture depletion, maximum infiltration rate, and maximum rooting depth within and around the weather station were also collected.

Fig.11 shows the flow chart for the determination of crop water requirements and irrigation requirements. Climate data, rainfall data, crop data and soil data collected from the study area was input in the CropWAT software. Evapotranspiration was determined from Penman-Monteith equation and rainfall was adjusted using USDA method. Crop water requirements and irrigation net requirements were further determined from the evapotranspiration.

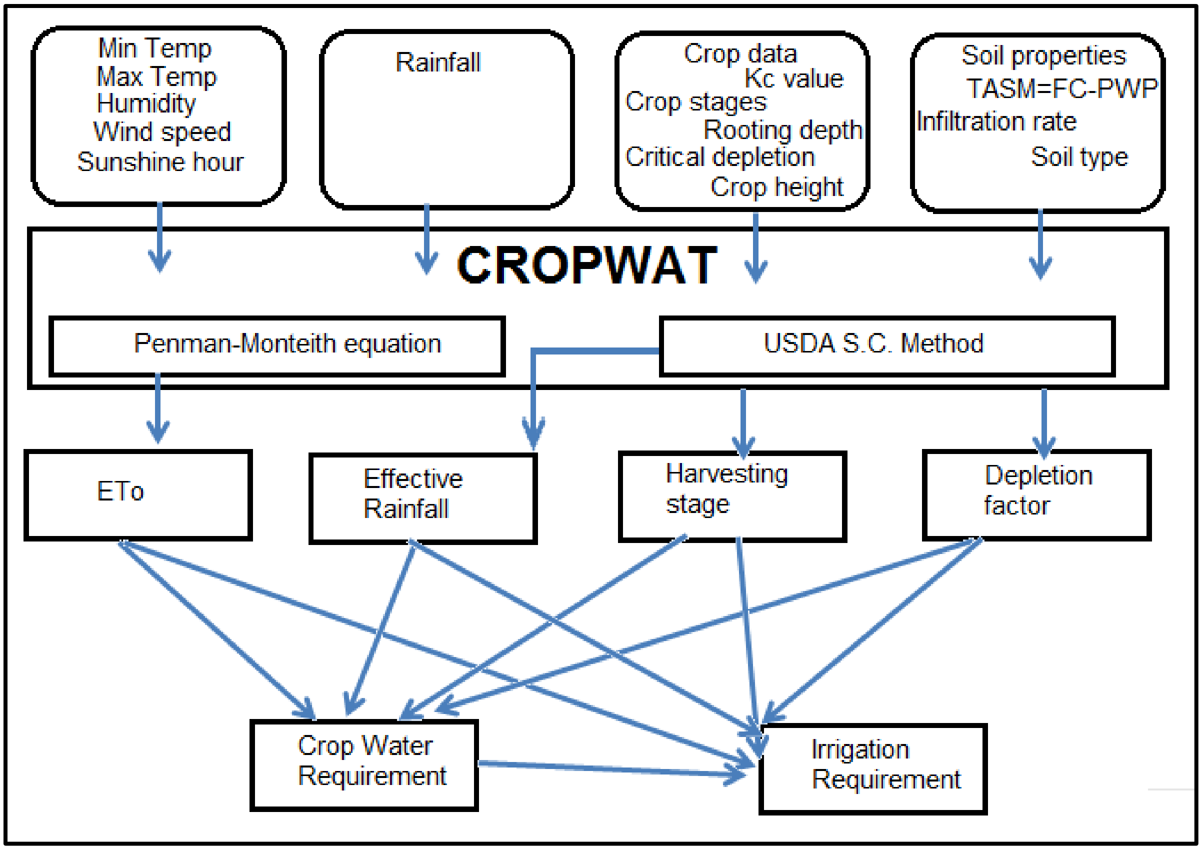


Figure 11: Flow chart for Irrigation requirement Computation in CROPWAT

3.6.2.1 Reference Evapotranspiration (ET_0)

Evapotranspiration refers to the combined loss of water from the soil (evaporation) and plant (transpiration) surfaces. With reference to a hypothetical crop of height 0.12 m, the albedo of 0.23 and a fixed canopy of 70 sm^{-1}, this rate of evapotranspiration is called reference evapotranspiration.

CROPWAT 8.0 software uses FAO Penman-Monteith equation to estimate reference evapotranspiration. This is because the equation takes into consideration most parameters recorded in the weather stations.

The Penman-Monteith equation is given as:

$$\lambda \mathrm{ET} = \frac{\Delta(\mathrm{Rn} - \mathrm{G}) + \mathrm{PaCp}\dfrac{(\mathrm{es} - \mathrm{ea})}{\mathrm{ra}}}{\Delta + \gamma\left(1 + \dfrac{\mathrm{rs}}{\mathrm{ra}}\right)} \qquad (19)$$

where Δ is the slope of the relationship between saturation vapour pressure and air temperature, Rn is the net radiation, G is the soil heat flux, Pa is the mean of air density at constant pressure, Cp is the specific heat capacity of the air, $(es - ea)$ is the vapour pressure deficit of the air, γ is psychometric constant, and rs and ra are the surface and aerodynamic resistances, respectively.

When the hypothetical crop characteristics and height of wind speed are standardized at 2 m to calculate the surface and aerodynamic resistance, the equation is modified to:

$$\mathrm{ET_o} = \frac{0.408\Delta(\mathrm{Rn} - \mathrm{G}) + \gamma \frac{900}{\mathrm{T} + 273} \mathrm{u2}(\mathrm{es} - \mathrm{ea})}{\Delta + \gamma(1 + 0.34\mathrm{u2})} \tag{20}$$

where ET_o is the reference evapotranspiration (mm/day), T is the mean daily air temperature (℃) at 2 m height, $u2$ is the wind speed at 2 m height (ms^{-1}), and es and ea are the saturation, and actual vapor pressure (kPa), respectively.

3.6.2.2 Crop Water Requirement (CWR)

For a crop to be healthy, it needs an amount of water equal to what it is losing through evapotranspiration. This amount of water required by a crop for this purpose of filling what it has lost is referred to as crop water requirement.

Estimation of CWR is stemmed from crop evapotranspiration (ET_c) and is calculated using the equation:

$$ET_c = K_c * ET_o \tag{21}$$

where K_c is the crop coefficient. It is the ratio of ET_c to ET_o. Due to variations of ET during growth stages, the K_c will also vary during the same growth stages.

The irrigation water requirement represents the difference between the crop water requirement and effective rainfall. The irrigation water requirement includes additional water for leaching of salts and to compensate for non-uniformity of water application (Allen et al., 1998).

3.6.2.3 Irrigation Scheduling

Irrigation scheduling is a science of determining the right amount of water to irrigate, the right time to irrigate, and the proper method to irrigate. The CROPWAT software develops the irrigation schedules based on the daily water balance in the root zone by considering the root zone depletion at the end of that day's irrigation.

The daily water balance of the root zone is estimated using the equation:

$$Dr,i = Dr,i - 1 - (P - RO)i - Ii - CRi + ET_c i + DPi \tag{22}$$

where Dr,i is the root zone depletion at the day's end i (mm), $Dr,i - 1$ is the water content in the root zone at the previous day's end (mm), Pi is the precipitation on day i (mm), ROi is the surface soil runoff on day i (mm), Ii is the net irrigation depth on day i which infiltrates the soil (mm), CRi is the capillary rise from the groundwater table on day i (mm), $ET_c i$ is the crop evapotranspiration on day i (mm), and DPi is the lost water of the root zone on day i (mm).

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1 Statistical analysis of annual rainfall in Kasungu ADD

The summary statistical analysis of rainfall data in Kasungu ADD is presented in Table 4. According to this table, it can be seen that Ntchisi received the highest mean annual (1093.0mm) and seasonal rainfall (154.3 mm). The mean annual rainfall varies from 781.1mm for Kasungu to 1093 mm for Ntchisi. Table 4 reveals that on average all the stations in the ADD receive rainfall below 200 mm during the period from October to April (ONDJFMA) and below 10 mm during winter, from May to September (MJJAS).

The higher rainfall values recorded in Ntchisi, Mchinji, Tembwe, Mkanda, and Dowa generally could be attributed to the wild nature of the areas, coupled with forest reserves and also the rich network of tributaries of rivers which supply a significant amount of atmospheric moisture for rainfall. The western part of the ADD (Kasungu, Mponela, Madisi, Mwimba) has farming as a core economic activity. Due to this farming activity, people have opened up more lands through the cutting down of trees and vegetation, leading to higher levels of deforestation. This could explain why these areas received a considerably lower rainfall. This is because deforested areas have low evapotranspiration rate (3.4 mm/day), which in turn reduce rainfall.

The coefficient of variation in all the station areas shows that the annual rainfall in the region is not dependable and is highly variable. The mean annual rainfall is skewed to the right with a peaked distribution as noted by positive skewness and positive kurtosis values hence not normally distributed. The high values of standard deviation also suggest annual rainfall fluctuations and high variability of rainfall in the region. This agrees with Nyatuame et al. (2014) who found out that rainfall with a high standard deviation is considered more unpredictable than rainfall with a low figure. The coefficient of variation in all the station areas is above 0.5, indicating that the annual rainfall in the region is highly variable. This agrees with Gomez (1984), who noted that the higher the CV value of a distribution, the lower the reliability of that distribution.

Table 7: Summary of Descriptive Statistics for the Study Area

Station	Mean annual (mm)	Maximum (mm)	Minimum (mm)	Standard deviation	Skewness	Kurtosis	Coefficient of variation	MJJAS	ONDJFMA
Dowa	852.1	469.9	0.0	103.7	1.02	1.43	1.47	0.56	121.3
Madisi	801.5	442.3	0.0	97.0	1.35	0.74	1.49	0.80	113.9
Mponela	830.3	652.1	0.0	100.7	1.31	0.82	1.46	0.77	118.1
Kasungu	781.1	513.2	0.0	97.3	1.38	1.03	1.51	0.53	111.2
Mwimba	850.2	441.6	0.0	100.3	1.33	0.52	1.42	5.52	117.5
Mchinji	1071.9	552.9	0.0	116.5	1.10	0.30	1.32	1.94	151.7
Mkanda	924.5	440.3	0.0	104.4	1.16	0.18	1.36	0.73	131.6
Tembwe	962.2	521.2	0.0	106.6	1.25	0.61	1.35	2.8	135.5
Ntchisi	1093.0	878.5	0.0	130.0	1.40	1.20	1.43	2.6	154.3

Table 8: Coefficients of Variation for Monthly Rainfall in the Study area

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
						DOWA						
Mean	246.04	192.60	147.81	32.15	1.45	0.65	0.39	0.21	0.11	4.31	43.04	183.35
C.V.	0.39	0.41	0.55	0.75	2.69	6.11	3.81	4.28	4.07	1.85	0.93	0.49
						MADISI						
Mean	231.37	201.84	119.13	26.18	2.34	0.34	0.53	0.20	0.83	5.79	47.05	165.91
C.V.	0.34	0.40	0.66	1.12	3.30	3.28	3.90	3.03	3.34	2.04	0.81	0.45
						MPONELA						
Mean	237.24	206.97	134.34	22.11	2.68	0.29	0.00	0.17	0.70	7.65	53.16	164.96
C.V.	0.42	0.33	0.59	1.13	3.43	3.26	6.40	3.36	3.25	1.38	1.11	0.47
						MCHINJI						
Mean	280.41	214.23	166.89	61.85	5.78	0.26	0.17	0.65	2.86	17.00	83.43	238.38
C.V.	0.31	0.39	0.60	0.70	3.25	4.24	4.08	3.79	2.56	1.03	0.77	0.41
						MKANDA						
Mean	234.17	198.58	165.95	39.60	2.53	0.15	0.27	0.19	0.48	9.50	71.88	201.21
C.V.	0.39	0.42	0.54	0.80	2.18	3.89	2.67	2.78	3.04	1.44	0.74	0.33
						TEMBWE						
Mean	248.83	202.72	152.38	46.97	6.14	0.59	0.37	1.73	5.01	15.13	72.03	210.27
C.V.	0.39	0.43	0.62	0.75	2.13	3.02	4.78	4.73	3.38	1.24	0.70	0.38
						KASUNGU						
Mean	206.03	195.60	131.08	22.65	2.12	0.02	0.12	0.13	0.25	4.70	42.72	175.66
C.V.	0.50	0.40	0.68	0.93	3.79	6.40	3.34	4.33	3.34	2.47	1.06	0.52
						MWIMBA						
Mean	193.10	228.19	185.18	129.79	22.51	2.18	0.15	0.32	2.42	1.30	12.63	72.41
C.V.	0.45	0.38	0.41	0.69	1.16	2.86	4.98	3.76	6.26	2.61	1.82	0.85
						NTCHISI						
Mean	281.76	240.47	202.49	58.67	7.60	1.35	2.40	0.72	1.03	6.58	52.25	237.70
C.V.	0.52	0.53	0.78	0.77	1.96	2.80	2.21	3.59	4.21	2.11	1.15	0.69

4.2 Monthly rainfall dependability and variability in the ADD

Table 5 shows the coefficients of variation in the ADD which are used to determine the variability or dependability of rainfall. Just as the annual rainfall analysis, the variability or reliability or dependability of monthly rainfall in the ADD was established based on the coefficient of variation (C.V.). The coefficient of variation (C.V.) is defined as the standard deviation divided by the mean annual rainfall. In rainfall variability studies, C.V. used to categorize rainfall events as high, moderate, and low. Areas with C.V. greater than 0.3 indicate high variation, and C.V. less than 0.2 indicate low deviation (Hare, 1983).

Table 5 revealed that lower values are generally exhibited from December to March. This is the rainy season in the country. However, even though the C.V. values show similar patterns and approximately smaller amounts within the year, they are higher than the threshold set by Hare (1983). This study tried to shift the C.V. base set by Hare (1983) from 0.3 to 0.5. It was still apparent that the coefficient of variation for October to April (rainy season) was on average, not dependable (C.V. = 0.77).

However, highly reliable rainfall is from December to February. The coefficient of variation was also above 0.5 for the period from May to September in all ADD. The high ratio of variability indicates that the monthly rainfall in the ADD is not reliable and highly variable both in time and in space. It is also evident from the table that rainfall that is dependable is from December to February. This calls for massive water management strategies such as rain water harvesting, drip irrigation systems, mulching and growing crops which require less amount of seasonal water requirement which save water in the ADD.

4.3 Temporal and Spatial Annual rainfall distribution in Kasungu ADD

The graphical representations of temporal and spatial annual rainfall for all the nine rain-gauge stations in Kasungu ADD are given in Fig. 12 to Fig.20.

Fig.12 shows the spatial distribution of mean annual rainfall in the ADD. It was noted that the eastern parts of Ntchisi and the western parts of Mchinji Boma received higher amounts of rainfall. The central part of the ADD which has a lot of lowlands showed a higher variation in the rainfall patterns of the ADD. The central part is the one with a lot of farms and agricultural activities as the source of economic living to the people, land cover and land use patterns could have a factor in the amount of rainfall received in that area.

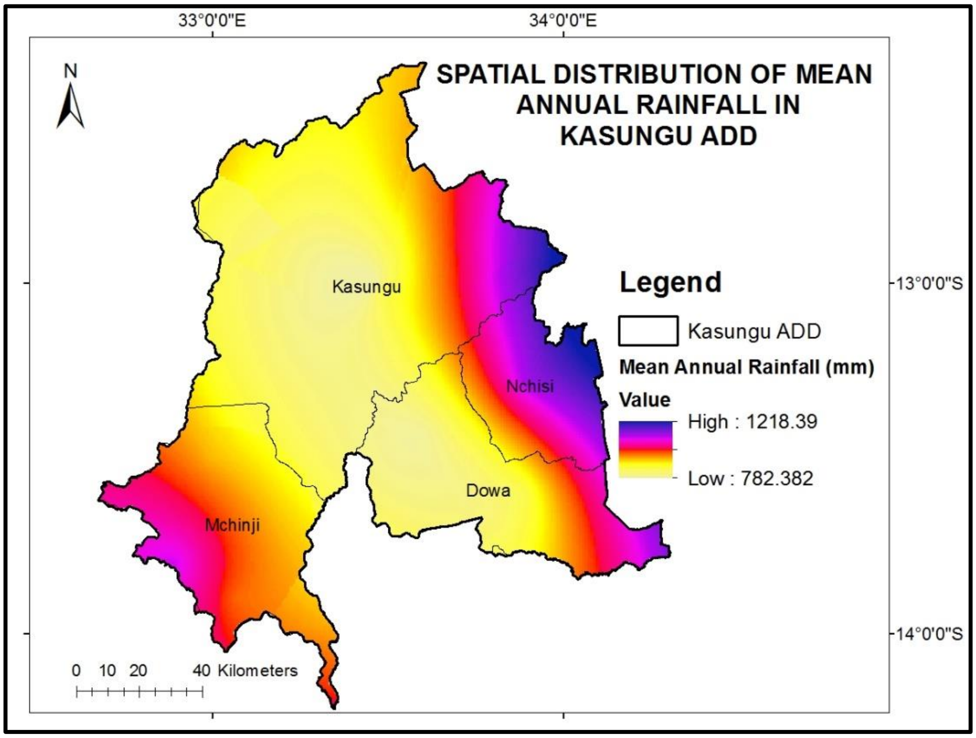


Figure 12: Spatial Distribution of Mean Annual Rainfall in Kasungu ADD

Fig 13 to Fig 20 shows the time series distribution of mean and annual rainfall in the ADD. The null hypothesis was that there was no significant difference in the mean annual rainfall among the climatic zones in Dowa district over the period from 1977 to 2017. Alternately the hypothesis was that there was a significant difference in the mean yearly rainfall among the climatic zones in Dowa district over the period from 1977 to 2017.

Analysis of Variance (ANOVA) was carried out to determine whether there was a significant difference in the mean annual rainfall among the areas in Dowa district. The results showed that there was a significant difference between the areas (P=0.000). The null hypothesis was, therefore rejected. As ANOVA revealed that there was a significant difference, two tail t-tests were carried out to establish which of the areas differed in terms of mean annual rainfall. If t Stat < -t Critical two-tail or t Stat > t Critical two-tail, the null hypothesis is rejected. This was not the case in all the areas (Dowa, Madisi, Mponela), -1.99 < -0.71 < 1.99, -1.99 < 1.18 < 1.99, -1.99 < 0.51< 1.99 respectively. Therefore, the null hypothesis was kept. This means that the observed difference between the sample means was not convincing enough to say that the average rainfall in the district differed significantly.

Correlation analysis was also done to establish if the rainfall in the district is correlated. This analysis uses a coefficient of correlation (R). The threshold value is 0.5. If it above 0.5, it indicates a strong correlation, and if below 0.5, it shows a weak correlation. The results showed that there was a strong correlation between rainfall data in Dowa and Mponela (R=0.73) just as between the rainfall data in Mponela and Madisi (R=0.596). However, there was a weak correlation between the rainfall data in Dowa and Madisi (R=0.39). The reason could be due to the geographical position and elevation of the areas. Dowa has mountains and is closer to Mponela whereas Madisi is far away from Dowa and has gentle slopes.

Fig. 15 shows the annual rainfall distribution in Kasungu district. The maximum annual rainfall happened at 1989 with amount of 1330.4 mm over Kasungu, and the maximum annual rainfall which fell down in Mwimba equals to 1184.5 mm at 1996. The minimum annual rainfall in Kasungu and Mwimba was 456 mm and 472.6 mm respectively. Fig.16 displays the mean annual rainfall in Kasungu and Mwimba. The maximum mean rainfall in Kasungu was 110.9 mm in 1989 and in Mwimba was 98.8 mm in 1996. The mean difference in annual rainfall observed over the period of 40 years was not statistically significant (P=0.102, Fcrit (3.96) > F (2.738)). The rainfall in the two areas (Kasungu and Mwimba) was correlated (R=0.62).

Fig.17 shows the annual rainfall distribution in Ntchisi district. The maximum annual rainfall was 2220.4 mm in 1989, and the minimum was 398.9 mm in 2005. It is clear that there was considerable variation in the annual rainfall in the district. Fig.18 depicts the mean rainfall in the district. The maximum mean rainfall was 185 mm in 1989, and the minimum mean rainfall was 33.2 mm in 2005. It is apparent that there was a significant variation in the mean rainfall in the region.

Fig. 19 and Fig 20. show the annual and mean rainfall distribution in Mchinji district, respectively. Fig. 19 shows that the highest annual rainfall was 1698 mm and was experienced in 1979 at Tembwe station. Mchinji Boma experienced the highest annual rainfall of 1483.6 mm in

2002 and Mkanda registered 1253 mm as the highest annual rainfall in 2003. However, the mean rainfall was higher in Mchinji Boma than Mkanda and Tembwe. The maximum mean rainfall at Mchinji Boma was 160.8 mm in 2017 whereas at Mkanda was 104.4 mm in 2002 and at Tembwe was 141.5 mm in 1978.

In Mchinji district, there was a significant difference in the mean annual rainfall (p=0.034; Fcrit (3.08) < F (3.49)). The null hypothesis is, therefore rejected. However, two tail t-tests were carried out to ascertain which of the areas differed. The null hypothesis is rejected if t stat < -t Critical two-tail or t stat > t critical two-tail. This was not the case in all the areas (Mchinji, Mkanda, Tembwe), -1.991< 1.809 < 1.991, -1.994 < -0.728 < 1.994 respectively. Therefore, the null hypothesis was kept. This means that the observed difference between the sample means was not conclusive enough to say that the average rainfall in the district differed significantly.

The mean annual rainfall of Mchinji and Tembwe was correlated (R=0.683). However, there was a weak correlation between rainfall of Mchinji and Mkanda (R=-0.170) and between Mkanda and Tembwe (R=-0.226). These results could be due attributed to the geographical position and elevation of the areas. Mchinji has hills and mountains and is closer to Tembwe whereas Mkanda is far away from Tembwe and has a gentle gradient.

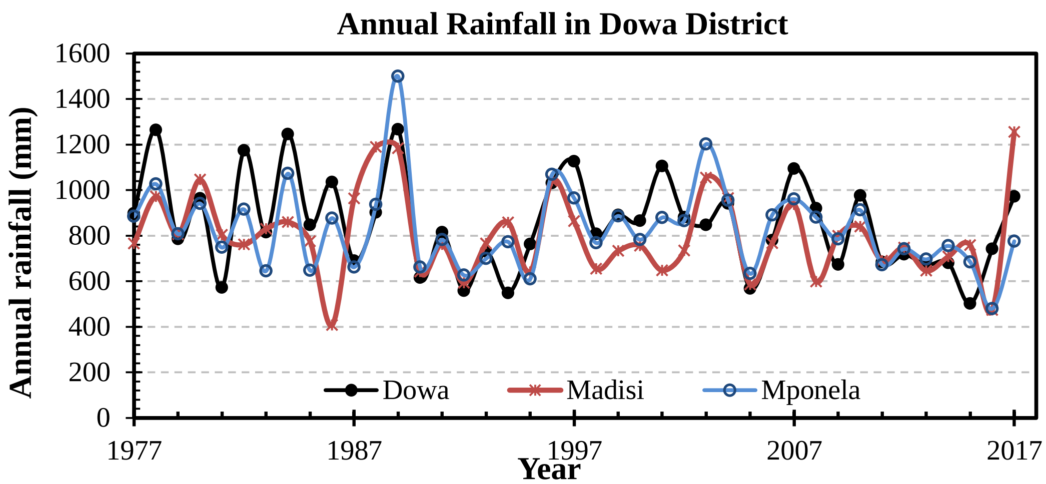


Figure 13: Annual rainfall in Dowa district

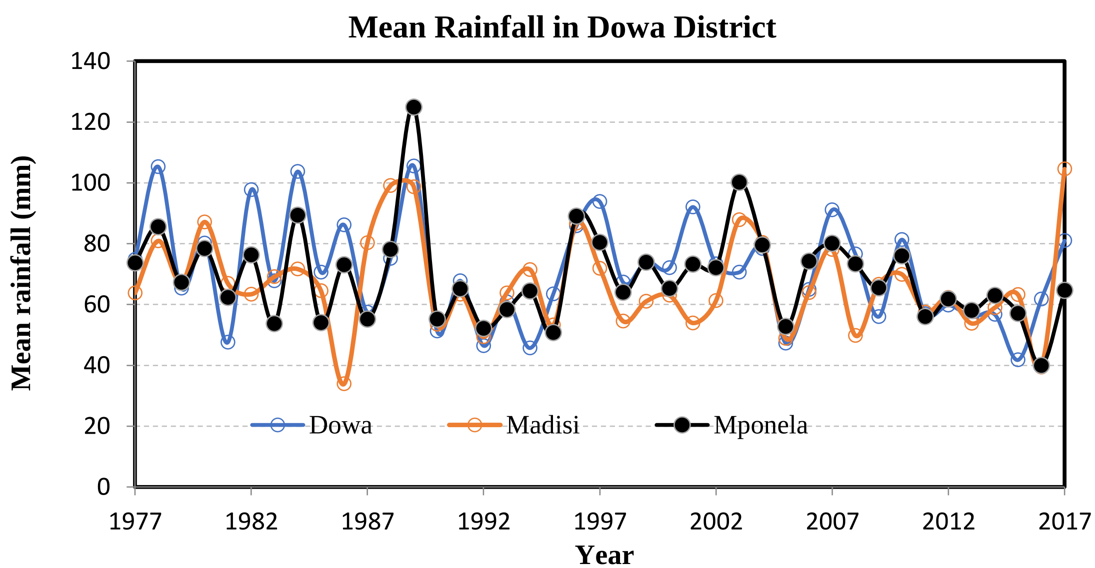


Figure 14: Mean rainfall in Dowa district

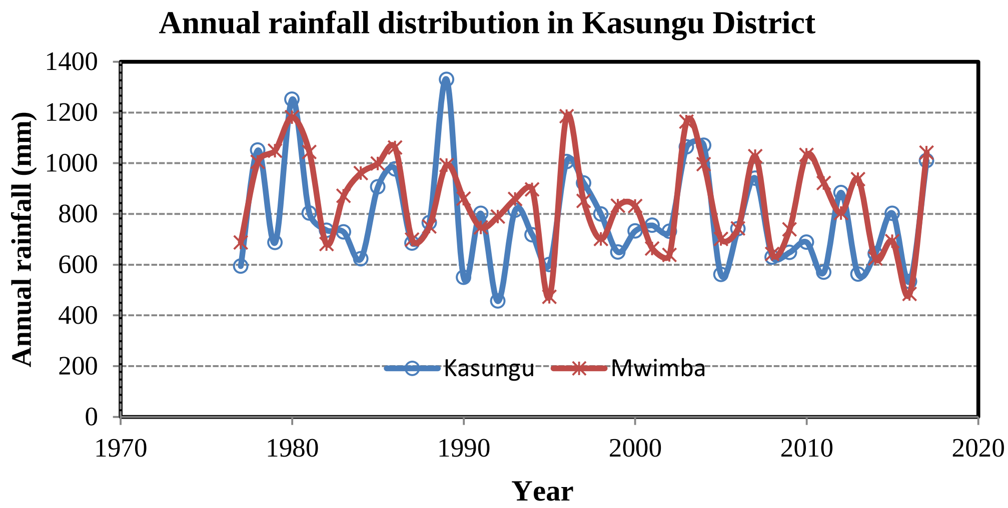


Figure 15: Annual rainfall distribution in Kasungu district

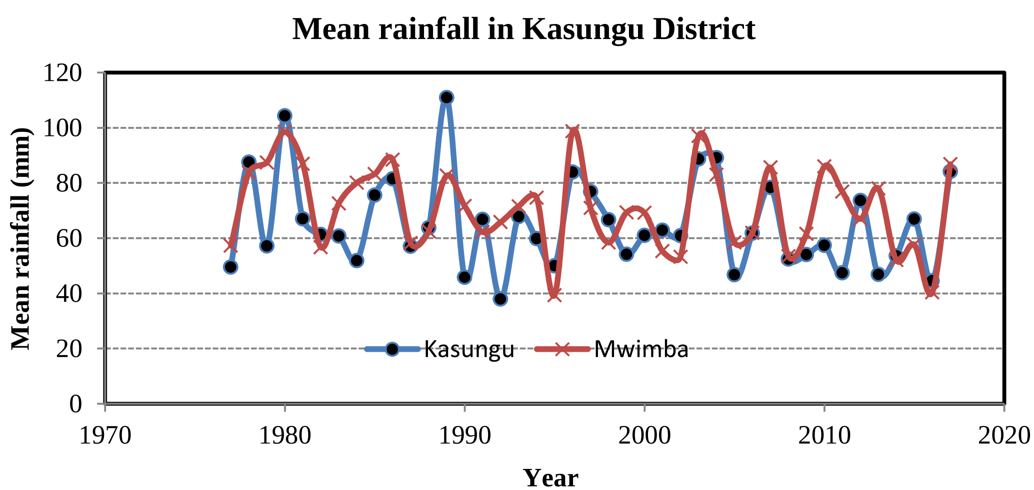


Figure 16: Mean rainfall in Kasungu district

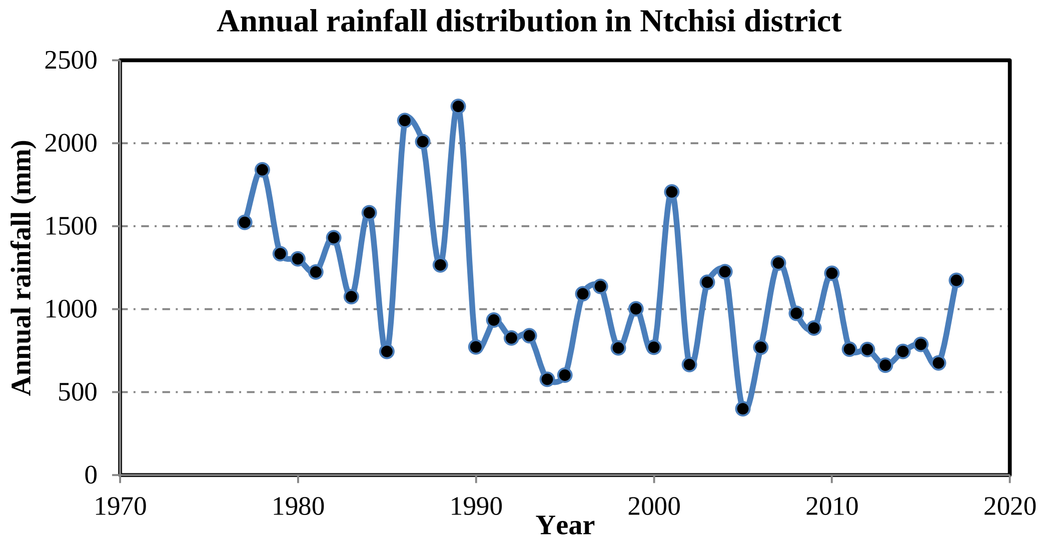


Figure 17: Annual rainfall distribution in Ntchisi district

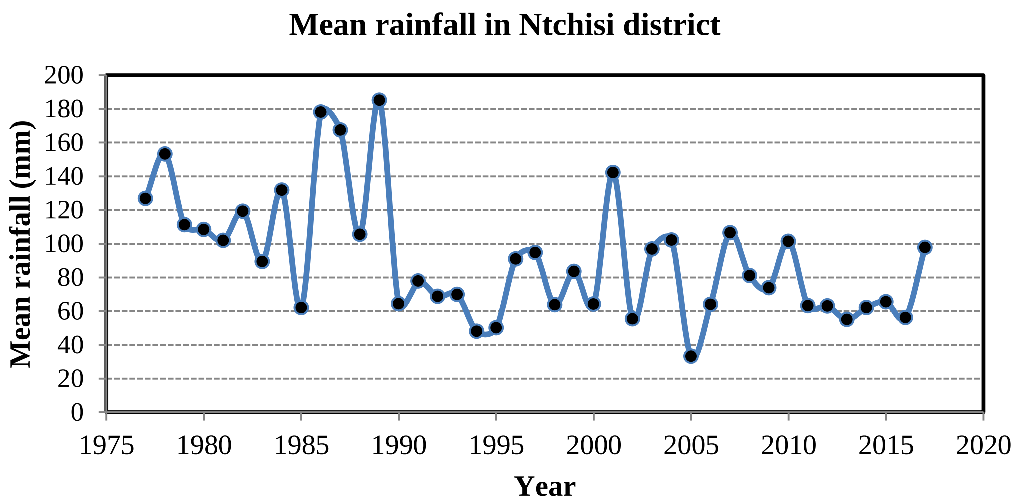


Figure 18: Mean rainfall in Ntchisi district

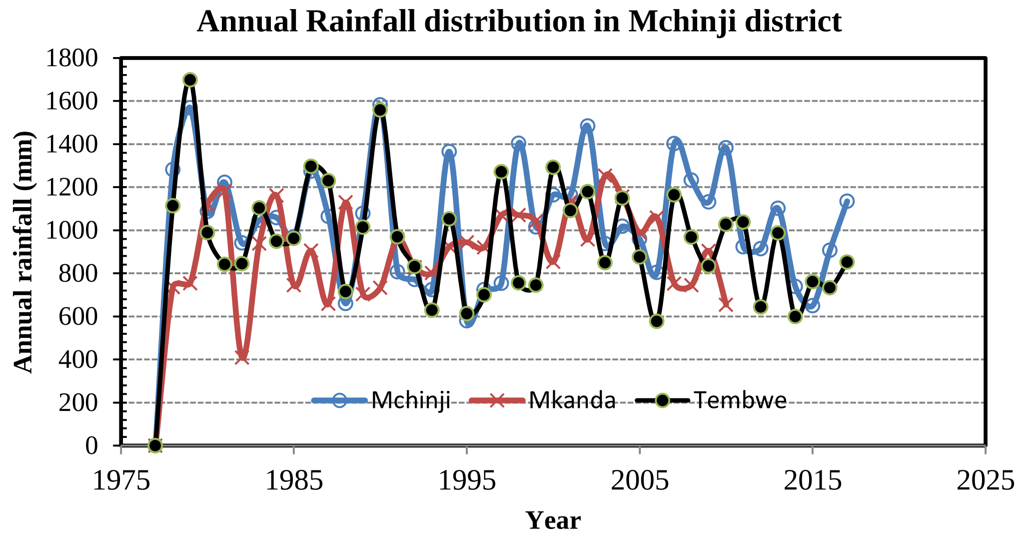


Figure 19: Annual rainfall distribution in Mchinji district

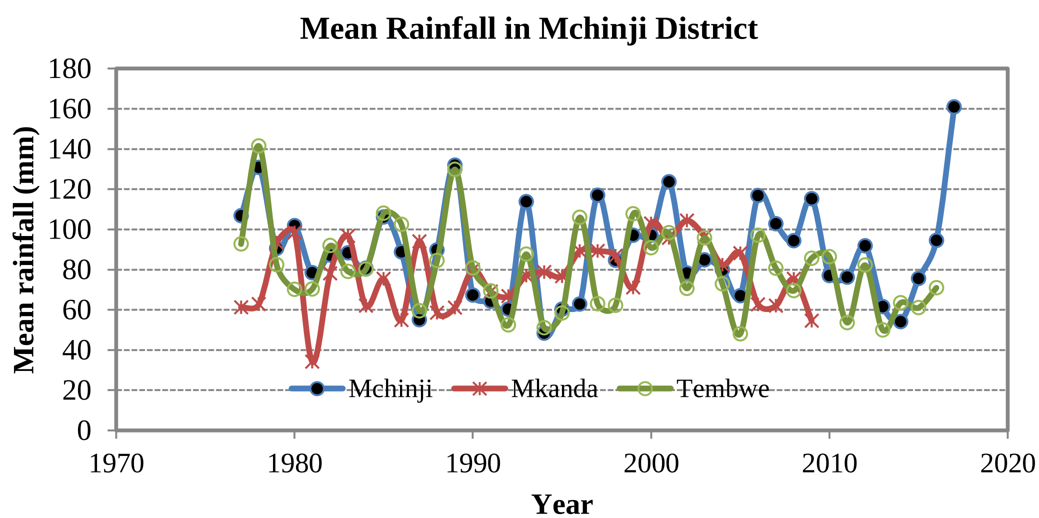


Figure 20: Mean rainfall in Mchinji district

4.4 Rainfall Trend Analysis using Regression

The results of the trend analysis using linear regression are displayed in Table 3 to Table 11, covering all the stations in the ADD. In the interpretation of these trends, rainfall trends from January to December for approximately 40 years in all the districts have been calculated independently for each month.

Table 9: Regression statistic results for annual and monthly rainfall for Dowa

Month	Equation	R-squared	P-value	Statistically Significant
Jan	$y = -1.2732x + 272.78$	$R^2 = 0.0241$	0.33	No
Feb	$y = 0.4586x + 182.97$	$R^2 = 0.0047$	0.67	No
Mar	$y = -2.4755x + 199.8$	$R^2 = 0.1314$	0.02*	Yes
Apr	$y = -0.1711x + 35.74$	$R^2 = 0.0071$	0.60	No
May	$y = -0.0708x + 2.9332$	$R^2 = 0.0462$	0.18	No
Jun	$y = -1.2732x + 272.78$	$R^2 = 0.0241$	0.89	No
Jul	$y = -0.0279x + 0.9704$	$R^2 = 0.0505$	0.16	No
Aug	$y = -0.0203x + 0.6405$	$R^2 = 0.0682$	0.10	No
Sept	$y = -1.2732x + 272.78$	$R^2 = 0.0241$	0.14	No
Oct	$y = -0.0091x + 4.5056$	$R^2 = 0.0002$	0.93	No
Nov	$y = -0.491x + 53.347$	$R^2 = 0.0211$	0.36	No
Dec	$y = -0.8573x + 201.36$	$R^2 = 0.013$	0.48	No
Annual	$y = -4.9393x + 955.83$	$R^2 = 0.0845$	0.07	No

The trend lines of the monthly rainfall of eleven months (January to December except for March) had a negative slope indicating a downward trend. Only the month of March had a positive slope, in all the months except March. The null hypothesis was that there is no trend in both the monthly and annual rainfall data. This null hypothesis was rejected (monthly *P*-values are higher than the P-value at a significant level, i.e., α =0.05. This signifies that the monthly and annual rainfall trends in Dowa district are not statistically significant. As if that was not enough, R-square statistic also shows a fragile relationship between rainfall and year.

Table 10: Regression statistic results for annual and monthly rainfall for Mponela

Month	Equation	R-squared	P-value	Statistically Significant
Jan	y = 0.8681x + 219.01	$R^2 = 0.0108$	0.52	No
Feb	y = -1.8106x + 244.99	$R^2 = 0.0999$	0.04	Yes
Mar	y = -0.6474x + 147.93	$R^2 = 0.0097$	0.54	No
Apr	y = -0.0511x + 23.188	$R^2 = 0.0006$	0.88	No
May	y = -0.1476x + 5.7832	$R^2 = 0.0368$	0.23	No
June	y = 0.003x + 0.2273	$R^2 = 0.0014$	0.81	No
July	y = 0.0003x - 0.001	$R^2 = 0.0114$	0.51	No
Aug	y = 0.0043x + 0.0751	$R^2 = 0.0086$	0.56	No
Sept	y = -0.0121x + 0.9515	$R^2 = 0.0041$	0.69	No
Oct	y = -0.1806x + 11.446	$R^2 = 0.0418$	0.20	No
Nov	y = -0.855x + 71.116	$R^2 = 0.0302$	0.28	No
Dec	y = -0.4793x + 175.03	$R^2 = 0.0055$	0.65	No
Annual	y = -3.3079x + 899.75	$R^2 = 0.0468$	0.17	No

Similarly, the linear trends of the monthly rainfall of Mponela indicated negative slopes signifying descending trends in February, March, April, May, September, October, November, and December. The rest of the months had positive trends. The annual trend was also negative. Based on probability values (P-values), the null hypothesis was also rejected; hence, both monthly and yearly rainfall trends were not statistically significant. The relationship between the tested variables (year and rainfall) was also fragile as the *R*-squared statistic was very low.

Table 11: Regression statistic results for annual and monthly rainfall for Madisi

Month	Equation	R-squared	P-value	Statistically Significant
Jan	y = 0.2055x + 227.05	$R^2 = 0.001$	0.85	No
Feb	y = -0.3102x + 208.36	$R^2 = 0.0021$	0.78	No
Mar	y = -1.3139x + 146.72	$R^2 = 0.0404$	0.21	No
Apr	y = -0.1684x + 29.715	$R^2 = 0.0047$	0.67	No
May	y = -0.0633x + 3.6741	$R^2 = 0.0096$	0.54	No
Jun	y = 0.0043x + 0.2504	$R^2 = 0.0022$	0.77	No
Jul	y = -0.0206x + 0.9585	$R^2 = 0.0144$	0.46	No
Aug	y = -0.0004x + 0.2101	$R^2 = 5E-05$	0.96	No
Sept	y = -0.0305x + 1.4727	$R^2 = 0.0174$	0.41	No
Oct	y = 0.0556x + 4.6232	$R^2 = 0.0032$	0.73	No
Nov	y = -0.252x + 52.341	$R^2 = 0.0063$	0.62	No
Dec	y = -0.5341x + 177.13	$R^2 = 0.0073$	0.60	No
Annual	y = -2.428x + 852.5	$R^2 = 0.0249$	0.32	No

Madisi linear trends of the monthly rainfall of nine months (February, March, April, May, July, August, September, November, and December) had a negative slope revealing a descending trend. January, June, and October displayed ascending trends. The annual rainfall trend was also descending. All trends for Madisi rainfall data was statistically insignificant as the p-value was greater than the alpha value at the significance level. The relationship between the tested variables was also weak as the R-squared statistic was minimal (less than 0.5).

Table 12: Regression statistic results for annual and monthly rainfall for Kasungu

Month	Equation	R-squared	P-value	Statistically Significant
Jan	$y = 1.4384x + 175.82$	$R^2 = 0.0282$	0.29	No
Feb	$y = 0.7235x + 180.41$	$R^2 = 0.0124$	0.49	No
Mar	$y = -1.7464x + 167.75$	$R^2 = 0.0549$	0.14	No
Apr	$y = -0.1351x + 25.491$	$R^2 = 0.0058$	0.63	No
May	$y = -0.0487x + 3.148$	$R^2 = 0.0052$	0.65	No
Jun	$y = 0.0004x + 0.0107$	$R^2 = 0.0016$	0.80	No
Jul	$y = 0.0019x + 0.0841$	$R^2 = 0.0031$	0.73	No
Aug	$y = 0.0032x + 0.0661$	$R^2 = 0.0045$	0.68	No
Sept	$y = -0.0142x + 0.549$	$R^2 = 0.041$	0.20	No
Oct	$y = -0.1891x + 8.6682$	$R^2 = 0.0382$	0.22	No
Nov	$y = -1.1662x + 67.214$	$R^2 = 0.0959$	0.05	No
Dec	$y = -1.8698x + 214.92$	$R^2 = 0.0591$	0.13	No
Annual	$y = -3.002x + 844.14$	$R^2 = 0.0334$	0.25	No

Table 13: Regression statistic results for annual and monthly rainfall for Mwimba

Month	Equation	R-squared	P-value	Statistically Significant
Jan	$y = -0.7447x + 208.74$	$R^2 = 0.0108$	0.52	No
Feb	$y = 0.9948x + 207.29$	$R^2 = 0.0194$	0.39	No
Mar	$y = -3.2024x + 252.43$	$R^2 = 0.2503$	0.00*	Yes
Apr	$y = -2.782x + 188.21$	$R^2 = 0.1391$	0.02*	Yes
May	$y = -0.5779x + 34.643$	$R^2 = 0.0698$	0.10	No
Jun	$y = -0.0817x + 3.898$	$R^2 = 0.0246$	0.33	No
Jul	$y = -0.0007x + 0.163$	$R^2 = 0.0001$	0.95	No
Aug	$y = 0.008x + 0.1488$	$R^2 = 0.0065$	0.62	No
Sept	$y = 0.2238x - 2.281$	$R^2 = 0.0314$	0.27	No
Oct	$y = 0.0579x + 0.0843$	$R^2 = 0.0417$	0.20	No
Nov	$y = 0.2661x + 7.042$	$R^2 = 0.0192$	0.39	No
Dec	$y = 2.038x + 29.609$	$R^2 = 0.1571$	0.01*	Yes
Annual	$y = -3.8007x + 929.98$	$R^2 = 0.0634$	0.11	No

Except for January, February, June, July, and August which had trends upward as their slopes were positive, the slopes for the rest of the months were negative. The trends were statistically insignificant (p values greater than 0.05) and the relationship between the variables (rainfall and year) was also weak (R-squared statistic less than 0.5).

Mwimba monthly rainfall trend lines of six months (January, March, April, May, June, and July) had a negative slope revealing a descending trend. The rest of the months showed positive gradients indicating ascending trends. The annual rainfall trend was also descending. Most trends for Mwimba rainfall data except for March, April, and December were statistically insignificant as the P-value was higher than the alpha value at significance level. The relationship between the tested variables was also weak as the R-squared statistic was very small (less than 0.5).

Table 14: Regression statistic results for annual and monthly rainfall for Mchinji

Month	Equation	R-squared	P-value	Statistically Significant
Jan	$y = 1.2039x + 255.13$	$R^2 = 0.0272$	0.30	No
Feb	$y = -1.0386x + 236.04$	$R^2 = 0.0218$	0.36	No
Mar	$y = 0.1003x + 164.78$	$R^2 = 0.0001$	0.94	No
Apr	$y = -0.3395x + 68.975$	$R^2 = 0.0088$	0.56	No
May	$y = -0.2494x + 11.016$	$R^2 = 0.0253$	0.32	No
Jun	$y = -0.0191x + 0.6612$	$R^2 = 0.0426$	0.20	No
Jul	$y = -0.0034x + 0.2368$	$R^2 = 0.0036$	0.71	No
Aug	$y = -0.031x + 1.2965$	$R^2 = 0.0229$	0.34	No
Sept	$y = -0.1574x + 6.1665$	$R^2 = 0.0663$	0.10	No
Oct	$y = -0.5176x + 27.864$	$R^2 = 0.1246$	0.02*	Yes
Nov	$y = 0.3403x + 76.28$	$R^2 = 0.0041$	0.69	No
Dec	$y = 0.3942x + 230.1$	$R^2 = 0.0023$	0.77	No
Annual	$y = -0.3172x + 1078.5$	$R^2 = 0.0002$	0.94	No

Except for October, all other monthly trends in Mchinji were statistically insignificant as the p-value was greater than the alpha value at the significance level. The relationship between the tested variables was also weak as the R-squared statistic was minimal (less than 0.5). Eight of the twelve linear trends of the monthly rainfall of six months (February, April, May, June, July, August, September, and October) had a negative slope showing a descending trend. The rest of the months showed positive gradients indicating ascending trends. The annual rainfall trend was also descending.

Table 15: Regression statistic results for annual and monthly rainfall for Mkanda

Month	Equation	R-squared	P-value	Statistically Significant
Jan	y = 1.9386x + 201.21	$R^2 = 0.0412$	0.26	No
Feb	y = 2.5441x + 155.33	$R^2 = 0.0888$	0.09	No
Mar	y = 1.0786x + 146.79	$R^2 = 0.0133$	0.49	No
Apr	y = 0.6164x + 27.887	$R^2 = 0.0368$	0.21	No
May	y = -0.2308x + 6.4566	$R^2 = 0.1631$	0.02*	Yes
Jun	y = -0.0118x + 0.3557	$R^2 = 0.0362$	0.29	No
Jul	y = -0.0192x + 0.5964	$R^2 = 0.0666$	0.15	No
Aug	y = -0.0064x + 0.3	$R^2 = 0.0137$	0.52	No
Sept	y = -0.0296x + 0.9877	$R^2 = 0.0376$	0.28	No
Oct	y = -0.5654x + 19.112	$R^2 = 0.16$	0.02*	Yes
Nov	y = -0.7306x + 84.303	$R^2 = 0.0177$	0.46	No
Dec	y = -0.9583x + 217.5	$R^2 = 0.019$	0.44	No
Annual	y = 2.9453x + 864.53	$R^2 = 0.0222$	0.31	No

In Mkanda, the trend lines of May and October were statistically significant ($p < 0.05$). The monthly trends of the rest of the months were not significant ($P > 0.05$). However, the slopes of successive months from May to December indicated a negative trend, whereas the rest of the months displayed a positive slope. The annual rainfall trend was also positive. There was a weak relationship between the tested variables as the R-squared statistic was very small (less than 0.5).

Table 16: Regression statistic results for annual and monthly rainfall for Tembwe

Month	Equation	R-squared	P-value	Statistically Significant
Jan	y = -0.2662x + 254.28	$R^2 = 0.001$	0.84	No
Feb	y = -1.7697x + 238.99	$R^2 = 0.0558$	0.14	No
Mar	y = -1.8884x + 191.09	$R^2 = 0.0543$	0.15	No
Apr	y = -0.7421x + 62.183	$R^2 = 0.061$	0.12	No
May	y = -0.2047x + 10.339	$R^2 = 0.0334$	0.26	No
Jun	y = -0.0049x + 0.6908	$R^2 = 0.001$	0.84	No
Jul	y = 0.0159x + 0.0385	$R^2 = 0.0114$	0.51	No
Aug	y = 0.1242x - 0.8158	$R^2 = 0.0315$	0.27	No
Sept	y = -0.3282x + 11.74	$R^2 = 0.0512$	0.16	No
Oct	y = -0.1598x + 18.406	$R^2 = 0.0099$	0.54	No
Nov	y = -1.1394x + 95.388	$R^2 = 0.0694$	0.10	No
Dec	y = -1.261x + 236.12	$R^2 = 0.0341$	0.25	No
Annual	y = -7.6244x + 1118.5	$R^2 = 0.1233$	0.03	Yes

Except for the significant annual rainfall ($p < 0.05$), all other monthly trends at Tembwe were statistically insignificant as the p-value was greater than the alpha value at the significance level. The relationship between the year and rainfall was also weak as the R-squared statistic was very small (less than 0.5). Two of the twelve linear trends of the monthly rainfall (July and August) had a positive slope showing an ascending trend. The rest of the months showed negative slopes indicating descending trends. The annual rainfall trend was also dropping.

Table 17: Regression statistic results for annual and monthly rainfall for Ntchisi

Month	Equation	R-squared	P-value	Statistically Significant
Jan	$y = -1.2868x + 308.79$	$R^2 = 0.011$	0.514	No
Feb	$y = -3.4121x + 312.13$	$R^2 = 0.1032$	0.041*	Yes
Mar	$y = -4.3926x + 294.73$	$R^2 = 0.1122$	0.032*	Yes
Apr	$y = -0.9845x + 79.345$	$R^2 = 0.068$	0.100	No
May	$y = -0.2889x + 13.663$	$R^2 = 0.0543$	0.143	No
Jun	$y = -0.0256x + 1.8834$	$R^2 = 0.0066$	0.614	No
Jul	$y = -0.0446x + 3.3349$	$R^2 = 0.0102$	0.531	No
Aug	$y = 0.031x + 0.0679$	$R^2 = 0.0207$	0.369	No
Sept	$y = -0.057x + 2.2235$	$R^2 = 0.025$	0.324	No
Oct	$y = 0.0209x + 6.1407$	$R^2 = 0.0003$	0.911	No
Nov	$y = -1.5282x + 84.346$	$R^2 = 0.0922$	0.054	No
Dec	$y = -6.4683x + 373.53$	$R^2 = 0.225$	0.002*	Yes
Annual	$y = -18.436x + 1480.2$	$R^2 = 0.2555$	0.001*	Yes

4.4 Rainfall Trend Analysis using Mann-Kendall Test

Mann Kendall test is a statistical test widely used for the analysis of the trend in climatologic data. Annual and seasonal trends of precipitation and their magnitude (in mm/year) obtained by the Mann–Kendall test, the Sen's slope estimator and the linear regression are given in Table 15 and Table 16 respectively. The annual trends found by the linear regression analyses were almost similar to the precipitation trends observed by the Mann–Kendall test and the Sen's slope estimator. Both positive and negative trends were identified by the statistical tests in annual precipitation data. However, most of the trends were non-significant at 95% confidence levels.

Table 18: Values (Slope b of the Linear Regression Analysis, Statistics (Z of the Mann – Kendall Test and Q of the Sen's Slope Estimator) for Annual Precipitation (1977 – 2017)

Station	Z	Q	b (mm/year)
Dowa Boma	-1.70+	-4.567	911.25
Madisi	-1.54	-2.853	814.01
Mponela	-1.20	-2.559	866.78
Kasungu	-1.00	-2.578	793.96
Mwimba	-1.74+	-3.703	915.77
Mchinji Boma	-0.64	-2.611	1085.7
Mkanda	0.91	4.412	868.9
Tembwe	-1.85+	-6.758	1057.3
Ntchisi	-3.22**	-17.057	1376

** If trend at *α=0.01* level of significance; * if trends at *α=0.05* level of significance; + if trend at *α=0.1* level of significance

Table 19: Values (Slope b of the Linear Regression Analysis, Statistics (Z of the Mann – Kendall Test and Q of the Sen's Slope estimator) for winter and Summer

	Winter (NDJFMA)			**Summer (MJJASO)**		
Station	Z	Q	b (mm/year)	Z	Q	b (mm/year)
Dowa Boma	-2.88**	-0.002	0.078	-1.63	-0.621	129.27
Madisi	-0.69	0.000	0.000	-1.49	-0.448	117.66
Mponela	-0.82	0.000	0.000	-1.12	-0.362	123.71
Kasungu	-0.51	0.000	0.120	-1.00	-0.363	113.27
Mwimba	-1.99*	-0.072	5.588	-1.40	-0.564	128.4
Mchinji Boma	-2.53*	0.000	0.000	-0.51	-0.311	152.58
Mkanda	-2.93**	-0.008	0.229	1.10	0.657	123.41
Tembwe	-1.56	-0.024	1.502	-1.83+	-0.881	145.82
Ntchisi	-2.49*	-0.047	1.995	-3.07	-2.337	194

** If trend at *α=0.01* level of significance; * if trends at *α=0.05* level of significance; + if trend at *α=0.1* level of significance

Fig.24 shows that the rainfall patterns of most parts in the ADD are decreasing. However, only some parts of Mchinji, Dowa and Ntchisi show increasing trends. Fig.23 however shows the level of significance at 95 % of those rainfall patterns. It was observed that the western parts of Dowa district and Kasungu district show significant decreasing trends. The eastern parts of Mchinji district and eastern parts of Dowa district and Kasungu district show decreasing trends but they are not significant. The western parts of Mchinji district show increasing trends but not statistically significant. A significant portion of some eastern parts of Ntchisi and Dowa district displayed an increasing yet significant rainfall trends.

The Mann-Kendall test (MK) presents a thought-provoking comprehension about the annual and seasonal rainfall trends in the ADD. The MK test statistic indicates that there is an increasing rainfall trend for western parts of Mchinji and Ntchisi. The statistic, however, is not very strong for these areas implying that the trend is not significant.

The study also observed that there was a small difference between the parametric (the linear regression) and nonparametric (the Mann-Kendall test and the Sen's Slope estimator) methods on the annual and seasonal rainfall series in Kasungu ADD. The knowledge and utilization of temporal and spatial pattern of rainfall trends analyzed in this study is a simple yet essential requirement for agricultural planning and management of water resources.

Fig. 21 and Fig 22 exhibit the mean annual spatial distribution and annual rainfall variability in Kasungu ADD. Both figures highlight that the rainfall patterns in the ADD vary a lot, especially the central area where most people cultivate. There is a strong need to promote rainwater harvesting technologies, best irrigation practices (those which are water-saving and efficient) for example drip irrigation and mini-sprinklers, and best agronomic practices such as mulching, growing short duration crops and winter cropping to utilize residual moisture.

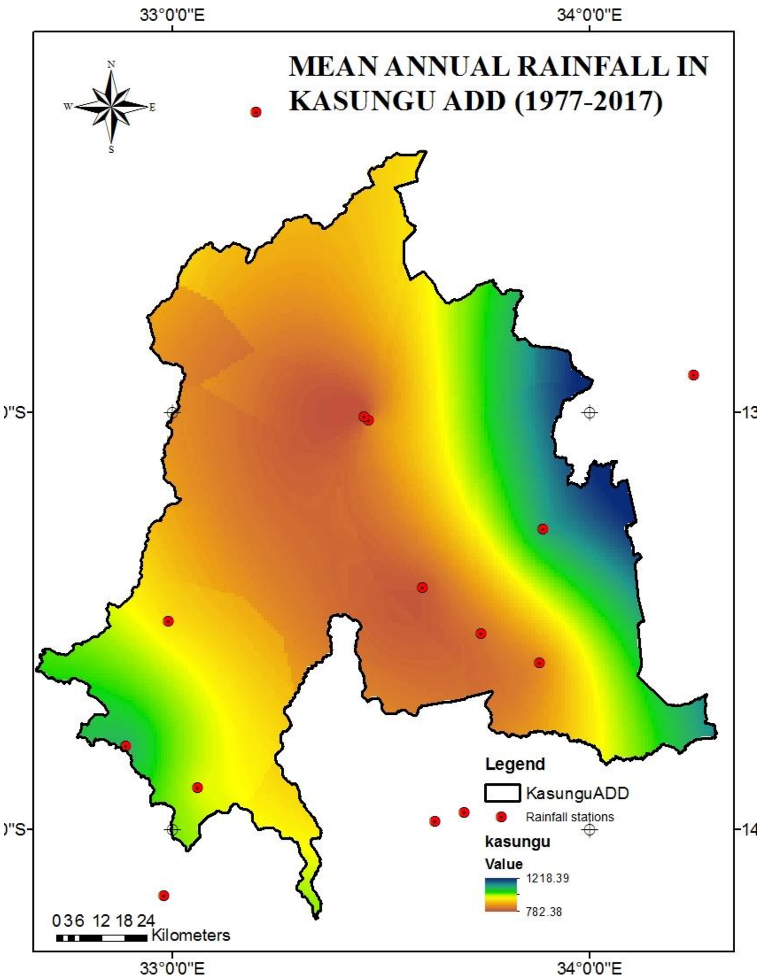


Figure 21: Mean annual rainfall in Kasungu ADD (1977- 2017)

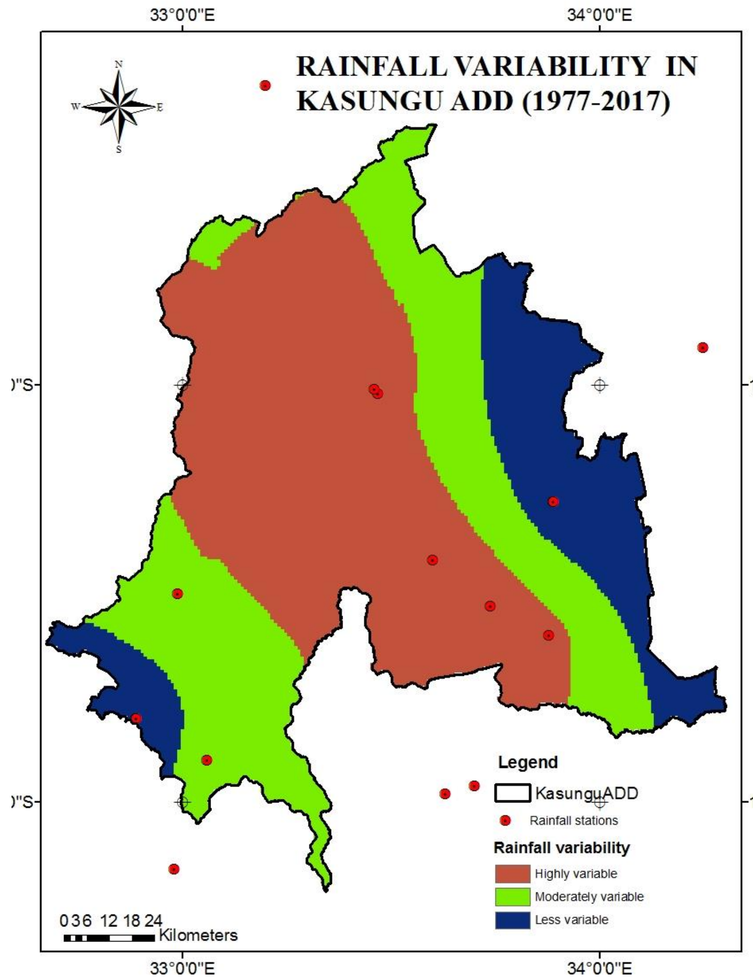


Figure 22: Rainfall variability in Kasungu ADD (1977- 2017)

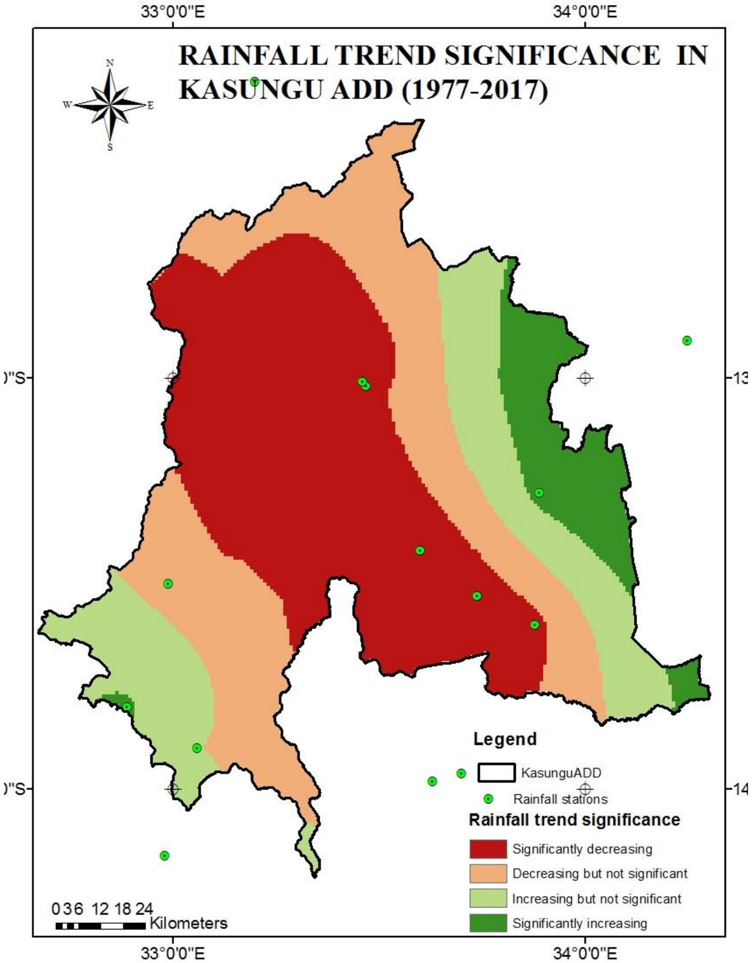


Figure 23: Rainfall trend significance in Kasungu ADD (1977- 2017)

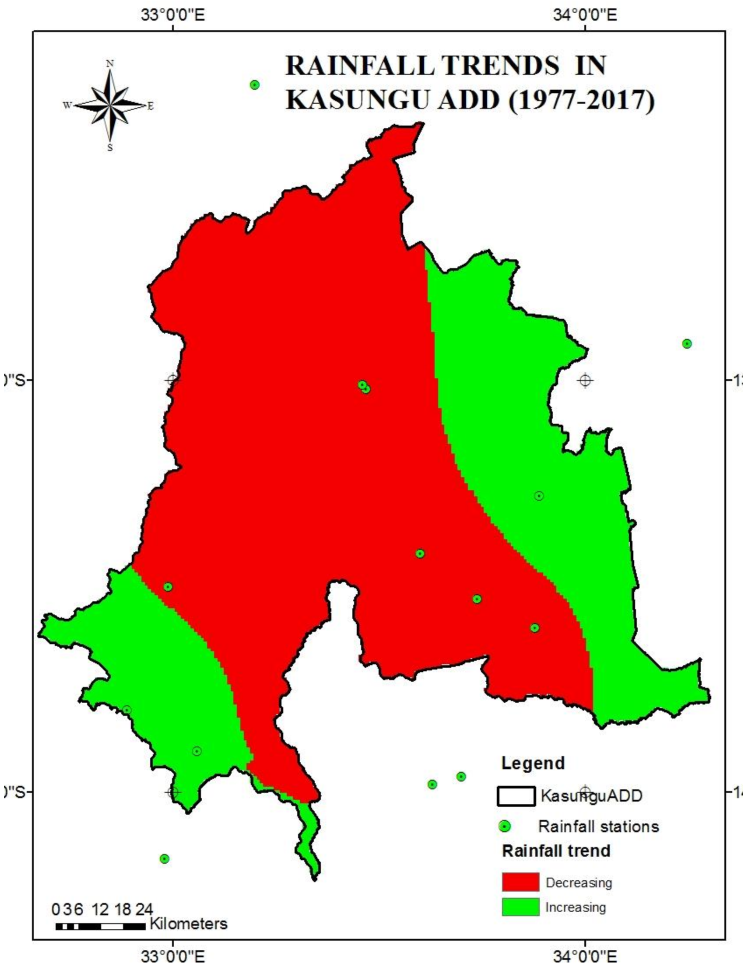


Figure 24: Rainfall trend analysis in Kasungu ADD (1977- 2017)

4.6 Crop yield analysis in Kasungu ADD

In Kasungu ADD, maize is grown to almost 87 percent of all the cultivated land in addition to pulses, root crops, and leafy vegetables. These crops are mainly produced due to the nature of the agroecology of the region. Maize (green and dry) is the most commonly grown crop for food security, and a surplus is sold along with vegetable crops grown on a small scale such as onions and tomatoes. Legumes such as beans, groundnuts, soya, cowpeas, and pigeon peas are grown not only as food crops but also for cash. Root crops and tubers such as cassava and sweet potato are grown for consumption and commercial purposes.

4.6.1 Cropping Patterns and Yields on Smallholder Farms and Estates

Crop production is mainly done on a small, medium, and large scale. Estates in the ADD mostly produce tobacco, whereas the other crops are grown on small farms. Yield production levels typically differ due to levels of management, agronomic practices, skills, technologies being used, and extension services. Fig.25 shows a comparison of crop yields grown under smallholder farming and estates.

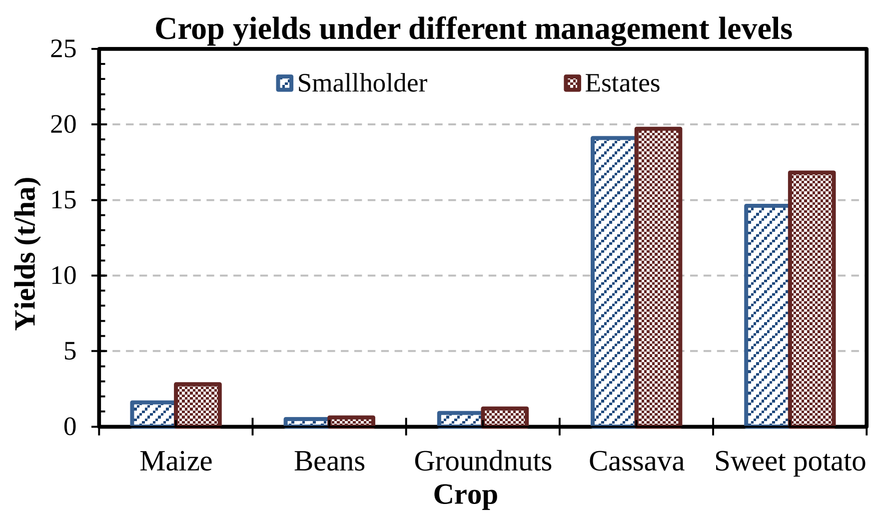


Figure 25: Crop yields under different management levels

Fig. 25 shows that estates produce more yields per hectare in almost all the crops grown than smallholder farmers. This is since there is a higher level of management in estates in terms of production, agronomic practices, and water usage. This shows that for smallholder farmers to improve their crop yields, there is a great need to manage their groupings through the constant provision of agricultural extension services on climate-smart based agriculture.

4.6.2 Spatial Analysis of Average Crop Yields in Kasungu ADD

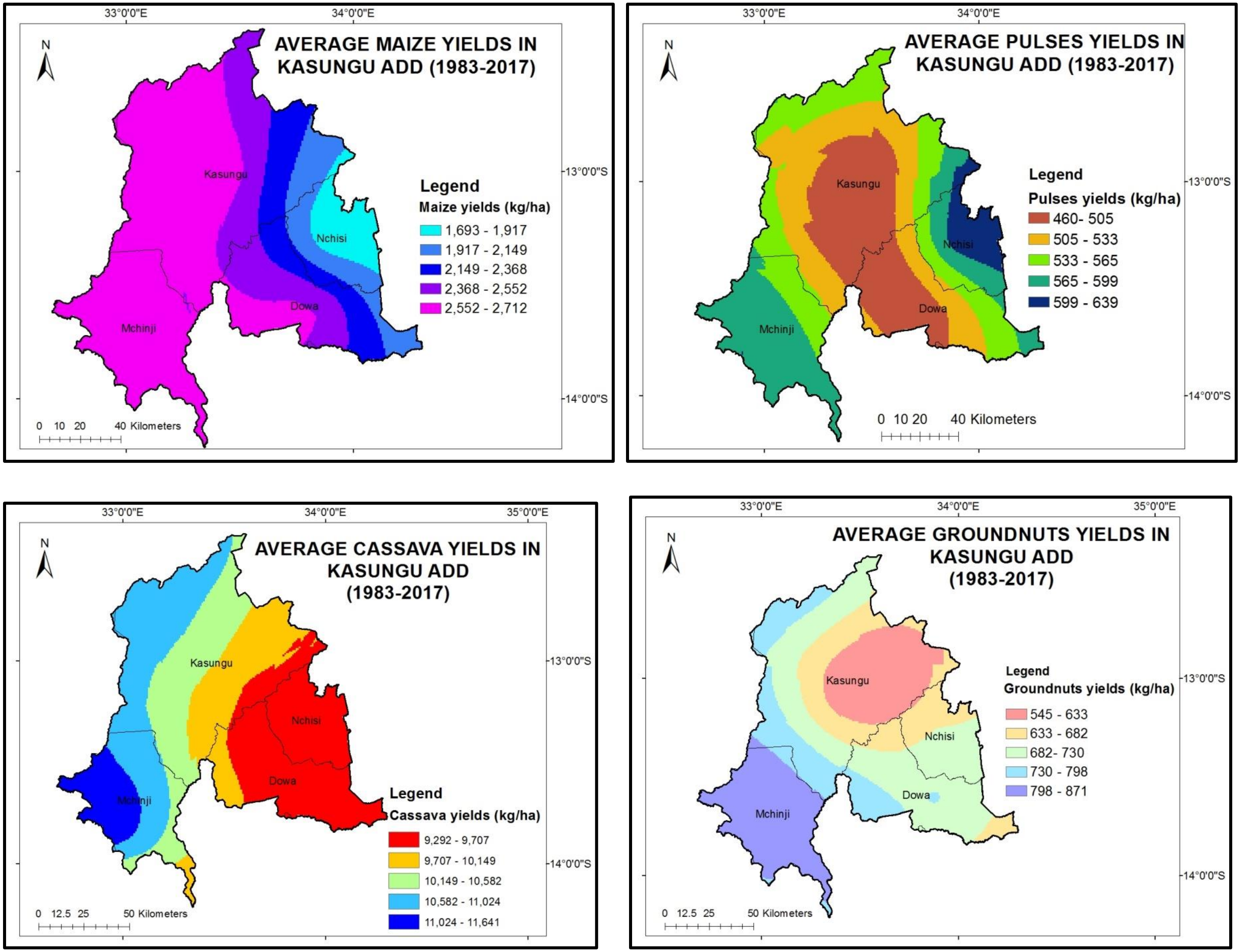
Figs. 26 (a - d) show the spatial distribution of average yields for different crop yields for Kasungu ADD from 1983 to 2017.

Fig. 26a exhibits the average maize yields in Kasungu ADD. Results indicate that the most significant part of Mchinji and Kasungu districts produced higher average yields within the range of 2.5 to 2.7 tons/ha for the studied period while Ntchisi indicated lower yields within the range of 1.6 to 1.9 tons/ha.

Figs 26 (b –d) unveiled similar trends in crop yields. On average, Mchinji recorded higher yields in most crops than Dowa, Ntchisi and Kasungu districts. The rainfall variation in the ADD is highly correlated to crop yields. This agrees with Gray (2004), who observed that in many African countries, there is a high correlation between rainfall variability and Gross Domestic Product (GDP) growth. In the ADD, periods of driest years (1994, 1995, 2005 and 2015) have correlated with a reduction in crop yields.

Kasungu ADDs’ agriculture constitutes about 90 percent of the major activities of most people in the region, basically smallholder farming and predominantly rain-fed maize production. As a result, varying weather patterns, temporally, and spatially affect agricultural production intensely. Furthermore, since the Malawian diet is tremendously dominated by maize, pulses, groundnuts, and cassava consumption, changes in these crop yields production have a direct negative impact on food security.

Figure 26: Average crop yields in Kasungu ADD (a. Maize b. Pulses c. Cassava d. Groundnuts)



4.6.3 Temporal Time Series Analysis of Crop Yields in Kasungu ADD

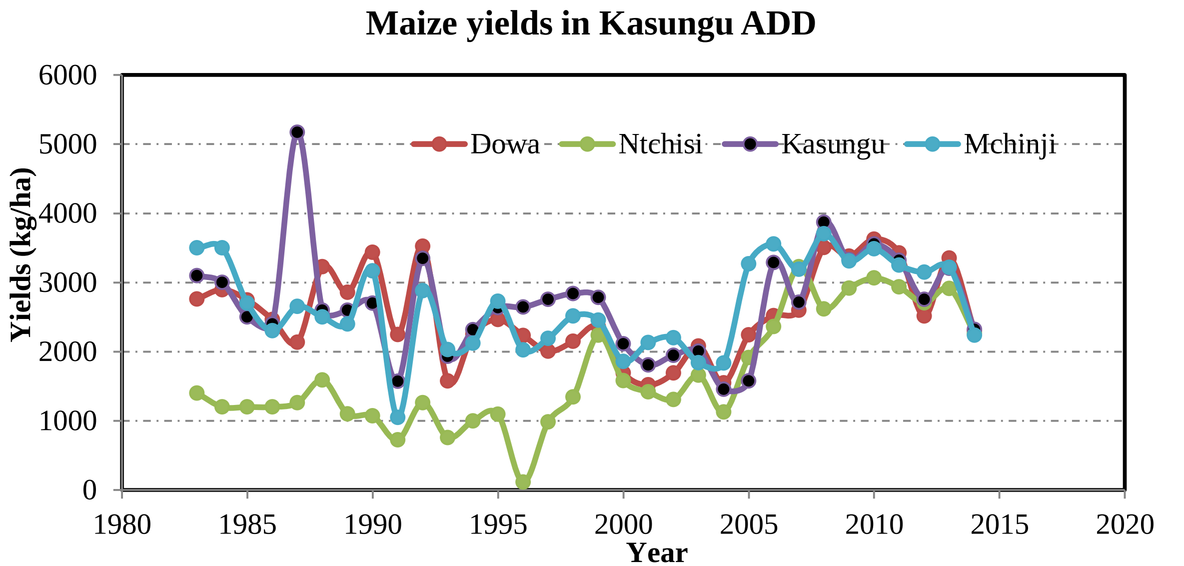
Fig. 27a shows that the highest maize yield was 5171 kg/ha in Kasungu in 1987, and the lowest maize yield was 112 kg/ha in Ntchisi in 1996. The average maize yield in Kasungu ADD was 2390 kg/ha. There was a sharp decrease in maize yields in all the regions in 1986, 1991, 1993, 2004, and 2012. The trend line of maize yields in Kasungu displays a negative slope showing a decrease in the yields. This could be attributed to the variability of rainfall and low production levels in the ADD. It must be recognized that the rainfall patterns of Kasungu were not dependable. In Dowa district, the maximum yield was 3627 kg/ha in 2010, the minimum was 1518 kg/ha, and the average yield was 2542 kg/ha. The average yield of Ntchisi (1673 kg/ha) was below the average maize yield for the ADD. The patterns show that medium to low maize production could be due to factors of crop production such as rainfall variation, agronomic aspects, type of seed variety grown or extension services.

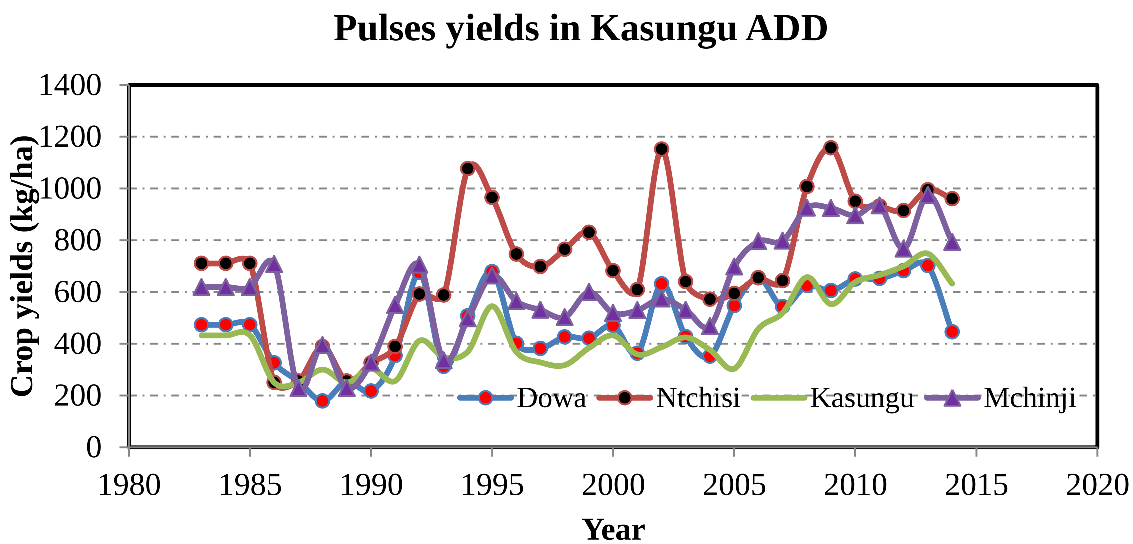
Fig. 27b shows pulses yields in Kasungu ADD. These pulses include beans, peas, and soya. The maximum pulses yield was 1157 kg/ha in Ntchisi in 2009, and the minimum was 178 kg/ha in Dowa in 1988. The average pulses yield was 559 kg/ha. Pulses yields were below the ADDs' average in Dowa (473 kg/ha) and Kasungu (432 kg/ha) whereas the averages in Ntchisi (710 kg/ha) and Mchinji (619 kg/ha) was higher than that of the ADD. The trend lines of pulses yields display positive slopes showing an increase in the yields. This could be attributed to the fact that many farmers shifted from growing only maize to increasing levels of pulses such as beans and pigeon peas on their fields. The pulses are mostly produced for cash than consumption.

Fig. 27c shows cassava yields in all the districts in the region. There were low patterns in 1993, 1995 and 2001. In all the districts, there was an increase in 1994 due to the low crop yields that were observed in 1993; hence, there was a promotion of cassava production in that year. The average cassava yield in the ADD was 10290 kg/ha, the minimum yield was 1500 kg/ha in Kasungu district, and the maximum yield was 28834 kg/ha in Mchinji district. The average cassava yield in Dowa, Ntchisi, Kasungu, and Mchinji districts were 9542 kg/ha, 9686 kg/ha, 10240 kg/ha, and 11648 kg/ha, respectively. Except for Mchinji, the yields in the other three districts were low than the average cassava yields. It was also observed that there was a gradual increase in the cassava yields from 1995 to 1998 and a tremendous boost from 1998 upwards. Minimum yields in Mchinji (1800kg/ha), Ntchisi (1600 kg/ha), and Dowa (1648 kg/ha) were higher than the minimum yield in Kasungu district. Since cassava needs to be irrigated for short intervals yet for longer times since it has higher crop water requirements, this crop needs to be promoted in the ADD. Save this; the crop has a multiplier effect as its leaves are eaten as a relish, the roots as raw food and source of carbohydrates and can be used make floor and the stem can be applied as firewood. These surplus beneficial uses of the crop make it vital in a region where food security a big issue.

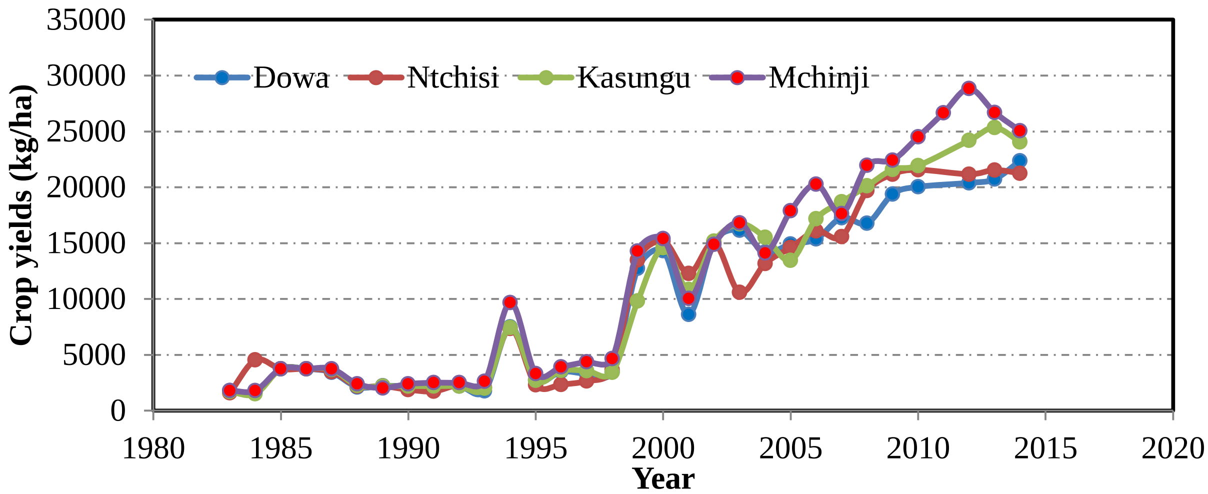
The average groundnut yield in the region was 717 kg/ha. The maximum groundnut yield was 1453 kg/ha in Dowa in 2009, and the minimum yield was 141 kg/ha in Mchinji in 1991. Ntchisi and Kasungu average yields were 689 kg/ha and 577 kg/ha respectively and were below the average groundnut yield for the ADD. Dowa and Mchinji had above average yields of 735 kg/ha and 868 kg/ha, respectively. This could be attributed to the geographical nature of the regions. Groundnut requires a considerably higher crop water requirement with frequent schedules. Since Mchinji receives a better amount of mean rainfall in the ADD, the groundnut yield correlates as shown in the Fig.27d. The trend lines of groundnuts display positive slopes showing an increase in the yields. This could be attributed to the fact that many farmers shifted from growing only maize to increasing levels of groundnuts in their fields. The topography and climatic nature of Dowa and Mchinji districts make it feasible for groundnuts production. This could be attributed to the fact that the mean rainfall in the districts through variable provided a better amount of moisture for crop production. Groundnut is a very beneficial leguminous crop as it fixes nitrogen in the soil hence improving the fertility of the soil. This crop has to be promoted in the region as it is used both for subsistence and cash crop. It can be used to make powder, which improves nutrition and can be used to extract oil which can be sold.

Figure 27: Time series crop yield analysis in Kasungu ADD (a. Maize b. Pulses c. Cassava d. Groundnuts)

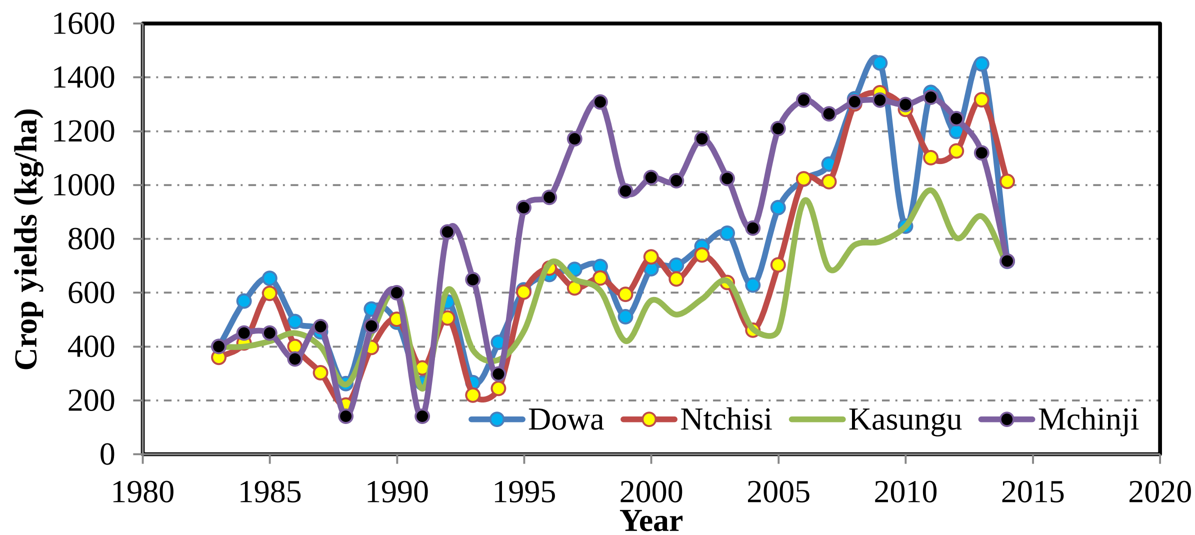




Cassava yields in Kasungu ADD



Groundnuts yields in Kasungu ADD



4.7 Crop Water Requirements

The CROPWAT program was developed to estimate potential evapotranspiration (PET) or ETo, which is also defined as reference evapotranspiration (FAO, 1998). When applied to a crop coefficient, this ETo helps to determine crop evapotranspiration, ETc. This refers to the amount of water a crop loses during evaporation and transpiration. In turn, it relates to the amount of water a crop requires for its growth. Hence, ETc ≈ Crop water requirement.

4.7.1 Summary of Potential Evapotranspiration in Kasungu ADD

Table 17 shows a summary of potential evapotranspiration in Kasungu ADD. The maximum evapotranspiration was observed at 7.41 mm/day in Dowa district, and the minimum evapotranspiration was noted as 3.08 mm/day in Mchinji district. On average, Dowa has higher evapotranspiration rate (4.76 mm/day) than the other districts in the ADD. The maximum evapotranspiration rates occurred in October, and the minimum values occurred in June across the ADD.

Table 17 further shows the availability of effective sunshine hours within the ADD. It can be observed that effective sun hours range from 7.1 to 7.9 hours. It can also be noted that solar radiation range from 19.1 to 20.7 MJ/m^2/day. These parameters suggest that solar can be utilized in the ADD for agricultural activities such as pumping water for irrigation, lightning on farms, and agro-processing.

Table 20: Summary of evapotranspiration in Kasungu ADD

District	ETo (mm/day)			Sun Hours (hr.)	Solar Radiation (MJ/m^2/day)
	Max	Min	Average		
Dowa	7.41	3.83	4.76	7.1	19.1
Kasungu	6.10	3.40	4.30	7.9	20.3
Mchinji	5.87	3.08	4.12	7.1	19.1
Ntchisi	6.31	3.95	4.62	7.9	20.7

4.7.2 Reference Evapotranspiration and Effective Rainfall Estimation

After interpolation in ArcGIS 10.5 using Kriging technique, reference evapotranspiration and effective rainfall maps were produced as seen in Fig. 28 and Fig 29, respectively.

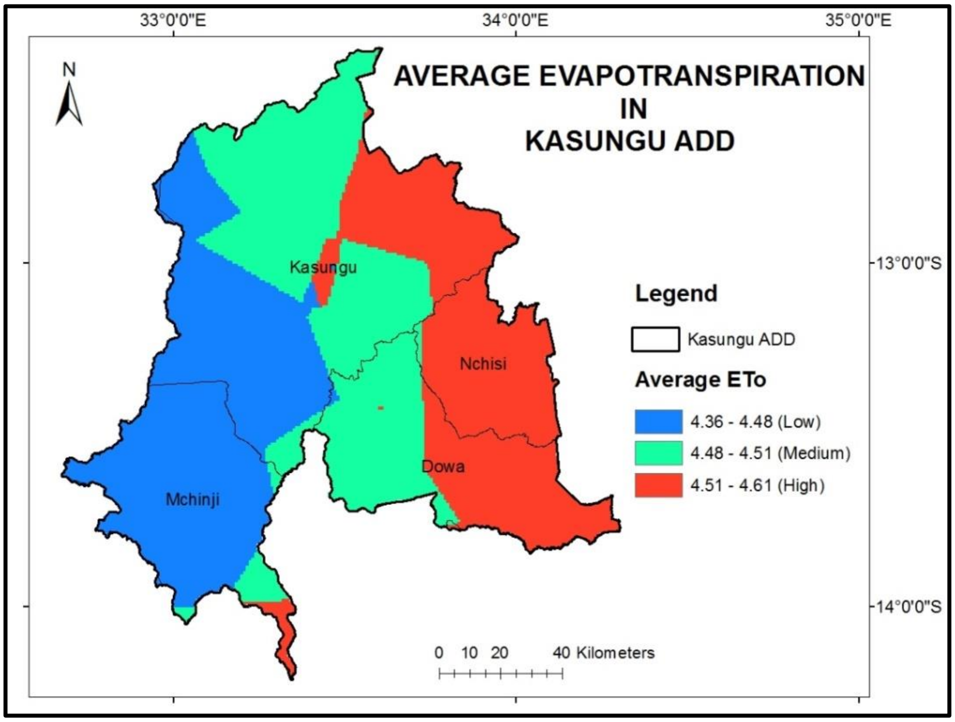


Figure 28: Map showing average reference evapotranspiration in Kasungu ADD

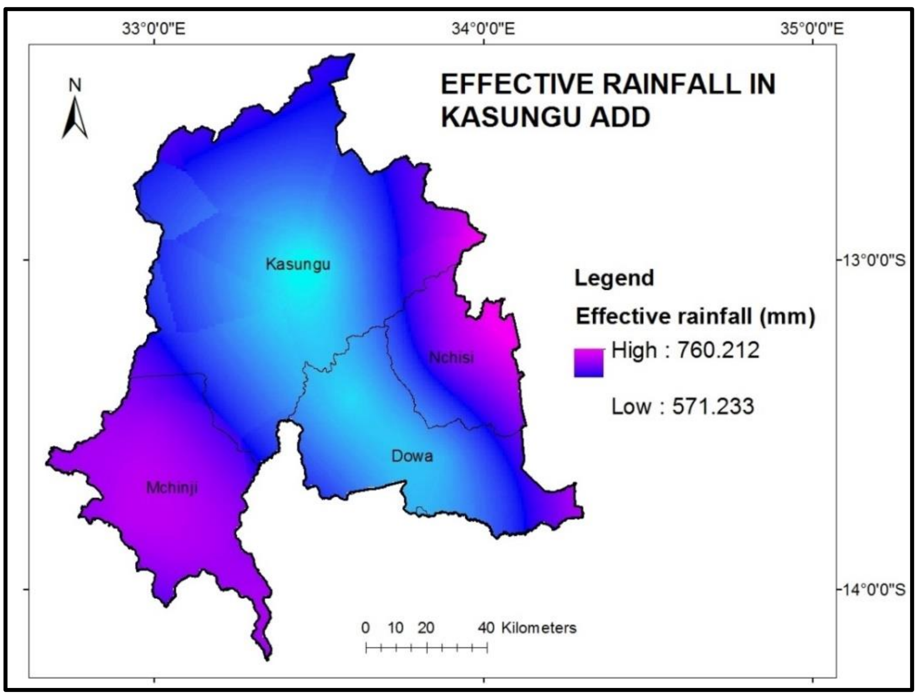


Figure 29: Effective rainfall in Kasungu ADD

For Kasungu district, the average ETo was 4.3 mm/day. The highest ETo value was in October (6.1 mm/day), and the minimum value was in June (3.4 mm/day). For Dowa district, the average ETo was 4.76 mm/day. The highest ETo value was in October (7.41 mm/day), and the minimum value was in February and March (3.83 mm/day). For Mchinji district, the average ETo was 4.12 mm/day. The highest ETo value was in October (5.87 mm/day), and the minimum value was in June (3.08 mm/day). For Ntchisi district, the average ETo was 4.62 mm/day. The highest ETo value was in October (6.31 mm/day), and the minimum value was in January (3.95 mm/day). The high evapotranspiration rate in the summer season could be attributed to high temperatures and lower relative humidity rates which are generally experienced in October and low temperatures which are experienced in winter (especially June and July). The differences in ETo values reveal the temporal variation in weather parameters in the study area. The ETo in the study area could be arranged in this order:

Dowa (4.76) > Ntchisi (4.62) > Kasungu (4.30) > Mchinji (4.12)

Effective rainfall is the part of the rainfall which is effectively used by the crop for its development and growth. It is the amount of rainfall which remains after losses due to surface runoff and infiltration. The total effective rainfall was 571.3 mm, 602.3 mm, 717.9 mm and 705.9 mm in Kasungu, Dowa, Mchinji, and Ntchisi districts respectively.

Effective rainfall is significant in agricultural production as it is used to estimate crop water requirements. The knowledge about the spatial and temporal features of the amount, frequency, and intensity of effective rainfall is essential for maximizing its potential.

The mean monthly rainfall of 40 years (1977-2017) and the CROPWAT rainfall from the USDA S.C. method were used to estimate the effective rainfall and to determine crop water requirements and irrigation schedules for maize, cassava, pulses, groundnuts, and vegetables in the study area. Table 13 to Table 17 showed that 73.1%, 70.7%, 66.9%, and 64.6% of rainfall were used effectively in Kasungu, Dowa, Mchinji, and Ntchisi districts, respectively.

4.8 Crop Water Requirements

Table 17 to Table 36 shows the crop evapotranspiration rates (ETc) of different crops for the districts in the study area. It was noted that there was an increase in the rates as the crop grows from initial to crop development stage and later a slight decrease in the maturity (late) stage. The variations observed can be due to changes in the crop coefficient (Kc) as the crop grows. The ETc values were low during the productive stage, and the crop water requirements were also low. During the mid-season stage, the Kc values were high, which influenced an increase in the ETc and hence the crop water requirements at this stage were also high. It is these values which are typically used when designing irrigation system capacity to the worst-case scenarios. In all the districts in the study area, the pattern for crop water requirements amongst the crops was similar in that cassava had the highest requirements and vegetables the lowest requirements. However, the variations were also in the schedules in that cassava and groundnuts needed a smaller depth of water application but frequently whereas the rest of the crops required a more considerable depth of water use from time to time. In times of droughts, crops which need a smaller depth of application and a system of irrigation which utilizes lower depths of application could be preferred.

In Kasungu district, the irrigation requirement (mm/dec) differed due to the type of crop being grown. The irrigation requirement was as follows:

Cassava (582) > Groundnuts (555.7) > Maize (509.7) > Pulses (447.2) > Vegetables (400.3)

In Dowa district, the pattern was also similar and was in the order below:

Cassava (768.2) > Groundnuts (726.9) > Maize (693.6) > Pulses (573.8) > Vegetables (504.8)

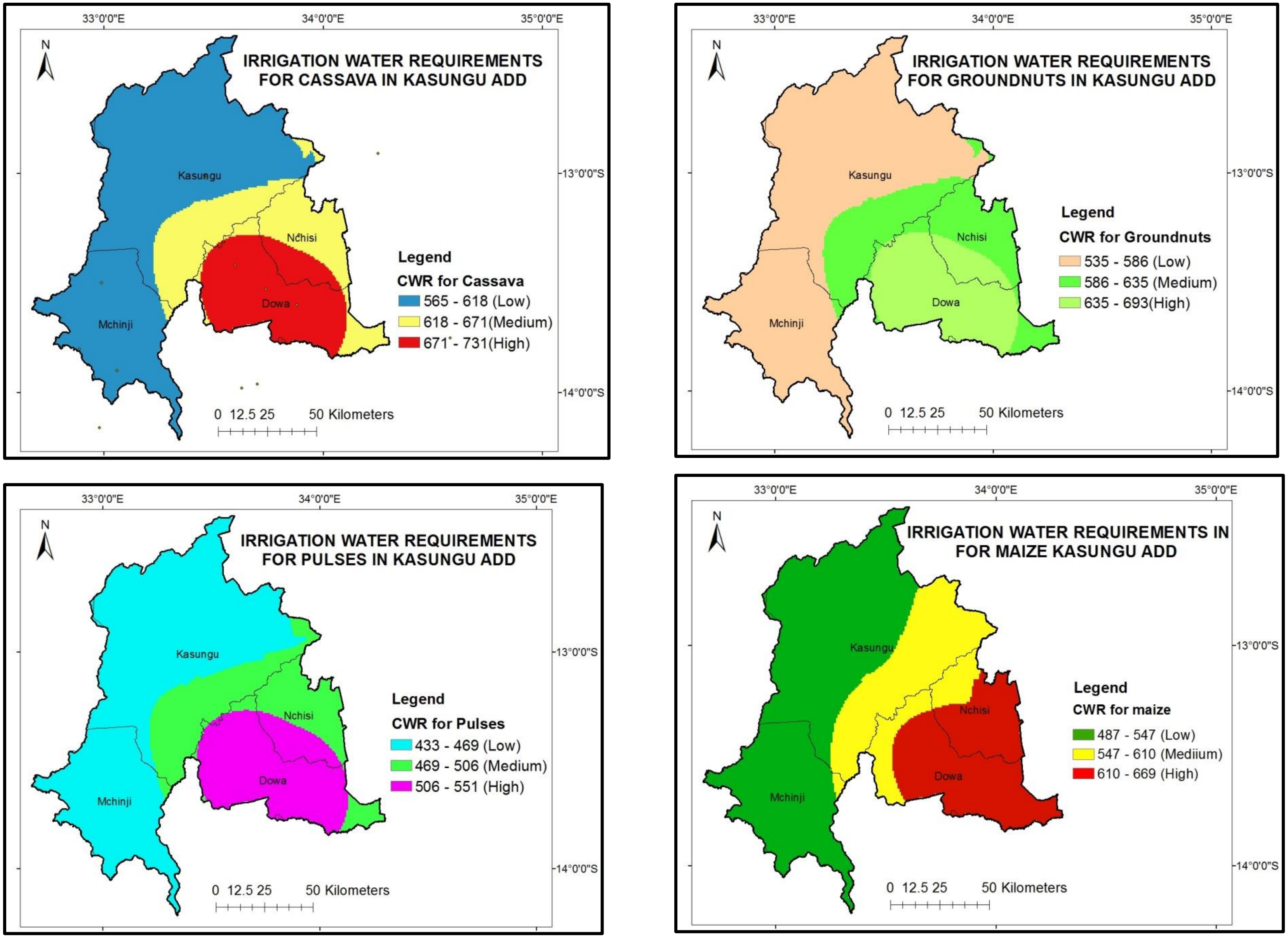
Similarly, in Mchinji district, the irrigation requirement displayed the same pattern.

Cassava (550.6) > Groundnuts (521.9) > Maize (482.8) > Pulses (424.5) > Vegetables (382.5)

As if that was not enough, in Ntchisi district, the irrigation requirement pattern was in the following order:

Cassava (617.9) > Groundnuts (586.5) > Maize (540.8) > Pulses (473.1) > Vegetables (426.3)

Figure 30: Irrigation Water Requirements (a. Cassava b. Groundnuts c. Pulses d. Maize)



4.9 Irrigation Requirements and Irrigation schedules

Irrigation water management is effective when water users have a better understanding and knowledge of crop water requirements and irrigation scheduling. This ranges from knowing how much water to apply to the crops, when to apply and how frequent to apply. When these features are done correctly, irrigation water management is said to have been beneficial.

The irrigation requirement is the amount of water that is needed to fill the soil to field capacity. It is calculated as in the equation below:

$$\text{Irrigation requirement (IR)} = \text{ETc} - \text{Effective rainfall (ER)} \tag{23}$$

Figure 27 to Figure 46 illustrate irrigation schedules of common crops in the study area. In the figures, total available moisture (TAM) expresses the total amount of water available to the cropand readily available water (RAM) indicates that part of (TAM) that the plant can get from the root zone without facing water stress.

In Kasungu district, there are seven irrigation schedules for maize, six for pulses, twenty-two for cassava, eleven for groundnuts and thirteen for vegetables. For maize, the maximum readily available water is 92 mm, and the maximum total available moisture is 140 mm. This represents a depletion level of 65.7%. For pulses, the maximum readily available water is 105 mm, and the maximum total available moisture is 140 mm. This represents a depletion level of 75%. For cassava, the maximum readily available water is 38 mm, and the maximum total available moisture is 84 mm. This represents a depletion level of 45.2%. For groundnuts, the maximum readily available water is 55 mm, and the maximum total available moisture is 111 mm. This represents a depletion level of 49.5%. For vegetables, the maximum readily available water is 37 mm, and the maximum total available moisture is 84 mm. This represents a depletion level of 45.9%.

In Dowa district, there are nine irrigation schedules for maize, seven for pulses, twenty-eight for cassava, fifteen for groundnuts and sixteen for vegetables. For maize, the maximum readily available water is 90 mm and the maximum total available moisture is 140 mm. This represents a depletion level of 64.3%. For pulses, the maximum readily available water is 91 mm and the maximum total available moisture is 140 mm. This represents a depletion level of 65%. For cassava, the maximum readily available water is 40 mm and the maximum total available moisture is 85 mm. This represents a depletion level of 47%. For groundnuts, the maximum readily available water is 42 mm and the maximum total available moisture is 111 mm. This represents a depletion level of 37.8%. For vegetables, the maximum readily available water is 40 mm and the maximum total available moisture is 87 mm. This represents a depletion level of 44%.

In Mchinji district, there are six irrigation schedules for maize, five for pulses, twenty-one for cassava, eleven for groundnuts and twelve for vegetables. For maize, the maximum readily available water is 98 mm and the maximum total available moisture is 140 mm. This represents a depletion level of 70%. For pulses, the maximum readily available water is 99 mm and the maximum total available moisture is 140 mm. This represents a depletion level of 70.7%. For cassava, the maximum readily available water is 35 mm and the maximum total available moisture is 84 mm. This represents a depletion level of 41.7%. For groundnuts, the maximum readily available water is 50 mm and the maximum total available moisture is 111 mm. This represents a depletion level of 45%. For vegetables, the maximum readily available water is 38 mm and the maximum total available moisture is 84 mm. This represents a depletion level of 45.2%.

In Ntchisi district, there are seven irrigation schedules for maize, six for pulses, twenty-four for cassava, twelve for groundnuts and fourteen for vegetables. For maize, the maximum readily available water is 82 mm and the maximum total available moisture is 140 mm. This represents a depletion level of 58.6%. For pulses, the maximum readily available water is 90 mm and the maximum total available moisture is 140 mm. This represents a depletion level of 64.3%. For cassava, the maximum readily available water is 35 mm and the maximum total available moisture is 84 mm. This represents a depletion level of 41.7%. For groundnuts, the maximum readily available water is 51 mm and the maximum total available moisture is 111 mm. This represents a depletion level of 45.9%. For vegetables, the maximum readily available water is 38 mm and the maximum total available moisture is 84 mm. This represents a depletion level of 45.2%.

This analysis enables farmers to easily choose right types of crops based on the availability, accessibility and quantity of water in the area. It is clear that the crop production in the ADD largely depends on rain fed and little on irrigation. With the vast variations in the rainfall trends in the ADD, there is an urgent need to revitalize and to restructure farming technologies and irrigation systems for the purpose of mitigating climatic shocks and enhancing food security.

Irrigation system reforms in times of droughts should consider the irrigation schedules so as to maximize the moisture levels necessary for plant growth. Modern irrigation methods which save water and apply frequent water even for longer times such as drip irrigation should be considered for these purposes. There is also a great need to raise awareness among water users especially farmers to save water, harvest rainwater and use modern methods of farming so as to adapt to the effects of drought regimes in the ADD.

4.10 Irrigation Technologies and Irrigation Systems in Kasungu ADD

There are five main methods that farmers access irrigation, through gravity (RDG), treadle pumps (TP), motorised pumps (DMP), solar powered pumps (SPP) and watering cans (WC). Water use efficiencies differ with the different methods. The area covered under these methods depends largely on water availability in the area.

The variability of rainfall, the increase in population and the agro-ecological nature of Kasungu ADD makes diversified farming vital in the area. With the impacts of global climate change, irrigation is a need in the area. However, the question of which type of irrigation needs to be practiced in which situation remains a mystery. Fig. 31 and Fig.32 show some irrigation technologies and irrigation systems respectively which are in place in Kasungu ADD.

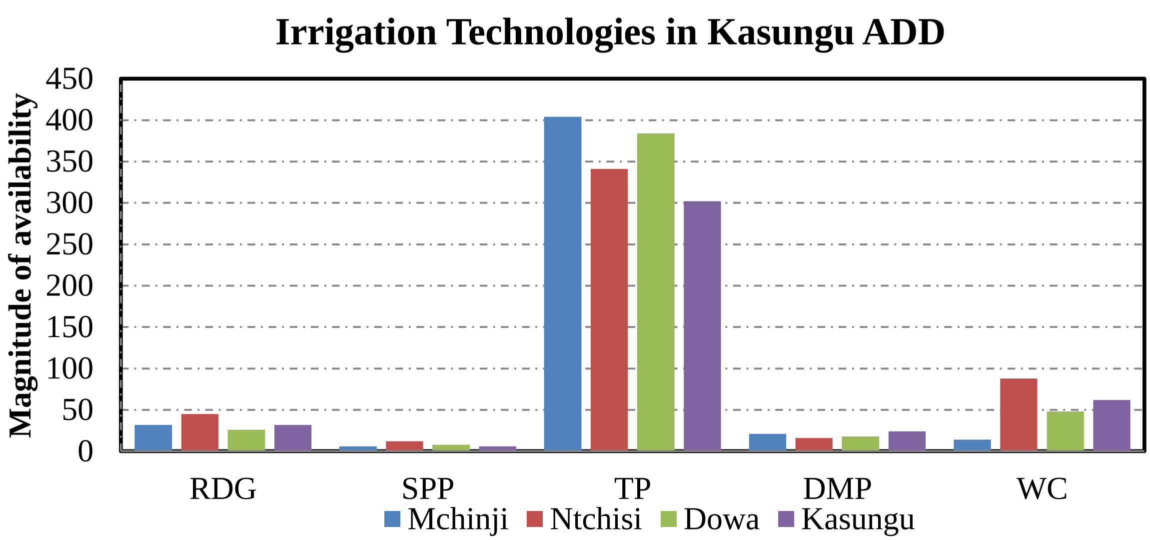


Figure 31: Irrigation Technologies in Kasungu ADD

In Mchinji district, most farmers use treadle pumps and watering cans. This could be due to the fact that these technologies are cheaper and easy to use. A considerable number of schemes use river diversion. This requires skill and in times of droughts and when rivers dry up, irrigation becomes difficult. Even though the area receives a considerable amount of radiation, the use of solar powered pumps for irrigation is not common. Similarly, in Dowa, Kasungu and Ntchisi districts, the use of treadle pumps is common and a significant number of people are opening up to using solar powered pumps. There is a need for massive awareness on the importance of using water saving technologies to check and adapt to the effects of climate change.

Irrigation technologies in the ADD are mostly characterized by smallholder farmers. This explains why mostly used technology (above 50%) in all the areas is a treadle pump. Second to the treadle pump are watering cans and then river diversion. Farmers in smallholder irrigation schemes normally grow their crops on plots within the range of 0.4 to 0.7 hectares. Their production is mainly for subsistence with the surplus for trade. Production systems are always low. Smallholder irrigation schemes mostly support the production of green maize and green leafy vegetables.

There is a great need to reform irrigation technologies in the ADD. Extension workers also should take a leading role in the promotion of water saving and climate smart irrigation technologies in the ADD.

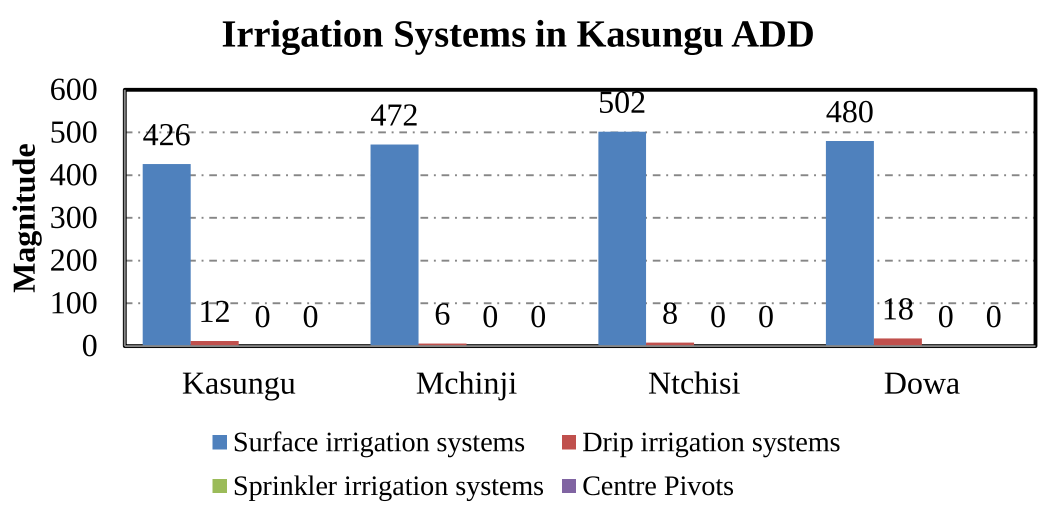


Figure 32: Irrigation Systems in Kasungu ADD

Fig. 32 shows irrigation systems in the ADD. It can be observed that most farmers use surface irrigation systems in the area. These systems largely depend on water from rivers which also depend on rainfall. Since the rainfall varies greatly in the study area, any impact and shift of the rainfall pattern will have adverse effects on agricultural production. Other systems which save water such as drip irrigation need to be promoted in the ADD. This finding agrees with Chidanti-Malunga (2009) who observed that government or NGOs should promote irrigation technologies that are acceptable to the farmers, increase yields through more efficient water use, subsidize input costs for solar pumps and irrigation drip kits and seen to benefit them under the local socioeconomic conditions. Chabvunguma (2014) also concurs that best drought management strategies are needed for the country to improve its food basket.

There is also laxity among irrigators among different levels from local to district level as irrigation is done in the concept of business as usual. This is due to reduced financing on climate smart irrigation based technologies by the government and NGOs in the ADD. Under global warming conditions which are worsening, current irrigation practices leave a lot to be desired in the ADD. This study concurs with Pakhale et al. (2010) who mentioned that the irrigation sector must be reformed and re-energized to unlock its potential by introducing innovative management practices and changing the way it is governed.

4.11 Drought Indices in Kasungu ADD

Rainfall, temperature, stream flow and potential evapotranspiration monthly values were used to compute SPI, SPEI, PDSI, SWSI, SDI, RAI and ETDI values for the region from 1977 to 2017 on yearly and monthly basis. The values were then used to plot trend graphs from which drought years and months were observed as shown in Fig. 34 – Fig. 69. Furthermore, drought characteristics were identified from the same graphs.

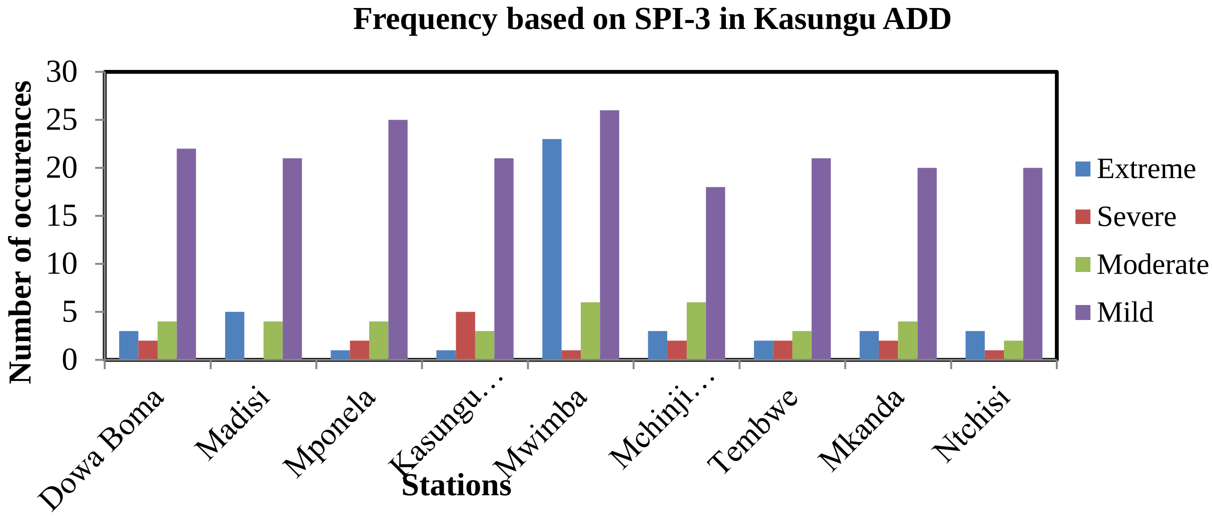
4.12 Temporal Analysis of Droughts

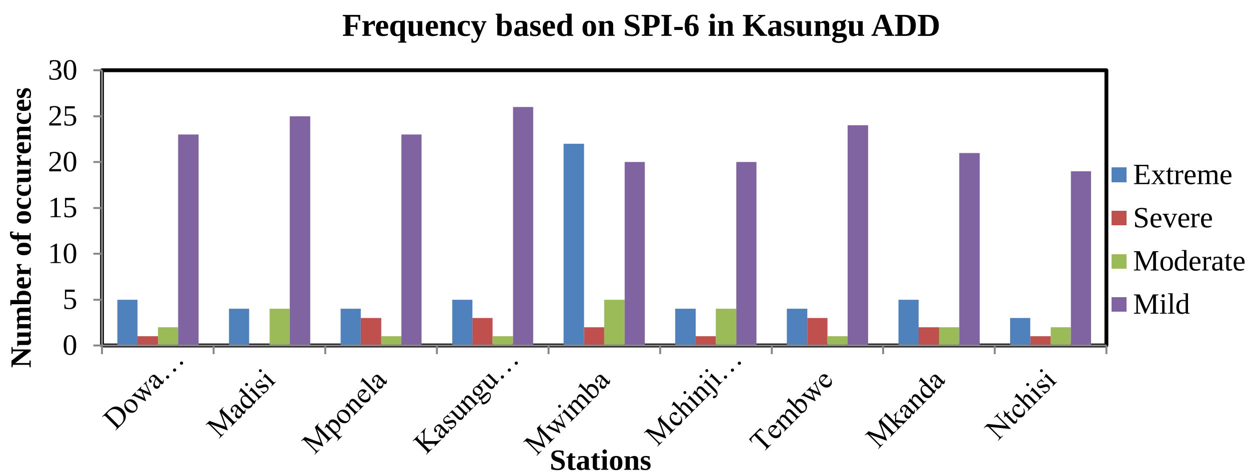
Fig.33 (a-f) show drought frequencies within Kasungu ADD based on different indices computed. From Fig. 33a, based on SPI-3, Mwimba experienced the highest number of extreme drought events (23) while Kasungu Aerodrome had the least (1). Kasungu Aerodrome experienced highest number of severe droughts (5) while Mwimba and Ntchisi had the least (1). Mwimba and Mchinji had more moderate droughts with a frequency of 6 apiece with Ntchisi recording the least (2). Mild drought conditions were frequent in Mwimba and the least in Mchinji. Fig.33b displayed similar patterns based on SPI-6.

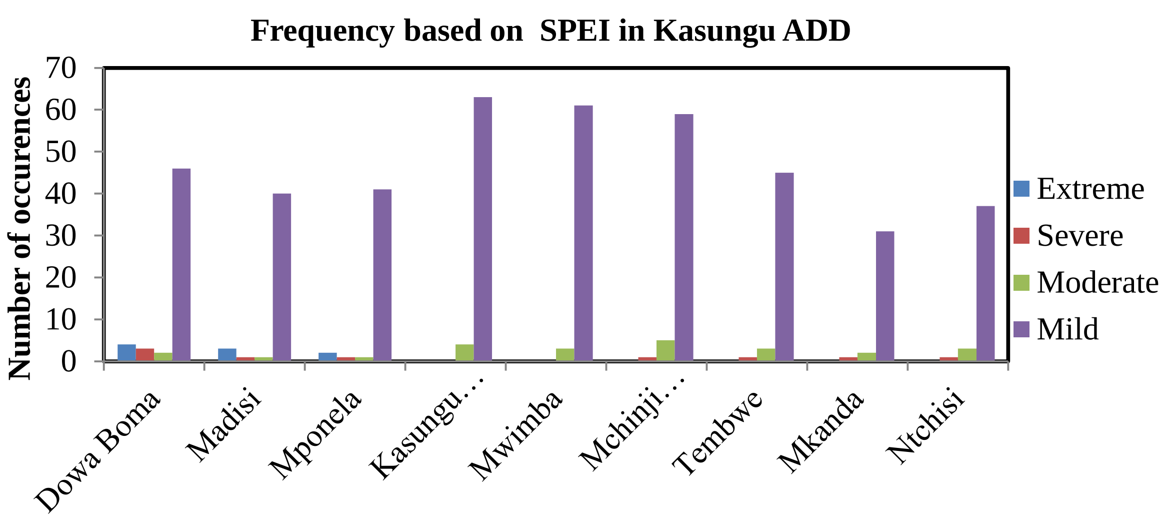
From Fig. 33 c, based on SPEI, Dowa recorded the highest number of extreme drought events (4) and severe droughts (3) while most parts did not experience these drought conditions. However, Mchinji registered the highest number of Moderate droughts followed by Madisi and Mponela. Mild drought conditions were experienced in the ADD with most occurrences in Kasungu Aerodrome and Mkanda the least occurrences.

From fig. 33d, based on PDSI, Mwimba experienced the highest number of different drought events while Mchinji, Tembwe and Mkanda had the least (1). From fig. 33e, based on ETDI, an agricultural based drought index, it showed that most areas suffered from droughts. Extreme drought conditions were highest in Dowa and lowest in Kasungu. Severe droughts were higher in Dowa and least in Tembwe. All the areas pinpointed that mild drought conditions were very frequent in the ADD. Fig.33f highlighted that the whole region suffered from extreme hydrological droughts based on the SWSI. This could be due to reduced river flows and little rainfall which reduced the contribution of water in the riverine system and groundwater.

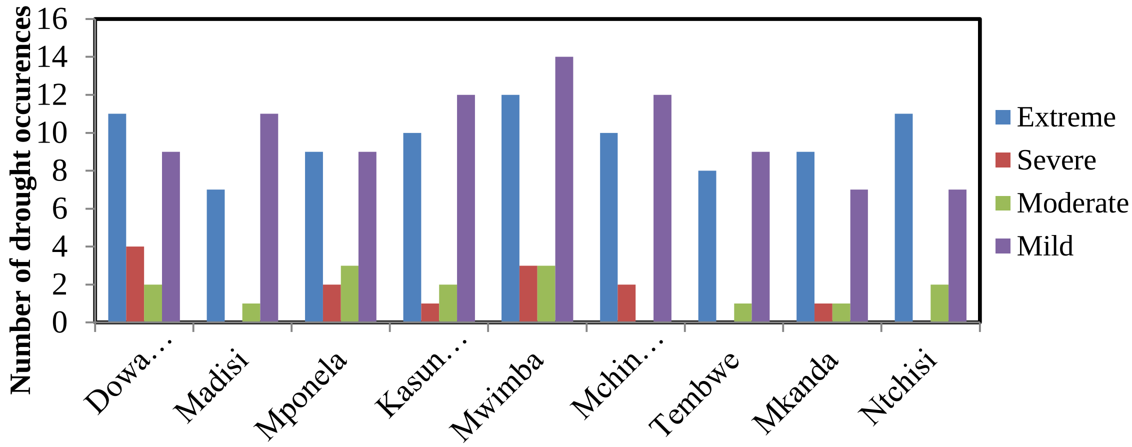
Figure 33: Drought Frequency in Kasungu ADD (a. SPI-3 b. SPI-6 c. SPEI d. PDSI e. ETDI f. SWSI)



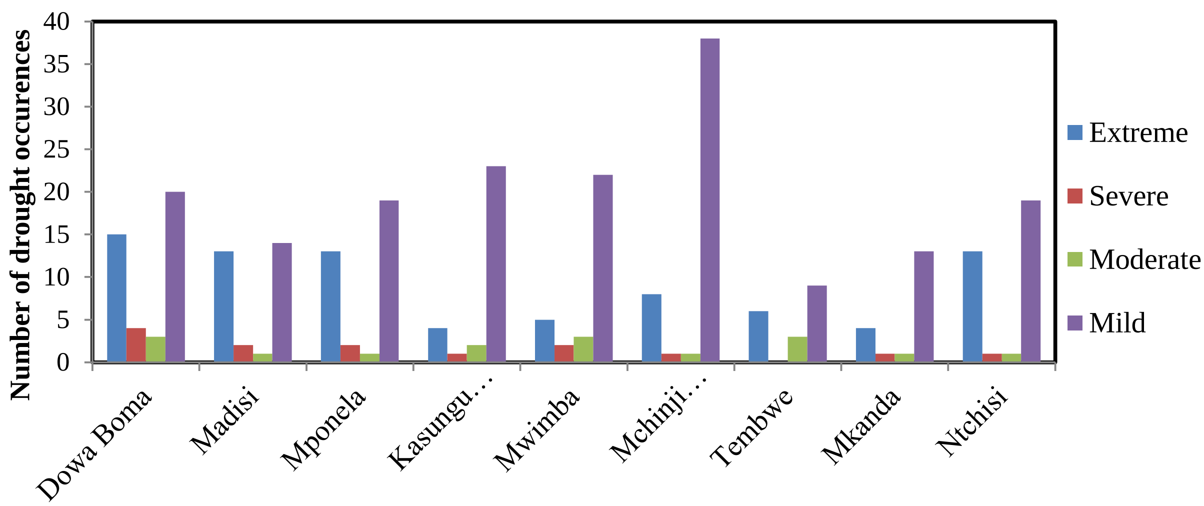




Frequency based on PDSI in Kasungu ADD



Frequency based on ETDI in Kasungu ADD



Frequency based on SWSI in Kasungu ADD

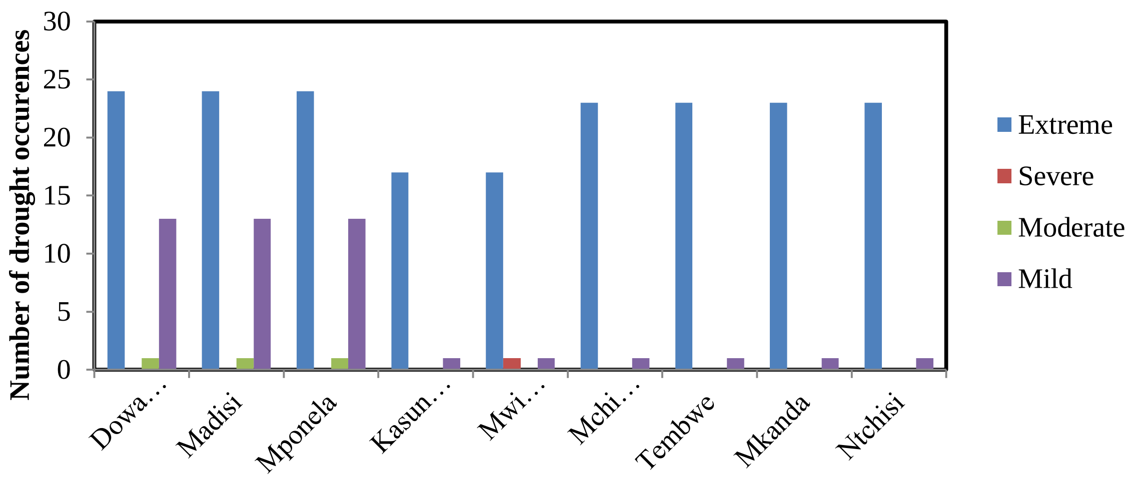


Fig. 34 to Fig. 69 show temporal variations of drought indices in Kasungu ADD. It can be seen that most drought indices illustrate similar trends with differences in their characteristics in terms of severity and duration.

In Kasungu district, drought events are noted in 1983, 1987, 1990, 1993, 1995, 1997, 1999, 2005, 2006 and 2007. SPI-3 detected one extreme drought in November 1999 (with duration of 121 days and a severity of 2.946); severe droughts were noted in February 1992 (with duration of 90 days and severity of 1.99), April 1994 (with duration of 61 days and severity of 1.644), February 2006 (with duration of 59 days and severity of 1.93), May 2007 (with duration of 61 days and severity of 1.935) and May 2014 (with duration of 61 days and severity of 1.506) ; and moderate droughts were identified in March 1990 (with duration of 61 days and severity of 1.357), January 2011(with duration of 90 days and severity of 1.145), and November 2016 (with duration of 92 days and severity of 1.213). Mild dry conditions were experienced in 1983, 1993, 1994, 1996, 2001, 2008, 2012, and 2014, especially in January, February, March, April and May. SPI-6 identified five extreme droughts in 1992, 1995, 1999, 2006, and 2011. The 1992 drought started in February and had duration of 182 days with severity of 4.169. The 1995 drought commenced in February and had duration of 120 days with severity of 2.414. The 1999 drought started in November and had a duration of 213 days with severity of 4.209. The 2006 drought started in February and had a duration of 150 days with severity of 2.994. The 2011 drought started in January and had a duration of 181 days with severity of 2.474. Three severe droughts in SPI-6 were noted in 1995, 2007, and 2014; one moderate drought was observed in 2016. SPI-12 identified five extreme droughts in 1992, 1995, 2000, 2005, and 2008. SPI-12 did not observe any severe and moderate droughts, but mild droughts were noted in 1990, 2002, 2009, 2013 and 2016. The most extreme drought started in February 1992 with a duration of 366 days and the severity of 7.81 while the less extreme started in February 2008 with a duration of 304 days and the severity of 2.43. SPEI and SPEI1 observed moderate and mild drought conditions in the district. SPEI identified moderate drought conditions in 1988, 1989, 1991, and 2008. Mild dry conditions were observed in the rest of the study period. SPEI1 noted moderate conditions in 1987, 1988, 2009, 2012, 2014, and 2016. PDSI identified ten drought indices in 1983, 1990, 1992, 1994, 2001, 2005, 2007, 2013, 2014, and 2015. Severe drought was noted in 2010; Moderate droughts were observed in 1999 and 2016. The rest of the seasons during the study period had mild drought conditions. Monthly PDSI noted that the longest extreme drought started in March 2007 and had duration of 731 days with the severity of 48.264.

The shortest extreme drought commenced in January 1990 with duration of 120 days and severity of 5.464. The agricultural drought indices ETDI and ARI highlight the monthly events over the study period in Kasungu district. ETDI indicated that four extreme droughts were observed in 1996, 1998, 2012, and 2014. The 1996 drought started in August and had a span of 334 days with the severity of 7.473. The 1998 drought started in March, had duration of 153 days and severity of 5.217. The 2012 extreme drought begun in July, had a span of 448 days with severity of 19.251. The longest extreme drought occurred in 2014. It started in December, took 609 days and had severity of 30.678. Severe drought was depicted in 2011. Moderate droughts were observed in 1994 and 2011. Except for September 2005 which indicated mild drought conditions, the rest of the study period hydrologically indicated extreme drought conditions based on the monthly SWSI index. The most extreme hydrological drought started in March 1994 and spanned for 702 days with the severity of 49.435.

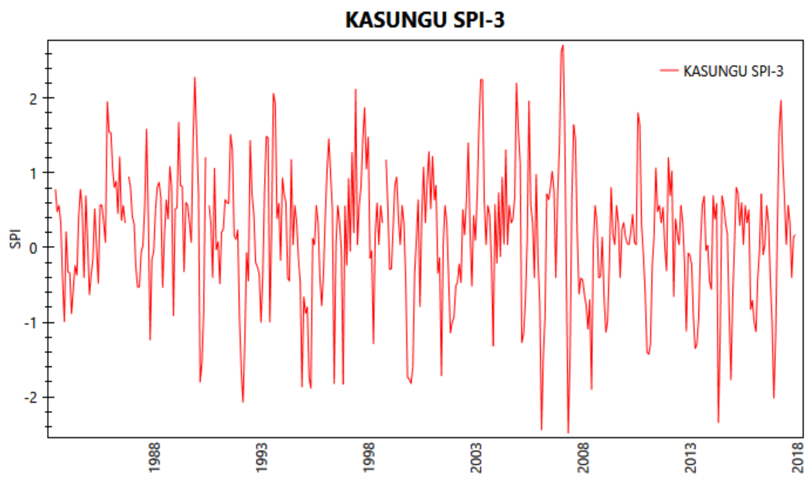


Figure 34: Temporal trends in SPI-3

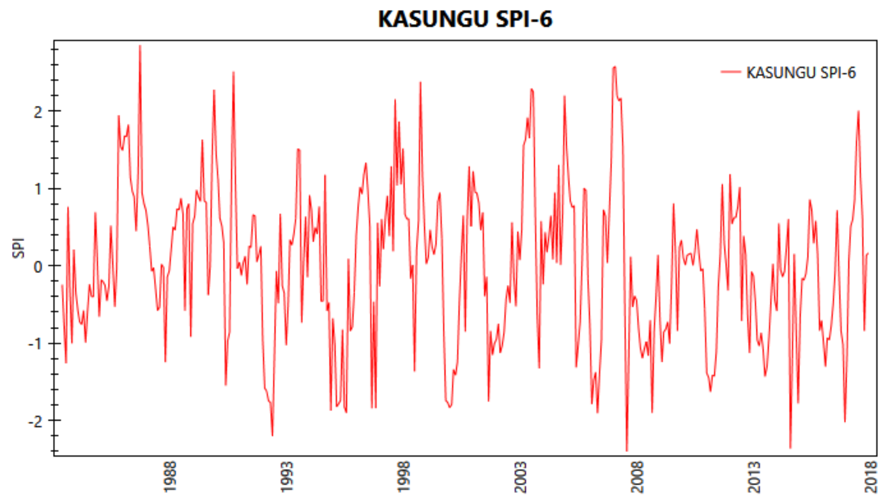


Figure 35: Temporal trends in SPI-6

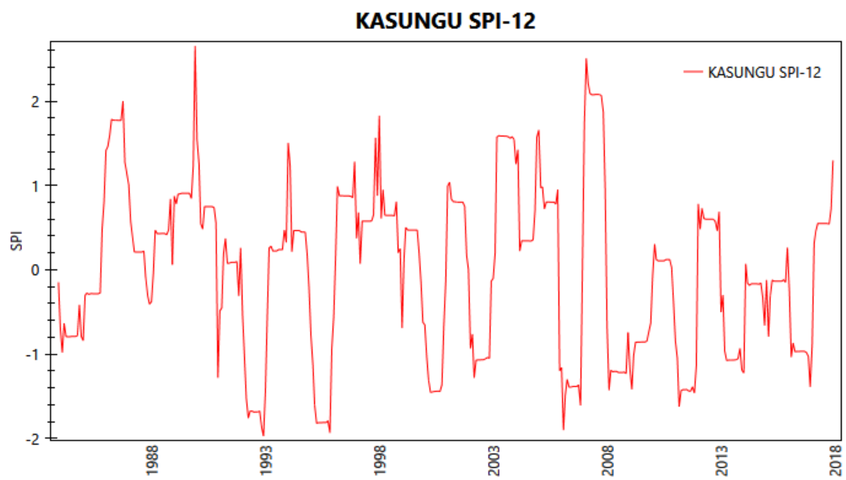


Figure 36: Temporal trends in SPI-12

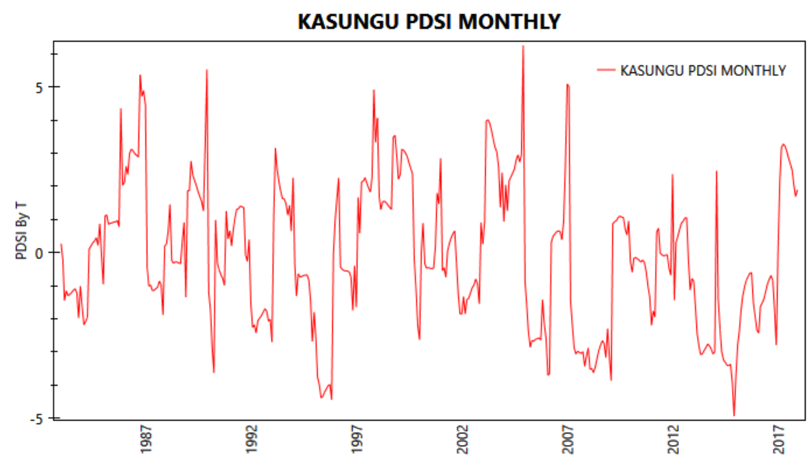


Figure 37: Temporal trends in monthly PDSI

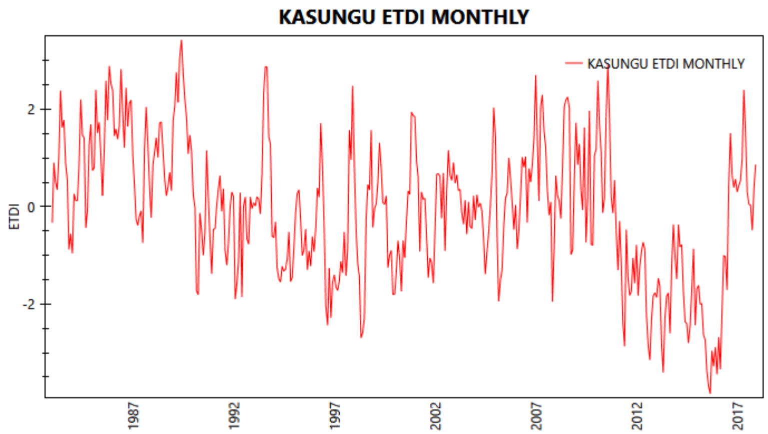


Figure 38: Temporal trends in monthly ETDI

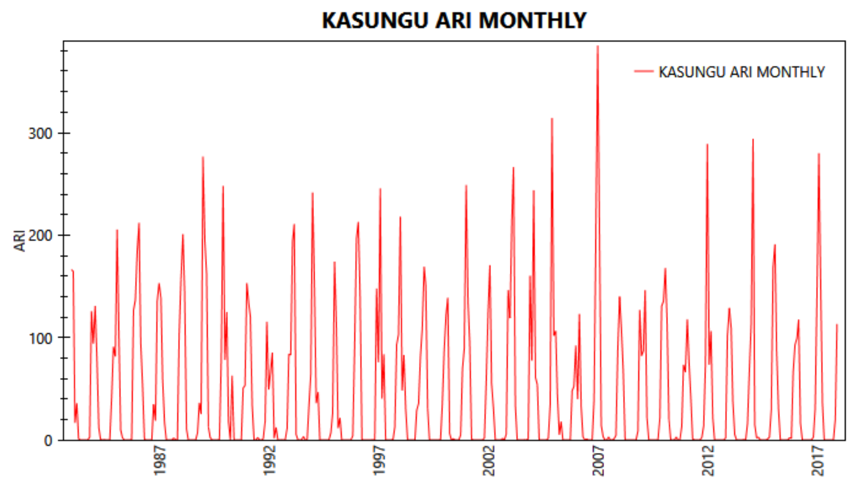


Figure 39: Temporal trends in monthly ARI

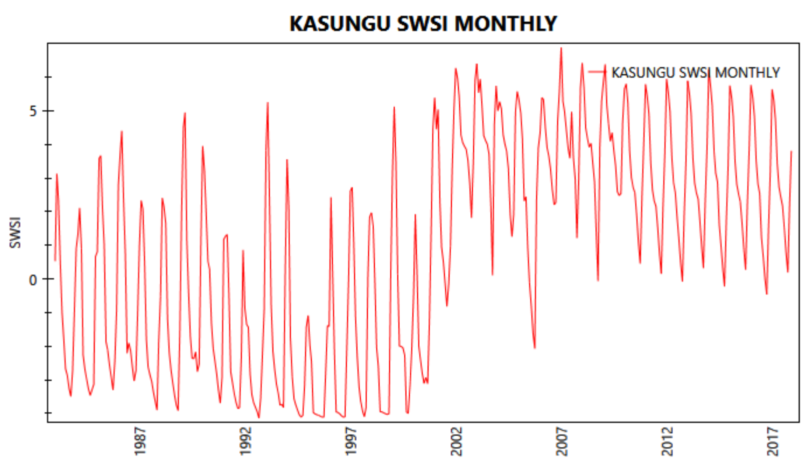


Figure 40: Temporal trends in monthly SWSI

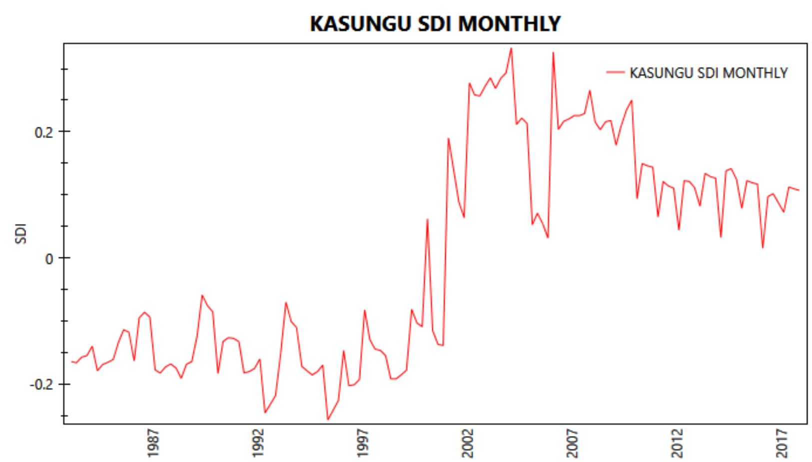


Figure 41: Temporal trends in SDI

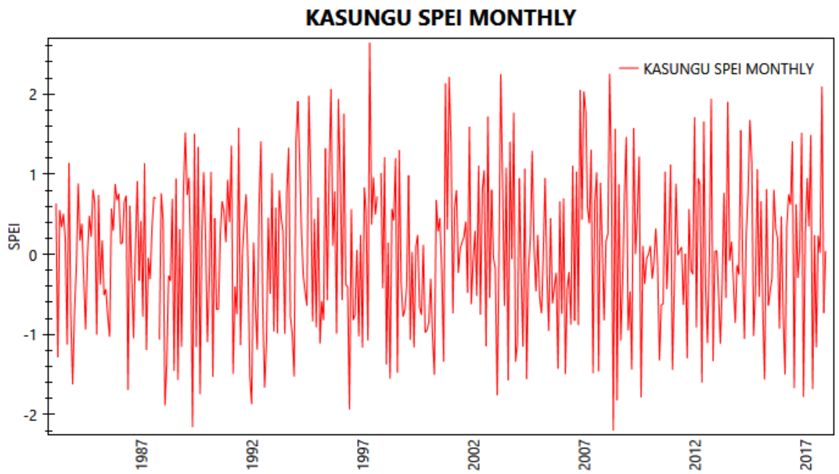


Figure 42: Temporal trends in monthly SPEI

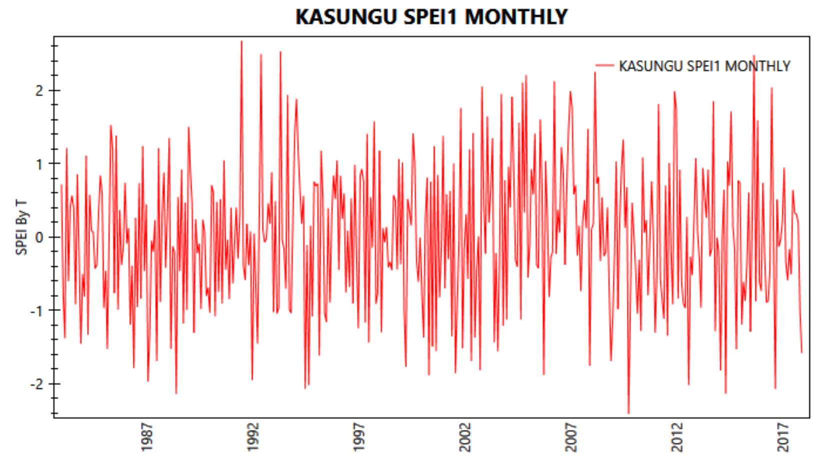


Figure 43: Temporal trends in SPEI1

In Dowa district, SPI-3 detected three extreme drought events in 1993, 1994, and 2005. The 1993 extreme drought began in December and prolonged for 90 days with the severity of 3.387 whereas the 1994 drought also started in December but was experienced for 62 days with severity of 2.311. The most extreme drought occurred in March 2005 with duration of 122 days, and severity of 4.681. Severe drought conditions as detected by SPI-3 occurred in 2003 and 2015. The drought in January 2015 was more severe than the one in November 2003. The 2015 severe drought prolonged for 151 days with severity of 1.772 whereas that of 2003 extended for 92 days with the severity of 1.673. The rest of the seasons indicated mild drought conditions. SPI-6 depicted five extreme droughts in 1992, 1993, 1994, 2005, and 2015. The 1992 extreme drought started in February an extended over 151 days with the severity of 2.545. The 1993 drought spanned for 182 days starting from December and had the severity of 6.445. The December 1994 drought extended over a period of 62 days with the severity of 2.289. In 2005, the extreme drought started in June and spanned over a period of 122 days with the severity of 4.948. The longest extreme drought started in January 2015 for 243 days and had the severity of 4.368. The severe drought started in November 2003 and hovered over 92 days with the severity of 1.688. The rest of the season was observed to have mild drought conditions. SPI-12 noted four extreme droughts in the district in 1992, 1994, 2005, and 2015. The longest extreme drought was that of 2015 which started in January, with the duration of 700 days. It was followed by 1992, 1994 and 2005 with duration of 366, 365 and 90 days respectively. SPEI observed four extreme droughts in 1979, 1986, 2008, and 2017. The longest extreme drought was 1986, which started in August and took 92 days. It had an intensity of 2.166. The other droughts had the same duration of 61 days but differed in terms of onset, offset, and intensity. Severe droughts were noted in 1994, 1997 and 2016. Moderate droughts were observed in 2004 and 2005. SPEI1 detected extreme events in 1978, 1979, 1980, 1981, 1983, 1984, 1987, 1988, 2017; severe drought conditions in 1986, 1987, 1988, 1989, 1990, 1993, 1995, 1996, 2002, 2004, 2005, 2008, 2009, 2013, 2014, 2015; and moderate drought conditions in 1979, 1980, 1981, 1985, 1986, 1987, 1990, 1991, 1992, 1993, 1996,1998, 2000, 2001,2003, 2006, 2010, 2011, 2014, 2017. Monthly PDSI identified extreme droughts in 1977, 1979, 1981, 1988, 1989, 1993, 1996, 1997, 1998, 2002, 2003; severe droughts in 1979, 1987, 1995, 1999; and moderate droughts in 2001 and 2012. ETDI and ARI highlighted agricultural droughts were extreme in 1977, 1979, 1987,1991, 1994, 1996, 1998, 2001, 2002, 2005, 2007, 2008, 2010, 2013, 2014; severe in 1979, 1987, 1995, 1999 and moderate in 1990, 2008, 2016. SDI and SWSI indicated that almost all the study period Dowa experienced extreme hydrological drought with the most extreme starting in March 1994, taking 702 days, and having severity of 94.956. It was further observed that hydrological droughts were beginning in March, April, May, June, and July.

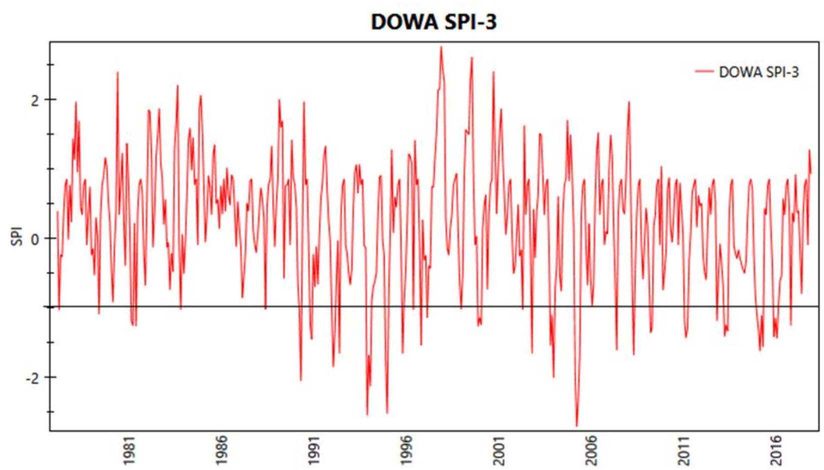


Figure 44: Temporal trends in SPI-3

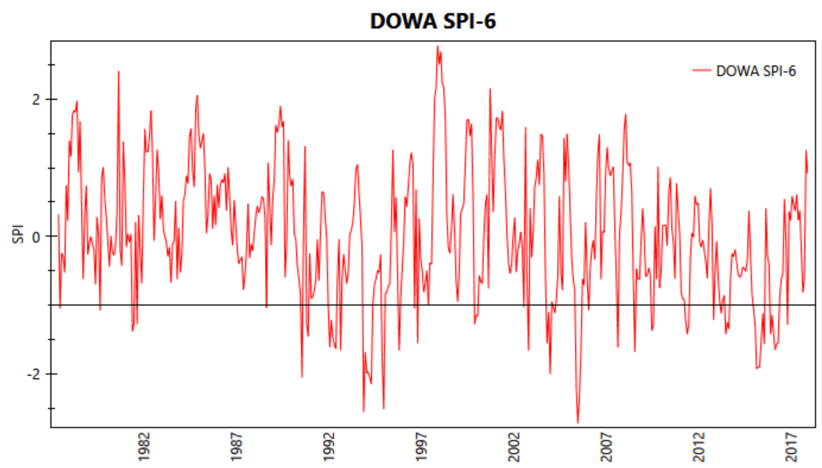


Figure 45: Temporal trends in SPI-6

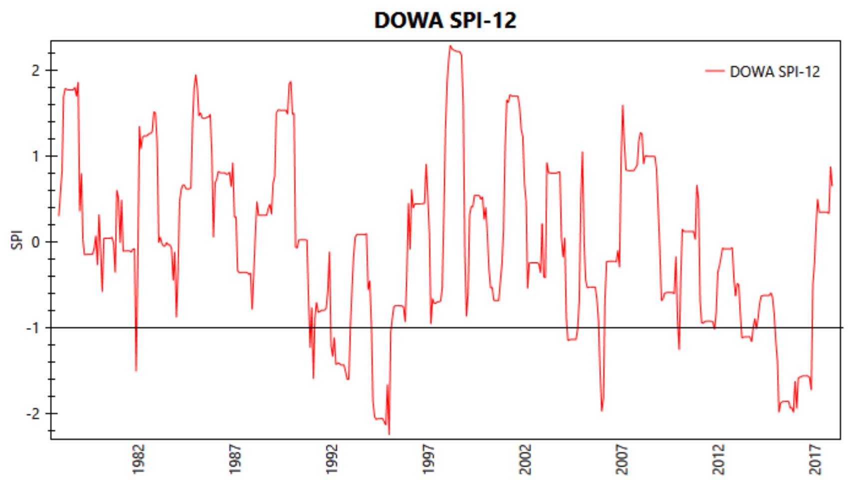


Figure 46: Temporal trends in SPI-12

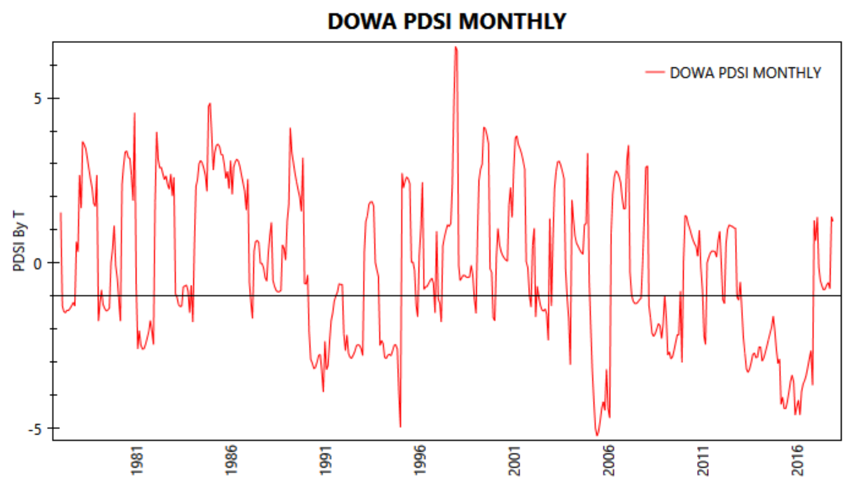
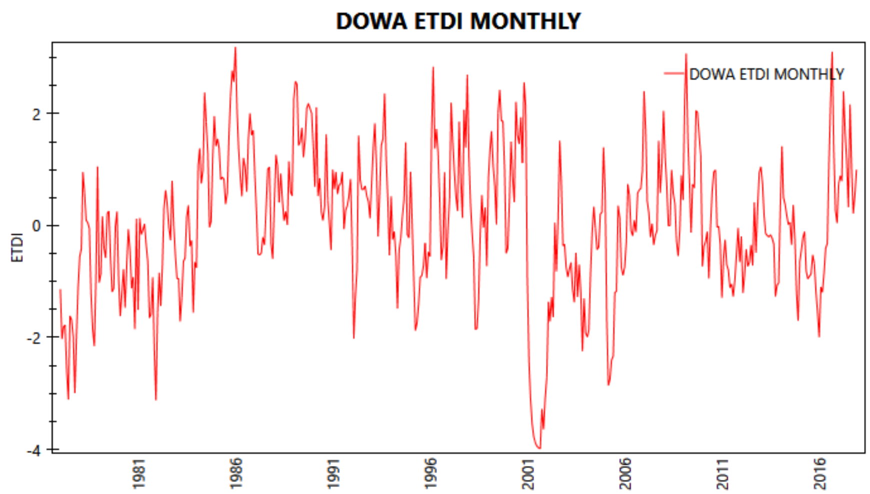


Figure 47: Temporal trends in monthly PDSI



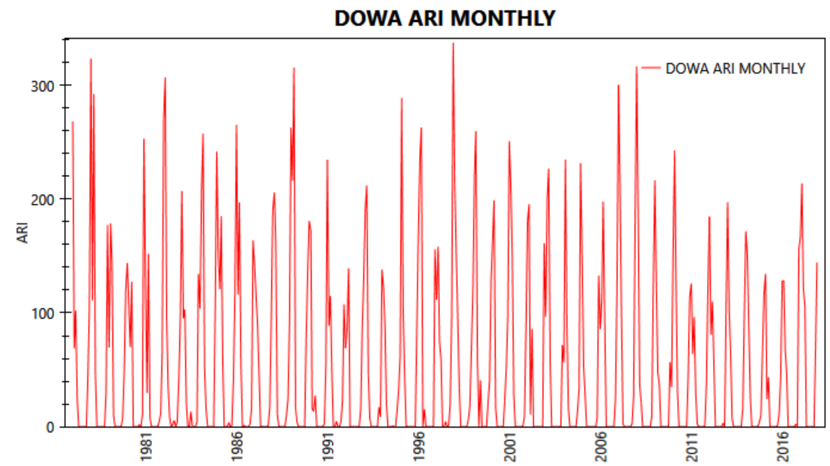
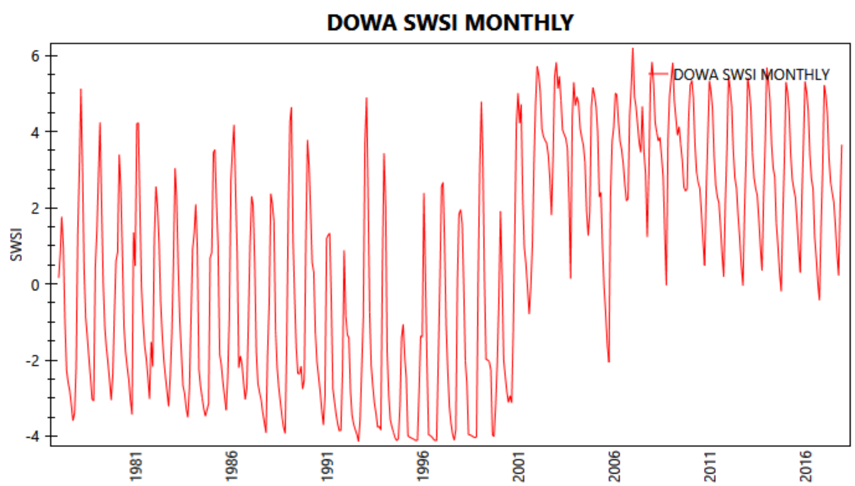


Figure 48: Temporal trends in monthly ETDI

Figure 49: Temporal trends in monthly ARI



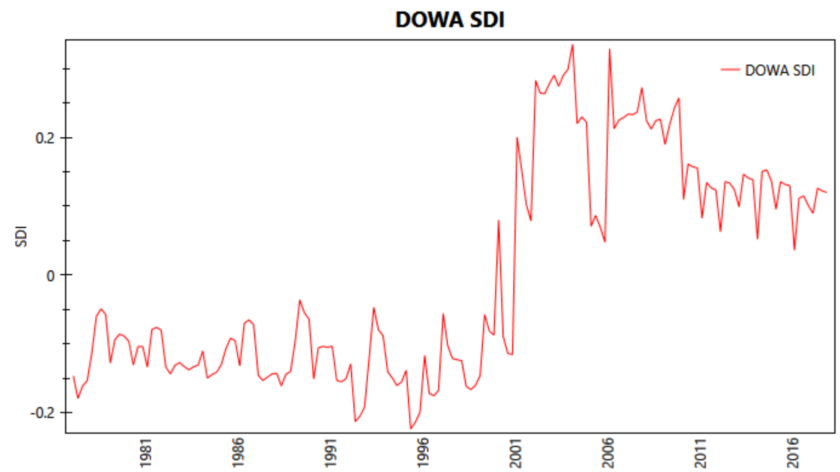


Figure 50: Temporal trends in monthly SWSI

Figure 51: Temporal trends in SDI

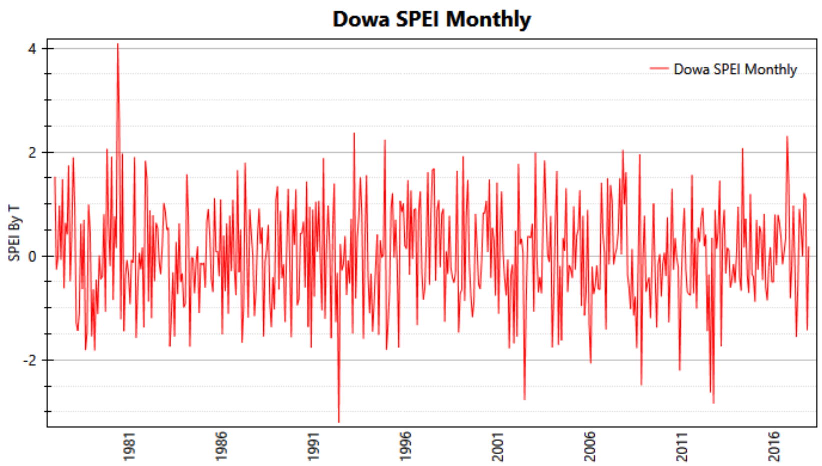


Figure 52: Temporal trends in monthly SPEI

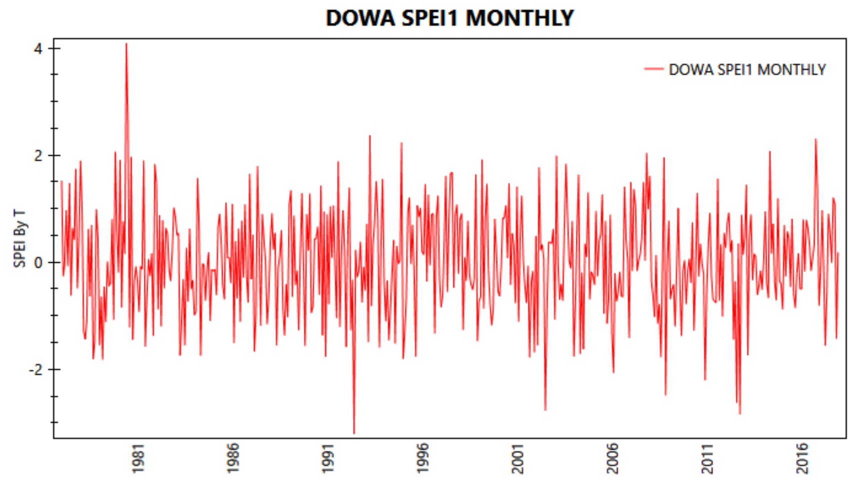


Figure 53: Temporal trends in SPEI1

In Mchinji district, SPI-3 detected extreme droughts in 1991, 1994, and 2005. The 1991 drought started in December, had a duration of 91 days and the severity of 3.383. The 1994 drought had a duration of 212 days, the severity of 5.372, and began in December. The 2005 drought had the severity of 2.378, duration of 122 days and started in March. This showed that the most extreme drought was the 1994 drought in terms of onset and intensity. Severe droughts were noted in February 1994 and November 2011. The 1999 drought, as pointed out by SPI-3, was more severe that the 1994 drought with regards to duration and severity. The 1999 drought had duration of 121 days and severity of 1.89 while that of 1994 had duration of 120 days and severity of 1.759. Moderate droughts were depicted in 1982, 1987, 1990, 2002, 2013, and 2014.SPI-6 observed four extreme droughts in 1991, 1994, 2005, and 2013. The 2013 was the most extreme with duration of 214 days beginning from March and the severity of 2.192. Severe drought was notable in 2014. This severe drought started in March, had duration of 214 days and the severity of 1.883. Four moderate droughts were noted in 1987, 1990, 2002, and 2003. SPI-12 identified three extreme droughts in 1991, 2005, and 2013. The 1994 drought which started in November was the most extreme with severity of 16.275. There were no remarkable severe droughts under SPI-12 and moderate droughts were noted in 1987. The rest of the seasons indicated mild droughts. From this analysis, it showed that meteorological droughts are not normally experienced in the Mchinji district. This could be because the district receives a considerably higher amount of rainfall, which provides enough moisture for crop growth. The droughts which were observed could be due to the temporal and spatial variation of rainfall within the pre-stated time scales. SPEI did not note any extreme drought. However, SPEI found severe drought in 1983, and moderate droughts in 1983, 1985, 1988, 2001, and 2017. SPEI1, on the other hand, pinpointed one extreme drought in 1983; one severe drought in 2004; five moderate droughts in 1984, 1991, 1994, 2002, and 2016. Monthly PDSI indicated a lot of extreme droughts in 1979, 1984, 1987, 1990, 1993, 1998, 2003, 2005, 2010, and 2012. Severe droughts were noted in 1999 and 2011. The index did not mark any moderate droughts in the district. ARI and ETDI marked eight extreme agricultural droughts in 1977, 1978, 1980, 1981, 1982, 1984, 2005, and 2015. The 1977 and 1978 extreme droughts were similar in terms of onset and duration but differed in intensity. Both droughts started in May and lasted for 214 days. The 1977 drought had the severity of 6.125 while the 1978 drought had severity of 5.679. The 1980 extreme drought started in July, had duration of 153 days and severity of 5.398. The 1981 and 1984 extreme droughts had an onset similarity on as both began in July but differed in terms of duration (215 days for 1982 and 123 days for 1984) and severity (6.64 for 1981 and 4.897 for 1984). The agricultural drought indices further noted one severe drought in 1992 and two moderate droughts in 1994 and 1998. The 1992 severe drought started in February and lasted for 90 days with severity of 3.417. The moderate droughts had the same duration of 92 days but differed in terms of onset and severity. The 1994 moderate drought started in March and had severity of 2.645 while 1998 commenced in May and had severity of 2.888. The rest of the season registered mild droughts. SDI and SWSI indicated that almost all the study period Mchinji experienced extreme hydrological drought with the most extreme starting in March 1994, taking 702 days and having severity of 49.416. It was further observed that hydrological droughts were beginning in February, March, April, May, June, and July.

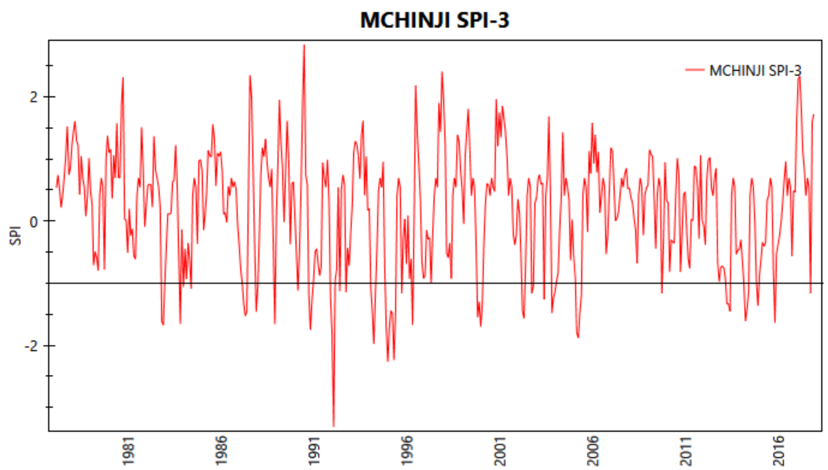


Figure 54: Temporal trends in SPI-3

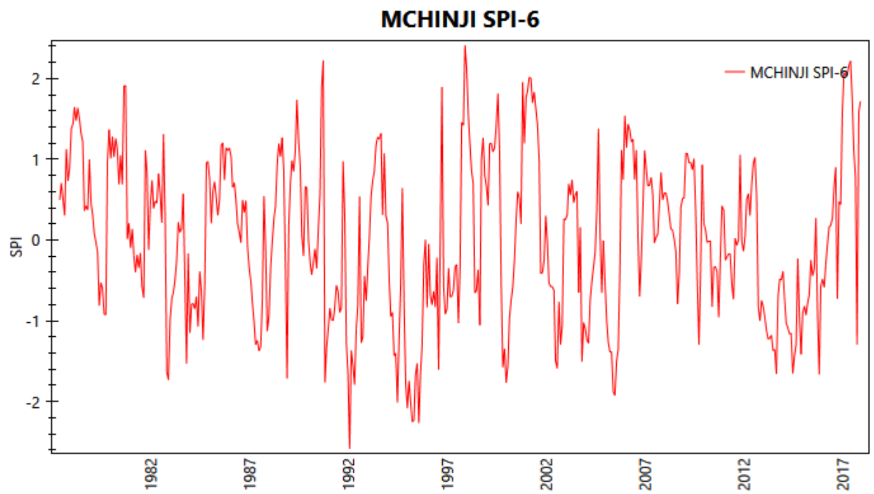


Figure 55: Temporal trends in SPI-6

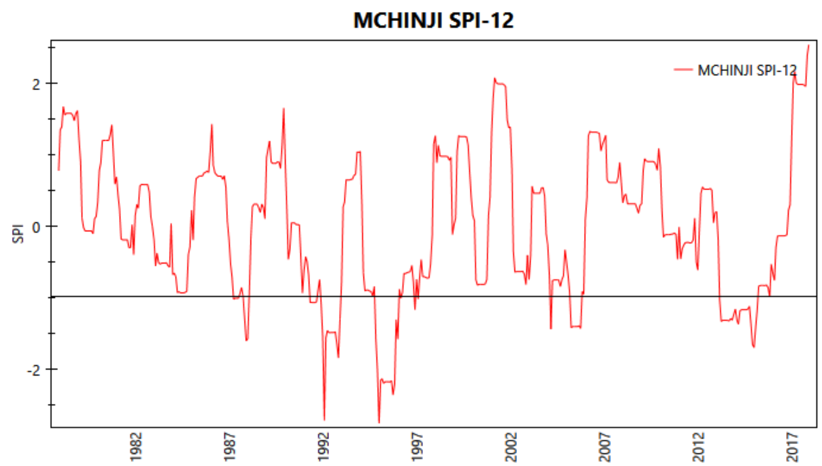


Figure 56: Temporal trends in SPI-12

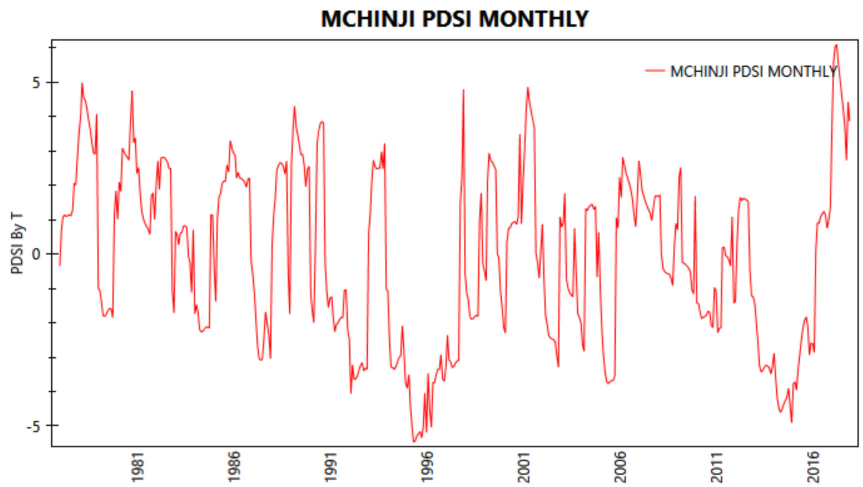


Figure 57: Temporal trends in monthly PDSI

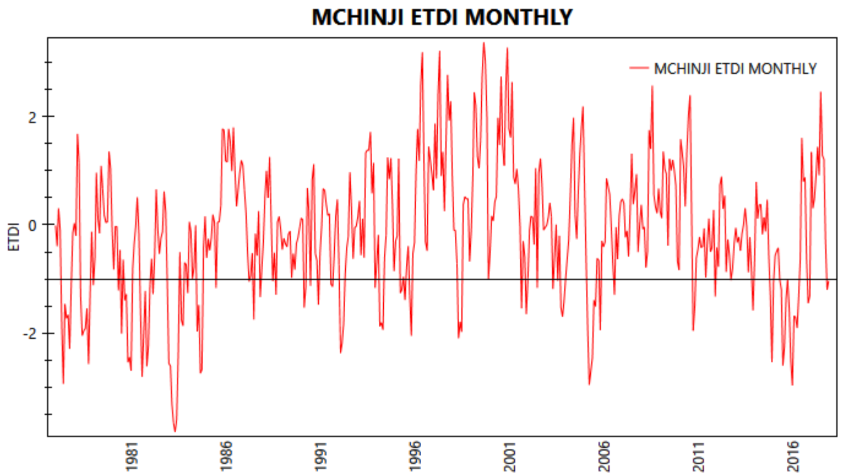


Figure 58: Temporal trends in monthly ETDI

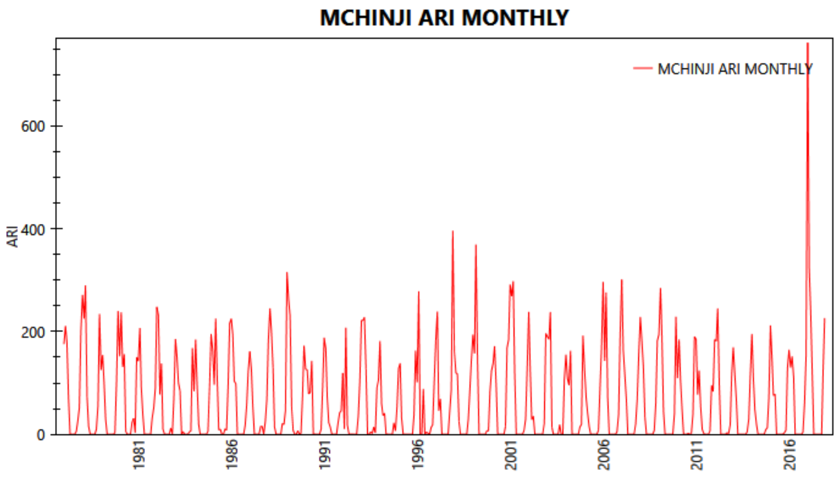


Figure 59: Temporal trends in monthly ARI

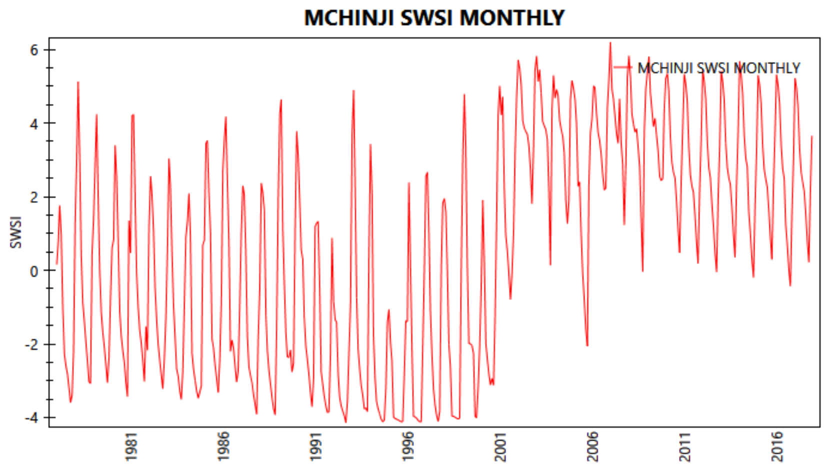


Figure 60: Temporal trends in monthly SWSI

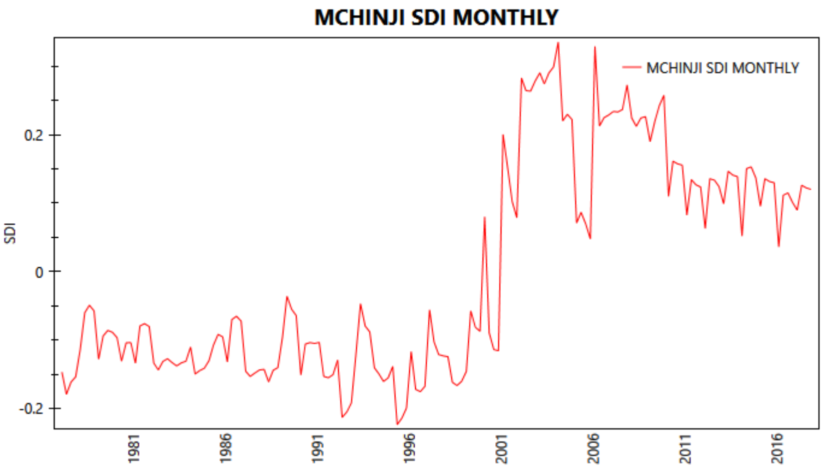


Figure 61: Temporal trends in SDI

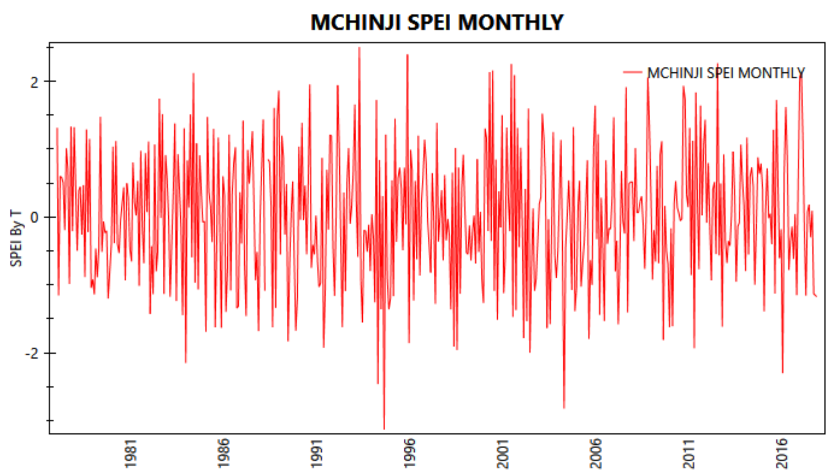


Figure 62: Temporal trends in monthly SPEI

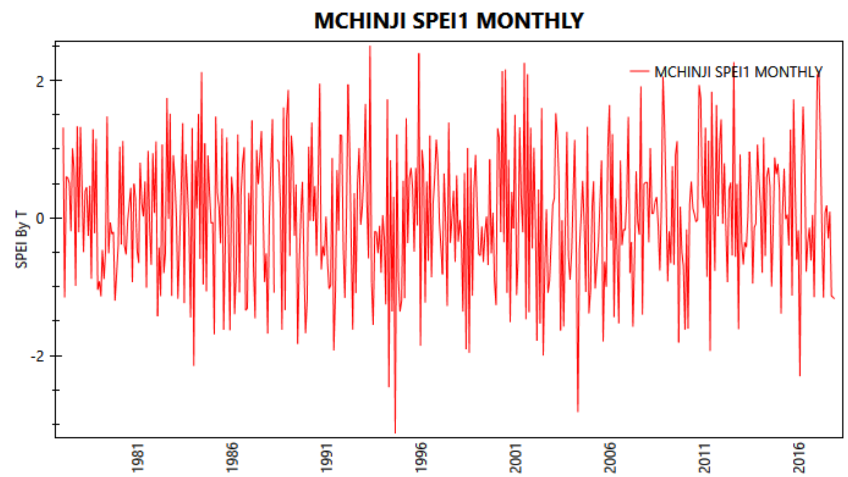


Figure 63: Temporal trends in SPEI1

In Ntchisi district, SPI-3 detected three extreme droughts in 1994, 1999 and 2005. The 1994 drought started in December, had duration of 212 days and severity of 5.245. The 1999 extreme drought also started in December, had duration of 91 days and severity of 2.126. The 2005 extreme drought started in March, had duration of 122 days and severity of 4.52. The SPI time scale of three months further noted only one severe drought in 1985. The severe drought started in March, duration of 61 days and severity of 1.715. SPI-3 further two moderate droughts in 2006 and 2013. The 2006 moderate drought started in January, had duration of 59 days and severity of 1.291; 2013 drought started in April and lasted for 91 days with severity of 1.395. SPI-6 marked three extreme droughts in 1994, 1999 and 2005. The 1994 extreme drought started in December, lasted for 304 days and severity of 8.921. The 1999 extreme drought also commenced in December, had duration of 183 days and severity of 2.747. The 2005 extreme drought started in May, had duration of 153 days and severity of 5.1. One severe drought which lasted for 120 days and severity of 1.799 was identified in 2006. Two moderate droughts were also noted in 1994 and 2013. The 1994 started in March, lasted for 184 days and ad severity of 1.003 whilst the 2013 moderate drought started in July, had duration of 92 days and severity of 1.496.

SPI-12 noted three extreme droughts in 1994, 2000 and 2005. The most extreme droughts was the one that started in April with duration of 640 days and severity of 14.327. The 2005 drought was less intense than the 1994 drought but more intense than the 2000 drought. The 2005 drought started in November, took 365 days with severity of 5.572 whilst the 2000 drought started in March with duration of 275 days and severity of 2.222. The SPI-12 index did not observe any severe drought. One moderate drought was noted in April 2013 with duration of 334 days and severity of 1.459.

Using SPEI, no extreme drought conditions were observed in Ntchisi district. However, SPEI noted severe drought conditions with severity of 1.63 in February 1977, for 28 days. Moderate drought conditions were noted in 1979, 1981, and 2012. Most of the dry conditions in the district indicated mild conditions based on SPEI. Most of these conditions were over a period from November, December, January, February, March and April. SPEI1 noted extreme drought conditions in 1977, 2006, and 2016. The 2006 drought which started in August was more intense (severity of 4.116) and long (92 days). The 1977 and 2016 droughts were similar in terms of duration as both took 31 days but differed in terms of onset and severity. The 1977 drought started in July with severity of 2.276 whilst that of 2016 started in May with severity of 2.998. PDSI noted extreme drought conditions in 1985, 1990, 1992, 1994, 1998, 1999, 2002, 2005, 2008, 2011, and 2013; moderate droughts in 1982 and 1990 ; and no severe droughts. ETDI, and ARI indicated that the district experienced more of moderate to mild drought conditions whereas SDI and SWSI indicated that the region faced more of extreme drought conditions.

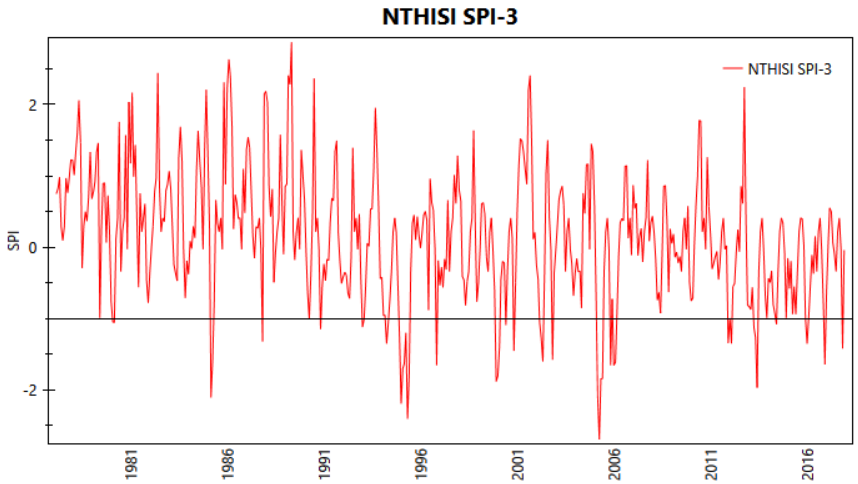


Figure 64: Temporal trends in SPI-3

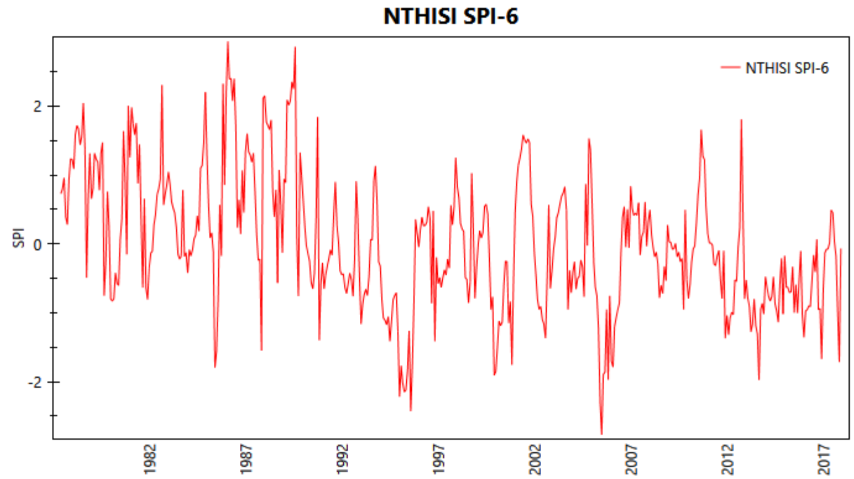


Figure 65: Temporal trends in SPI-6

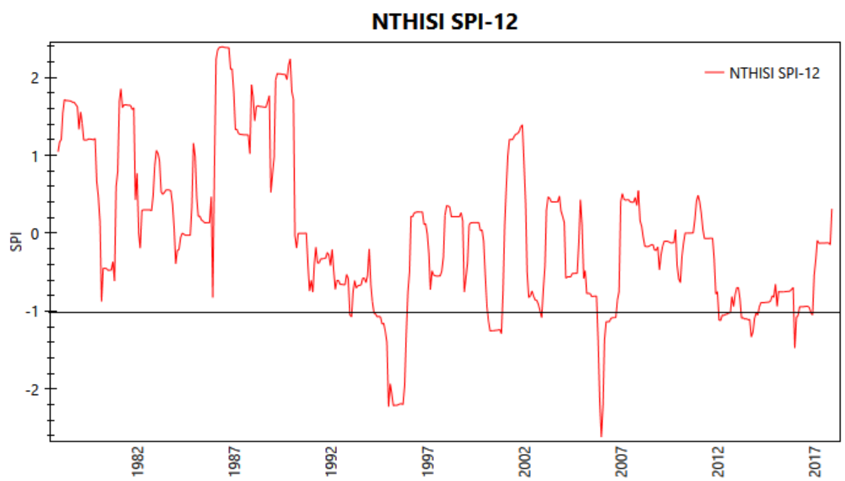


Figure 66: Temporal trends in SPI-12

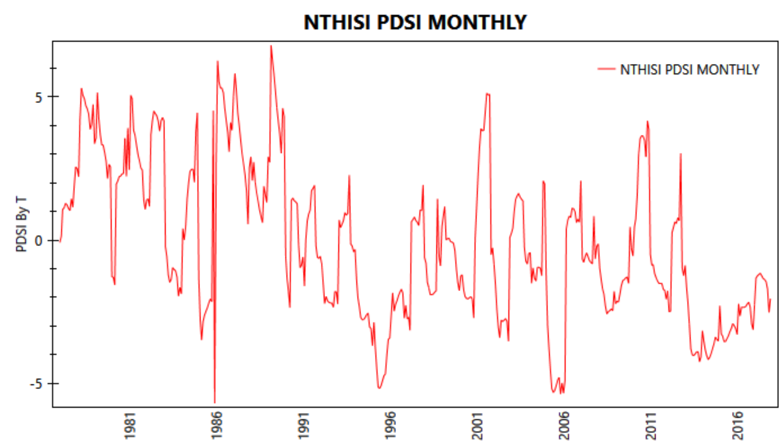


Figure 67: Temporal trends in monthly PDSI

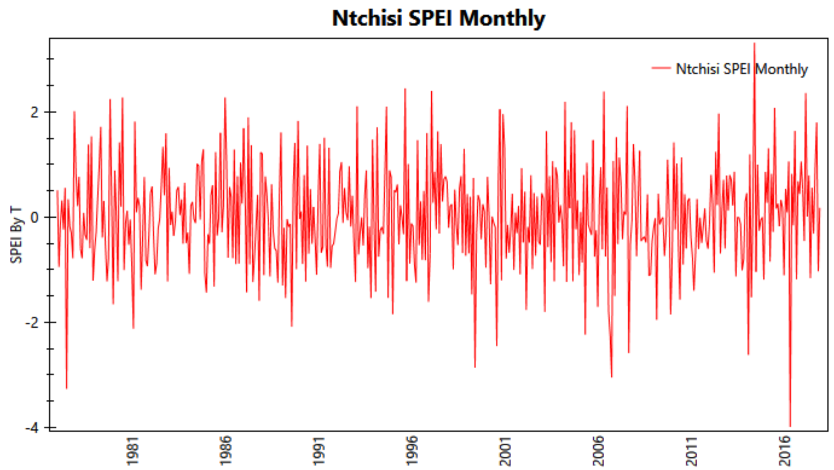


Figure 68: Temporal trends in monthly SPEI

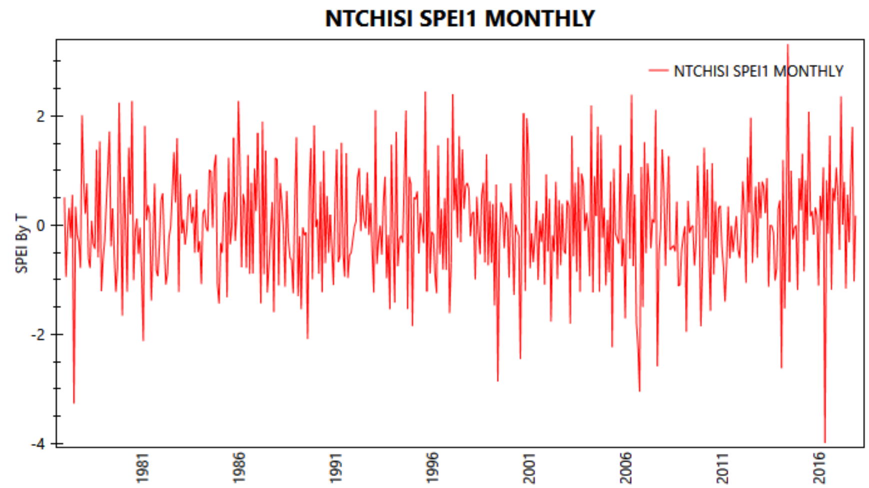


Figure 69: Temporal trends in SPEI1

4.13 Spatial Analysis of Droughts

The spatial distribution of drought severity conditions was assessed using the Kriging interpolation technique using the point data. Using Kriging interpolation method in ArcGIS 10.5, drought severities for Kasungu ADD were mapped for the driest years namely 1994, 1999, 2005 and 2015.

Results indicate that the largest part of Kasungu district showed higher severities with an average of 3.857 (3.443-4.171) in 1994, highest drought severities were noted in Mchinji and parts of Ntchisi in 1994 with an average of 4.7645 (4.171-5.358). In 1999, most parts of Kasungu district exhibited higher drought severities with an average of 3.01 (2.384- 3.636) whereas Dowa and Ntchisi also had dry conditions. Lower drought severity was noted in Mchinji district. In 2005, most parts in Dowa district and Ntchisi experienced drought events with higher severities than Mchinji and Kasungu district. In 2015, results indicated that Kasungu experienced highest drought severities whereas Mchinji displayed lower severities.

With reference to the topography of the ADD, Kasungu is at a lower elevation than most areas. This suggests that the area receives less rainfall as there is reduced moisture into the atmosphere responsible for rainfall formation. This explains why the area is more vulnerable to droughts.

On the contrary, some parts of Mchinji district, some parts of Dowa district and some parts of Ntchisi are at higher elevations such that they receive better amount of rainfall enough for crop production. Notably, these areas are less vulnerable to drought risks. This notion agrees with Wambua et al. (2015) who stated that areas at lower elevations are more prone to drought risks.

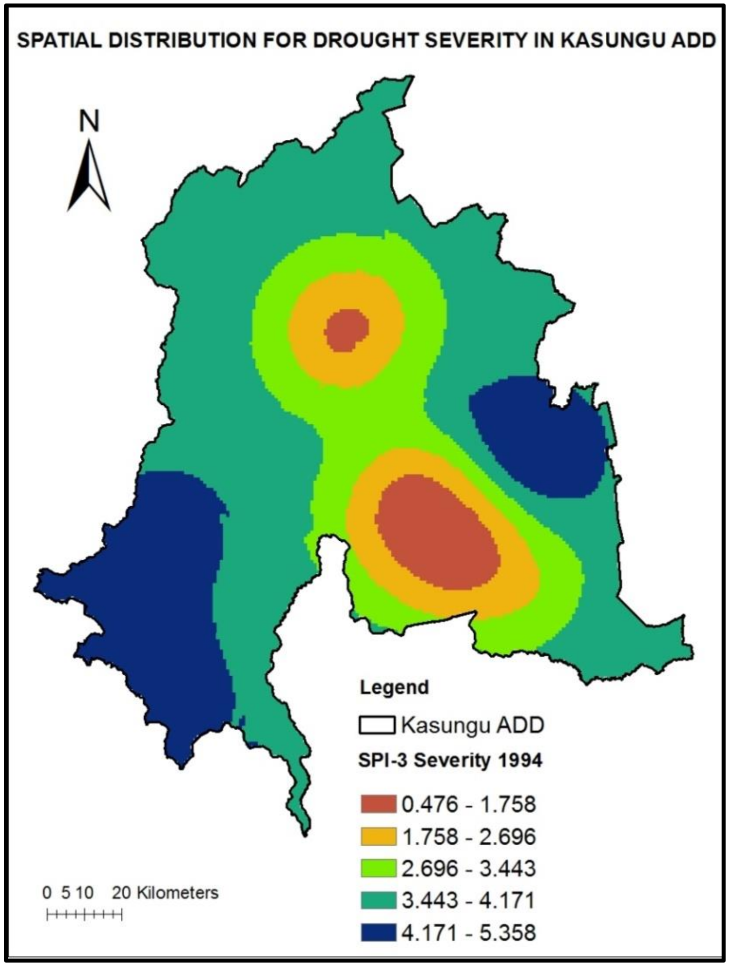


Figure 70: SPI-3 Severity for 1994

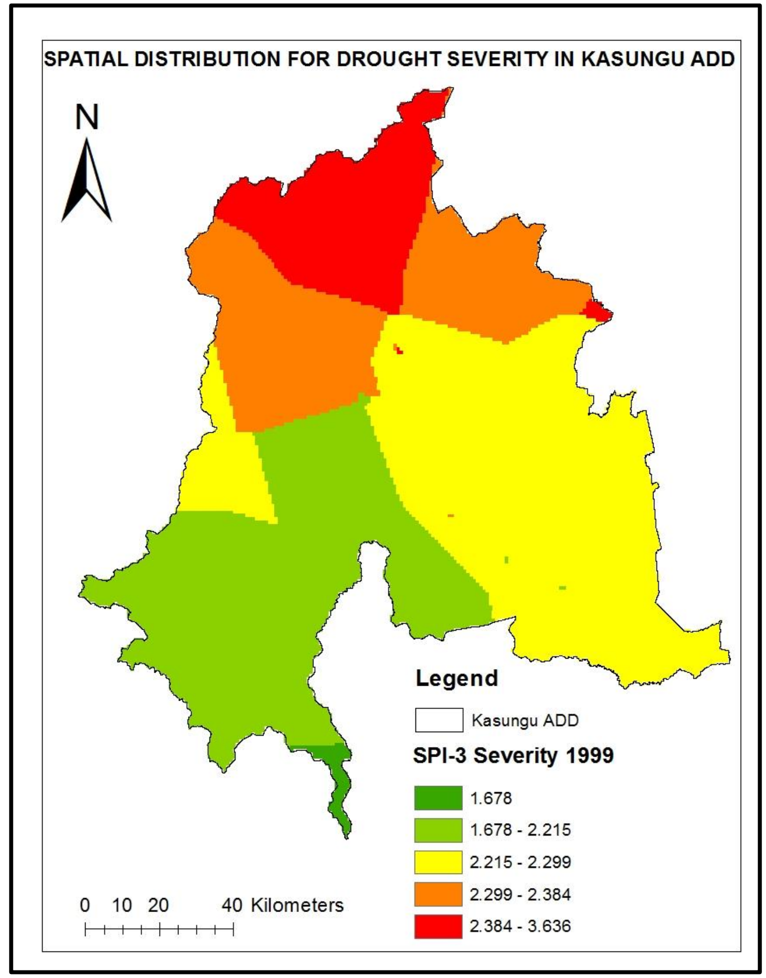


Figure 71: SPI-3 Severity for 1999

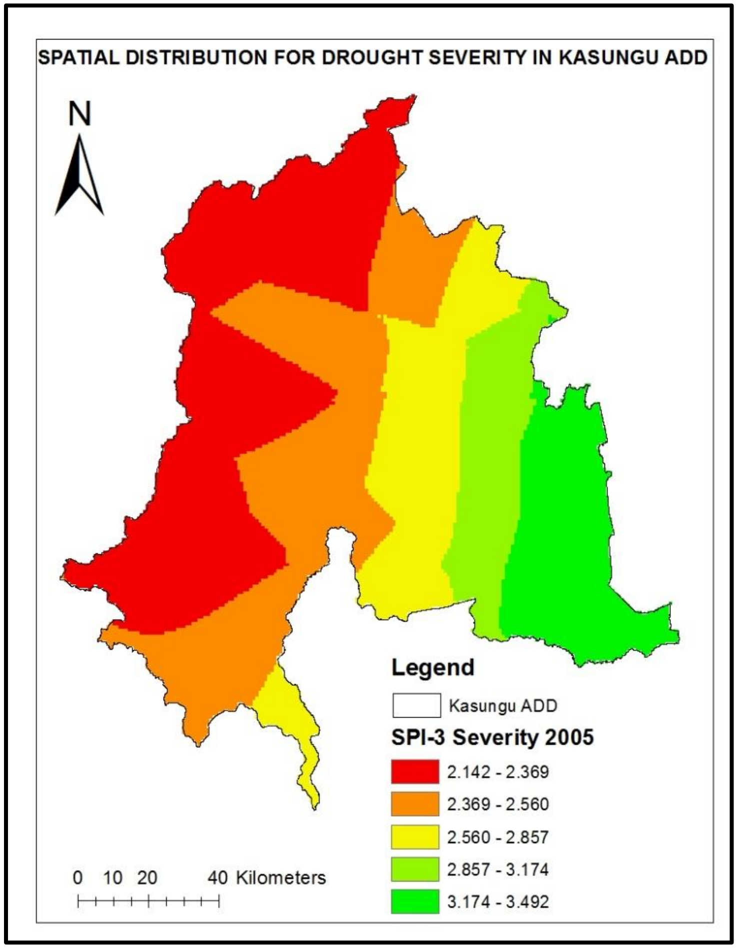


Figure 72: SPI-3 Severity for 1994

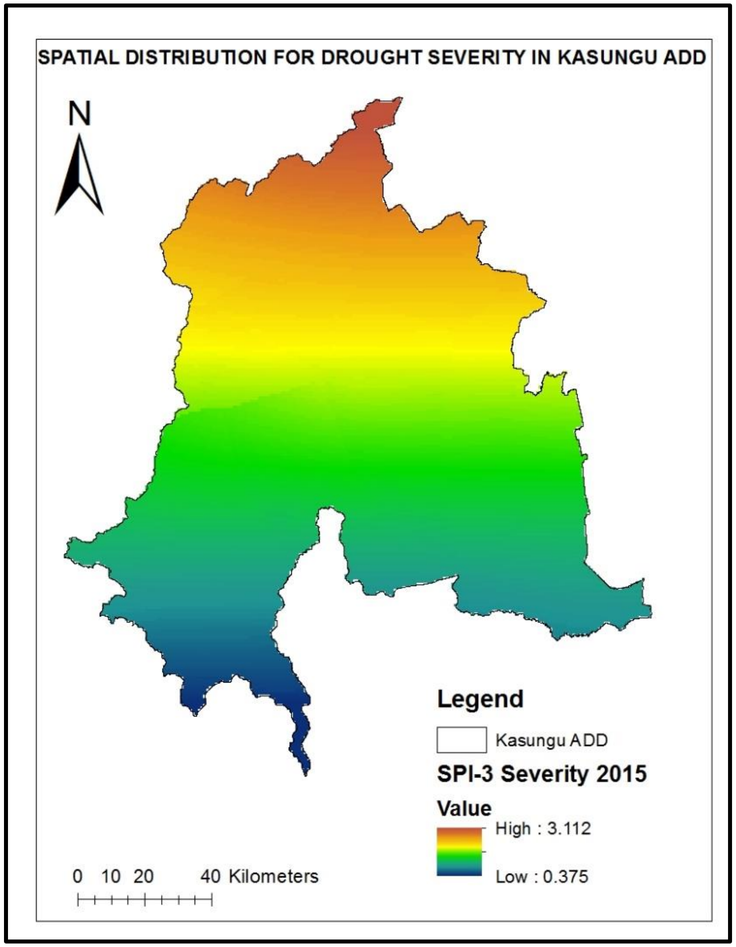


Figure 73: SPI-3 Severity for 1994

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The study was aimed at characterizing droughts in the spatiotemporal regimes in view of the best irrigation practices in Central Malawi. With the help of DMAP software, the drought indices revealed that Kasungu ADD has experienced more of moderate and mild droughts (meteorological and agricultural) and extreme hydrological droughts. Kasungu district experienced more droughts followed by Dowa, Ntchisi and Mchinji. Mann-Kendall test in corroboration with linear regression analysis revealed decreasing trends in the rainfall patterns of most areas in the ADD. There has been a direct link between rainfall variability and drought occurrence in the ADD. The DEM showed that Mchinji, Dowa and some parts of Ntchisi have highlands which contribute to rainfall in the region. However, these regions contribute less amount of soil water content as most of the rainfall in such area is converted to runoff and not infiltration.

The study has further showed that climate-smart irrigation technologies such as drip irrigation, micro-sprinkler irrigation and piped gravity systems are not largely practiced in the ADD. This would provide the much needed stimulus for rapid expansion of smart water saving technologies in the ADD. The ADD uses more surface irrigation systems which have very low efficiencies. The study has also determined that most high yielding crops grown in the ADD require frequent irrigation but during longer periods of time as shown by the crop water requirements and scheduling.

The study also noted that in order to monitor and assess a drought effectively, no single drought index is sufficient because they give different results which need a very critical analysis. Given that crop production is influenced by a combination of factors including streamflow, soil moisture condition, temperature, evapotranspiration and rainfall, this study found the importance of using multiple indices to effectively monitor a drought.

This study further concludes that a good understanding of spatial and temporal characteristics of droughts in view of best irrigation practices in a region where irrigation is practiced is required for efficient and effective water resources management.

5.2 Recommendations

Based on the findings from this study, it is recommended that:

- Comprehensive in -situ study on soil types, residual soil moisture and water holding capacity be done in the ADD to determine causes for moisture variations in the catchment and verify satellite based soil moisture. The usage of satellite images, remote sensing and GIS must be enhanced.
- Ministry of Irrigation and Water Development must improve their long term stream flow data for better calculation of hydrological based drought indices. This calls for the provision of gauges in rivers which have no gauges in the ADD. As if that was not enough, streamflow data must always be collected and updated in the ADD.

- The Meteorological Services Department must enhance and expand their meteorological stations so that early warning systems monitoring can be effective, reliable and efficient in the ADD.

- The Ministry of Agriculture should promote the usage of climate smart agriculture especially drip irrigation, micro-sprinklers and gravity-fed piped systems in areas with high elevation. The Ministry should also promote crop diversification especially replacing some varieties of maize with drought resistant crops such as cassava and sweet potatoes.

- Rainfall harvesting should be promoted in the ADD since most areas are characterized by varying rainfall patterns. Since the ADD is dominated by farming as a socio-economic activity, rainfall harvesting would increase water availability which could enhance crop production hence food security.

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APPENDIX

Table 21: Climate characteristics, rainfalls, and ETo of Kasungu district (average for 1977–2017 period) obtained using the CLIMWAT tool attached to the CROPWAT software.

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo	Rain	Eff. Rainfall
	°C	°C	%	km/day	hours	MJ/m^2/day	mm/day	mm	mm
January	18.8	27.5	84.0	173.0	5.0	18.0	3.8	206	138.1
February	18.3	27.9	85.0	207.0	5.4	18.5	3.9	195.6	134.4
March	15.8	28.0	84.0	242.0	6.8	19.9	4.1	131.1	103.6
April	12.8	27.7	80.0	259.0	8.4	20.5	4.2	22.7	21.9
May	10.5	27.1	76.0	233.0	8.7	18.8	3.8	2.1	2.1
June	10.3	25.5	71.0	181.0	8.7	17.7	3.4	0	0
July	12.4	24.9	61.0	164.0	9.0	18.5	3.6	0.1	0.1
August	15.5	26.3	60.0	156.0	9.2	20.6	4.1	0.1	0.1
September	18.1	28.9	51.0	181.0	9.8	23.6	5.4	0.3	0.3
October	19.4	30.9	52.0	190.0	9.7	24.9	6.1	4.7	4.7
November	19.1	28.9	63.0	216.0	8.5	23.4	5.5	42.7	39.8
December	18.6	28.2	79.0	181.0	5.8	19.2	4.2	175.7	126.3
Total								781.1	571.3
Average	15.8	27.6	71.0	199.0	7.9	20.3	4.3		

Table 22: Climate characteristics, rainfalls, and ETo of Dowa district (average for 1977–2017 period) obtained using the CLIMWAT tool attached to the CROPWAT software.

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo	Rain	Eff. Rainfall
	°C	°C	%	km/day	hours	MJ/m^2/day	mm/day	mm	mm
January	17.7	26.3	83	294	5.3	18.6	3.91	246	149.2
February	17.3	26.5	84	285	5.4	18.6	3.83	192.6	133.2
March	17	26.4	83	320	5.8	18.4	3.83	147.8	112.8
April	14.8	25.8	80	354	7.5	19.1	3.93	32.1	30.5
May	11.7	25.3	73	380	7.7	17.2	3.98	1.4	1.4
June	8.9	23.5	68	432	7.2	15.6	3.93	0.6	0.6
July	8.6	22.9	66	467	7.4	16.3	4.07	0.4	0.4
August	10.5	24.7	59	493	7.9	18.7	5.09	0.2	0.2
September	13.1	27.5	54	536	8.3	21.3	6.45	0.1	0.1
October	16.1	29.3	53	562	9.1	24	7.41	4.3	4.3
November	17.9	29.6	63	484	7.5	21.9	6.35	43	40
December	18.1	27.5	79	346	5.7	19.1	4.39	183.4	129.6
Total								851.9	602.3
Average	14.3	26.3	70	413	7.1	19.1	4.76		

Table 23: Climate characteristics, rainfalls, and ETo of Mchinji district (average for 1977–2017 period) obtained using the CLIMWAT tool attached to the CROPWAT software.

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo	Rain	Eff. Rainfall
	°C	°C	%	km/day	hours	$MJ/m^2/day$	mm/day	mm	mm
January	18.2	26.7	84	121	5.3	18.6	3.79	280.4	153
February	17.8	27.1	85	112	5.1	18.1	3.67	214.2	140.8
March	17.3	27.2	83	121	6.5	19.3	3.85	166.9	122.3
April	15.1	26.7	80	138	7.7	19.3	3.74	61.8	55.7
May	12.1	26.1	73	138	8.2	18	3.46	5.8	5.7
June	9.5	24.3	68	156	7.1	15.4	3.08	0.3	0.3
July	9.3	23.8	65	173	7.8	16.7	3.28	0.2	0.2
August	10.4	25.8	59	190	7.8	18.5	4.00	0.6	0.6
September	13	28.4	52	216	7.8	20.5	5.05	2.9	2.9
October	15.9	30.3	53	225	8.9	23.6	5.87	17	16.5
November	17.8	30.4	62	207	7.7	22.2	5.46	83.4	72.3
December	18.4	28.2	79	156	5.5	18.9	4.14	238.4	147.5
Total								1071.9	717.9
Average	14.6	27.1	70	163	7.1	19.1	4.12		

Table 24: Climate characteristics, rainfalls, and ETo of Ntchisi district (average for 1977–2017 period) obtained using the CLIMWAT tool attached to the CROPWAT software.

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo	Rain	Eff. Rainfall
	°C	°C	%	km/day	hours	$MJ/m^2/day$	mm/day	mm	mm
January	21.1	28.5	83	138	5.4	18.7	3.95	281.8	153.2
February	21.4	28.6	81	147	5.7	19	4.06	240.5	148
March	20.9	28.5	81	164	6.9	20	4.17	202.5	136.9
April	20.1	28	77	190	8	19.9	4.16	58.7	53.2
May	17.9	26.9	72	251	8.7	18.8	4.07	7.6	7.5
June	15.7	25.7	66	268	9.2	18.3	4.04	1.3	1.3
July	15.3	25.4	65	242	9	18.5	3.97	2.4	2.4
August	15.9	26.9	62	225	9.5	21.1	4.54	0.7	0.7
September	18	29.5	59	233	9.9	23.8	5.51	1	1
October	20.8	31.8	58	242	9.9	25.2	6.31	6.6	6.5
November	22	31.5	63	225	9	24.2	6.01	52.3	47.9
December	21.3	29.4	77	181	6.6	20.5	4.59	237.7	147.3
Total								1093.1	705.9
Average	19.2	28.4	70	209	8.2	20.7	4.62		

Table 25: Crop Water Requirements for Maize in Kasungu

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.3	1.06	5.3	0	5.3
Jul	2	Init	0.3	1.08	10.8	0	10.8
Jul	3	Deve	0.35	1.32	14.5	0	14.4
Aug	1	Deve	0.59	2.33	23.3	0	23.3
Aug	2	Deve	0.84	3.48	34.8	0	34.7
Aug	3	Mid	1.1	5	55	0.1	54.9
Sep	1	Mid	1.18	5.87	58.7	0	58.6
Sep	2	Mid	1.18	6.36	63.6	0	63.6
Sep	3	Mid	1.18	6.62	66.2	0.4	65.8
Oct	1	Late	1.17	6.91	69.1	0.1	69
Oct	2	Late	0.97	5.98	59.8	0.1	59.7
Oct	3	Late	0.68	4.05	44.6	4.5	40.1
Nov	1	Late	0.43	2.47	17.3	5.4	9.5
Total					522.8	10.8	509.7

Table 26: Crop Water Requirements for Pulses in Kasungu

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.4	1.42	7.1	0	7.1
Jul	2	Init	0.4	1.44	14.4	0	14.4
Jul	3	Deve	0.45	1.69	18.6	0	18.6
Aug	1	Deve	0.68	2.7	27	0	27
Aug	2	Deve	0.93	3.84	38.4	0	38.3
Aug	3	Mid	1.12	5.11	56.3	0.1	56.2
Sep	1	Mid	1.14	5.65	56.5	0	56.5
Sep	2	Mid	1.14	6.13	61.3	0	61.3
Sep	3	Mid	1.14	6.37	63.7	0.4	63.3
Oct	1	Late	1.03	6.05	60.5	0.1	60.4
Oct	2	Late	0.64	3.96	39.6	0.1	39.5
Oct	3	Late	0.39	2.31	6.9	1.2	4.7
Total					450.3	2.1	447.2

Table 27: Crop Water Requirements for Cassava in Kasungu

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.5	1.77	8.8	0	8.8
Jul	2	Init	0.5	1.8	18	0	18
Jul	3	Deve	0.5	1.9	20.9	0	20.9
Aug	1	Deve	0.64	2.53	25.3	0	25.2
Aug	2	Deve	0.85	3.52	35.2	0	35.1
Aug	3	Mid	1.07	4.86	53.5	0.1	53.4
Sep	1	Mid	1.14	5.65	56.5	0	56.5
Sep	2	Mid	1.14	6.13	61.3	0	61.3
Sep	3	Mid	1.14	6.38	63.8	0.4	63.4
Oct	1	Mid	1.14	6.7	67	0.1	66.9
Oct	2	Late	1.1	6.76	67.6	0.1	67.5
Oct	3	Late	0.96	5.73	63	4.5	58.5
Nov	1	Late	0.83	4.7	47	7.8	39.3
Nov	2	Late	0.75	4.12	8.2	2.2	8.2
Total					596.1	15.3	583

Table 28: Crop Water Requirements for Groundnuts in Kasungu

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.4	1.42	7.1	0	7.1
Jul	2	Init	0.4	1.44	14.4	0	14.4
Jul	3	Deve	0.4	1.52	16.7	0	16.7
Aug	1	Deve	0.54	2.13	21.3	0	21.2
Aug	2	Deve	0.75	3.1	31	0	30.9
Aug	3	Deve	0.97	4.42	48.6	0.1	48.5
Sep	1	Mid	1.13	5.63	56.3	0	56.3
Sep	2	Mid	1.14	6.14	61.4	0	61.4
Sep	3	Mid	1.14	6.39	63.9	0.4	63.5
Oct	1	Mid	1.14	6.72	67.2	0.1	67.1
Oct	2	Late	1.13	6.96	69.6	0.1	69.5
Oct	3	Late	0.96	5.72	62.9	4.5	58.5
Nov	1	Late	0.73	4.18	41.8	7.8	34
Nov	2	Late	0.6	3.32	6.6	2.2	6.6
Total					568.8	15.3	555.7

Table 29: Crop Water Requirements for Vegetables in Kasungu

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.7	2.48	12.4	0	12.4
Jul	2	Init	0.7	2.52	25.2	0	25.2
Jul	3	Deve	0.72	2.73	30	0	30
Aug	1	Deve	0.83	3.28	32.8	0	32.8
Aug	2	Deve	0.94	3.89	38.9	0	38.9
Aug	3	Mid	1.03	4.69	51.6	0.1	51.6
Sep	1	Mid	1.04	5.16	51.6	0	51.5
Sep	2	Mid	1.04	5.59	55.9	0	55.9
Sep	3	Late	1.02	5.72	57.2	0.4	56.8
Oct	1	Late	0.96	5.68	45.4	0.1	45.3
Total					401.1	0.7	400.3

Table 30: Crop Water Requirements for Maize in Dowa

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.3	1.21	10.9	0.1	10.7
Jul	2	Init	0.3	1.22	12.2	0.1	12.1
Jul	3	Deve	0.45	1.99	21.9	0.1	21.8
Aug	1	Deve	0.77	3.65	36.5	0.1	36.5
Aug	2	Deve	1.07	5.46	54.6	0.1	54.5
Aug	3	Mid	1.33	7.39	81.3	0.1	81.2
Sep	1	Mid	1.36	8.16	81.6	0	81.5
Sep	2	Mid	1.36	8.77	87.7	0	87.7
Sep	3	Mid	1.36	9.21	92.1	0.2	91.9
Oct	1	Late	1.29	9.32	93.2	0	93.1
Oct	2	Late	0.97	7.41	74.1	0	74.1
Oct	3	Late	0.62	4.45	49	4.4	44.6
Nov	1	Late	0.38	2.6	7.8	2.3	3.9
Total					702.7	7.5	693.6

Table 31: Crop Water Requirements for Pulses in Dowa

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.4	1.61	14.5	0.1	14.3
Jul	2	Init	0.4	1.63	16.3	0.1	16.1
Jul	3	Deve	0.54	2.39	26.2	0.1	26.1
Aug	1	Deve	0.84	3.98	39.8	0.1	39.7
Aug	2	Deve	1.12	5.7	57	0.1	57
Aug	3	Mid	1.25	6.92	76.1	0.1	76
Sep	1	Mid	1.25	7.48	74.8	0	74.8
Sep	2	Mid	1.25	8.05	80.5	0	80.5
Sep	3	Late	1.24	8.42	84.2	0.2	84
Oct	1	Late	0.96	6.91	69.1	0	69
Oct	2	Late	0.53	4.03	36.3	0	36.3
Total					574.7	0.9	573.8

Table 32: Crop Water Requirements for Cassava in Dowa

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.5	2.01	18.1	0.1	17.9
Jul	2	Init	0.5	2.03	20.3	0.1	20.2
Jul	3	Deve	0.53	2.36	25.9	0.1	25.8
Aug	1	Deve	0.77	3.64	36.4	0.1	36.3
Aug	2	Deve	1.02	5.19	51.9	0.1	51.9
Aug	3	Mid	1.24	6.87	75.5	0.1	75.5
Sep	1	Mid	1.26	7.56	75.6	0	75.6
Sep	2	Mid	1.26	8.14	81.4	0	81.4
Sep	3	Mid	1.26	8.54	85.4	0.2	85.2
Oct	1	Late	1.26	9.1	91	0	91
Oct	2	Late	1.17	8.93	89.3	0	89.3
Oct	3	Late	1.03	7.41	81.5	4.4	77.1
Nov	1	Late	0.9	6.1	48.8	6.2	41.1
Total					781.2	11.4	768.2

Table 33: Crop Water Requirements for Groundnuts in Dowa

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.4	1.61	14.5	0.1	14.3
Jul	2	Init	0.4	1.63	16.3	0.1	16.1
Jul	3	Deve	0.43	1.91	21	0.1	20.9
Aug	1	Deve	0.65	3.11	31.1	0.1	31
Aug	2	Deve	0.9	4.57	45.7	0.1	45.6
Aug	3	Mid	1.15	6.38	70.2	0.1	70.1
Sep	1	Mid	1.25	7.49	74.9	0	74.9
Sep	2	Mid	1.25	8.06	80.6	0	80.6
Sep	3	Mid	1.25	8.46	84.6	0.2	84.4
Oct	1	Mid	1.25	9.03	90.3	0	90.3
Oct	2	Late	1.2	9.16	91.6	0	91.6
Oct	3	Late	0.98	7.05	77.6	4.4	73.2
Nov	1	Late	0.77	5.2	41.6	6.2	33.9
Total					739.8	11.4	726.9

Table 34: Crop Water Requirements for Vegetables in Dowa

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.7	2.81	25.3	0.1	25.2
Jul	2	Init	0.7	2.85	28.5	0.1	28.3
Jul	3	Deve	0.77	3.41	37.5	0.1	37.4
Aug	1	Deve	0.93	4.4	44	0.1	43.9
Aug	2	Deve	1.07	5.46	54.6	0.1	54.6
Aug	3	Mid	1.14	6.31	69.4	0.1	69.4
Sep	1	Mid	1.14	6.83	68.3	0	68.3
Sep	2	Late	1.14	7.34	73.4	0	73.4
Sep	3	Late	1.1	7.43	74.3	0.2	74
Oct	1	Late	1.05	7.6	30.4	0	30.4
Total					505.7	0.8	504.8

Table 35: Crop Water Requirements for Maize in Mchinji

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.3	0.96	4.8	0	4.8
Jul	2	Init	0.3	0.98	9.8	0.1	9.8
Jul	3	Deve	0.35	1.24	13.6	0.1	13.5
Aug	1	Deve	0.61	2.29	22.9	0.1	22.7
Aug	2	Deve	0.88	3.51	35.1	0.1	34.9
Aug	3	Mid	1.15	5.01	55.1	0.4	54.6
Sep	1	Mid	1.24	5.82	58.2	0.4	57.8
Sep	2	Mid	1.24	6.25	62.5	0.5	62.1
Sep	3	Mid	1.24	6.59	65.9	2.1	63.8
Oct	1	Late	1.23	6.97	69.7	2.7	67
Oct	2	Late	1.02	6.07	60.7	3.6	57.1
Oct	3	Late	0.71	4.09	45	10.4	34.6
Nov	1	Late	0.44	2.49	17.4	12.1	0.1
Total					520.7	32.7	482.8

Table 36: Crop Water Requirements for Pulses in Mchinji

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.4	1.28	6.4	0	6.4
Jul	2	Init	0.4	1.31	13.1	0.1	13
Jul	3	Deve	0.45	1.58	17.4	0.1	17.3
Aug	1	Deve	0.7	2.62	26.2	0.1	26.1
Aug	2	Deve	0.95	3.82	38.2	0.1	38
Aug	3	Mid	1.16	5.04	55.5	0.4	55.1
Sep	1	Mid	1.17	5.52	55.2	0.4	54.8
Sep	2	Mid	1.17	5.93	59.3	0.5	58.8
Sep	3	Mid	1.17	6.25	62.5	2.1	60.3
Oct	1	Late	1.06	6	60	2.7	57.3
Oct	2	Late	0.66	3.94	39.4	3.6	35.8
Oct	3	Late	0.39	2.27	6.8	2.8	1.6
Total					439.8	13	424.5

Table 37: Crop Water Requirements for Cassava in Mchinji

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.5	1.6	8	0	8
Jul	2	Init	0.5	1.64	16.4	0.1	16.3
Jul	3	Deve	0.5	1.77	19.4	0.1	19.3
Aug	1	Deve	0.65	2.43	24.3	0.1	24.2
Aug	2	Deve	0.87	3.49	34.9	0.1	34.7
Aug	3	Mid	1.1	4.8	52.8	0.4	52.3
Sep	1	Mid	1.18	5.53	55.3	0.4	54.9
Sep	2	Mid	1.18	5.94	59.4	0.5	58.9
Sep	3	Mid	1.18	6.26	62.6	2.1	60.5
Oct	1	Mid	1.18	6.66	66.6	2.7	63.9
Oct	2	Late	1.14	6.8	68	3.6	64.4
Oct	3	Late	1	5.79	63.7	10.4	53.3
Nov	1	Late	0.85	4.84	48.4	17.3	31.1
Nov	2	Late	0.77	4.3	8.6	4.6	8.6
Total					588.4	42.5	550.6

Table 38: Crop Water Requirements for Groundnuts in Mchinji

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.4	1.28	6.4	0	6.4
Jul	2	Init	0.4	1.31	13.1	0.1	13
Jul	3	Deve	0.4	1.41	15.6	0.1	15.4
Aug	1	Deve	0.54	2.04	20.4	0.1	20.3
Aug	2	Deve	0.76	3.06	30.6	0.1	30.4
Aug	3	Deve	1	4.33	47.7	0.4	47.3
Sep	1	Mid	1.17	5.48	54.8	0.4	54.4
Sep	2	Mid	1.17	5.92	59.2	0.5	58.8
Sep	3	Mid	1.17	6.25	62.5	2.1	60.3
Oct	1	Mid	1.17	6.65	66.5	2.7	63.8
Oct	2	Late	1.17	6.97	69.7	3.6	66.1
Oct	3	Late	0.99	5.77	63.4	10.4	53
Nov	1	Late	0.76	4.3	43	17.3	25.7
Nov	2	Late	0.62	3.47	6.9	4.6	6.9
Total					559.7	42.5	521.9

Table 39: Crop Water Requirements for Vegetables in Mchinji

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.7	2.25	11.2	0	11.2
Jul	2	Init	0.7	2.29	22.9	0.1	22.9
Jul	3	Deve	0.72	2.55	28	0.1	27.9
Aug	1	Deve	0.84	3.17	31.7	0.1	31.6
Aug	2	Deve	0.97	3.87	38.7	0.1	38.5
Aug	3	Mid	1.06	4.63	51	0.4	50.5
Sep	1	Mid	1.07	5.04	50.4	0.4	50
Sep	2	Mid	1.07	5.41	54.1	0.5	53.7
Sep	3	Late	1.05	5.61	56.1	2.1	53.9
Oct	1	Late	0.99	5.63	45.1	2.2	42.4
Total					389.1	6	382.5

Table 40: Crop Water Requirements for Maize in Ntchisi

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.3	1.2	6	0.4	5.6
Jul	2	Init	0.3	1.19	11.9	0.9	11
Jul	3	Deve	0.35	1.45	16	0.7	15.3
Aug	1	Deve	0.6	2.6	26	0.4	25.6
Aug	2	Deve	0.86	3.89	38.9	0.2	38.7
Aug	3	Mid	1.12	5.45	60	0.2	59.8
Sep	1	Mid	1.21	6.26	62.6	0.2	62.4
Sep	2	Mid	1.21	6.65	66.5	0.1	66.4
Sep	3	Mid	1.21	6.97	69.7	0.8	68.9
Oct	1	Late	1.2	7.32	73.2	0.5	72.7
Oct	2	Late	0.99	6.36	63.6	0.5	63.1
Oct	3	Late	0.69	4.35	47.8	5.7	42.1
Nov	1	Late	0.44	2.69	18.8	6.7	9.3
Total					560.9	17.2	540.8

Table 41: Crop Water Requirements for Pulses in Ntchisi

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.4	1.6	8	0.4	7.6
Jul	2	Init	0.4	1.59	15.9	0.9	15
Jul	3	Deve	0.45	1.86	20.5	0.7	19.8
Aug	1	Deve	0.69	3	30	0.4	29.6
Aug	2	Deve	0.94	4.27	42.7	0.2	42.5
Aug	3	Mid	1.14	5.54	61	0.2	60.8
Sep	1	Mid	1.15	5.99	59.9	0.2	59.7
Sep	2	Mid	1.15	6.36	63.6	0.1	63.5
Sep	3	Mid	1.15	6.67	66.7	0.8	65.8
Oct	1	Late	1.04	6.36	63.6	0.5	63.2
Oct	2	Late	0.65	4.18	41.8	0.5	41.2
Oct	3	Late	0.39	2.45	7.3	1.5	4.5
Total					480.8	6.4	473.1

Table 42: Crop Water Requirements for Cassava in Ntchisi

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.5	2	10	0.4	9.6
Jul	2	Init	0.5	1.98	19.8	0.9	18.9
Jul	3	Deve	0.5	2.09	23	0.7	22.3
Aug	1	Deve	0.64	2.79	27.9	0.4	27.5
Aug	2	Deve	0.86	3.9	39	0.2	38.9
Aug	3	Mid	1.08	5.27	57.9	0.2	57.7
Sep	1	Mid	1.15	5.99	59.9	0.2	59.7
Sep	2	Mid	1.15	6.36	63.6	0.1	63.5
Sep	3	Mid	1.15	6.67	66.7	0.8	65.9
Oct	1	Mid	1.15	7.05	70.5	0.5	70.1
Oct	2	Late	1.12	7.15	71.5	0.5	71
Oct	3	Late	0.98	6.13	67.4	5.7	61.8
Nov	1	Late	0.83	5.15	51.5	9.6	41.9
Nov	2	Late	0.75	4.59	9.2	2.7	9.2
Total					638	22.8	617.9

Table 43: Crop Water Requirements for Groundnuts in Ntchisi

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.4	1.6	8	0.4	7.6
Jul	2	Init	0.4	1.59	15.9	0.9	15
Jul	3	Deve	0.4	1.67	18.4	0.7	17.7
Aug	1	Deve	0.54	2.35	23.5	0.4	23.1
Aug	2	Deve	0.76	3.43	34.3	0.2	34.1
Aug	3	Deve	0.98	4.77	52.5	0.2	52.3
Sep	1	Mid	1.15	5.95	59.5	0.2	59.3
Sep	2	Mid	1.15	6.36	63.6	0.1	63.5
Sep	3	Mid	1.15	6.67	66.7	0.8	65.8
Oct	1	Mid	1.15	7.05	70.5	0.5	70
Oct	2	Late	1.15	7.35	73.5	0.5	73
Oct	3	Late	0.97	6.12	67.3	5.7	61.6
Nov	1	Late	0.74	4.57	45.7	9.6	36.1
Nov	2	Late	0.61	3.7	7.4	2.7	7.4
Total					606.6	22.8	586.5

Table 44: Crop Water Requirements for Vegetables in Ntchisi

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.7	2.79	14	0.4	13.6
Jul	2	Init	0.7	2.78	27.8	0.9	26.9
Jul	3	Deve	0.72	3	33	0.7	32.4
Aug	1	Deve	0.84	3.63	36.3	0.4	35.9
Aug	2	Deve	0.95	4.33	43.3	0.2	43.1
Aug	3	Mid	1.05	5.09	56	0.2	55.8
Sep	1	Mid	1.05	5.47	54.7	0.2	54.5
Sep	2	Mid	1.05	5.81	58.1	0.1	57.9
Sep	3	Late	1.03	5.98	59.8	0.8	59
Oct	1	Late	0.98	5.97	47.7	0.4	47.3
Total					430.6	4.2	426.3

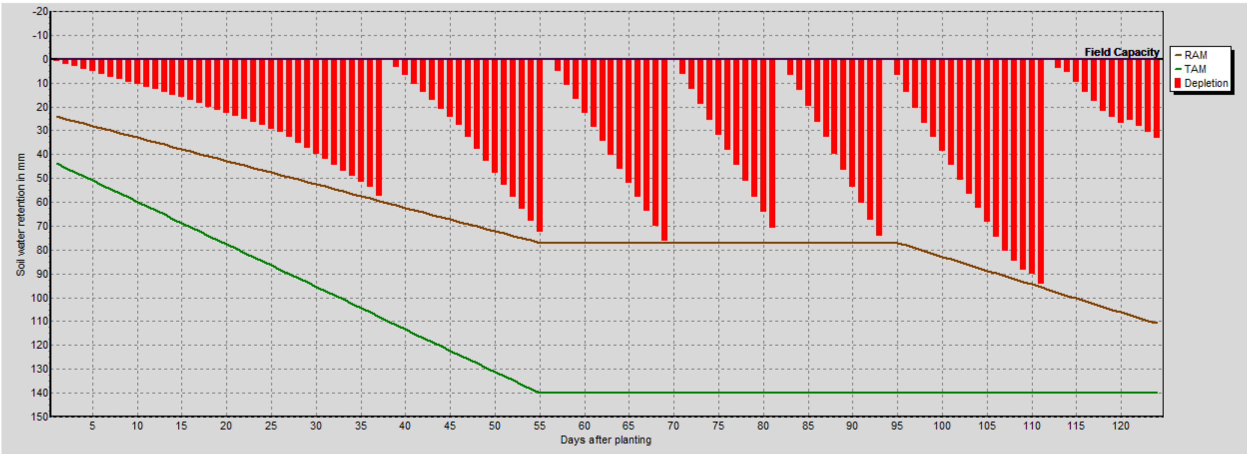

Figure 74: Irrigation Schedules for Maize in Kasungu

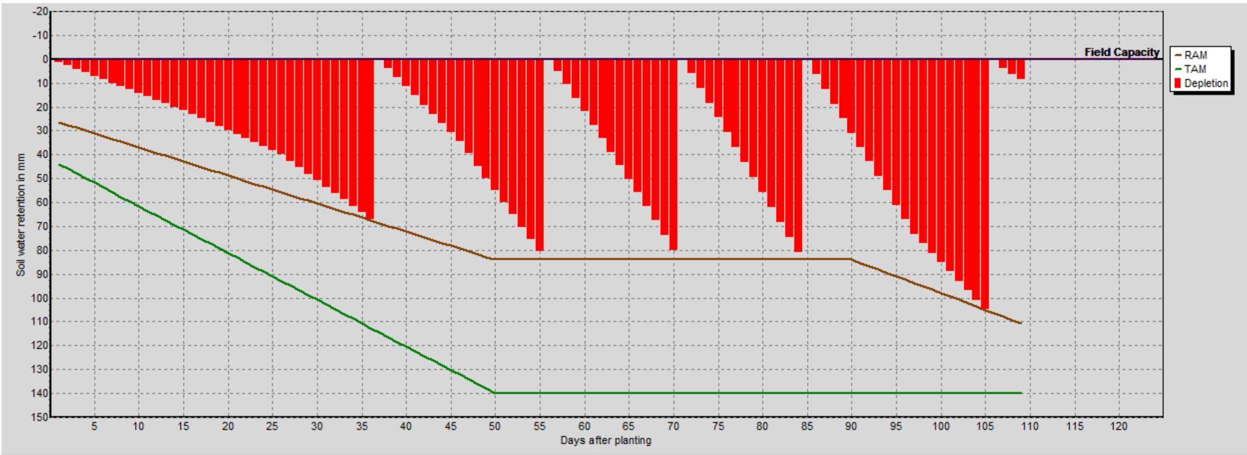

Figure 75: Irrigation Schedules for Pulses in Kasungu

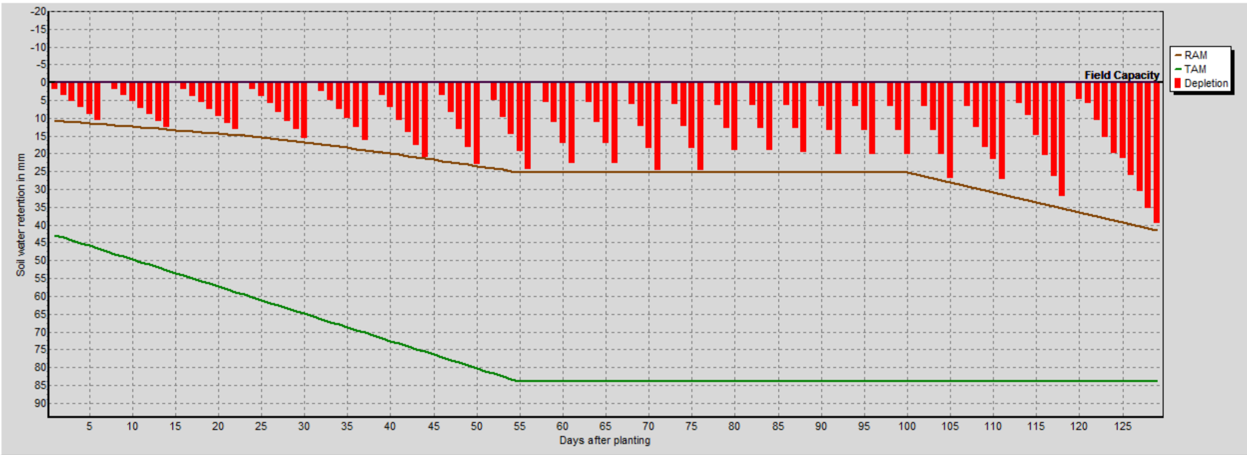

Figure 76: Irrigation Schedules for Cassava in Kasungu

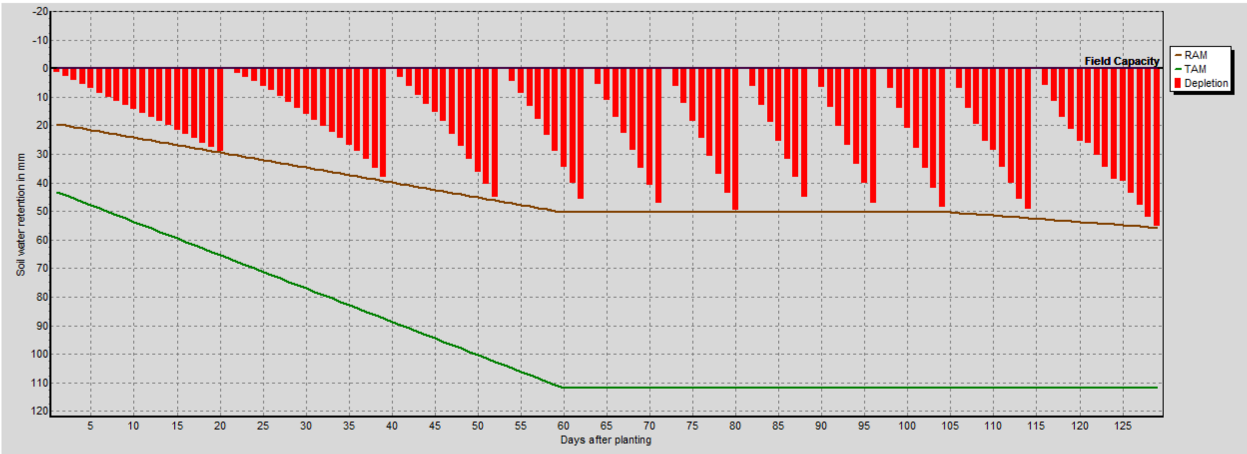

Figure 77: Irrigation Schedules for Groundnuts in Kasungu

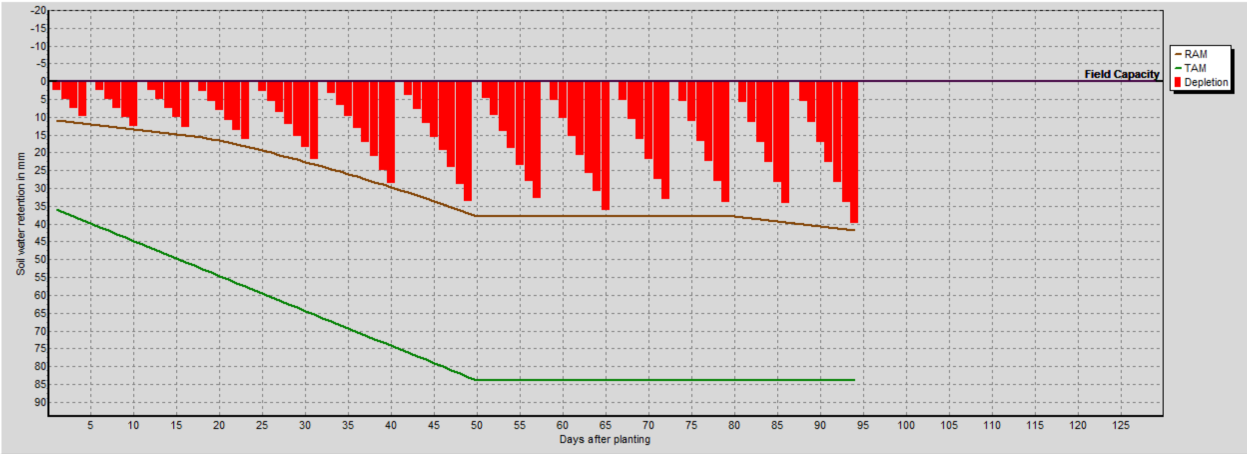

Figure 78: Irrigation Schedules for Vegetables in Kasungu

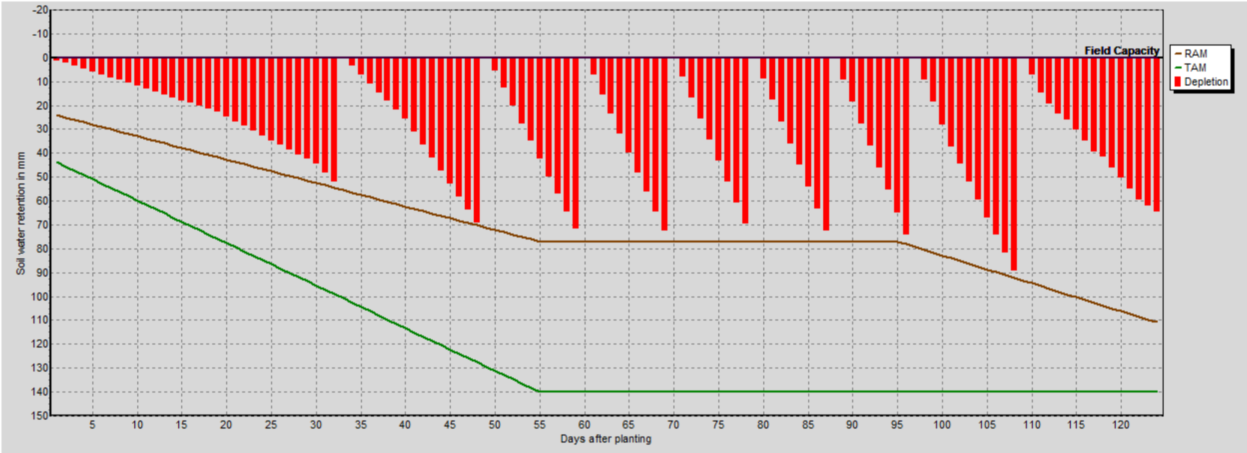

Figure 79: Irrigation Schedules for Maize in Dowa

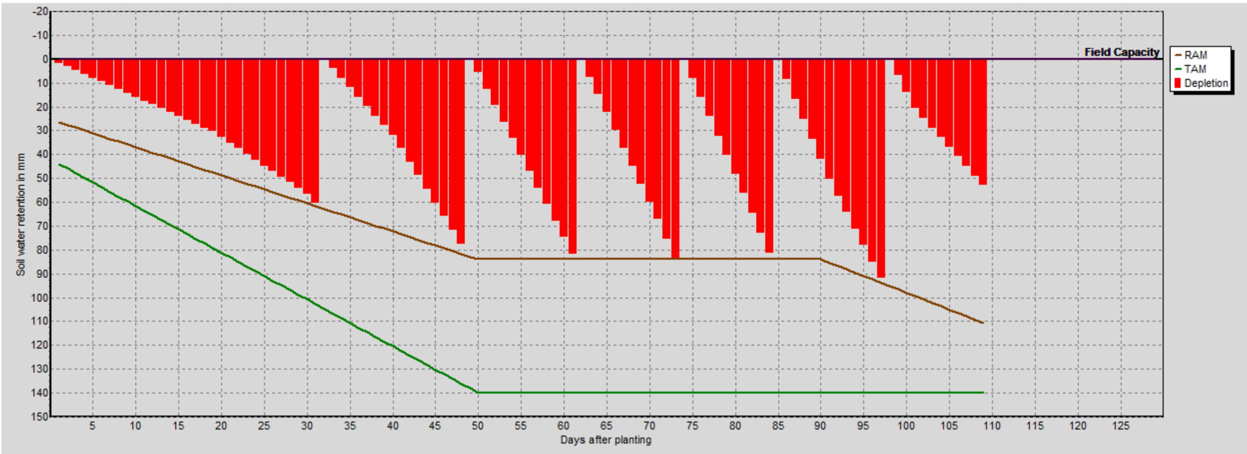

Figure 80: Irrigation Schedules for Pulses in Dowa

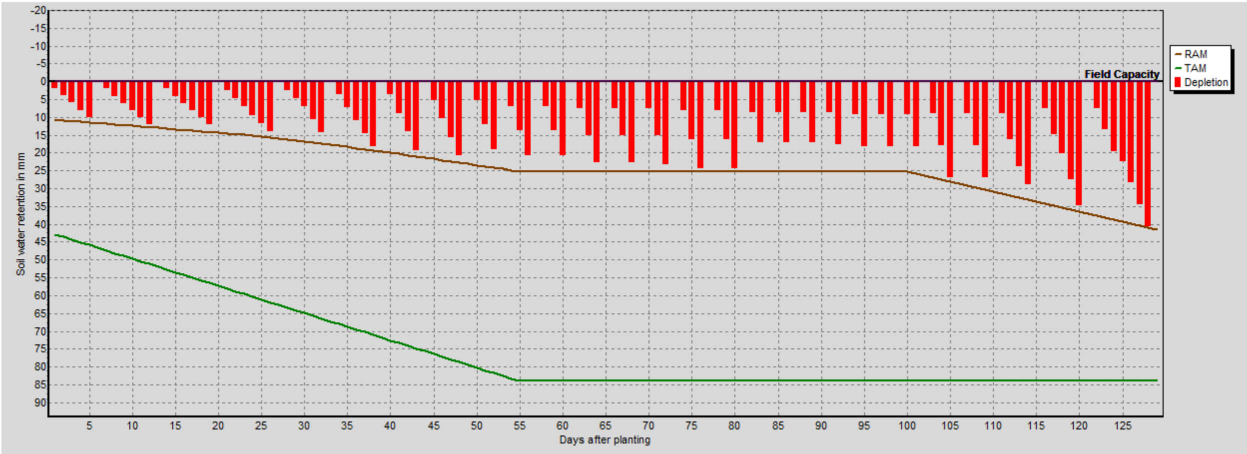

Figure 81: Irrigation Schedules for Cassava in Dowa

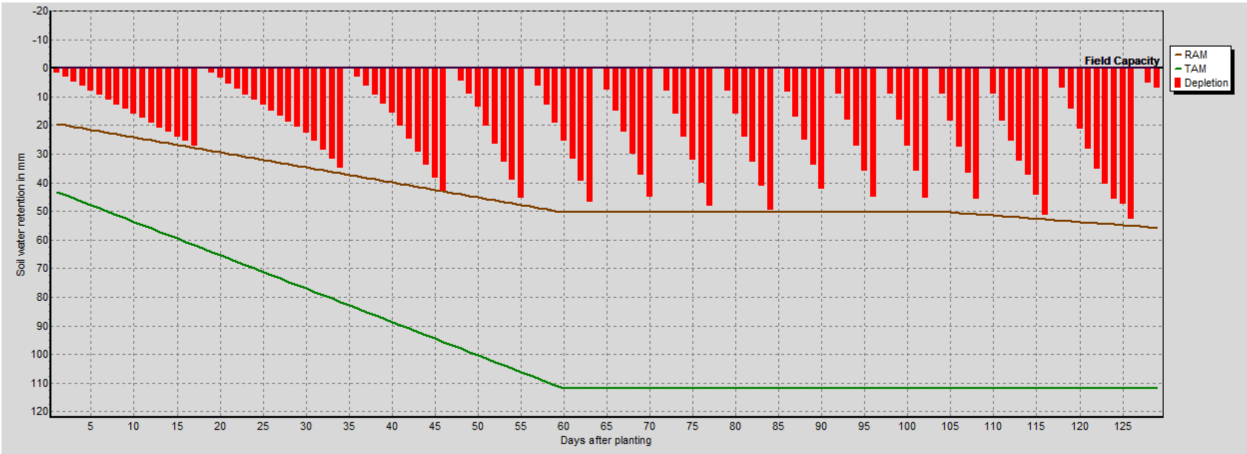

Figure 82: Irrigation Schedules for Groundnuts in Dowa

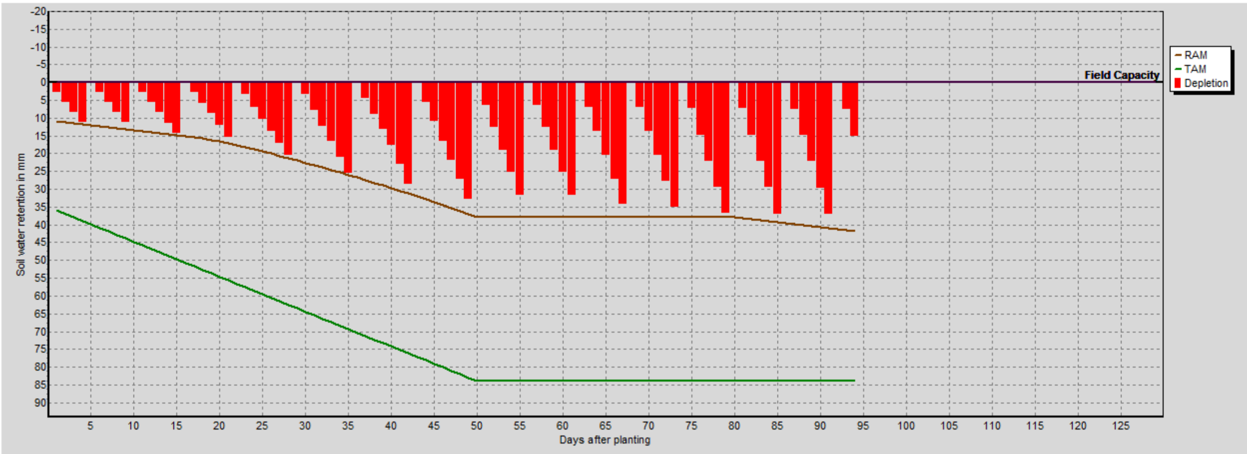

Figure 83: Irrigation Schedules for Vegetables in Dowa

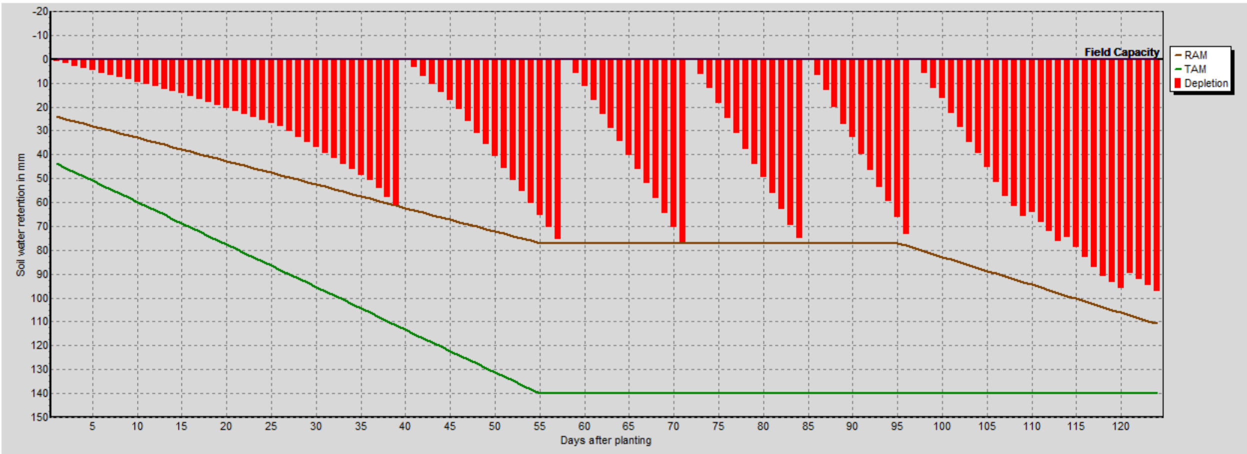

Figure 84: Irrigation Schedules for Maize in Mchinji

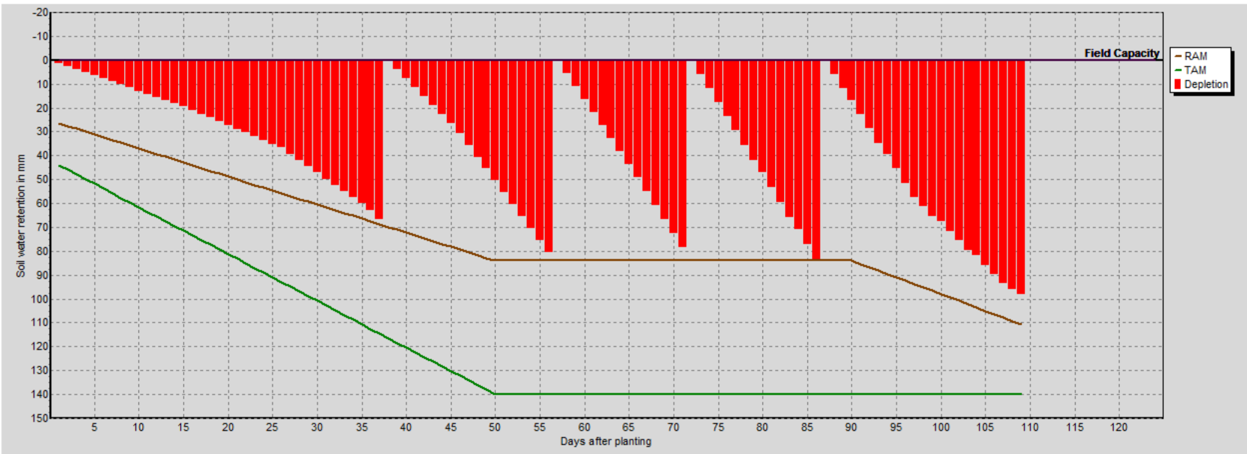

Figure 85: Irrigation Schedules for Pulses in Mchinji

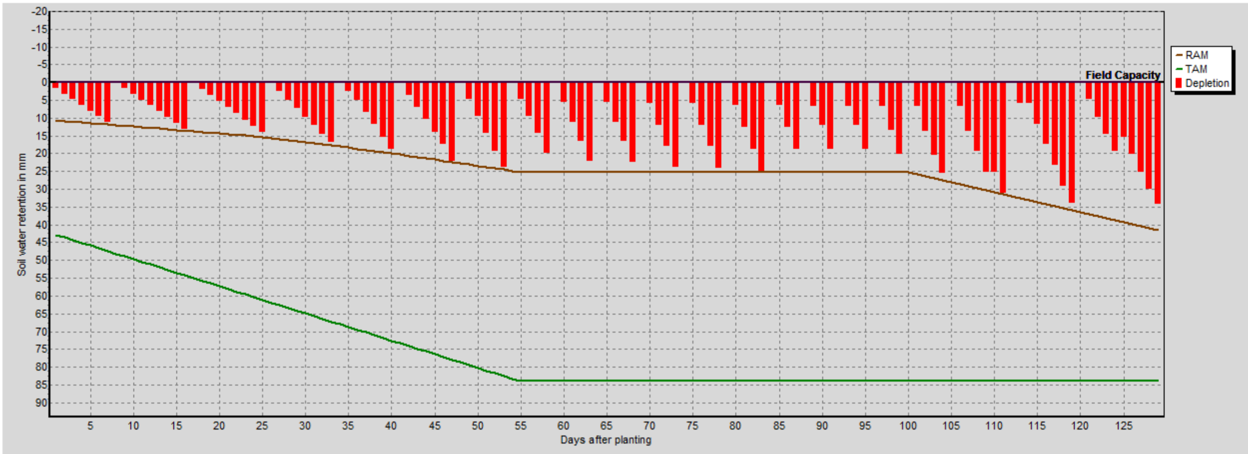

Figure 86: Irrigation Schedules for Cassava in Mchinji

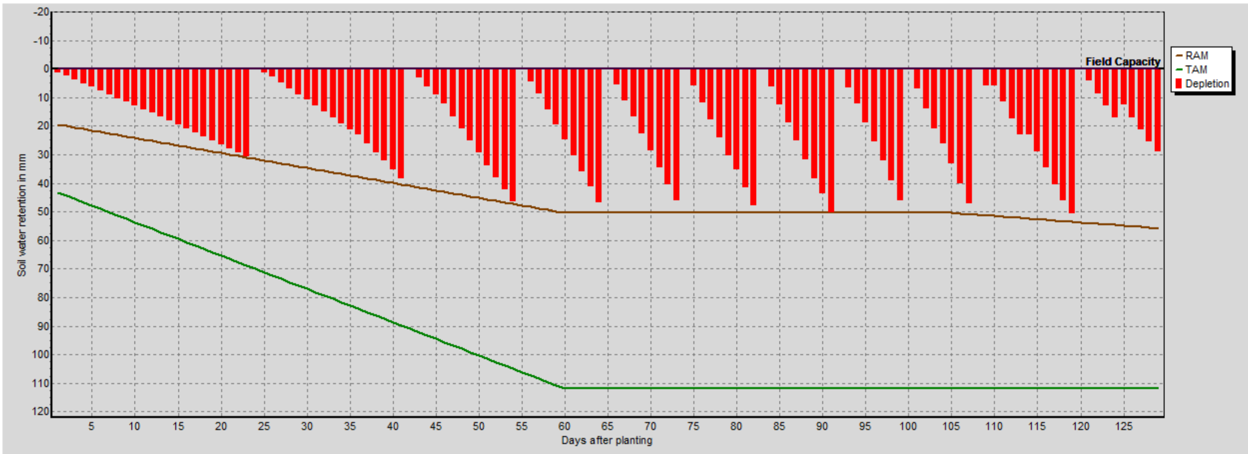

Figure 87: Irrigation Schedules for Groundnuts in Mchinji

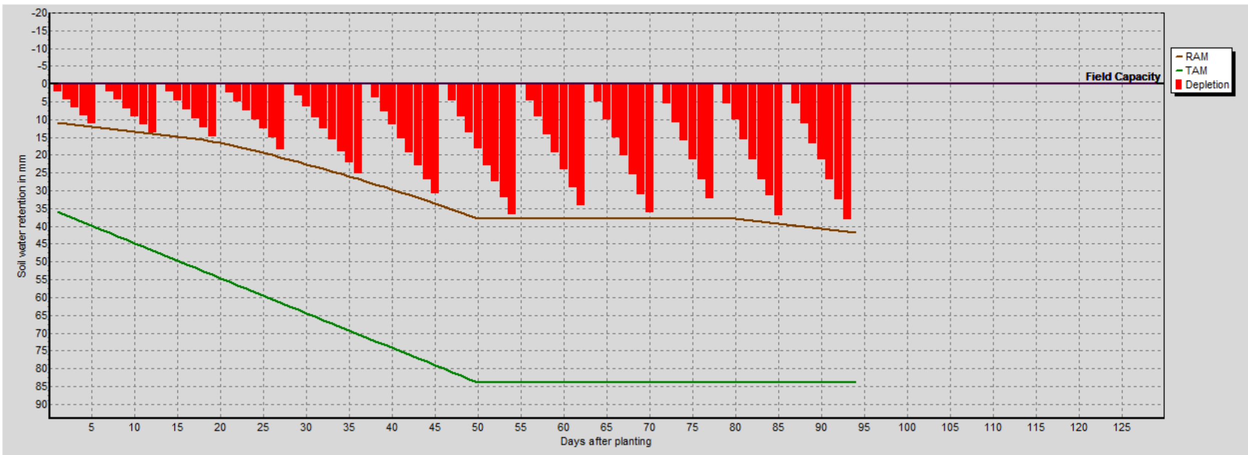

Figure 88: Irrigation Schedules for Vegetables in Mchinji

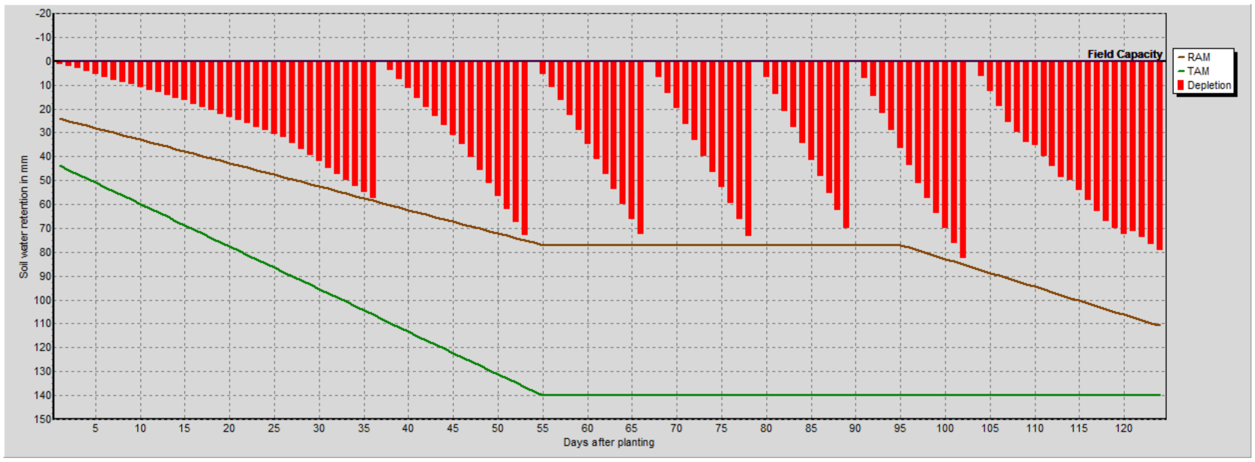

Figure 89: Irrigation Schedules for Maize in Ntchisi

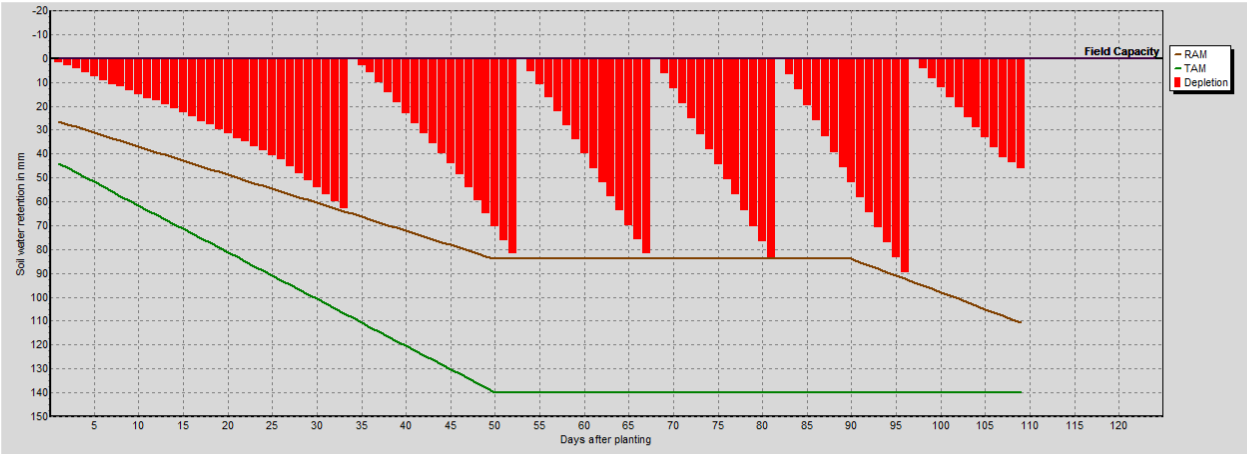

Figure 90: Irrigation Schedules for Pulses in Ntchisi

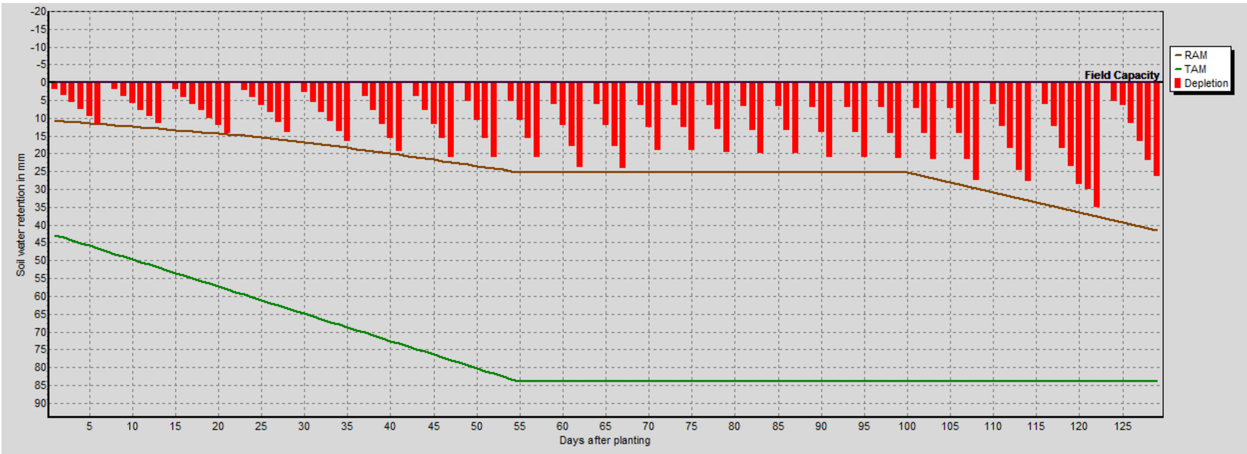

Figure 91: Irrigation Schedules for Cassava in Ntchisi

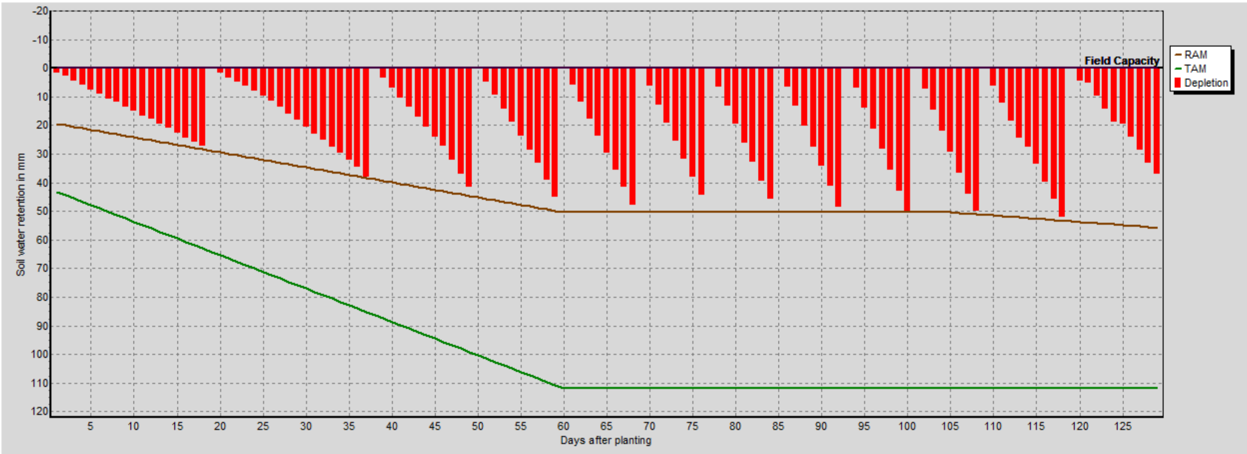

Figure 92: Irrigation Schedules for Groundnuts in Ntchisi

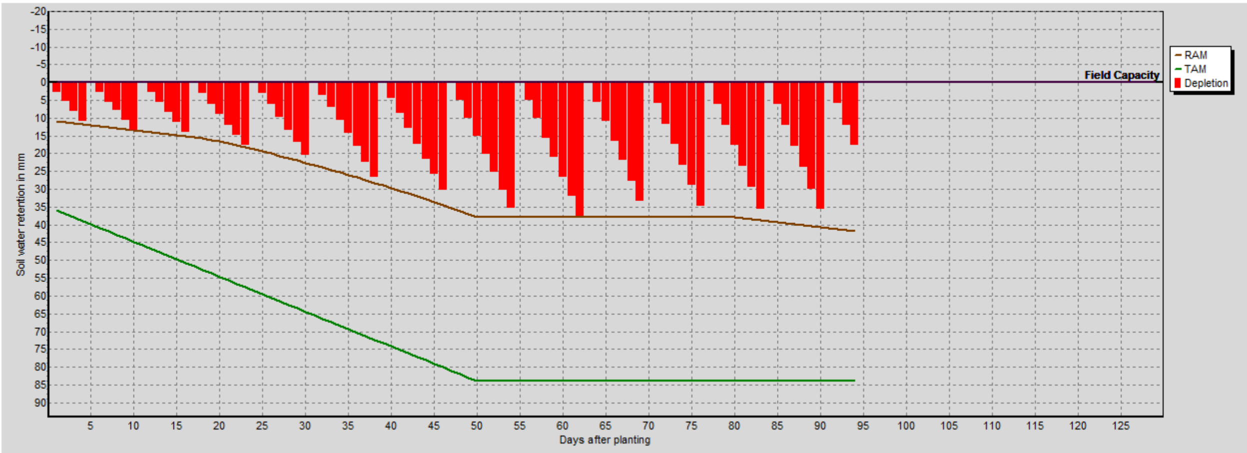

Figure 93: Irrigation Schedules for Vegetables in Ntchisi

Table 45: Drought events in Dowa district

Category	SPI-3	SPI-6	PDSI	ETDI	SWSI
Extreme drought	1993, 1994, 2005,	1992, 1993, 1994, 2005, 2015	1977,1979, 1981, 1988, 1989, 1993, 1996, 1997, 1998, 2002, 2003	1990, 2005, 2013	All years
Severe drought	2003, 2015	2003	1979, 1987, 1995, 1999	1992	None
Moderate drought	1990, 1992, 2013,2015	1990, 2013	2001, 2012	1994	None
Mild drought	Other seasons	Other seasons	Other seasons	Other seasons	Other seasons

Table 46: Drought events in Kasungu district

Category	SPI-3	SPI-6	PDSI	ETDI	SWSI
Extreme drought	1999	1992, 1995, 1999, 2006, 2011	1983, 1990, 1992, 1994, 2001, 2005, 2007, 2013, 2014, 2015	1996, 1998, 2012, 2014	1983-2000
Severe drought	1992, 1995, 2006, 2007, 2014	1995, 2007, 2014	2010	2011	None
Moderate drought	1990, 2011, 2016	2016	1999, 2016	1994, 2011	None
Mild drought	Other seasons	Other seasons	Other seasons	Other seasons	Other seasons

Table 47: Drought events in Ntchisi district

Category	SPI-3	SPI-6	PDSI	ETDI	SWSI
Extreme drought	1994, 1999, 2005	1994, 1999, 2005	1985, 1990, 1992, 1994, 1998, 1999, 2002, 2005, 2008, 2011, 2013	1998, 2014	All years
Severe drought	1985	2006	None	1992	None
Moderate drought	2006, 2013	1994, 2013	1983, 1990	1994	None
Mild drought	Other seasons	Other seasons	Other seasons	Other seasons	Other seasons

Table 48: Drought events in Mchinji district

Category	SPI-3	SPI-6	PDSI	ETDI	SWSI
Extreme drought	1991, 1994,2005	1991, 1994, 2005, 2013	1979, 1984, 1987, 1990, 1993, 1998, 2002, 2003, 2010, 2012	1977, 1978, 1980, 1981, 1982, 1984, 2005, 2015	All years
Severe drought	1994, 1999,	2014	2011	1992	None
Moderate drought	1982, 1987, 1990,2002,2013,2014	1987, 1990, 2002, 2003,	None	1994	None
Mild drought	Other seasons	Other seasons	Other seasons	Other seasons	Other seasons