INTEGRATED DROUGHT MONITORING FRAMEWORK FOR ESWATINI APPLYING THE STANDARDISED PRECIPITATION INDEX AND THE NORMALISED DIFFERENCE VEGETATION INDEX

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DEDICATION

To my parents, my wife, my children, my sisters and my friends

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My great thanks go to my parents for mentoring me, and for providing me with the moral and financial support to undertake this educational journey. Special appreciation to my mother Martha Caroline Mlenga for encouraging me to be a pioneer and a leader and making me realise that the sky is the limit.

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ABSTRACT

The spatiotemporal analysis of drought is of great importance to Eswatini as the country has been facing recurrent droughts with negative impacts on its agriculture, environment and economy. In 2016, Eswatini experienced the worst drought in over 35 years resulting in food shortages, drying up of rivers and livestock deaths due to shortage of grazing. The frequent occurrence of extreme drought events makes the use of drought indices essential for drought monitoring, early warning and planning. The gathering of climatic data is fragmented between government agencies in Eswatini; there is limited use of multiple indices to assess the drought hazard, and there is no coordinated mechanism in place to collect, monitor and communicate drought information in a proactive rather than reactive manner.

The aim of this study was to set a new paradigm for drought management focusing on drought monitoring and early warning. To enable Eswatini to better analyse, prepare and respond to drought the study assessed the applicability of the Standard Precipitation Index (SPI) and Normalised Difference Vegetation Index (NDVI) for near real time and retrospective drought monitoring in Eswatini. The results indicated that the climate of Eswatini exhibits geospatial and temporal variability. Droughts intensified in terms of frequency, severity, and geospatial coverage, with the worst drought years being observed during 1985/1986, 2005/2006, and 2015/2016 agricultural seasons. Moderate droughts were the most prevalent while the frequency of severe and very severe droughts was low. Most parts of the country were vulnerable to mild and moderate agricultural drought. Spatial analysis showed that the most severe and extreme droughts were mostly experienced in the lowveld and middleveld agro ecological zones.

The 3, 6, and 12-month SPI computation and use of NDVI detected the onset of early season drought, thereby affirming the applicability drought indices for monitoring near real time and retrospective droughts in Eswatini. Using regression analysis, SPI and NDVI were combined to develop a model for drought severity assessment which was incorporated into the newly developed integrated drought monitoring framework for Eswatini. The study determined that a value of Y (drought severity) greater than 0.54 is an indication of a significant dry spell that is likely to result in reduced cereal yields, which should inform drought planning amongst stakeholders.

The adoption of the proposed framework would provide the country with valuable information for planning and programming, considering that the country will regularly face dry periods. Further, the drought monitoring information will help to implement drought preparedness measures and to adjust farming and water practices accordingly, before and after drought impacts. Drought preparedness and risk mitigation will help to reduce the eventual drought relief costs, protect livelihoods and food security, and reduce the humanitarian impact on the population.

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ACRONYMS

AEZ	Agro-ecological Zoning
AVHRR	Advanced Very High Resolution Radiometer
CMI	Crop Moisture Index
CPC	Climate Prediction Centre
DEWS	Drought Early Warning System
DRR	Disaster Risk Reduction
EWS	Early Warning System
FAO	Food Agricultural Organisation
FEWS NET	Famine Early Warning Systems Network
GIS	Geographical Information System
MOA	Ministry of Agriculture (Eswatini)
MODIS	Moderate Resolution Imaging Spectroradiometer ()
NDMA	National Disaster Management Agency
NDVI	Normalised Difference Vegetation Index
NGO	Non-Governmental Organization
PSDI	Palmer Drought Severity Index
RDI	Reconnaissance Drought Index
SADC	South African Development Community
SADC	Southern African Development Community
SPEI	Standardised Precipitation-Evapotranspiration Index
SPI	Standard Precipitation Index
SVAC	Eswatini Vulnerability Assessment Committee
VCI	Vegetation Condition Index
WMO	World Meteorology Organisation
WSVI	Water Supply Vegetation Index

GLOSSARY OF TERMS

The different concepts and definitions used in this thesis are discussed and explained in the following section. In order to remain in line with international concepts and definitions, the main source for definitions is the United Nations International Strategy for Disaster Reduction (UNISDR) (www.unisdr.org/eng/library/lib-terminology-eng, 2004). Definitions are discussed in alphabetical order.

Climate change:	Changes in climate may be due to natural processes or to persistent anthropogenic changes in atmosphere or in land use (UNISDR, 2004). According to the UNDP (2008), climate change refers to deviations from natural climatic variability observed over time that are attributed directly or indirectly to human activity, and that alter the composition of the global atmosphere.
Coping capacity:	The means by which people or organisations use available resources and capabilities to face adverse consequences that could lead to a disaster. In general, this involves managing resources, both in normal times as well as during crises or adverse conditions. The strengthening of coping capacities usually builds resilience to withstand the effects of natural and human-induced hazards (UNISDR, 2004).
Disaster:	A serious disruption of the functioning of a community or a society causing widespread human, material, economic, or environmental losses, which exceed the ability of the affected community or society to cope using its own resources. (UNISDR, 2004).
Disaster risk management:	The IDRM (2009) describes disaster risk management as a development approach to disaster management that focuses on underlying conditions of the risks, which lead to disaster occurrence. The objective is to increase

capacities to effectively manage and reduce risks, thereby reducing the occurrence and magnitude of disasters.

Disaster management: UNDHA (1999) defines disaster management as the body of policy and administrative decisions and operational activities, which pertain to the various stages of a disaster at all levels.

Disaster risk reduction: The conceptual framework of elements considered with the possibilities to minimise vulnerabilities and disaster risks in a society, to avoid (prevention) or to limit (mitigation and preparedness) the adverse impacts of hazards, within the broad context of sustainable development.

Droughts: Drought is described by the UNDP (2008) as the naturally phenomenon that occurs when rainfall is ominously below normal recorded levels, resulting in hydrological imbalances that adversely affect land resource production systems.

Drought contingency plan: A document that identifies specifications that can be taken before, during, and after a drought to mitigate some of the impacts and conflicts that result. Frequently these actions are triggered by a monitoring system (Knutson et al., 1998).

Drought impact: A specific effect of drought. People also tend to refer to impacts as *'consequences'* or *'outcomes'*. Impacts are symptoms of vulnerability (Knutson et al., 1998).

Drought impact assessment: The process of looking at the magnitude and distribution of droughts effects (Knutson et al., 1998)

Dry period:	Refers to a period of below mean precipitation where vegetation and water resources are impacted negatively. The dry period is not as serious as drought.
Early warning:	The timely provision of information that allows persons imperilled to a hazard to act, to avoid, or moderate their risk, and prepare for effective response. (UNISDR, 2004).
Hazard:	A potentially damaging physical event, phenomenon, or human activity that may cause the loss of life or injury, property damage, social and economic disruption, or environmental degradation. (UNISDR, 2004). Hazard in the perspective of this study relates to drought.
Hazard analyses:	Detection, classification, and monitoring of any hazard to determine its potential, origin, characteristics, and behaviour (UNISDR, 2004).
Mitigation:	Structural and non-structural measures undertaken to limit the adverse impact of natural hazards, environmental degradation, and technological hazards (UNISDR, 2004).
Natural hazards:	Natural processes or phenomena occurring in the biosphere that may constitute a damaging event. Natural hazards can be classified by origin, namely: geological, hydro meteorological, or biological. Hazardous events can vary in magnitude or intensity, frequency, duration, area of extent, speed of onset, spatial dispersion, and temporal spacing (UNISDR, 2004).
Preparedness:	In the framework of this study, preparedness suggests the readiness of stakeholders, government, UN agencies,

private sector, farmers, and communities to minimise the adverse impacts of drought.

Relief/response: The provision of assistance or intervention during or immediately after a disaster to meet the life preservation and basic subsistence needs of those people affected. It can be of an immediate, short-term, or protracted duration (UNISDR, 2004).

Risk: The probability of negative impacts that include deaths, injuries, property, livelihoods, disruption of economic activity, damage to the environment consequential to the interactions between natural or human-induced hazards, and vulnerable conditions (UNISDR, 2004).

Risk assessment/analysis: An approach to ascertain the type and magnitude of risk by analysing impending hazards and assessing prevailing vulnerability conditions that could pose a potential threat or damage or injury to people, their livelihoods, and their environment (UNISDR, 2004).

1. INTRODUCTION AND STUDY BACKGROUND

Climatic hazards affect all continents with varying impacts and intensities. However, when natural hazards are rated based on attributes such as duration, severity, spatial extent, lives lost, financial impact, social effect, and lasting impact, Bryant (1991), ranked drought number first amongst all-natural hazards worldwide. Drought is often regarded as a '*creeping phenomenon'* developing slowly and across a wide area, and often protracted with high economic and environmental impact (Masih et al., 2014; Miao, 2018 and Tannehill, 1947).

Damages caused by drought is conceivably severe enough to be classified in the top five worst natural disasters that occurred in the world during the 20th century, of which four were droughts (Kim et al., 2014). Drought affects economies and societies differently. Today, it has become the worst natural disaster with annual losses of billions of American dollars for those communities affected (Subin and Ignatius, 2015). In 2015/16 Southern Africa experienced a severe drought and the strong El Niño event, both afflicting livelihood conditions (Baudoin et al., 2017). In South Africa in 2013, the Food and Agriculture Organization (FAO) and the Department of Rural Development and Land Reform agreed that drought remained a major obstacle affecting economy and peoples' livelihoods (Muyambo et al., 2017).

Almost 30 percent of the population in sub-Saharan Africa live in areas prone to drought, with the majority being in rural areas, where their income and employment depend on rainfed agriculture (Benson et al., 1997; IRIN, 2017; Ngaka 2012; UNEP, 2008). In 2016, seventeen countries (8 in Southern Africa) were affected by two consecutive drought years resulting in over 38 million people at risk of food insecurity (IRIN, 2017). Drought incidents are becoming more frequent and severe in many countries of Sub-Saharan Africa, having a devastating impact on peoples and economies.

A succession of droughts combined with human actions may result in soil degradation and desertification. The impacts of drought affect natural resources such as water bodies, pasture for livestock, thus impacting the viability of farming systems and regional economies. This provides a rationale to the monitoring of drought impacts and the formulation of appropriate responses and mitigation planning (Jordaan, 2011).

1.1 DROUGHT MANAGEMENT

1.1.1 Drought in Southern Africa

Drought will always occur somewhere in southern Africa each year (Unganai, 1994), though with varying intensity. This makes drought a normal feature of the region's climate. During the last century, southern Africa—and Eswatini in particular—had been characterised by an increased frequency of droughts (EM-DAT, 2018). Over the past thirty-five years, recorded drought years in Southern Africa include 1982-1983, 1987-1988, 1991-1992, 1994-1995, 1997-1998, 2002-2003 (Covele, 2011), 2005-2006, 2007-2008, 2009-2010, 2012-2013, and 2015-2016 (EM-DAT, 2018). Droughts in Eswatini have followed a similar pattern, and have hit the country differently in terms of location and time (SVAC, 2004, 2006, 2007, 2008, 2016). For example, the drought in 1982-1983 resulted in the largest loss of human life (500 people), whereas the 2005/2006 one affected 410,000 people. With the population of Eswatini estimated at 1,403,362, this indicates that 13% of the population were affected, which is significant share of the population. considering Eswatini being also affected by many other hazards, most significantly HIV/AIDS (CIA, 2018).

1.1.2 Drought Monitoring

Rainfall monitoring in Eswatini is the duty of the Meteorology Department under the Ministry of Tourism and Environmental Affairs and the Ministry of Agriculture (MOA), whereas drought disaster declaration is the primary responsibility of the National Disaster Management Agency (NDMA) and MOA. They depend on information and data from different public agencies and development partners such as the Eswatini Weather Services, the Eswatini Vulnerability Assessment Committee, the United Nations Development Programme (UNDP) and FAO. With increasingly adverse weather events, the meteorological services across the South African Development Community (SADC) region are demanded to afford apt agro-meteorological information and support (SADC, 2012b).

Discussions with the NDMA revealed major failings in the development and implementation of drought monitoring, including inadequate tools and procedures for drought monitoring, a lack of capacity within monitoring bodies, and insufficient data sharing. There are many approaches and tools used to monitor drought. However, the use of drought indices has been utilised to forecast the possible occurrence and progression of an existing drought. In a regional context, drought indices are predominantly functions of precipitation, temperature, and river discharge (Zehtabian et al., 2013). However, precipitation remains the most widely used indicator for drought monitoring (Kumar et al., 2009).

Drought indices have been in existence for a long time. The earliest indices used include the Munger's Index of 1916 and Kincer's Index of 1919 (Heim, 2002). There were however improvements that were achieved in the 1960s leading to the development of the crop moisture index (Palmer, 1968), the percent of normal, the Palmer drought severity index [PDSI] (Palmer, 1965), deciles (Gibbs, 1967), the standardised precipitation index (SPI), the standardised precipitation evaporation index (McKee et al., 1993) and the more modern reconnaissance drought index (Tsakiris and Vangelis, 2005).

The reliance on precipitation based drought indices might not be sufficient to monitor drought in all areas, especially in southern Africa, where data can be incomplete, unavailable, untimely, and often unreliable. Additional drought indices or data is necessary to provide a reliable and clear picture of the drought condition. Remote sensing data is one of many options available to complement the precipitation based indices as it is able to characterise drought both spatially and temporally, thus providing a near real time depiction of the drought conditions (Peters et al., 2002). The normalised difference vegetation index (NDVI), the water supply vegetation index (WSVI), the vegetation condition index (VCI), and the standard vegetation index are some of the remote sensing indices used for monitoring drought (Bhuiyan, 2004; Brown et al., 2008; Covele, 2011; Jain et al., 2010; Moulin et al., 1998; Sing et al., 2003).

Of the many drought indices available, the SPI and NDVI are widely used globally and in Africa in particular for drought monitoring and early warning system. In South Africa, the South African Weather Services (SAWS) releases agro-meteorological bulletins that depict the severity of the rainfall or drought situation using SPI maps on the SAWS Drought Monitoring Page http://www.weathersa.co.za/DroughtMonitor/ DMDesk.jsp (Botai et al, 2016; Jordaan, 2017b; Sivakumar, 2011). In Eswatini, NDVI images are provided by the Eswatini Meteorology Services and used in reports that include the Eswatini Vulnerability Assessment reports (GOS, 2016). Based on the World Meteorological Organization data specific countries that are using SPI and NDVI include Turkey, South Africa, USA, India, Greece and many others (WMO/GWP 2018).

Despite the existence of the multiple drought indices and the use of SPI and NDVI by many countries, the fragmentation of data collection agencies within government ministries, the lack of understanding of the drought phenomenon and the lack of systems and infrastructure necessary for monitoring, the process of drought monitoring remains a challenge for many countries. With the advent of the Sendai Framework for Disaster Risk Reduction 2015-2030 (UN, 2015), there has been a fundamental change in drought disaster risk management, from emergency response to an inclusive approach that includes preparedness (where drought monitoring is important) and preventive approaches to acknowledge and reduce risk (WMO, 2014).

1.2 PROBLEM STATEMENT

In Eswatini precipitation-based drought indices are applied to characterise drought conditions. The drawback however is the lack of continuous spatial rainfall data coverage, thereby reducing the Eswatini Meteorology Services and other supporting stakeholders ability of monitoring and characterising detailed spatial and temporal patterns of drought. The gathering of climatic data is fragmented between government agencies in Eswatini; there is limited use of multiple indices being used to explain the drought hazard, and there is no coordinated mechanism in place to collect, monitor and communicate drought information in a proactive rather than reactive manner. This often results in loss of human life and livestock, deprived livelihoods, food insecurity, and significant financial impact for the economy.

The 2015/16 drought affected pastures and water resources leading to the death of 80 000 cattle across the country. Similarly, over 300,000 people faced acute food shortage, which represented almost 30 percent of the population (FAO, 2016a; GOS, 2016; USAID, 2017). There were also water scarcity affecting all aspects of society, including education (with an estimated 189,000 learners affected) and health system (UNCT, 2016). Drought-induced disaster consequences in the country were severe, which has been the case in 1984, 1992 2006 and 2009 (EM-DAT, 2018). The impact of these droughts and many others could have been reduced if there were effective drought monitoring and early warning systems. For the 2015/2016 drought, the Government of Eswatini declared a national drought emergency on 18 February 2016 (FAO, 2016b) after the impacts of the droughts were already observed.

Looking at past drought episodes in other southern Africa countries, especially the drought in 1994, the Government of Lesotho declared a national drought disaster in December 1994, while Zimbabwe's and Zambia's drought declarations were announced as late as July and August 1995, respectively (Holloway, 1995). This shows that for droughts experienced in the same time with almost the same severity there were differences in the time of declarations across countries.

The southern African countries use various tools and methods to monitor and report drought across the country and at different timescales. Simple, user-friendly, reliable, well-coordinated and less costly tools and systems are required to timely detect the spatial and temporal dimensions of drought for early warning and decision-making. This is even more important for Eswatini which has an agro-based economy and is more vulnerable to the effects of drought on the natural resources and agricultural systems.

1.2.1 Key Research Questions

The research is built upon the following questions ;

- Can the use of SPI and NDVI be optimised for near real-time drought monitoring in Eswatini?
- What are the strengths and weaknesses of satellite-based indices versus station-based meteorological indices (SPI)?
- What are the precipitation and vegetation status thresholds that are necessary to effect early warning systems?
- How can the use of SPI and NDVI by stakeholders be enhanced for effective drought monitoring and early warning? and
- What is the appropriate framework applicable for effective drought monitoring?

1.3 RESEARCH OBJECTIVES

The main objective of the research is to develop an integrated framework for drought monitoring to direct and improve early warning and drought disaster preparedness. To achieve the aforementioned, the specific objectives of the research are:

- to optimise SPI and NDVI for characterising the spatial and temporal variability of drought in Eswatini;
- to derive a critical rainfall threshold necessary for activation of early warning systems;
- to formulate a. integrated, inclusive drought monitoring framework and
- to develop a coordination mechanism for an integrated drought monitoring framework.

The recommendations and framework formulated will support Eswatini in the establishment of an integrated multi-sectorial mechanism that will be responsible for drought monitoring, the eventual development of drought policy incorporating the drought monitoring framework as well as in the development and implementation of drought disaster management plans.

1.4 RESEARCH HYPOTHESIS

The study will test the following hypothesis:

- The station-based drought index (SPI) and satellite-based drought indices (NDVI) cannot elucidate the spatial and temporal drought variability in Eswatini.

1.5 SIGNIFICANCE OF THE STUDY

For any drought disaster management plan, the monitoring of the drought dimensions is important. The efficient use of SPI and NDVI will improve drought monitoring in Eswatini. Using a combination of indices enhances efficiency and reliability of drought monitoring, thereby enhancing timely decision-making. This is turn will enable stakeholders and farmers to adjust farming practices accordingly and will be useful for government to promote disaster risk reduction measures.

The recommendations of the study will contribute towards the effective and timely coordination of government agencies, development, private and research partners in the data collection, processing, analysis and dissemination of climate data for drought monitoring and decision-making. This will:

- improve detection of drought onset,
- enhance early warning,
- provide information for preparedness and management,
- provide data for vulnerability mapping, and
- enhance evidence-based drought declarations and actions.

The contribution of knowledge will be;

- the integration of the SPI and NDVI for the quantification of drought;
- The development of a drought trigger threshold;
- The formulation of a systematic drought monitoring framework, a mechanism for effective drought monitoring and drought information dissemination for Eswatini.

1.6 ASSESSING THE CONTRIBUTION

In answering the research questions and their contribution to research, the opinion of Whetten (1989) will be considered, in which he articulated the components that constituted a theoretical contribution, namely;

- What factors and concepts are part of the elucidation of the contribution?
- After recognition of the factors and concepts forming the contributions, the researcher should reflect on interrelationships of the factors;
- What are the underlying assumptions of the theory or model?
- The logic of the proposed conceptualisation should be of interest to other researchers and;
- Who, where and when? These enquiries define the boundaries for generalisation.

1.7 LIMITATIONS AND DELIMITATIONS

Precipitation is the primary factor controlling the formation and persistence of drought conditions, but evapotranspiration is also an important variable. The SPI uses precipitation only, which led to its augmentation and development into the standard precipitation evaporation index (SPEI). However, evaporation data is not commonly collected by many developing countries such as Eswatini, making the use of the SPI more relevant due to fewer data requirements. For station-based precipitation data, not all weather stations had data for a 30-year period or more, thereby limiting the use of some of these stations. Satellite imagery for vegetation for Eswatini was not available in Eswatini before 2001; thereby analysis was done based on data from 2002 onwards.

1.8 BACKGROUND OF STUDY AREA

The Kingdom of Eswatini (also known as Eswatini), is the second smallest country in Africa and precisely located in south eastern Africa. It is a small, landlocked country occupying 17,364 km^2 of land, located between South Africa and Mozambique. It has a population of

1,403,362 inhabitants (CIA, 2018), of which 74.5% are classified as rural (FAO, 2013) with approximately 100,000 farm households (FAO, 2011). The farm size averages about 1.3 ha, but has reportedly decreased as a result of demographic changes. Although Eswatini is classified as a lower middle-income country, it currently faces challenges similar to low-income economies. The country ranks 148 out of 187 countries in the 2016 UNDP human development index (UNDP, 2016).

The country has four administrative districts (Hhohho, Manzini, Lubombo, and Shiselweni) and four agro-ecological regions, the Highveld, Middleveld, Lowveld and, in the east, the Lubombo Plateau. The four ecological regions display a range of climatic conditions, varying from tropical to near temperate, with the Lowveld exhibiting the extreme weathers. The general climatic characterisation of Eswatini is subtropical with wet hot summers (October-March) and cold dry winters (June-August). Mean annual rainfall ranges from 1,500 mm in the northern Highveld to 500 mm in the southern Lowveld.

The national long-term average rainfall is 788 mm/year. Precipitation varies considerably from year to year, which may either lead to periods of flash flooding or drought. Mean annual temperature varies from 17 °C in the Highveld to 22 °C in the Lowveld (GoS, 2013). These climatic conditions make the country very vulnerable to meteorological hazards such as drought, floods, gusty winds, and lightening, as well as epidemics during the wet and hot season. The Lowveld is the hottest and driest zone and the most vulnerable to drought.

Table 1. Rainfall in Agro Ecological Zones of Eswatini

Agro-Ecological Region	Rainfall (mm)
Highveld	700-1550
Middleveld	550-850
Lowveld	400-550
Lubombo Plateau	550-850

Source: FAO: AQUASTAT Survey 2005

Eswatini has approximately 12,220 km^2 of agricultural land—71% of the total land area (FAO, 2013). Of that, just over 10% is classified as arable land, 28% under permanent pastures, 62% forests, and 0.7% under permanent crops (New Agriculturist, 2002). Smallholders constitute 70% of the population, and occupy 75% of the crop land. Agricultural productivity is low, accounting for only 11% of total agricultural outputs. The main food crops include, maize (which is the most susceptible to drought impact), sorghum, sweet potatoes and legumes.

1.9 CHAPTER OUTLINE

Chapter 1 introduces drought hazard, importance and challenges in monitoring the hazard, the tools available to monitor drought, and what can be done to optimise the use of drought monitoring tools to depict the drought characteristics in Eswatini.

Chapter 2 details the methodology used to assess the hazard as well as the theoretical frameworks used for the study. Hazard analysis using SPI and NDVI were however described in detail in Chapter 4 and 5.

Chapter 3 provides information on disaster risk management, the drought hazard, different definitions of drought and the descriptions of the four main categories of drought. To understand drought fully, the chapter examines causative factors of drought, the drought variables and parameters. When there is a drought, there are risk, vulnerability and possible impacts. The chapter introduces the principles of drought risk, vulnerability, and impacts in Eswatini.

Chapter 4 analyses the SPI and its application in real-time and retrospectively to monitor drought. The focus is on spatial and temporal analysis using SPI as well as drought mapping using the SPI.

Chapter 5 discusses available satellite-based images with a focus on the use of NDVI for drought monitoring.

Chapter 6 discusses the different country drought monitoring frameworks looking at how they are formulated, what tools and indices are used, and how effective they are.

Chapter 7 develops a composite drought-monitoring framework based on the SPI and NDVI. The developed framework is compared against different country frameworks. Action research is applied to determine the applicability of the framework, its effectiveness, and capacity to respond to the needs of Eswatini.

In Chapter 8 Based on results of research, a comprehensive framework for drought monitoring is recommended. Issues of legislation, financing, and the process of rolling out are also considered. This chapter completes the report with the conclusions and recommendations on the effective use of the framework

2. THE RESEARCH DESIGN AND METHODOLOGY

The essence of the research was to optimise the use of SPI and NDVI for drought monitoring in Eswatini. To achieve this, drought, indices are used to explain the hazard through a hazard assessment. This Chapter describes the methodology used to assess drought hazard and theoretical frameworks applied for the study. Precipitation deficit, river discharge and vegetation quality are some of the factors considered during a drought hazard assessment. In this study, to measure the precipitation deficit, the researcher used the SPI because of its simplicity, and fewer data requirements. It is based solely on one parameter—precipitation data—which is readily accessible from the weather stations.

This section details the research design and methodology. It articulates the structure of the inquiries, tools and empirical analysis made during the course of this PhD study. The research design was formulated to ensure the author is able to answer the research questions as adequately as possible. The detailed methodological approaches especially for the calculation of SPI and extrapolation of NDVI have been elaborated them in Chapters 4 and 5 respectively, especially the methodologies utilised to establish prevailing drought scenarios.

Dahler-Larsen (2008) has shown a connection between the levels of research as the 'meta and paradigm', 'logics of research', and the 'techniques and methods 'and how these elements constantly interact. In describing the relationship between individual elements of research design, the author used an adapted Dahler - Larsen framework (Figure 1) as presented in this chapter. In the framework research, levels have been adapted to suit the study. The 'logics of research' were considered vital to be analysed first as they provide the body of the study by elaborating the fundamentals of the hazard and drought monitoring which are the core of the study.

The overall structuring and logics seek to answer the fundamental research questions. The 'meta and paradigmatic' and the 'techniques and methods' provide linkages between the hazard and the units of measurement and use in design science to come up with a system, which in this study is a drought monitoring framework. Here there is a consideration of the of the explorative research efforts that lead to the design of the artefact in this case the framework. Exploratory research is an approach that seeks not to provide conclusive answers to the research question, but rather to explore the topic with varying depth (Love 2007 and Shield &

Rangarajan 2013). The research design can be expressed in an adapted Dahler-Larsen's framework;

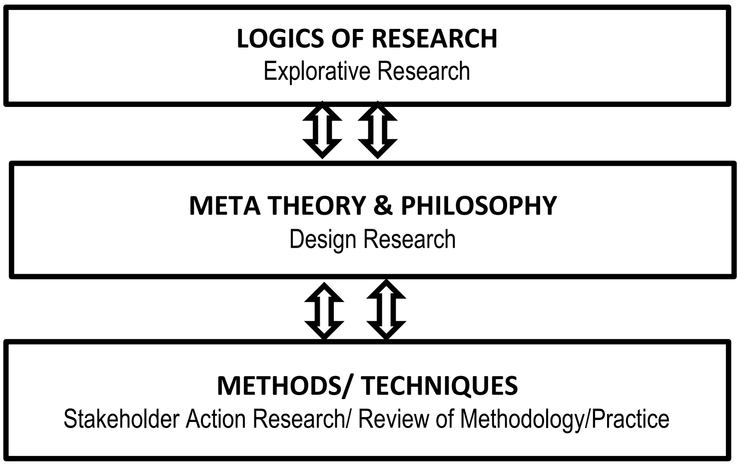

Figure 1. Research design components. Adapted from Dahler-Larsen's (2008) framework of interactions between research levels.

2.1 RESEARCH CONCEPTUAL, THEORETICAL FRAMEWORKS AND ASSUMPTIONS

The study used methods from both the positivist and phenomenological paradigms to strengthen the research by limiting views of reality to objective or subjective. The research thesis objectives were addressed through exploring and expounding the research questions epistemology and ontology. This included the analysis of the methodology', 'theoretical perspective', 'theoretical structure' and 'paradigm'. In the different Chapters, there was a disconnection of the hazard and the context where there was a manifestation of the hazard. This was done to ensure the research questions were answered in detail while at the same time avoiding misperception between varying epistemological and ontological assumptions.

The author used more than one method to investigate the research questions to limit views of reality to objective or subjective, This has been encouraged by many scholars (Denscombe 1998; Denzin, 2017; Mathison, 1988; Yeasmin and Rahman, 2012). They emphasised importance of using multi-methods for the corroboration of findings and enhancing the validity of the data. Having multi-dimensional data sources for this study, i.e. rainfall data, information from cases studies and design science can present challenges with regard to linking the data sources to come up with a scientific and logical narrative.

2.1.1 Design Science Theory

The theoretical framework used for this study is '*design science'.* Whilst natural science attempts to understand reality, design science attempts to create things that serve human purposes, and is technology-oriented (March and Smith, 1995). The "Design theory" is described by Gregor (2007) as a process for solving problems, providing explicit guidance in constructing an artefact and answering questions regarding how the construction should be done (Berhan et al., 2011). The role of design research is to identify a design theory that links a specific design 'problem' to a specific design ' solution' (Durling, 2002 and Love (2007), meaning that the focus is on research for the development of scientifically based artefacts. This therefore shows that this study is practical in its effort of designing a framework rather than philosophical.

Flood (1995) argued that a philosophical review of system research is essential if new aspects of the alternate post-positive perspectives are to be reflected. He further pointed out that social concerns have been well justified in management theories (Love 2007). In support of this, I have thus looked beyond positivism in my study and included the qualitative contexts of designed systems. By adopting research design steps used in the study, I have included in the system the important role of stakeholders. Their ability to perform in a system is a qualitative aspect and a careful analysis of how they function is fundamental to achieve an effective implementation of the system.

Good designing of science research often begins by identifying and representing opportunities and problems in an actual application environment (Hevner, 2007). Simon (1996) described an artefact as a facet that is artificial and of human creation, as opposed to a facet that occurs naturally. Von Alan et al. (2004) presented seven guidelines which are necessary to conduct design science research. These are *design as an artefact, problem relevance, design evaluation, research contributions, research rigor, design as a search process, and communications research.*

However, the artefact was adopted and modified by Berhan et al., (2011) with modification by von Alan et al., (2004) from seven guidelines into six steps: *identification, modelling, tracking, prediction, comparison, and communication with stakeholders.* The artefact for the process of knowledge discovery, which encompasses the six steps, incorporates use of data from satellite imagery as well as meteorological data. In the study, therefore, the artefact denotes the abstract representation of the design-science research process and its communication to decision-makers. The design theory, the artefact and its structure, theoretical perspectives and processes involved are the main research tools and processes.

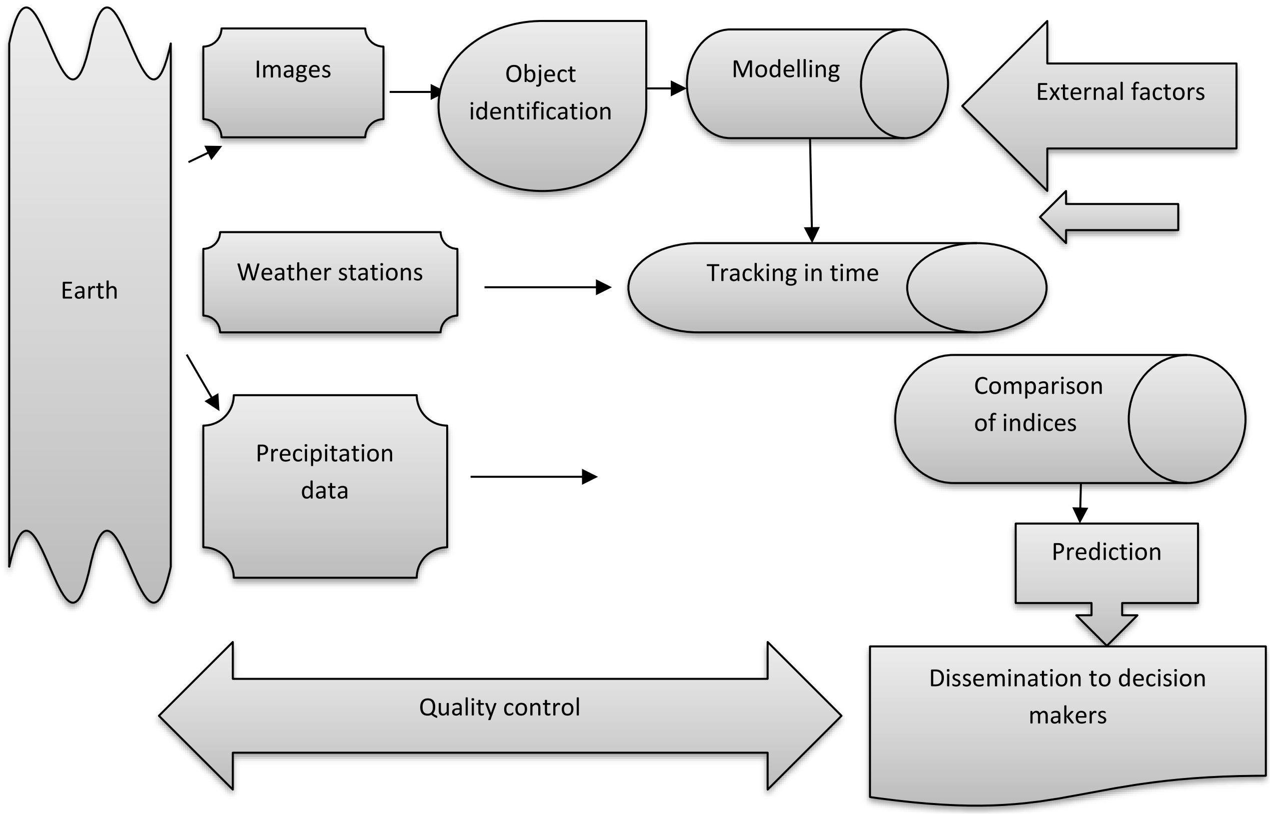

Figure 2. Artefact for the Process of Knowledge Discovery from Meteorological Data and Satellite Imageries (Adapted from Berhan et al., 2011; Stein et al., 2009)

The progression of knowledge origination from meteorological data and satellite images is presented in Figure 2. The process comprises quantitative and qualitative approaches required for the design of systems. It can be challenging to use a mixed method approach in system design, however Love (2007), argues that the design of theoretical foundations should include the qualitative aspects that are integral to the design. This confirms the suggestion by Cross (1992) that a successful simplification of design thinking is needed to answer questions similar to those outlined in this study.

Simplifying system-engineering paradigms that play a part in design research consists to find a design theory which refers to a particular design ' problem ' and to a specific design ' solution ' Love (2007). He argues further that simplifying design paradigms have failed as they have attempted to conceive design as a mechanical process. This argument is supported by multiple authors such as Coyne and Newton 1992; Coyne, Snodgrass and Martin 1992 and Reich 1994). For this reason, the use of design science was essential to address the research questions as well as the ontological and epistemological perspectives (Table 2), helping to define relationships in system design. The design theory is critical as it helps in addressing the research problem based on the theory and on the internal process of the designers.

Table 2. Components of theoretical perspective

Theoretical Perspective	
Ontological Perspective	Mechanistic, deterministic
Epistemological Perspective	Mathematical, logical empiricism (positivist)
Methodological Perspective	Scientific

Source: Love, 2007

2.1.2 Disaster Risk Assessment Methodology

The research adopted the disaster risk-assessment methodology as a framework (Figure 3) for drought risk reduction. However, the research only addressed the risk analysis stage, where the focus was on the assessment of the drought hazard. The methodology addressed the following steps:

Step 1-*Identifying the risk, understanding of current situation, knowledge of the needs and gaps*.

The research assessed drought probability, frequency, intensity, exposure, and predictability, documented what already existed, and built on existing information and capacities.

Step 2-*Hazard assessment*.

Hazard assessment and monitoring was the fundamental focus of the research, where an understanding was sought for the drought hazard. The research aimed at identifying, characterising, and understanding drought by virtue of the nature, location, intensity, and likelihood of recurrence.

Step 3-*Exposure assessment*.

Drought impacts are non-structural and spread over a larger geographical area. Exposure in the study was considered as the area that was exposed to drought.

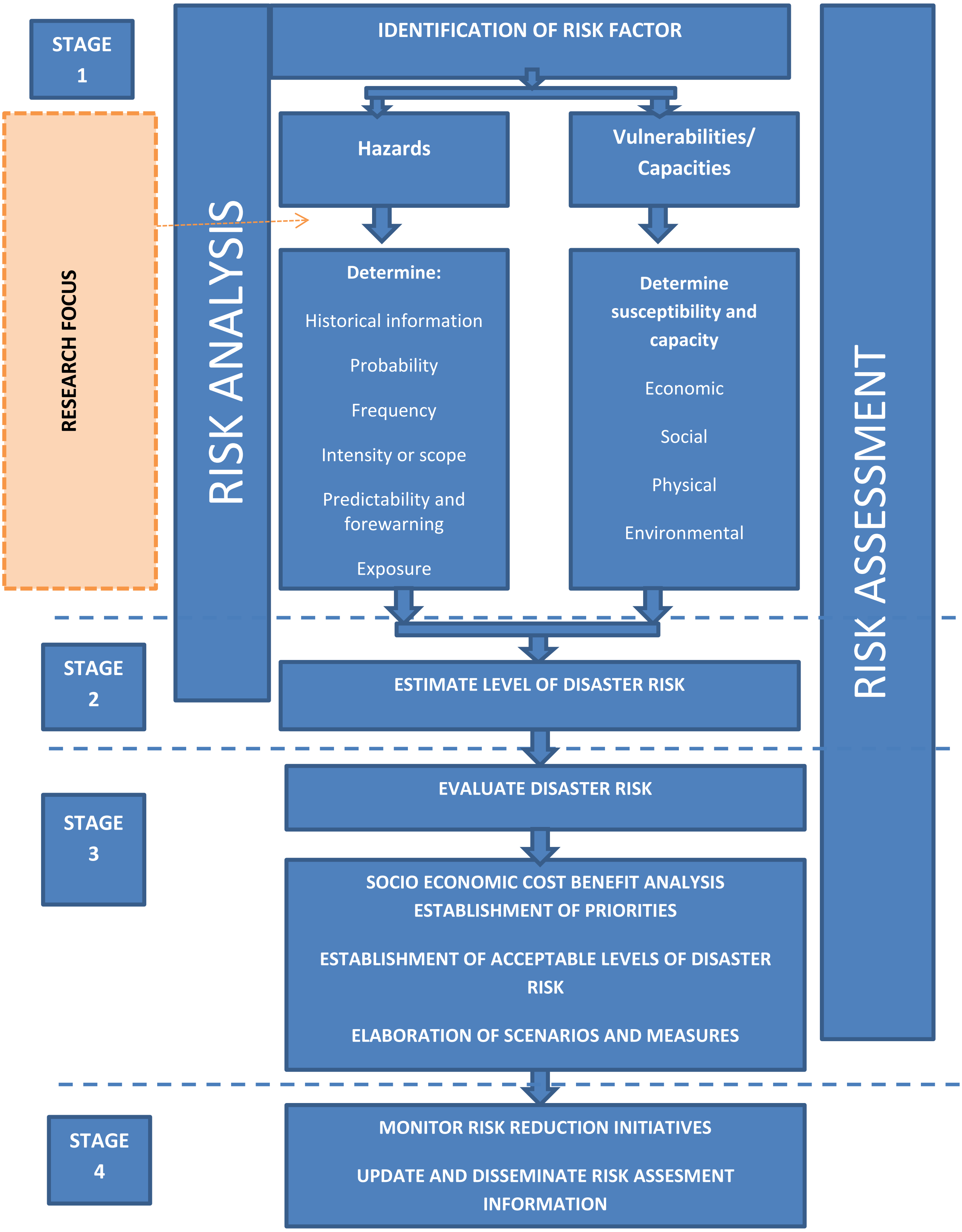

Figure 3. Disaster Risk Assessment Methodology. *Source: Government of South Africa: NDMF, 2005*

2.2 DATA PREPARATION

2.2.1 Rainfall Data Acquisition

Monthly rainfall datasets were acquired for a period of 32 years, ranging from 1986–2017 from 14 rain stations (Figure 4). Monthly precipitation data was used to calculate SPI. The Eswatini Weather Services, the Department of Meteorology, the University of Eswatini, and the Eswatini Water Services supplied the data. Only data from rainfall stations with minimal data gaps in the 1986–2017 time series was used.

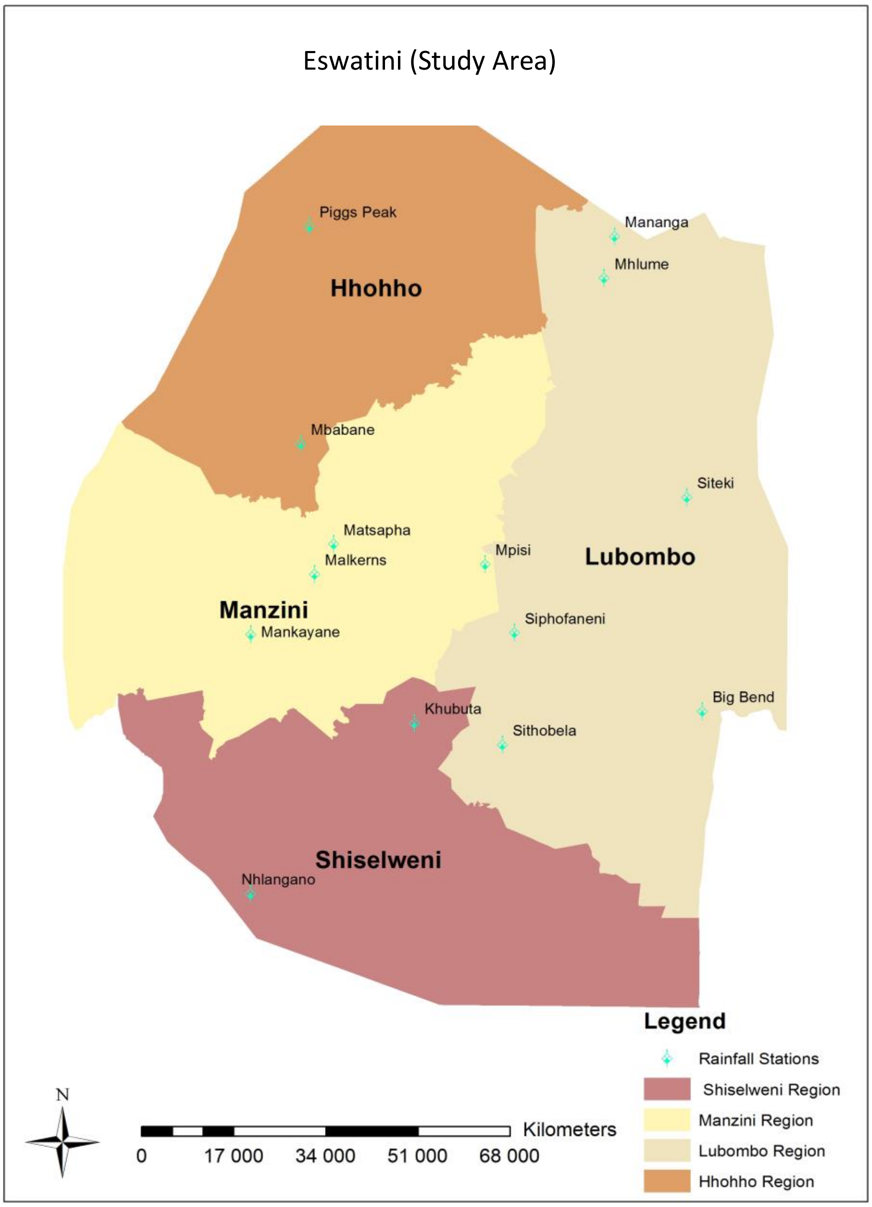

Figure 4. Map of Eswatini with Rainfall Stations used in the Study

2.2.2 SPI Computational Methodology

The study was based on examination of historical data on precipitation, analysis of remote sense data, and discussions with disaster management practitioners. The SPI was identified as an essential index for Eswatini and therefore adopted for this study. Chapter 4 presents a comprehensive discussion of SPI and other drought indices. The steps taken to calculate the SPI are shown in Figure 5. The agro - ecological regions and at the national level SPI calculation were based on the long-term precipitation records for the study period.

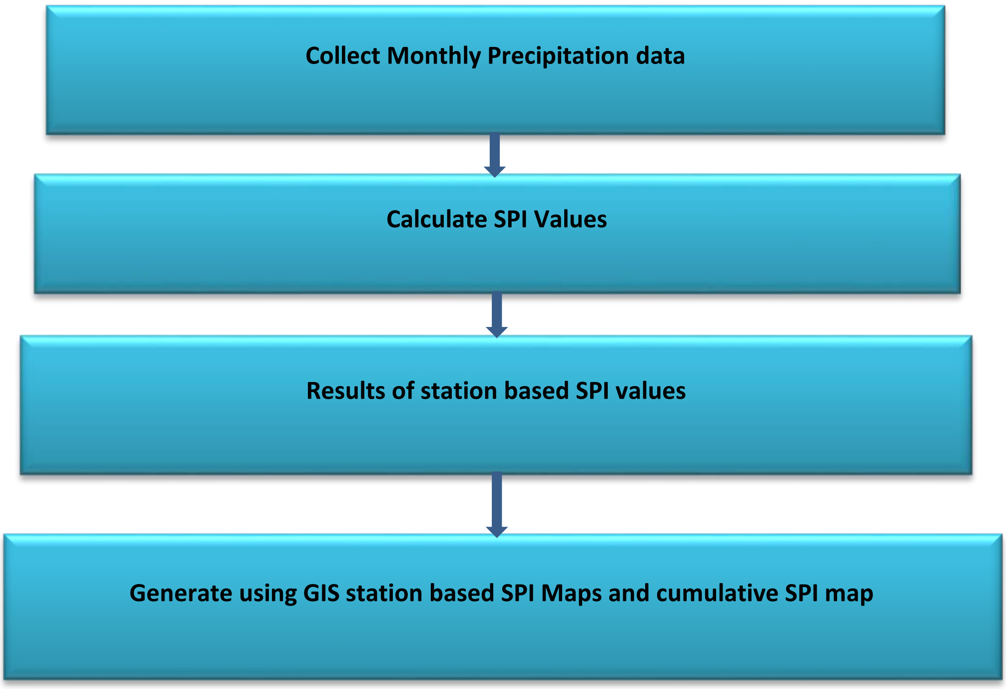

Figure 5. Methodology of SPI Estimation and Spatial Representation.

The SPI was calculated according to the methodology explained by Giddings et al. (2005). However, the SPI computation was achieved through use of DrinC software. The selection a software was based on its simplicity, so that it can be easily adopted for the use in Eswatini. DrinC is a user-friendly tool software package which was developed for providing a simple, though adaptable interface for the calculation of several drought indices (Tigkas, Vangelis and Tsakiris, 2015). The software operates on Windows platform and is programmed in Visual Basic. A series of at least 30 years period of data was used to determine SPI values for 3, 6 and 12 months timescales.

The Eswatini rainfall data set 2006-2017 was obtained from the Eswatini Meteorological Services. The MS Excel dataset was uploaded onto the DrinC software for manipulation. The SPI was calculated at 3, 6 and 12 month time scales. The primary reference base in DrinC is the hydrological year (October to September). However, the study defined the hydrological year based on the Eswatini rainfall calendar. For the three-month SPI, the hydrological year covered October, November and December. Ji and Peters (2003) found that the 3-month SPI is the most effective for monitoring drought impact on vegetation, especially when the 3-month period coincided with the peak-growing season. The six-month SPI hydrological year covered July to December whereas the twelve-month SPI hydrological year covered January to December.

The 3 month SPI indicates the conditions of short-term drought, mostly soil moisture, drought stress with an impact on agriculture while 6 and 12 month SPI indicates medium to long term drought which affects ground water supplies and pasture conditions. The study therefore mapped drought severity at 3, 6 and 12 months scales in the four agro ecological regions of Eswatini. Month of December was chosen for calculating SPI for 3, 6 and 12- month time scale since October coincides with the rainfall or beginning of agricultural season, whereas December is the mid-season where the main cereal crops (maize) will be flowering. The 3-month period of October to December is normally the critical wet season, where an onset of drought will significantly affect crop production.

2.2.3 SPI Verification Methodology

The SPI is an appropriate tool for monitoring agricultural drought, but in combination with other information. To ensure the data derived is accurate and representative, the drought characteristics and dimensions were verified using historical data from yield reports, agro-meteorological reports, Eswatini vulnerability assessment reports, water balance reports from the Eswatini Water Services, statistical reports from the Central Statistical Office, and disaster management reports from disaster management agencies, Non-Governmental and UN agencies.

2.2.4 SPI Mapping Methodology

Rainfall-related data originated from weather station-based data. Spatial representation of SPI was performed using ArcGIS 10.1 where the geo-statistical method of kriging was chosen for the representation of spatial distribution and intensity of the drought for the selected drought years. The SPI for the selected years, 1985/1986, 2004/05, 2005/06 and 2015/16 were krigged to allow spatial interpolation of drought across agro ecological zones. GIS offers a useful tool in disaster management since it maps the areas where the problems occur and people are affected (Bolstad 2005).

2.2.5 NDVI Application and Mapping Methodology

Data used in determination of NDVI are closely related to the radiation absorbed and reflected by vegetation in the photosynthetic process (Jain et al., 2010). The primary data sources were the MODIS NDVI CMG data made available by NOAA-NASA. The NDVI data in use was from the MODIS platforms Terra and Aqua, which have provided global coverage since 2000 (Terra) and mid-2002 (Aqua), at about 5 km resolution with a temporal frequency of overlapping 16-day periods. The process of NDVI representation is presented in Figure 6 below.

The NDVI images used were based on the month of January, which shows the highest amount of vegetation produced, as per observation of the crop calendar over time, data from the Ministry of Agriculture in Eswatini.

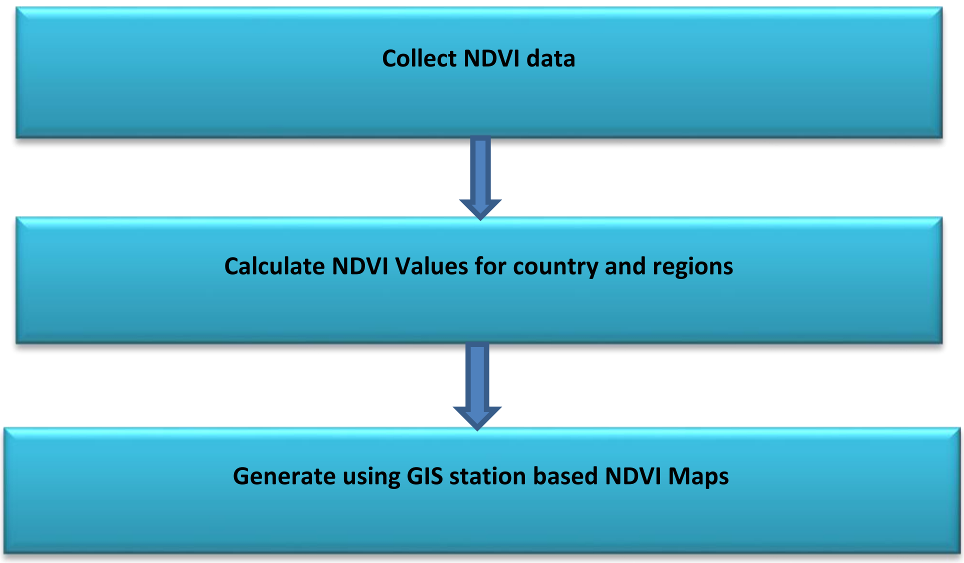

Figure 6. Methodology of NDVI Spatial Representation.

2.3 QUALITATIVE DATA COLLECTION

In order to achieve the objectives of the dissertation, a qualitative research was conducted to collect key informants' opinions regarding the research subject. Specifically, the qualitative analysis sought to obtain information from key informants on how they looked at the aspect of drought monitoring and early warning in Eswatini. The research employed both structured and unstructured interviews and questionnaires.

A total of 20 informants were selected through purposive sampling based on the organization/ institution they worked for and their expertise and involvement in the subject matter. According to this method, which belongs to the category of non - probability sampling techniques, sample members are selected on the basis of their knowledge, relationships and expertise regarding a research subject (Freedman et al ., 2007). The informants for the interviews were drawn from international and local NGOs, UN, government ministries, district and provincial bodies, as well as the community and traditional leaders.

A total of 20 questionnaires including structured and unstructured questions were sent to key informants in February 2016, after obtaining their consent. Of these questionnaires, only 16 questionnaires were completed and sent back by April 2016..Upon receiving the completed questionnaires, the researcher had further individual interviews in October 2016 to get more elaboration on the responses as well as to share the proposed drought monitoring and early warning framework in order to discuss its feasibility and acceptance for use in the country.

Content analysis was used to analyze the data gathered from personal interviews. The recorded interviews were transcribed verbatim by the researcher within 24 hours of being conducted, and written text was created from each interview. The identity of the participants was kept confidential.

The research also involved literature review on previous related work in Eswatini, on agriculture, food security, environment policies and the impacts of droughts, NGO and government drought interventions. Various data was collected from secondary sources books, articles, local and national government reports, published interviews and newspaper clippings and mapping and diagramming.

Triangulation is the foundation on which a methodology to assess impact must be based and from which the qualitative methods are applied (Turner et al., 2017). Due to the nature of this research, having multi-dimensional data sources – triangulation was used to negate or counterbalance the deficiency of a single data collection strategy, so as to increase the validity and improve the ability to interpret the findings.

The following chapter will define the drought hazard in detail. It will introduce the concept of disaster risk management, the drought hazard, different definitions of drought and explores the causative factors of drought. To ensure there is a clear understanding on the need to study the drought hazard, the chapter introduces the principles of drought risk, vulnerability, and impacts in Eswatini.

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3. DROUGHT DISASTER RISK MANAGEMENT

3.1 INTRODUCTION

The reduction of disaster risk involves analysis of the hazard exposure, managing people's and property vulnerabilities, and the improvement of early warning and preparedness systems (UNISDR 2012). The foundation of this study is to reduce the risk to drought disaster. It is therefore imperative to understand what drought is, its causes, how it is defined and characterized, how frequently it occurs and how it can be efficiently monitored. These aspects facilitate greater understanding of how to plan and manage for drought. The ability to make decisions and plan timely for drought is an important component of disaster risk reduction. Effective decision-making can be made only when stakeholders are provided with timely, relevant and user-friendly drought information timely. This can be achieved only if there is a reliable, consistent, accurate monitoring of the drought through assessment of the rainfall and vegetation conditions in near real time.

Drought can occur in areas with high as well as low rainfall. However, the lack of a universally accepted drought definition increases the uncertainty about the existence of a drought and its severity (Wilhite, 2000). The resulting uniqueness in the phenomenon makes the identification and quantification of drought a challenge (AghaKouchak et al., 2015). Drought is normally assessed and quantified in relation to different factors, which include the amount, distribution, and frequency of rainfall in relation to crop growth (Adhyani et al., 2017; El Kenawy et al., 2016). Drought impacts are non-structural and spatial, as they span wide areas. All these factors make each drought a unique event in its climatic characteristics and impacts (Kilimani et al., 2018).

In contrast to aridity, which is considered a permanent climatic characteristic in many low precipitation zones, Wilhite (2006) regards drought as a temporary deviation. He also points out that the phenomenon represents a cumulative reduction of the amount of precipitation received for a certain area over a period of time. For instance, reduced water flows, low groundwater tables and low reservoir levels may take months for the impact to be observed.

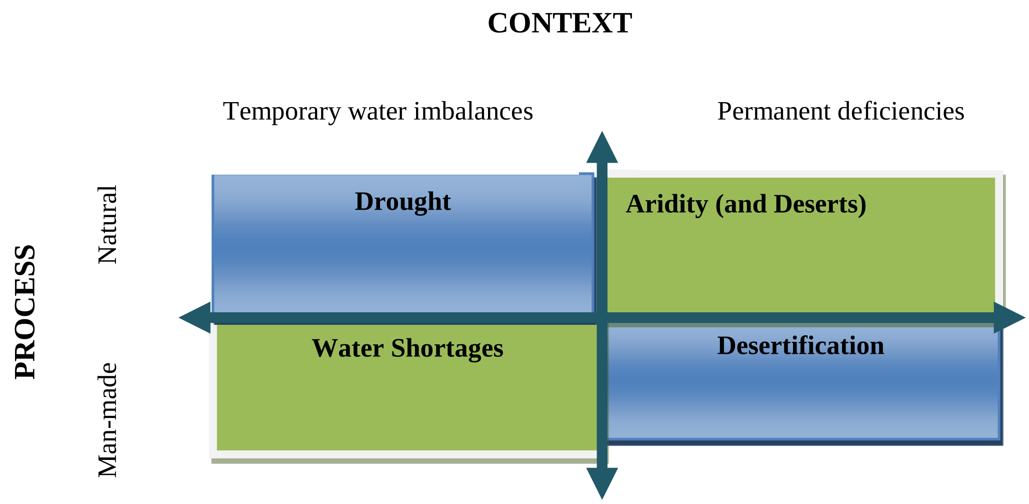

Figure 7. Typology of Water Stress Condition: *Source: Vlachos, 1982.*

Figure 7 characterises the transitory phases of water deficit, which is the main determinant of severe droughts. It's evident that increased drought leads to water shortages and an increase in aridity leads to an increase in desertification, as also indicated by Wilhite (2006). Water shortages and desertification are man-made, while droughts and aridity occur as a result of natural phenomena.

Therefore, accurately monitoring drought is not an easy task because of its complexity (Hao et al., 2017; He et al., 2015); the fact that it has a slow onset and no defined termination date (Coêlho et al., 2017; Porfiriev, 2015; Staupe-Delgado and Kruke, 2017) makes quantification of drought more complex. Because drought severity varies by the precipitation deficit, spatial extent, and duration, it is usually difficult to compare one drought event with another. Nonetheless, the development and use of drought indices over the last few decades has helped to typify and monitor drought. The challenge is, however, that no single drought index can effectively define or characterize the phenomena (Homdee et al., 2016; Jain et al., 2015; Lloyd-Hughes, 2014; Waseem et al., 2015).

Consequently, to reduce drought risk in an effective manner, it is essential to understand the level of drought risk characterized by the vulnerability, capabilities and the resilience of individuals and institutions as well as knowledge and application of indices (Lei et al., 2014; Lei et al., 2016; Maleksaeidi et al., 2017; Wilhite et al., 2014). This chapter will lay the foundation of the body of the study by reviewing drought and its characteristics, exploring the principles of drought management, looking at drought monitoring, early warning systems, drought vulnerability, capacity, and resilience.

3.2 DROUGHT

3.2.1 Drought Definitions

There is no universally acknowledged definition of drought; the events are area specific and region specific, reflecting differences in climatic characteristics with different socio-economic and physical variables. The importance of different drought definitions due to different effects on various sectors of a society was emphasised by Wilhite and Glantz (1985). They further argued that the definitions must be specific to how they will be applied or the region they will be exercised. This explains why there are currently more than 150 definitions in existence. Therefore drought cannot be viewed just as a physical phenomenon; it is necessary to also consider both conceptual and operational definitions of drought.

3.2.2 Conceptual Definition of Drought

For ease of understanding, different conceptual definitions of drought have been formulated. For example the NDMC (2006a) defines drought as a prolonged period of inadequate precipitation that leads to extensive harm to crops and consequent loss of yield. Conceptual definitions only refer to meteorological influences and do not consider the socio-economic and environmental impact of drought and dry periods. A selection of conceptual definitions of drought is presented below.

(i) The World Meteorological Organization (WMO, 1986) defines drought as 'a sustained, extended deficiency in precipitation'.

(ii) Knutson et al. (1998) define drought as 'a deficiency of precipitation from expected or a normal, that, when extended over a season or longer period of time, is insufficient to meet demands. This may result in economic, social, and environmental impacts. It should be considered a normal, recurrent feature of climate. Drought is a relative condition, rather than absolute, that should be defined for each region. Each drought differs in intensity, duration, and spatial extent'. The author considered Knutson et al. (1998) definition of drought as applicable for this study.

(iii) The UN Convention to Combat Drought and Desertification UNCDD (1994) defines drought as a natural phenomenon when precipitation is significantly below the normal recorded levels, leading to severe hydrological imbalances that have an adverse effect on land resource and production systems.

(iv) The Food and Agriculture Organization of the United Nations (FAO, 1983) defines drought as ‘the percentage of years when crops fail from the lack of moisture’.

(v) The Encyclopaedia of Climate and Weather (Schneider and Hare, 1996) defines drought as ‘an extended period - a season, a year, or several years - of deficient rainfall relative to the statistical multi-year mean for a region’.

(vi) Palmer (1965) defines drought as ‘a significant deviation from the normal hydrologic conditions of an area’.

(vii) The United Nations Development Programme (UNDP) (2008) defines drought as ‘the naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems’.

(viii) Chopra (2006) defines drought as ‘a period of rainfall deficiency, extending over months or year of such nature that crops and pastures for stock are seriously affected, if not completely burnt up and destroyed, water supplies are seriously depleted or dried up and sheep and cattle perish’.

3.2.3 Operational Definition of Drought

Monacelli et al. (2005) offered an operational definition of drought that identifies the beginning, end, and degree of severity of a drought event. Operational definitions ascertain the deviation from the average precipitation over time. The severity, frequency and duration of drought for a time series can be operationally characterised by the use of data on precipitation from various time scales. This is suitable for planning and preparing for possible future droughts. However, there is still no operational definition of drought that works in all circumstances. The use of indicators therefore helps to ease the complexity of defining drought. Mawdsley et al. (1994) defined two classes or types of indicators:

- *Environmental indicators*: help to identify the duration and/or severity of a drought and can be used to analyse the frequency of drought and the degree of departure from average conditions.

- *Water resource indicators*: measure severity in terms of the impact on water for domestic and agricultural supplies, groundwater recharge, surface abstractions and the impact on fishing or leisure.

Wilhite and Glantz (1985), Wilhite (2000), and Castillo (2009) characterised drought into four common classifications with specific operational definitions. The four types of operational drought classifications are meteorological drought, agricultural drought, hydrological drought, and socio-ecological drought (NDMC, 2006a). These classifications are illustrated in Figure 8.

- <u>Meteorological</u>

Meteorological drought considers the departure of the amount of precipitation from the average. Several indices are used to define the meteorological drought, such as the rainfall anomaly index (RAI), the deciles index (DI), the SPI, the standard precipitation evapotranspiration index (SPEI), and the percentage of normal rainfall.

- <u>Agricultural</u>

Agricultural drought suggests conditions where the lack of soil affects plant development and ultimately final yield. This definition takes into account the susceptibility of crops at various phases of crop development.

- <u>Hydrological</u>

Hydrological drought relates to surface and subsurface water supplies and their magnitude and frequency are normally affected by changes in land use and land. Hydrological droughts are observed later than other forms of droughts, as it takes longer for the lack of moisture to be visible in water bodies. .

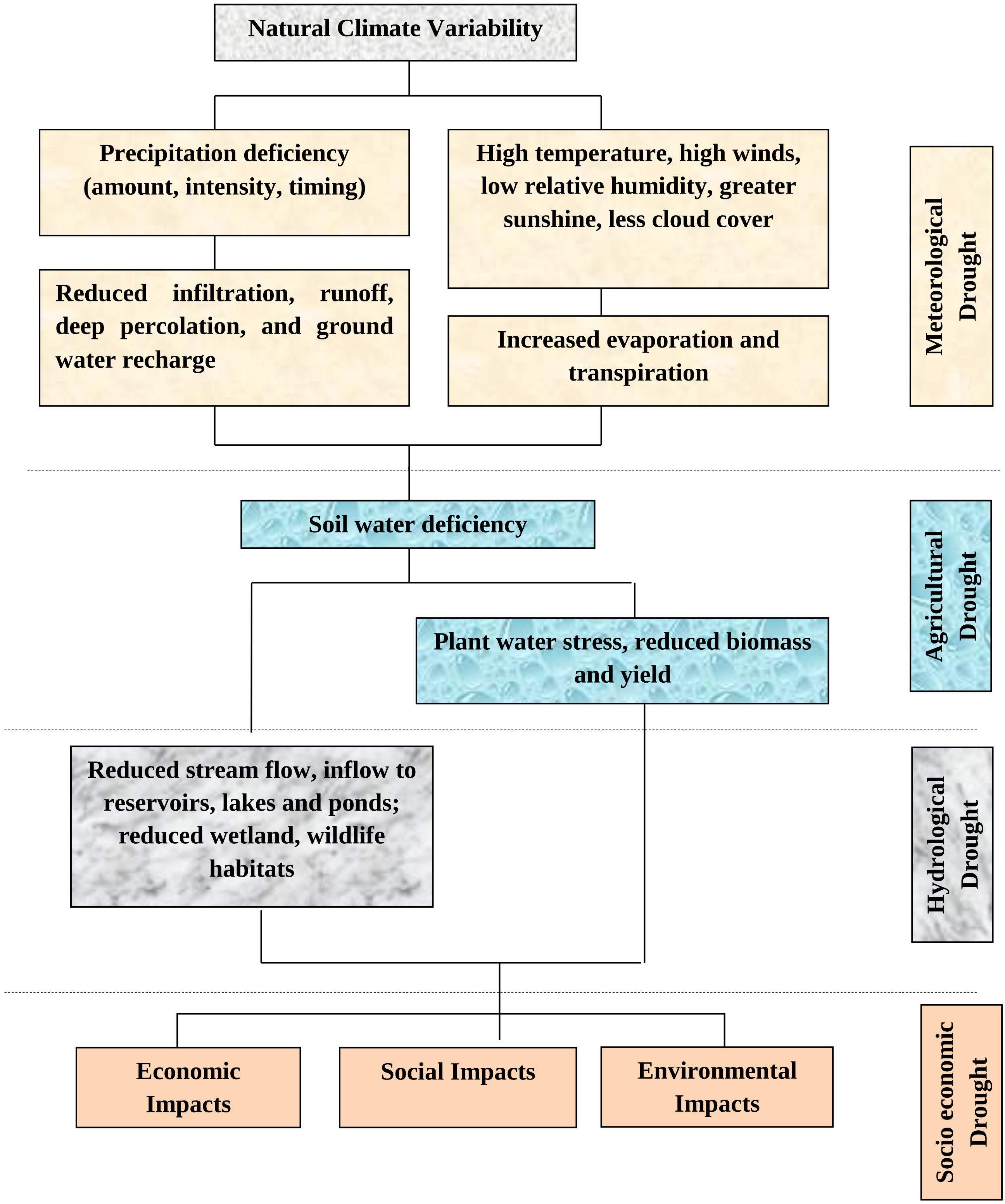

Figure 8. Flow Chart illustrating the Progression of Drought, and the Relationship between Meteorological, Agricultural, and Hydrological Droughts. *Source: National Drought Mitigation Centre, 2006.*

- Socioeconomic

Socioeconomic drought is based on the process of water supply and demand therefore normally occurs when the supply of economic goods cannot meet demand, due to water supply challenges

3.3 DROUGHT VARIABLES AND PARAMETERS

3.3.1 Drought Variables

A drought variable is the main variable for assessing drought effect and is important in defining drought and the process by which it is analysed. For meteorological drought, the determinant variable is precipitation; river runoff, stream flow, reservoir levels, and groundwater levels for hydrological drought, whereas for agricultural drought the main variable is soil moisture and consumptive use. The time series of the variables provides the framework for evaluating the drought parameters of interest (Panu and Sharma, 2002).

3.3.2 Time Scales of Droughts

Time scales are important when monitoring drought. Many time scales are used, with the most common being the year followed by the month (Sharma, 1997). Whilst yearly time scales are considered lengthy, the time-period can be used to abstract information on the regional behaviour of droughts. Monthly time scale is used for monitoring droughts in agricultural, water and water abstraction situations (Panu and Sharma, 2002) whereas daily time scale is used to analyse short - term droughts (Sharma, 1996; Tallaksen et al., 1997).

3.3.3 Drought Parameters

Important parameters quantifying drought are duration, severity, initiation and termination time points, and areal coverage (Panu and Sharma, 2002). Others include the magnitude, the intensity, the severity, the geographical coverage and the frequency. The magnitude is the accumulated deficit of water below a threshold during a drought period and the intensity represents the ratio of drought magnitude to its duration (Zagar et al., 2011). The severity is the degree of the precipitation deficit with reference to a desired threshold level (Dercon, 2004; Dracup et al., 1980; Yevjevich, 1967). The geographical coverage is the spatial extent, while the frequency is expressed as the average period between drought events that have a severity equal to or above a threshold (Zagar et al., 2011).

3.4 DROUGHT MANAGEMENT STRATEGIES

3.4.1 Drought Planning and Management

Historically, of all climate hazards, drought has the greatest effect on people's livelihoods in Eswatini (UNDP, 2011a). It has different and interconnected social, economic, and environmental impacts that include fire, a decline in crop yields resulting in increased food insecurity, livestock losses, the forced sale of household assets, the forced sale of land, increased crime, depletion of water for human consumption, decline in health, displacement/migration, civil unrest/conflict, and famine (Jordaan, 2011).

Droughts accentuate food insecurity, and have a long-term effect on livelihoods; this in turn leads to diversification of food acquisition options and patterns, forcing families into unsustainable livelihood patterns (Davis, 2003). Drought planning is therefore gaining considerable momentum globally, resulting in the development of drought plans by many governments. Most of the drought plans already prepared have largely been reactive and response-oriented rather than proactive (Baudoin et al., 2018; Derner and Augustine, 2016; Engle et al., 2016; Gerber and Mirzabaev, 2017; Wilhite, 2017). Wilhite (2000) and Wilhite et al. (2014) highlighted that the conventional reactive approach of managing drought is ineffective because it is ill-timed, poorly coordinated, and often expensive.

The 'hydro-illogical' cycle presented in Figure 9 illustrates the attitude of many stakeholders when affected by drought (Jordaan, 2011; Van Zyl, 2006; Wilhite, 2000).

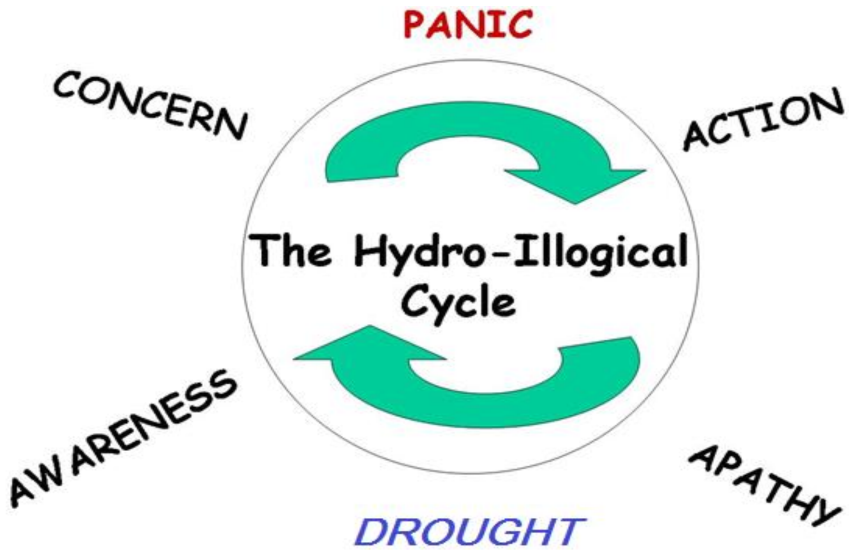

Figure 9: The Hydro-Illogical Cycle *Source: Wilhite, 2000.*

In the aftermath of a ‘good rain’, stakeholders have little concern about drought. However, with changing conditions and the threat of impending drought, they experience concerns, followed by panic. This triggers action or response through various drought mitigation plans and strategies, implemented until the next good rains come. Then, all is forgotten, no lesson is learnt and the cycle starts over again. Governments normally respond to a drought disaster through impact and vulnerability evaluations that often lead to response, recovery and rehabilitation activities (Wilhite and Svoboda, 2000), with minimum focus on preparedness measures.

Preparedness has to be proactive utilising all aspects of the disaster management cycle (Figure 10). This proactive approach requires coordination among monitoring agencies to ensure reliable and timely early warning information is available to decision - makers, farmers, business and all involved in the agriculture sector (Jordaan, 2011).

Figure 10. Disaster Management Cycle *Source: Wilhite, 2011.*

Wilhite and Svoboda (2000) argue that the promotion of institutional capacity is a strong necessity which ensures that the organizational structure improves the ability to monitor, take response actions, improves the flow of information and coordinates government’s activities. Eswatini more often reacts to crises rather than mitigating or preventing their negative impacts. According to Jordaan (2011), the existence of relief organizations and external assistance has exacerbated this approach. In reality, several responses from national and international bodies have aggravated affected peoples' vulnerability by increasing their dependence on internal or external support.

More often, relief organisations - such as non-governmental organisations (NGOs) and UN organisations - come to the rescue when crises strike in Africa, yet in most cases, no change in governance or strategy is detected after they have dealt with the crises (Jordaan, 2011). In addition, large-scale food distribution schemes in response to drought are often seen as humanitarian, saving people's lives; however, they have little regard to the long-term consequences (Adams et al., 1998). Shamano (2010) argues that such actions in many cases exacerbate inequality and undermine people's ability to help themselves.

The capacity for management of the effects of drought varies according to country and region, depending on the level of development. National governments implement different policies and strategies to guide action in the event of drought. In many African countries, preparedness for drought is done through establishing food reserves to help addressing production deficits and providing possible emergency relief. While these costly relief efforts have been perceived as a necessity, such short-term interventions have generally precluded support for longer-term development processes. Further, they are seen to instil dependency syndrome among vulnerable communities.

3.4.2 Drought Management Strategies in Sub Saharan Africa

Drought mitigation strategies have traditionally been explained in terms of improving food security. After a drought, mitigation measures are usually given more consideration by government and donors. These often relate to larger-scale investment in irrigation or water resources and investment in agriculture production (Benson and Clay, 1998). African governments have realised the high financial cost of relief actions, and have progressively increased efforts to implement risk reduction policies (UNDP, 2000).

Often strategies for drought management try to integrate drought disasters into programme management cycles aimed at mitigation and prevention (FAO, 2004). In South Africa an example of such strategy is the Disaster Management Act (GoSA 2002). In Eswatini, the establishment of the NDMA, a body responsible for the enactment of the Disaster Management

Act of 2006, the adoption of the National Action Plan for Disaster Risk Reduction 2008–2015 (GS, 2008) and the National Disaster Risk Management Policy 2011 are some of the strategies and initiatives implemented.

3.5 PREDICTION, MONITORING, AND EARLY WARNING

The slow onset of drought makes the utilization Early Warning Systems (EWSs) important to enhance drought mitigation. An EWS is a mechanism and process for monitoring people's access to food so that a quick notification of an eventual food crisis can be provided (Buchanan-Smith, 2000). The system provides information about hazards that may develop into catastrophes without an early response. This information provides evidence needed to launch and close down drought preparedness and emergency response programs (Wilhite and Svoboda, 2000).

An EWS with the focus on drought has the following objectives:

i. to provide timely information about the onset of drought and also its food security implications;
ii. to provide information on food availability during droughts;
iii. to build a reliable database of baseline information that can be utilised for local development planning.

There are many existing drought early warning systems in use. Some of them are listed below and will be discussed in detail in the next chapters:

- United States Drought Monitor (USDM)
- National Oceanic and Atmospheric Administration (NOAA)
- The FAO Global Information and Early Warning System on Food and Agriculture (GIEWS)
- Famine Early Warning System (FEWS NET)

In southern Africa, the presence of many EWSs has not led to improved monitoring and early communication of drought hazard to stakeholders. A lot is yet to be done to make early warnings and monitoring instruments more reliable and more communicable.

3.5.1 Prevention

Drought is difficult to detect, and normally lasts much longer than other weather events. It is also very difficult to eliminate because it is a natural event (Changnon, 1987; Hou, et al., 2018; Lee et al., 2018; Müller et al., 2018; Valverde-Arias et al., 2018). However, measures to reduce the potential negative effects can be taken. Although the hazard cannot be eliminated, vulnerability can be reduced and the ability to withstand, react and recover from that danger will be increased, thereby minimising the adverse effects (McEntire, 2012; Nelson, 2018).

3.5.1.1 Preparedness and mitigation

All regions of the world face the probability of drought, with negative impacts to the environment, food production, and property, making preparedness essential. Preparedness can be achieved by having a drought management plan (Beyaztas et al., 2018; Oloruntoba et al., 2018; WHO, 2003). Mitigation means reducing the severity of the human and material damage caused by the disaster (WHO, 2003). Drought mitigation strategies indicate what can be done to lessen the force or intensity of dry periods.

3.5.1.2 Coping capacity

Coping capacity is the ability by which people or organisations use available resources and capabilities to face adverse conditions that could lead to a disaster (UNISDR, 2017b). This involves managing resources, both in normal times as well as during crises or adverse conditions. The coping ability of individuals in this study can be seen as the ability to deal with periods of drought or to manage them in a manner that prevents drought disasters. The capacity to cope with drought depends on - amongst other factors - ownership and access to resources, such as land ownership, farmers' income, farm land size, education level, access to credit, crop insurance, technical information, social networking, and public support programs (Ellis, 2000; Jordaan, 2011).

3.5.1.3 Response

Drought usually results in major impediments, such as loss of livestock, crops, and natural resources, which in turn negatively affect on-going development. Drought response can be considered an aggregate of decisions and measures taken to contain or mitigate the effects of a drought-disastrous event to prevent any further loss of life or assets. Drought response includes taking immediate action by increasing supplies and reducing water consumption for vulnerable households, improving access to medical care, fire protection, and general health and sanitation

(EPA, 2016). It also encompasses improved access to emergency food assistance, cash transfers, improved nutrition, emergency health care and animal vaccinations (DuBois et al., 2018; IFRC, 2016). Such response mainly focuses on immediate or short-term needs. In many countries, for effective drought response, governments usually develop a drought response or management plan.

3.6 DROUGHT RISK REDUCTION

Poverty, vulnerability, and disasters are linked; it is most often the poorest that are worst affected and suffer most. People who live in dry areas are vulnerable to disasters, where they are subject to recurrent droughts, and can also be affected by serious floods. Drought disaster risk reduction is the concept and practice to avoid, minimise, or transfer the adverse effects of drought hazards and the potential impacts of disaster by systematically analysing and managing the factors behind the disaster (van Niekerk, 2011). A proactive rather than reactive approach to risk reduction is the best means for mitigating impact from drought (Gerber and Mirzabaev, 2017; Gichere, 2013; Jarvis and Erickson, 1986).

3.7 DROUGHT RISK ASSESSMENT

Natural hazards occur worldwide, but predominantly in underdeveloped countries where the impact is greatest, and their outcomes more keenly felt (Jacques, 1995). A risk assessment is a key component of policy - and decision - making process (UNDP, 2010). To understand the potential impact, the drought risk has to be known. Drought risk assessment is a key component in the management of drought to help to identify drought associated areas, enabling communities to plan, prepare and mitigate potential consequences (Carrão et al., 2016; IDMP, 2016). Such assessment helps to highlight the extent of the drought risk by integrating hazard data with adaptation, vulnerability, and coping capacity (Jordaan et al., 2013).

Disaster and climate risk assessments are the underpinning of decision-making processes for planners. Calculating risk and anticipated future losses is the initial phase in any disaster risk reduction programme with the outputs and scenarios of a risk assessment influencing the shaping of overall development projects (GFDRR, 2014).

Determining which are the appropriate options to minimise disaster risk is the fundamental purpose of risk-informed planning (ADB, 2017). In the disaster risk management cycle, risk assessments are performed for various reasons. This includes assessing the extent and probability of potential losses and understanding the causes and effects of the losses (UNDP, 2010), focusing on expenditure and effort on risk mitigation and control strategies (GroupMap, 2018), developing financial plans to support disaster response, and aiding recovery (Avagyan et al., 2018; Gallina et al., 2016; Liu, et al., 2018; Sugathapala and Munasinghe, 2005).

There are many equations for calculating disaster risk. Jordaan (2011) proposed the following formula based on the work of Wisner et al. (2004) which incorporates people's coping capacity:

$$R = (H * V) / C \tag{3.1}$$

where R = Risk; H = Hazard (drought); V = Vulnerability (degree of exposure to economic, social and environmental factors), C = Coping capacity.

The risk is expressed by the likelihood that a natural hazard will occur, its intensity, natural hazard exposure, and the vulnerability level (ADB, 2017). Table 3 highlights the relationship between risk, hazard, and vulnerability.

Table 3. Correlation between Risk, Hazard, and Vulnerability

Risk	=	Hazards	X	Vulnerability
The likelihood of harm or anticipated losses arising from interactions between natural and human hazards and vulnerable conditions		A potentially damaging physical event, phenomenon, or human activity that may cause loss of life or injury, property damage, social and economic disruption, or environmental degradation		The conditions determined by factors or processes, physical, social, economic and environmental, that increase the community's susceptibility to the risk

Source: UNISDR, 2004

3.7.1 Hazard Assessment

Drought risk-assessment analyses risks by evaluating the nature of the hazard, the people and assets exposed, and the vulnerability of these elements (ADB, 2017). The main factor in drought hazard assessment is therefore precipitation deficit from normal production due to little precipitation and excessive evapotranspiration (Jordaan, 2011; Wilhite, 2000). Characterising the drought hazard is intricate, mainly due to the difficulty in determining both the onset and end of the phenomenon (Jiang et al., 2015; Khadr, 2017; Kumar et al., 2017; WMO and GWP, 2016; Zarafshani et al., 2016).

For effective disaster risk reduction, there is need to identify the hazards and who is vulnerable to them. Each hazard is characterised by its location, intensity, frequency, and probability (UNISDR, 2004). Hazard assessment is therefore a component of drought risk assessment. Meteorologists, researchers, and other specialists have developed drought indices to help characterise drought hazard, by intimating the onset, severity, and end of droughts. Indices are calculated numerical representations of the severity, assessed using climatic or hydro-meteorological inputs, often interpreted on a scale of abnormally wet, average, and abnormally dry (Hayes, 2006; WMO and GWP, 2016).

3.7.2 Drought indices

Rainfall data alone will not indicate the presence, severity, or duration of a drought (NDMC, 2014; WMO and GWP, 2016). Innumerable indicators of drought have been derived in recent decades and are in use for drought monitoring. Application and tracking of these indicators provide the necessary and important instruments for monitoring drought. A drought index is therefore a prime variable for defining different drought parameters, which include intensity, duration, severity, and spatial extent (Mishra and Singh, 2010; Morid et al., 2006).

Considering the existence of different indices, users choose the index that suits their needs. Although none of the indices are significantly better than any other in all situations and environments, there are some indices that are well-matched for explicit uses than others (NDMC, 2006a). To complement precipitation-based indices remote sensing based indices are in use. These use satellite imagery mirroring the health of vegetation impacted by climatic variability. Use of precipitation-based indices and remote sensing-based indices allows for complementarity and comparability of drought characteristics (Ji et al., 2018; Jiao et al., 2017; Thavorntam et al., 2015).

Examples of precipitation-based indices include the percent of normal precipitation index, the PDSI (Palmer, 1965), the deciles index (Gibbs, 1967), the rainfall deciles method (Erasmus, 1991), the drought area index (Bhalme and Mooley 1980), the effective drought index (Byun and Wilhite, 1996), the Keetch-Byram drought index (Keetch and Byram, 1968), the reclamation drought index (US Bureau of Reclamation, and promulgated in the Reclamation States Drought Assistance Act, 988), the rainfall anomaly index (van Rooy, 1965), the reconnaissance drought index (Tsakiris and Vangelis, 2005), the Bhalme-Mooley drought index (Bhalme and Mooley, 1980), the U.S. drought monitor (NDMC, 2018), and the SPI (McKee et al., 1993).

Examples of agriculture drought indices include the soil-moisture anomaly index and the crop moisture index (Bergman et al., 1988; Palmer, 1968). Examples of hydrological drought indices include the Palmer Z-index and the Palmer hydrological drought index (PHDI) (Palmer, 1965), and the surface water supply index (Shafer and Dezman, 1982)

3.7.2.1 Selecting Indices

In 2016, WMO and GWP provided guidance on selecting indicators and indices. They suggested fundamental issues to be considered before a choice is made on appropriate indices to be selected. These include:

- timeliness in the detection of drought to trigger appropriate response actions;
- spatial and temporal sensitivity to climate variability;
- sensitivity of the impacts for a given location or region;
- long term data needed for calculation available and stable;
- ease of use.

3.7.2.2 Desirable Properties Required of Drought Indices

The meteorological, agricultural, and hydrological droughts are linked with a deficiency in precipitation. Keyantash and Dracup (2002) developed the work of Redmond (1991), establishing key parameters required for an index. These include robustness, tractability, transparency, sophistication, extendibility, and dimensionality, which are summarised below:

i. robustness: signifies the index versatility over varying physical conditions.
ii. tractability: represents the ease of use in terms of computation and data requirements.
iii. transparency: refers to simplicity of understanding; an index should be user friendly, understood by both scientists and the general public.

iv. sophistication: refers to the quality and sophistication of the index using a thorough method and quality data for calculation.

v. extendability: is the degree to which the index may be extended across time to alternate drought scenarios.

vi. dimensionality: talk about to the index being dimensionless, thereby used to compare features between different locations or periods.

On a weighted set of six evaluation criteria, Keyantash and Dracup (2002) evaluated the strengths and weaknesses of drought identification. Indices were classified based on the drought they were categorising. In their analysis, they determined that robustness (Table 4) was the most important aspect in drought identification..

Table 4. Weights Assigned to Drought Index Evaluation Criteria.

Criterion	Weight	Relative importance
Robustness	8	28%
Tractability	6	21%
Transparency	5	17%
Sophistication	5	17%
Extendability	3	10%
Dimensionality	2	7%
Score for each criterion1-5		
Maximum weighted score possible 145		

Table 5. Comparison of Drought Indices across Evaluation Criteria

Index	Weighted total	Raw scores (1–5)					
		Robustness	Tractability	Transparency	Sophistication	Extendability	Dimensionality
Meteorological drought							
Rainfall deciles	116	5	3	4	3	5	4
SPI	115	5	2	3	5	5	4
RAI	94	3	4	4	2	4	2
DAI	70	2	3	2	3	3	1
PDSI	61	2	1	1	4	4	1
Hydrological drought							
Total water deficit	102	3	4	5	2	3	5
SWSI	75	4	1	2	3	2	3
PHDI	58	2	1	1	4	3	1
Agricultural drought							
Soil moisture anomaly index	83	3	2	3	3	3	4
Z index	77	3	2	1	4	3	1
CMI	55	2	1	1	4	2	1

Source: Keyantash & Dracup, 2002.

In their comparison of selected drought indices already discussed in this chapter, they ranked drought indices according to superiority. Table 5 presents the ranked, commonly used precipitation-based indices.

3.7.2.3 Meteorology

Percent of Normal Rainfall. This index defines drought as a precipitation deviation from the normal. The index is simple and transparent, and thus is favourable for communicating drought levels to the public (Keyantash and Dracup 2002). The limitation of the index is that it is a rather crude measure of precipitation deficit. Hayes (2006) criticised the index for its incapacity to compare drought across seasons and regions, thereby lacking the required robustness necessary for planning and management (Zagar et al., 2011).

- *Palmer Drought Severity Index (PDSI)*, (Palmer 1965). The PDSI uses precipitation, temperature, and the local available water content data for computation. The index ranges between −4 and 4 (Table 6), with negative quantities indicating dry spell and 3.0 to 3.9 representing a very moist spell. The index has several shortcomings, which include a lag (several months) between its values and emerging droughts. It is also complex to calculate and less comparable regionally.

Table 6. Palmer Drought Index classes

Palmer Drought Classes			
≥ 4.0	Extremely wet	-0.5 to -0.99	Incipient dry spell
3.0 to 3.99	Very wet	-1.0 to -1.99	Mild drought
2.0 to 2.99	Moderately wet	-2.0 to -2.99	Moderate drought
1.0 to 1.99	Slightly wet	-3.0 to -3.99	Severe drought
0.5 to 0.99	Incipient wet spell	≤-4.0	Extreme drought
0.49 to -0.49		Near normal	

Source: Palmer 1965.

- *The Decile Index* (Gibbs, 1967). This index ranks precipitation totals of the previous three months against historical records. It is based on the division of the monthly rainfall into deciles (10% parts). The deciles are categorised into five classes, two deciles per class (Table 7). If precipitation falls into the lowest 20% (deciles 1 and 2), it is classified as significantly below normal. Deciles 3 to 4 (20 to 40 %) indicate a situation below normal precipitation, whereas 9 and 10 (80 to 100%) indicate significantly above normal precipitation (Morid et al., 2006).

Table 7. Classification of Drought Conditions according to Deciles Index

Classifications	
Deciles 1-2: lowest 20%	significantly below normal
Deciles 3-4: next lowest 20%	below normal
Deciles 5-6: middle 20%	near normal
Deciles 7-8: next highest 20%	above normal
Deciles 9- highest 20%	10: significantly above normal

The index has been widely used and accepted because of its ease of calculation. However, its simplicity results in difficulties in conceptual understanding, such as when drought is terminated, or when precipitation is close to or above normal conditions.

- *The Effective Drought Index* (EDI) (Byun and Wilhite, 1996). The EDI is a function of the 'precipitation needed for a return to normal' (PRN), or in other words, for the recovery from the accumulated deficit since the beginning of a drought. The formula for EDI is

$$EDIj = \frac{PRN_j}{ST\ (PRN_j)} \tag{3.2}$$

where $_j$ is actual duration,

ST(PRN) is the standard deviation of each day's *PRN*,
EP is 'effective precipitation' and
MEP is the mean of each day's *EP*.

The EP refers to the summation of all daily precipitation with a time reduction function. The EDI values are standardised, allowing comparability of drought severity at two or more locations, irrespective of climatic differences between them. The EDI varies from −2.5 to 2.5 indicative of the range of wetness - from extreme drought conditions to extremely wet conditions. The '*drought range'* of the EDI indicates extreme drought at EDI less than -2, severe drought at EDI between -2 and -1.5, and moderate drought at EDI between -1.5 and -1.0. Near normal conditions are indicated by EDI between -1 and 1.0.

- *Keetch-Byram Drought Index*. This index uses precipitation and soil moisture analysed in a water budget model, whereby the index increases for each day without rain and decreases when it rains (Altman, 2013). The index has 5 classes (Table 8). The lowest class (0–150) means high availability of moisture and very low risk of fire, whereas above 700, the risk of fire is very high.

Table 8. Keetch-Byram Drought Index Categories

KBDI	Class
0 to 150	Upper soil and duff layer are very wet during this stage and do not contribute to the fire very much.
150 to 300	Pine and hardwood stumps can ignite in this stage, but the fire hardly goes below ground. Snags may cause escaped fires but can be controlled by standard control tactics. More attention is needed when the KBDI levels are close to 300.
300 to 500	Fire intensity at this stage increases significantly. If the KBDI exceeds 350, all the planned winter and spring understory fire should be cancelled.
500 to 700	In this stage, fire behaviour tends to become unpredictable and more urban interface type fire starts to occur. Severe wind condition aggravates the fire.
≥700	Urban interface fires become a major cause of wildfires. Every burning activity should be prohibited until the KBDI levels go down below 500.

Source: Melton, 1996.

Rainfall Anomaly Index (RAI) developed by van Rooy (1965) encompasses a ranking technique assigning magnitudes to positive and negative precipitation anomalies. The index is assessed against a 9-unit scale ranging from extremely wet to extremely dry (van Rooy, 1965). The index is calculated based on the following formula (Keyantash and Dracup 2002):

$$RAI = \pm 3 \frac{P-\overline{P}}{\overline{E}-\overline{P}} \tag{3.3}$$

where P = measured precipitation,

$\bar{P}$ = average precipitation, and

$\bar{E}$ = average of 10 extrema.

- *U.S. Drought Monitor*. The USDM is an index developed within the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Department of Agriculture with the NDMC as a tool that centralises drought monitoring activities (Altman, 2013). The index assimilates the PDSI, the SPI, the percentage of normal precipitation, the soil moisture model percentiles, the daily stream flow, percentiles and the satellite vegetation health index, together with other secondary indicators such as the KBDI, snowpack conditions, reservoir levels, groundwater levels, and direct soil moisture measurements (Svoboda, 2000). The categories of USDM (Table 9) start from DO, which indicates abnormal dryness to D4 indicating exceptional drought.

Table 9. U.S. Drought Monitor drought intensity categories

Categories	
D0	Abnormally dry
D1	Moderate drought
D2	Severe drought
D3	Extreme drought
D4	Exceptional drought

Source: Svoboda, 2000.

The main advantages of this index reflect a drought perspective of multiple experts based on several indicators (Altman, 2013). A limitation, however, lies in its attempt to show on one map drought at several temporal scales (from short-term to long-term drought) (Heim, 2002).

Standard Precipitation Index. The SPI has been widely used due to its minimum data requirement, computational simplicity, reliable interpretation thereby making it ideal for countries where rainfall is the only data available, or data collection is not as extensive, such as in Eswatini. As SPI is a precipitation - based assessment, wet and dry periods can be evaluated in a relatively simple and effective way (WMO, 2012). The indicator quantifies multiple timescales of precipitation deficit that reflect the impact of drought on various water resources.

The primary weakness of the index is that it can only measure precipitation deficits values based on preliminary data can change as the season progresses. The computation of the SPI drought index is established based on the long-term precipitation record of at least 30 years cumulated over a selected time distribution (Belayneh and Adamowski, 2012). Positive SPI values signify wet conditions with greater than median precipitation, and negative SPI values signify dry conditions with lower than median precipitation. Table 10 below shows the SPI drought classes (WMO, 2012).

Table 10. Drought Classification based on SPI

SPI values	Class
>2	Extremely wet
1.5–1.99	Very wet
1.0–1.49	Moderately wet
−0.99 to 0.99	Near normal
−1 to −1.49	Moderately dry
−1.5 to −1.99	Very dry
−2	Extremely dry

Standard Precipitation Evaporation Index. To counter the weaknesses of the SPI, Vicente-Serrano et al., (2010) developed the SPEI. The SPEI fulfils the requirements of a drought index, because its multi-scalar character enables it to be used by different scientific disciplines to detect, monitor, and analyse droughts. Similar to the PDSI and the SPI, the SPEI can measure drought severity based on intensity and duration. It can also identify the onset and end of drought episodes.

The SPEI allows comparison of drought severity through time and space, since it can be calculated over a wide range of climates, as can the SPI. Similar to the SPI, the SPEI is very simple to calculate as it is founded on the original SPI calculation procedure. The SPEI uses the monthly (or weekly) difference between precipitation and potential evapotranspiration. This represents a simple climatic water balance, which is calculated at different time scales to obtain the SPEI (Beguiria et al, 2010).

3.7.2.4 Soil Moisture

- *Soil Moisture Anomaly Index*. Bergman et al. (1988) developed this index to illustrate droughts on a global basis. It is based on Thornthwaite's (1948) monitoring of precipitation and evapotranspiration, and functions within a two-layer soil model used to monitor water movement for the determination of percentage soil saturation.

Crop Moisture Index (CMI) (Palmer, 1968). The CMI is the sum of an evapotranspiration shortfall and soil water recharge. It reflects moisture supply in the short-term, affecting crops (Table 11).

Table 11. Crop Moisture Index Classes

Values	CMI Classes
≥3.0	Excessive wet, some fields flooded
2.0 to 2.99	Too wet, standing water in some fields
1.0 to 1.99	Prospects good, but fields too wet
0.0 to 0.99	Moisture adequate for immediate needs
0.0 to -0.99	Conditions improved but need more rain
-1.00 to -1.99	Prospects improved but still only fair
-2.00 to -2.99	Drought eased, but more rain needed
≤-3.0	Situation still serious, rain badly needed

Source: Palmer 1968.

The index is calculated weekly based on parameters that take into account the average temperature, total precipitation and soil moisture from last week's. The advantage of CMI is that it identifies potential agricultural droughts by looking at present conditions for crops. However, it is inferior for monitoring long-term drought (Hayes, 2000).

The Palmer Z-Index. This index illustrates short-term soil moisture, droughts and wetness with the soil moisture anomaly, on a monthly scale. The Z index is able to monitor agricultural drought due to its sensitivity to soil moisture changes (Karl, 1986; Altman, 2013). The index has a higher frequency of indicating a drought and indicates short duration droughts more often. The disadvantage of the Z index is its complexity to compute.

Z-Score. This is a statistical score comparable to SPI that is used to identify and monitor drought periods. The index can be used to identify wet and dry periods (WMO and GWP, 2016).

3.7.2.5 Hydrology

- *Palmer Hydrological Drought Severity Index* (PHDI). The PHDI, developed by Palmer in 1965, is comparable to the PDSI as it uses identical water balance assessment on a two-layer soil model. It has an advantage over the PSDI because it measures the long-term cumulative impact, more accurately reflecting groundwater conditions and reservoir levels. The disadvantage of the PHDI is its slow response to drought changes.

3.7.2.6 Remote Sensing Based Indices

Drought assessment and monitoring with satellite images and geospatial information technologies has recently been gaining momentum, making the use of remote sensing important. Remote sensing is the collection of digital data in the reflective, thermal, or microwave portions of the electromagnetic spectrum through satellite, aircraft, or ground-based systems (McVica and Jupp, 1988). A schematic illustration of the earth observation systems and geospatial information technology is presented below in Figure 11.

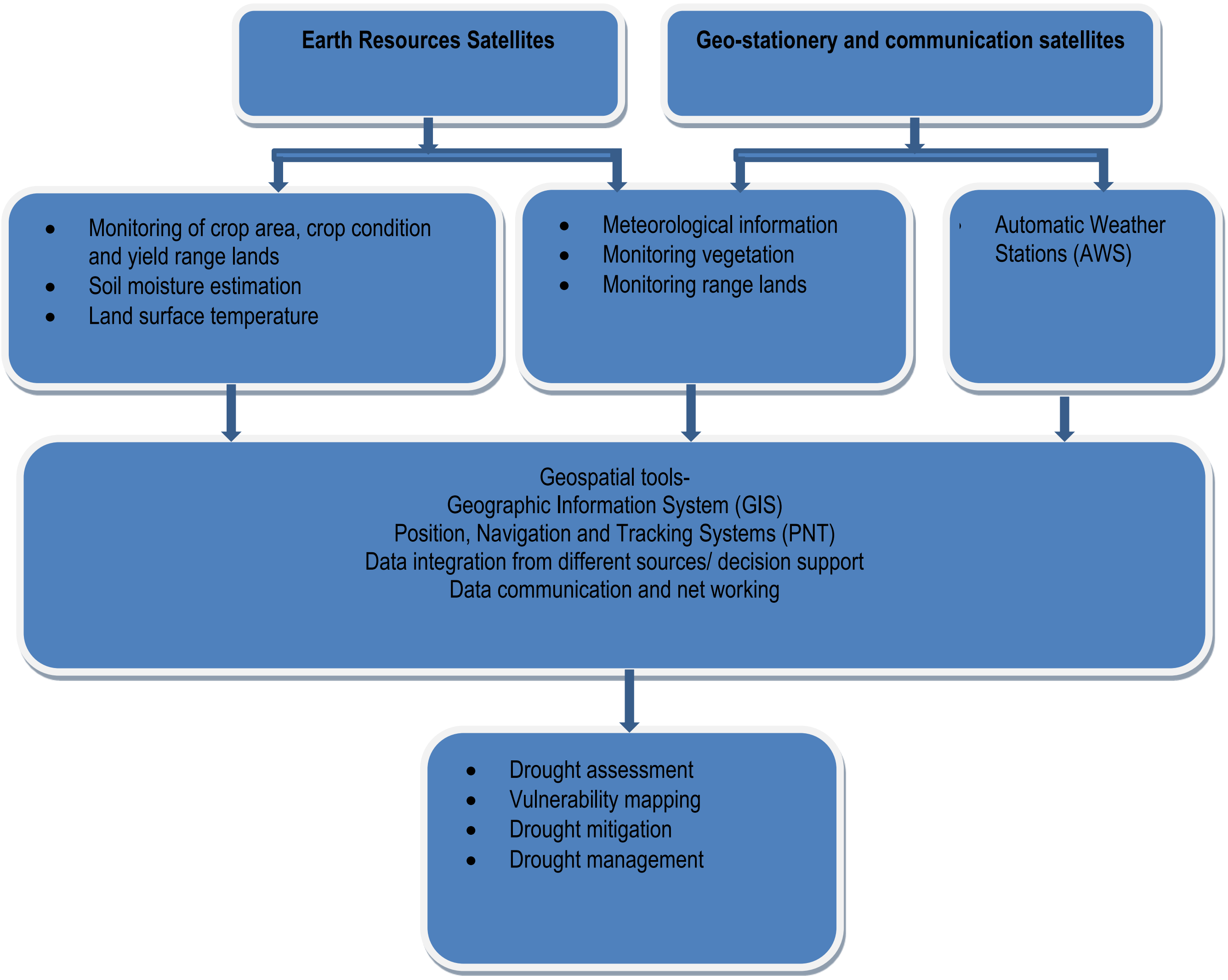

Figure 11. Earth Observation Systems and Geospatial Information Technology for Drought Assessment. *Source: Adapted from Murthy, 2008.*

Remote sensing has a wide range of applications, such as hazard assessment through tracking of hurricanes, earthquakes, erosion, flooding, and drought. Figure 12 presents a visual illustration of the hydrological cycle, showing linkages with remote sensing focusing on agricultural drought. The image depicts how remote sensing mostly focuses on vegetation, and any change of vegetation is a reflection of agricultural drought. Remote sensing-based drought indices include the NDVI (Rouse et al., 1974), the VCI, (Kogan, 1990) and the vegetation health index (VHI) (Kogan, 1995b, 1997).

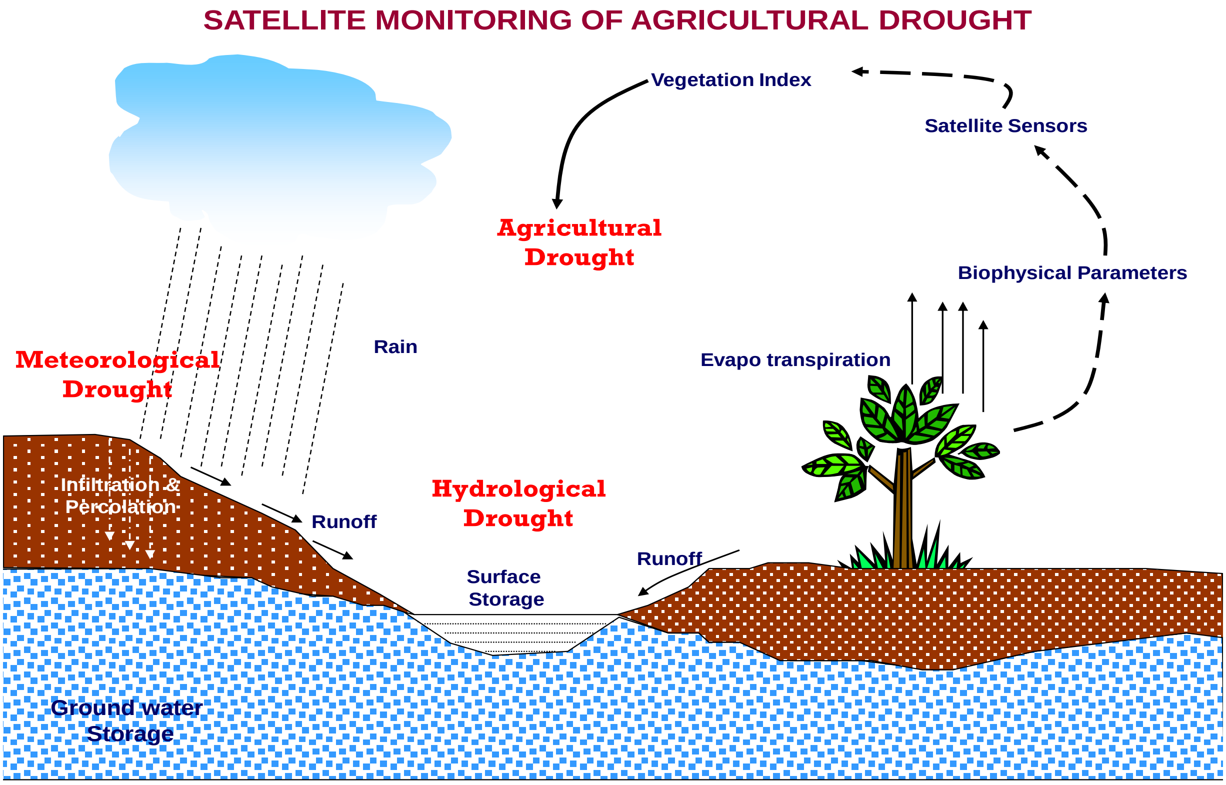

Figure 12. Satellite Monitoring of Agriculture Drought. *Source Murthy, 2008*

The vegetation indicators (NDVI anomaly, VCI, and VHI) provide alternative measures of the relative vegetation health. These remote, sensing-based indices are therefore useful for monitoring areas where vegetation may be stressed, as a proxy to detect potential drought.

For this study, after a thorough analysis of the various precipitation-based and remote sensing-based drought indices, two indices (SPI and NDVI) were selected for use and further analysis. Table 12 indicates the advantages and disadvantages of the selected indices used for this study.

Table 12. Advantages and Disadvantages of SPI and NDVI.

SPI (McKee et al., 1993) Precipitation	Advantages	Disadvantages
	Simplicity; SPI relies only on precipitation data. As SPI is adaptable for the analysis of drought at variable time scales, it can be used for monitoring agricultural and hydrological droughts	Uses only precipitation, loosely connected to ground conditions. Lacks the ability to identify regions with greater tendency to droughts. Requires knowledge of the local climatology.
NDVI	Simple algorithms. While resolution is high (1 km) (compared to weather stations) AVHRR covers a large land area (Ji and Peters 2003). NDVI actually measures dryness (rather than interpolation or extrapolation).	NDVI is sensitive to darker and wet soil background (Huete et al., 1985). The NDVI may vary with soil moisture variations. Vegetation stress is influenced by more factors than moisture alone such as regional rainfall patterns and soil type as well events such as floods, insect infestation, wildfire, etc. (Ji and Peters (2003)).

Source: Zagar et al., 2011.

3.7.3 Drought Vulnerability

Natural hazards affect the southern African region frequently, and vulnerable communities are affected differently. Some lose habitats, their livelihood, and community infrastructure; health is affected and there is possible environmental destruction. Drought vulnerability can be considered as the exposure and susceptibility of a population group to a drought hazard event, as well as their capacity to withstand or cope with the resulting effects. (UNISDR, 2004).

3.7.3.1 Components of drought vulnerability

Social vulnerability depends on social factors, such as population, demographics, policies, social behaviour, patterns of land use, water use, economic development, economic diversity and cultural constructions. Social vulnerability to drought describes the vulnerability of the farming community to the negative impacts of a severe drought (Jordaan et al., 2017b; NDMC, 2006a).

Economic vulnerability – economic vulnerability is defined as the exposure of an economy to exogenous shocks (Briguglio et al., 2009). Economic vulnerability to drought indicates the susceptibility of the economy of communities and different sectors to droughts

(Jordaan, 2011; Jordaan et al., 2017b). There are direct and indirect economic losses that result from drought. These can include high animal mortality, loss of markets due to under-supply (during extreme droughts), and possible loss of jobs, all resulting in lower than normal turnover in small towns and communities (Jordaan 2011; Jordaan et al., 2017a; NDMC 2006a).

Environmental vulnerability - Environmental vulnerability to drought is described as the susceptibility of the environment to drought conditions, with impact of severe drought mostly visible on vegetation. For example, a vegetation can dry up due to reduced photosynthetic activity. Extreme droughts can cause soil degradation, bush encroachment, and extinction of certain species (Jordaan, 2011; Jordaan et al., 2017b; NDMC, 2006a).

3.7.3.2 Drought Vulnerability Assessment

Vulnerability assessment is a tool for characterising the potential for harm to occur within human and ecological systems of value in response to global climate change (Adger et al., 2007). Assessments assist in the understanding of community and environmental needs, with respect to the identification of adaptation actions for vulnerability reduction and capacity-building needs (Adger et al., 2005). Vulnerability assessment is a fundamental aspect of disaster preparedness and plays an important part in the establishment of disaster preparedness programs at all levels (Heijmans and Victoria, 2001).

The purpose of dryness assessments is to communicate possible damage caused by the drought that interacts with the local context. One of the potential benefits of vulnerability mapping is that it helps to support spatial planning (Clark et al., 1998). A drought vulnerability map provides the precise location of sites where people, the natural environment, or property are at risk due to a drought event that could result in a social or environmental impact. Vulnerability mapping facilitates improved communication about risks and exposure to those risks, and ensures enhanced graphic presentations and understanding of the risks and vulnerabilities, so that decision-makers prioritise for resource allocation. These maps are of use in all phases of disaster management, including during prevention, mitigation, preparedness, operations, relief, recovery and lessons-learned (Edwards et al., 2007).

3.8 DROUGHT RESILIENCE AND ADAPTIVE CAPACITY

The resilience concept highlights how the risk / vulnerability relationship is. Risk is defined as the "prospect of an occurrence or condition" (Miletti, 1999). Risk can subsequently be reduced through physical, social, governmental, or economic means, thereby reducing the likelihood of damage and loss (Topping et al., 2010; UNISDR (2007).

3.8.1 Relationship between Vulnerability, Resilience and Adaptive Capacity

A number of factors such as technological capacity, skills and education, economic status and prospects of growth must be taken into account to be resilient to drought. These include environment, the management of natural resources, the livelihood, political structures and processes, infrastructure, information and knowledge flows, speed and breadth of innovation (Mitchell and Harris, 2012). Many authors take the view that vulnerability measures the exposure of households to hazard, and their susceptibility and sensitivity to that hazard, while resilience focuses on the capacities of households and communities to resist or recover from a disturbance, through their hardiness and flexibility (Frankenberger et al., 2013).

Topping et al., (2010) state that vulnerability is the absence of capacity to resist or absorb a disaster impact. Changes in vulnerability can then be achieved by changes in capacities. Gallopı´n (2006) identified the conceptual linkages between vulnerability, resilience and adaptive capacity. Modelling the components of vulnerability, he showed that vulnerability is the overreaching concept and resilience is considered a subset or component of system's capacity for response (Figure 13). He further defined capacity for response as the ability to adapt to a disturbance, moderate the effects, benefit from the possibilities available and cope with the effect of any change of system.

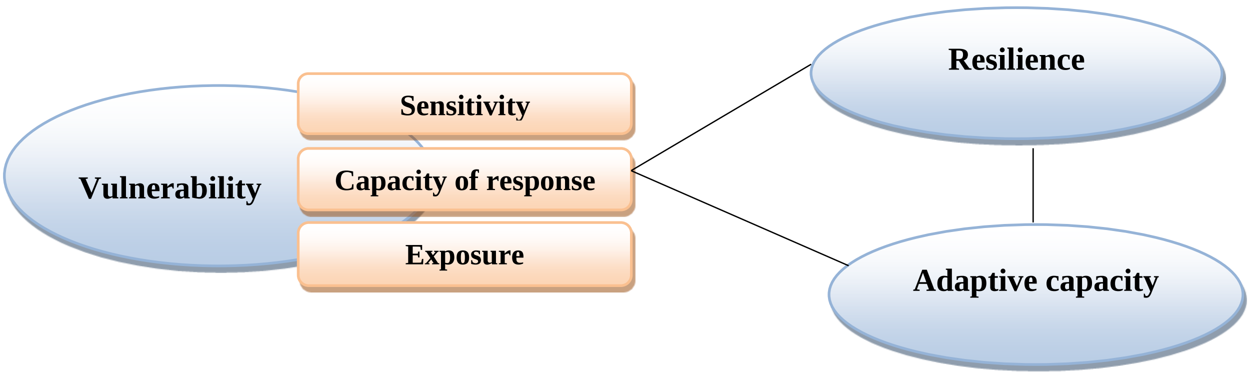

Figure 13. The Concept of Vulnerability. *Source: Bhamra et al., 2011*

3.8.2 Resilience-Adaptive Capacity Approach

Malone (2009) presents a different approach to operationalising resilience. He suggests for analytic and practical purposes that resilience be equated with adaptive capacity. The adaptation process requires the capacity to learn from previous experiences to cope with current climate, and to apply these lessons to cope with future climate, including unexpected events. The ability to prevent, cope, adjust or adapt to drought is an important factor in characterising the vulnerability. Coping capacity is considered in the short term; however, adaptation is the longer-term strategy, which involves significant changes in lifestyles, livelihoods, and farming practices (Smit and Wandel, 2006; Vogel, 1995). Adaptive capacity varies between countries, communities, social groups, individuals and over time, and is context specific.

3.8.3 Adaptive Capacity to Drought Events

Like vulnerability (which is spatial-temporal based), adaptation is considered at the macro, meso, and micro level, with macro level adaptation related to the domain of policy changes and implementation. Adaptive capacity (adaptability) at the micro level is similar or closely related to other commonly used concepts, such as coping capacity, management capacity, stability, robustness, flexibility, and resilience (Smit and Wandel, 2006). The link between government, governance, and adaptive policies at national (macro) level and the adaptive capacity of farmers at the micro level are of critical importance (Jordaan, 2011). Farm-level adaptive capacity is unlikely to be sufficient in poor regions and under-developed economies without sufficient markets and resources (Lotze-Campen and Schellnhuber, 2009).

Béné et al. (2014) state that three types of capacity (Figure 14) are important in living with change and uncertainty:

- absorptive capacity—the ability to cope with the effects of shocks and stresses
- adaptive capacity—the ability of individuals or societies to adjust and adapt to shocks and stresses, but keeping the overall system functioning in broadly the same way
- transformative capacity—the ability to change the system fundamentally when its functioning is no longer viable.

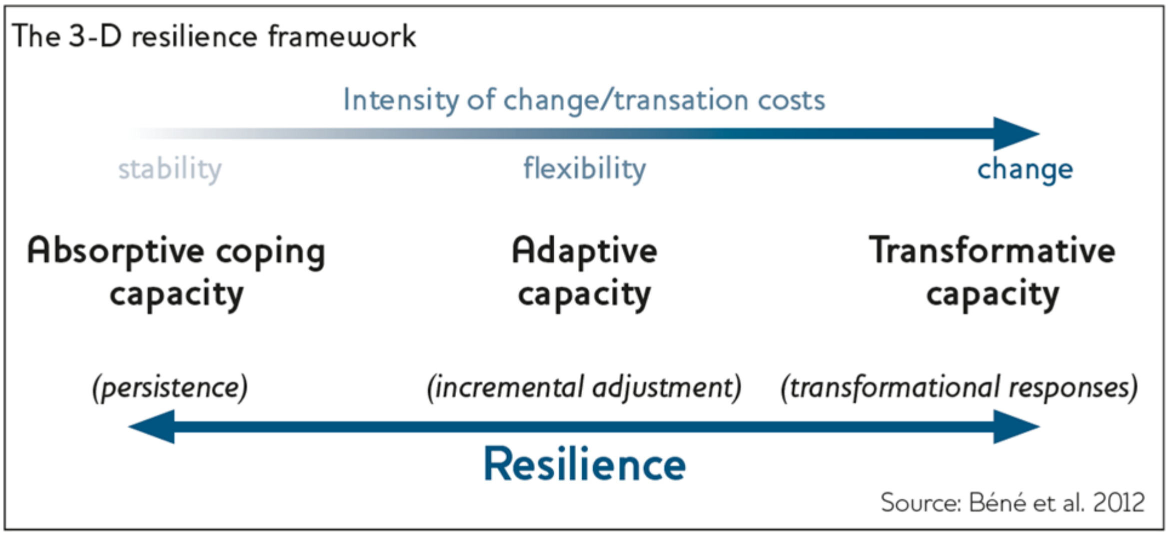

Figure 14. The 3-D Resilience Framework

These capacities are interconnected, mutually reinforcing, and exist at multiple levels (individual, household, community, state, and ecosystem) (Béné et al., 2014; Frankenberger et al., 2012). The framework in Figure 13 highlights the fact that resilience develops not from one but all of these three capacities: absorptive, adaptive, and transformative. Each results in different outcomes: persistence, incremental adjustment, or transformational responses. Therefore, enhancing community resilience requires an integrated approach to building community's capital that will enhance the capacity of communities for collective action in the areas of disaster risk reduction (Frankenberger et al., 2013).

3.9 CHAPTER SUMMARY

Preparedness to drought coupled with appropriate mitigation measures and programs can reduce or eliminate drought - related effects. The paradigm shift from post drought disaster response to a proactive risk reduction approach requires a multisectoral collaboration and coordination of professionals from different backgrounds and agencies. It is therefore imperative for Eswatini to invest in drought preparedness and drought risk assessment in order to be able to estimate the probability of drought occurring and its potential magnitude, as well as the communities that are likely to be exposed.

Eswatini has taken a step forward through the establishment of disaster risk reduction instruments and policies that aim to reduce risk at all levels. For any effective disaster risk reduction programme, the starting point is a quantitative assessment, which combines information about the hazards with exposures and vulnerabilities of the population or assets. The hazard side of the equation uses historical data and forward-looking modelling, together with forecasting about drought conditions, which is then enhanced by socio-economic data quantifying exposure and vulnerability. With such quantitative drought risk information, Eswatini can develop risk management strategies using EWS to reduce impact and build livelihood resilience. Through the enacted policies, legislation, legal frameworks, and institutional coordination mechanisms, the nation will be better positioned to respond to drought disasters.

The next chapter will assess the applicability of the use of the Standardized Precipitation Index for drought characterisation and early warning system. The chapter determines if SPI can be applied in real-time and retrospectively for drought monitoring in Eswatini.

4. APPLYING SPI FOR NEAR REAL TIME AND RETROSPECTIVE DROUGHT MONITORING IN ESWATINI

4.1 INTRODUCTION

Eswatini has been affected by the recurring droughts over the last 50 years, with the 2015/16 drought being regarded as one of the most severe in over 35 years. The different parts of the country have also faced different drought events with the low lying area of the Lowveld facing dry spells more often the other Agro-Ecological Zones (EAZs). The droughts have hit the country differently with the impacts mostly manifesting by low food production, low groundwater recharge, drying of rivers and shortage of pasture resulting in livestock deaths. Drought is therefore an economic, environmental and social concern to the country. The recurrence of droughts over the last decade has led to the government's increased emphasis in drought management. However the interventions have been mostly reactive management - after the drought has occurred - rather than proactive and preparedness.

Scientists are predicting that the frequency and impact of drought events are going to increase especially is southern Africa (Funk, 1998; Masih et al; 2014; UNEP/ICRAF, 2006; van Wilgen, 2016). This will require therefore more resources being put to manage and respond to drought events. The effective management of drought will require a clear understanding of the drought risk, how the communities are susceptible to be impacted and what resources or capitals they have to be able to respond to the events.

Analysing the risk requires understanding the hazard. However, as has been mentioned in the above chapters, drought is difficult to describe accurately, because it is spatially variant and context dependent. The onset and end are also difficult to define. Despite these challenges, drought indices have been developed to be able to provide more scientific, comparable information that stakeholders can use to quantify drought. Despite the existence of many drought indices, it has been documented that there is no single index that unilaterally can be able to effectively describe the drought phenomenon.

Drought indices exist since the early 1900 and have been used to provide various types of information to decision makers. Over time drought indices have been used for crop yield prediction (Kumar and Panu, 1997), early drought warning (Lohani and Loganathan, 1997;

Lohani et al., 1998), probability of drought termination (Karl et al., 1987), amount of drought relief to be provided (Wilhite et al., 1986), and to make comparisons between different regions (Alley, 1984, 1985; Dai et al., 1998; Kumar and Panu, 1997; Nkemdirim and Weber, 1999). Of all the drought indices developed over the last decade the SPI has been the most widely used and recommended drought index worldwide (Kumar et al., 2009; McKee et al.,1993).

In this Chapter, the effectiveness of the SPI is assessed through analysing near real time temporal and spatial drought in Eswatini. Precipitation data from the Eswatini Meteorology Department from 1986 to December 2017 was used to characterise the retrospective dry periods and to assess the frequency and intensity of drought events.

4.2 STANDARDIZED PRECIPITATION INDEX

4.2.1 Introduction to the Standardized Precipitation Index

Comparing the indices described in Chapter 2, the SPI was accepted as the worldwide standard index for meteorological drought measurement and reporting, and the preferred index for drought monitoring and risk assessment (WMO, 2012). This index was created by McKee et al in the early 1990s. It is widely recommended because of its advantages which include the ability to compare drought in different regions and time scales, limited data requirement as precipitation is the only data required (McKee et al., 1995; Moreira et al., 2008). Due to the many advantages of SPI, scientists and many stakeholders have adopted the drought indices for quantifying drought as well as a scientific indicator for communicating drought risk (Giddings et al., 2005; Guttman, 1998; Hayes et al., 1999; Jordaan, 2011).

4.2.2 Description of the Standardized Precipitation Index

For its effective use for drought monitoring it is essential to have a deep understanding of the concepts related to SPI. The SPI was designed to be a spatially invariant drought indicator based on statistical probability. It is usually calculated at intervals of 1 month, 3 months, 6 months, 9 months, 12 months and 24 months. The different timescales are a reflection of the drought impact on agriculture, forestry, river flow or waterbodies (Bokal, 2006; Guttman, 1999), which are a manifestation of the meteorological, agricultural and hydrological droughts. Soil moisture is sensitive to a short time precipitation deficit, while groundwater, streamflow and storage better reflect long-term precipitation deficits (WMO, 2012). McKee et al. (1993) classified drought intensities resulting from the SPI (Table 10).

The onset of drought is when the SPI is negative (-1.0 or less), and when the SPI becomes positive it indicates near normal condition or wet spell (McKee et al., 1993; McKee, 1995). The WMO (2012) summarised the key strengths and weaknesses of the SPI. However, as mentioned in Chapter 2, the advantages of the SPI together with its simplicity outweigh the disadvantages, especially for drought monitoring in resource-poor countries such as Eswatini. The strengths and weaknesses of the SPI are summarised below (WMO, 2012):

Strengths

- uses precipitation only;
- can characterise drought or abnormal wetness over different time scales;
- more comparable across locations and climates;
- less complex to calculate;

Weaknesses

- based on precipitation only and does not account for evapotranspiration;
- requires long-term data of 30–50 years;
- does not take into account the impact of precipitation amount on runoff, streamflow, and water availability

4.2.3 Spatial and Temporal Interpretation of SPI

One advantage of the SPI expressed in the above section is that the index can be calculated and used for many time scales. Figure 15 is a schematic representation of the different droughts and their relationship over time. In order to determine the SPI best use in variable timescales, the WMO (2012) examined and compared the short-term and long-term SPI values. The study focussed on 3, 6, and 12-month time scales for drought monitoring. The following discussion focuses on the 3, 6, and 12-month SPI interpretations, as summarised by WMO (2012).

3-month SPI: measures anomalies that mainly affect the soil water and agriculture production over a 3-month period.

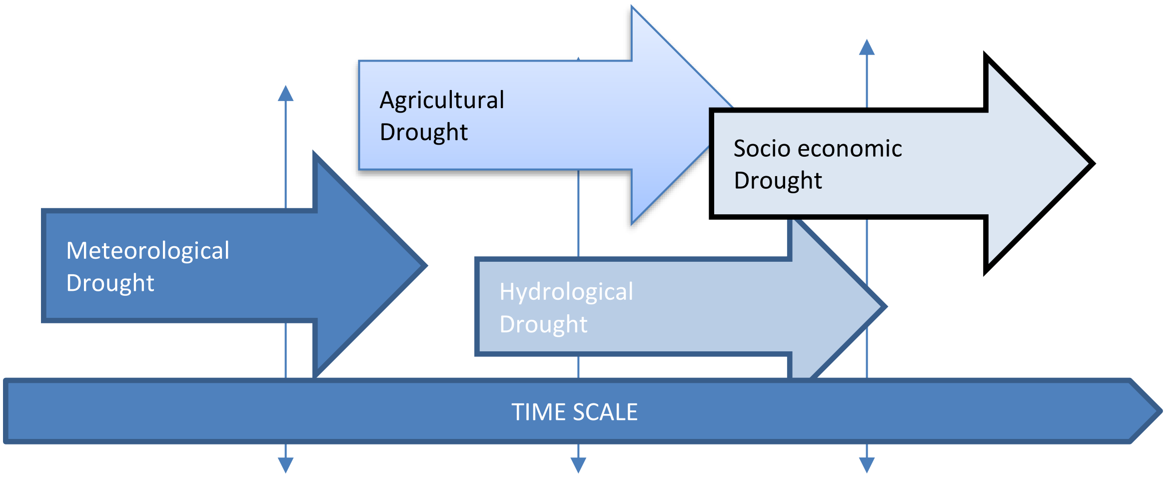

Figure 15**.** SPI Evaluation of Drought over Multiple Timescales.

6-month SPI*:* compares precipitation in the same period to the same 6-month period in history. The time frame represents medium-term rainfall trends, and reflects the rainfall over different seasons.

12-month up to 24-month SPI: compares long-term precipitation for the same period of history. The time scale reflects long term droughts which may lead to shortages in soil, stream flow and fresh water in reservoirs.

4.2.4 Mathematical Calculation of SPI

The calculation of the SPI is area specific and required long-term precipitation data of 30 years or more. It involves changing the frequency distribution (e.g. gamma) to another (normal or Gaussian) frequency distribution. The historic rainfall data of the station is fitted to a gamma distribution (Thom, 1966).

The first step in calculating the SPI is to choose a particular probability distribution (e.g., gamma distribution), incomplete beta distribution (McKee et al., 1993, 1995), and Pearson III distribution (Guttman, 1998; 1999) that reliably fit the long-term precipitation time series, and conduct fitting to that distribution. Figure 16 below illustrates the gamma distribution with parameters $\alpha = 2$ and $\beta = 1$. This distribution is skewed rightwards with a lower bound of zero, much like a precipitation frequency distribution. Calculation of the SPI entails fitting a gamma probability density function to a given frequency distribution of precipitation totals for a station.

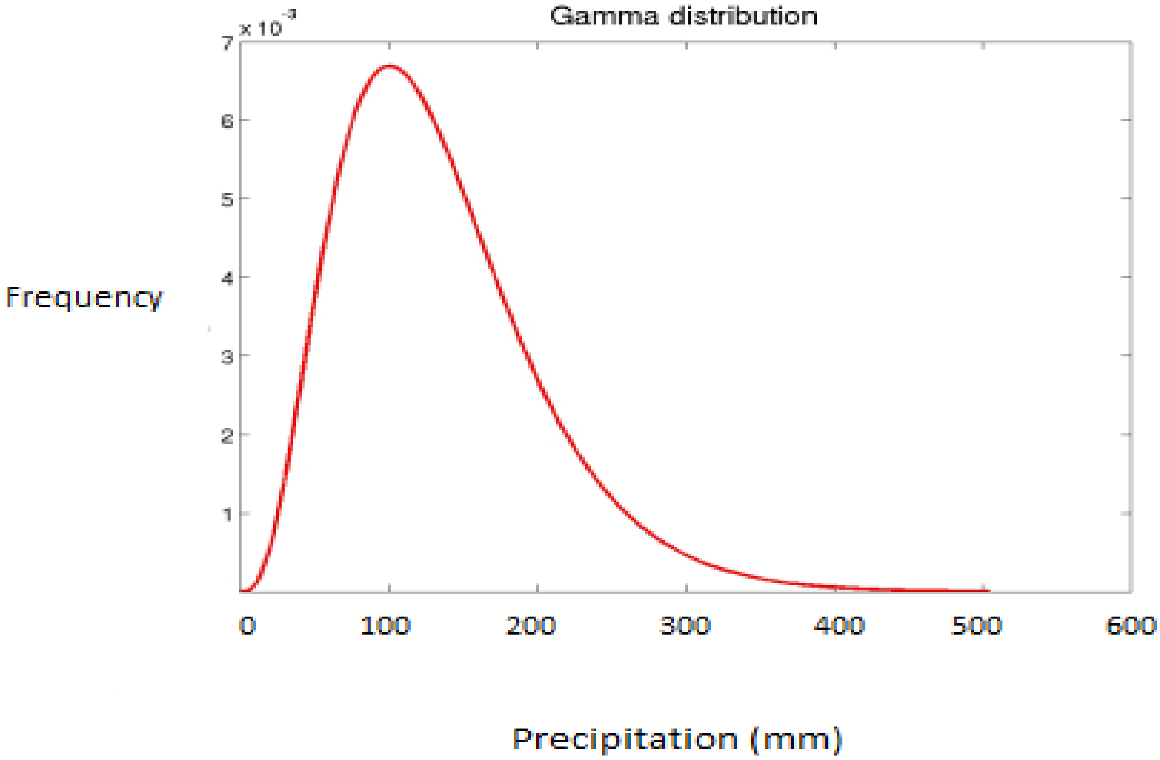

Figure 16. Gamma Frequency Distribution with Parameters alpha = 2 and beta = 1.

The alpha and beta parameters of the gamma probability density function are projected for each station, for each time scale (3, 12, 48 months etc.), and for each month of the year (Edwards, 1997; McKee et al., 1993; Sakulski, 2002).

$$g(x) = \frac{1}{\beta^{\alpha}\,\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \qquad \text{for } x > 0 \qquad (4.1)$$

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

From Thom (1966), as referenced by Edwards (1997) and Sakulski (2002), it was noted that the maximum likelihood solutions are used to optimally estimate α and β:

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{4.2}$$

$$\hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \tag{4.3}$$

where

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \tag{4.4}$$

n = number of precipitation observations.

Thereafter, the ensuing parameters are used to determine cumulative probability of an observed precipitation occurrence for the specific month, time scale, and location. The cumulative probability is given by:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\int_0^x x^{\alpha-1}e^{-x/\beta}dx \tag{4.5}$$

If $t = x/\beta$, the equation becomes the incomplete Gamma function:

$$G(x) = \frac{1}{\Gamma(\alpha)}\int_0^x t^{\alpha-1}e^{-t}dt \tag{4.6}$$

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

$$H(x) = q + (1-q)G(x) \tag{4.7}$$

where **q** is the probability of a zero. If *m* is the number of zeros in a precipitation time series, **q** can be estimated by *m*/*n* (Thom, 1966). He further used tables of the incomplete gamma function to determine the cumulative probability G(x). H(x), the cumulative probability, is then transformed to the standard normal random variable Z with mean zero and variance of one, which then is the value of the SPI. The computation of the Z value of the SPI can be attained using a calculation postulated by Abramowitz and Stegun (1965) that converts cumulative probability to the standard normal random variable Z. Theoretically, the SPI or Z score is a representation of the number of standard deviations above or below mean (Figure 17).

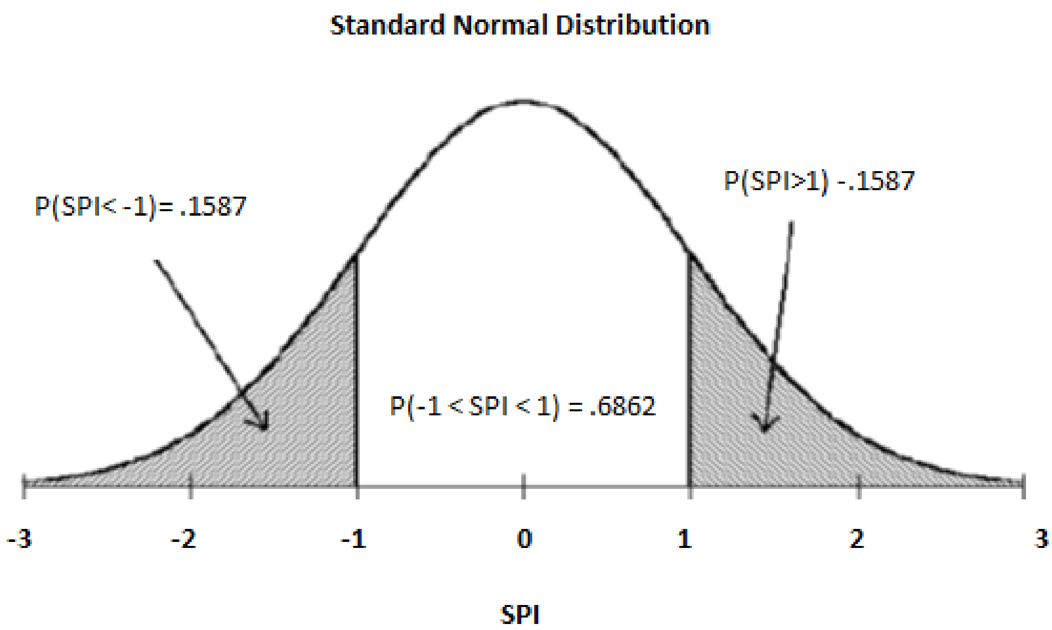

Figure 17. Standard Normal Distribution with the SPI having a Mean of zero and a Variance of one.

$$Z = SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t_3}\right), \qquad 0 < \mathrm{H(x)} \leq 0.5 \tag{4.8}$$

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t_3}\right), \qquad 0.5 < \mathrm{H(x)} < 1 \tag{4.9}$$

where $$t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)}, \qquad 0 < \mathrm{H(x)} \leq 0.5 \tag{4.10}$$

$$t = \sqrt{\ln\left(\frac{1}{(1 - H(x))^2}\right)}, \qquad 0.5 < \mathrm{H(x)} < 1 \tag{4.11}$$

$c_0 = 2.515517$

$c_1 = 0.802853$

$c_2 = 0.010328$

$d_1 = 1.432788$

$d_2 = 0.189269$

$d_3 = 0.001308$

The advantage of the SPI is that it takes into account space and time dimension of drought, as opposed to other drought indices. Standardisation of the procedure for computing the SPI is necessary so that all users will calculate index values that are comparable both spatially and temporally. If the same observed precipitation time series leads to different SPIs that depend on the computational procedures, then comparisons will not quantified, and will be confusing or misleading (Guttman, 1999). To cater for this, the SPI is normalised to account for the frequency distribution of precipitation, as well as the variation in the region or station, and for the calculation of the different time scales. Further to this, Sakulski (2002), Giddings et al. (2005), Kim et al., (2009), and Jordaan (2011) noted that irrespective of the location or time scale, the SPI represents a cumulative probability in relation to the base period for which the gamma parameters were estimated.

4.3 SIMPLE TOOLS FOR CALCULATING SPI RELEVANT FOR ESWATINI

WMO Experts at the 2009 WMO Inter-Regional Workshop on Indices and early warning systems agreed that SPI should be adopted for classifying meteorological droughts worldwide (WMO, 2012). There are many tools and software currently available globally for calculating SPI. However, what is critical is that any tool should be simple to use if it is to be easily adopted, especially by poorer African countries.

The available tools include simple algorithms created in Microsoft Excel software, such as the commonly used SPI_SL_6.exe developed by the National Drought Mitigation Centre (NDMC) at the University of Nebraska (NDMC, 2006b), SPAtial and Time Series Information Modelling (SPATSIM) developed by the Institute for Water Research (IWR) of Rhodes University in South Africa (1999-2002), Internet Application for Disaster Risk Reduction http://dimtecrisk.ufs.ac.za/nc/, developed for South Africa Northern Cape agricultural drought monitoring by the University of the Free State-Disaster Management Training and Education Centre for Africa (DiMTEC) (Sakulski and Jordaan, 2011), and the Drought Indices Calculator

(DrinC), which was developed by the Laboratory of Reclamation Works and Water Resources Management of the National Technical University of Athens, Greece (Tsakiris and Vangelis, 2005).

Of the reviewed tools, DrinC was the selected tool for analysis in this study. The software selection was based on its simplicity, since it could easily be adopted and improved for use in Eswatini. The applications of DrinC in several locations - especially in arid and semi-arid regions - suggests that it is gaining ground as a useful research and operational tool for drought analysis (Tigkas et al., 2015). The effective use of DrinC requires that a data series of at least 30 years must be available to produce reliable results for drought characterisation. When calculating indices on an annual basis, data must be presented either on an annual or monthly basis, while for calculations on a seasonal basis (monthly, 3-months, 6-months, or other time step), monthly data is required.

4.4 METHODOLOGY FOR DROUGHT IDENTIFICATION USING SPI FOR DROUGHT MONITORING IN ESWATINI

The variability in precipitation, the lack of data on soil moisture, and the absence of data on evaporation throughout the country constitutes an almost ideal environment for the application of SPI for drought monitoring in Eswatini. Droughts in Eswatini are becoming more frequent, with increasingly adverse impacts on the economy, social life, and on the environment (Ebi and Bowen, 2016; Kunene, 2018). This gives therefore importance to drought monitoring to be able to detect the onset of drought and provide drought early warning information.

4.4.1 Data Set

The SPI was used for drought monitoring for the time series from the period 1986 to 2017. Representative meteorological stations of the Eswatini Meteorological Service were selected to ensure coverage of all agro ecological regions (Figure 18) in the administrative regions in Eswatini presented in Table 13. Monthly rainfall dataset was supplied by the Eswatini Meteorological Services.

The data was collected from fourteen meteorological stations namely, Mbabane, Nhlangano, Matsapha, Malkerns, Big Bend, Mhlume, Siteki, Piggs Peak, Sithobelweni, Mananga, Mankayane, Mpisi, Khubuta, and Siphofaneni. Only stations will full data were considered for analysis. To be able to present natural drought conditions raw precipitation data was used. All the selected precipitation stations displayed good data quality with no data gaps in the time series. This is because only rainfall stations that had the complete 32-year dataset were considered. There was therefore no data filling or corrective homogeneity enforced.

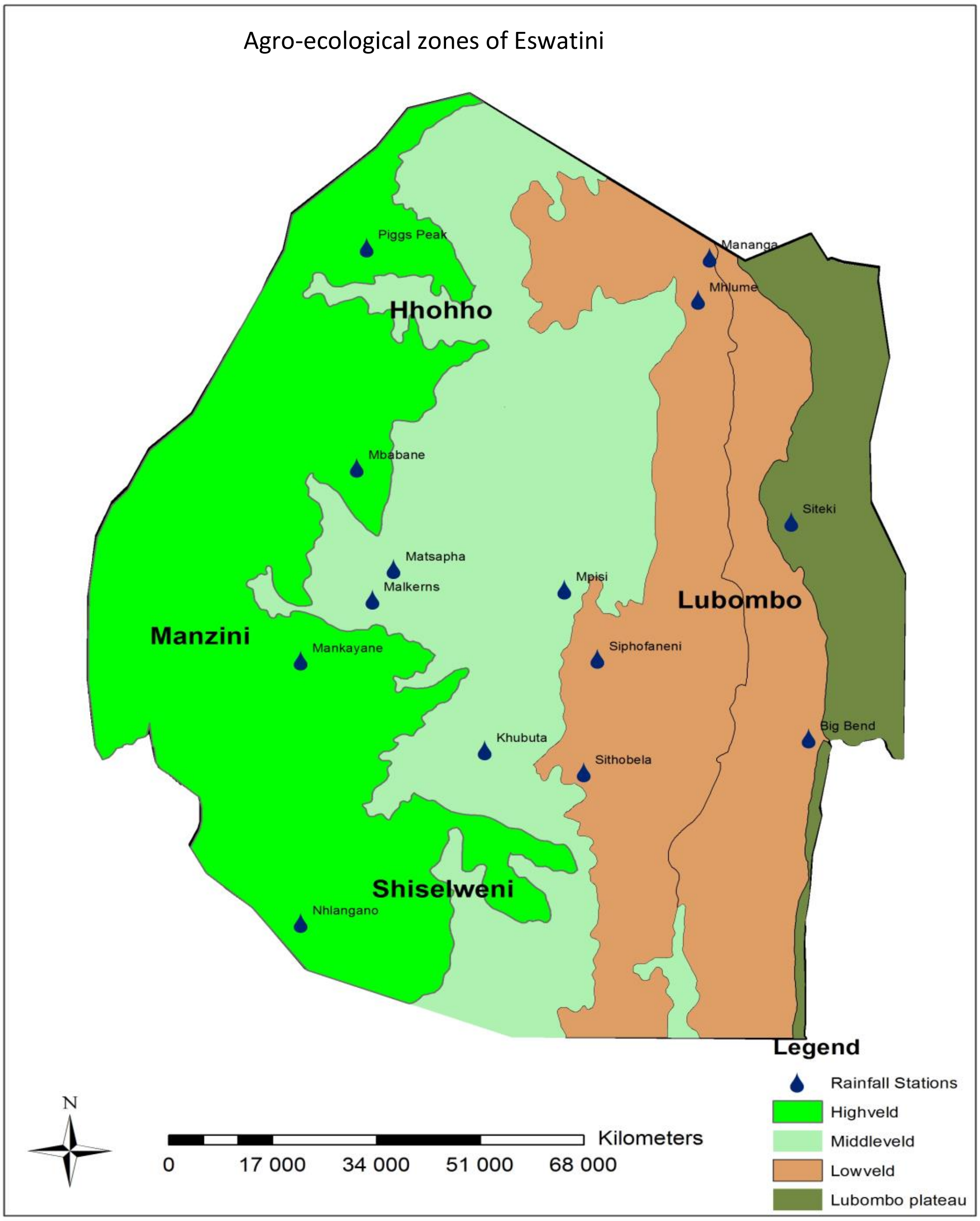

Figure 18**.** Map of Eswatini with Agro-Ecological Zonation and the Rainfall Stations

Table 13. Meteorological Stations and their Geographic Coordinates

Agro Ecological region	Station Name	Latitude (S)	Longitude (E)	Time Series
Highveld	Mbabane	-26,33	31,15	1986-2017
	Nhlangano	-27,12	31,2	1986-2017
	Mankayane	-26,67	31,05	1986-2017
	Mhlume	-26,03	31,15	1986-2017
Middleveld	Matsapha	-26,53	31,3	1986-2017
	Piggs Peak	-25,82	31,42	1986-2017
	Khubutha	-26,83	31,47	1986-2017
	Mpisi	-26,43	31,53	1986-2017
	Malkerns	-26,55	31,87	1986-2017
Lowveld	Big Bend	-26,85	31,87	1986-2017
	Sithobelweni	-26,88	31,62	1986-2017
	Mananga	-26,00	31,75	1986-2017
	Siphofaneni	-26,67	31,68	1986-2017

4.4.2 Precipitation over Time Graphs

Precipitation level is an important factor affecting crop selection and ecological changes in a region. It is common knowledge that the main reason for drought is the lack of precipitation, or the negative deviation from the mean precipitation for a specific period at a specific place (Alley, 1984; Vicente-Serrano et al., 2010; Wilhite, 2000). Therefore, monitoring and understanding precipitation becomes important for planning and decision-making in the different sectors of the economy, as accurately predicting precipitation trends can contribute to a country's future economic development (Ahmad et al., 2015).

Precipitation trends can provide an interesting proxy and statistical insight into rainfall patterns. Observations suggest that large areas of the world are characterised by more negative than positive trends. These variations mean that, for accurate, unbiased long-term precipitation over-time analysis, large variability in time and space require long-term climate analyses based on homogeneous data (Longobardi and Villani, 2010). Precipitation over-time graphs were made for all fourteen stations to visualise the data time-series and to serve as an *ad hoc* quality control for precipitation values.

Figure 19 presents the mean historical monthly rainfall for Eswatini from1986 to 2017. The rainfall pattern between all the assessed rainfall stations shows similarities, with the months of

May and June being the dry winter months where rainfall only occurred in (mostly) the Highveld AEZ, with little or no rainfall in the Lowveld AEZ. The rainy season commences in September (with a progressive increase in rainfall), culminating in peak rainfall during the months of December and January. Both December and January coincide with the summer crops main vegetative development and reproductive stages. Thus, prolonged rainfall stress in these months will result in reduced crop yields.

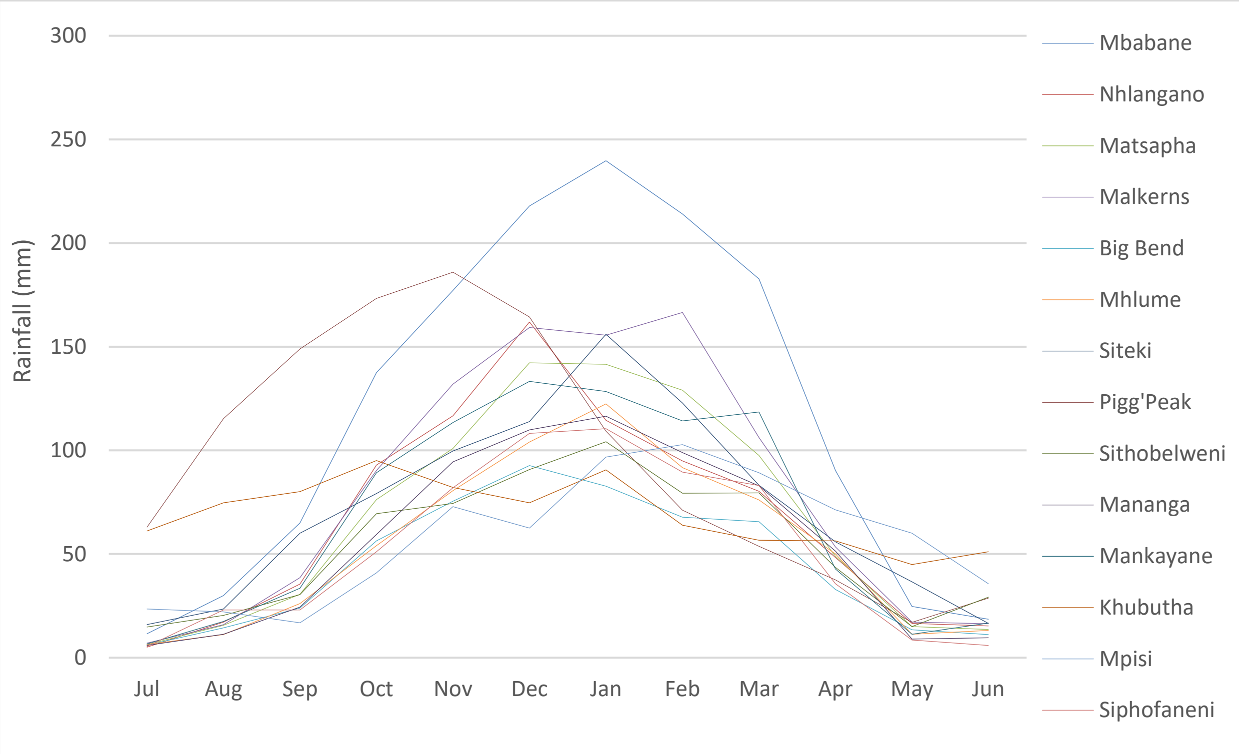

Figure 19. Mean Historical Monthly Rainfall for Eswatini during the Time Period 1986–2017

In order to determine whether the Eswatini rainfall pattern is changing, it is essential to analyse the spatial and temporal variations in monthly precipitation. This is crucial for economic development, management of water resources, and disaster management. Table 14 presents descriptive statistics for the annual rainfall during the study period. The total rainfall during the 32 years ranged from 363 mm in 2016 to 1309 mm in 2000, with an average of 819 mm. The lowest rainfall corresponds to the 2015/16 El Nino occurrence, which was classified as one of the worse climatic events in 50 years (PhysOrg, 2016).

Most rainfall fell in the months of January, February, and March (JFM) quarter (Figure 20), which coincides with the growing season for maize and sorghum—the main cereal crops. For maximum production, a medium maturity maize crop requires between 450 and 800 mm of water, depending on the agro-ecological region. However, the data clearly indicates that in the year 2015/2016, the rainfall was not adequate for cereal production. The long-term decline in maize production, the country's staple food can be attributed to the significant variation in spatial and temporal patterns of total annual rainfall (especially during the critical months of the growing season) (FAO/GIEWS, 2015; Oseni and Masarirambi, 2011; SVAC, 2017).

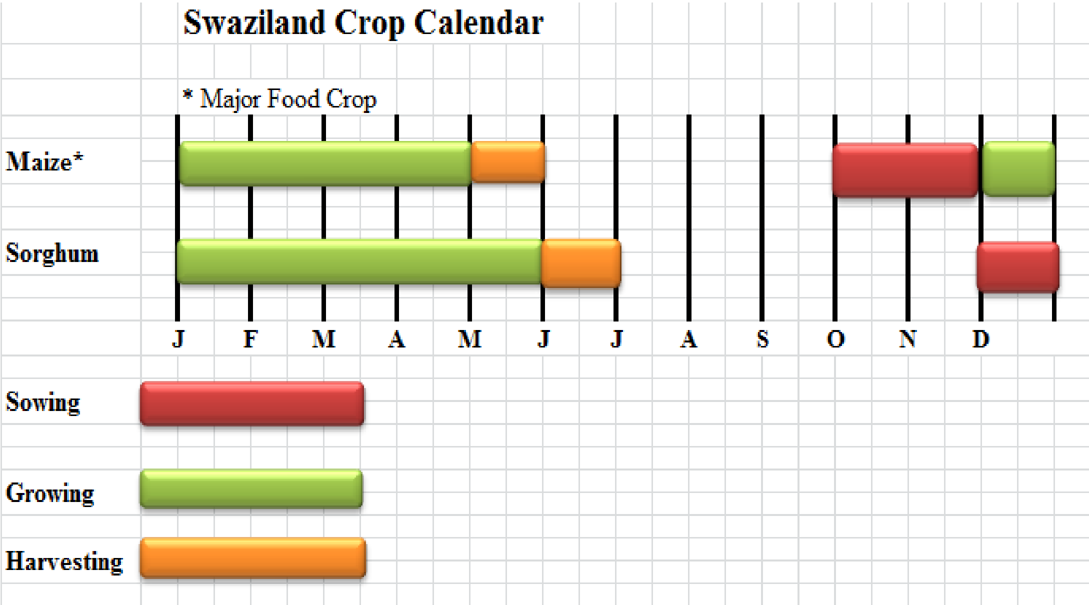

Figure 20. Eswatini Crop Calendar: *Source: Adapted from FAO/GIEWS: 2017*

The rainfall months had a low coefficient of variation (CV), meaning a reduced variability of year-to-year rainfall in Eswatini; this depends on whether this statistic considers deviations from averages by determining whether the country has a high or low rainfall. The CV increases with decreasing precipitation. Thus, the CV of annual precipitation can be used as an index of climatic risk, indicating a likelihood of fluctuations in reservoir storage or crop yield from year to year (UWC, 2001). Locations and seasons with a low annual rainfall are likely to be more badly affected because they will suffer additionally from high deviations around their already low average rainfall (Schulze, 1979, 1982).

Table 14. Annual Rainfall Data for Eswatini (1986–2017)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total Annual Rainfall
1986	148	80	93	79	10	10	2	8	29	34	45	135	673
1987	88	45	142	53	3	5	2	60	153	110	104	136	901
1988	60	221	102	48	14	31	15	27	40	172	55	137	922
1989	72	225	49	27	16	66	2	8	19	96	170	138	888
1990	143	83	67	58	13	10	4	29	16	71	98	139	731
1991	229	114	116	26	57	40	28	17	41	47	111	140	966
1992	63	73	35	39	9	13	12	29	52	57	95	141	618
1993	85	132	105	35	21	17	16	54	34	92	75	142	808
1994	92	77	83	31	18	21	15	37	44	99	116	143	776
1995	107	51	85	48	39	25	32	59	32	105	105	144	832
1996	153	179	84	46	42	28	51	32	39	122	72	145	993
1997	111	92	119	50	44	50	41	50	62	101	120	146	986
1998	139	91	83	45	31	24	25	22	60	135	175	147	977
1999	97	141	90	58	44	28	45	43	61	74	114	148	943
2000	187	309	152	79	44	12	35	61	52	81	148	149	1309
2001	75	121	76	99	28	16	20	18	52	68	197	150	920
2002	88	60	58	47	21	46	27	26	34	59	67	151	684
2003	112	104	28	18	10	38	15	16	50	55	92	152	690
2004	162	114	118	47	6	9	26	12	39	59	105	153	850
2005	160	84	90	48	17	15	7	21	13	54	99	154	762
2006	150	159	131	54	17	9	10	49	36	62	92	155	924
2007	97	74	54	80	5	39	7	28	43	79	122	156	784
2008	89	50	93	62	17	16	14	41	41	59	96	157	735
2009	137	109	47	14	20	14	7	77	27	102	177	158	889
2010	160	62	70	107	17	16	9	4	8	72	180	159	864
2011	174	53	82	85	34	3	19	28	31	78	62	160	809
2012	205	90	72	26	7	0	3	3	172	118	68	161	925
2013	232	87	75	71	34	3	7	10	37	126	85	162	929
2014	82	64	212	24	3	1	2	7	17	74	104	163	753
2015	91	86	86	36	4	0	12	7	34	41	41	164	602
2016	41	45	23	5	4	3	3	3	10	22	69	165	393
2017	44	38	22	14	7	2	2	4	10	16	39	166	363
Min	24	38	22	5	3	0	2	3	8	16	29	135	363
Max	233	309	212	107	57	66	51	77	172	172	197	167	1309
Mean	118	101.8	84.15	47.61	20.15	18.58	15.7	27.09	42.67	77.52	100.82	151	819
SD	51.9	59.05	39.48	24.88	14.51	16.09	13.32	20.03	33.89	34.68	42.53	9.52	176.26
CV	0.45	0.59	0.48	0.53	0.73	0.88	0.86	0.75	0.81	0.45	0.43	0.06	0.22

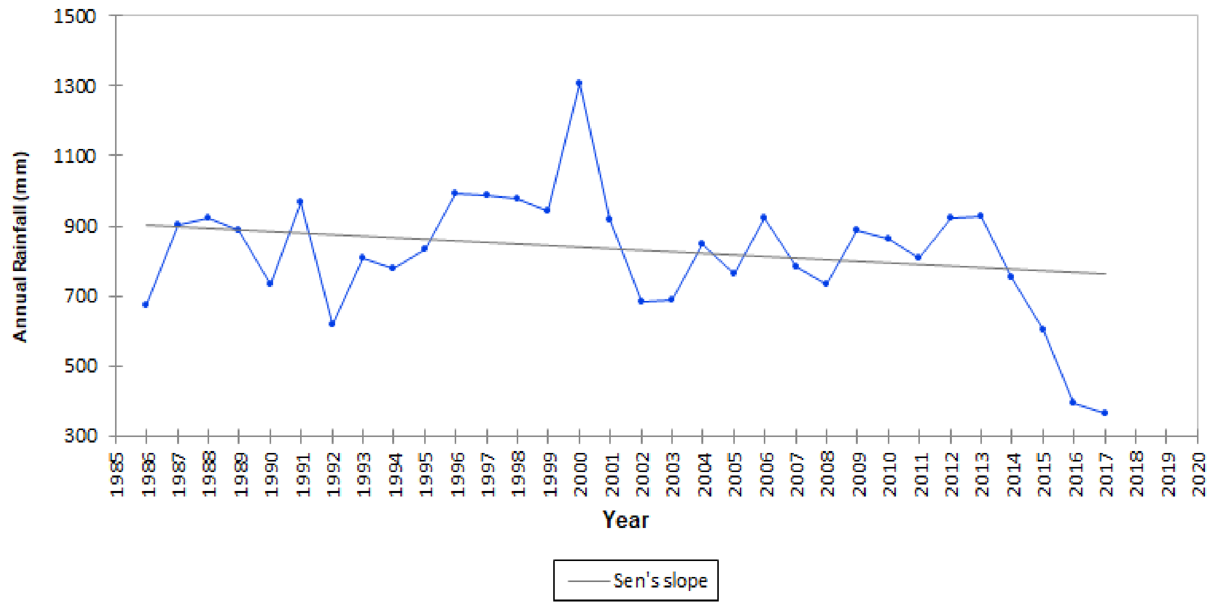

Figure 21. Annual Rainfall Trend for Eswatini (1986-2017).

Table 15. Mann-Kendall trend test / Two-tailed test (Annual Precipitation):

Kendall's tau	-0,161
S	-80,000
Var(S)	3802,667
p-value (Two-tailed)	0,195
alpha	0,05
Mean	819 mm
Standard deviation	179
Trend equation	y = -6,3389x + 13506
	R^2 = 0,1103

Analysing the time series of the Eswatini annual average precipitation from 1986–2017, it is evident that there were years where rainfall was below the national average. The notable years were 1986, 1990, 1992, 1994, 2002-2003, 2005, 2007, 2008, 2011, 2014, and 2015. After comparing with known drought years, Oseni and Masarirambi (2011), Masih et al. (2014), and EM-DAT (2016) have highlighted that the severe drought years in Eswatini occurred in 1981, 1983,1984, 1990, 1992, 2001, 2007, 2008, 2014, 2014, and 2016. Trend analysis was also performed on an annual scale, to examine whether any trends existed in the data. The annual rainfall time series, averaged over the whole dataset, is illustrated in Figure 21 with the corresponding Sen slope plotted. The variability around the mean (819 mm) was evident and pronounced, indicating a decrease over time in annual rainfall. The standard deviation of the annual rainfall shows higher values than the average, indicating that the deviation from normal is considerable. Further, Mann-Kendal test results (Table 15) indicate a decreasing trend in annual rainfall across all meteorological stations. The Sen's slope estimate of rate of decrease is -80 mm per year. However, the decreasing rate is not statistically significant at α = 0.05.

Analysing the seasonal rainfall from October to March, the standard deviation (143) indicates that the deviation from normal is considerable. The Mann-Kendal test results (Table 16) suggest a decreasing trend in annual rainfall across all meteorological stations. The Sen's slope estimate of rate of decrease is -44 mm per year (Figure 22). However it is not statistically significant at α = 0.05.

Table 16. Mann-Kendall trend test / Two-tailed test (Seasonal rainfall):

Kendall's tau	-0,089
S	-44,000
Var(S)	3802,667
p-value (Two-tailed)	0,476
alpha	0,05
Mean	643
Standard deviation	135
Trend equation	y = -3,1994x + 7046,8 R² = 0,0497

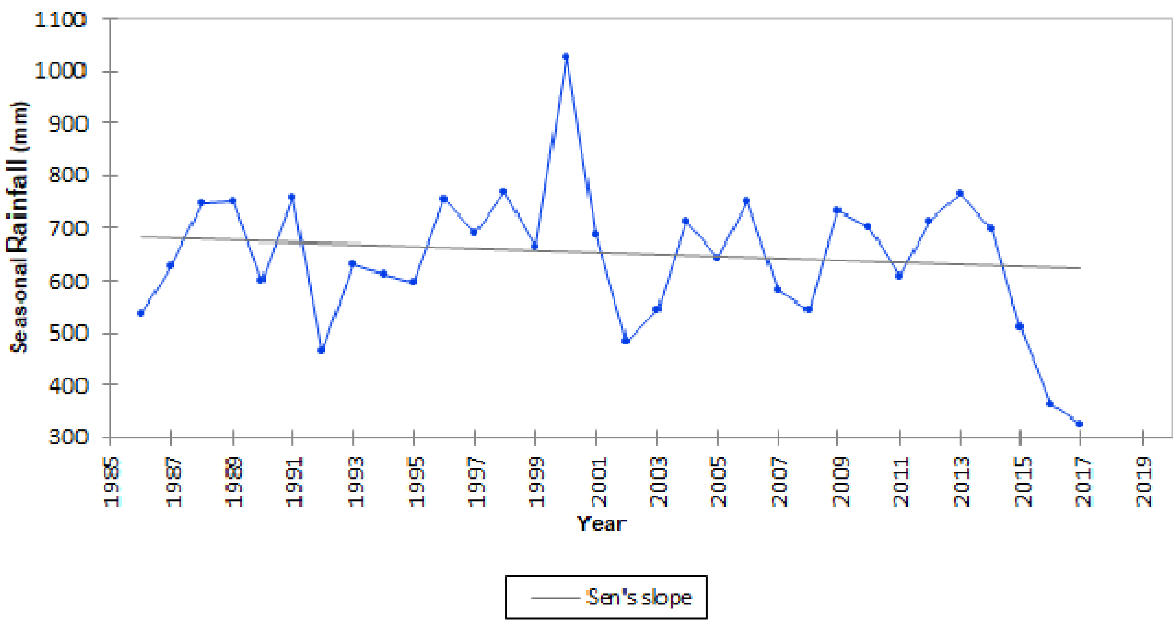

Figure 22. Seasonal Rainfall Trend of Eswatini (1986–2017).

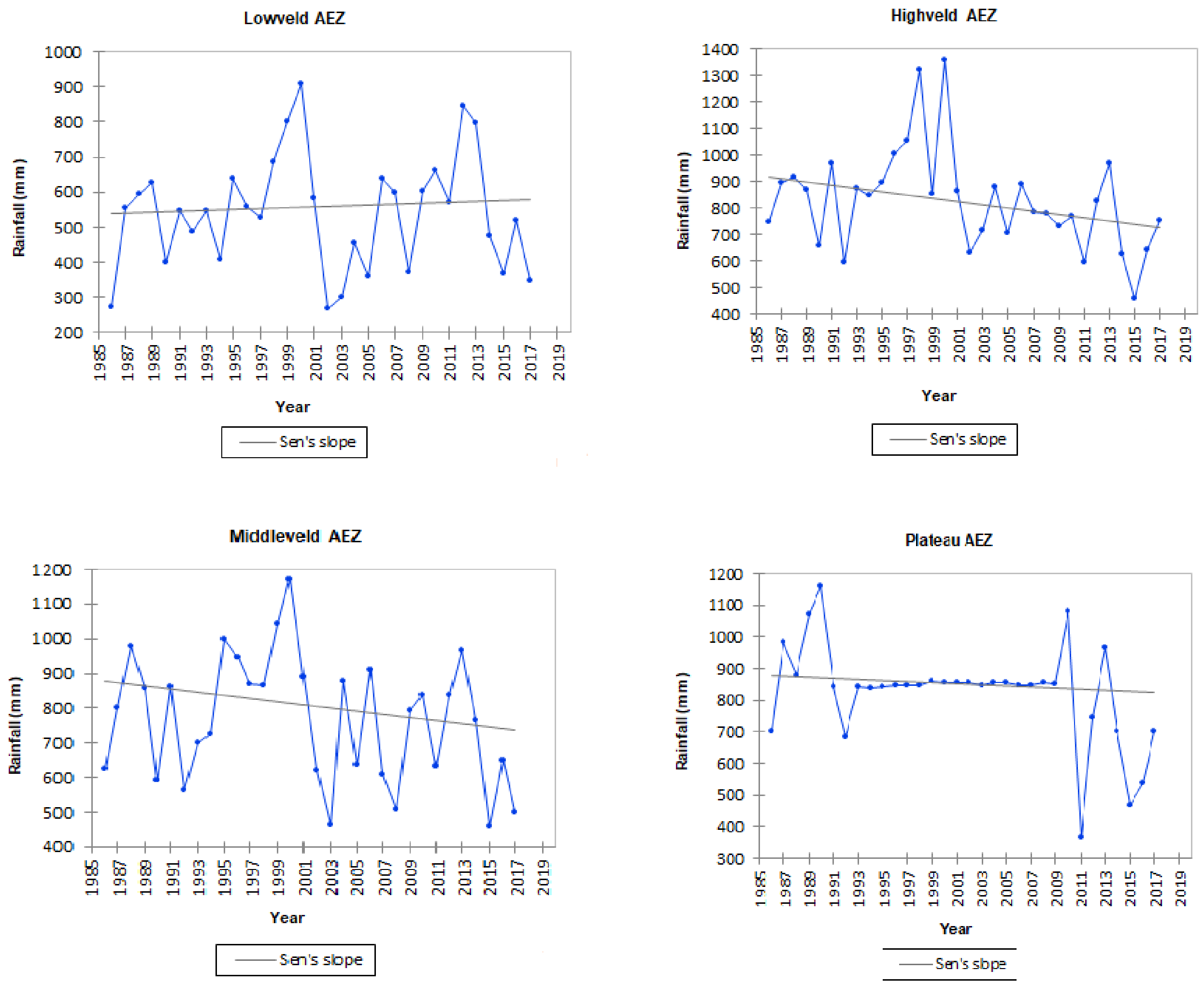

Figure 23. Rainfall Trend for Eswatini Agro-Ecological Zones (AEZ) (1986–2017)

Table 17. Mann-Kendall trend test / Two-tailed test (Eswatini AEZ)

	Plateau	Middleveld	Highveld	Lowveld
Kendall's tau	-0,161	-0,141	-0,254	0,036
S	-80,000	-70,000	-126,000	18,000
Var(S)	3802,667	3802,667	3802,667	3802,667
p-value (Two-tailed)	0,195	0,256	0,041	0,770
alpha	0,05	0,05	0,05	0,05
Mean	823,000	768,000	827,000	543,000
Standard deviation	160,000	182,000	191,000	163,000
Trend equation	$y = -7{,}6294x + 16094$ $R^2 = 0{,}2011$	$y = -4{,}8194x + 10414$ $R^2 = 0{,}0617$	$y = -6{,}7637x + 14365$ $R^2 = 0{,}1109$	$y = 0{,}9527x - 1364{,}9$ $R^2 = 0{,}003$

Rainfall trends were different depending on the spatial variations of the Highveld, Middleveld, and the Lebombo Plateau agro-ecological regions. The Lubombo plateau had the highest mean rainfall (Table 17), whereas the Lowveld had the lowest mean rainfall over the study period. The

Mann-Kendal test results illustrate a decreasing trend in annual rainfall in the Plateau, Middleveld, and Highveld AEZs. Looking at all the AEZ, the Sen's slope estimates of rate of decrease in these years was only significant for the Highveld AEZ. In the Lowveld, however, the results were surprising, as the trend indicated a positive increase in average rainfall (Figure 23). This increase, however, does not correspond to an increase in cereal production; there is in fact, a decrease in maize output (FAO/GIEWS, 2017; SVAC, 2017).

4.5 TEMPORAL AND SPATIAL ANALYSIS OF DROUGHT IN ESWATINI

The WMO recommends adopting the SPI to monitor the severity of drought events (Man-chi, 2013), and Ji and Peters (2003) found that the 3-month SPI is the most effective for monitoring drought impact on vegetation, especially when the 3-month period coincided with the peak growing season. This is because the 3-month SPI reflects short-term and medium-term moisture and provides a seasonal precipitation estimate (NDMC, 2006a; WMO, 2010). For drought monitoring in Eswatini, the study adopted the use of the 3 and 12-month SPI, with results compared against the official government declarations. According to drought disaster declarations made by the government, and drought events recorded for 1900–2016 (EM-DAT, 2016), drought years were experienced in Eswatini in 1981, 1984, 1990, 2001, 2007, and 2016. Though not included on the EM-DAT database, 2004, 2010, and 2014 were also considered as moderate drought years by the media and UN Agencies (UN, 2007; WFP, 2015) and NGOs.

4.5.1 Drought Severity Temporal Dynamics Based on SPI

The study calculated SPI for the time series 1986 to 2017 using the SPI on 3-, 6- and 12-month time scales, corresponding to the past 3, 6, and 12 months of observed precipitation totals, respectively. These time scales reflect the soil moisture conditions (SPI-3) or the underground waters, river flows, and lake water levels (SPI-12) (Bokal, 2006; Livada and Assimakopoulos, 2007; Rouault and Richard, 2003). The use of the 12-month SPI prevents a misinterpretation of a drought that might have ended. This is because a relatively normal 3-month period could occur in the middle of a longer-term drought that would only be visible over longer time scales (DNR, 2018). Therefore, SPI-based drought area mapping was carried out for the same period. Selected months for 3-month SPI were October, November, and December (OND), whereas for the 6-month SPI, it covered July to December, in line with similar research by Rouault and Richard (2003) in South Africa. The SPI-based drought classes proposed by McKee et al. (1993) were adopted in this study, because of their wider applicability to different regions of climatology (Bokal, 2006; Jordaan, 2011; Livada and Assimakopoulos, 2007; McKee et al., 1993).

Overall, the temporal SPI analysis suggests that Eswatini experienced moderate to extreme drought episodes in the years 1986, 1990, 1992, 2006, 2012, 2014, and 2016. Moderate drought occurred in 1986, 1990, and 2012 (Figure 24), whereas severe droughts occurred during 1992 and 2006. The only extreme drought recorded was in 2016, which corresponds to the strongest El Nino period in over half a decade and the government drought disaster declaration in 2016 (NDMA, 2016; Phys.Org, 2016; SVAC, 2016). The difference in the years reflected by EMDAT database and that of SPI is the fact that the EMDAT data presented droughts which had a significant impact with regard to economic, environmental human and animal impact. The extreme drought result is consistent with research by Rouault and Richard (2003) who highlighted that an SPI of -2.00 happens twice per century, from -1.5 to -1.99 about 4 times per century, and from -1 to -1.5 about 9 times per century. The minimum SPI value (–2.95) detected in 2016 across Eswatini was persistent, with varying severity in the different AEZs (Figure 25).

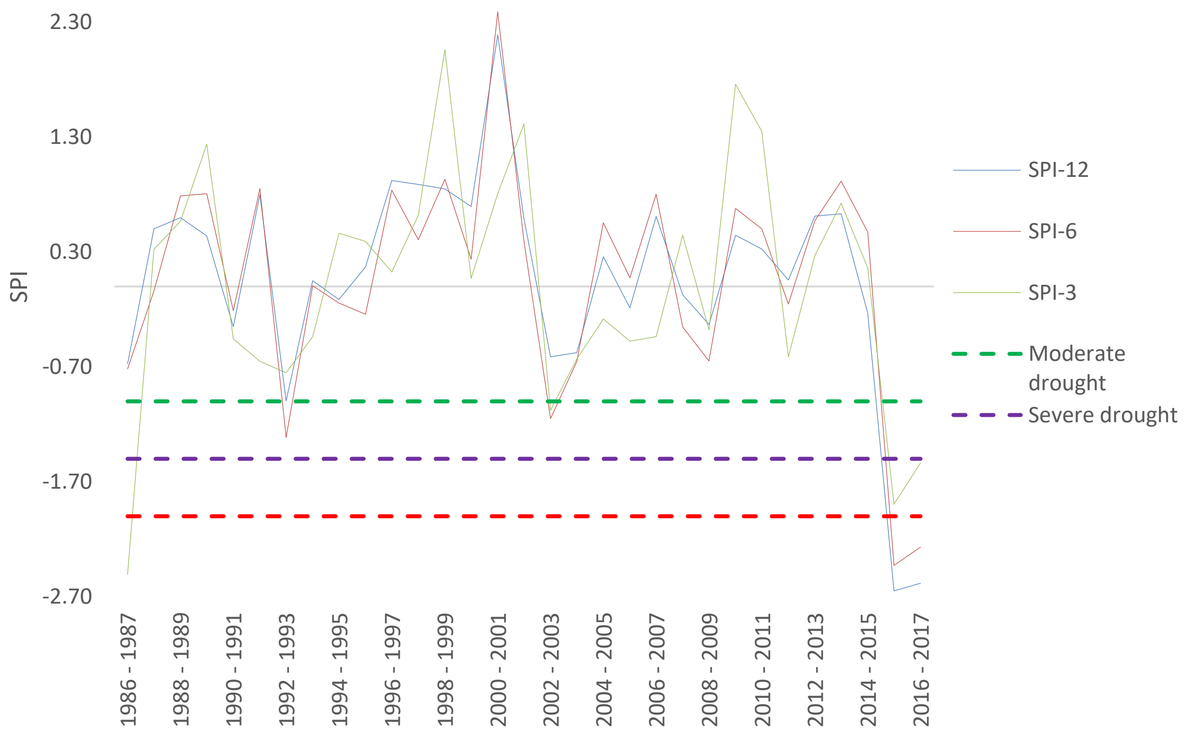

Figure 24. Eswatini SPI Values for Three Different Time Scales for 3 Months, 6 Months, and 12 Months

Differences were observed in the SPI results across different time scales. Moderate droughts were the most frequent within 3, 6, and 9 months categories, with the Middleveld having the highest occurrences. In 1992 for example, the 6-month and 12-month SPI indicated moderate drought, whereas the 3-month SPI showed no drought conditions. In 2006, the 3-month SPI indicated severe drought conditions, whereas the 6 and 12-month SPI indicated mild to normal drought periods.

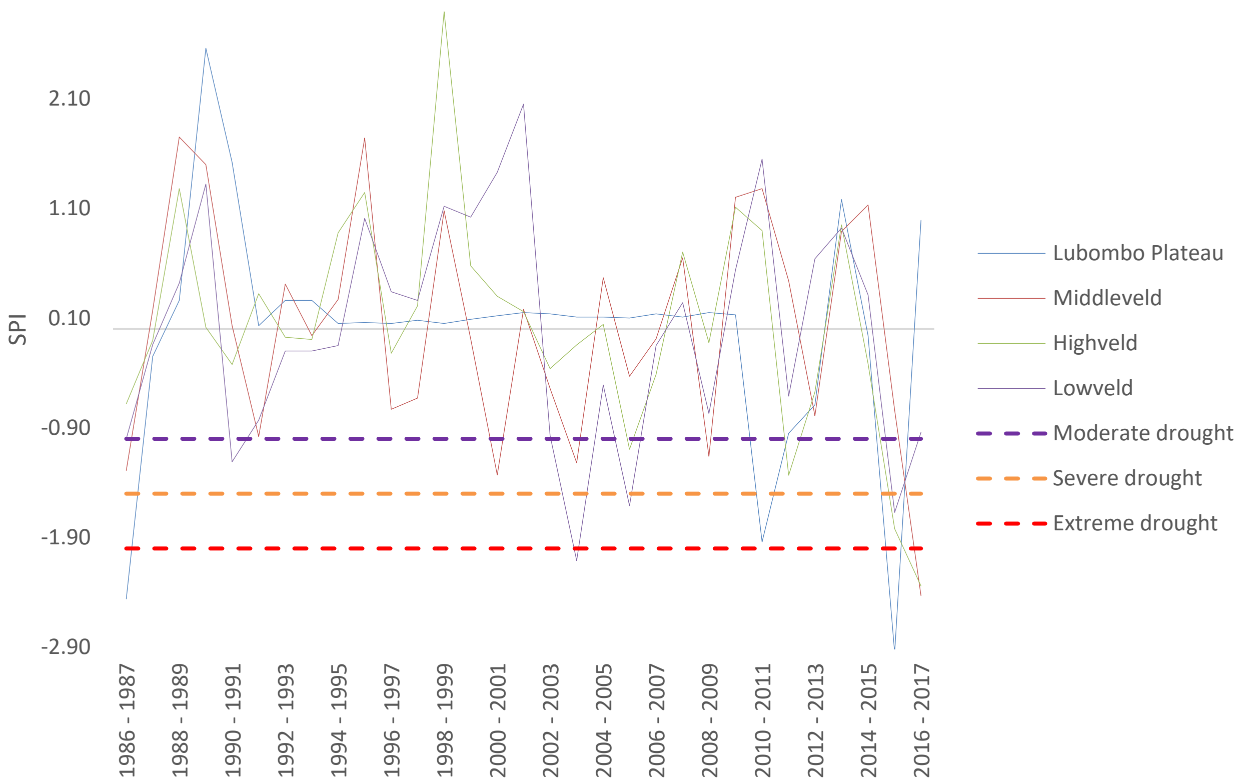

Figure 25. 3-Month SPI Values for the Highveld, Middleveld, Lowveld, and Plateau AEZ

The 3-month SPI may be misleading, especially in areas where it is normally dry during that 3-month period. The differences in drought conditions may therefore be related with the response of the short-term soil moisture conditions to precipitation during that short time scale for both 3-month and 12-month SPI (Saada and Abu-Romman, 2017; WMO, 2012). In 2006, it is evident that a drought event (as indicated by the 3-month SPI) was occurring in the middle of a longer-term drought, as evidenced by the 12-month time scale result. Therefore, it is important to compare the 3-month SPI with longer time scales (NDMC, 2006a; Rouault and Richard, 2003).

Comparing the 3-month SPI across AEZs, most drought events were experienced in the Middleveld and Lowveld zones. Extreme droughts were experienced in all AEZs in 1986 and 2016. When the 3-month SPI was calculated for the different AEZs, there were parallels with the drought periods that were declared and documented in the EM-DAT database. This means that within the country, there are spatial differences for drought severity and intensity. For moderate drought however, the SPI calculation typifies the droughts, which were also declared in most of the AEZs. Therefore, the SPI can be used to typify drought by AEZ, with the Lowveld being the region that is most prone to drought.

4.5.2 Drought Severity Spatial Dynamics Based on SPI

Estimating drought severity at a station or AEZ provides useful information for drought planning and management. It is therefore important to assess the drought over a specified agro-ecological region. This allows the administrative areas that fall within these regions to plan effectively. The drought analysis based on these zones is useful for determining the spatial distribution and characteristics of drought and for evaluating the most affected areas for a specific drought event.

Figures 25 to 28 present the spatial extent of drought in Eswatini from 1986 to 2017. The spatial analysis was performed by plotting 3-month SPI values using ArcGIS 10.1. All the interpolated SPI maps and graphs were reclassified into four classes. Specifically, SPI value from -1 to 1 as no drought, -1.5 to -1.0 as moderate droughts, ≤ 2 to -1.5 as severe drought, and SPI value ≤ 2 as extreme drought categories. In 1986, moderate and extreme droughts were mostly experienced in the Lowveld AEZ, whereas between 2004 and 2006 moderate to extreme droughts were experienced countrywide.

The results identified that there were spatial differences in moderate, severe, extreme, and no drought events experienced in the study period. The 2015/16 and the 2005/06 droughts were most severe, and could be observed by spatial coverage indicated in red (see Figures 27 to 29). The 1986 drought was less severe, with less spatial coverage (in red). Moderate and extreme droughts were mostly experienced in the Lowveld AEZ, whereas between 2004 and 2005 moderate to extreme droughts were experienced countrywide. There were significant differences in the analysis of droughts across administrative areas and AEZs.

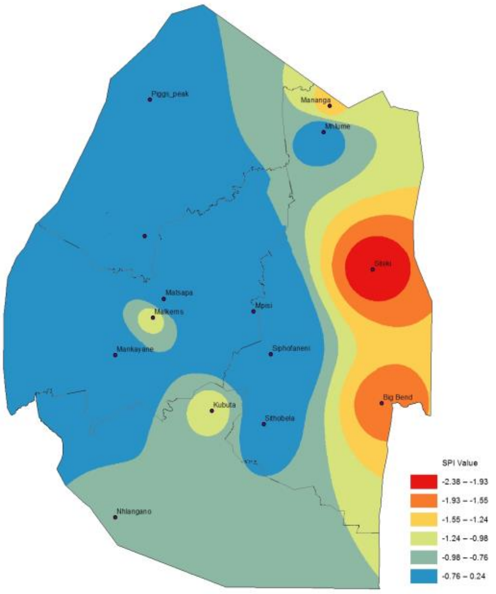

Figure 26. SPI 3-Month Time Scale 1986

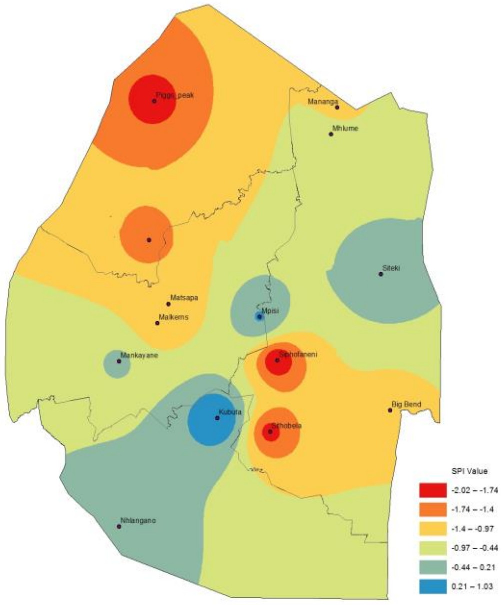

Figure 27. SPI 3-Month Time Scale 2004

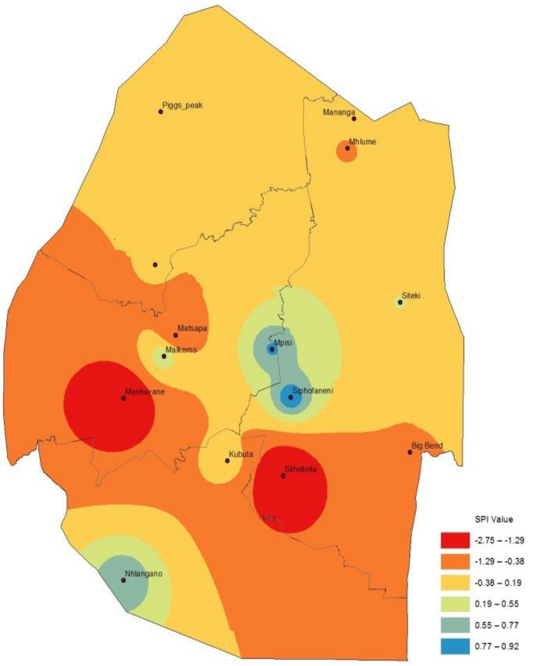

Figure 28. SPI 3-Month Time Scale 2006

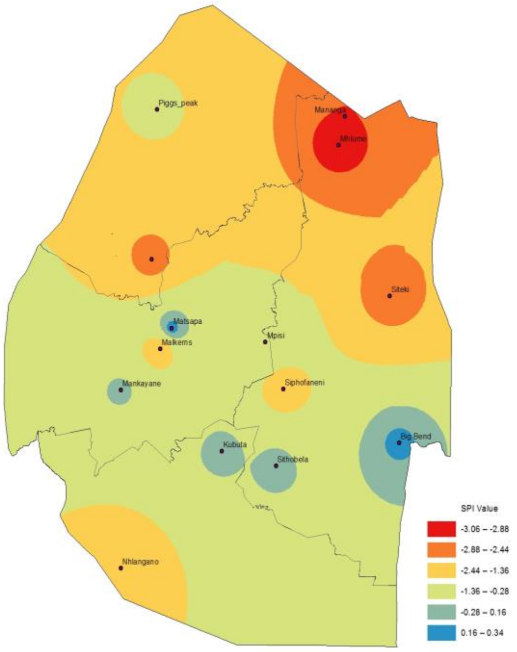

Figure 29. SPI 3-Month Time Scale 2016

Field surveys and information sourced from key informants have verified that these droughts were the most severe, with greatest impact being felt in the Lowveld and Middleveld. However, the impact of the 2015/16 drought was felt country-wide with massive crop and livestock losses. Therefore, estimating drought severity at a station or AEZ provides useful information for drought planning and management. Understanding the spatial extent allows effective planning within the administrative areas that fall with these regions. The spatial differences across the country therefore allow for localised drought monitoring, enabling more accurate area-specific results, and therefore area-specific drought management planning.

4.6 CHAPTER SUMMARY

The climate of the African continent—and Eswatini in particular—exhibits large geospatial and temporal variability. This study was focused on presenting analysis of the temporal and spatial characteristics of droughts in Eswatini. The spatial and temporal extents of drought were analysed by interpolating the station SPI values across the study area. The 3, 6, and 12-month SPI were computed to detect drought and used as an indicator for analysing severity and onset of meteorological drought in the country.

Overall, SPI effectively described the drought conditions in Eswatini. The analysis of droughts during 1986–2017 indicated that droughts have intensified in terms of their frequency, severity, and geospatial coverage over the last few decades. The results demonstrated that moderate droughts are the most prevalent in Eswatini, while the frequency of severe and very severe droughts is low. Most parts of the country were vulnerable to mild and moderate agricultural drought (3 and 6 months) time scales. The worst drought years were 1985/1986, 2005/2006, and 2015/2016 agricultural seasons, and this was evident from the SPI at 3, 6, and 12-month time scales. The drought periods were consistent with drought declarations by the government after the drought event has occurred.

At national level and agro-ecological level, severe droughts were experienced in the last few decades, for instance, in 1990, 2001, 2004, 2006, and recently in 2016. There were temporal and spatial differences across the country and AEZs. The spatial SPI visualisation has the ability to provide drought management planners with a tool for immediate drought categorisation. The drought analysis (using the SPI at different time scales) has therefore a potential for use for drought monitoring in Eswatini, with minimal data requirements. This can provide information for early warning, particularly in drought-prone areas by depicting a drought before the effects have begun to be felt. Due to the difference in results indicated by the different timescale, the SPI can be appropriate for drought monitoring only when used in combination with other indices and methodologies. In the next chapter, other indices that can be used to complement SPI will be discussed. Focus will be on satellite-based indices that are being used for drought monitoring.

5. VEGETATION STATUS INDICES FOR NEAR-REAL-TIME DROUGHT MONITORING IN ESWATINI

5.1 INTRODUCTION

The main cause of risk and uncertainty in agriculture is the climate-related natural disasters (drought and floods) (FAO, 2018; Gobin et al., 2013). The drought phenomenon has become more frequent and severe (Carty, 2017; Schwalm et al., 2018; Spinoni et al., 2018) as has already been experienced with the droughts in 2001/02, 2004/05, 2006/07, and 2015/16 in Eswatini. This has led to an increasing interest in monitoring the impact of a drought on the local economy and the lives of citizens by climate scientists and national administrations.

The economic cost to society and the environment of drought can be substantial; for example, drought has historically been linked to large food shortages and famines in various parts of Africa (Hanif et al., 2010; Molua and Lambi 2007). More than half the terrestrial earth is susceptible to drought each year (Kogan, 1997), and because drought is a recurring phenomenon the most productive lands of all continents can lose millions of tons of agricultural production annually (FAO, 2018; Pimentel & Burgess, 2013; Stocking, 1995).

In order to establish effective and comprehensive monitoring and EWS, it is important to understand the characteristics of drought (Wilhite, 2000). Information provided through drought monitoring can minimise the effects, if conveyed to decision-makers in a timely and proper format, and if alleviation measures and readiness plans are in place. It is therefore essential that accurate monitoring of the occurrence, frequency, and severity of the distribution of drought is implemented for disaster mitigation and informed decision making (Lavaysse et al. 2015).

5.2 THE POTENTIAL USE OF GEOSPATIAL DATA AND DROUGHT INFORMATION SYSTEMS

New geospatial information-based technologies to support decision-making can be accessed for determining risk and vulnerability to a drought system and for developing monitoring and EWSs, using real-time information (Carbone et al., 2008; Svoboda et al., 2002). Drought mitigation actions and preparedness plans must be based on complete, transparent, and integrated drought risk information (Vicente-Sarrano et al., 2012). This should incorporate geospatial information centred on the analysis of past drought events, to facilitate the elaboration of mitigation and preparedness plans, but also on real-time information about the current drought conditions and their expected impacts to facilitate sound decision-making (Vicente-Sarrano et al., 2012).

The use of multi-scaling drought indicators is necessary to address the drought impacts on a variety of ecosystems and societies (Lorenzo-Lacruz et al., 2010; Vicente-Serrano and López-Moreno, 2005). Global coverage from higher spatial and temporal resolution satellite data is available from meteorological and environmental satellites, such as the National Oceanic and Atmospheric Administration (NOAA), Terra, Quickbird, Landsat, Radarsat, Resourcessat, and Advanced Land Observationsat currently in use (AghaKouchak et al., 2015; Berhan, et al., 2011; Gouveia et al., 2009; Senay et al., 2015). The images and data emanating from some of these satellites are being used for drought monitoring, environmental management, hydrology, oceanography, geology, glaciology, along with military, intelligence, commercial, economic, planning, and humanitarian applications (Bala et al., 2017).

Remote sensing should therefore be used to make decisions and, most importantly, to monitor drought, in particular where limited, reliable and precipitation data is limited and untimely (AghaKouchak, 2015; Dutta, 2018). The use of remote sensing data can be done independently, or triangulated or modelled with precipitation data - especially for real time drought monitoring (AghaKouchak et al., 2015; Bijaber et al., 2018; Norman et al., 2016). Remote sensing images provide data and information in real-time or near-real-time, meaning that the data or information reflects the actual or near-actual time during which the process or particular event happens (Zhang and Kerle, 2008).

Data and information from remote sensing can provide current to near real time information, and can therefore be relevant to decision-making in emerging and on-going events. Real-time drought monitoring is essential to guarantee the achievement of drought preparedness plans and EWSs. The use of satellite technology is significant for drought information systems for Africa, in terms of generating seasonal/monthly drought hazard maps, drought vulnerability maps, real-time drought monitoring based on indicators, and real-time drought early warning.

5.3 SATELLITE IMAGERY FOR DROUGHT MONITORING

Accurate spatial and temporal monitoring of drought is a vital instrument to inform humanitarian assistance decision-making and disaster planning and mitigation. Use of different satellite-based drought monitoring indices, such as the NDVI and its derivatives (the VCI, the SVI, and Vegetation Productivity Index), together with other indices such the FAO Agriculture Stress Index (ASI), are essential for drought monitoring (Du et al., 2018; Garg and Eslamian, 2017; Van Hoolst et al., 2016), or the detection of near-real-time onset, evolution, intensity, and duration of drought in Eswatini.

Weather data is a good source of information that can be used for drought assessment. However, the sparse location of weather stations in some areas in Eswatini makes drought monitoring a daunting task. Lack of information about a drought becomes especially acute in areas where the weather station network is limited. Furthermore, the data is often incomplete for the few available weather stations and/or is not available sufficiently early to enable timely drought detection and impact assessment. Thus, the use of remote sensing can help to address these challenges (AghaKouchak, 2015; Dutta, 2018).

The accuracy of operational drought monitoring on a global scale depends on the availability of rainfall estimation and, therefore, on both spatial coverage and temporal frequency of in-situ observations. Several studies (Dinku et al., 2007; Dutra et al., 2013; Liebmann et al., 2012) have already documented a significant observation error affecting regions with low station coverage; even after off-line post-processing and quality control have taken place, especially in Africa, a continent with notoriously low observation coverage.

5.4 REMOTE SENSING BASED INDICES

In recent decades, remote sensing has been recognised as a viable technological tool for estimating drought over a large area (Ceccato and Dinku, 2010). A variety of drought monitoring models have been developed using satellite data. These drought indices, together with satellite sensor data play an increasingly important role in the monitoring of drought-related vegetation conditions (AghaKouchak, 2015; Dutta, 2018). Therefore, remote sensing can be used to monitor any vegetation situation, before, during, or after the drought (Persendt, 2009). This study utilised the NDVI, which will be discussed in detail in the sections below.

5.4.1 Water Supply Vegetation Index (WSVI)

The Water Supply Vegetation Index (WSVI) is a method used to detect drought information by using meteorological satellite data (Zhao et al., 2005). The index is founded on the connexion between the NDVI and the land surface temperature. The WSVI is based on the fact that, in drought conditions, the NDVI values will decrease below normal (Jain et al., 2010).

$$\text{WSVI} = \text{NDVI}/\text{Ts} \tag{5.1}$$

(*NDVI*: normalised difference vegetation index
Ts : surface temperature derived from AVHRR channel 4)

The higher the values of WSVI, the higher the moisture levels and canopy temperature, and the lower the NDVI (Wambua et al., 2014). The WSVI values range from -4 for extreme drought to +4 for extremely moist conditions. The values of WSVI are obtained by analysing the effect of vegetation on the reflection of red, near-infrared and thermal bands (Luke et al., 2001). In many countries the WSVI is used to collect data that will help in decision-making to improve water resources management and analysis (Elhag, 2014; Wambua, 2016).

5.4.2 Vegetation Condition Index (VCI) Images

The VCI is a satellite-based index computed based on NDVI data (Quiring and Ganesh, 2010; Wambua et al., 2014). It is an indicator of the status of the vegetation cover that normalises NDVI and allows for a comparison of different environments (Jain et al., 2010). The VCI has been used to model crop yield and to detect the early onset of drought. Results have confirmed the index's ability to typify spatial and temporal characteristics of drought (Kogan and Unganai, 1998; Dutta et al., 2015). The VCI is defined as:

$$\text{VCI} = 100\ (\text{NDVI} - \text{NDVImin}) / (\text{NDVImax} - \text{NDVImin}) \tag{5.2}$$

where NDVI, $NDVI_{max}$ and $NDVI_{min}$ are monthly NDVI, multi-year maximum NDVI and multi-year minimum NDVI, respectively, for each grid cell (Jain et al., 2010). The VCI changes from zero to one hundred corresponding to changes in vegetation condition, from extremely unfavourable to optimal. In the case of an extremely dry month, the vegetation condition is poor and VCI is close or equal to zero. A VCI of 50 reflects fair vegetation conditions. At optimal condition of vegetation, VCI is close to 100.

5.4.3 Agriculture Stress Index

The global information and early warning system (GIEWS), part of FAO, defined the regional drought indicator: the agricultural stress index (ASI) based on the work of Rojas et al. (2011). They demonstrated that major historical drought and the impact of these events on agricultural areas can be identified over the whole African continent, using a combination of historical time series of (*i*) the VHI, (*ii*) phenology maps, and (*iii*) ancillary data. The index is based on the integration of the VHI, both temporally and spatially.

The calculation of the ASI involves three steps, as follows:

- Step one is a temporal averaging of the VHI, assessing the intensity and duration of dry periods occurring during the crop cycle at pixel level.
- Step two determines the spatial extent of drought events by calculating the percentage of pixels in arable areas with a VHI value below 35% (FAO-GIEWS, 2017). The VHI value of below 35% is a critical threshold in assessing the extent of drought (Kogan, 1995a).
- In step three, each administrative area is classified according to its percentage of affected area, to facilitate the quick interpretation of results by analysts (FAO-GIEWS, 2017).

The ASI represents the percentage of cropped or grassland areas within each administrative region affected by drought, as derived from earth observations and defined over the course of the growing season (Van Hoolst et al., 2016). This helps to indicate how stressed crop areas are by combining vegetation condition and temperature variables. The compiled results are then analysed over time, by comparing current values to the long-term minimum and maximum, and spatially by aggregating agriculture areas by administrative area. Annual ASI values relate to a specific calendar year. Through the ASI, hot spots can be detected for agricultural drought and the start and end of production can be determined. Therefore, the ASI has the advantage of showing the location, extent, intensity, duration of any period of drought and is available for free.

For the study, the ASI for January was used to monitor drought resulting from the rainfall anomalies for the first three months of season (October, November and December). This is because the impact of rainfall received in the third dekad of December will mostly be reflected in the first dekad of January. The first phase of the ASI was completed and the alpha version was implemented in 2014, as results from ASI data are only available from 2014 onwards. Images below illustrate the ASI for Eswatini for the months of February 2014 and January 2015 to 2017.

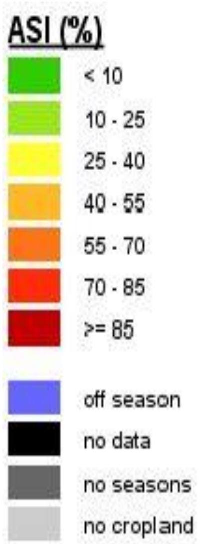

Figure 30. Agriculture Stress Index Legend

Figure 30 represents the ASI Legend enlarged to provide more visual clarity and ease of interpretation of the ASI images below. Analysing the images presented in Figures 31 to 34, it can be observed that the ASI varied for the months of January and February for the years where ASI data was available. According to the cropping calendar, the months of January are normally lush with healthy green vegetation, as it is mid-season and most of the crops will be in the vegetative stages. The ASI values are analysed as a percentage. The higher the percentage the higher the moisture stress, whilst the lower the percentage the healthier the vegetation of crops. In February 2014 (Figure 31), the ASI percentage was below 10%, 50-60% into the season. In January 2016, the average ASI across Eswatini was greater than 50% when the progress of the season was 40-50% (Figure 35).

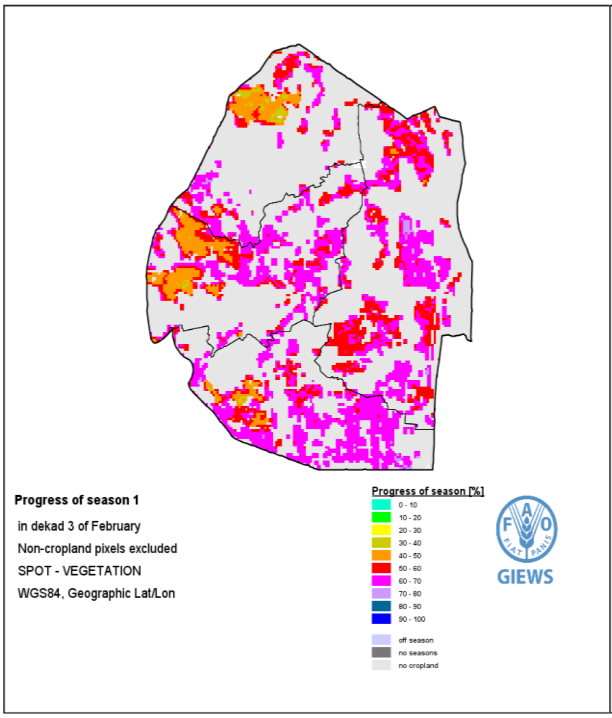

Figure 31. Progress of the Season in February 2014. *Source: FAO/GIEW-Eswatini*

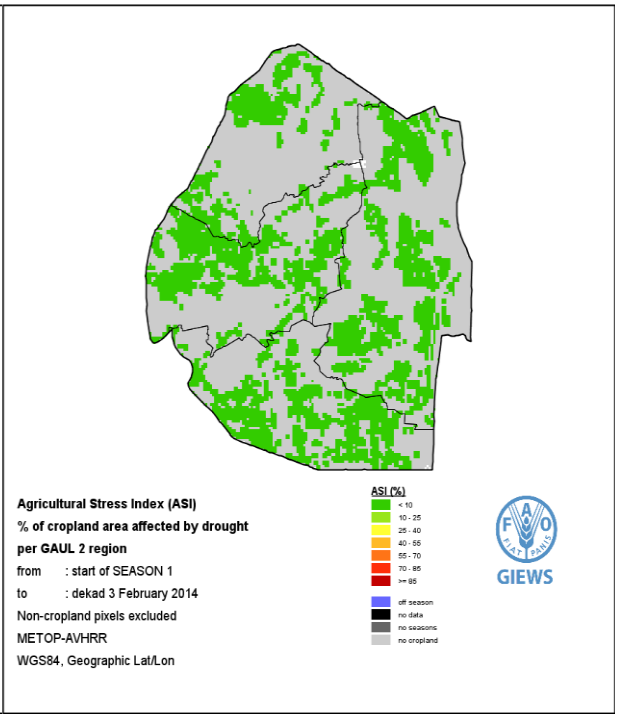

Figure 32. ASI for February 2014 *Source: FAO/GIEW-Eswatini*.

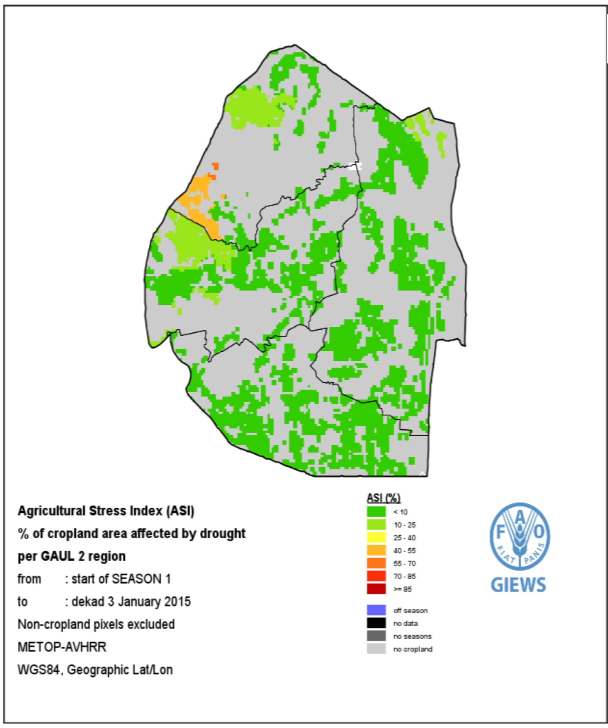

Figure 33. ASI January 2015. *Source: FAO/GIEW-Eswatini*

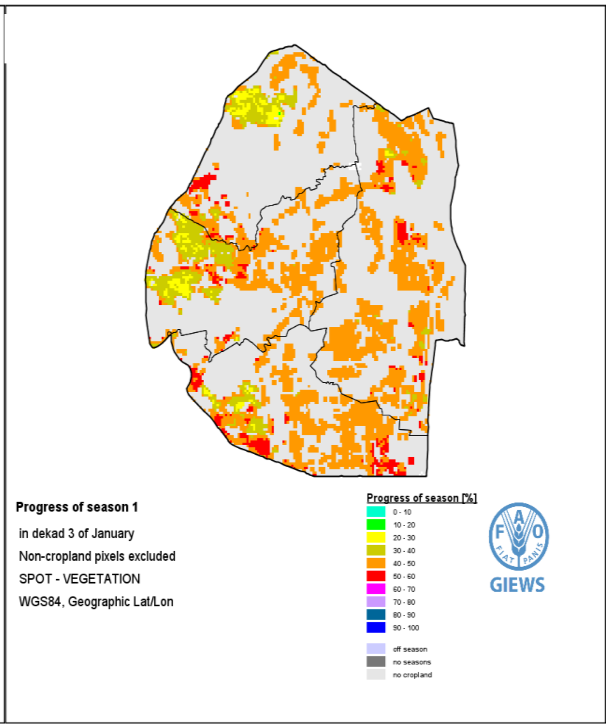

Figure 34. Progress of the Season- January 2015 Source: FAO/GIEW-Eswatini

This means that for this particular year, in that period, the vegetation was healthy. Considering that the progress of the season was 50-60% and the main crop maize had flowered, the likelihood of significant yield losses due to a small deviation in the moisture conditions was minimal.

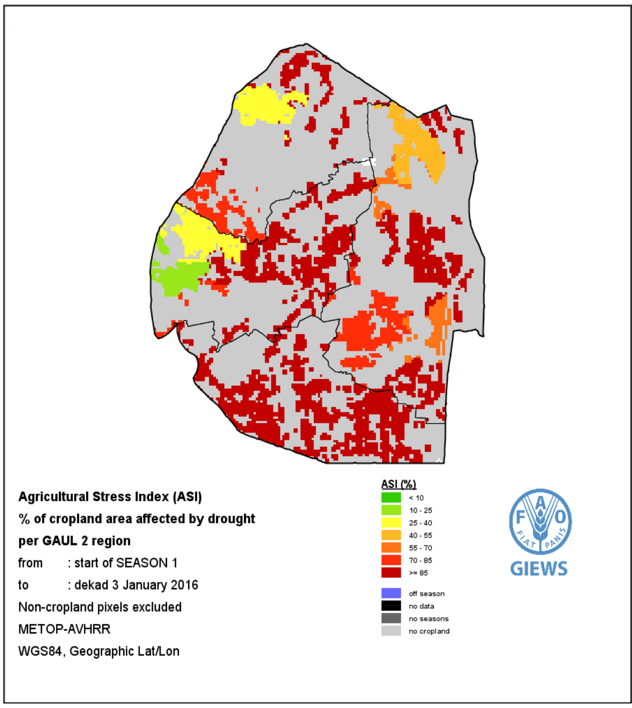

Figure 35. ASI January 2016
Source: FAO/GIEW-Eswatini

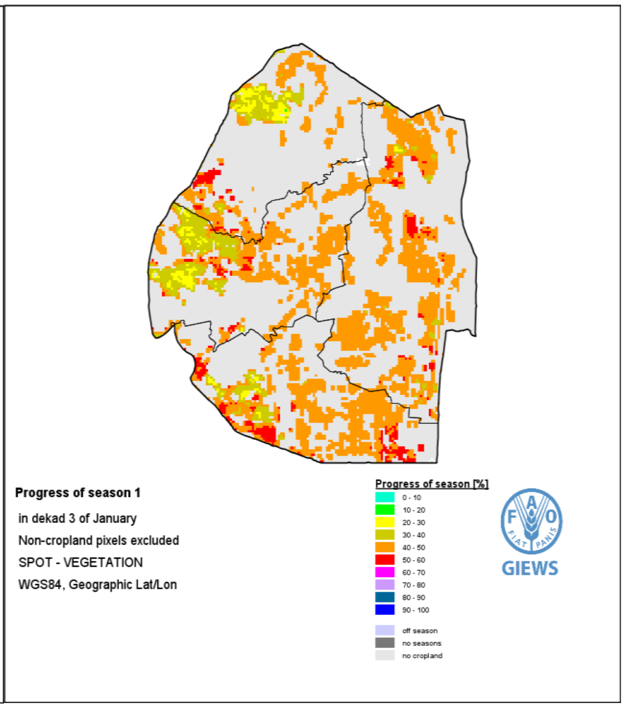

Figure 36. Progress of Season-January 2016 Source: *FAO/GIEW-Eswatini*

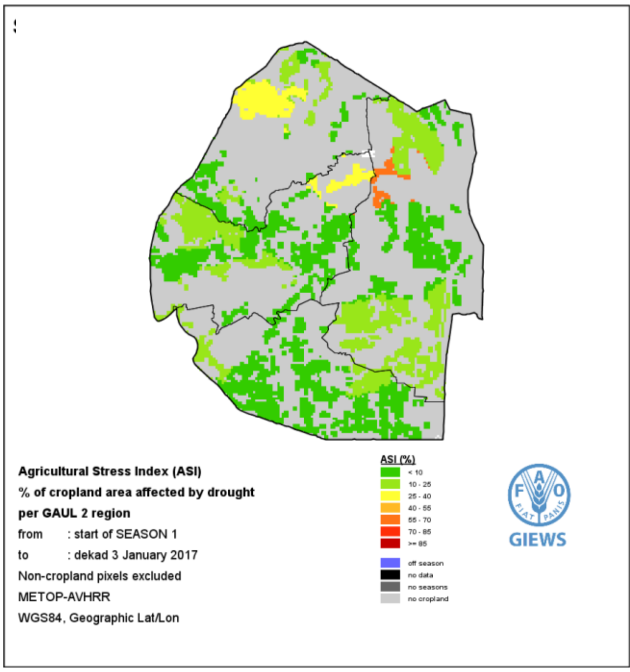

Figure 37. ASI January 2017.
Source: FAO/GIEW-Eswatini

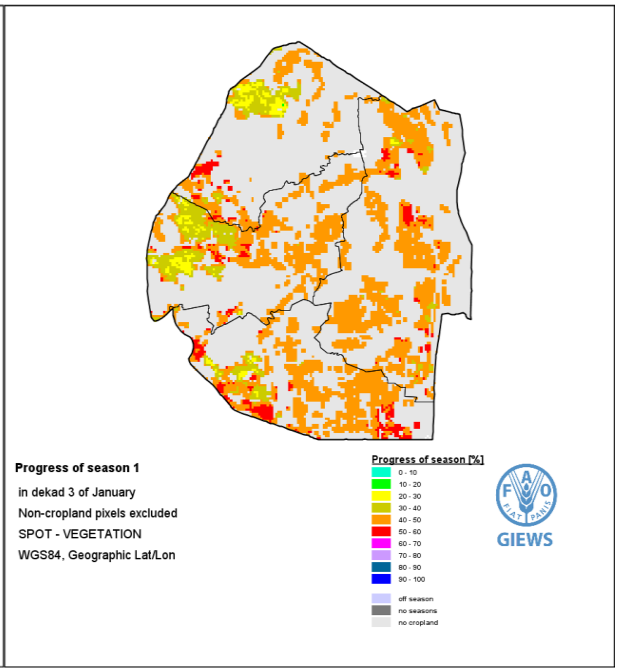

Figure 38. Progress of Season-January 2017 *Source: FAO/GIEW-Eswatini*

The critical processes (such as tasselling and silking) were therefore affecting the severe moisture stress, which compromised the overall harvest. The impact of the crop is reflected in the poor harvest recorded in 2016 and the declaration of a drought disaster thereafter. This indicates that the ASI can be used to monitor drought, and the likely impact of the moisture stress on the yield. For January 2017, the ASI across the country was below 20%; as such the impact of moisture stress would be minimal on crop yield if in the preceding months the rainfall conditions were normal.

5.5 NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

5.5.1 Introduction to NDVI

The NDVI is a remote sensing-based index that measures vegetation conditions (Rouse et al., 1974). The index uses the advanced, very-high resolution radiometer (AVHRR)-reflected red and near-infrared channels to calculate the health of vegetation (Zagar et al., 2011). The time-series NDVI data have been widely used to monitor vegetation at regional through to global scales (deBeurs and Henebry, 2004; Malingreau, 1986; Myneni et al., 1997; Reed et al., 1994; Townshend et al., 1987; Tucker et al., 1985). The index is calculated from the visible and near-infrared light reflected by vegetation. The greater the variance between the near-infrared and the red reflectance, the more vegetation there has to be.

Green and healthy vegetation reflects much less solar radiation in the visible channel (1) compared to those in the near-infrared (channel 1). The NDVI are generated using radiation measured in the red and near-infrared spectral channels (Jain et al., 2010). Then the NDVI algorithm subtracts the red reflectance values from the near-infrared values and divides it by the sum of near-infrared and red bands (Holme et al., 1987; Roderick et al., 1996; Rouse et al., 1974). The formula for the NDVI is as follows:

$$NDVI = (NIR - VIS) / (NIR + VIS) \tag{5.3}$$

Calculations of NDVI for a given pixel always result in a number that ranges from -1 to +1; however, no green leaves give a value close to zero. A zero means no vegetation and close to +1 (0.8–0.9) indicates the highest possible density of green leaves. Daily NDVI images are routinely composited over seven days by saving those values that have the largest difference between radiance for the near-infrared and visible wavelengths during that period for each pixel (Kogan, 1995b). This is done to minimise the effect of cloud contamination (Quiring and Ganesh, 2010). In the NDVI formula, the NIR is the reflectance radiated in the near-infrared waveband and RED is the reflectance (Figure 39) radiated in the visible red waveband of the satellite radiometer (Justice et al., 1985).

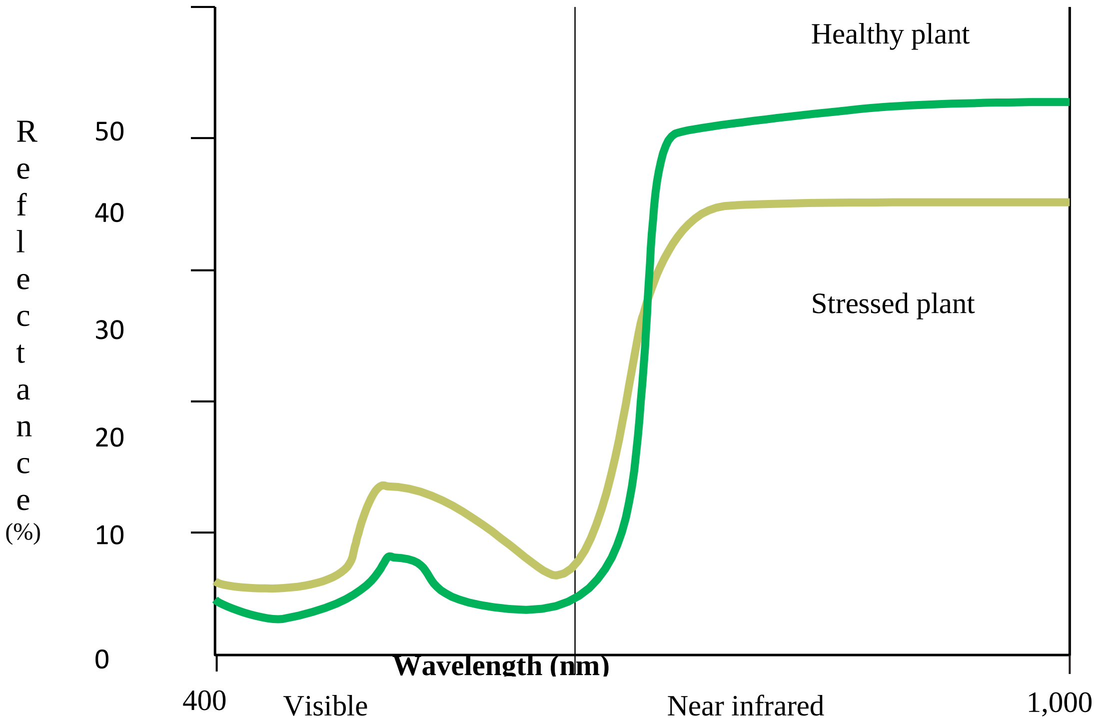

Figure 39. Typical Reflectance Spectrum of a Healthy and a Stressed Plant. *Source: Govaets & Verhuslt, 2010.*

Reflectance is the ratio of energy that is reflected from an object to the energy incident on the object (Govaets & Verhuslt, 2010). The NDVI is responsive to changes in both chlorophyll content and the intracellular space in the spongy mesophyll of plant leaves. The contrast between vegetation and soil is at a maximum in the red and near-infrared regions. The NDVI is successful in predicting photosynthetic activity, because this vegetation index includes both near-infrared and red light (Govaets and Verhuslt, 2010). Moreover, the NDVI can either be determined by the spectral analysis of satellite images, which makes it possible to perform regional examination (Knight et al., 2006; Wang and Tenhunem, 2004), or by using optical measurement devices used in the field, making it possible to conduct plot-scale evaluation (Hancock and Dougherty 2007).

The NDVI is in close relationship with the development of the plant population (Nambuthiri, 2010), its chlorophyll content (Cui and Shi 2010), nitrogen content (Wei et al., 2010), biomass production (Hancock and Dougherty, 2007), and yield (Pan et al., 2015). By temporally and spatially determining the NDVI, it is possible to monitor the development of the plant population (Martin, et al., 2007), to survey the health status and levels of nitrogen supply to the population (Nambuthiri, 2010), and to determine any nitrogen shortage and replenishment shortage in a differentiated way (Singh et al., 2006).

The NDVI has been used to evaluate drought conditions by directly comparing it to precipitation or drought indices (Gutman, 1990). To make the NDVI comparable by dates, geographic locations, and vegetation types, it has been standardised on the basis of relative values. Seasonal timing of measurements is an important factor in the understanding of vegetation vigour and precipitation relationship and should be considered. It has been noted that the impact of water availability on vegetation changes varies considerably within different phonological periods of vegetation growth cycles (Teare and Peet, 1983). However, the drawback of utilising the NDVI-based method for drought monitoring is that there is a delay between the occurrence of a drought and the NDVI changes. The NDVI methods best serve as an after-effect indicator of a drought and may be outdated when focusing on real-time monitoring of drought conditions. Vegetation stress can also result from other factors such as floods, pest/diseases, infection, nutrient deficiency, wild fire, grazing, and human activities.

The complexity of the relationship has been described by some investigators. They have found that the relationship is influenced by regional rainfall patterns (Farrar et al., 1994), soil type (Nicholson and Farrar, 1994), vegetation type (Paruelo and Lauenroth 1995), as well as the temporal and spatial scale of the data (Eklundh, 1998). Understanding climatic influences (in particular precipitation and temperature) on NDVI enables prediction of productivity changes under different climatic scenarios.

5.5.2 Near Real Time Monitoring of Drought Using NDVI

The NDVI is effective in monitoring climate variability, land use, and vegetation type (Covele, 2011). To monitor drought using NDVI, the simple differences method can be used where a comparison is made of current NDVI images with past NDVI images. This can be achieved by (i) comparing the difference between current NDVI with long-term average images for the same period, (ii) comparing differences between current NDVI with previous NDVI images, and (iii) comparing differences between current NDVI with NDVI from the same period in the previous year.

Unlike the SPI and the ASI, this study analysed the NDVI images for January across all the drought years. This is because the impact of rainfall received in October, November, and December will mostly be reflected in January. Mkhabela et al. (2005) noted that the best time to make an accurate forecast was from the third dekad of January to the third dekad of March, depending on the agro-ecological region. Maize production forecasts using the developed models can be made at least two months before harvest, which would allow food security stakeholders enough time to secure maize imports in case of a deficit. The analysis of the NDVI in the months of January in this study is in line with the findings of Mkhabela et al. (2005). Mid-season drought conditions can therefore be assessed in these months, which can be used to report and project overall drought conditions and the impact on agriculture, food security, and water resources.

5.5.3 Drought Severity Temporal and Spatial Dynamics Based on NDVI

This study analysed the NDVI based on images from the GLAM - Global Agricultural Monitoring; a technical collaboration between The U.S. Department of Agriculture (USDA) and the National Aeronautics and Space Administration (NASA) which is based at the University of Maryland, Department of Geography, the Goddard Space Flight Centre (GSFC), and the USDA Foreign Agricultural Service (FAS). To complement and authenticate the accuracy of the GLAM images, NDVI images produced from moderate resolution imaging spectroradiometer (MODIS) data was used to track the evolution of the growing season compared to referenced long-term mean conditions.

The MODIS NDVI average values (Figure 40) for Eswatini show that for the months of January to May the NDVI values are high, indicating the growing season. High NDVI values between 0.6 and 0.9 resemble dense vegetation similar to temperate and tropical forests or crops at their peak growth stage (USGS, 2018). The peak-growing season is between March and April, where the NDVI values fall between 0.65 and 0.75, corresponding to dense vegetation. Low NDVI values in the months of March were observed for the years 2006/2007, 2015/2016, and 2007/2008. The years 2006 and 2015/2016 experienced the El Nino phenomenon, which explains the low NDVI values.

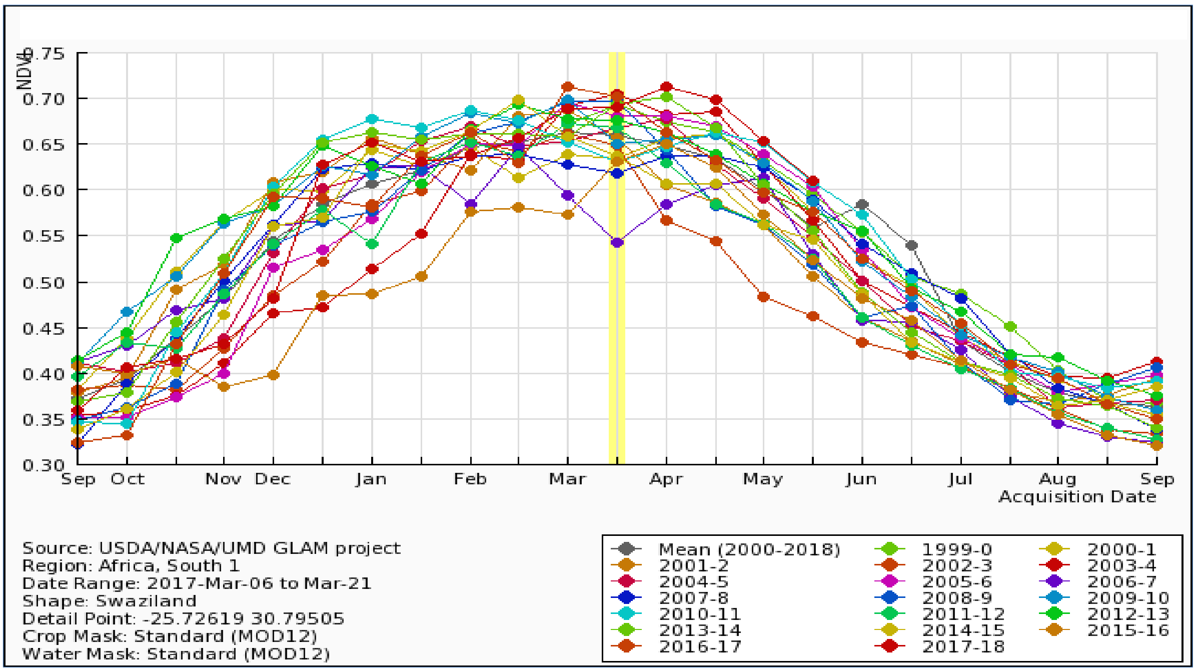

Figure 40. MODIS NDVI (Terra) (MOD44 16-day) Graph for 2000 to 2018

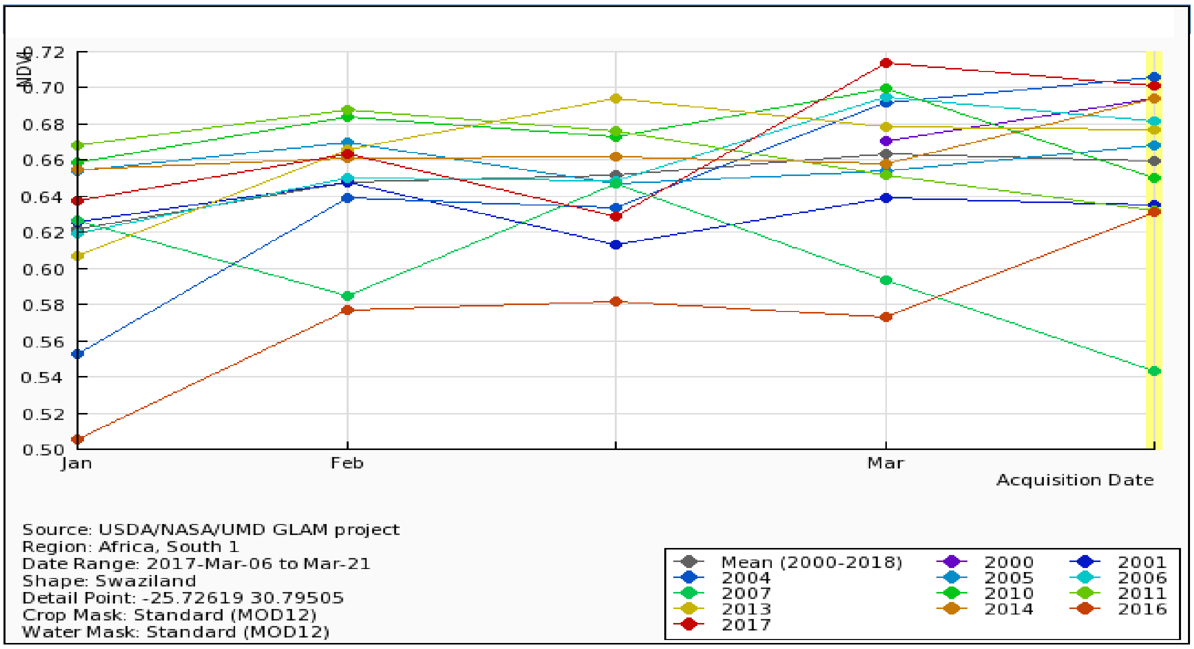

Figure 41. MODIS NDVI (Terra) (MOD44 16-day) 3-Month Graph (Jan–Mar) for 2000 to 2018

Analysis of the months under study—January to March (Figure 41, Table 18)—demonstrates that low NDVI values correspond to the drought years that have been indicated for Eswatini. The 2015–2016 season experienced low rainfall, which is reflected by the year 2016 having the lowest NDVI. This is further corroborated by the declaration of a drought and national emergency in 2016 by the Eswatini Government, after which the National Emergency Response, Mitigation, and Adaptation Plan (NERMAP) was launched, and the international community was invited to assist. Over 300,000 people (25% of the population) - inclusive of 135,144 children - faced acute food shortages, due to poor rainfall in the 2014–2015 and 2015–2016 cropping season, which was attributed to the El Nino phenomenon.

Table 18. Lowest MODIS NDVI (Terra) (MOD44 16-day) 3-Month Graph (Jan–Mar) for 2000 to 2018

Year	2016	2007	2008	2002	2005	2011	2014
NDVI	0,57	0,59	0,63	0,64	0,65	0,65	0,66

Looking at the NDVI anomaly for the February and March data for 2016 to 2018 (Figures 42 to 44), it is evident that there are both spatial and temporal variations in NDVI. In February and March, the Lowveld AEZ is prone to low NDVI, especially in the southern parts of Eswatini, which are characterised as the driest areas of the country.

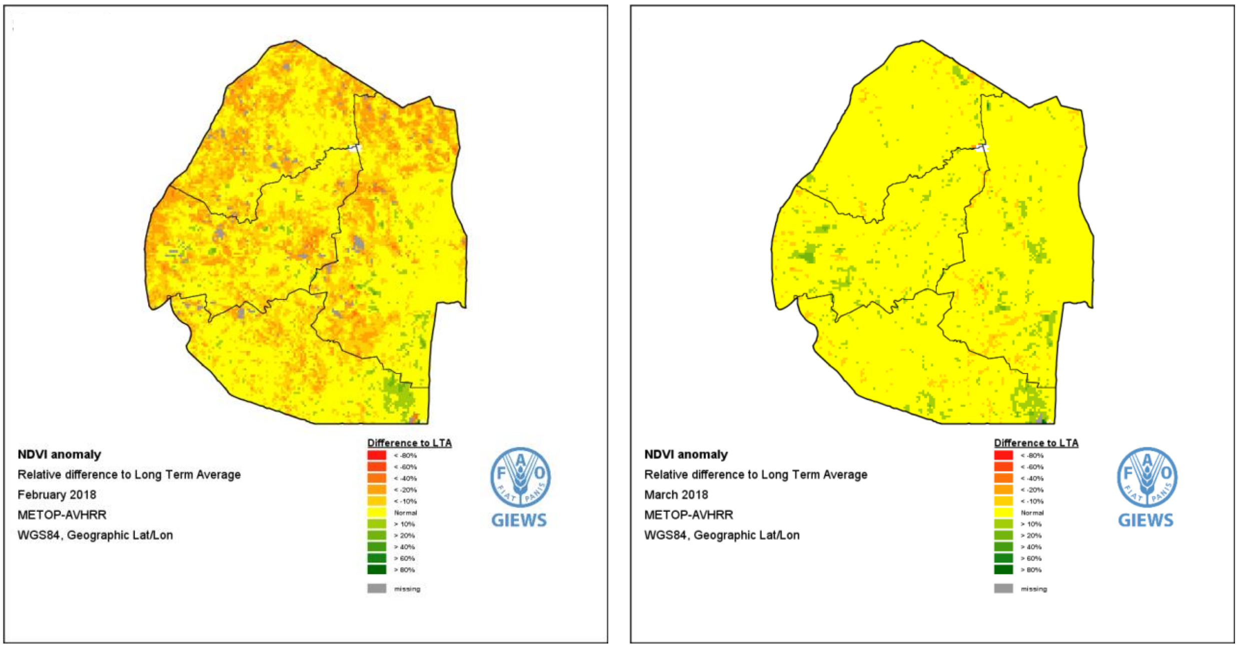

Figure 42. NDVI Anomaly in February and March 2018; *Source: FAO/GIEW-Eswatini*

Figure 43 presents the NDVI for February 2017, after the country was affected by two consecutive years of droughts (2014–2015 and 2015–2016) - comparable the rest of southern Africa - when the country experienced an extremely pronounced El Niño weather system, categorised as the worst El Niño to affect southern Africa in 35 years.

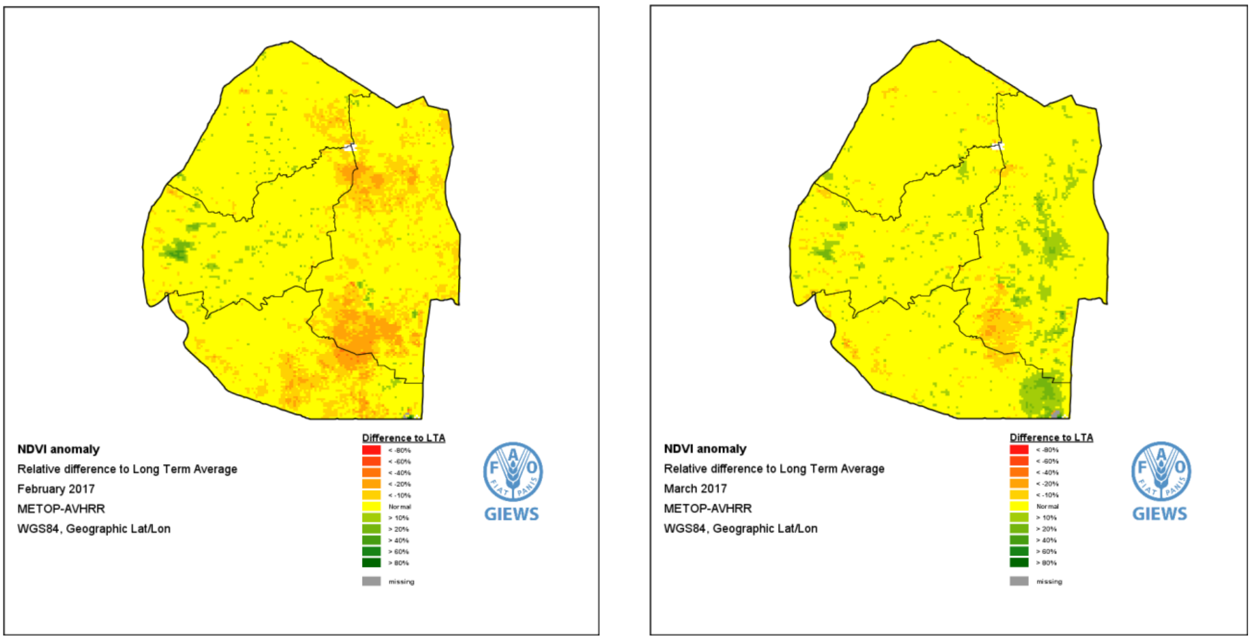

Figure 43. NDVI Anomaly in February and March 2017. *Source: FAO/GIEW-Eswatini*

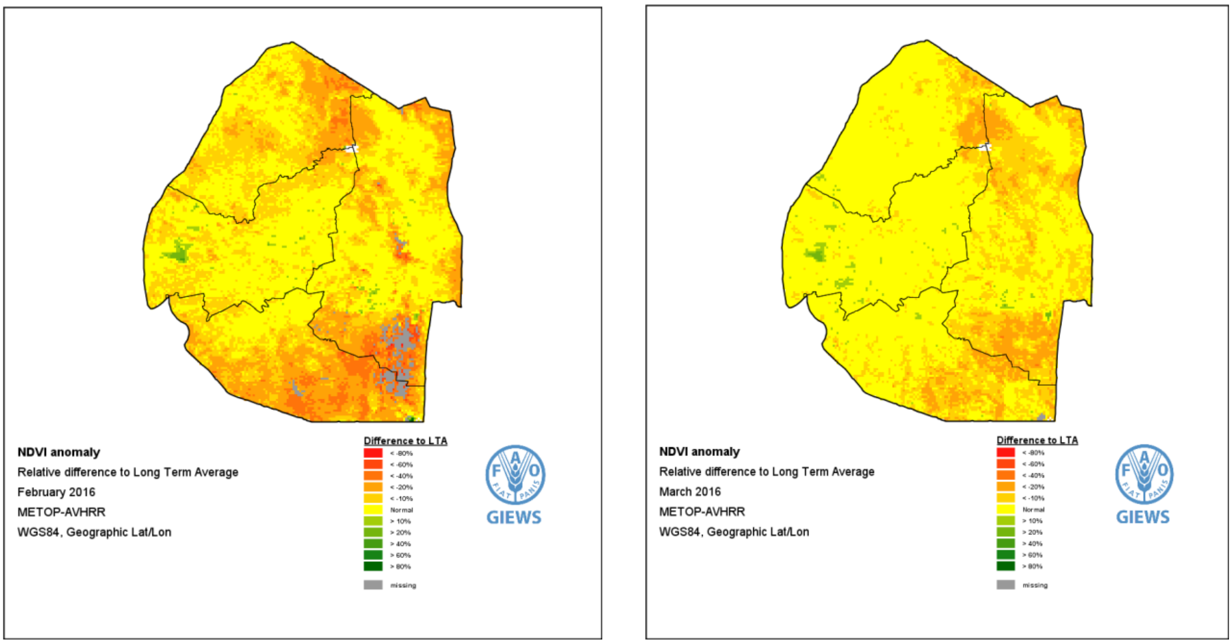

Figure 44. NDVI Anomaly in February and March 2016

5.5.4 Relationship between NDVI and SPI

The relationship between NDVI and SPI was investigated, to determine how close the indices were in relation to explaining drought conditions. This was completed to ascertain whether their statistical relationship could be modelled to explain the occurrence of a drought. The Pearson product-moment correlation coefficient, which is a measure of the extent of linear association between two variables and is represented by the value R, was used to explain the relationship between the two indices (Laerd Statistics, 2018). Using the formula below for calculating the correlation coefficient, the R value was generated for the months of December (for the SPI) and January (for the NDVI) (Table 19) for the selected drought years.

$$r_{XY} = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \overline{Y})^2}} \tag{5.4}$$

A linear correlation coefficient returns a value of between −1 and +1. A strong negative correlation is indicated by −1, and +1 means that there is a strong positive correlation. No correlation is indicated by 0.

Table 19. NDVI, Temperature, and SPI for Years 2001–2017

Year	NDVI	Temperature	SPI-3	SPI-6	SPI-12
2017	0.67	24.26	-1.54	-2.27	-2.58
2016	0.61	24.07	-1.90	-2.43	-2.65
2015	0.69	23.82	0.16	0.47	-0.23
2014	0.72	23.93	0.72	0.92	0.63
2013	0.67	24.14	0.27	0.57	0.61
2012	0.68	24.23	-0.61	-0.15	0.05
2011	0.72	23.99	1.35	0.50	0.33
2010	0.69	24.00	1.76	0.68	0.45
2009	0.66	23.22	-0.38	-0.65	-0.33
2008	0.69	23.39	0.45	-0.35	-0.07
2007	0.71	23.92	-0.44	0.80	0.61
2006	0.65	23.64	-0.48	0.08	-0.19
2005	0.70	23.66	-0.28	0.55	0.26
2004	0.60	23.21	-0.63	-0.65	-0.58
2003	0.66	24.26	-1.08	-1.15	-0.61
2002	0.67	23.38	1.41	0.39	0.59
2001	0.67	23.45	0.81	2.39	2.19

The values of R for 3 and 6-months SPI and NDVI correlation coefficient are presented in Table 20, and the relationship is visualised in the Figure 44 scatter plots. The correlation coefficient for both the SPI and the NDVI for the time series 2002 to 2017 was R determined at 0.55, which also demonstrated a positive correlation. This suggests that high X variable scores go with high Y variable scores (and vice versa). The scatter points (Figure 45) are close to the line, indicating the two variables have a positive correlation, which indicates only a moderate to positive linear relationship between the variables.

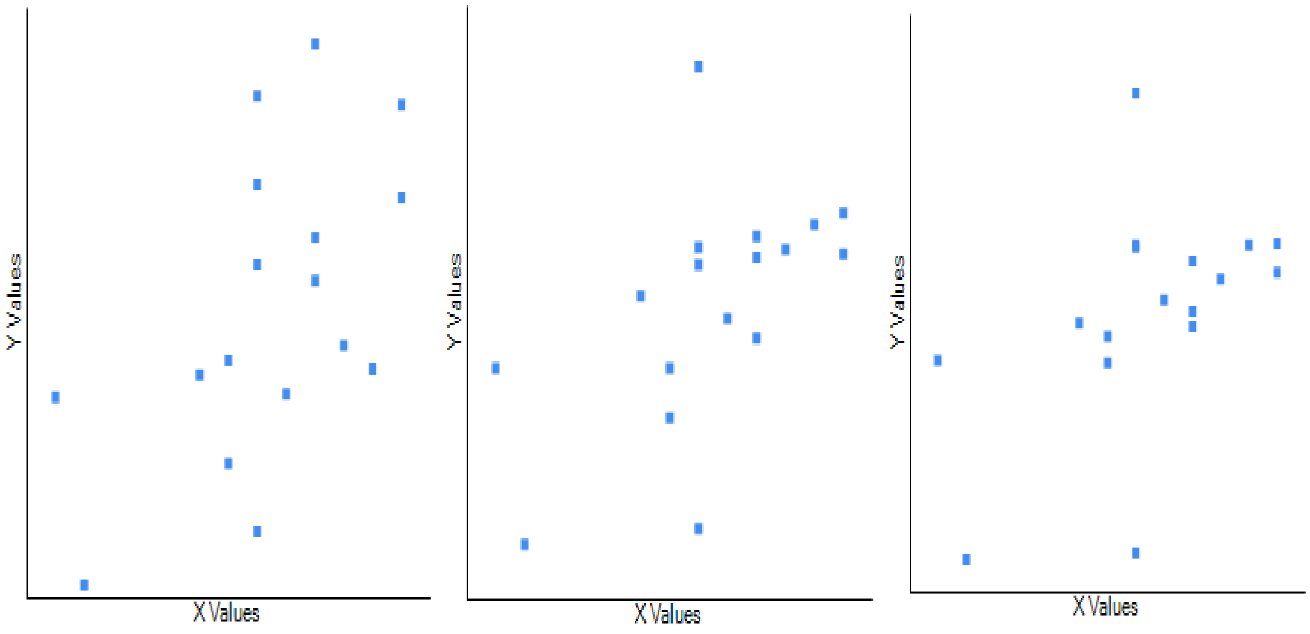

Figure 45. Correlation Coefficients Scatterplots for 3, 6, and 12-Month Time Scales (left to right)

The value of R for the 12-month time scale was lower at 0.50. Although technically showing a positive correlation, the relationship between the variables is weak. With the positive correlation between the NDVI and SPI, it therefore means that the two variables can be used in combination for drought monitoring.

Table 20. Pearson Correlation Coefficient between the NDVI and SPI at 3, 6, and 12-month Time Scales

3-month	6-month	12-month
X Values ∑ = 11.46 Mean = 0.674 ∑(X - Mx)2 = SSx = 0.018 **Y Values** ∑ = -0.41 Mean = -0.024 ∑(Y - My)2 = SSy = 16.938 X and Y Combined N = 17 ∑(X - Mx)(Y - My) = 0.303 **R Calculation** r = ∑((X - My)(Y - Mx)) / √((SSx)(SSy)) r = 0.303 / √((0.018)(16.938)) = **0.5544**	**X Values** ∑ = 11.46 Mean = 0.674 ∑(X - Mx)2 = SSx = 0.018 **Y Values** ∑ = -0.3 Mean = -0.018 ∑(Y - My)2 = SSy = 22.283 X and Y Combined N = 17 ∑(X - Mx)(Y - My) = 0.343 **R Calculation** r = ∑((X - My)(Y - Mx)) / √((SSx)(SSy)) r = 0.343 / √((0.018)(22.283)) = **0.5474**	**X Values** ∑ = 11.46 Mean = 0.674 ∑(X - Mx)2 = SSx = 0.018 **Y Values** ∑ = -1.52 **Mean = -0.089** ∑(Y - My)2 = SSy = 21.121 X and Y Combined N = 17 ∑(X - Mx)(Y - My) = 0.303 **R Calculation** r = ∑((X - My)(Y - Mx)) / √((SSx)(SSy)) r = 0.303 / √((0.018)(21.121)) = **0.4964**

5.5.5 Determination of Drought Early Warning Trigger Threshold

The analysis of remote sensing-based drought indices and SPI can provide a far-reaching understanding of the spatio-temporal dynamics of large-scale drought patterns. To quantify the onset of droughts, the study derived statistical and threshold-based parameters from NDVI and time series of SPI-3, 6, and 12-month timescales. Due to the positive correlation between NDVI and SPI, the two indices (combined with temperature) can be used to monitor and detect drought and thereby provide early warning information to stakeholders.

The NDVI for the month of March for all drought periods ranged between 0.60 and 0.72, with 0.60 being the year the country experienced an extremely pronounced El Niño weather system categorised as the worst El Niño to affect southern Africa in 35 years. The 3-month OND SPI values ranged from 1.41 to −1.90, while the 6-month and 12-month SPI ranged between 2.39 and −2.43, and 2.19 to −2.65, respectively. For the main drought years 2006/2007 and 2015/2016, the 3, 6, and 12-month SPI closely indicated a severe drought, while the NDVI was the lowest. Similarly, in the non-drought years for the same months, SPI values were mostly positive, whereas the NDVI were also high.

The 3, 6, and 12-month SPI, NDVI, and temperature data from 2001 and 2017 was modelled to classify drought severity. Though SPI data was available from 1986, NDVI data was only available from the year 2001 onwards; therefore, only data for both indices from 2001 to 2017 was used for the regression analysis. The available data (Table 18) was used to develop a model to enable a drought early warning trigger threshold. The method used was the least squares, which simply minimises the sum of the squares of the deviations of the observed response from the fitted response (Naoum and Tsanis, 2003). This involves the initial assumption that a certain type of relationship, linear in unknown parameters, holds.

The drought severity is represented by the value of Y being the dependent (response) variable, and the model function is a specified form that involves both the predictor variables (NDVI and SPI) and the parameters. Interaction effects between the variables were also considered. The unknown parameters were estimated under certain other assumptions with the help of available data, so that a fitted equation was obtained. In the model, drought determination was based on three main parameters: SPI, NDVI, and temperature.

The general form of the final model was:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3, \qquad (5.5)$$

where

Y is Drought Occurrence (severity),

X_1 is NDVI,

X_2 is SPI, and,

X_3 is Temperature.

Based on the model, integrating NDVI, SPI and temperature ,the study determined the value of Y (drought severity). The Y varied between 0.06 and 0.84 for the years 2001 to 2017 (Figure 46), with lower Y values indicating wet years and higher Y values representing drier years. However, not all high Y values represented drought years. There was a non-linear relationship between NDVI and SPI with intercepts at Y greater than 0.54 (Figure 46). Looking at the Y values, it was consistent that a value greater than 0.54 represented a significantly dry year, resulting in reduced cereal production, and in some cases, in an official drought declaration. Table 21 shows that official declarations were made by the Government of Eswatini 50% of the time when Y was > 0.54 for the 3-month SPI time scale. Similarly, 100% of the time, the Y value of > 0.54 was considered a dry spell or drought by Government and UN/ INGOs, based on the reduced yields and increased vulnerably, as defined by Eswatini vulnerability assessments.

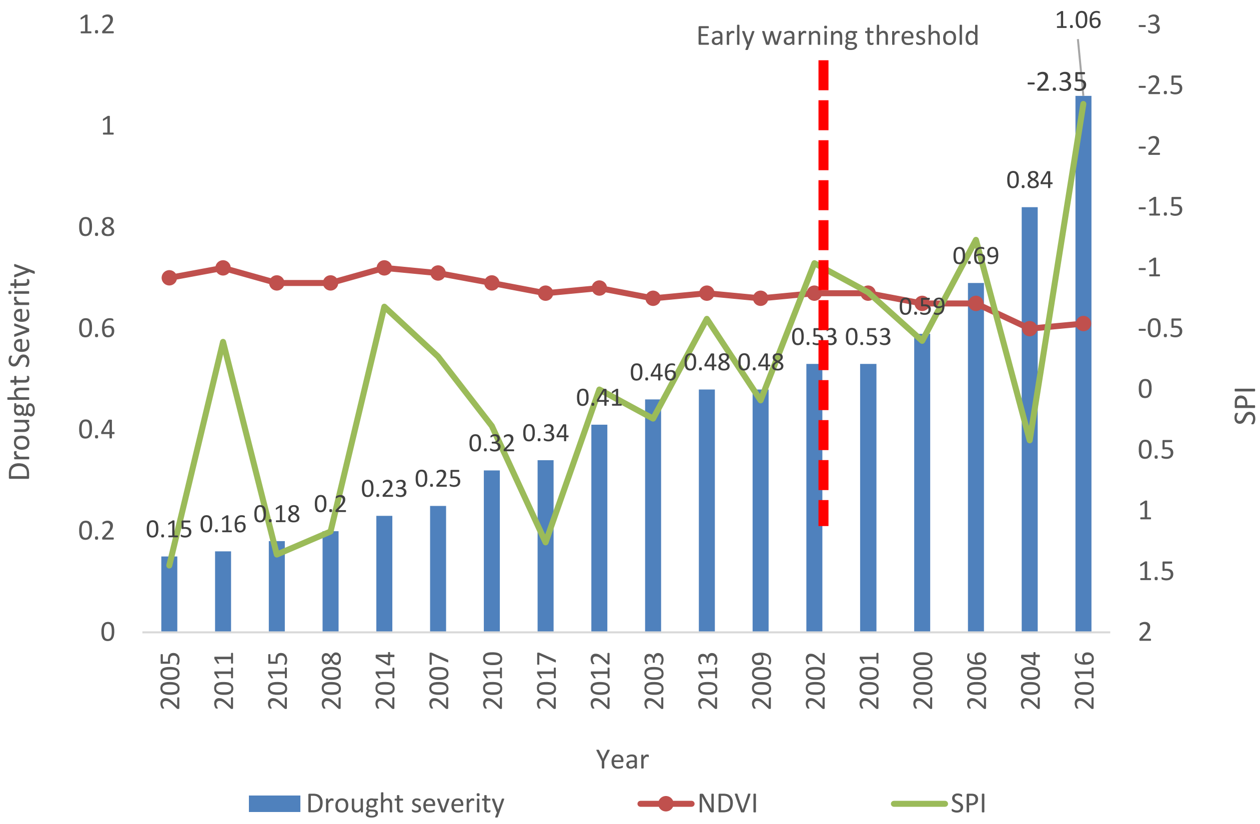

Figure 46. Determination of Y (Drought severity)

For the 6-month and 12-month SPI time scales, the probability of Y > 0.54 was considered a drought spell (with official declarations), and based on yield and vulnerability on average 75% of the time. The probabilities, though not statistically significant, indicate that a Y value of > 0.54 can be considered a good representation of drought, especially meteorological and agricultural droughts. This result is significant for the study, as the Y value provides a figure (like above) which the country can use to determine if it is in a drought period, and thereby can be used as an early warning trigger value. However, this requires confirmation based on other additional sources of information, such as crop assessments and water balance sheet. High Y values for the years 2007 and 2016 coincide with the two strongest El Niño events, and one remarkable La Niña episode in 2010/2011 rainfall season. Similarly, the retrospective analysis of agriculturally relevant droughts over Africa indicates that major drought events, which are mentioned in literature or registered in the EM-DAT disaster database of 2016, are largely mirrored in the data (Table 21).

Table 21. Drought Severity Determination based on the Relationship between SPI, NDVI, and Temperature

Year	Drought Severity			Drought Declaration Status*	Recognized Droughts Based on Yield and Vulnerability*
	SPI Timescale				
	3-month	6-month	12-month		
2016-2017	0,356157	0,497748	0,549072		
2016-2017	0,06165	0,024907	0,070636		
2015-2016	0,538125	0,512889	0,614307	Official declaration	√
2014-2015	0,635436	0,617027	0,636389		√
2013-2014	0,239596	0,159834	0,123431		
2012-2013	0,34424	0,270323	0,210162		
2011-2012	0,599801	0,723044	0,726466		√
2010-2011	0,22795	0,335999	0,348891		
2009-2010	0,546404	0,668646	0,627087		√
2008-2009	0,651257	0,83573	0,790365		√
2007-2008	0,690508	0,544053	0,549981	Official declaration	√
2006-2007	0,295794	0,235428	0,272603		
2005-2006	0,673756	0,601755	0,636671	Official declaration	√
2004-2005	0,027779	0,062797	0,065609		
2003-2004	0,272383	0,286389	0,180285		
2002-2003	0,365377	0,528062	0,490495		
2001-2002	0,385711	0,146923	0,153912		

**Source: SVAC 2005; 2007;2016, EM-DAT, 2016*

5.6 CHAPTER SUMMARY

To be able to conduct effective drought monitoring, there is a need for reliable drought information in order to determine the onset or extent of the drought. This can be sourced from weather data, which is mostly available in Eswatini. However, reliance on weather data alone is inadequate, especially if there are limited weather stations, infrastructure, and staff resources, or when the data is untimely, sparse, and incomplete. Complementing weather data with remote sensing data can help to provide a clearer picture of drought conditions. Therefore, the combination of NDVI and SPI is important for enhancing the quality and reliability of drought information, as it provides better information on location and coverage of drought, which is useful information for both planning and decision-making.

By calculating the association between SPI and NDVI, it can be clearly stated that they demonstrate a positive correlation, indicating that SPI and NDVI - when used in combination - can be employed to detect the start of drought in Eswatini. The results of Y > 0.54 at 3, 6, and 12-month time scales indicated that the country was experiencing a drought. The findings therefore confirm that combined SPI and NDVI, supported by other tools, are useful for assessing the extent and severity of drought. The results disprove the hypothesis that the relationship between SPI and NDVI cannot elucidate the spatial and temporal drought variability in Eswatini. Consequently, the NDVI and SPI are adequate and proficient in providing a near-real-time indicator of drought conditions at national level and across AEZs. However, they need to be used in combination with other information, as the SPI and NDVI did indicate identical results in all cases.

It is also critical to note that the SPI and NDVI are not the only drought indicators that can be used. The study adopted these two particularly because of the available infrastructure in the country that is able to effectively collect and analyse precipitation and remote sensing data. Other available indicators that are being adopted in the region, particularly in South Africa, are the percent annual seasonal greenness (PASG), the VCI, the water satisfaction index (WSI), dam levels zone (Z-score), stream flow (Z-score), and ground water level percentage (Jordaan et al., 2017b). They can be adopted by Eswatini in the future, once the country has the required infrastructure and expertise for data collection and analysis of these indicators.

Based on achieved integration of SPI and NDVI for drought monitoring, the study will incorporate the two indices in the development of an integrated drought monitoring and early warning framework. However, to ensure proper development, it is essential to review other country, regional and international drought monitoring frameworks, to assess what worked and did not, and what can be adopted for Eswatini. Chapter 6 will review different country drought monitoring frameworks looking at how they are formulated, what tools and indices are used, how effective they are and what aspects can be adopted for Eswatini.

6 DROUGHT MONITORING FRAMEWORKS: A COMPARATIVE ANALYSIS

6.1 INTRODUCTION

Though drought is a normal feature of climate, it is also one of the most common and severe of natural disasters. It can affect communities and the environment in various ways. For meteorological drought, the most immediate consequence of drought is a decline in crop production, due to insufficient and poorly distributed rainfall, thereby affecting food security and water availability (Toulmin, 1986). While such drought may affect any climatic region at any time, the El Niño phenomenon - which causes a rise in temperature in the pacific that adversely affects global weather patterns - has resulted in the region experiencing little and erratic rainfall in past decades. Extensive droughts have afflicted African countries, resulting in major losses to local economies (Sivakumar et al., 2005).

Over the last 30 years, frequent droughts in sub-Saharan Africa have resulting in food crises affecting millions of people, having a negative impact on the economic and social situation (Haile, 2005; Tadesse et al, 1998). How to react to and reduce drought and its impact has become an urgent scientific and social issue necessitating the need for adequate and up-to-date information on drought severity impacts (Mutai et al., 1998; Shanko and Camberlin, 1998).

6.2 HISTORICAL PRACTICES OF DROUGHT MANAGEMENT

Historically, risk aversion has been noted to be more cost-effective than disaster relief in dealing with major natural disasters, with respect to reducing hazard risks and their impact (Wu et al., 2015). The 3rd UN World Conference on Disaster Reduction underscored the significance and importance of disaster monitoring and loss prevention, when establishing the aims of disaster reduction (Liu et al., 2016). The cost of drought disaster impact has necessitated the design of appropriate monitoring, mitigation, and coping strategies. The advancement of a scientific approach or framework applicable for drought monitoring framework is therefore critical for Eswatini and the region.

Many African countries have drought monitoring mechanisms that are conventional. These methods use a country's meteorological data, together with forecasting and predictions.

Eswatini uses information from the Eswatini Meteorological Service or from regional bodies, such as the South African Weather Service, the Southern African Regional Climate Outlook Forum (SARCOF), and the Famine Early Warning Systems Network (FEWS NET). However, it is not sufficient to monitor drought using only weather or meteorological data, as it normally indicates drought periods when the drought is already happening, thereby not giving enough time for the government and populations to plan and respond effectively.

Improved drought monitoring and drought monitoring products are both fundamental for effective drought preparedness and the development of national drought policy and plans (Gerber and Mirzabaev, 2017). Sivakumar and Wilhite (2002) described the factors required for consideration in establishing an effective drought monitoring system. Consequently, their work has underpinned the drought-monitoring framework developed during this study. The key elements for consideration are as follows:

- effective analysis of the risk and its impact on agricultural production;
- provision of early warning information or products that are easily accessible, timely, and easy to use and understand;
- a system that includes products that are reliable, scientifically acceptable, and that people can be confident to use;

This chapter provides an overview of current drought monitoring and EWS in different countries. It also examines whether the established systems in these countries can inform the formulation of a drought-monitoring framework for Eswatini and effectively support drought management in terms of impact minimisation and mitigation. The consolidation of such detailed information from different countries selected as case studies is critical in formulating an inclusive and effective drought-monitoring framework for Eswatini.

6.3 APPROACHES TO DROUGHT MONITORING AND EARLY WARNING

Traditionally, drought management has been reactive or 'crisis' led in approach (Gerber and Mirzabaev, 2017; Wardlow et al., 2012; Wilhite, 2014, 2017). A new approach has emerged, with a focus on proactive, risk-based approaches, such as preparedness planning, mitigation, monitoring, and early warning (Hayes et al., 2012; Tsakiris, 2017; Wilhite, 2016; Wilhite, 2017). The development of a comprehensive drought monitoring system, capable of providing early warning of a drought's onset, severity, persistence, and spatial extent in a timely manner is a critical component in formulating a national drought policy or strategy (Hayes et al., 2011). Whilst different drought indices have been developed and applied for drought monitoring and prediction (Hao and Aghakouchak, 2014), current trends and scientific advances have led many stakeholders to advocate for more integrated drought monitoring.

6.4 INITIATIVES TOWARDS A GLOBAL DROUGHT MONITORING FRAMEWORK

Under the WMO regional networks, there are two drought monitoring centres (DMCs) for eastern and southern Africa. They comprise two operational centres; one in Nairobi, Kenya and one in Gaborone, Botswana. Each is charged with the timely monitoring of drought intensity, geographical extent, duration, and impact on agricultural production, together with the issuance of early warnings (Jayasuriya and Stefanski, 2011). This enables the improved application of meteorological and hydrological data and products. They avail 10-day weather advisories, decadal climatological summaries, decadal agro-met conditions and impacts, decadal synoptic reviews and weather outlooks, and provide monthly drought monitoring bulletins for the sub-regions (Wilhite et al., 2000). Eswatini is the beneficiary of the outputs from the Gaborone DMC and the Pretoria-based Global Producing Centre of Long-Range Forecasts, a member of the networks of institutions coordinated by the WMO.

Global initiatives such as the Global Drought Early Warning System (GDEWS) (Figure 47) aim to improve existing regional and national drought monitoring and forecasting capabilities by adding a global component, facilitating continental monitoring and forecasting at various scales. This thereby increases the capacity of national and regional institutions that lack drought EWSs, or complements existing ones. The system also aims to improve coordination of information delivery for drought-related activities and relief efforts across the world (Pozzi et al., 2013). This is important for countries in Africa particularly those with low capacity for drought early warning.

The first part of a GDEWS is the drought-monitoring component where precipitation, soil moisture, evapotranspiration, snowpack, river flows, and groundwater are monitored, along with agricultural productivity and natural ecosystem health (Garcia et al., 2018; Pozzi et al., 2013). To do this globally is challenging, due to the sparse network of '*in situ'* measurements of these variables. Many parts of the world - especially in the wet and dry tropics - are sparsely gauged, or the data are not easily available (Pozzi et al., 2013).

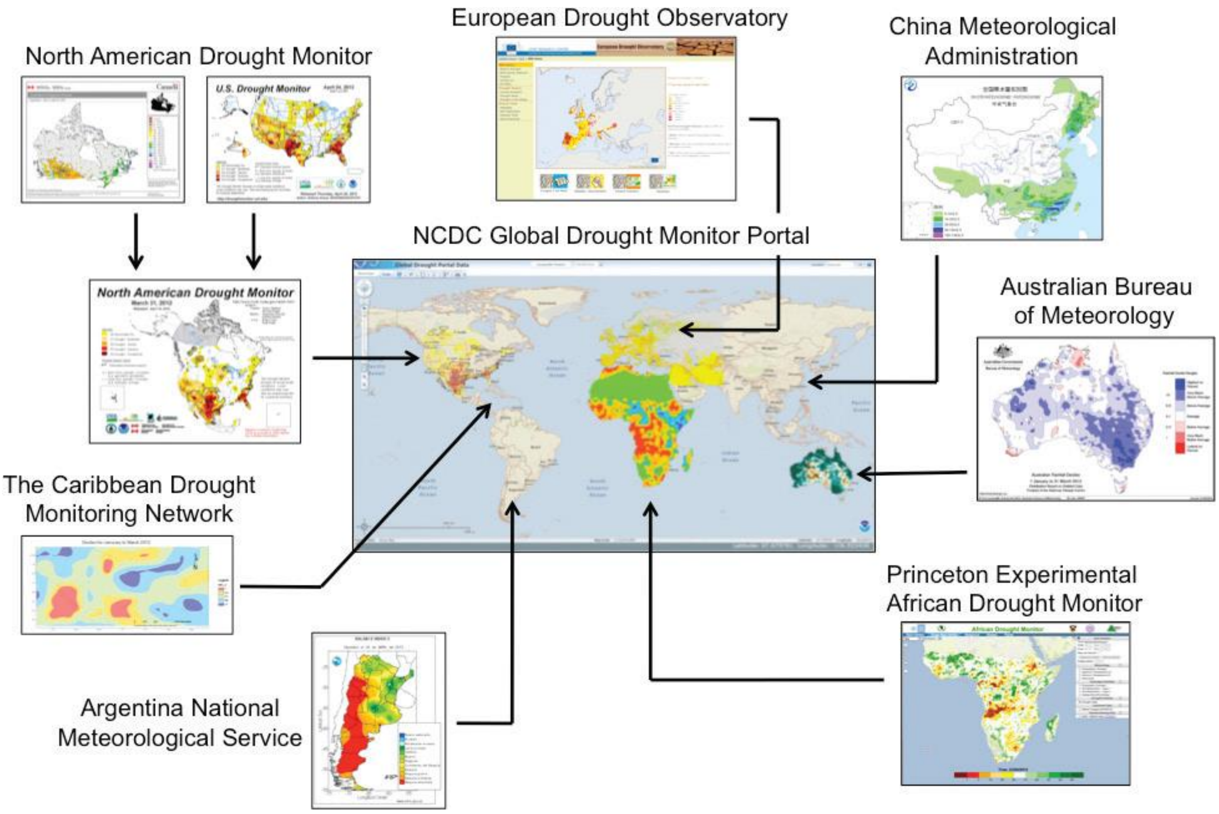

Figure 47. Global Drought Early Warning System (GDEWS). *Source: Pozzi et al., 2013.*

GDEWS is aimed at enhancing existing regional and national monitoring and prediction capabilities. Such a worldwide network and partnership will provide a framework for consistent improvement of forecasting and monitoring efforts.

6.5 THE CONCEPT OF EARLY WARNING SYSTEMS IN DISASTER RISK REDUCTION

There has been progress globally in the development and use of EWSs mostly due to technological advancements (Carabine and Jones, 2015). To be classified as an EWS, the United Nations International Strategy for Disaster Reduction (UNISDR) outlined four critical, interrelated elements or phases (Figure 48), which are fundamental principles for the drought monitoring framework developed for this study. These elements are as follows:

(i) risk knowledge;

(ii) detection, monitoring, and analysis of the hazards;

(iii) timely dissemination and communication of accurate and actionable warnings, and

(iv) preparedness at all levels to respond to the warnings received (UNISDR, 2017a).

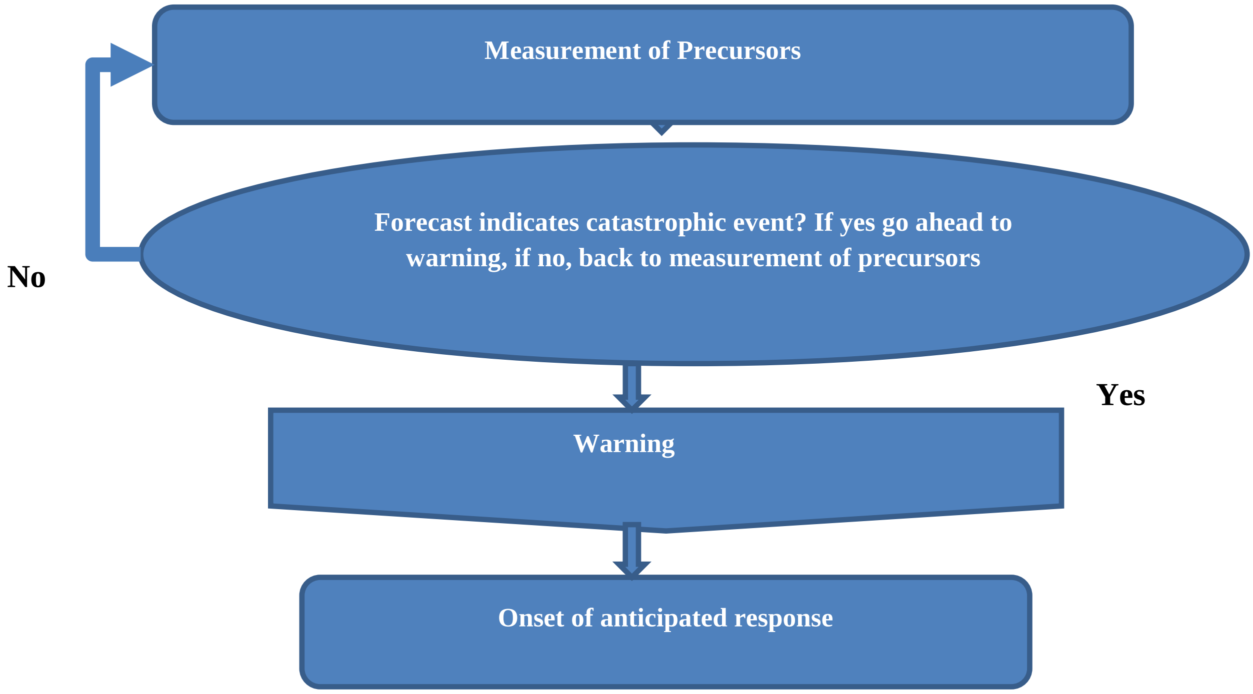

Figure 48. Phases of an Early Warning System (Source: *UNISDR, 2017a*)

There are several definitions of EWSs available. However, for the purposes of this study an EWS describes the set of capacities required to create and distribute timely and meaningful warning information to individuals, communities, and organisations susceptible to drought hazard, to enable timely preparation for, response to, and reduction of possible harm or loss (Buchanan-Smith, 2000; Monnik, 2000). Therefore, EWSs are the procedures and actions through which information is produced in advance about the occurrence of hazards. Early warning systems fall under the DRR framework as part of preparedness strategies.

6.5.1 Drought Early Warning Systems Definition

An EWS is defined as 'the provision of timely and effective drought information, through identifying institutions, that allow individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response' (Grasso and Singh, 2011). Early warning systems are a practical tool for implementing timely and appropriate responses to droughts and famine via food aid and other mitigation strategies. Early warning involves developing regional drought histories, monitoring current weather, using climate projections, and determining possible outcomes of developing drought events, whilst also answering questions on drought duration and severity. Effective EWSs should involve both technology and all interested parties in drought planning and response (WMO, 2006).

A drought early warning system (DEWS) is designed to identify climate and water supply trends, thus allowing to detect the emergence or probability of occurrence, onset, development, persistence, alleviation, severity, and the end of a drought. This information can reduce the impact if delivered to concerned stakeholders on time and in appropriate formats (Shamano, 2010). Effective DEWS have high potential in contributing towards tackling the cycle of droughts. This happens when timely, relevant, and comprehensible information on impending droughts is provided. The information can be used to mitigate the effects of droughts and therefore reduce their negative impact.

Successful DEWS rely on weather forecasting systems. However, implementation of such systems in many African countries is hampered, by among other things, inadequate coverage by weather stations, and the very poor utilisation of the seasonal climate forecasts by the farmers (Masinde, 2014). A DEWS needs to encompass mechanisms and procedures for the collection and analysis of information in a timely manner, and should be able to disseminate that information through locally appropriate channels to the end user. End users should be made aware of the essentiality of this information and continuous information flow should be encouraged once a drought is foreseen (Grasso and Singh, 2011).

To that end, EWS products can include:

- Short to medium-term weather forecasts;
- Forecast of the onset and end of a rainy season;
- Prediction of wet and dry spells;
- Climatic forecasts and soil moisture monitoring;
- Outlook for onset of drought (Akeh et al., 2000).

6.5.2 The Need for EWS for Drought

The aim of early warning is to empower individuals and communities vulnerable to hazards to act on time and in an appropriate way to reduce the prospect of personal injuries, deaths, and damage to property or surrounding environments. It is important to be able to predict a drought as quickly as possible, so that the implementation of emergency measures and the organisation of aid can be given sufficient time, thus minimising damage (Wilhite, 2006). The effects of drought are incremental, and occur over a long period of time, hence receiving little attention in the early phases. Each year, droughts result in significant socioeconomic harm and ecological damage across the globe. Given the increasing intensity and frequency of droughts, there is now an urgent need to establish effective EWSs for drought, especially in developing countries (Hanif et al., 2010; Molua and Lambi 2007). There is a pressing need to discuss and recommend standard indices for droughts of different categories and to improve EWSs.

As a major element of disaster risk reduction, and in addition to preventing loss of lives and reducing negative impacts of disasters, EWSs help people to deal with potential disasters and aid in the process of recovery (Renwick, 2017). Moreover, EWSs provide decision-makers and stakeholders (including communities at risk from a hazard) with information on the onset, continuation, end of a hazard, and the commencement of disaster status (Newman, 2017). DEWSs at the global, national, and regional level are necessary because they provide the timely and reliable information required to make decisions regarding the management of water and other natural resources (DePauw, 2000).

Preparedness and early warning are key factors for improved operational management and help to reduce social vulnerability to drought (Sivakumar and Wilhite, 2002). The United Nations Environment Programme advocates a drought prediction system based on a comprehensive and integrated approach that includes multiple drought indicators. While droughts originate from a deficit in precipitation, an effective drought monitoring and prediction system should integrate multiple drought-related variables (Hao, 2014).

According to Shamano, (2010), DEWSs allow for early drought detection, proactive (mitigation) and reactive (emergency) responses, trigger actions within drought plans, support provision of information for decision-making, all allowing response to drought well before famine indicators occur. For a DEWS to be effective, the following should be available (Li, 2000):

- A system that can capture, analyse, and transfer drought information on time.
- A setting up of criteria to confirm drought affected areas.
- A monitoring of the status of and estimating future availability of water and soil moisture.
- A department or unit to enforce criteria and issue/cancel warnings.

6.5.3 Institutional Challenges Limiting the Effectiveness of Drought Monitoring and Early Warning Systems

Countries in sub-Saharan Africa have climate information and predictions services, which are normally government-managed meteorological services, and services provided by research institutions and universities. However, the challenge is that the collection of data is usually poorly coordinated between agencies and ministries, due to government structures in most of the countries (Wilhite, 2006). The key challenges are inadequate infrastructure and instruments, lack of qualified staff, and ineffective dissemination facilities (SADC, 2012b; Sigudla, 2015). Tadesse et al. (2008) summarised the challenges in developing a drought monitoring system, which were factored into the development of the Eswatini drought-monitoring framework. These are as follows:

i. inadequate meteorological and hydrological data, resulting in poor data;
ii. poor data sharing between government agencies and research institutions;
iii. disseminated information is too technical and detailed, often being delivered late and not using very user-friendly formats;
iv. forecasts frequently unreliable and lack specificity for use in agriculture sector;
v. selected drought indices cannot detect the onset and end of drought;
vi. vulnerability assessment methodologies are not standardised. However, in southern Africa there is a harmonisation of vulnerability assessments through the SADC Regional Vulnerability Assessment infrastructure.

6.5.4 Review of Country Drought Early Warning Systems

The following discussion will examine country and regional case studies to understand what is being done elsewhere. Comparison of the different strategies adopted worldwide will enable an analysis of what works and what can be adopted or improved for use in the Eswatini drought-monitoring framework.

6.6 COUNTRY CASE STUDIES

6.6.1 Botswana

Botswana is a semi-arid country and regularly experiences drought. The effects of drought are wide-ranging, affecting almost all sectors of development especially agriculture, water, and health. Loss of income (either due to loss of crops, livestock or employment) in these sectors causes great stress on people's livelihoods (Jacques, 1995; Van Apeldoom, 1981; Ziervogel, 2017). Drought adversely affects the already fragile food and agricultural situation and seriously impairs the rural economy and socio-cultural structures (Mante-Suaneng, 2014). About 70% of rural households derive part of their livelihoods from agriculture, with crop production mainly based on rain-fed farming. Rangeland resources - which cover more than 60% of the country and are the basis for the cattle industry - are the most affected by drought—albeit to varying degrees (Jacques, 1995).

Botswana has an organised drought-monitoring system (Mante-Suaneng, 2014), and there is a strong network of stakeholders and organisations dealing with drought monitoring and mitigation. These include the National Early Warning Technical Committee, the Inter-Ministerial Drought Committee, and the Rural Development Council. Institutions that monitor drought comprise the Ministry of Agriculture, the Ministry of Health, the Ministry of Local Government and Rural Development, the Ministry of Environment, Wildlife and Tourism, and the Ministry of Minerals, Energy, and Water Resources. Mante-Suaneng (2014) further highlighted that indicators used in the monitoring system include rainfall, area planted, conditions of rangeland, livestock, water and wildlife, and malnutrition levels. The above institutions hold early warning monthly meetings to track trends of these indicators.

An annual food security assessment is conducted between April–May, after the rainy season, mostly to augment regular early-warning reports (Mante-Suaneng, 2014). The assessment authenticates prevailing information at different administrative levels with that of the national level (Mante-Suaneng, 2014; UNW-DPC., 2015). The objectives of the exercise are twofold (Mante-Suaneng, 2014), to ascertain whether it is a drought year and to determine the need for government or external support.

The country also hosts the Monitoring for Environment and Security in Africa programme for southern Africa which provides a wide range of drought information products - including 10-

day drought maps and monthly drought-risk maps - for use by countries in the region (Mante-Suaneng, 2014). The limitation of the drought monitoring system is that most of the drought monitoring occurs when the drought impact is already being felt, delaying drought mitigation planning and response.

6.6.2 India

Drought in the Indian region is monitored from the progress of the onset and the withdrawal of the southwest monsoon (Carvalho et al., 2016). The National Disaster Management Authority oversees the drought monitoring system (as described below). Weather forecasts are broadly classified into three categories (NDMA, 2010), as follows:

- short range forecast (valid for less than 3 days),
- medium range forecast (valid from 3-10 days), and
- long range forecast (valid for more than 10 days).

These forecasts are issued by the Indian Meteorological Department through radio and print media, while the National Centre for Medium Range Weather Forecasting disseminates the information through its network of agro-met advisory service units, situated in state agricultural universities.

The different state governments monitor drought by obtaining information on rainfall, water levels, surface water/groundwater, soil moisture, and sowing/crop conditions from various state sources (NIDM, 2009). The challenge however is the lack of a centralised database for drought management. The drought management methodology that is utilised in India is illustrated in Figure 49.

Drought Declaration: Different states adopt different methodologies for drought assessment, preparation of drought memoranda, drought declarations, and assessment of magnitude of relief required. The administrative units for drought declaration also differ from state to state. The time of declaration also differs from state to state. The issues that need to be reflected upon in this context are listed in the following section. There are inconsistencies amongst the states regarding drought declaration. These include:

- different criteria by different states,
- differences in time and the timeliness of declaration from state to state,
- rainfall improvements after declaration are not accounted for and,
- drought declaration at the end of the season, being too late for relief work.

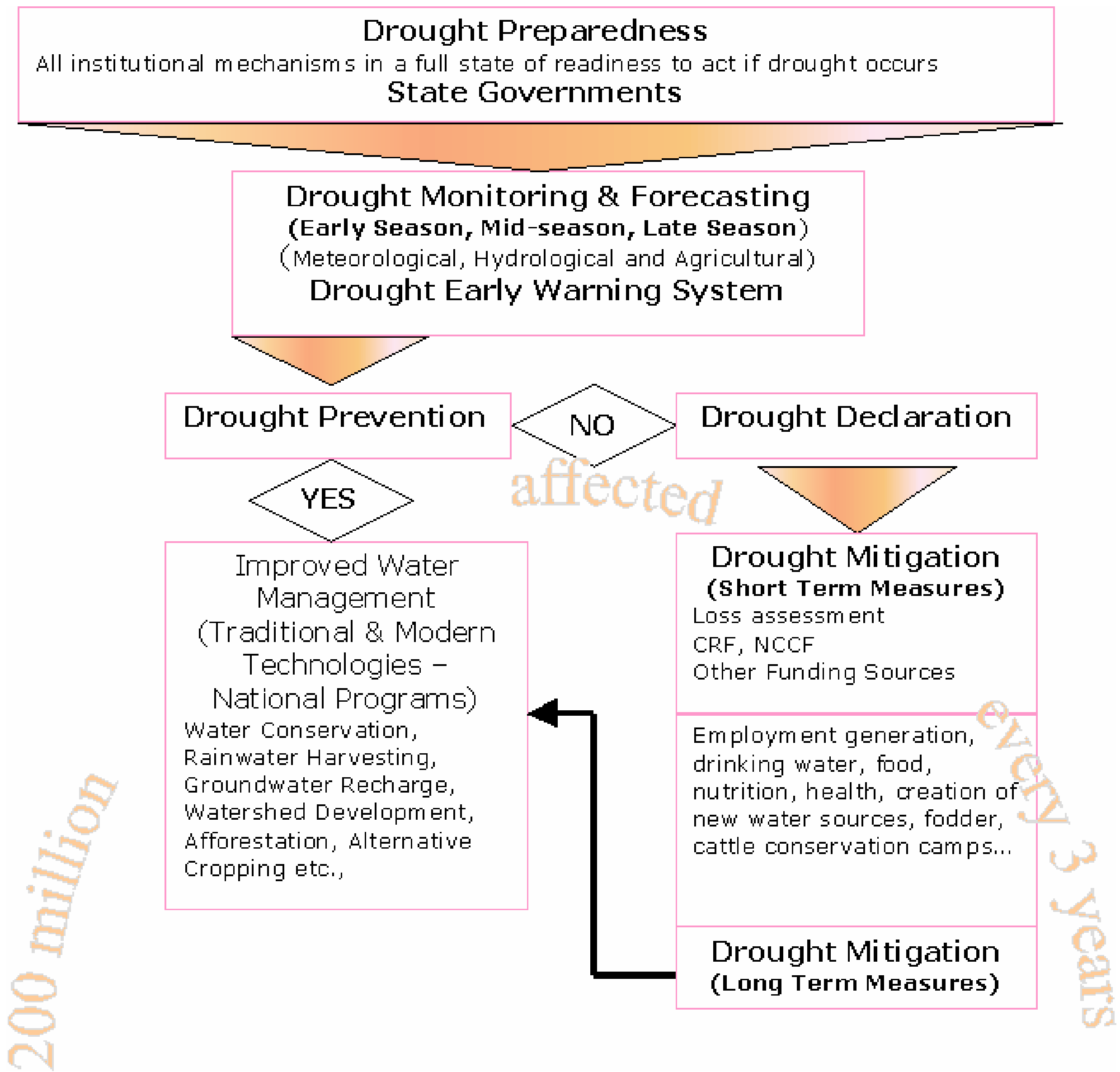

Figure 49. Drought Management Methodology in India

The main lessons from the experience of India that are applicable in Eswatini are the fact that the NDMA should be coordinating with the meteorology department; for effective coordination. It is also possible to make early declaration if there is effective coordination, since late declarations are not helpful for emergency relief if required.

6.6.3 South Africa

Drought is the most dominant hazard in South Africa (Walz et al., 2018) which in the past has resulted in significant economic, environmental, and social impacts, highlighting the country's continuing vulnerability (Blamey et al., 2018; Jordaan, 2011; Senyolo et al., 2018; Wilhite, 2006). The drought in 2015/16 had a devastating effect on the agricultural, forestry, and fisheries sectors, as well as the agricultural value chain (GCIS, 2016). It is estimated that the 2015 drought costs farmers up to USD 689,655 in losses (Muyambo et al., 2017), increased unemployment and water restrictions (Baudoin et al., 2017). These substantial effects necessitated the South African government to develop capacity and expertise to respond in a timely and effective way to mitigate drought across various farming communities, especially those with poor resources. Previously, responses to drought were only reactive, due to a lack of proactive measures (DoA, 2005).

Strategic objectives of the Drought Management Plan (DMP)

According to the DoA (2005), reducing drought risk and managing drought entail the following:

- setting up a system of information management;
- monitoring and evaluating drought situations;
- suggesting counter action;
- compiling drought indicator maps portraying the onset or end of drought;
- compiling vegetation indicator maps;
- implementing and improving early warning systems and;
- establishing and implementing preparedness, mitigation, response, recovery, and rehabilitation initiatives.

Institutional arrangements for drought management

The national, provincial and local authorities, the farmer communities, the private sector and civil society have responsibility for the management of drought. The National Department of Agriculture makes the following strategic interventions to reduce drought risk (DoA, 2005):

- Setting up and maintaining a comprehensive National Drought Plan and a system of information management, monitoring, and evaluation;
- Conducting research in drought-prone areas;

- Assisting provincial departments with drought assessments;
- Implementing and improving early warning systems;
- Outlining the criteria for drought assistance, and
- Active international cooperation.

Integrated institutional capacity for disaster management.

The government of South Africa established the NDMC which acts under the Department of Provincial and Local Government, with the National Department of Agriculture chairing the Inter-Departmental Working Group on Drought. They are responsible for drought predictions and early warning and monitoring systems (DoA, 2005; NDMC, 2018).

Disaster governance (including drought)

The Disaster Management Act (2002), provides for the declaration of disasters through national, provincial, and local government (DoA, 2005; Malherbe et al., 2016; NDMC, 2018). When provincial and local authorities have determined that a disastrous drought is in progress or is about to occur, the disaster management centre of both the province and local municipality must act immediately (DoA, 2005), in the following ways:

- initiate efforts to assess the actual or potential magnitude and severity of the disaster;
- inform the national centre of the disaster with an initial assessment of the actual or potential magnitude and severity of the disaster;
- alert disaster management role-players in the province who may be of assistance; and
- initiate the implementation of any contingency plans and emergency procedures that may be applicable.

Declaration of a national state of disaster

The NDMC is responsible for classifying drought as a natural disaster (NDMC, 2018). The NDMC consults with provincial disaster management centres and assesses the magnitude and severity of the ongoing drought condition in the country (CoGTA, 2018). The involvement of advisory services and local government in a province's assessment is crucial to advise the National Department of Agriculture on the scale and extent of the damage caused by drought (DoA, 2005). A classification of a national disaster ensures the national executive has the responsibility to coordinate and manage the disaster in close cooperation with provincial and local government, the private sector, and civil society, using the applicable contingency plans and existing legislative mechanisms at its disposal to deal with the effects of the disaster effectively (CoGTA, 2018).

Primary data and information products

Primary data used for these information products are daily rainfall, daily maximum temperature, and NOAA AVHRR. This data is generally easily available in near-real-time. The available drought monitoring products used in South Africa include decile rainfall, percentage of normal precipitation, the percent annual seasonal greenness (PASG), the SPI, the NDVI, the VCI, the WSI, dam levels zone (Z-score), stream flow (Z-score), and ground water level percentage (Z-score). The Primary users of early warning information are government departments and the agro-industry organisations (Jordaan et al., 2017a; Monnik, 2000).

Muthoni Masinde's Drought Monitoring Framework

To complement existing frameworks, Masinde (2014) proposed a drought-monitoring framework (Figure 50) in the form of a bridge that delivers a DEWS composed of the following elements:

- drought knowledge
- drought monitoring and prediction;
- drought communication and dissemination;
- response capability.

The Information Technology and Indigenous Knowledge with Intelligence (ITIKI) group has an overall aim to develop a relevant, affordable, sustainable, integrated, resilient, useable, effective, generic, and micro-level EWS for droughts for sub-Saharan Africa and Africa at large. The incorporation of indigenous knowledge was an important element to the framework. Indigenous knowledge is valuable knowledge that has helped local communities all over the world survive for generations (Iloka, 2016). Muyambo et al. (2017) highlighted that indigenous knowledge was still an integral part of agricultural practices, and when applied to drought risk reduction strategies it could contribute to resilience against disasters.

The drought-monitoring framework is founded on four key elements, outlined below:

Element 1: Drought Risk Knowledge. Using wireless sensors that are capable of sensing temperature, humidity, atmospheric pressure, wind (direction and speed), precipitation, and soil moisture, weather data is automatically collected and sent to a structured store in the form of text messages (SMS).

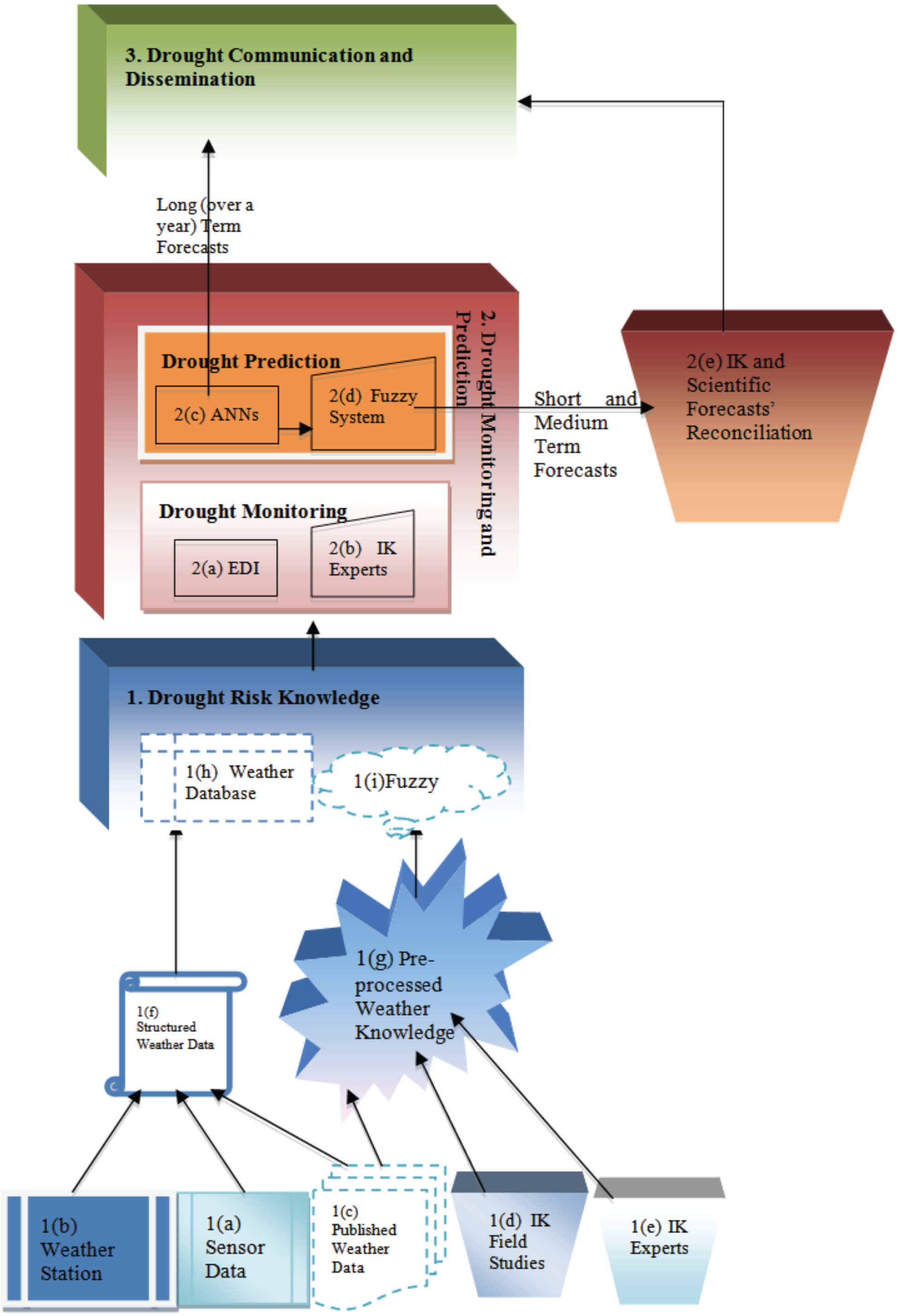

Figure 50. ITIKI Architecture: *Source: Masinde, 2014*

Element 2: Monitoring and Prediction. This was implemented using two sub-components: (1) drought monitoring that pre-processes the data to detect suggestive patterns as well minimise duplicates and other errors, and (2) drought prediction using artificial neural networks.

Element 3: Forecasts Communication and Dissemination. Mobile phones are used to send customised forecasts in the form of text messages and, where possible, free phone calls to farmers. Forecasts are posted on websites, while others are generated in audio formats that can be broadcasted via community radio stations and visual displays on strategically located village digital billboards.

The elements proposed by Masinde (2014) are applicable to the Eswatini context. However, there is a need to incorporate the SPI (the drought index being proposed for Eswatini) due to its ease of use and use of precipitation data that is readily collected by the meteorology department.

6.6.4 Zimbabwe

The Meteorological Services Department in the Ministry of Environment, Water and Climate and the Agriculture Research and Extension Services in the Ministry of Agriculture are the key public institutions responsible for drought monitoring. They are responsible for observation and monitoring of hydro-meteorological indicators, the publication of information and forecasts, and the provision of products and services related to weather and climate (Mavhura, 2017; Nangombe, 2014). According to Nangombe (2014), the early warning system for drought in Zimbabwe at the national level is ineffective, or to some extend not non-existent.

As it is common for many southern African countries, and in this instance Zimbabwe, government and stakeholders tend to focus on short-term emergency response after drought periods (Sunday News, 2015). However, the government in Zimbabwe realised the need to develop appropriate action plans to counter both the short and long-term effects of drought, to develop institutional capacity, and to invest more resources to meet the needs of the most vulnerable population groups (FAO, 2004; Nangombe, 2014). In Zimbabwe, government commitment for disaster management has been demonstrated by the existence and enactment of legal statutes, which create a conducive environment for disaster risk reduction initiatives (Gwimbi, 2007; Nangombe, 2014). The government developed the National Policy on

Drought Management (NPDM), which was formulated in 1998 and approved in 1999. The policy documents are in conformity with international standards, the Hyogo Framework of Action (Betera, 2013) and the Sendai Framework for Disaster Risk Reduction 2015–2030 (UN, 2015).

In Zimbabwe, existing EWSs include:

- the Civil Protection Unit,
- the Meteorology Department,
- the National Early Warning Unit in the Ministry of Agriculture,
- FEWS NET,
- the Drought Monitoring Centre (DMC),
- the Zimbabwe National Water Authority (ZINWA) (the hydrological section is one major partner in the flood early warning system in conjunction with the Meteorological Services Department and Civil Protection) (Nangombe, 2014).

6.6.5 Uganda

In Uganda in the last decade, hazards such as floods, drought and conflict have caused a number of disasters. Atyang (2014) conducted a study to map existing early warning systems in Uganda, for hazards affecting economic and social sectors, and geographic locations. This showed how Uganda is implementing a DEWS. The Uganda DEWS consists of collecting data on a monthly basis from communities, district offices, and the Department of Meteorology, analysing it at district level in collaboration with district heads of department. The DEWS produces a monthly drought bulletin, and disseminates key messages to communities and development partners.

All steps of this system are fully integrated into the structure of government. The list of indicators covers six main sectors: livestock, crops, water, nutrition, livelihood, security, and information on vulnerability of the population and risk of drought. The DEWS monitors drought and analyses its likely impact on livelihoods. On a monthly basis, data is systematically collected from sentinel sites representing the main livelihood zones in each district, using both printed forms and mobile phone technology.

The Department of Meteorology began to issue weather forecasts for each district of Karamoja on a monthly basis. This Department has improved the capacity of the DEWS to predict the risk of drought and possible impact of the weather on the population more accurately. This has been achieved after collecting historical weather data from many districts of Uganda and establishing models and correlations with sea surface temperature data.

The DEWS issues a monthly drought bulletin that describe the current situation, advises on mitigation measures to alleviate the impact of any events, and forecasts the duration of an event. The four drought risk classification levels (normal, alert, alarm, and emergency) are based on thresholds for Karamoja, and early warning messages are disseminated as monthly early warning bulletins by electronic mail to decision-makers (Atyang, 2014). The adopted system is simple and can act as a model for resource-poor countries, as it uses local precipitation and vulnerability mapping to ascertain risk and impact. The DEWS (especially the monthly analysis and issuance of DEWS bulletin) is embedded within the local government structure, thereby ensuring ownership and sustainability.

6.6.6 Portugal

There are two drought-monitoring systems in Portugal, managed by two different entities: the Drought Observatory and the National Information System for Water Resources (Acácio et al., 2013; ISA, 2013). The Drought Observatory (DO) was established in 2009 and is coordinated by the Meteorology Institute (IM). Precipitation and temperature data are collected from a national network of meteorological stations that belong to IM and from another network of stations that belong to the Water Institute (INAG). The occurrence of meteorological droughts is based on calculations of SPI and PDSI (averaged for main river basins and for mainland Portugal), and agricultural droughts based on soil water content (percent).

The National Information System for Water Resources is coordinated and managed by the Water Institute, and monitors water resources through a national network of stations, which includes the following types of stations:

- Meteorological network: stations that only register precipitation, and stations that register precipitation, temperature, humidity, wind speed, among other;

- Hydrometric network: stations that register streamflow, river and reservoir water levels, and reservoir volumes;
- Superficial water quality network: stations that register physical, chemical, and biological water properties;
- Groundwater network: stations that register groundwater quantity and groundwater quality.

A subsystem for drought monitoring and early warning was developed by INAG/APA within the National Information System for Water Resources. Meteorological and hydrological droughts are monitored, based on precipitation, streamflow, reservoir storage, groundwater storage, and water quality, then analysed. The type of data collected (input data for drought monitoring) are presented in Table 22. Drought and its severity are evaluated four times along the hydrological year, namely:

- end of January, to evaluate autumn precipitation (intermediary analysis);
- end of March, to evaluate wet semester precipitation (intermediary analysis);
- May, to confirm drought severity of the current year;
- end of September, to calculate a statistical analysis of precipitation occurrence for the past hydrological year.

Table 22. Data Collection for Drought Monitoring in Portugal

Data category	Authority in charge	Frequency of data collection	Means for data exchange
Precipitation, temperature (monthly data for drought monitoring)	IM (SPI and PDSI calculations)	Monthly, daily and hourly data	Website Monthly reports
• Precipitation Streamflow • Water storage in reservoirs • Groundwater storage • Water quality parameters • (monthly data for drought monitoring)			

Source: Acácio *et al., 2013*

The DO and IM provides information, including maps and figures on:

- historic evolution (1942–2010) of SPI 3, SPI 6, SPI 9, and SPI 12, for mainland Portugal, Douro, Tejo, and Guadiana river basins (the three largest river basins);

- monitoring of SPI 3, SPI 6, SPI 9, and SPI 12, for the current hydrological year for main river basins for mainland Portugal;
- forecasting of PDSI for the following month based on 3 scenarios for the occurrence of precipitation; and
- soil water content (percent) for the last month of the current hydrological year for mainland Portugal.

Drought declaration

There is no officially approved drought declaration process in Portugal. According to Acácio et al. (2013), the process adopted in the two last drought events (2005 and 2012) is as follows:

– <u>Before the Drought:</u>

- Before a drought period is detected and declared, both the IM and the Water Institute monitor the climate variables used for drought indices as described before. The National Commission for Reservoir Management follows the situation through periodical meetings and regional sub-commissions.

- When a meteorological drought is detected by IM, this entity informs the Commission for Reservoir Management that analyses the situation, and if it is decided that a drought is present, the Commission proposes that the Government declares a state of drought. Then a drought monitoring and impact-mitigating programme is drawn up.

– <u>During the Drought</u>

- After governmental approval, an institutional solution for managing the drought is established and organised. The organisational solution comprises two action levels: the drought commission that addresses political and strategic issues, and the technical secretariat, dealing with technical and operational issues. The operation of the organisational model focuses on the permanent availability of information to all authorities, economic agents, and the general public, using information and communication technology.

- The drought evolution is evaluated in real-time, using the quantification of water availability in rivers, reservoirs, and groundwater, and the water requested by different users, with different levels of priority and restrictions.

- The secretariat establishes intense contacts with the main users to evaluate the technical and economic measures to mitigate the drought impacts.

– <u>After the Drought</u>

- When the results of drought monitoring show a normal situation (based on precipitation and reservoir storage levels), the Commission for Reservoir Management proposes the end of the drought. After governmental approval, climate monitoring in normal situations begins as described before.

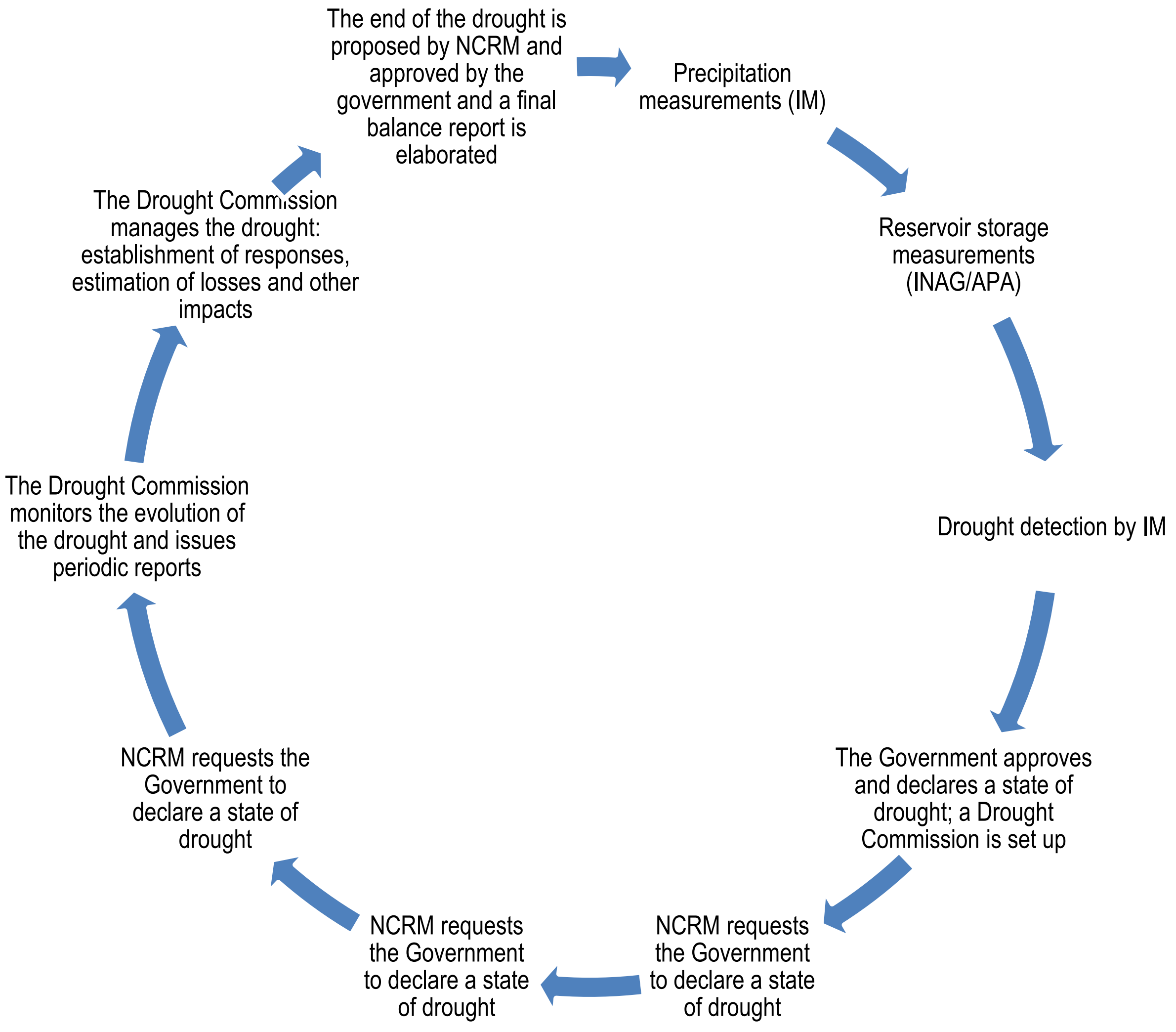

Figure 51. Flow chart of the drought declaration process in Portugal: *Source: Acácio et al., 2013*

The flow chart (Figure 51) summarises the process of drought declaration with roles and responsibilities for each stakeholder clearly defined. The challenge of this process is that it is reactive rather than proactive. However the outputs are reliable and of good quality, and have been efficiently used to monitor the major drought events (Acácio et al., 2013; ISA, 2013).

6.6.7 Summary of Country Drought Early Warning Systems

There were some differences as well as common elements in the different country drought monitoring and early warning networks. The key elements that can be adopted for Eswatini are summarised in four sub topics below:

1. **drought monitoring and prediction:**

    - Drought monitoring using drought indices and remote sensing,
    - Use of drought indices is complemented with food security, agriculture and vulnerability assessments,

2. **drought communication and dissemination:**

    - Decentralised drought declarations. Declarations can be made at national level or sub national level,
    - Differences in time and the timeliness of declaration from state to state,
    - For a system to work ,there is a need of an effective information management system,
    - Use of various media for communication,
    - There is a need to develop policies to support the functioning of the system,
    - There is a need for releasing monthly or quarterly agro-met bulletins,

3. **response capability/ coordination**

    - There should be a strong network of stakeholders and organisations dealing with drought monitoring and mitigation. This involves different ministries, research and private sector,
    - There is a need for response plans in place for effective drought response,

4. **system challenges**

- Most monitoring is implemented when the droughts impacts are being felt

6.7 REVIEW OF REGIONAL DROUGHT MONITORING AND EARLY WARNING NETWORKS

In this section, descriptions of active regional networks are summarised for Europe, Africa, and Latin America. Each section focuses on the network's organisational structure, mission and goals, while providing a comprehensive overview of the network's main efforts, difficulties, and successes in assessing and monitoring drought at the regional level.

6.7.1 Africa

In Africa, regional and national institutions have involved with drought monitoring, assessment, and forecasting. The most representative regional institutions are detailed below:

6.7.1.1 The Sahara and Sahel Observatory (OSS)

The OSS is an international institute based in Tunisia, with a mandate to stop desertification and to mitigate drought by providing a forum to share experiences and unify data collection approaches, and to process data to feed into decision-support tools (OSS, 2018).

6.7.1.2 IGAD Climate Prediction and Applications Centre (ICPAC)

The Centre consists of a network of national meteorological and hydrological services from Djibouti, Eritrea, Ethiopia, Kenya, Somalia, Sudan, South Sudan, Uganda, Burundi, Rwanda, and Tanzania. The network develops early warning products and organises forums, linking them with information users (ICPAC, 2018).

6.7.1.3 USAID Famine Early Warning Systems Network (FEWS NET)

The Famine Early Warning Systems Network makes available regular and timely early warning and vulnerability information on evolving food security issues. Further, FEWS NET monitors and analyses relevant data and information in terms of the impact on livelihoods and markets, to identify potential threats to food security (FEWS NET, 2018).

6.7.1.4 SADC Southern Africa Regional Climate Outlook Forum (SARCOF)

This is a seasonal weather outlook prediction and application process for SADC that facilitates information exchange among forecasters, decision-makers, and climate information users. Its main objective is to promote technical and scientific capacity-building in the region by producing, disseminating, and applying climate forecast information in weather sensitive sectors of the region's economic activities (SADC, 2018; WMO/GWP, 2018a).

6.7.1.5 SADC Climate Services Centre (CSC)

The Centre monitors near-real-time climatic trends and produces 10-14 days and 3-6 months climate outlook products (SADC, 2018).

6.7.2 Europe

There are various institutions and networks in Europe that are responsible for drought monitoring, which are summarised below:

6.7.2.1 European Drought Observatory (EDO)

The EDO is a continuous monitoring and forecasting tool, providing up-to-date information on the availability of water resources throughout Europe. The EDO manages a series of indicators of drought that assess and quantify the occurrence, duration, and severity of drought events (EDO, 2018).

6.7.2.2 Drought Management Centre for South-Eastern Europe (DMCSEE)

An important regional network has been established for the south-eastern region of Europe through the Drought Management Centre for South-Eastern Europe, located in Ljubljana, Slovenia. The DMCSEE coordinates the development, assessment, and application of drought risk-management tools and policies in South-Eastern Europe, with the goal of improving drought preparedness and reducing drought impacts (DMCSEE, 2018).

6.7.2.3 European Drought Centre (EDC)

The European Drought Centre is a virtual network of scientists working on drought-related issues. Described as a virtual knowledge centre, its aim is to coordinate drought-related activities in Europe to mitigate the environmental, social, and economic impact of droughts more effectively (EDC, 2018).

6.7.3 Latin America

In Latin America, operational drought assessment and monitoring is undertaken by a number of active networks which are highlighted below:

6.7.3.1 CAZALAC

The Centre coordinates and articulates scientific and technological actions aimed at attaining sustainable water management in arid and semi-arid zones in Latin America and the Caribbean. This is achieved by reinforcing the region's technical, social, and educational development (CAZALAC, 2018).

6.7.3.2 CAALCA

The Centre is a platform that contributes to the water sustainable management in the Latin American and Caribbean countries. It aims to reduce the environmental impact of climate change in regional environments through research projects, technological developments, consultancy, curricular activities, and continuous education programs (CAALCA, 2018).

6.7.3.3 CIIFEN

CIIFEN aims to improve climate variability, understanding, and early warning at the regional level, to reduce its social and economic impact. The Centre promotes, complements and initiates scientific and application research projects to improve the knowledge on El Niño phenomena (CIIFEN, 2018).

6.8 GLOBAL AND NATIONAL DROUGHT MONITORING PRODUCTS

Table 23. Global and National Drought Monitoring Products

Coverage	Drought Product	Drought Indicator
Global	Flood and Drought Portal	Standardized Precipitation Index (SPI), Effective Drought Index (EDI), Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), Soil water index (SWI), Vegetation health index (VHI), Agricultural Stress Index (ASI), Combined Drought Index (CDI)
Global	FAO's Agricultural Stress Index System (ASIS)	Agricultural Stress Index (ASI)
Africa	African Flood and Drought Monitor	Standardized Precipitation Index (SPI), Normalized Difference Vegetation Index (NDVI), Drought Index, Streamflow Percentile
South Africa	National Integrated Water Information System - Drought status and management	Dam levels, Rainfall, Standardized Precipitation Index (SPI)
Turkey	Meteorological Drought Situation according to Standardized Precipitation Index Method	Standardized Precipitation Index (SPI)
UK	UK Drought Portal	Standardized Precipitation Index (SPI)
USA	United States Drought Monitor	Palmer Drought Severity Index (PDSI), CPC Soil Moisture Model (Percentiles), USGS Weekly Streamflow (Percentiles), Standardized Precipitation Index (SPI), Objective Drought Indicator Blends (Percentiles)
India	Drought Monitoring	Aridity Anomaly Index (AAI), Standardized Precipitation Index (SPI)

Source: WMO/GWP 2018

6.9 MOVING TOWARDS AN INTEGRATED DROUGHT MONITORING AND EARLY WARNING SYSTEM

To complement and support the work of national governments, especially those that cannot afford to institute an improved and sustainable drought monitoring and EWSs, regional drought monitoring networks and EWSs have been development. Regional networks sometimes consist of representatives from countries in the region and beyond, and are set up to improve the assessment, monitoring, and mitigation of drought and its impacts on human activities from regional to national levels. They facilitate sharing information, experiences, and best practice through global, regional, and national partnerships.

A proactive risk management strategy requires the use of information provided from reliable drought monitoring tools. By using this set of data, the risk of drought and its impact on food security is analysed in real time. Although the current systems for early warning and drought control relatively function, some challenges are posed to reliability of such systems. In reviewing the country and regional drought monitoring and EWSs, there are positive and negative elements that should be considered in any recommended system to be used by any country. Similarly, some of the systems have gaps that need to be addressed to improve the efficacy and efficiency of the systems.

What is critical in all the systems is that they require an integrated approach, the involvement and coordination of many stakeholders, and need efficient and reliable tools. While it ensures inclusiveness, involving several stakeholders often results in institutional barriers and lack of ownership of systems. In the various research and monitoring systems reviewed in this chapter, the following actions were identified as common action points for moving toward an integrated drought monitoring and early warning system. There is a need to:

i. Have an common understanding of the indices to be used for monitoring
ii. Determine who are the participants in the implementation, management and monitoring of the system are, and what are their clear roles and responsibilities.
iii. Have a clear and sustainable funding mechanism for the system. Funding should come mostly from national government, the private sector, and research agencies. Innovate funding solutions could also be explored.
iv. Establish effective collaboration between national and regional agents, and encourage harmonisation of policies, data collection, and sharing mechanisms. The data sharing should be vertical and horizontal.
v. Establish well-coordinated data and product-sharing between international and national agencies to support integrated drought monitoring and EWSs.
vi. Have a system that is integrated, allows triangulation of data and monitoring outputs to ensure accuracy, and is embedded within existing government structures for ownership and sustainability.

6.10 CHAPTER SUMMARY

The development of the drought information system necessitates participation and collaboration between local authorities and research institutions (Hao, 2017). The review of country case studies indicates the need for scientists and planners to improve drought-monitoring tools further in sub-Saharan Africa, at local, national, and regional levels, as there are weaknesses and gaps in all systems and approaches being used. By adopting effective planning and mitigation strategies, the risks and associated impact of drought can be significantly minimised. This can be achieved through adoption of proactive procedures, which implies a paradigm shift from crisis to risk management (Gerber and Mirzabaev, 2017; Jordaan et al., 2017a; Knutson et al., 1998; Wilhite, 2000; 2014).

An effective, proactive risk management strategy requires that the information from drought monitoring tools must be mutually analysed to provide objective and consensual information for near-real-time food security assessments. A comprehensive, integrated and risk-based approach or framework is therefore essential to monitor drought in Eswatini more effectively and provide early warning to reduce the impact of the drought natural hazard. The next chapter will develop a composite drought-monitoring framework based on the SPI and NDVI, incorporating systems and approaches that are already exist in Eswatini and in other country and regional frameworks.

By adopting a framework based on the emerging risk-based approach, Eswatini will be developing a more effective approach to drought, through the ability to formulate relevant mitigation measures and the most appropriate drought responses in a proactive and anticipatory way (Tadesse et al., 2008; Wilhite and Svoboda, 2000; WMO, 2006; WMO/GWP 2018). Risk management in drought response includes preparedness planning, mitigation, monitoring and early warning, and prediction to reduce the impacts of drought -both in current situations and into the future (Gerber and Mirzabaev, 2017). In this way, damage is effectively mitigated and drought impact is comprehensively reduced.

Drought and early warning information (resulting from integrated drought monitoring and EWSs) will be used to trigger contingency planning and emergency needs assessments to support advocacy and resource mobilisation efforts, and to support policy development and the implementation of private sector and government developmental priorities (Gerber and Mirzabaev, 2017; Hayes et al., 2004; Tadesse et al., 2008; Wilhite and Svoboda, 2000).

7 COMPREHENSIVE FRAMEWORK FOR DROUGHT MONITORING IN ESWATINI

7.1 INTRODUCTION

Eswatini is mostly affected by natural and man-made hazards such as droughts, floods, wild fires, windstorm, hailstorm, and epidemics. These cause destruction to infrastructure, environmental losses, and humanitarian consequences, and increasingly, disruption to provision of basic services and loss of life (GoS, 2012; Mohammed, 2016). Like many African countries, Eswatini has repeatedly been affected by droughts over recent decades, resulting in considerable environmental, social, and economic damage, along with worsening food security, with 2015 and 2016 being the worst years to date (Mohammed, 2016; UN, 2016).

In 2015/16, southern Africa experienced the driest agricultural season in 50 years as a result of the El Niño phenomenon (Phys.org, 2016). Eswatini was one of the countries in the region hardly hit by the drought. The exceptional lack of precipitation, compounded by the impact of poor rainfall in the previous year resulted in significant losses of rain-fed yields, underperforming irrigated crops, and leading to poor pasture conditions (IRIN, 2017; Phys.org, 2016; UN, 2016). This contributed to an increasingly vulnerable situation, with food insecurity affecting over 30% of the population, 350,000 of them requiring food assistance (WFP, 2016).

7.2 POINTERS FOR DEVELOPING A DROUGHT MONITORING SYSTEM FOR ESWATINI

A comprehensive and integrated approach is required to monitor drought more effectively and provide early warnings. The collection of climatic and hydrologic data is fragmented between many agencies or ministries in most countries, and often these data are not reported in a timely fashion (WMO, 2006). In Eswatini, precipitation data is collected by the Meteorology Department under the Ministry of Tourism and Environmental Affairs, with the National Early Warning Unit (NEWU) being under the Ministry of Agriculture. The Ministry of Agriculture works directly with the Eswatini Meteorological Service (MET), with the latter providing the early warning information (such as agro-meteorological updates) for relevant hazards. In turn, MET works directly with regional and international institutions such as South

African Weather Services and SADC Climate Service Centre (CSC) and WMO. Challenges do however exist.

7.2.1 Institutional Mechanisms for Drought Monitoring in Eswatini.

The main stakeholders involved in the monitoring and management of drought in Eswatini include the following:

- the Deputy Prime Minister's office,
- the Ministry of Agriculture,
- the Ministry of Tourism and Environmental Affairs,
- the Ministry of Tinkhundla Administration,
- the Ministry of Economic Planning and Development,
- the Ministry of Finance, and
- the Ministry of Natural Resources and Energy.

Within each ministry there are various departments mandated to coordinate drought planning and response. The following subsections will discuss the roles of each line ministry. The main coordinating body is the NDMA, which was established in 2008 under the Disaster Management Act of 2006 within the Deputy Prime Minister's office. It was given the mandate of coordinating a coherent disaster risk management system in the country to safeguard the attainment of the National Development Strategy, the Vision 2022 (GoS, 2006; NDMA, 2016). For the coordination of humanitarian actions, the Government of Eswatini, through the NDMA, has the primary role of initiation, coordination, and implementation of humanitarian assistance in the country (NDMA, 2016).

The NDMA, in collaboration with the humanitarian community in the country, has adopted a multi-sectoral approach as the coordination structure for all emergencies, whilst the framework is articulated in the National Multi-Hazards Contingency Plan. For effective coordination of the drought response, an inter-sectoral coordination platform to facilitate bi-weekly inter-cluster coordination meetings was put in place, chaired by the NDMA and co-chaired by the UN. In response to the El Niño-induced drought, a state of emergency was declared in February 2016 and the government launched the National Emergency Response

Mitigation and Adaptation Plan (NERMAP), requesting financial and technical support to implement it (WFP, 2016).

The NDMA with support from the United Nations and non-governmental organisations coordinated the production of the National Multi Hazard Contingency Plan (MHCP) for the period 2008 to 2015 (GoS, 2012). The MHCP provides an outline for implementing preparedness response and mitigation measures. The MHCP articulates the coordinated actions that the Government of Eswatini will take to prevent or reduce any potential adverse impacts emanating from natural and man-made hazards, as well as guidance on how to respond to these risks or disasters (GoS, 2012). The MCHP is a document that is reviewed regularly, with the aim of updating it, taking into account new risks and other emerging dynamics and issues that may impact disaster prevention, preparedness, and early recovery or response efforts (GoS, 2012; NDMA, 2016).

7.2.2 Challenges in Drought Monitoring in Eswatini

Drought management strategies in southern Africa have relied on more reactive, crisis management or short-term response approaches in providing post-drought relief (Gerber and Mirzabaev, 2017; Hassan, 2013). The importance of adopting a more proactive approach to managing drought as an integral part of regular climate variability, agricultural production, planning, and management, and decision-making has been recognised (Buurman et al., 2017; Hassan, 2013; Wilhite et al., 2014). In 2005, the Government of Eswatini, together with UNDP, conducted a national disaster risk reduction capacity needs assessment, which identified resource constraints and capacity gaps in the following areas:

- institutional and legal systems for disaster risk reduction;
- risk identification;
- information and knowledge management;
- emergency response and preparedness; and
- risk management.

This led to:

- the enactment of legal and institutional frameworks for disaster risk reduction, including the National Disaster Management Policy initiated in 2008 and the National Action Plan for Disaster Risk Reduction covering the period 2008-2015;
- the establishment of disaster risk reduction focal points in ministries;
- the institutionalisation of the Eswatini SVAC and its integration into the new NDMA structure;
- the development of disaster risk reduction information, education, and communication materials, in collaboration with education stakeholders;
- media advocacy for disaster risk reduction with media personnel;
- training on emergency response and preparedness for ministries and communities??;
- implementation of a drought early recovery needs assessment and publishing of the report;
- development of a drought early recovery strategic framework;
- formulation of a national contingency plans;
- training in the following disaster risk reduction areas:
    - understanding the concept;
    - early recovery including development of drought early recovery strategic plan;
    - application of disaster risk reduction tools for mainstreaming into development programmes, plans, and policies; and
    - contingency planning.

Despite the presence of these policies and structures, there has been a significant limitation in their operationalisation. Eswatini has an *ad hoc* disaster and emergency response which is reactive rather than proactive, and this can be explained by the absence of drought risk data and preparedness plans towards the drought risk. Despite the existence of disaster risk reduction policies, there is explicit information relating to drought disaster risk assessment. In many cases, in the event of a drought disaster, a fund is requested and put in place to respond to the disaster and provide emergency responses. However, in many cases it is delayed or not readily available.

The lack of drought hazard data hinders the consideration of the drought for planning and implementation of projects that respond to droughts. Although there are many NGOs that are working on climate change and drought mitigation programmes, this is done *ad hoc*, without a drought risk assessment, or consideration of who are the most vulnerable to drought and to what extent. Although the annual vulnerability assessment is carried out by the Eswatini Vulnerability Assessment Committee, the main focus has been vulnerability only. It does not consider the risk of drought, but instead looks at the risk to food security, nutrition, water, and sanitation in general.

Looking at the key challenges of the current monitoring and preparedness mechanisms mentioned during interviews with stakeholders from different government ministries, research institutions and Tinkhundla administration, it clearly appeared that there were coordination challenges among drought monitoring agencies. Stakeholders felt that capabilities of Eswatini to monitor drought was good, with 42% (Figure 52) of the stakeholders indicating that is was good and 20% indicating that it was very good. It is interesting to note that 36% felt that the capabilities were limited indicating that the gaps need to be addressed.

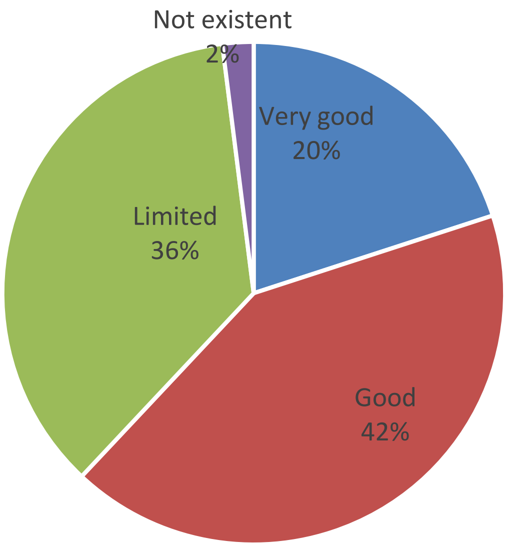

Figure 52. Assessment of Current Drought Monitoring Capabilities based on interviews

Despite the existence of the NDMA who is coordinating response mechanisms and the Ministry of Agriculture coordinating the drought monitoring with other agencies, the respondents felt that the coordination structure needs be further improved. Stakeholders also highlighted the need for increased resources (Figure 53) and improved tools for drought monitoring.

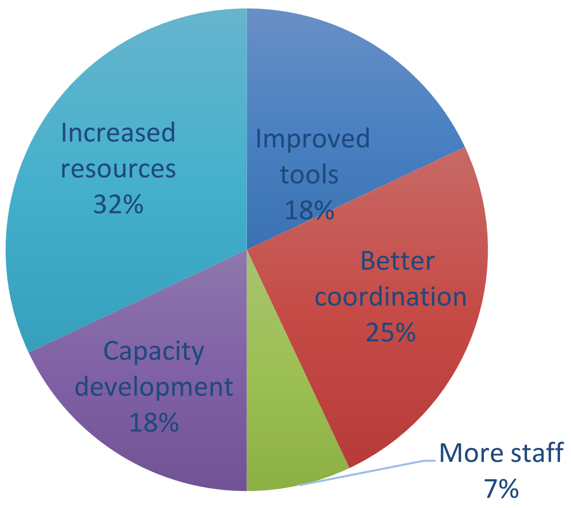

Figure 53. Improving Drought Monitoring System in Eswatini

Survey results showed that during a drought event, the different government structures are activated under the leadership of the Ministry of Agriculture. The Ministry collects field level data mostly with the support of FAO. The Meteorology Department provides rainfall information and weather forecasts received from SARCOF. The field level data collected by the Agriculture ministry only happens when the drought impact is felt (Figure 54).

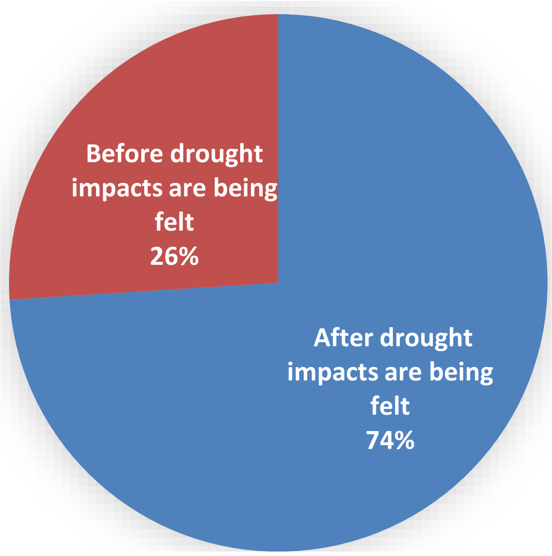

Figure 54. Perception of Stakeholders on the Timeliness of Drought Declarations

Though the information is useful for planning and response, the majority of the respondents believe that the assessments are late to enable effective preparedness mechanisms. They also highlighted that the level of stakeholder participation was not adequate in terms of number of agencies and timeliness of the participation. The range of potential stakeholders in Eswatini is large and their active participation should contribute to the sustainability of drought monitoring and early warning system at different levels, national, sub national and community level. From these factors, it was shown that the current system in not perfect and needs to be reviewed for improvement.

Eswatini is constrained in terms of resources to establish drought preparedness mechanisms. Much of the focus is placed on emergency relief and recovery programming, more than the actual risk assessments and preparedness programs. Various stakeholders are providing funding to strengthen capacity for coordination during drought emergencies, as well as relief efforts. However, little is known of the drought risk, and this somehow leads to poor resource prioritisation and allocation, as well as poor targeting of drought mitigation and relief programming.

7.2.2.1 National Emergency Response, Mitigation and Adaptation Plan 2016-2022

The National Emergency Response, Mitigation and Adaptation Plan (NERMAP) 2016-2022 is the Government's response to the drought situation. The plan has been developed in collaboration with different stakeholders from diverse backgrounds. The plan also sets a foundation for adaptation to drought (NDMA, 2016). Key stakeholders responsible for the development, implementation, and monitoring of the plan include the Deputy Prime Minister's Office who coordinate the responses, the Ministry of Agriculture, the Ministry of Natural Resources and Energy, the Ministry of Tinkhundla, the Ministry of Housing and Urban Development, the Ministry of Health, and the Ministry of Education. The United Nations agencies participate through the World Food Program (WFP), the United Nation's Children Fund (UNICEF), the United Nations Development Program (UNDP), the World Health Organization (WHO), and the Food and Agriculture Organization (FAO) (NDMA, 2015; 2016)

The NERMAP focuses on food and water security through intensified local maize production and rehabilitation, and expansion of water systems to increase access to potable water. It also aimed at better incorporation of adaptation measures to tackle the situation more effectively, both presently and in the future (NDMA, 2016). Within the NERMAP, there is the National Drought Mitigation and Adaptation Plan, which details the total budget and planned activities for eight sectors, namely: Agriculture and Food Security; Education; Water and Sanitation; Health and Nutrition; Social Protection; Environment and Energy; Storm damages; and Coordination (NDMA, 2016). However, the challenge of the NERMAP is that most of the planned actions or responses are reactionary; nothing in the plan focuses on a proactive approach to drought management.

Considering all the mentioned challenges, there is a need to build upon the existing system or processes and develop a drought monitoring and EWS that is the foundation of effective, proactive drought management, together with effective policy development (WMO/GWP, 2018b). The system should identify climate and water supply trends and detect the emergence, probability of occurrence, and likely severity of drought and its impact. At the same time, it should allow timely communication of early warning information to farmers, water and land managers, policy makers, and the public through appropriate communication channels. That information, if used effectively, can be the basis for reducing vulnerability and improving mitigation and response capacities for people and systems at risk (WMO/GWP., 2018).

7.3 DEVELOPING A COMPREHENSIVE FRAMEWORK FOR DROUGHT MONITORING AND EARLY WARNING IN ESWATINI

To establish a comprehensive framework for drought monitoring, early warning and risk reduction in Eswatini, it is imperative to define the key elements, objectives, and key stakeholders to be involved in the implementation, monitoring, and funding of the system. When these elements are fully considered and adopted, the system will be able to provide information that can trigger actions and identify drought-vulnerable areas and communities. The tools to be used in the process would be the ones already used in the country, or the country should be able to develop capacity to utilise the tools in a sustainable way. Additionally, these tools should be used to determine the spatial and temporal extent of drought, thereby providing information about which geographical areas might be affected. This will provide information to trigger contingency planning and emergency needs assessments, which will be used to triangulate the data collected by use of the indicators.

To provide appropriate assistance for drought mitigation, the first step would be to develop a better understanding of the spatial and temporal dimensions of the most-at-risk populations. The adoption of SPI and NDVI will provide information on the spatial and temporal dimensions of drought, thereby indicating who will be at risk and when. This will rely on data collected in relation to seasonal data and the agricultural calendar. The type of data and its analysis should integrate long-term rainfall data, agricultural statistics, market data, and socio-economic information. Eswatini is already collecting precipitation data, and limited remote sensing data. Moreover, it has the capacity to enhance its remote sensing capacity, which is essential for any drought monitoring and early warning system. Based on the experiences from other countries and regional networks, the following are key requirements for an effective drought monitoring and EWS.

7.3.1 Key Stakeholders

A comprehensive and integrated approach is fundamental to monitor drought in Eswatini and southern Africa as a whole. This will enable the enhanced provision of timely early warning information, thereby enabling the mitigation of natural hazards affecting the region and the related impact of food security and the economy. For drought monitoring in Eswatini to be effective, it has to involve a variety of key stakeholders from different ministries, UN agencies, communities, and non-state actors. The key stakeholders should include the following:

LINE MINISTRIES

7.3.1.1 The Deputy Prime Minister's Office

The Deputy Prime Minister’s office exists to establish and oversee the national policy and institutional environment to support effective delivery of government services. This is achieved through a well-coordinated system with a special emphasis on a proactive disaster preparedness within the development discourse. Since already discussed earlier in this document, details of the role of the Deputy Prime Minister’s office and the NDMA are not discussed in this section.

7.3.1.2 Ministry of Agriculture

This Ministry has the responsibility of ensuring household food security and increased sustainable agricultural productivity. It is also responsible for the development and promotion of appropriate technologies and efficient extension services, while ensuring stakeholder participation, sustainable development, and the management of natural resources in the country. The key parastatal organisations that are relevant to drought monitoring and EWSs include the National Agricultural Marketing Board (NAMBoard), the National Maize Corporation (NMC), and Eswatini Water and Agricultural Development Enterprise (SWADE). Through its officers and parastatals, the ministry would provide the following services and information:

- crop assessment;
- water assessments (SWADE);
- maize stocks (NMC); and
- vegetable production and food prices (NAMBoard).

- ***The National Early Warning Unit (NEWU)***

The NEWU is controlled by the Ministry of Agriculture: Economic Planning and Analysis Division. The unit is responsible for the following:

- conducting food supply assessment in conjunction with other stakeholders;
- providing advice on food supply policies;
- gathering, analysing, and disseminating information on food security issues;
- providing early warning information on the expected weather conditions and crop production, in liaison with the Eswatini Meteorological Service;
- liaising with regional and international bodies on issues related to food security that have a bearing on the local food security context.

7.3.1.3 Ministry of Tourism and Environmental Affairs.

Amongst the many key ministries, this ministry serves a vital role, as it collects and disseminates key data and information on climatic hazards, through the Meteorology Department. Services provided include specialised weather forecasts to various stakeholders, such as game parks, forest companies, railway company, towns and cities, aviation entities, television, radio, and newspapers. The service is currently free and is rendered through email, fax, and the government website: www.swazimet.gov.sz. The Meteorology Department also provides agro-meteorological bulletins. These bulletins depict current weather situations in relation to crops and are disseminated through the internet. Seasonal forecasts prepared by the department are issued through the Ministry of Agriculture.

- ***Meteorological Department***

The Meteorological Department provides the weather forecast, which is then interpreted and formulated into messages to inform the farming community on what the forecast means for agriculture. The Vulnerability Assessment Committee - composed of officers from the Eswatini Meteorological Service, the NDMA, the Ministry of Agriculture, the Deputy Prime Minister's office, and the Central Statistics Office - conducts assessments to inform interventions by various stakeholders to minimise impact and build resilience. The Eswatini Meteorological Service liaises with the SADC on the forecast, while the NDMA is the custodian of the disaster policy and are fully aware of and monitor the triggers for disasters such as drought. The Early Warning Unit based in the Ministry of Agriculture collaborates with the Eswatini Meteorological Service and interprets data to produce messages for the farming community.

7.3.1.4 Ministry of Tinkhundla Administration

The Ministry of Tinkhundla Administration and Development has a mandate to facilitate the management of regional development and to facilitate and promote service delivery at Tinkhundla and Chiefdoms (ward) levels. The Tinkhundla are the local government institutions and are considered the third level of governance. A major focus is the development, implementation, monitoring, and evaluation of evidence-based, integrated development plans funded by development grants and central government budget (where applicable). One key service of this Ministry is the overall administration and co-ordination of social and economic development of the regions, and to enhance community initiatives, by promoting socio-economic development through community participation, mobilisation, empowerment, and skills development at grassroots level for sustainable development. The role of the Ministry in early warning and drought monitoring is to promote community-based EWSs and to ensure the effective participation of community structures. Any government activities will also have to go through this ministry, thereby making it a key conduit between government and the people.

7.3.1.5 Ministry of Natural Resources and Energy (MNRE)

The Ministry of Natural Resources and Energy (MNRE) objectives are to provide and manage resources to ensure the optimal land use, mineral exploration, and adequate water and energy to meet national aspirations. Services relevant to drought monitoring and EWSs that are provided by the ministry include:

- Surveying
- Mapping
- Regulation of water sector
- Water resources planning and development
- Provision of potable water to all areas in the country
- Provision of consultation services and expert advice to interested parties.

7.3.1.6 Ministry of Finance

The mission of the Ministry of Finance is to promote macroeconomic stability in Eswatini by formulating and implementing fiscal and financial policies that optimise economic growth and improve the welfare of its citizens. This ministry will be essential in providing regular and consistent funding through cabinet approval for the management of an early warning and drought monitoring system.

7.3.1.7 Ministry of Information Communication and Technology

The Ministry of Information, Communications and Technology provides a coordinated ICT delivery framework for the country. Information on climatic hazards is shared through many channels such as radio, television, publications and other media technology formats. This makes this Ministry key in information management and dissemination. The Ministry is charged with the responsibility of overseeing the following parastatals: Eswatini Posts and Telecommunications, the Eswatini Television Authority, the Royal Science and Technology Park Project and the National Research Council. These parastatals are key in research and development, thereby making them relevant in the development and management of early warning and drought monitoring system.

7.3.1.8 Ministry of Economic Planning and Development

The mandate of the Ministry is to assist Government in the formulation, co-ordination, and implementation of economic policies and intervention measures that will effectively and efficiently accomplish the country's major economic and development objectives. Some of the key services of the Ministry include:

- mobilisation and management of external assistance for the implementation of various programmes and projects within and outside government;
- effectively coordinating the national statistical system, collecting, analysing, and providing quality statistical information required for evidence-based policy, planning, and decision making;
- capacity-building and empowerment of beneficiary communities through the process of training and direct disbursement of funds for the establishment of self- help infrastructure projects;
- Responsibility for the monitoring and evaluation of all development programmes in the country, with the purpose of ensuring that the capital programme delivers the desired effects and has the net positive impact on the intended beneficiaries.

United Nation Agencies

7.3.1.9 Food and Agriculture Organization

The Food and Agriculture Organization supports Eswatini in areas including institutional strengthening and efficiency, sustainable agricultural productivity, market access and competitiveness, boosting domestic production and increasing market access for medium- and small-scale producers. It also provides assistance in sustainable management of natural resources, strengthening adaptation to climate change while promoting the conservation of plant and animal biodiversity, and the mitigation of food insecurity by improving livelihoods and reducing vulnerability. They support the government, through the SVAC, in conducting crop assessments.

FAO has experience in drought monitoring, especially through crop monitoring and early warning. This has occurred particularly through the Global Information and Early Warning System (GIEWS). The GIEWS supports countries in gathering evidence for policy decisions, planning by development partners through its Crop and Food Security Assessment Missions (CFSAMs), fielded jointly with the World Food Programme (WFP). The GIEWS utilises remote sensing data that can provide a valuable insight on water availability and vegetation health during cropping seasons. In addition to rainfall estimates and the NDVI, GIEWS and the Agricultural Stress Index (ASI) provide a quick-look indicator for early identification of agricultural areas probably affected by dry spells, or drought in extreme cases. In terms of a country-level application of tools for earth observation and price monitoring, GIEWS also strengthens national capacities in managing food security-related information.

7.3.1.10 The World Food Programme

WFP and the Government are in the planning stages for a 'zero hunger strategic review' in Eswatini, to develop a roadmap to achieve Sustainable Development Goal (SDG) 2: 'end hunger, achieve food security and improved nutrition, and promote sustainable agriculture'. (UN General Assembly, 2015:14).

Globally, WFP works to prevent, mitigate, and prepare for disasters, an essential part of its mandate to combat global hunger. Many of WFP's programmes address the risks of natural disasters and their repercussions on food security. WFP's policy on disaster risk reduction presents a commitment to preventing acute hunger and investing in disaster preparedness and mitigation measures, which are critical elements in disaster management (within which drought monitoring and early warning fall). WFP works with governments to strengthen their capacity to prepare for, assess, and respond to hunger caused by disasters, and to develop national policies and plans that address the impact of disasters on nutrition.

Like FAO, WFP is also a member of the SVAC. One key role of WFP in the EWS is preparedness and response. In situations where the government has requested support or declared drought disasters, WFP has provided emergency food and cash-based assistance to drought-affected people. The assistance is normally short-term, to coincide with the next harvest, thereby covering the food gap in the lean period. WFP has also provided technical assistance to the NDMA to enhance early warning and to support national disaster preparedness and mitigation measures, linking with existing WFP development projects in the country.

7.3.1.11 United Nations Development Programme

UNDP has implemented projects with the objective of reducing the vulnerability of smallholder farmers in targeted drought-prone or impacted communities. To this end, UNDP Eswatini has been implementing projects seeking to strengthen national and institutional capacities for disaster risk management at national, regional, and community level. The core objectives have been to conduct national risk assessment, to build an EWS and monitor disaster risks, and to improve emergency preparedness and response capacities, thus ensuring security for the population and sustainable development for the country. Much effort has been made in the fields of drought response, preparedness, adaptation, and mitigation through initiatives implemented with the NDMA.

Two key aspects of an integrated early warning and drought monitoring system are funding and coordination. It is therefore paramount that multi-sectoral stakeholders' coordination mechanisms be first in place as a preliminary condition, to ensure the successful implementation of all the following mainstreaming steps. The UNDP has contributed to strengthening multi-sectoral coordination mechanisms for the implementation of the National Emergency Drought Response in Eswatini and El Nino Drought Coordination.

7.3.1.12 Donors/ Other Stakeholders

Considering that country and regional drought monitoring and EWSs provide operational, regional services for monitoring and predicting extremes in climate condition, it is essential that these systems are well funded and that there is effective coordination between the systems, stakeholders, and funding agencies

Other key stakeholders include non-government organisations (NGOs) and civil society organisations (CSOs). The Eswatini Government and Tinkhundla administration need to involve NGOs in organising drought monitoring, EWSs and drought relief. The majority of NGOs and CSOs in Eswatini have a better community outreach, which could be utilised for setting up community-based EWSs and in times of disaster for organising distribution of relief assistance and implementing mitigation programmes. NGOs and CSOs - through the Coordinating Assembly of Non-Governmental Organisations (CANGO) - have set up coordination forums for NGOs and CSOs. The coordination forum meetings are normally convened to discuss the drought situation and the implementation of relief programmes.

7.3.1.13 Community Stakeholders

The Tinkhundla are the foundation of the bottom-up, development planning process and the delivery of local services in partnership with central government. They also provide a platform through which traditional leadership participates meaningfully in the administration and development of local areas. The traditional leadership includes the Tinkhundla Council (Bucopho), which comprises Indvuna Yenkhundla (Chairman), Bucopho (chiefdom councillor), members of parliament, the Tinkhundla executive secretary and the Chief. They are essential in the management of community-based drought monitoring and EWSs and also in managing the response in times of disasters. They are essential because they have the advantage of local presence, community outreach, and community control.

The most successful drought risk-management practices incorporate community involvement and a community basis for action. Incorporating indigenous knowledge throughout all aspects of drought risk management and community-based decisions is significant, because of the need to encourage community organisations, such as farmer's groups and water resource associations, to lead and participate in sustainable development and local natural resource management practices (Knutson et al., 1998, Liang, 2017; Muyambo et al., 2017; Pulwarty and Sivakumar, 2014; Victoria, 2002).

7.3.2 Concepts of Mainstreaming

Mainstreaming of drought monitoring and early warning helps to define drought, not simply as a natural phenomenon but as a more complex developmental issue. It internalises drought risks throughout the planning, funding, and implementation stages of any development framework. The mainstreaming process also serves to ensure that sectoral policies do not counter their intended purposes of drought mitigation and preparedness-related efforts, and that enabling environments are created to reinforce the adaptive capacity of communities and societies in a sustainable fashion (UNDP, 2011b). Methodological mainstreaming involves the integration of different approaches and concepts representing key actors, based on varying degrees of intensity and covering different points in time. In this context, mainstreaming calls for a critical assessment of institutional mandates on the one hand, and their relationship with other institutions and structures, such as line ministries, local government structures, communities, private sector, NGOs, and CBOs, on the other (UNDP, 2011b). Building on the basic understanding of mainstreaming, UNDP (2011b) proposes a generic, five-step process in order to mainstream drought monitoring and early warning, as follows:

i. Setting up a stakeholders' coordination mechanism. A robust and broad-based institutional setting must be established as a preliminary step to spearhead any drought monitoring system.
ii. It is important to collect data about hazards and assess the vulnerability and resilience of a given community or system.
iii. Based on the defined drought risk profile, a series of risk management options and adaptive measures will then be identified to help enhance local coping capacities.
iv. Drought monitoring and early warning is internalised into the country's development framework.
v. Monitoring and evaluation of the mainstreaming process, either from the perspective of measuring policy change or from the perspective of measuring changes in adaptive capacity.

7.3.3 Institutional Framework for Drought Monitoring

Drought monitoring and management always provide a measure of the responsiveness and resourcefulness of governments at different levels (Kumar et al., 2009). It requires a strong, institutional structure to monitor and provide a timely response to drought (Wilhite, 2014). While it is primarily the responsibility of the Government to monitor and manage drought, the Government also plays an important role in monitoring drought and providing financial assistance to the districts.

Most of the southern African districts have established disaster management agencies, civil defence units, drought management units, or task forces (Africa Disaster Risk Management Team, 2010; Dube, 2015; van Niekerk et al., 2018). These units or task forces comprise various ministries, private sector organisations, and international and national NGO communities, who coordinate efforts to deal with drought crises and their impacts. National contingency plans and drought emergency programmes have been established to monitor (through an inter-governmental national committee) and alleviate drought impacts on people, crops, and livestock.

In a situation of severe drought, the Eswatini Government normally constitutes a Cabinet sub-committee or a group of ministers to take prompt policy decisions to deal with drought. The current committee, the Ministerial Disaster Management Team (DMT) within the cabinet under the Prime Minister, is tasked to ensure a sound policy and institutional framework is in place for sustainable disaster management to assist the country to reduce disaster risk through the creation of a resilient society. The team is comprised of the following line ministries and departments:

i. Foreign Affairs;
ii. Local Government;
iii. Natural Resources and Energy;
iv. Tourism, Environment and Communication;
v. Economic Planning and Development;
vi. Health and Social Welfare;
vii. Public Works and Transport;
viii. Agriculture and Cooperatives;
ix. Finance; and
x. Disaster Management Department.

The main functions of the DMT include the following:

a. Advising and making recommendations to the Cabinet on policy and coordination issues relating to disaster management;
b. Advising cabinet on the oversight of disaster management at all levels;
c. Advising the Prime Minister on emergency declarations and emergency assistance management;
d. Making recommendations to the Prime Minister regarding compliance with international obligations and regional cooperation in disaster management.

Building on the existing structure, where overall coordination of disaster-related activities is managed by the NDMA, this study recommends that the NDMA, the NEWU and the Meteorology Department form the core of the coordination mechanism. They will hold the overall responsibility as a government arm to ensure an effective coordination amongst the stakeholders that are involved in monitoring, managing, and responding to drought and drought disaster. Figure 55 presents the institutional framework for drought monitoring and management proposed for the government of Eswatini, together with the levels of responsibilities of the various stakeholders. The functioning of the system requires mainstreaming of drought monitoring and EWSs in the normal mandates of the line ministries.

In the proposed institutional arrangement, at the central level, the Ministry of Agriculture is the department responsible for drought monitoring and management with the support of the Ministry of Tourism and Environmental Affairs, and the Department of Meteorology. In terms of relief and response, through the coordination of the Deputy Prime Ministers’ Office and the NDMA, the Ministry of Economic Planning and Development, and agencies such as WFP, FAO, UNDP, NGOs and CSOs are responsible for relief measures. The framework is divided into steps, which are critical for drought monitoring and early warning. These are:

i. Drought monitoring and early warning,
ii. Drought proofing/drought relief/response coordination,
iii. Drought relief funding,
iv. Drought information dissemination.

This institutional framework has been developed in such a way to feed into the proposed drought-monitoring framework developed by the study. This will allow effective coordination at different levels of both the institutional framework and drought and early warning framework. Therefore, it will help all stakeholders to understand their roles at each stage in the monitoring and response continuum.

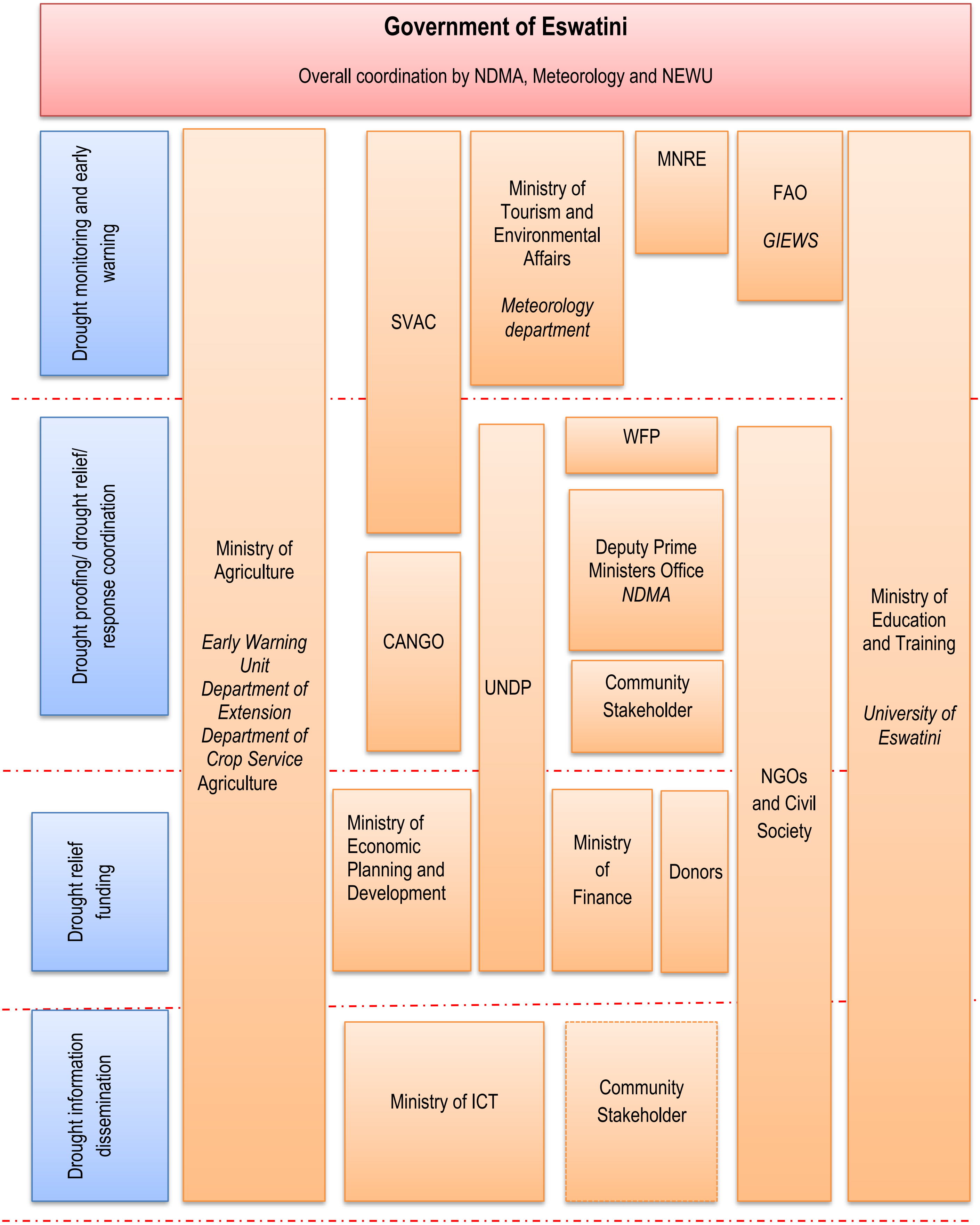

Figure 55. Institutional Framework for Drought Monitoring and Management

7.3.4 Proposed Drought Monitoring and Early Warning Framework for Eswatini

A drought monitoring and EWS is the foundation of effective proactive drought policies. (WMO/GWP, 2018a). An effective monitoring, early warning, and delivery system continuously tracks key drought indicators and climate-based indices and delivers this information to decision-makers. This allows for the early detection of drought conditions and timely triggering of mitigation and emergency response measures, the main ingredients of a drought preparedness plan.

Using 'design theory' (Gregor, 2007) as a problem-solving process, the study allowed the logical combination of drought indices, modelling, and various assessments to formulate a drought monitoring and early warning framework for Eswatini. The study adopted design science research (Hevner, 2007), by identifying the challenges of drought monitoring and early warning affecting Eswatini, the opportunities and resources available, and by formulating a framework that can address those challenges.

The development of the framework adopted six guidelines for conducting design science research, 'identification, modelling, tracking, prediction, comparison and communication with stakeholders' (Berhan et al., 2011; von Alan et al., 2004). The framework encompasses these six steps by incorporating the use of data from satellite imagery, meteorological data, stakeholder coordination, and effective and timely communication. Therefore, in this study, the framework denotes the abstract representation of the design-science research process and its communication to decision-makers.

A variety of concepts have been applied to drought monitoring and management frameworks. The study proposes the main elements of a drought monitoring and early warning framework in line with the priorities of the Sendai Framework (UN, 2015), namely,

i. understanding disaster risk;
ii. strengthening disaster risk governance to manage disaster risk;
iii. investing in disaster reduction for resilience; and
iv. enhancing disaster preparedness for effective response, to 'Build Back Better' in recovery, rehabilitation, and reconstruction.

This study proposes that the final development and adoption of the drought monitoring framework and its mainstreaming into national development frameworks be done in a participatory process, involving a variety of key stakeholders, such as national and local governments, community-based and civil society organisations, the research and scientific community, the development partners, the private sector, and the media. The main government stakeholders include the Ministries of Foreign Affairs; Local Government; Natural Resources and Energy; Tourism, Environment and Communication; Economic Planning and Development; Tinkhundla; Health and Social Welfare; Public Works and Transport; Agriculture and Cooperatives; and Finance and Disaster Management.

Key non-governmental and UN stakeholders include FAO, WFP, WHO, UNICEF, UNFPA and UNDP. Additionally, NGOs such as World Vision, Save the Children, and ADRA, together with community-based organisations can play significant roles in capacity development and community mobilisation.

A flow chart (Figure 57) has been developed to highlight the logical steps that need to be taken to adopt the drought monitoring and early warning framework (Figure 56). The framework is based on the following elements:

- drought knowledge;
- drought management coordination;
- drought monitoring and prediction;
- drought communication and dissemination; and
- response capability.

Drought management coordination in this study is considered a key element that brings together various stakeholders into a common framework for monitoring drought, providing effective and harmonised communication, and drought monitoring and early warning products.

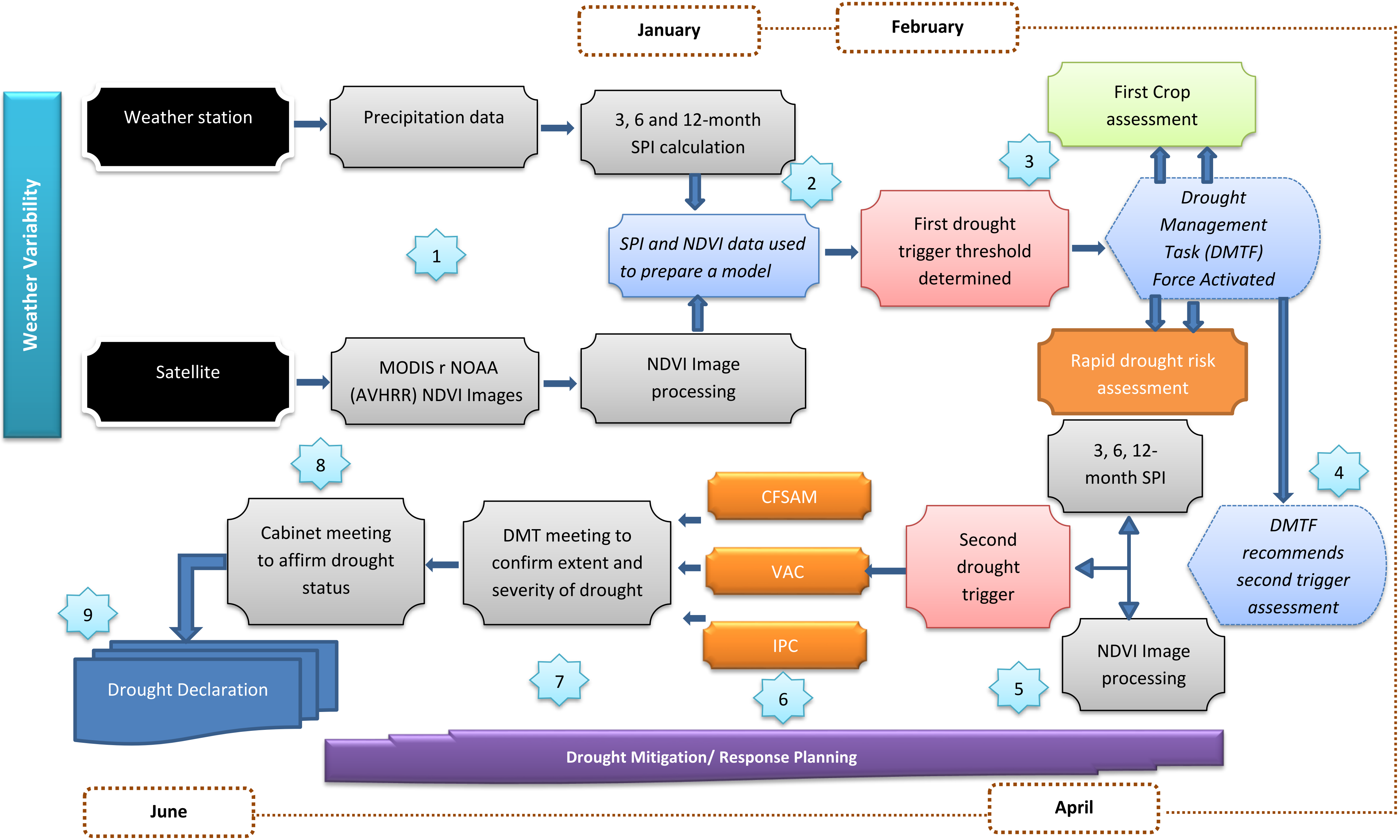

Figure 56. Drought Monitoring and Early Warning Framework

Key steps in the implementation of the drought monitoring and early warning framework are as follows:

1. **Data Collection and Processing:** Collection of precipitation and satellite imagery for the calculation of SPI and determination of NDVI.

2. **Data Modelling:** Using SPI, NDVI, and temperature data, a drought severity model is determined, applying the following formula:

   $$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3.$$

   If additional parameters such as evapotranspiration, soil water, and temperature become available, they can be used to improve the reliability of the model.

3. **Drought Quantification-Level 1:** Using SPI for the month of December and NDVI for the month of January, results are fitted into the model determined in Step 2. Where Y is greater than 0.54, this indicates a significant dry spell that is likely to result in reduced cereal yields. A Drought Management Task (DMTF) is activated to coordinate the drought management process. Based on the value of Y, the DMTF decides if additional data is required to ascertain the severity and extent of the drought. Crop assessment and other rapid vulnerability assessments can be initiated to verify the drought status.

4. **Drought Management Task Force Review:** Based on the results of the vulnerability assessments, the DMTF can recommend a second drought quantification. If the assessment results have confirmed the extent and severity of the drought, Step 5 of the proposed framework can be omitted and recommendations for either a CFSAM, VAC, or IPC can be made to determine the extent of aid/support the country will require.

5. **Drought Quantification-Level 2:** Using SPI for the month of April and NDVI for the month of May, the results are fitted into the model determined in Step 2. Where Y is greater than 0.54, this indicates a significant dry spell and recommendations for a CFSAM, VAC or IPC can be made to determine the extent of aid/support the country will require. The step will characterise dry spell in levels that will trigger different

responses. Drought mitigation/response planning is initiated to ensure that when a declaration is made, all state apparatus is ready for a response. Other stakeholders (such as NGOs and the UN) can start their own planning and resource mobilisations.

6. **Conducting Food Security and Vulnerability Assessments-VAC, CFSAM or IPC:** The DMTF will coordinate any of the standard food security and vulnerability assessments - such as VAC, CFSAM or IPC - that need to be conducted. These assessments will be coordinated with various stakeholders, the UN, NGOs, the private sector, and local communities.

7. **Drought Management Task Force Final Review:** A final DMTF meeting is conducted to confirm the extent and severity of drought and to determine what recommendations are made to government. A meeting is convened with cabinet within one week of the technical drought determination to recommend an official drought declaration, or a drought response without official drought declaration.

8. **Government Drought Declaration:** The government will officially declare a drought state and put in place emergency measures to prevent a drought disaster.

The drought monitoring and early warning framework proposed includes elements of early warning, which integrate hazard monitoring and analysis, vulnerability and capability analysis, assessments of possible impacts, and the use of early warning and communication systems. Discussions and a review of the framework with the FAO, the Ministry of Agriculture, and the NDMA indicate that the proposed framework is important for the country and its adoption and use will enable the decision-makers to effectively monitor drought and make preparedness mitigation and response planning in a timely and systematic manner.

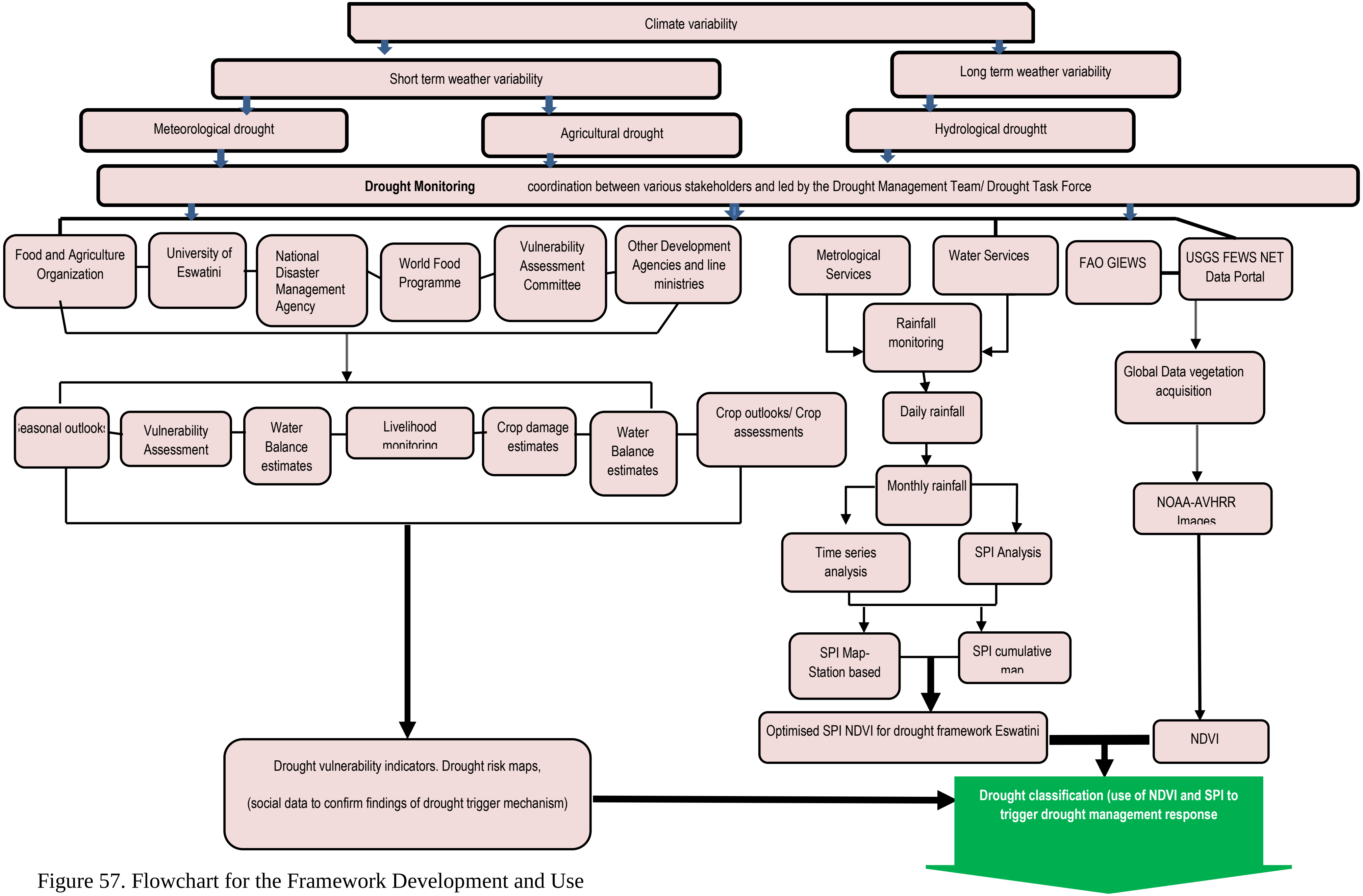

Figure 57. Flowchart for the Framework Development and Use

7.3.5 Timing for Drought Monitoring

Based on the Eswatini crop calendar (Figure 20), the main rain-fed planting period occurs from October through to December, with the majority of the planting being done in October and November. Harvesting for dry grain is between May and June (FAO, 2018). Drought monitoring is therefore critical during the entire growing season, especially mid-season, as it is easier to determine if rainfall variability will affect productivity and yields. Despite the critical periods in the growing season, drought monitoring should be done from planting to after harvesting, to enable stakeholders to detect early warning signs and propose early action if elements affecting food security are determined.

The proposed drought-monitoring framework (Figure 56) for implementation of a drought monitoring and EWS clearly stipulates in which critical periods various elements of the system should be conducted.

7.3.6 Methods of Information Dissemination

Countries in the southern African region - including Eswatini - are still employing a reactive approach in addressing drought (Gerber and Mirzabaev, 2017). It is necessary that these countries start to move towards a proactive drought management approach, based on short and long-term measures, including monitoring systems for a timely warning of drought conditions (WMO/GWP, 2016). Drought monitoring and EWS are therefore crucial to mitigate drought because they provide information to drought-prone communities on how to mitigate and deal with drought. (Gutiérrez, 2014; Wilhite et al., 2014).

Drought management requires regional cooperation and sharing of drought information which remains at a very low level, and in many cases does not exist (UNCCD, 2016; WMO/GWP, 2018). Some countries have established a national committee or commission with responsibility for drought management, coordination, action plans, and dissemination systems. The committees include members from ministries, universities, international organisations (mainly UN organisations), NGOs, and research centres. (Bogan, 2014; CARIAA, 2017; UN, 2013). To ensure the right target group is reached with drought information relevant for their needs, the use of the correct tools and methods is essential (Graham, 2013; ONS, 2010). Once drought monitoring and early warning information is produced and agreed upon by the stakeholders, there are various mechanisms for sharing and disseminating the information.

The method of communication chosen should be based on the information, the audience requirements and the timeframe for a requested response (Abudi, 2009). Elements of early warning require early action, as any delays can be costly (Rogers and Tsirkunov, 2011; van Aalst et al., 2014). To design and agree on a data and information sharing mechanism, stakeholders will need to discuss and agree on the following points:

- who will share what data and information (and in what format) with whom;
- why do we need to communicate with them;
- what do we wish to communicate with our stakeholders (not all stakeholders should receive the same information on drought or early warning - stakeholders should receive information that they can effectively process and use);
- how it will be shared, distributed, or delivered to the relevant people and organisations (for example on what media - printed paper, CD, by radio, by post, called through on mobile phone);
- how frequently it will be shared, for example, daily, weekly, monthly, annually;
- what are the foreseen challenges to effective communication;
- what resources should be allocated for communicating information including time expectations and budget; and
- flow charts depicting information flow in the system, including workflows, with sequence of authorisation, reporting, and meeting plans (Halls, 2005).

It is important that the selected dissemination mechanisms are realistic and sustainable. For example, if the information is to be shared through mass cell phone messages, there must be resources available to pay for the cost of these messages; if the internet is to be used, there needs to be guaranteed internet reliable connectivity for the key stakeholders. With regard to stakeholders, Table 24 provides information sharing mechanisms that can be used within Eswatini for drought monitoring and early warning information.

Table 24. Appropriate Communication Media and Methods with Stakeholders

Communication media or method	Dissemination to groups	Dissemination to individuals
One-to-one meetings		√
Group/village meetings	√	
Workshops/conferences	√	
Websites		√
Electronic files/Portals		√
Video conferencing	√	
E-mail/Fax		√
Telephone		√
Radio broadcasts	√	√
Posters	√	
Mail	√	√
Newspaper articles/newsletters	√	√
Technical reports		√

Source: Halls, 2005.

7.3.7 Governance and Legislation

A number of principles need to be addressed when creating a policy framework. It is important that policies and planning accentuate proactive prevention of drought over a reactive response (Gerber and Mirzabaev, 2017). Despite the fact that reactive measures are helpful, they do not address the underlying causes of drought, which lead to multifaceted impacts and the depletion of resources (UN, 2013; UNCCD, 2017). Furthermore, the resources required for providing emergency food security and water relief after a drought disaster are significant and are never used in the most efficient and effective ways. To utilise resources and funding most effectively, proactive drought monitoring and early warning are required to enable effective drought mitigation (van Aalst et al., 2014; Gerber and Mirzabaev, 2017; Rogers and Tsirkunov, 2011; UNCCD/FAO/WMO., 2012). This requires incorporating proactive drought mitigation principles into national and local policies.

There are variations between drought management policies and responses to droughts in different countries. Recently, many African countries have become increasingly concerned with the problem of drought, and some progress in dealing with this natural disaster has been achieved (DEWFORA, 2011; Ngaka, 2012; Tirivangasi, 2018; Wilhite, 2000). One action taken is the establishment of national committees or units, where different ministries are represented to coordinate efforts and actions to reduce the effects of drought on populations, crops, and livestock, thus improving the livelihoods of the poor. Local committees have also been constituted to implement drought relief measures set up by the national committee (Aid and

Protection, 2012; Jordaan, 2011; Mante-Suaneng, 2014; NDMA, 2016). With assistance from international organisations, southern African countries have focused on drought relief measures (USAID, 2016; WFP, 2016). Additionally, UN agencies and NGOs can help to provide the necessary support, funding, and leverage required when planning and creating drought policies (UN, 2018). Creating a policy framework that promotes coordination between stakeholders on all levels (governmental and non-governmental) is essential (UNW-DPC, 2013; Wilhite, 2011, 2014)

In 2005, the Government of Eswatini, together with UNDP, conducted a national disaster risk reduction capacity needs assessment where drought hazard was incorporated as a risk. Resource constraints and capacity gaps were identified in the following areas:

- institutional and legal systems for disaster risk reduction;
- risk identification;
- information and knowledge management;
- emergency response and preparedness; and
- risk management. This led to:

    - The enactment of a legal and institutional framework for disaster risk reduction, such as the National Disaster Management Policy initiated in 2008,
    - The approval of the National Action Plan for Disaster Risk Reduction covering the period 2008–2015,
    - The institutionalisation of the SVAC and its integration into the new NDMA structure,
    - The development of disaster risk reduction information, education, and communication materials in collaboration with education stakeholders. (GoS, 2006; NDMA, 2016; WFP, 2016).

The country has had a disaster risk management policy in place since 2010. However, it still faces challenges in becoming drought resilient (SEPARC, 2017). Despite the presence of these policies and structures, there has been a significant limitation in their operationalisation. Notwithstanding drought emergencies, there is still no agricultural drought policy in existence (Manyatsi and Mhazo, 2014; Vilane et al., 2015); as such there is no coordinated, proactive drought management within the government and other development stakeholders such as NGOs and the private sector (NDMA, 2015). The existence of the National Food Security Policy of 2005, which aimed at addressing the threats and opportunities relating to food security, recognises the effects of drought and advocates for an early warning system. This has not yet been fully operationalised (Manyatsi and Mhazo, 2014). Despite these national government limitations within southern Africa, countries have become more involved in regional and international workshops, networks, and research programs aimed at the development of strategies for long-term drought management (UNW-DPC, 2013; Wilhite, 2011, 2014).

7.3.8 Finances and Resources

Various regional drought monitoring systems have received funding from various donors to enable them to achieve their function. The SADC Climate Services Centre has been well funded, receiving constant in-kind and funding support from many cooperating partners (SADC, 2012a). The UNDP, the WMO, the World Bank, the United States Agency for International Development (USAID), the Kingdom of Belgium and others, have all provided funding to the Drought Monitoring Centre (Madzimure, 2018; SADC, 2012a; Tirivangasi 2018). The potential financing and funding sources include the member states themselves; international funding agencies including the World Bank, the African Development Bank, and the European Union, and bilateral arrangements between SADC member states and other developed countries (SADC, 2012b). At the national level, funding can be agreed and provided by the Ministry of Finance, in collaboration with the Ministry of Economic Planning and Development. Additional support can be sourced from various donors through partners between line ministries or UN agencies, such as UNDP, FAO, and the WFP. Various additional resources can be mobilised from already existing regional centres and bodies, universities, and research centres. These institutions already have existing infrastructure and teams that can be used to develop capacity of national bodies. With the scarcity of external financial resources and the donor fatigue, it is fundamental for countries to develop innovative resource mobilization strategies, for example through more involvement of private sector.

7.4 CHAPTER SUMMARY

The loss of life, the number of people affected, and the economic losses associated with natural hazards like drought are more severe in the SADC Region (SADC, 2012b). Reducing the risks (and therefore the impacts associated with drought) requires that greater emphasis be placed on preparedness and mitigation. Improving the level of readiness or preparedness for drought involves building institutional capacity and improving coordination within government (Eslamian and Eslamian, 2017; Wilhite, 2002). Drought monitoring and early warning provide the foundation on which timely decisions can be made by decision-makers at all levels - from farmers on the ground to national policy-makers (Svoboda and Tang, 2011; Wilhite and Svoboda, 2000).

This review had identified the main challenges for Eswatini and other countries in terms of drought monitoring and EWS, through a lack of a completed drought policy framework, a lack of coordination between institutions that provide some type of drought early warning, and a lack of vulnerability databases. To counter these limitations, the study recommends that Eswatini develops a drought monitoring system that encompasses effective coordination and use of precipitation and remote sensing-based drought indices. The use of the drought indices and the development of an effective EWS will allow the detection of the onset of drought conditions, thereby facilitating a timely response and mitigation planning.

The drought monitoring and EWS must make its information accessible and easy to interpret, and it must deliver a clear, consistent message to decision-makers so that they can act accordingly (Wilhite and Svoboda, 2000). Early warning information is most likely to be used if it is trusted, and it will mostly likely to be trusted if the decision-makers have a stake in the system and really understand it (Buchanan-Smith, 2000). The formulation of a consistent modern drought monitoring and EWS would prove to be cost effective by enabling the country to adopt a more effective, proactive approach toward drought impact management. Based on the different country case study reviews, in Chapter 8, this study has proposed an institutional drought management or coordination framework that brings together various stakeholders for monitoring drought and providing effective and harmonised communication, drought monitoring, and early warning products.

8 CONCLUSIONS, RECOMMENDATIONS AND FURTHER RESEARCH

8.1 INTRODUCTION

Weather data is a good source of information that can be used for drought assessment. However, the sparse location of weather stations in some areas in Eswatini makes drought monitoring a daunting task (SADC, 2012b; Sigudla, 2015). Any effective and reliable drought monitoring would require the integration of multiple hydro-climatic variables or indices from different sources to track multiple aspects of drought (Hao et al., 2017). This can be achieved through the use of remote sensing (AghaKouchak, 2015; Dutta, 2018), especially to complement precipitation data and increase accuracy of drought monitoring. Analysing the spatio-temporal drought patterns and understanding the relationships between conventional drought indices and remote sensing techniques are therefore critical for monitoring of the drought hazard (Belal et al., 2014; Naresh et al., 2012).

From the literature review, it was evident that drought magnitude, duration, and intensity in Eswatini are increasing over time, thus justifying the necessity to develop a drought disaster-management plan integrating drought monitoring and EWS. It has demonstrated that the efficient use and integration of SPI and NDVI in a drought-monitoring framework will improve drought monitoring, early warning, and drought risk reduction in Eswatini. Adopting the proposed framework, monitoring tools, and methodology would provide the Eswatini and region with valuable information for planning, considering that the country will experience dry periods regularly. Furthermore, the drought monitoring information will help to implement risk reduction measures and to adjust farming practices accordingly. Therefore, for the first time, this study presents a unique framework that incorporates use of precipitation, remote sensing tools to monitor drought, provide early warning information, enabling mitigation and response planning before the drought impact is felt by the population, environment, and the economy.

This study was intended to set the stage for a new paradigm for drought management focused on drought monitoring and early warning by developing an integrated framework for drought monitoring, that can enhance early warning and contribute to the reduction of drought risk.

This would ensure a shift from a crisis management approach to a more proactive or risk reduction approach.

The study adopted the use of design science and the design theory in an attempt to build on existing technology to create a system that best serve human purposes. Various authors have elaborated that good design science research often begins by identifying and representing opportunities and problems in an actual application environment (Hevner, 2007). The author adopted the Berhan et al., (2011) six-design science research guidelines which include *identification, modelling, tracking, prediction, comparison, and communication with stakeholders.* The research process enabled the development of an integrated drought monitoring framework, an artefact addressing the challenges of drought monitoring being experienced by Eswatini.

In this chapter, a conclusion of the research effort is made by analysing how each chapter has contributed towards addressing the research questions. I have achieved this by discussing the research contributions and their implications. I assess the contributions of this study, using criteria formulated by Whetten (1989) in his article on "What constitutes a theoretical contribution". The final section outlines the study limitations and opportunities for further research.

8.2 OVERVIEW OF THE RESEARCH

In Chapter 1, I examined the nature of the research problem which is highlighted by the drought hazard. Climatic hazards affect Eswatini with varying impacts and intensities. However, when natural hazards are rated on the basis of attributes such as duration, severity, spatial extent, lives lost, financial impact, social effect, and lasting impact, drought is ranked number one amongst all-natural hazards in the country. Eswatini is dependent on an agro-based economy; therefore, the impact of drought has a profound effect on livelihoods and the economy with many persons, livestock, water and forestry resources affected. This accentuates the significance of the design of appropriate responses and mitigation planning through drought monitoring and early warning products for decision-making.

The chapter introduced drought monitoring which forms the basis of the research. The accurate monitoring of the spatial and temporal distribution of drought attributes (the onset, frequency, and severity of drought) forms an important process for informed drought management. The absence of continuous spatial rainfall data coverage, the inadequate use of drought indicators and the lack of thresholds above or below by which a drought can be declared make objective drought monitoring and drought declaration difficult and often late. This often results in avoidable loss of life and livestock, food insecurity, and significant financial impact for the economy.

Based on the challenges in monitoring the drought hazard, I looked at why it is important to monitor the hazard, what tools are available to monitor drought, and what can be done to optimise the use of the tools to explain the drought characteristics in Eswatini. From the literature review it was argued that the use of single precipitation-based indices alone or remote sensing data alone cannot fully give a near real time picture of an emerging or ongoing drought. The combined use of precipitation based drought indices and remote sensing is therefore essential for effective drought monitoring. There is also an added need to use multiple indices complemented by other approaches that include vulnerability assessments, to provide reliable and well accepted drought information. I also suggested the need to harmonise and coordinate for an efficient drought monitoring system to function, since multiple and fragmented data sources are used by various agencies.

Chapter 2 also presented the research design as well as data collection techniques employed in the thesis. The theoretical framework that guided the thesis and how they are assessed in their contribution towards knowledge development was also discussed. It was important to note that design science as a process of designing artefacts in context. For the study, the Berhan et al., (2011) six research guidelines were discussed and adopted. The guidelines include *identification, modelling, tracking, prediction, comparison, and communication with stakeholders.* The artefact (framework) has to be designed to interact with a problem context in order to improve a challenge or limitation in that context. To assess the theoretic contributions to research, I considered Whetten (1989) guidelines on what constitutes a theoretical contribution.

Chapter 3 explored the concept of drought risk, by detailing what disaster risk management is, the drought hazard, different definitions of drought and the descriptions of the four main categories of drought. It was imperative to understand what drought is, how it is defined and characterised, what are the causative factors, the frequency of occurrence, and how it can be monitored. These aspects facilitate greater understanding of how to plan and manage for drought. To understand drought fully, the chapter examined causative factors of drought, the drought variables, and parameters. When there is a drought, there is risk and vulnerability, thus, a key component of drought risk reduction is monitoring to enable effective decision-making and planning.

The chapter introduced four major viewpoints providing fundamental tenets in the development of the drought-monitoring framework. There are presented below:

i. drought can occur anywhere, and it can occur in both high and low rainfall areas;
ii. there is an absence of a universally accepted definition of drought which augments the uncertainty on whether a drought exists, making the identification and quantification of drought a challenge;
iii. drought is normally assessed and quantified in relation to different factors, which include the amount, distribution, and frequency of rainfall in relation to crop growth and;
iv. there are no standalone drought indices that can effectively define or characterise drought.

The literature review argued that to reduce drought risk effectively, it is inherent that there is both knowledge and application of indices and an understanding of the level of drought risk, which is characterised by vulnerability, capacity, and resilience of people and institutions. Through this chapter, the study reviewed drought and its characteristics, exploring the principles of drought management, looking at drought monitoring, early warning systems, drought vulnerability, capacity, and resilience which layered the foundation of the body of this study on drought monitoring and early warning systems.

In line with the first guideline of Berhan et al., (2011), the chapter identified the hazard of concern and how it can be incorporated into an artefact. The artefact for the process of knowledge discovery incorporates the use of data from satellite imagery as well as meteorological data. In the study, therefore, the artefact denotes the abstract representation of the design-science research process and its communication to decision-makers.

In the identification of the hazard, it is evident that rainfall data alone will not indicate the presence, severity, or duration of a drought. Innumerable indicators of drought have been derived in recent decades and are in use for drought monitoring. The choice of use of any depends mainly on the timelines in the detection of drought to trigger appropriate response actions; the spatial and temporal sensitivity to climate variability to determine drought onset and termination; the responsiveness to the impacts for a given location or region and the long term data needed for calculation. Based on the review of the various drought indices the SPI and NDVI were selected for use under this study. The SPI was selected because of its simplicity, and since it has fewer data requirements and is based solely on one parameter - precipitation - which is readily accessible from the weather stations. NDVI was used to complement the limitations of SPI as well as increase the reliability of the drought-monitoring framework proposed for Eswatini.

Chapter 4, 5 and 6 outlined four of the Berhan et al., (2011) research guidelines namely *modelling, tracking, prediction* and *comparison.* The chapters incorporated the philosophical and system assumptions underpinning this research, which include epistemological and ontological assumptions of interpretive research. The aim of the research was to create a better understanding of the integration of SPI and NDVI for their incorporation in a drought monitoring framework for Eswatini. Chapter 4 analysed the SPI and its application in near real-time and retrospectively to monitor drought. The focus was on spatial and temporal analysis using SPI as well as mapping drought using the SPI. Chapter 5 presented comparative analysis of available satellite-based images with a focus on the use of NDVI for drought monitoring.

The aspect of integration was chosen as it allows use of complementarity of indices for more accuracy, reliability of the resultant output, which can be used by stakeholders for decision making. In Chapter 4, the first level of analysis attempted to explain drought severity based on temporal dynamics based on SPI. This helps to elucidate the cycle of drought over the period 1986 to 2017. The second level of analysis attempted to elucidate drought severity spatial dynamics based on SPI. This helps to explain the differences in severity across various AEZ of Eswatini. Chapter 5 empirical research focused on the near real time monitoring of drought using NDVI, the drought severity temporal and spatial dynamics based on NDVI, the causal relationship between NDVI and SPI and the determination of drought early warning trigger threshold. The correlation and causal relationship between the SPI and NDVI allowed the determination of drought trigger threshold, which was a critical component of the drought monitoring framework.

Chapter 6 was critical in the overall development of the framework and it provided a comparative analysis of the different country and regional case studies focusing on drought monitoring frameworks. This chapter uses translated knowledge from case study review into action and discussed how it can be used for developing a framework for monitoring drought in Eswatini. By analysing how country frameworks were developed, information for development of an artefact for Eswatini was obtained. The connection between elements in the artefact which links ideas from the case study review and evidence from the SPI and NDVI analysis to produce a representation was a critical element of the research strategy developed in this study. In the review process, common elements that were identified and adopted in framework development included the use of various indices for drought monitoring, the role of stakeholders in the process, the type of communication and modality of sharing information, the various challenges experienced and the different types of early warning and drought monitoring systems in place.

Chapter 7 dealt with the conceptualisation of the integrated drought monitoring framework. The conceptualisation is based on the design theory and five steps (*modelling, tracking, prediction, comparison, and communication with stakeholders*) of research guidelines for the development of an artefact, for the process of knowledge discovery from meteorological data and satellite imageries (Berhan et al., 2011). The key contribution of this study arises from the effective integration of drought indices, modelling and systematic coordination of various stakeholder into an operational framework that allows the timely collection, analysis and communication of drought information to users.

The framework consists of seven levels of analysis and implementation. At the first level there is data collection and processing of precipitation and satellite imagery for the calculation of SPI and determination of NDVI. The second level is data modelling with the resultant data being used in the third level. The third level entails the first drought quantification using SPI for the month of December and NDVI for the month of January. The results of the drought quantification would trigger a drought management task force (DMTF) in the case where drought is determined. The fourth level entails DMTF deciding the process to follow and making recommendation of further analysis or disaster response. If further analysis is required, the fifth level of analysis entails a second drought of drought quantification. The six and seventh level of analysis entails collecting additional evidence to determine the level of vulnerability of the affecting communities and the eventual recommendation by the DMTF on drought status and the nature of response.

8.3 ADDRESSING THE RESEARCH QUESTIONS

A set of research questions were posed that would help in explaining what challenges Eswatini was facing with regard to drought monitoring and how the challenges could be addressed. The main objective of these questions was to meet the overall objective of this thesis, which was to understand drought monitoring challenges, opportunities available through the use of various indices, how best these indices can be optimised for the effective monitoring of drought and what mechanism can be proposed for Eswatini to ensure that there is a harmonised system of drought monitoring that incorporates multiple stakeholders in the data collection, analysis and communication of drought information.

In this subsection, the research questions are revisited in light of the results of the empirical analysis and review of various country case studies and the development of the drought monitoring framework.

- **Can Eswatini use a station-based drought index (SPI) and a remote sensing-based index (NDVI) for drought monitoring?**

The question was answered through chapters 4, 5 and 7. Chapters 4 and 5 analysed the use of SPI and NDVI and how the two indices can be used independently and in an integrated manner for near real time drought monitoring. Chapter 7 formulated a framework incorporating SPI and NDVI that ensures Eswatini could use a station-based drought index and a remote sensing-based index for monitoring of drought.

- **How can the use of SPI and NDVI be optimised for near real-time drought monitoring?**

Chapter 5 addressed the relationship between SPI and NDVI and how the indices can be optimised for spatial and temporal drought analysis. Chapters 4 and 5 described the drought dimensions and how these can be used to explain the phenomena. Chapter 5 highlighted the positive correlation identified through the regression analysis and the eventual determination of a R value which is proposed to be used as an early warning sign or drought threshold/ trigger value.

- **What are the strengths and weaknesses of satellite-based indices versus station-based meteorological indices (SPI)?**

Chapter 4 and 5 examined the various satellite-based indices and meteorological based indices to identify the strengths and weakness and select the best indices applicable to Eswatini. The review enabled the comparison of the data requirement for the various indices, the analytical approaches and the applicability or use in in spatially and temporally. SPI is user-friendly, requires less data and can be comparable in time and space. Satellite based indices like NDVI are cost-effective once the infrastructure is installed, can cover wider area and can collect data in real time. The challenge however for NDVI in Eswatini is that there is no long-term data to be able to do trend analysis.

- **How can precipitation and satellite vegetation indices detect droughts, describe their severity in near real-time or retrospectively?**

Chapter 4 and 5 examined the spatial and temporal drought dimensions through the use of SPI and NDVI. The analysis results helped to explain the onset, severity of drought in time and space. In time, the SPI was able to explain the drought phenomenon through looking at historical droughts and how severe they were.

- **What are the precipitation and vegetation status thresholds that are necessary to effect early warning systems?**

Chapter 5 enabled the integration and optimisation of SPI and NDVI through the development of a drought trigger threshold Y=0.54, which has been proposed within the drought monitoring framework as an early warning early action trigger, which activates the whole framework to function. The value of Y above the trigger threshold activates the DMTF.

- **How can the use of SPI and NDVI by stakeholders be enhanced for effective drought monitoring and early warning, and?**

Chapter 7 evaluated the key stakeholders and resources required in drought monitoring. Key stakeholders were considered critical resource for data collection, processing and communication to users of drought information. The effective coordination of the different stakeholders was deemed to enhance timeliness and quality of the data collected and disseminated.

- **What is the appropriate framework applicable for effective drought monitoring?**

Chapter 7 proposed an integrated drought monitoring framework that was built on literature review, empirical analysis, case study reviews from chapter 1 to 6. The different steps within the framework and the roles of each stakeholder are explained, and the timing of each critical action in the effective functioning of the framework is proposed. The adoption of the framework is expected to ensure timely provision of acceptable drought information for effective decision-making and mitigation planning.

8.4 RESEARCH CONTRIBUTIONS

8.4.1 Theoretical contributions

Founded on Whetten's framework for the evaluation of the theoretical contribution, I considered a set of questions to weigh the theoretical contribution of this study. This is because both qualitative and empirical findings should be construed and associated to theoretical concepts and previous research. The questions "w*hat is new? Why is it important? Why now? Who cares about the area of research?"* answer how the design theory contribute to research. For this study the contribution to research is expressed through the below questions and answers:

- *Does this study make a significant contribution to current thinking?*

The importance of agriculture to the Eswatini population and economy makes drought the biggest impediment to the country's food security (Dlamini, et al., 2016; Van Zyl Engelbrecht, 2018), and a very important hazard to monitor. The monitoring, prediction, management, and mitigation of drought hazard are therefore essential elements of reducing the impact of drought (Bokal et al., 2014; Wilhite et al., 2014). Based on the challenges and limitations identified in the previous chapters, the primary objective of drought monitoring and warning system development is to ensure the availability of accurate, timely, reliable, and high-resolution characterisations for Eswatini and the region, through objective science-based methods, providing information that can be used to make drought preparedness, mitigation, and response decisions by stakeholders and communities.

In this research, I have developed an approach for using artefacts for addressing human problems. In this research through design, I have modelled SPI and NDVI and integrated their combined use in drought monitoring into a drought monitoring framework. The framework and model of SPI and NDVI enhance the understanding and explanation of drought severity and provide evidence of prevailing drought phenomena. This is in line with the concrete framing of the problem and a description of a proposed, preferred state in design research (Zimmerman et al. 2007)

This approach is innovative because it takes advantage of system design in creating simple but efficient products, in this case a drought monitoring framework that will contribute to efficient management of drought and its impacts. The process takes into cognizance the happenings in everyday life of drought monitoring in Eswatini and takes ideas from other countries in the region and beyond to suggest a new paradigm. The process of the paradigm shift in drought monitoring, though achieved through design science takes into account inputs from various stakeholders. The propositions made are considered to be demand-driven as they reflect the stakeholders' existing and future needs.

This framework was developed from various countries' experiences. Applying critical artefact design methods and theory enabled me to develop a rationale to support the framework development as discussed in Chapter 7. The systematic approach of the framework was critical to its design. There is a simple stepwise process of data collection, processing, modelling and use in decision making, while understanding what has been done before, what is being done now, what can be improved and what exactly the stakeholders need.

- *Is it likely that the framework will change the way in which drought initiatives are implemented in the Eswatini and southern African context?*

One of the main contributions resulting from this study are the drought trigger threshold developed from modelling SPI and NDVI. It provides a value above which a drought can be considered to have started. Similarly, the proposed drought monitoring framework is a major contribution to science as it provides a logical stepwise process of identify drought severity and reporting to stakeholders in a scientific and simpler and understandable manner for user to process and make decisions. The framework intends to enable a holistic multi sectorial management of drought in a proactive manner. In this case both technology and social research will be used for effective and timely decision making. The demonstration of the framework with critical stakeholders in the ministries and UN agencies, ensuring their understanding and interest on how the framework can contribute to effective drought monitoring, provides evidence that it can be adopted and used in the real world.

- *Are the underlying logic and supporting evidence compelling?*

This research was the first to recognize that drought frequency and severity is increasing in Eswatini specifically using SPI and NDVI, and that the indices can explain the frequency and severity temporally and spatially. While the use of drought indices has been the focus for drought monitoring for decades, most research has focused on using single indices as well as absence of an integrated approach or systematic approach for drought monitoring especially in southern Africa. Most emphasis was on management of droughts when the impacts are being felt. The study therefore, provided an innovative understanding into systematic process of drought monitoring and drought communication for early action.

- *Does the research work reflect seasoned thinking, conveying completeness and thoroughness?*

The impact of the drought disasters has been significant as outlined in Chapter 1 and 3. To answer the research questions, a thorough analysis of literature, empirical analysis and review of country case studies was conducted. This means that there was an effort to look at various angles to identify the problem, i.e. through analysing the drought hazard using various drought indices, designing the framework through both systems design and stakeholder involvement. The use of multi methods approach in conceptualizing and the eventual development of drought monitoring framework indicates attention to detail on the part of the researcher.

- *Is the topic of contemporary interest to scholars and practitioners in this area?*

In Eswatini there has been development of policies and mechanisms through the government and non-state actors and community-based organisations with the main purpose of improving disaster management. However, focus has been more on the reactive response rather than proactive response. Researchers in Eswatini have looked at the climatic variability over time and have expressed the frequency and the impact of drought on farmers and the economy. It was therefore important to conduct empirical analysis on drought severity in Eswatini to contribute to a better understanding of the manifestation of the phenomenon, how it can be identified, monitored and communicated for better management and decision-making.

The multi stakeholder approach was important to enable systematic and well-coordinated drought monitoring mechanism, as well as sustainability of the proposed system through stakeholder buy-in and institutionalisation of the process. This study also underscores the consideration of the existing infrastructure or mechanisms for drought monitoring, how they can be complemented or improved through the innovative approach of a proactive multi-sectorial drought monitoring process.

- *What percentage of academic readers is interested in this topic?*

With the advent of concepts of climate resilience, the researcher has been working on disaster risk reduction and resilient building and drought was considered one impediment to effective resilient building. The subject of drought monitoring is a concern to many researchers in Eswatini and southern Africa, with different government and regional bodies investing finance and expertise to try to identify mechanisms to mitigate the impact of disaster. There has been significant funding by USAID and other donor agencies to come up with mechanisms to provide climate information on a timely basis, i.e. through FEWSNET, SARCOF etc.

Various tools were developed and research is conducted on climate aspects in South Africa through various research institutions within universities and external entities. I have also authored a research papers titled '*Integrating SPI and NDVI for near-real-time drought monitoring in Swaziland Integrating SPI and NDVI for near-real-time drought monitoring in Swaziland*' and '*Monitoring droughts in Swaziland: A spatiotemporal variability analysis using the standardized precipitation index'*. These papers were accepted for publication in the Jàmbá: Journal of Disaster Risk Studies, an influential, frequently cited, accredited, peer reviewed and Open Access journal. This clearly proves that the aspect of drought monitoring is a very active area of research and major concern for research, government and donors.

8.4.2 Methodological contributions

Quantifying the strength and duration of droughts will have a significant impact on the population and the economy due to the early determination of drought periods, thereby allowing early mitigation and response planning. The methodology for proactive drought severity determination proposed in this research is based on the statistical and threshold-based parameters from the NDVI and time series of SPI-3, 6, and 12. Due to the strong positive correlation between NDVI and SPI, the two indices can be used to monitor and detect drought severity and thereby provide early warning information to stakeholders. Based on the model, the study determined that when the value of Y (drought severity) is greater than 0.54 (trigger threshold), this indicates a significant dry spell that is likely to result in reduced cereal yields, which could trigger drought planning amongst stakeholders when used in combination with other sources of information, such as assessments, visual observation, and water balance.

- **Standard Precipitation Index**

The study computed SPI at various time scales for Eswatini rainfall stations where data was available. Through the SPI, it is possible to compare two different stations in different agro-ecological regions at different times, and compare how severe are the drought conditions. The SPI is therefore a good index for spatial analysis of drought (Botai, et al., 2016; 2017; Vicente-Serrano et al., 2012). The temporal and spatial drought analyses indicated that Eswatini experienced quite frequent moderate and severe droughts on a seasonal basis. The identification of the temporal and spatial characteristics of droughts in the different AEZs will be useful for the development of a drought preparedness plan at regional and district level.

The SPI can be computed for different time scales, providing early warning of drought and helping to assess drought severity. The study recommends the use of 3, 6, and 12-month SPI for different drought determination, and 3-month SPI for monitoring early season droughts and the impact on agricultural production. Therefore, the tools required for analysis and interpolation are tools that are readily available for Eswatini and their adoption and use will not require heavy investment for the Government.

- **Normalised Difference Vegetation Index**

In this study, the NDVI times-series was used to estimate vegetation health and to monitor drought. The NDVI spatial pattern generated indicated the stations under drought, whereas temporal patterns highlighted the years in addition to each respective month experiencing drought. Therefore, the study concluded that the time-series NDVI is a good indicator of moisture condition and can be an important data source when used for detecting and monitoring dry periods in Eswatini. One critical concern, however, is that factors like seasonality, spatial variability, and vegetation type have significant effects on NDVI values. Therefore, a final declaration of drought (based on NDVI) needs to be analysed and supported by other tools, indices, and assessments. The NDVI patterns for the month of January are recommended, as they indicate the impact of drought on the critical stages of crop growth, when vegetation growth is expected to be at its peak.

- **Correlation between NDVI and SPI**

The study determined that for the months of October, November, and December (for rainfall) and the NDVI for January, the SPI and NDVI generally have a positive correlation in Eswatini. Due to the positive correlation, both indices can be used to detect and monitor severity of drought in Eswatini by providing a near-real-time indicator of vegetation condition and drought conditions within drought regions, and more specifically areas or AEZs with varying drought conditions. The results invalidate the hypothesis that the relationship between SPI and NDVI cannot elucidate the spatial and temporal drought variability in Eswatini.

- **Other Determinants of the Drought Monitoring and Early Warning Framework**

The use of precipitation and remote sensing indices SPI and NDVI in drought monitoring will require additional supporting information to ensure stakeholders fully accept information emanating from the indices. The study is building on existing tools to ensure the adoption and buy-in of the drought monitoring and early warning framework. The country is employing various pre- and post-drought monitoring tools. These tools are listed below and have been incorporated in the proposed framework.

i. FAO/WFP Crop and Food Security Assessment Mission to Eswatini.

A Crop and Food Security Assessment Mission (CFSAM) is normally undertaken jointly by FAO and WFP. It assesses the seriousness of a crisis situation by looking at the food produced nationally and the extent to which poor people can meet their basic food needs. However, the assessment is in most cases completed after an emergency, that is, when a drought has already occurred, and the impacts are already seen. The assessment, though conducted after a drought event, is also used as an early warning tool that facilitates timely and appropriate actions to be taken by the government and the international community to minimise the impact of the crisis on affected populations (FAO/WFP, 2009). The assessment in the proposed framework will be used to confirm results from the drought indicators and to model the extent of geographic coverage of the drought impact.

ii. Eswatini Vulnerability Assessment Report

The Eswatini Vulnerability Assessment examines the capacity of households and individuals to deal with external hazards such as drought, economic crises, and climate change. Critical elements include meteorological and crop projections, household economic analysis, and food and nutrition security surveys. This leads to recommendations for short-term and long-term interventions. The adoption of the Integrated Food Insecurity Phase Classification (IPC) protocols facilitates comparisons of the severity of food insecurity between areas and countries (Global Partners, IPC, 2012). This can help in the comparison of agro-ecological regions affected by drought with regard to food security status. Multi-sectorial committees led by relevant government ministries with wide ranging memberships conduct the assessment. These include different government departments, NGOs, and international organisations involved in poverty reduction and socio-economic development.

The assessment (like the CFSAM) is also normally conducted after an emergency. The SVAC and the CFSAM both generally confirm whether an emergency has occurred and what are the likely impacts on households. The SVAC uses many data sources, including the rainfall and NDVI (Global Partners, IPC, 2012), instead of waiting until an IPC is completed; the trigger threshold developed under this study will be used to initiate response planning and stakeholder coordination. This allows a proactive, rather than a reactive approach.

iii. Crop Assessment

Crop assessments are conducted during the growing season to evaluate the state of the crops in the country. It helps government and partners to identify upcoming agricultural and food assistance needs. Obtaining data on crop conditions is critical for assistance planning, while it also connects extension agents to farmers, helping to build stronger relationships. Crop assessments are critical to the framework as they are completed before the season ends and before crops are harvested. The crop assessments can be correlated with the NDVI images to determine which areas are severely affected by the dry spells, thereby indicating drought conditions.

iv. SADC Climate Services Centre

Eswatini and SADC countries use the SADC Climate Services Centre for monitoring and predicting extremes in climate condition. The products from the Centre are to be used to validate the results of the drought monitoring tools and output of the drought-monitoring framework. Products like the Food Security Early Warning System Agro-met Update, agro-meteorological updates, and climate outlook bulletins are vital to the validation process.

v. Famine Early Warning Systems Network (FEWS NET)

The FEWS NET monthly reports and maps detail current and projected food insecurity. Timely alerts are vital to the framework as they will support information provided by SADC

Climate Services Centre and the national meteorological services, by providing timely specialised reports on weather and climate, markets and trade, agricultural production, livelihoods, nutrition, and food assistance. This will complement and provide supporting evidence to the declarations provided through the framework.

vi. UN/NGO Assessment Reports

The FAO, WFP and NGOs conduct various assessments during the growing season and after. As part of the drought monitoring task force, results and datasets should be shared with drought monitoring task forces, to be used for provision of micro-level information on the status of the growing season.

- **DROUGHT MONITORING AND EARLY WARNING FRAMEWORK**

The drought monitoring and early warning framework proposed includes elements of early warning, which comprise hazard monitoring and analysis, vulnerability and capability analysis, assessments of possible impacts, and the use of early warning and communication systems.

8.4.3 Practical contributions

For the practical contributions, I looked at the ability of the framework to address shortcomings in the existing drought monitoring mechanisms in Eswatini. The comprehensive and integrated approach will help Eswatini monitor drought more effectively and provide early warning products timely to all stakeholders. The proposed framework will address many shortcomings of the current systems and processes used in the country, thereby improving drought preparedness. Key issues that will be addressed will include the following:

i. **Continuous drought monitoring.** Developing a continuous drought monitoring system will allow the enactment of national drought policies that focus on risk reduction, and the use of tools that provide early warning information (WMO/GWP, 2018a). The use of the drought indices and the development of an effective EWS will allow timely detection of the onset of drought conditions. The task of drought monitoring and early warning will be a responsibility of many stakeholders and the framework will allow effective coordination of the process.

ii. **Integrated drought monitoring and early warning system.** The system adopts an integrated and novel approach for monitoring and assessment of the drought risk, based on a combination of meteorological data, NDVI from satellite imagery, and targeted collection of ground truth crop-yield and vulnerability data. The framework introduces an operational drought monitoring and early warning prototype, with well-connected sharing of information with various stakeholders, scientists, and communities at different levels within the country and the region. Having a comprehensive and integrated approach enables monitoring of drought more effectively and provides early warning (WMO, 2006). The adoption of an integrated framework allows early buy-in of key decision-makers of early warning information, thereby enabling the government and UN agencies to enact mitigation and response planning mechanisms.

iii. **Effective spatial and temporal drought monitoring.** To date, monitoring and EWSs have been based on a single indicator or climatic index. The framework allows the use of vegetation health indicators and rainfall anomalies from satellite data and targeted *in situ* data collection vulnerability and crop-yield data. Using NDVI and SPI, the country can implement drought risk analysis across agro-ecological regions and prepare region or district-specific adaptation measures. The main drought impacts are normally felt in the Lowveld AEZ; as such, the regional drought analysis can provide adequate early warning information during dry spells, thereby enabling targeted response.

iv. **Effective communication**. The framework will serve as a link between drought task forces and various stakeholders by communicating information to all stakeholders concerned with drought and its impacts. Effective communication will be achieved through dissemination of customised national drought monitoring products, both through centralised at government level and decentralised at regional and community level levels. The framework, being in line with recommendation by Wilhite et al., (1986), enables the dissemination of the following:

   i. reliable and timely informational products and dissemination plans;

ii. improved impact assessment techniques, especially in the agricultural sector, for use by governments to identify periods of enhanced risk and to trigger assistance measures;
iii. administratively centralised drought declaration procedures that are well publicised and consistently applied; and
iv. standby assistance measures that encourage appropriate levels of risk management by producers and that are equitable, consistent, and predictable.

The framework will use various communication mechanisms, such as radio, print, stakeholder meetings, and television. The combination of Internet, print, and electronic media delivery will be effective in ensuring information reaches a wider audience (WMO, 2006).

v. Funding. Eswatini is constrained in terms of resources. There is therefore a need for sustained funding to enable the drought monitoring and early warning system to function. However, due to the involvement of various stakeholders who have various roles and responsibilities and are semi-autonomous to the system, funding of each unit within the system is independent. Yet, they continue to contribute to the overall functioning of the system. The involvement of the Ministry of Finance in the framework allows the incorporation of the framework in the government budget planning and objective setting.

vi. **Effective drought management coordination.** Various stakeholders are setting aside funding to strengthen capacity for coordination during drought emergencies, as well as for relief efforts (UNDP, 2011a). However, little is known of the drought risk, and this can lead to poor resource prioritisation and allocation, as well as poor targeting of drought mitigation and relief programming. The framework allows for effective coordination and prioritisation of activities and response by a coordinating body. Stakeholders in the framework are involved in the design, data collection, analysis and use.

By promoting effective stakeholder involvement from the early stages of product development, this ensures that the drought information will serve their varied timing and content needs (WMO, 2006). By virtue of having a taskforce and coordination mechanisms at different levels, this enables them to bring ideas and issues together to the table, thereby allowing timely prioritisation and decision-making. The analysis of climate and water data is most effective when it is coordinated under a single authority. Therefore, WMO (2006) proposes the merging of the NDMC and NEWU, in support of the framework.

In general, the framework will allow stakeholders to identify drought early in a systematic manner, while at the same time incorporating vulnerability into drought declaration in a timely manner. The overall methodology presented in this thesis provides a general framework on the use of spatio-temporal information from both NDVI and SPI timescales, for the effective monitoring of the onset, severity, and magnitude of drought, while involving various stakeholders in the monitoring and dissemination of drought-related information.

8.5 RECOMMENDATIONS

Findings from this study suggest that the development and adoption of a drought monitoring and EWS will need to be addressed through an integrated approach that adopts science, social science, and coordinated drought planning and research. Effective use of the framework will require implementation of proactive strategies for drought monitoring and, importantly, a high level of coordination of existing structures and practices that vary considerably across spatial and temporal scales, administrative areas, and different management and leadership levels.

8.5.1 Policy

The elaboration and enactment of a national drought policy and supporting preparedness plans should be immediately established. However, the plan should be considered as a living document and an ongoing process, continuously evaluating the successes and failures of the policy (especially the proposed framework and other drought mitigation plans). This will allow the timely formulation and implementation of appropriate adjustments if required.

Developing and enacting a drought policy should be supported by mechanisms that ensure the actions identified in the policy are implemented. Human resources, political and financial investment in prevention, and mitigation and preparedness measures have to be guaranteed.

8.5.2 Operational Implementation of the Framework

The proposed framework only focuses on the operational aspect of monitoring and does not dwell on other aspects of the disaster management cycle, particularly drought planning, response, and recovery. Legislation to ensure that drought risk reduction strategies are carried out should be developed and enforced. Therefore, for the framework to be fully adopted and used, Eswatini needs to adopt and integrate into the framework the 10-Step drought planning process as proposed by Wilhite et al., (1999)., as follows:

i. **Appoint a Drought Task Force**. The drought-planning process is initiated by the Prime Minister through the appointment of a drought task force. The task force is already in existence, however there is need to incorporate other stakeholders as identified and recommended in the study. The role of the task force should be expanded to the supervision and coordination of the framework and the resultant development of the drought management plan, which is critical for the country.

ii. **State the Purpose and Objectives of the Drought Plan**. Key aspects of the drought management plan should detail how the framework can be incorporated into domestic policy. The roles and responsibilities of the different stakeholders and members of the task force should be clearly stated. Most importantly, the resources (human and economic) that the government is willing to commit to the framework adoption and planning process should be made known.

iii. **Seek Stakeholder Participation.** Multi stakeholder involvement and strong coordination is vital for effective drought monitoring, based on the framework. It is essential for task force members to identify all citizen groups that have a stake in drought planning (stakeholders) and their interests. These groups must be involved early and continuously for their fair representation and effective drought management and planning.

iv. **Inventory Resources and Identify Groups at Risk.** It may be necessary for the taskforce to initiate and conduct an inventory of natural, biological, and human resources, including the identification of constraints that may impede the planning process. This should be undertaken using SVAC, IPC, Ministry of Natural Resources and Energy, Ministry of Agriculture, UNDP, FAO and mechanisms within the Central Statistical Office.

v. **Develop Organisational Structure and Prepare a Drought Plan.** The proposed framework is part of a drought plan that needs to be incorporated into a comprehensive national drought plan. The overall drought plan should have three primary components: monitoring, risk assessment, and mitigation and response.

vi. **Integrate Science and Policy; Close Institutional Gaps.** An essential aspect of the planning process is integrating both science and policy in relation to drought management.

vii. **Publicise the Proposed Plan; Solicit Reaction.** The proposed framework requires involvement and buy-in from various stakeholders and community members. Communication with the public and key stakeholders should occur throughout the process of establishing a drought plan. Stakeholders should have a solid understanding on what it will cost to implement each option, and how it will be funded. The drought task force should work with public information professionals to keep the public well informed of the current status of water supplies, whether conditions are approaching 'trigger points' that will lead to requests for voluntary or mandatory use restrictions, and how victims of drought can access assistance.

viii. **Implement the Plan.** The drought plan, which incorporates the proposed framework, should be implemented once the task force and any stakeholders have agreed on the plan. The task force and its designated representatives should oversee implementation of both the short-term operational aspects of the plan and long-term mitigation measures. Periodic testing, evaluation, and updating of the drought plan will help to maintain responsiveness to state needs.

ix. **Develop Education Programs.** Education programmes to raise awareness of short- and long-term food security and water supply issues will ensure that people know how to respond to drought when it occurs, and that drought planning does not diminish or cease during non-drought years.

x. **Post-Drought Evaluation.** A post-drought evaluation or audit will document and analyse the monitoring process, drought assessments, and response actions of government, NGOs, and others, providing a mechanism to implement recommendations for improving the system.

8.5.3 Drought Declaration Thresholds

Using the proposed framework, a drought declaration is required if all indicators direct towards drought conditions. Based on the current situation (where drought declarations occur after the drought impact is felt), there is need to refine the methodology for drought disaster declarations and ensure that it is agreed upon by the drought taskforce and stakeholders who have vested interest in drought management. Therefore, this study proposes the adoption of 3, 6, and 12-month SPI for the monitoring of drought and its impact on crops, livestock production, and water supply. However, this has to be agreed and adopted nationally. Further, research should be conducted using the 24-month SPI to assess the suitability of SPI on livestock and forestry. Additionally, the adoption and use of vulnerability criteria in drought declaration need to be refined.

Vulnerability is important in the determination of disaster risk, but the methodology should be harmonised. The use of IPC protocols is recommended as this harmonises the process and allows the use of internationally agreed thresholds. Moreover, there is a need to incorporate crop assessments that are conducted in a scientific manner and that can be comparable year-to-year.

8.5.4 Response

Users of climate information must be educated on how that information can be applied to reduce the risks associated with extreme climatic events such as drought. Drought response planning is critical, especially considering the current response approach is *ad hoc*, and therefore more biased towards humanitarian food aid. There is a need for education at various levels, including stakeholders and communities, of the different response mechanisms that can be adopted and implemented.

8.5.5 Limitations and Further Research

i. As a result of this study, the following gaps were identified and should be researched in order to increase the accuracy and robustness of drought risk assessments. First, the framework only uses NDVI and SPI to provide early warning information on drought, however, research highlights various indices and elements that can be used to help to identify drought conditions. There is a need to conduct further research on factors that influence drought so that they can be incorporated into the drought monitoring and early warning framework. Such factors already being collected that can be incorporated include the following:

  - soil moisture,
  - evaporation,
  - water levels,
  - pasture conditions,
  - agricultural information,
  - production estimates,
  - price trends of food and feed,
  - availability of drinking water,
  - household vulnerability.

ii. It is important to incorporate drought risk analysis, especially elements of vulnerability and coping capacity, to identify the impact of the drought risk more effectively on specific communities that are drought-prone. The risk assessments need to identify and address the most vulnerable people and sectors at the national and district level.

iii. A vulnerability profile should be conducted to capture the socioeconomic conditions of diverse population groups.

iv. This study was restricted to a limited time scale, due to the unavailability of long-term NDVI data. Similar evaluations should be performed across the entire growing season and over a longer-term period to improve the accuracy of model. Further assessment of results under varying levels of drought severity should be conducted to characterise both rapid and slow-onset drought stress events.

v. The drought monitoring and early warning framework should be further evaluated and compared to other drought monitoring tools, with the involvement of regional researchers, governmental authorities, and policy-makers. This would enable a harmonised approach in the region for drought monitoring and sharing of harmonised drought related information.

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10 ANNEXES

10.1 SPI DATA

10.1.1 12, 3 Month SPI for Rainfall Stations

Table 25. 3 Month SPI Data for Targetted Rainfall Stations

Rainfall Station	GPS Coordinates		SPI 3		
	X	Y	**1986-1987**	**2006-2007**	**2015-2016**
Mbabane	-2915595	23318	-0.56	-0.34	-2.81
Matsapa	-2934682	29363	-0.31	-0.92	0.34
Big Bend	-2966495	97442	-1.85	-0.41	-0.92
Kubuta	-2968722	44315	-1.18	-0.14	-0.10
Mananga	-2876147	81218	-1.47	0.01	-2.88
Malkerns	-2940409	25863	-1.23	0.54	-1.98
Siteki	-2925775	94579	-2.38	0.20	-2.87
Mpisi	-2938500	57358	0.24	0.80	-0.42
Sithobela	-2972858	60539	-0.59	-2.75	-0.11
Mankayane	-2951861	14092	-0.43	-2.70	-0.17
Mhlume	-2884100	79309	-0.45	-0.44	-3.06
Piggs_peak	-2874238	24909	-0.58	-1.83	-1.24
Siphofaneni	-2951543	62766	-0.14	-2.02	-1.85
Nhlangano	-3001171	14092	-0.83	0.74	-2.29

Table 26. 12 Month SPI Data for Targetted Rainfall Stations

Rainfall Station	GPS Coordinates		SPI 12		
	X	Y	**1986-1988**	**2006-2008**	**2015-2017**
Mbabane	-2915595	23318	-0.80	0.83	-2.13
Matsapa	-2934682	29363	-0.26	0.87	0.03
Big Bend	-2966495	97442	-1.08	-0.95	-0.61
Kubuta	-2968722	44315	-1.71	-1.34	-2.05
Mananga	-2876147	81218	-0.82	-0.69	-2.10
Malkerns	-2940409	25863	-0.33	1.60	-2.14
Siteki	-2925775	94579	-1.25	-0.08	-3.61
Mpisi	-2938500	57358	-0.77	0.80	-1.23
Sithobela	-2972858	60539	-0.23	-0.83	-0.94
Mankayane	-2951861	14092	-0.07	-0.66	-0.16
Mhlume	-2884100	79309	0.01	0.84	-2.65
Piggs_peak	-2874238	24909	-0.38	-0.64	-1.27
Siphofaneni	-2951543	62766	-0.68	-1.06	-1.51
Nhlangano	-3001171	14092	-1.31	-0.04	-2.12

10.1.2 12, 6, 3 Month SPI for all AEZ

Table 27. 12 Month SPI for all AEZ

Year	**Lubombo Plateau**	**Middleveld**	**Highveld**	**Lowveld**
1986 - 1987	-1.30	-0.90	-0.60	-0.79
1987 - 1988	0.80	0.17	0.33	0.13
1988 - 1989	0.07	1.72	1.14	0.25
1989 - 1990	1.39	1.01	0.16	0.30
1990 - 1991	1.92	-0.78	-0.64	-1.15
1991 - 1992	-0.19	0.32	1.36	0.59
1992 - 1993	-1.46	-0.91	-1.38	-0.94
1993 - 1994	-0.19	-0.17	0.06	-0.12
1994 - 1995	-0.22	-0.27	0.21	-0.79
1995 - 1996	-0.19	0.72	0.06	0.94
1996 - 1997	-0.18	1.37	0.97	0.46
1997 - 1998	-0.17	0.75	0.90	0.59
1998 - 1999	-0.15	0.68	2.20	0.57
1999 - 2000	-0.06	1.75	-0.23	1.36
2000 - 2001	-0.08	1.13	2.41	3.06
2001 - 2002	-0.10	0.35	-0.07	1.18
2002 - 2003	-0.10	-0.86	-0.93	-1.00
2003 - 2004	-0.16	-1.79	-0.46	-1.77
2004 - 2005	-0.11	0.46	0.13	0.06
2005 - 2006	-0.09	-0.86	-0.97	-0.75
2006 - 2007	-0.17	0.67	0.37	0.68
2007 - 2008	-0.17	-0.49	0.08	-0.21
2008 - 2009	-0.10	-0.94	-0.22	-1.29
2009 - 2010	-0.14	0.46	0.62	-0.23
2010 - 2011	1.43	0.33	0.20	0.31
2011 - 2012	0.67	-0.17	-0.29	-0.48
2012 - 2013	0.59	-0.31	-0.16	1.01
2013 - 2014	0.67	0.62	0.67	1.04
2014 - 2015	-1.31	0.67	-0.61	-0.70
2015 - 2016	-3.57	-1.66	-1.54	-1.80
2016 - 2017	1.07	-2.65	-2.42	-0.70

Table 28. 3 Month SPI for all AEZ

Year	Lubombo Plateau	Middleveld	Highveld	Lowveld
1986 - 1987	-2.46	-1.29	-0.68	-1.00
1987 - 1988	-0.25	0.17	-0.10	-0.14
1988 - 1989	0.26	1.75	1.28	0.42
1989 - 1990	2.56	1.50	0.02	1.32
1990 - 1991	1.52	0.03	-0.32	-1.21
1991 - 1992	0.03	-0.98	0.32	-0.83
1992 - 1993	0.26	0.41	-0.07	-0.20
1993 - 1994	0.26	-0.06	-0.09	-0.20
1994 - 1995	0.05	0.27	0.88	-0.15
1995 - 1996	0.06	1.74	1.24	1.01
1996 - 1997	0.05	-0.73	-0.22	0.34
1997 - 1998	0.08	-0.63	0.21	0.26
1998 - 1999	0.05	1.08	2.89	1.12
1999 - 2000	0.09	-0.09	0.58	1.02
2000 - 2001	0.12	-1.33	0.30	1.43
2001 - 2002	0.15	0.18	0.16	2.05
2002 - 2003	0.14	-0.54	-0.36	-0.97
2003 - 2004	0.11	-1.22	-0.15	-2.11
2004 - 2005	0.11	0.47	0.04	-0.51
2005 - 2006	0.10	-0.43	-1.09	-1.61
2006 - 2007	0.14	-0.09	-0.41	-0.15
2007 - 2008	0.11	0.65	0.70	0.24
2008 - 2009	0.15	-1.16	-0.12	-0.77
2009 - 2010	0.13	1.20	1.11	0.54
2010 - 2011	-1.94	1.28	0.90	1.55
2011 - 2012	-0.95	0.44	-1.33	-0.61
2012 - 2013	-0.69	-0.79	-0.57	0.64
2013 - 2014	1.18	0.89	0.95	0.92
2014 - 2015	-0.06	1.13	-0.32	0.31
2015 - 2016	-2.95	-0.74	-1.82	-1.67
2016 - 2017	0.99	-2.43	-2.34	-0.94

Table 29. 6 Month SPI for all AEZ

Year	Lubombo Plateau	Middleveld	Highveld	Lowveld
1986 - 1987	-1.78	-0.56	-0.39	-0.59
1987 - 1988	-0.99	-0.13	-0.21	-0.49
1988 - 1989	0.66	2.38	1.41	0.14
1989 - 1990	1.85	1.60	0.65	0.47
1990 - 1991	1.79	0.03	-0.40	-1.07
1991 - 1992	0.03	0.42	1.72	0.16
1992 - 1993	-1.44	-1.24	-1.22	-0.90
1993 - 1994	0.03	-0.51	-0.09	0.22
1994 - 1995	-0.01	-0.47	0.35	-0.64
1995 - 1996	0.04	0.12	0.31	0.47
1996 - 1997	0.06	0.53	0.75	0.58
1997 - 1998	0.09	-0.50	0.08	0.31
1998 - 1999	0.09	0.24	2.43	0.70
1999 - 2000	0.19	-0.37	-0.38	1.35
2000 - 2001	0.15	0.71	1.86	3.16
2001 - 2002	0.15	-0.13	-0.32	0.97
2002 - 2003	0.13	-1.47	-1.04	-1.51
2003 - 2004	0.10	-1.11	-0.57	-1.95
2004 - 2005	0.14	1.01	0.26	0.42
2005 - 2006	0.17	-0.23	-0.72	-0.53
2006 - 2007	0.07	1.48	0.20	0.70
2007 - 2008	0.11	-0.54	-0.40	-0.24
2008 - 2009	0.17	-1.45	-0.87	-1.05
2009 - 2010	0.12	0.89	0.71	-0.04
2010 - 2011	-1.48	0.83	0.74	0.52
2011 - 2012	-1.90	0.09	-0.70	-0.36
2012 - 2013	-0.13	-0.27	-0.35	0.91
2013 - 2014	1.94	0.94	0.93	1.15
2014 - 2015	-0.39	1.60	0.20	0.09
2015 - 2016	-2.40	-0.83	-1.01	-1.86
2016 - 2017	1.35	-2.05	-2.13	-0.60

10.2 SPI MAPPING

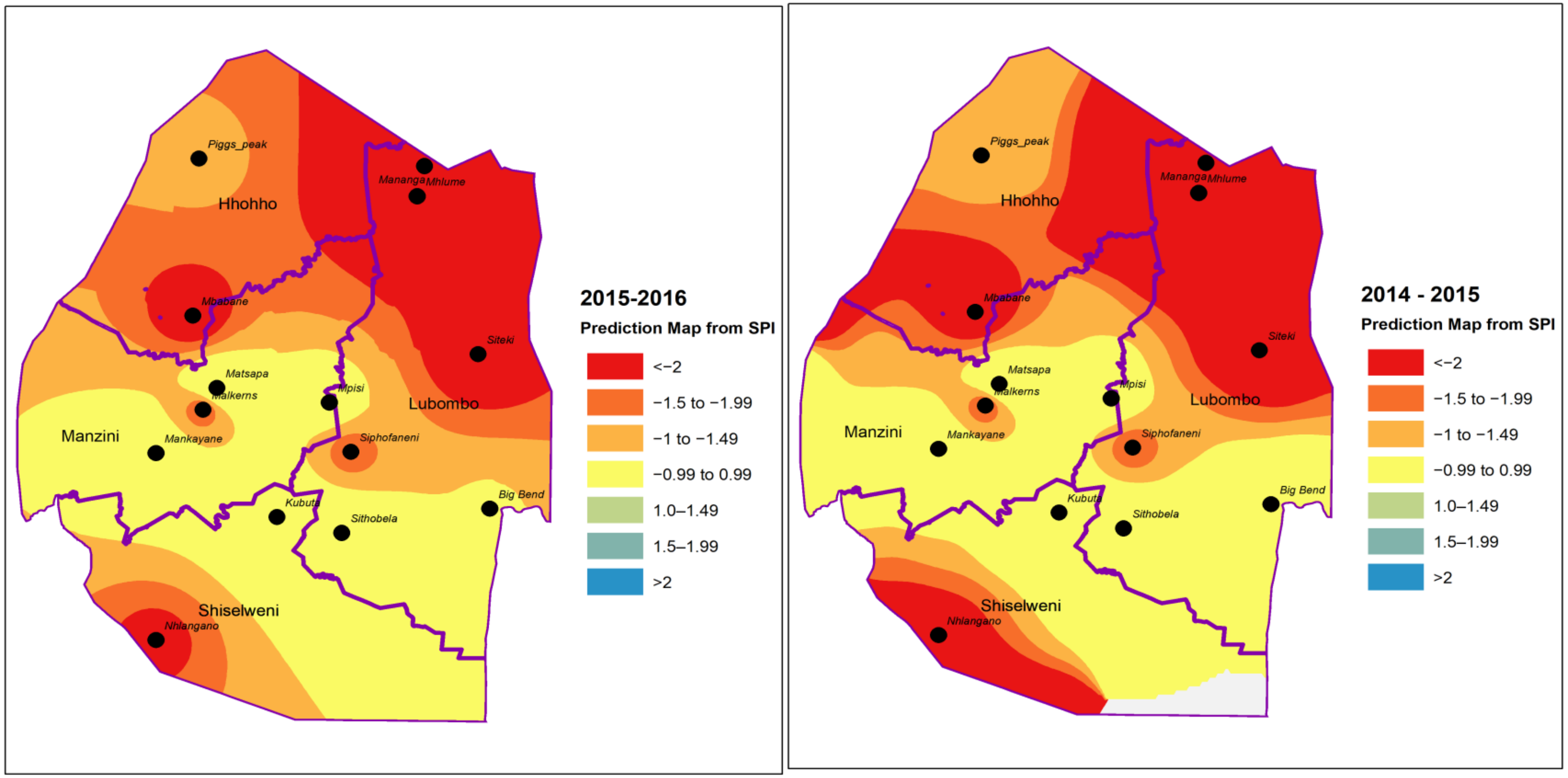

Figure 58. 12 Month SPI for 2016/ 2016 and 2014/2015

10.3 DROUGHT SEVERITY MODELLING DATA

10.3.1 3-Month Drought Severity Calculation

Table 30. Summary of Outputs- 3-Month Drought Severity Calculation.

Regression Statistics	
Multiple R	0,441084211
R Square	0,194555281
Adjusted R Square	0,021959984
Standard Error	0,496092843
Observations	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0,832264257	0,277421419	1,127233965	0,371691318
Residual	14	3,445513521	0,246108109		
Total	17	4,277777778			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	2,724090907	8,494641607	0,320683442	0,753186973	-15,49510333	20,94328514	-15,49510333	20,94328514
NDVI	8,738966373	4,987263935	1,752256646	0,101592621	-1,957650924	19,43558367	-1,957650924	19,43558367
Temperature	-0,345337936	0,402887828	-0,857156537	0,405792598	-1,209446386	0,518770515	-1,209446386	0,518770515
SPI-3	-0,119151647	0,162532174	-0,733095758	0,475596925	-0,467748489	0,229445195	-0,467748489	0,229445195

Y = β0 +β1 X1 + β2 X2 + β3 X3

10.3.2 6-Month Drought Severity Calculation

Table 31. Summary of Outputs- 6-Month Drought Severity Calculation

Regression Statistics	
Multiple R	0,51902
R Square	0,269382
Adjusted R Square	0,112821
Standard Error	0,472488
Observations	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	1,152355	0,384118	1,720618	0,208536
Residual	14	3,125423	0,223244		
Total	17	4,277778			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	4,521466	8,11882	0,556912	0,586381	-12,8917	21,9346	-12,8917	21,9346
NDVI	9,681273	4,300777	2,251052	0,040973	0,457023	18,90552	0,457023	18,90552
Temperature	-0,4469	0,374933	-1,19195	0,253094	-1,25105	0,35725	-1,25105	0,35725
SPI-6	-0,15995	0,112363	-1,42348	0,176501	-0,40094	0,081049	-0,40094	0,081049

10.3.3 12-Month Drought Severity Calculation

Table 32. Summary of Outputs – 12-Month Drought Severity Calculation

Regression Statistics	
Multiple R	0,524937
R Square	0,275559
Adjusted R Square	0,120322
Standard Error	0,470486
Observations	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	1,178781	0,392927	1,775083	0,198019
Residual	14	3,098997	0,221357		
Total	17	4,277778			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	5,283146	8,239854	0,64117	0,531769	-12,3896	22,95587	-12,3896	22,95587
NDVI	9,633658	4,230746	2,277059	0,039009	0,55961	18,70771	0,55961	18,70771
Temperature	-0,4781	0,381286	-1,25391	0,230408	-1,29588	0,339678	-1,29588	0,339678
SPI-12	-0,17068	0,116057	-1,47069	0,16349	-0,4196	0,078233	-0,4196	0,078233

10.3.4 Temperature data 1986-2017

Table 33. October, November, December Temperature 1986-2017

Year	Oct	Nov	Dec	Average Temperature
1986	24.4	24.6	22.0	23.6
1987	24.2	24.3	23.4	24.0
1988	23.3	23.9	23.4	23.5
1989	24.9	25.0	22.8	24.2
1990	23.7	23.9	23.9	23.8
1991	23.8	23.7	22.6	23.4
1992	24.2	25.2	23.5	24.3
1993	24.2	23.7	22.4	23.5
1994	23.1	23.2	22.9	23.1
1995	24.1	24.3	22.9	23.8
1996	23.7	23.8	21.9	23.1
1997	23.8	23.6	22.5	23.3
1998	23.8	24.1	24.0	24.0
1999	24.0	23.5	23.5	23.7
2000	23.3	23.9	23.4	23.5
2001	23.7	23.4	23.2	23.4
2002	23.9	23.0	23.2	23.4
2003	24.2	25.1	23.5	24.3
2004	22.7	24.1	22.8	23.2
2005	24.2	24.5	22.3	23.7
2006	24.4	24.6	22.0	23.6
2007	24.2	24.7	22.9	23.9
2008	23.3	24.3	22.7	23.4
2009	24.0	23.5	22.2	23.2
2010	24.2	24.3	23.4	24.0
2011	23.8	24.3	23.9	24.0
2012	24.9	25.0	22.8	24.2
2013	23.6	25.1	23.6	24.1
2014	24.2	24.8	22.9	23.9
2015	23.7	23.9	23.9	23.8
2016	24.2	24.1	23.9	24.1
2017	24.2	25.1	23.5	24.3

10.4 APPENDIX A : DATA COLLECTION TOOLS

10.4.1 PhD thesis questionnaire survey

COVER LETTER

Name: Daniel Hodges Mlenga

Institution: University of the Free State (**UFS**), Disaster Management Training and Education Centre for Africa (**DiMTEC)**

Address: Bloemfontein Campus, 205 Nelson Mandela Drive Bloemfontein 9300. South Africa

Dear Sir/Madam,

I am currently pursuing a PhD at the University of the Free State, Disaster Management Training and Education Centre for Africa (**DiMTEC)** focusing mainly on drought monitoring and early warning systems. The purpose of my study is to learn more about drought monitoring tools that are in existence and are being used in Africa and around the world. I would like to determine which tools are applicable for Eswatini and how they can be best used to monitor and report drought in the country. I would also want to know what structures operate nationally, how they can be improved to ensure that they effectively work together to timely monitor drought and disseminate the drought risks to all users who need the information.

I believe the results will not only be valuable to government drought planners but will also be essential to key decision makers, policy makers, researchers, farmers and general communities at large, as a well-functioning drought monitoring and early warning system will allow timely planning, effective preparedness, timely response thereby saving time, lives and allow effective use of resources.

The company/institution you are working for is part of the current drought monitoring, early warning infrastructure. Therefore, your contribution is solicited, as your knowledge and experience will be critical to the success of this study. I recognize the value of your time, and sincerely appreciate your efforts. Individual responses are anonymous, and data will be held in confidence.

Thank you for your time.

Your Sincerely

Daniel Mlenga
Doctoral Research Candidate in Disaster Management-Cell: 0027780243682-

Kindly provide responses/ information to the questions below:

1. What drought indices are being utilised for Eswatini?
    - NDVI Yes ☐ No ☐
    - SPI Yes ☐ No ☐
    - Deciles Yes ☐ No ☐
    - Percent of Normal Yes ☐ No ☐
    - River Flow Yes ☐ No ☐
    - Crop Moisture Index Yes ☐ No ☐
    - Vegetation Crop Index Yes ☐ No ☐
    -
2. What is the frequency of large-scale droughts?
    - Seasonal Yes ☐ No ☐
    - Annual Yes ☐ No ☐
    - 1 in 3 years Yes ☐ No ☐
    - 2 in 5 years Yes ☐ No ☐
    - 1 in 10 years Yes ☐ No ☐
    - 1 > 10 years Yes ☐ No ☐
    - 2 > 10 years Yes ☐ No ☐
    - Irregular Yes ☐ No ☐

3. What are the most important time scales of drought for region/your applications?
    - Daily Yes ☐ No ☐
    - Weekly Yes ☐ No ☐
    - Seasonal Yes ☐ No ☐
    - Annual Yes ☐ No ☐
    - Multi-annual Yes ☐ No ☐
    - Trends Yes ☐ No ☐

4. How effective are Drought Indices currently used?
    - Effective Yes ☐ No ☐
    - Not effective Yes ☐ No ☐
    - Somehow effective Yes ☐ No ☐

5. When is drought declaration made by Cabinet?
    - After drought impacts are being felt Yes ☐ No ☐
    - Before drought impacts are being felt Yes ☐ No ☐

6. Do you feel drought disaster declaration is made on time?
    - On time Yes ☐ No ☐
    - Late Yes ☐ No ☐

7. Existence of Drought Early Warning System? Yes ☐ No ☐

8. Do you already have a drought early warning system? Yes ☐ No ☐
9. if yes, what does that entail?

- monitoring Yes ☐ No ☐
- prediction Yes ☐ No ☐
- plans and/or Yes ☐ No ☐
- triggers in place to respond to warnings, Yes ☐ No ☐
- impact collection Yes ☐ No ☐
- drought mitigation Yes ☐ No ☐
- recovery support)? Yes ☐ No ☐

10. What is your assessment of current drought prediction capabilities (e.g., the ability to predict the onset, persistence, and end of a drought)?

- Very good Yes ☐ No ☐
- Good Yes ☐ No ☐
- Limited Yes ☐ No ☐
- Not existent Yes ☐ No ☐

11. What regional and/or national drought information and prediction capabilities do you have (if any)?

----

12. Is there a need to develop, strengthen an Eswatini drought monitoring system/ drought information capabilities/products do you currently use? Yes ☐ No ☐

13. If yes how best can the system be improved?

----

14. Do the relevant national institutes have the technical and human capacity to (a) run or (b) use such an improvement in the system? Please explain where do you see any challenges? 3: Requirement for infrastructural support?

----

15. Suggestions for implementation of Eswatini Drought Monitoring/ Drought Early Warning System?

- Improved tools Yes ☐ No ☐
- Better coordination Yes ☐ No ☐
- More staff Yes ☐ No ☐
- Capacity development Yes ☐ No ☐
- Increased resources Yes ☐ No ☐
- Other (explain)--

THANK YOU