DEVELOPMENT OF AN AGRICULTURAL DROUGHT PREPAREDNESS FRAMEWORK FOR SOUTH AFRICAN CROPLANDS AND GRASSLANDS

Report to the
WATER RESEARCH COMMISSION

by

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WRC Report No. 2968/1/23
ISBN 978-0-6392-0532-8

July 2023

Obtainable from
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EXECUTIVE SUMMARY

Extreme climate events serve as the most costly natural disasters in Africa, with drought alone accounting for 25% of all natural disasters that occurred between 1960 and 2006. There is an increasing concern that the frequency, severity and duration of droughts might increase as a consequence of climate change and observed increases in extreme climate events. In South Africa, drought represents one of the most important natural factors contributing to large reductions in agricultural production, food insecurity, reduced livelihoods and economic losses. Crop production in the country varies a lot from one year to another, mainly due to climate variability. Years of poor harvests negatively affect South Africa's economy, which is highly reliant on the agricultural industry. In addition, the negative impact of drought on grazing land remains a concern with regard to livestock production.

In 2015/16, South Africa faced a disaster-drought, resulting in greatly reduced summer crop production. For example, only 7.7 million tonnes of maize were produced, which is about 40% lower than the previous 5-year average. This is because seasonal rainfall was about 30% lower than the long-term average (550 mm) in the summer crop production areas. Similarly, drought events occurred in 1972/73, 1978/79, 1981/82, 1982/83, 1991/92, 1994/95 and 2006/07. These statistics indicate that devastating agricultural droughts occur at least every 5 to 10 years in South Africa. Commonly, it is the resource-poor farmers that are most affected, due to insufficient or lack of proper drought information.

It is evident that drought is the biggest risk to agriculture in South Africa, and the main challenge we are facing is how to use climate information for risk management strategies that assist in coping with rainfall variability. In the 21st century, new techniques and algorithms are required to address food security challenges and provide solutions for agriculture. The use of model simulations, remote sensing and GIS technologies coupled with the collection of field samples for monitoring has yielded positive outcomes. The collection of field samples, although labour intensive, can give indications of available data for the upcoming season that can assist farmers to avoid practices that will exacerbate land degradation.

In recent decades, ample scientific and institutional efforts have been devoted to developing drought early warning systems (DEWS) worldwide. These systems, encompassing reliable weather and climate forecasts, are in use in many countries to assist in preparing for the upcoming season and mitigating climate risk. Farmers, pastoralists and land managers can thus use tailored seasonal forecasts to inform on-farm decisions. However, low adoption of scientific developments has been noted in many cases, the reasons for which centre around trust issues between scientists and end-users, interpretation – and thus relevance – of the information, and the dissemination platforms that are utilized. There is a need to advance on dissemination methods used during the COVID-19 pandemic on communication platforms such as Zoom, Microsoft Teams, SMSs, e-mail and media.

In Africa, very few countries have succeeded with approaches towards improving agricultural DEWS, with certain aspects still needing to be improved. Early warning activities in countries such as Tunisia, Ethiopia, Ghana, Uganda and Kenya have provided great benefits in terms of alerting the respective governments and stakeholders on agricultural drought risks. Activities from these countries demonstrate the significant role of policies and structures by governments to plan for and reduce the resulting impacts on drought-sensitive sectors. Furthermore, various regional centres have established programmes and progressively improved in providing climate forecasts, as well as drought early warning information to decision-makers and the agricultural community at large.

Globally, many other initiatives exist which show how web-based systems can provide effective drought monitoring and timely warnings to enhance drought preparedness and response. However, the gaps that exist in these aforementioned developments leave ample room for improvement. Thus, this study aimed to develop an agricultural drought preparedness framework to improve operational capabilities of South Africa to cope with drought. The specific aims of the project were to:

- Undertake a review on agricultural drought preparedness and systems in South Africa;
- Develop a drought monitoring and early warning system; and
- Improve agricultural drought preparedness, response, mitigation and recovery framework.

The study acknowledged the necessity to use drought indices in detecting and describing the various characteristics of agricultural drought. These drought indices are functions of a single or multiple variables providing quantitative meaning of the concept. Peer-reviewed literature was assessed using Google Scholar as the main search engine to identify the different drought indices. Several factors contributing to agricultural drought were considered, viz. climate, soil and crop factors; and a presentation of agricultural drought indices based on *in-situ* and remote sensing data was followed. A total of 50 drought indices have been identified by the study, and established drought indices mainly used for monitoring agricultural drought were described.

Composite drought indices are the most recent generation developed since the year 2000 but they have not found much application in many parts of the world. In general, the use of spatio-temporal dense datasets requires multiple observation networks. Hence, institutions and authorities with complementary resources need to collaborate to provide comprehensive drought monitoring and share financial commitments. Using this listing, the study provided a means of comparing drought indices to further identify suitable indices within each group of application.

Based on South Africa's high climatic variations, the country's agriculture is very diverse. Activities ranges from cattle ranching and sheep production in the Savanna biome and Nama-Karoo, respectively, to intensive crop and mixed farming systems in the summer and winter rainfall regions. Crop production serves as a vital source of food security and a contributor to GDP, mainly through commercial farming (about 90% of total output). However, small-scale systems contribute toward employment even though they are commonly poorly resourced.

The state of rangelands around the world has deteriorated tremendously due to the high demand of natural resources exacerbated by the growing human population and the study further discussed the challenges facing rangelands in agricultural production. Rangeland uses range from providing natural resources such as water and land, goods and services and grazing. Although multiple strategies are in place to use rangelands sustainably, there remains a gap to come up with innovative strategies to improve on existing ones. Land degradation is one of the most important challenges in rangelands and its causes include overgrazing, overpopulation, over-cultivation and climate vagaries.

Livestock production contributes massively to the global economy and is important for feeding people, particularly by providing livestock products. Climate change and variability are other factors threatening rangeland production across the world. Therefore, the sustainable management of rangelands is vital for the continued supply of resources to current and future generations with less degradation. Extensive research, policies and funds should be invested in the rangelands sector to realize this vision. Future assessments should, therefore, focus on improving current strategies to become sustainable for future generations. The following strategies can be adopted in various rangelands both locally and globally:

- The participation of the local community in research projects (co-development).
- The use of machine learning and big data to enhance adaptation.
- Planting new cultivars that are stable and resilient to climate extremes.
- Attempts at the restoration of forests (a long-term investment).
- Financial incentives for pastoralists that comply with rules set by government.
- The establishment of centres for cross-breeding plants, stock breeding, as well as research facilities for rangelands.
- The use of marketing to improve sales of products and income.
- The use of an early warning system for farmers and other key decision-makers.

The study revealed that, ideally, early warning systems should include the functionality of collecting, storing and processing data to assess risk and vulnerability at a specified location and period. Moreover, it is vital to utilize climate forecasts together with drought indices to predict impending agricultural droughts and to incorporate field observations in agricultural drought monitoring. It is also necessary for early warning systems to communicate information in a simplified manner through a variety of methods, to ensure minimum delay in delivery and to improve usefulness. These may include various formats (interactive map, text and graphs) and by using media as a communication channel (internet, radio, television, social media, etc.). More broadly, for future studies, it is recommended to explore how other opportunities outside the domain of the traditional desktop, including technologies of the 4th Industrial Revolution (4IR), such as cloud computing, big data analytics, Artificial Intelligence and Internet of Things can inform the next wave in the era of web-based agricultural DEWS.

It was further observed that an effective drought early warning system should comprise contingency plans for a realistic disaster risk reduction strategy. These plans add value to the proactive nature of DEWS such that they minimize loss as opposed to responding to loss. In addition, potential challenges to be anticipated when developing agricultural DEWS should be acknowledged. The role of policy was also assessed and the findings revealed certain drawbacks with regard to implementation. Based on the survey conducted, the majority of participants (73%) do not fully understand seasonal forecasts, thus raising concern for incorrect interpretation necessary for early warning. Current DEWS in South Africa are manual, thus necessitating the need for improvement.

Accordingly, the project developed a new Agricultural Drought Early Warning System (ADEWS). This is a web-based system that provides free information to registered users. Products available are based on a wide range of input data sourced from the ARC's automatic weather station network and an in-house database of historical and near-real-time satellite imagery for environmental monitoring. The ADEWS produces daily updates on developing drought conditions across South Africa, based on observed and forecasted data. It also allows for weekly updates and alerts for user-specified locations. In this report we demonstrate the products and functionality of the ADEWS while also creating awareness to environmental monitoring in South Africa.

In summary, the study aligned the use of drought early warning systems with current overall disaster policy by analysing its effectiveness. It was revealed that South Africa has made commendable progress in its policies and frameworks for drought risk management. The inclusive approach adopted in policy formulation, as well as the establishment of the Disaster Management Act (DMA) and the National Disaster Management Framework (NDMF), are positive steps. However, there is room for improvement, particularly in integrating proactive measures into the funding system, strengthening the implementation of the NDMF, and enhancing coordination among relevant entities. By addressing these areas, the country can further enhance its disaster management capabilities and better protect its population and resources from the impacts of drought and other disasters.

ACKNOWLEDGEMENTS

The authors would like to thank the Water Research Commission (WRC) for funding this project. We also express gratitude to the following reference group members for their time, valuable insights and specific inputs to this study:

Dr L Nhamo	: Water Research Commission (Chairman)
Prof. NS Mpandeli	: WRC
Prof. ERM Archer	: University of Pretoria
Prof. B Ncube	: Cape Peninsula University of Technology
Prof. M Cho	: Council for Scientific and Industrial Research (CSIR)
Dr S Hlophe-Ginindza	: WRC
Ms M Kapari	: WRC
Mr K Tshipala	: Transnet

We gratefully acknowledge the assistance of the following colleagues from the ARC:

Dr MP Maila
Dr TP Fyfield
Mr PM Nakana
Mr MP Letjeku
Ms PV Mooketsi
Ms MN Ramogale

We would further like to express our sincere appreciation to all the government department representatives who participated in the survey for this research project. Your valuable inputs and willingness to engage with us were instrumental in enhancing our understanding and significantly contributed to the comprehensiveness of this study. Your contributions greatly enriched the quality and depth of our research findings, and we extend our heartfelt gratitude for your time, expertise and dedication.

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LIST OF ABBREVIATIONS AND ACRONYMS

AAI	Aridity Anomaly Index
ACMAD	African Centre of Meteorological Applications for Development
ACTED	Agency for Technical Cooperation and Development
ADEWS	Agricultural Drought Early Warning System
ADI	Accumulated Drought Index
ADMS	Agricultural Drought Monitoring System
AETc	Actual Crop Evapotranspiration
ANPP	Annual Net Primary Production
ARC	Agricultural Research Council
ARC-NRE	Agricultural Research Council – Natural Resources and Engineering
ARC-SCW	Agricultural Research Council – Soil, Climate and Water
ARID	Agricultural Reference Index for Drought
ATI	Apparent Thermal Inertia
AU	African Union
BMDI	Bhalme and Mooley Drought Index
CariCOF	Caribbean Climate Outlook Forum
CCAM	Conformal Cubic Atmospheric Model
CDI	Combined Drought Indicator
CERES	Crop Environment Resource Synthesis
CILSS	Committee for Drought Control in the Sahel
CIMH	Caribbean Institute for Meteorology and Hydrology
CMI	Crop Moisture Index
CoGTA	Department of Cooperative Governance and Traditional Affairs
CRCC	Caribbean Regional Climate Centre
CRID	Coarse-Resolution Imagery Database
CSDI	Crop Specific Drought Index
CSIR	Council for Scientific and Industrial Research
CTCN	Climate Technology Centre and Network
CWB	Climatic Water Balance

CWSI	Crop Water Stress Index
DALRRD	Department of Agriculture, Land Reform and Rural Development
DEWS	Drought Early Warning System(s)
DMA	Disaster Management Act
DMCN	Drought Monitoring Centre – Nairobi
DMP	Drought Management Plan
DMPmax	Maximum Dry Matter Production
DMTT	Drought Management Task Team
DRR	Disaster Risk Reduction
DSI	Drought Severity Index
DSSAT	Decision Support Tool for Agrotechnology Transfer
DTx	Agricultural Drought Index
DWS	Department of Water and Sanitation
EDI	Effective Drought Index
EDTI	Evapotranspiration Deficit Index
ENCU	Emergency Nutrition Coordination Unit
ENSO	El Niño Southern Oscillation
EO	Earth Observation
EPA	Environmental Protection Agency
ESI	Evaporative Stress Index
ET0	Reference Evapotranspiration
EVI	Enhanced Vegetation Index
EWRD	Early Warning and Response Directorate
EWU	Early Warning Unit
FAO	Food and Agriculture Organization
FEWS NET	Famine Early Warning Systems Network
GDP	Gross Domestic Product
GEFS	Global Ensemble Forecast System
GFS	Global Forecast System
GIDMaPS	Global Integrated Drought Monitoring and Prediction System
GIS	Geographical Information System

HDSI	Hutchinson Drought Severity Index
HTC	Hydro-thermal Coefficient of Selyaninov
ICDM	Intergovernmental Committee on Disaster Management
ICPAC	IGAD Climate Prediction and Applications Centre
IGAD	Intergovernmental Authority for Development
IIT-GN	Indian Institute of Technology – Gandhi Nagar
ISDI	Integrated Surface Drought Index
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
KBDI	Keetch-Byram Drought Index
Kc	Crop Factor
KPAs	Key Performance Areas
LEAP	Livelihoods, Early Assessment and Protection Index
LWCI	Leaf Water Content Index
MAAIF	Ministry of Agriculture, Animal Industry and Fisheries
MAI	Moisture Adequacy Index
MODIS	Moderate Resolution Imaging Spectroradiometer
MSD	Moisture Stress Days
MSDI	Multivariate Standardized Drought Index
NAC	National Agro-meteorological Committee
NCC	National Climate Center
NCDC	National Climatic Data Center
NDI	NOAA Drought Index
NDII	Normalized Difference Infrared Index
NDJCC	National Joint Drought Coordination Committee
NDMA	National Drought Management Authority
NDMAF	National Disaster Management Advisory Forum
NDMC	National Disaster Management Centre
NDMF	National Disaster Management Framework
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index

NECOC	National Emergency Coordination and Operations Centre
NetCDF	Network Common Data Form
NIDIS	National Integrated Drought Information System
NSMs	National Meteorological Services
PAI	Pálfai Aridity Index
PASG	Percentage of Average Seasonal Greenness
PAW	Plant-Available Water
PDMC	Provincial Disaster Management Centre
PDSI	Palmer Drought Severity Index
PET	Potential Evapotranspiration
PNI	Percent of Normal Index
PSNP	Productive Safety Net Programme
RAI	Rainfall Anomaly Index
RCMRD	Regional Centre for Mapping of Resources for Development
RDI	Reconnaissance Drought Index
RWDI	Relative Water Deficit Index
SADC	Southern African Development Community
SADC-CSC	Southern African Development Community – Climate Services Centre
SAI	Standardized Anomaly Index
SAVI	Soil Adjusted Vegetation Index
SAWS	South African Weather Service
SDMP	Sectoral Drought Management Plan
SDRMP	Sectoral Disaster Risk Management Plan
SMAI	Soil Moisture Anomaly Index
SMDI	Soil Moisture Deficit Index
SMS	Short Message Service
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SVI	Standardized Vegetation Index
SWOT	Strengths, Weaknesses, Opportunities and Threats
TCI	Temperature Condition Index

TVDI	Temperature-Vegetation Dryness Index
TVX	Temperature-Vegetation Index
UNDP	United Nations Development Programme
UNECA	United Nations Economic Commission for Africa
USDM	United States Drought Monitor
VCI	Vegetation Condition Index
VegDRI	Vegetation Drought Response Index
VHI	Vegetation Health Index
VIC	Variable Infiltration Capacity
VIIRS	Visible Infrared Imaging Radiometer Suite
VSWD	Vegetation-Soil Water Deficit
WASP	Weighted Anomaly Standardized Precipitation
WFP	World Food Programme
WHC	Water-Holding Capacity
WRC	Water Research Commission
WRSI	Water Requirement Satisfaction Index

CHAPTER 1. INTRODUCTION

1.1. Research background

Agricultural drought is a multifaceted challenge across many parts of the world. According to Bordi and Sutera (2007), this type of drought occurs when soil moisture is inadequate to meet crop water requirements during the growing season, thus resulting in a decline in agricultural production. However, it reaches a state of disaster when the impacts ultimately affect human activities such as availability of food, health and quality of life (Cunha *et al.*, 2019). Drought-induced disasters are commonly not immediately evident; they can last for long periods and usually end within 12-36 months (DAFF, 2005). Unlike other climate-related disasters, there is often a time lag between the onset of drought and its resulting impacts on agriculture (Malherbe *et al.*, 2016; Rouault and Richard, 2005).

In South Africa, drought is an inevitable climate-related disaster and an important aspect of agricultural productivity. The occurrences thereof have had adverse implications on the agricultural sector, mainly affecting vulnerable communities and the country's economy (Archer *et al.*, 2019; Botai *et al.*, 2016). South African crop production varies a lot from one year to another due mainly to rainfall variability (Tsubo and Walker, 2007). Years of poor harvests negatively affect the country's economy, which is highly reliant on the agricultural industry. In recent history, the summer rainfall region experienced one of the most extreme droughts of the past century during the 2015/16 agricultural season. By the end of the season, only 7.7 million tons of maize were produced, which is about 40% lower than the previous 5-year average (DAFF, 2019). This led to the importation of maize (the largest summer crop produced in South Africa), thus resulting in the loss of foreign exchange normally derived from agricultural exports.

Following a poor harvest caused by drought during the 2015/16 season, the total production for both commercial and non-commercial maize reached a peak of 6.37 and 1.99 tons/ha, respectively, during the 2016/17 season (DALRRD, 2020c). The gross value of maize during that season contributed 10.9% to the total gross value of agricultural commodities. In contrast, the winter rainfall region experienced severe to extreme drought conditions during the 2016/17 season and consequently contributed negatively to the production of wheat. In real terms, South Africa's total agricultural production by the end of the 2018/19 season contributed 2.4% to GDP (DAFF, 2019). This was the highest percentage of total value added since 2010.

Amongst other factors, the positive economic activity during the 2018/19 season was partially driven by a rise in the value of animal products and field crops. The months of December 2018 and January 2019 were associated with below-normal rainfall over much of eastern South Africa which raised a major concern for dryland crop producers (BFAP, 2018). However, in February the summer rainfall region received above-normal rains (ARC-SCW, 2022), which allowed farmers to continue planting. This prevented South Africa from moving to import parity which would have resulted in major increases in food staple prices, thus signifying the important implications of drought on the socio-economic well-being of the country.

Similarly, drought events occurred in 1972/73, 1978/79, 1981-83, 1991/92, 1994/95, 2004/05, 2006/07, 2015/16 and 2018-20 (Malherbe *et al*., 2016; Meza *et al*., 2021; Archer *et al*., 2022). These statistics indicate that devastating agricultural droughts occur at least every 5 to 10 years in South Africa. In addition, the negative impact of drought on grazing land (Vetter *et al*., 2020) is a concern with regard to livestock production. Thus, drought is the biggest risk to agriculture in South Africa, and the main challenge we are facing is how to use climate information for risk management strategies that assist in coping with rainfall variability.

1.2. Motivation

Extreme climate events serve as the most costly natural disasters in Africa, with drought alone accounting for 25% of all natural disasters that occurred between 1960 and 2006 (Gautam, 2006; EM-DAT, 2022). There is an increasing concern that the frequency, severity and duration of droughts might increase as a consequence of climate change and observed increases in extreme climate events (Seneviratne *et al*., 2012). Extreme drought occurrences in recent years in South Africa have had large socio-economic impacts and contributed to lower agricultural productivity in major cropping and livestock areas of the country. Drought represents one of the most important natural factors contributing to large reductions in agricultural production, food insecurity, reduced livelihoods and economic losses (Vogel *et al*., 2000; Wilhelmi *et al*., 2002; Khalili *et al*., 2013).

In drought risk management, little has been done to address the comprehensive connection between drought risk, vulnerability to the risk, and the capability of regions to mitigate future drought impacts, thus limiting an accurate reflection of the concept of drought. Commonly, it is the rural and resource-poor farmers that are most affected by drought risk due mainly to insufficient or lack of proper climate information. In this regard, there needs to be a continuous drought monitoring, early warning and mitigation system in place to promote drought preparedness and reduce the impacts of drought on agricultural practices. This system should link information on drought risk to a communication system that provides adequate time for implementing possible mitigation measures (Pulwarty and Sivakumar, 2014).

One of the widely used ways of communicating climate risk in South Africa is through the media, viz. newspapers, television, radio and social media platforms. However, such information should be timely, easily accessible and simple to interpret (Andersson *et al*., 2019). In addition, it is necessary to convey the information at all levels (local to national), so as to allow for early detection and possible coping measures during and after the drought (Hayes *et al*., 2000). This could ideally promote a high level of interaction and communication between researchers, policy-makers and farmers for better understanding and decision-making regarding the impacts of agricultural drought.

The recurrence of drought in many regions around the world has led to the implementation of risk management strategies as well as improvements in government policies and plans to minimize impacts on various economic sectors (Hao *et al*., 2017). The capacity of each region to effectively prepare for and respond to the effects of drought depends mainly on various biophysical (e.g. soil properties and cropping system) and socio-economic factors (e.g. social behaviour and economic development). Hence, the need for efficient disaster management in order to reduce the impacts accompanied by the occurrence of drought for any region. In practice, effective drought management can be carried out by utilizing the continuous disaster management cycle, which involves four steps, viz. mitigation, preparedness, response and recovery (NDMC, 2013). These steps can occur prior to, during and after a drought event, in order to prevent it (although it is not entirely preventable), reduce its impacts or recover from potential damages.

A study undertaken by Malherbe *et al*. (2016) shows the tendency of an increasing drought frequency of different magnitudes from 1980 to 2014. It is also documented by FAO (2019) that agriculture, especially in developing countries, is among the most vulnerable sectors with losses exceeding 29 billion US dollars in the 10 years between 2005 and 2015. Wilhite (1996) argues that increasing vulnerability to drought incidences in most countries has heightened the impact of drought hazards on communities, resulting in drought-induced natural disasters. This illustrates a need for each country to have a fully functional drought preparedness plan. Unfortunately, most countries delay preparing such a plan until they forced to do so after being confronted by a disaster that was caused by drought.

There is no denying that an ability to foresee drought way ahead of time enhances the capacity to reduce its impact. Many developed countries have invested considerable resources to ensure that they have a well-functioning drought early warning system. Although there have been mixed accomplishments due to challenges regarding the accuracy of medium to seasonal forecasts, the emergence of seasonal forecasting aligned with ENSO cycles in southern Africa has led to recent successes. Thus, it is a worthy investment for governments to improve their early warning for drought for a variety of economic reasons.

1.3. Research objectives

The main aim of the project was to develop an agricultural drought preparedness framework to improve operational capabilities of South Africa to cope with drought. The specific objectives were:

i. To undertake a review on agricultural drought preparedness and systems in South Africa.
ii. To develop a drought monitoring and early warning system.
iii. To improve agricultural drought preparedness, response, mitigation and recovery framework.

1.4. Report outline

This final project report outline provides a structured framework for presenting the research methods, findings and conclusions in a systematic manner. The report starts with CHAPTER 1: INTRODUCTION, which presents the research background and provides context for the study. It also includes sections on the motivation behind the research, research objectives, and an overview of the report's structure (report outline). CHAPTER 2 includes a LITERATURE REVIEW which explores relevant literature on drought indices for agricultural drought, rangeland uses and challenges, and current practice on drought early warning systems. CHAPTER 3 focuses on THE ROLE OF POLICY ON AGRICULTURAL DROUGHT EARLY WARNING SYSTEMS, examining current policy provisions, the early warning systems utilized in the agricultural sector, and how policy can ensure their effectiveness. This chapter concludes with a section summarizing the key findings and implications.

CHAPTER 4 discusses the COLLECTION OF CLIMATE DATA AND INDICES FOR THE DEVELOPMENT OF A DROUGHT EARLY WARNING SYSTEM, covering various types of climate data, remote sensing data, selected drought indices, and modelling approaches for crops and grazing. The chapter ends with conclusions drawn from the collected data. CHAPTER 5 explores the DEVELOPMENT OF AN AGRICULTURAL DROUGHT EARLY WARNING SYSTEM, including user-interface aspects, automated early warning e-mails, system programming and concluding remarks, while CHAPTER 6 focuses on STAKEHOLDER ENGAGEMENT TO TEST ADEWS, to assess the system’s functionality, determine how well it meets user expectations and receive valuable feedback from potential end-users.

CHAPTER 7 focuses on IMPROVING THE EFFECTIVENESS OF DISASTER RISK REDUCTION ON THE MANAGEMENT OF AGRICULTURAL DROUGHT, including sections on introduction, methodology, results, discussion, and concluding remarks. This is followed by a REFERENCES section, listing all literature sources cited in the report. The report concludes with APPENDICES, where additional supporting information, data or supplementary materials can be found.

CHAPTER 2. LITERATURE REVIEW

2.1. Drought indices suitable for quantifying agricultural drought

2.1.1. Introduction

Quantification and monitoring of agricultural drought serve as critical processes to numerous drought early warning systems worldwide (NCC, 2020; NIWA, 2020; Svoboda *et al*., 2002). Previous research has shown that agricultural drought can be characterized based on when water in the soil drops below a certain threshold level and consequently fails to meet the typical crop growth and expected yield requirements (Heim, 2002; Mannocchi *et al*., 2004; Padhee, 2013). This highlights the importance of defining "significant" threshold levels through operational definitions (Mannocchi *et al*., 2004). These definitions are very often represented by a drought index or multiple indices, that strongly guide the meaning of drought by identifying its characteristics, viz. duration, severity, frequency, spatio-temporal patterns and impacts (Mishra and Singh, 2010).

Drought indices are tools that incorporate data from a set of variables (e.g. precipitation and temperature) into numerical values that delineate threshold levels, as opposed to solely using raw data in explaining drought (Zargar *et al*., 2011). Therefore, based on these levels, a user can have a better understanding of the various characteristics of drought in agriculture. Common to most agricultural drought indices is the usage of rainfall data in their calculation. This is mainly due to the fact that all types of drought originate from meteorological drought, as well as the common availability of reliable rainfall observations in most countries (Heim, 2002; Sivakumar *et al*., 2011). However, agricultural drought is related to soil factors and crop phenological cycles (Sivakumar *et al*., 2011).

Currently, numerous indices have been developed to measure agricultural drought worldwide. These indices can be grouped into two categories, viz. *in-situ* and remote sensing. *In-situ* drought indices employ ground-based meteorological variables such as precipitation, temperature, evapotranspiration and soil water content, obtained from weather stations (Wang *et al*., 2015). In contrast, remote sensing drought indices are generated from satellite data, consisting of both meteorological variables and vegetation factors (Hazaymeh and Hassan, 2016). Earth observation

(EO) satellites have been improving since the 1980s and the latest technology satellites are equipped with sensors mainly in the optical domain, providing enhanced remotely sensed information for drought characterization (Niemeyer, 2008). Suitable remote sensing systems are those that can provide low spatial and high temporal resolution data necessary for continuous monitoring (Dalezios *et al*., 2014). Numerous drought indices have been developed to describe vegetation activity, with the potential to detect and monitor agricultural droughts.

There is much discussion on which category of drought index is best suited to measure and monitor agricultural drought. According to Hazaymeh and Hassan (2016), *in-situ*-based indices are efficient and provide the most accurate assessments at a given point. Conversely, Dalezios *et al*. (2014) argued that remote sensing-based indices are potentially better and the usage thereof has been swiftly increasing mainly due to the high reliability caused by the improvement of EO satellites. However, other recent studies preferred a combination of both *in-situ* and remote sensing-based drought indices (e.g. Sun, 2009; Zhao *et al*., 2011), influencing another potential avenue of composite drought indices, especially in regions with diverse climatic conditions. Nonetheless, selecting which type of index to use in an attempt to assess agricultural drought depends on various factors, such as the user's location, objectives and availability of data.

2.1.2. Methodology

In order to search subject-relevant literature, peer-reviewed articles were collected through Google Scholar using the following keywords: assessing agricultural drought; crop water requirements; drought indices; evapotranspiration; growing season; plant water stress; precipitation deficiency; rain-fed agriculture; soil water balance; and vegetation activity. The keyword-based search was limited to the titles of the articles in order to obtain the most relevant literature.

Drought indices were grouped, listed and a short description was provided. The grouping was achieved by selecting indices that met the following criteria, based on their input variables:

- Rainfall only, to detect deviations in precipitation (McKee *et al*., 1993).
- Rainfall and temperature, to account for water lost through evapotranspiration (Vicente-Serrano *et al*., 2010).

- Rainfall, temperature and agronomic factors (soil and/or crop characteristics), to assess water availability in the soil as well as during the growing phases of crops (Sivakumar *et al.*, 2011).
- Remote sensing-based, to assess spatio-temporal variations of drought (Hazaymeh and Hassan, 2016).

The next step was to select drought indices that were identified with the potential suitability of assessing agricultural drought in South Africa. Based on preliminary search results on Google Scholar, established drought indices were further selected following criteria stating that (WMO and GWP, 2016):

- A code or program of the index is easily accessible.
- A single or multiple variables are needed as inputs.
- Missing data are allowed.
- There is minimal complexity of calculations.
- The index is not region-specific and can be applied across various climates.

One optional condition was that the index output should already be produced operationally and available online. Some recognized indices such as the PDSI were omitted, due to their minimal applicability in regions with high rainfall variability. Therefore, a lot of factors feed into determining which index is the best suited for a particular application or region. It is noteworthy that based on their popularity and prevalent use, this review merely highlights recommendable agricultural drought indices.

2.1.3. Drought indices based on input variables

Rainfall data are widely used to calculate drought indices because long-term rainfall records are often available. Rainfall data alone may not broadly depict all features of agricultural drought, but it can be used as a practical solution in areas where other data is unavailable (Smakhtin and Hughes, 2004). Table 2.1 provides drought indices, from as early as the 1960s, which use only rainfall data and have been commonly applied in most agricultural drought assessments worldwide.

Table 2.1: Drought indices based on rainfall only.

Index	Description	Reference
Rainfall Anomaly Index (RAI)	Characterizes drought based on the average rainfall over various periods, viz. weekly, monthly or annual. Relative drought is then ranked based on the ten most severe droughts within the long-term record.	Van-Rooy (1965)
Bhalme and Mooley Drought Index (BMDI)	Considers the monthly or annual rainfall anomaly to describe drought episodes.	Bhalme and Mooley (1980)
Standardized Anomaly Index (SAI)	This index is based upon the results of RAI, and standardized deviations are then averaged over stations within a region to obtain a single SAI value.	Katz and Glantz (1986)
NOAA Drought Index (NDI)	Based on the aggregate of a running 8-week average of measured rainfall. If the actual rainfall is greater than 60% of the normal rainfall for the 8-week period, then the current week is assumed to be under drought conditions, until the actual rainfall is back at 60% or more of normal.	Strommen and Motha (1987)
Pálfai Aridity Index (PAI)	Predominantly applied in Hungary and illustrates drought according to rainfall, temperature and groundwater data.	Pálfai (1991)
Drought Severity Index (DSI)	Calculates accumulated monthly rainfall deficit in preceding months to describe drought and is frequently used in the UK.	Bryant *et al*. (1992)
Dry Spell Drought Indicator	Determines the number of dry days during a crop's growing season.	Sivakumar (1992)
Hutchinson Drought Severity Index (HDSI)	Uses the same concept as Palmer's moisture balance drought index, with only rainfall data.	Smith *et al*. (1992)
Standardized Precipitation Index (SPI)	Determines rainfall probabilities for different time scales to define drought.	McKee *et al*. (1993)
Percent of Normal Index (PNI)	Expressed as a percentage of normal rainfall to its long-term mean.	Willeke *et al*. (1994)
Effective Drought Index (EDI)	Uses daily rainfall data to develop and compute parameters associated with effective precipitation, to identify the onset and end of water deficit periods.	Byun and Wilhite (1999)

Several drought indices that integrate temperature as an input variable have also been developed (Table 2.2), mainly due to the dynamics between temperature and surface water in explaining drought. During the development of a drought, incoming solar radiation causes air temperatures to rise by heating up dry land and also contributing to high evaporative demand (Palmer, 1965). Thus, evapotranspiration serves as an important variable in drought monitoring as it describes water availability and the rate at which the water is consumed by both crops and the soil (Vicente-Serrano *et al*., 2010). There are other variables, however, that can further explain this process, such as relative humidity and wind speed (Allen *et al*., 1998).

Table 2.2: Drought indices based on rainfall and temperature.

Index	Description	Reference
Hydro-Thermal Coefficient (HTC) of Selyaninov	Based on decadal and monthly rainfall and temperature data. However, the index is climate-regime specific and cannot be compared across different climates.	Selyaninov (1928)
Moisture Adequacy Index (MAI)	The MAI is expressed as a percentage and compares the water requirements to the rainfall and stored soil water for a given location.	McGuire and Palmer (1957)
Moisture Anomaly Index (Z-index)	Uses weekly or monthly rainfall and potential evapotranspiration data in a simple water balance equation to determine drought.	Palmer (1965)
Keetch-Byram Drought Index (KBDI)	Calculates rainfall and evapotranspiration to produce a moisture deficiency value in the soil upper layers. The index also gives an indication of the amount of rainfall needed to recover from drought stress.	Keetch and Byram (1968)
Crop Moisture Index (CMI)	Calculated by subtracting the difference between rainfall and potential evapotranspiration to determine any deficit.	Palmer (1968)
Reconnaissance Drought Index (RDI)	Measures accumulated deficit between the evaporative demand and actual rainfall for different periods of time.	Tsakiris and Vangelis (2005)
Standardized Precipitation Evapotranspiration Index (SPEI)	Uses probabilities of a simple climatic water balance for different time scales to define drought.	Vicente-Serrano *et al*. (2010)
Relative Water Deficit Index (RWDI)	Defined by the relative difference between actual and potential evapotranspiration for the period considered.	Sivakumar *et al*. (2011)

Index	Description	Reference
Accumulated Drought Index (ADI)	Uses a relation between rainfall and evapotranspiration. However, there is limited information available in the literature regarding the establishment or verification of the ADI.	CIIAGRO (2012)
Aridity Anomaly Index (AAI)	Uses a water balance for weekly or bi-weekly period and for each period, the actual aridity for the period is compared to the normal aridity for the same period.	WMO (2012)

Agricultural drought is further related to soil type, texture, water-holding capacity, wilting point and crop phenological cycle (Sivakumar *et al*., 2011). According to Dalezios *et al*. (2014), research confirms that drought affects crop growth and development at different phases by impacting various plant processes such as water uptake, root growth, respiration and photosynthesis. It is, therefore, critical that an agricultural drought index is able to account for critical soil water deficits that are unable to maintain average crop growth and ultimately yields. Some indices that are based on soil water measurements and/or crop factors for the quantification of agricultural drought are given by Table 2.3.

Table 2.3: Drought indices based on rainfall, temperature and agronomic factors.

Index	Description	Reference
Palmer Drought Severity Index (PDSI)	Computes water supply and demand by incorporating soil water. A popular drought index, especially in the USA.	Palmer (1965)
Water Requirement Satisfaction Index (WRSI)	Monitors the development and water stress of crop during the growing season.	Frere and Popov (1979)
Soil Moisture Anomaly Index (SMAI)	Determines the degree of dryness or saturation of soil compared to normal conditions, as well as how it impacts the development of crops.	Bergman *et al*. (1988)
Crop Specific Drought Index (CSDI)	Calculates a basic soil water balance, and takes into account the soil and crop phenology information on a daily basis. This index is based only on maize and soybean.	Meyer *et al*. (1993)
Soil Moisture Deficit Index (SMDI)	Based on soil water deficit at different depths.	Narasimhan and Srinivasan (2005)
Evapotranspiration Deficit Index (EDTI)	Based on the deficit in evapotranspiration.	Narasimhan and Srinivasan (2005)

Index	Description	Reference
Agricultural Drought Index (DT*x*)	Uses a soil water balance model with soil, crop and weather parameters as inputs. The index has been defined and effectively tested in three Mediterranean areas.	Matera *et al*. (2007)
Agricultural Reference Index for Drought (ARID)	Based on a combination of water stress estimates and crop models to identify the impact of water stress on plant growth, development and yield for specific crops. The index has been developed and tested only in the USA and is not easily transferable.	Woli *et al*. (2008)

Remote sensing systems can also be used to monitor agricultural drought. Numerous drought indices have subsequently been developed to describe vegetation activity, with the potential to detect and monitor agricultural droughts (Table 2.4).

Table 2.4: Drought indices based on remote sensing data.

Index	Description	Reference
Normalized Difference Vegetation Index (NDVI)	Uses the global vegetation index data, to measure greenness and vigour of vegetation, in both the visible and near-infrared bands of the electromagnetic spectrum.	Rouse *et al*. (1974)
Crop Water Stress Index (CWSI)	Defined as the proportion of actual potential evapotranspiration given by the difference in canopy and air temperature. The index is essentially applied for irrigation scheduling.	Idso *et al*. (1981)
Normalized Difference Infrared Index (NDII)	Based on canopy and leaf water content.	Hardisky *et al*. (1983)
Leaf Water Content Index (LWCI)	Measures vegetation health through the use of remotely sensed leaf water content.	Hunt *et al*. (1987)
Soil Adjusted Vegetation Index (SAVI)	An extension of NDVI, taking into account the soil adjustment factor.	Huete *et al*. (2002)
Vegetation Condition Index (VCI)	Characterizes drought by determining the impact of weather variability on NDVI signals.	Kogan (1990)
Temperature Condition Index (TCI)	Determines vegetation stress caused by excessive wetness and temperature.	Kogan (1990)

Index	Description	Reference
Vegetation Health Index (VHI)	Combines VCI and TCI by using a weight factor *a* for the contributions of both indices.	Kogan (1995)
Temperature-Vegetation Index (TVX)	Combines NDVI and land surface temperature to determine drought conditions.	Lambin and Ehrlich (1995)
Normalized Difference Water Index (NDWI)	Defines by means of vegetation water content based on the near-infrared and shortwave infrared channels.	Gao (1996)
Enhanced Vegetation Index (EVI)	Uses a similar technique to NDVI and is more receptive to canopy variations, type and vegetation characteristics.	Huete *et al*. (2002)
Standardized Vegetation Index (SVI)	Based on weekly NDVI to calculate the probability vegetation conditions anomaly.	Peters *et al*. (2002)
Temperature-Vegetation Dryness Index (TVDI)	Measures the soil moisture status by using each pixel's observed surface temperature.	Sandholt *et al*. (2002)
Weighted Anomaly Standardized Precipitation (WASP)	Based on a 12-month overlapping aggregation of weighted and standardized monthly rainfall anomalies. Uses gridded data for detecting drought in tropical regions.	Lyon (2004)
Evaporative Stress Index (ESI)	Uses geostationary satellites to compare actual to potential evapotranspiration and can be produced at high resolutions without using precipitation data.	Anderson *et al*. (2010)
Vegetation-Soil Water Deficit (VSWD)	Uses multi-source remote sensing data, including soil water datasets to measure water balance.	Cao *et al*. (2019)

2.1.4. Established drought indices

This section provides extended description of six established drought indices that were identified for assessing agricultural drought in South Africa. Of the selected indices, four are based on *in-situ* data and two are remote sensing based. A summary of the selected indices is given by Table 2.5, ordered according to the required input variables.

Standardized Precipitation Index (SPI)

The SPI is based solely on rainfall and, thus, requires less input data and calculation effort. Computation of SPI is based on long-term rainfall data at the desired station, which is fitted to a probability distribution and then transformed into a normal distribution to give a mean of zero (McKee *et al*., 1993). The SPI can be calculated at different time scales (e.g. 1-month, 3-months..., 60-months) allowing for flexibility when monitoring drought conditions. Moreover, the use of different time scales gives an indication of the impacts of rainfall deficiency on agriculture. For example, 1-month indicates soil water and crop stress during the season, while the 6-month time scale is regarded as effectively indicating the degree of dryness for the whole season (e.g. October to March) (FAO, 2016).

The SPI uses a standardized classification system for monitoring both wet and drought conditions, reflected by positive and negative values, respectively (Sönmez *et al*., 2005). Positive SPI values indicate above-normal rainfall, while negative values indicate below-normal rainfall. According to McKee *et al*. (1993), SPI values can be divided to indicate the various drought categories, viz. mild (SPI < 0), moderate (SPI < -1), severe (SPI < -1.5) and extreme (SPI < -2). So far, the SPI is one of the most popularly used drought indices, mainly because it requires less input data, the calculations are flexible and it can be applied over different climate regions (Smakhtin and Hughes, 2004). A program for calculating SPI (http://drought.unl.edu/archive/climdiv_spi/spi/program/spi_sl_6.exe) was developed by the National Drought Mitigation Centre and is readily available to the public.

Table 2.5: Established indices for monitoring agricultural drought in South Africa.

Drought index	**Year**	**Input variable(s)**
Standardized Precipitation Index (SPI)	1993	Rainfall
Percent of Normal Index (PNI)	1994	Rainfall
Standardized Precipitation Evapotranspiration Index (SPEI)	2010	Rainfall, Temperature (Evapotranspiration)
Water Requirement Satisfaction Index (WRSI)	1979	Rainfall, evapotranspiration, soil water-holding capacity, crop coefficient values
Normalized Difference Vegetation Index (NDVI)	1974	Satellite data
Vegetation Condition Index (VCI)	1990	Satellite data

Percent of Normal Index (PNI)

The PNI is another widely used index based on rainfall deficiency. It defines drought as deviation of rainfall from the normal – usually corresponding to the long-term mean of the historical 30-year period (Zargar *et al*., 2011). Due to its flexibility, the index may be calculated for different time periods, e.g. a day to a season. However, numerous definitions of a drought based on the percent of normal exist. In the USA, a drought is set to occur when annual precipitation is ≤75% of normal or monthly precipitation is ≤60% of normal (Bates, 1935). In India, mild drought is defined when monthly rainfall is ≤75% of its long-term mean, while moderate drought corresponds to 50-74% and severe drought is realized when the percentage drops below 50 (Banerji and Chabra, 1964). In South Africa, percent of normal defines drought as a period with rainfall that is ≤75% of its long-term mean, and severe drought as two consecutive seasons with ≤75% of normal rainfall (SAWS, 2016).

The PNI is simple and its calculations are easy, making it a favoured operational signal for communicating drought levels. However, one PNI value may have different specific impacts at different locations, as the index is region-specific and the duration of dry periods for defining drought levels may commonly differ (WMO and GWP, 2016). According to Hayes (2006), this index lacks robustness since there is no statistical transformation needed for the distribution of rainfall data. Similarly, the PNI is incapable of comparing drought across seasons and regions, making it an inappropriate method to use.

Standardized Precipitation Evapotranspiration Index (SPEI)

The SPEI is a multi-scalar drought index based on the difference between precipitation and potential evapotranspiration (Vicente-Serrano *et al*., 2010). The index uses the original SPI calculation procedure developed by McKee *et al*. (1993), with the inclusion of temperature as an input variable. The calculation of SPEI uses a monthly climatic water balance, which is a simple measure of water deficit or surplus, calculated at different time scales, given by (Vicente-Serrano *et al*., 2010):

$$\mathrm{D} = \mathrm{P} - \mathrm{PET} \qquad \text{(Eq. 2.1)}$$

where:

D = Climatic water balance

P = Precipitation

PET = Potential evapotranspiration

Similar to computing SPI, the aggregated D is then fitted to a parametric probability distribution and standardized to obtain SPEI values corresponding to the various drought levels. Hence, the wet and drought categories are the same as those given by McKee *et al*. (1993). By including both rainfall and evapotranspiration in its calculation, the SPEI has an advantage of being used specifically for operational use in drought planning and management. The R package for SPEI calculation is available online at https://cran.r-project.org/web/packages/SPEI/SPEI.pdf

Water Requirement Satisfaction Index (WRSI)

The WRSI is a commonly used index for specifying the extent to which water requirements of a seasonal crop have been dis/satisfied, in a cumulative way at any stage of its growing period. This index is calculated on a decadal basis and is defined as the ratio of actual evapotranspiration to crop water requirement corresponding to maximum evapotranspiration (Senay and Verdin, 2003):

$$\mathrm{WRSI} = \mathrm{AET}/\mathrm{WR} \times 100 \qquad \text{(Eq. 2.2)}$$

where:

AET = Actual evapotranspiration

WR = Crop water requirement

Crop water requirement is given as the product of evapotranspiration and crop coefficient for a particular stage (Allen *et al*., 1998) while the actual evapotranspiration represents the actual amount of water lost from the soil water reservoir. At any time when the soil water content is above critical soil water level, AET will remain the same as WR and excess water will be regarded as runoff or deep drainage (Senay and Verdin, 2003). However, when the soil water content drops below the critical soil water level, AET will be lower than WR in proportion to the remaining soil water content and thus the crop will endure drought stress. The index at the end of the growing season will reflect cumulative water stress experienced by the crop through water excess and deficits and is closely related to the final yield of the crop (Frere and Popov, 1979). Thus, WRSI can be used to monitor crop performance during the growing season and in lieu of actual crop yield data, which is generally scarce or unreliable in many countries. This index is being used as an indicator of agricultural drought and is successfully operational in southern Africa (http://www.fews.net).

Normalized Difference Vegetation Index (NDVI)

Operationally, the NDVI is one the most widely used remote sensing-based indices for agricultural drought monitoring over the past 20+ years. It uses the Advanced Very High Resolution Radiometer (AVHRR) reflected red and near-infrared channels to calculate vegetation response to conditions such as drought or stress due to insect infestation (Zargar *et al*., 2011). Computation of the NDVI is based on the following equation (Rouse *et al*., 1974):

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{Red}) / (\mathrm{NIR} + \mathrm{Red}) \qquad \text{(Eq. 2.3)}$$

where:

Red = Visible red

NIR = Near-infrared range of the electromagnetic spectrum

Visible red indicates decreasing reflectance due to chlorophyll absorption, while the near-infrared range shows increasing reflectance from the spongy mesophyll layer (Rouse *et al*., 1974). Under healthy vegetation conditions, chlorophyll absorbs light and thus reflects less Red resulting in lower NDVI and vice versa (Zargar *et al*., 2011). The NDVI values can range from 0 for surfaces with little or no vegetation to approximately 1 for densely vegetative locations with permeable soil and extensive soil water (Eden, 2012). Various institutes around the world use the NDVI, mainly because its calculations are easily applicable to data from various instruments with red and near-infrared bands (WMO and GWP, 2016). In South Africa, the Agricultural Research Council (ARC) uses NDVI as an indicator for drought monitoring activities reported in its Umlindi newsletter (http://www.arc.agric.za/ARC%20Newsletters). In addition, the NDVI has served as the basis for other remote sensing indices that similarly measure vegetation activity, e.g. Vegetation Condition Index (VCI).

Vegetation Condition Index (VCI)

The VCI is an extension of NDVI and measures the health of vegetation for a specific period (Kogan, 1990). The VCI determines the departure of current NDVI from the minimum NDVI with respect to long-term NDVI and is expressed by the following equation (Kogan, 1990):

$$VCI = \frac{NDVI - NDVImin}{NDVImax - NDVImin} \quad \text{(Eq. 2.4)}$$

The VCI is derived from AVHRR satellite data, adjusted for land, weather, climate and ecological conditions (Kogan, 1995). It allows for relative assessments of changes in the NDVI, and is thus able to detect the onset, intensity and duration of drought as well as its impact on vegetation (Moorhead *et al*., 2015). Since the VCI is based on vegetation activity it is primarily useful for the summer growing season when vegetation is largely active (Heim, 2002). Moreover, one disadvantage of NDVI-based indices for drought monitoring is that they do not differentiate between crop types and whether vegetation stress is caused by drought alone or due to other stressors such as diseases, pests and lack of nutrients (Moorhead *et al*., 2015).

2.1.5. Hybrid drought indices

In-situ and remote sensing-based drought indices alone are mainly useful for particular regions and/or specific applications and do not provide a comprehensive classification of drought events. Thus, another potential avenue of monitoring drought conditions in a region with diverse climatic conditions is to utilize a drought index which integrates *in-situ* meteorological data with remote sensing-derived land surface data. These indices are used to give a more robust and integrated measure of drought that captures the diverse range of vegetation response to the level of dryness across various ecosystems (AghaKouchak *et al*., 2015). These are the most recent generation of drought indices developed since the year 2000 and include the Vegetation Drought Response Index (VegDRI), Combined Drought Indicator (CDI), Multivariate Standardized Drought Index (MSDI), Integrated Surface Drought Index (ISDI) and Global Integrated Drought Monitoring and Prediction System (GIDMaPS).

The VegDRI combines NDVI datasets with *in-situ*-based SPI and PDSI as derived from observations from selected weather stations (Brown *et al*., 2002). The CDI is composed of three warning levels (watch, warning and alert) by integrating SPI, soil moisture and remotely sensed vegetation data (Sepulcre-Canto *et al*., 2012). The MSDI uses information on both rainfall and soil water to identify and classify drought events. It is useful for identifying drought where typical precipitation-based indicators or soil-moisture-based indicators may not indicate the presence of drought (Hao and AghaKouchak, 2013).

The ISDI was established using data-mining technology, including the PDSI as a dependent variable and eight other factors as independent variables based on the traditional meteorological drought data, remotely sensed data and biophysical data (Wu *et al*., 2013). The recently developed GIDMaPS by Hao *et al*. (2014) is an operational product produced on a gridded basis in near-real-time and combines three drought indices, viz. Standardized Soil Moisture Index, SPI and MSDI, to monitor drought. Due to the fact that most of these indices are quite recent, they have not found much application in many parts of the world.

2.1.6. Conclusions

The study listed 50 different drought indices, with sufficient description provided for the established indices suitable for monitoring agricultural drought in South Africa. The description highlighted major advantages for the different drought indices in order to provide a means of comparing and selecting suitable indices for various objectives. For example, as compared to the SPI, the SPEI is regarded to work better in characterizing agricultural drought, due to its inclusion of temperature corresponding to soil water balance. However, in areas where data is not available, the SPI remains a good representative.

The flexibility of time scales was also notable in the study, as drought indices calculated over long periods (e.g. monthly) do not account for dry spells that might cause crop failure within the season. Another component to consider is that agricultural drought comprises several factors including meteorological and agronomic, which leads to the WRSI being the best option. The study also highlighted that, unlike *in-situ*-based indices, remote sensing-based indices such as NDVI and VCI provide a spatial context for measuring agricultural drought impacts, which have shown to be a valuable source of timely and continuous monitoring. However, the dissociation of the selected drought indices has prompted a recommendation to use combined indices as the best option to pursue further.

2.2. Rangeland uses and challenges for the agricultural sector

2.2.1. Introduction

Rangelands have many uses including grazing for livestock, providing shelter, forage and water resources (Hunt *et al*., 2003; Lund, 2007; Dong *et al*., 2010; Cobon *et al*., 2017). Approximately 80% of agricultural land in the world is covered by rangelands (Lund, 2007) which include grasslands, savannas and woodlands. However, the state of these rangelands is deteriorating due to human practices and natural causes – the most prevalent of which is climate vagaries. Climate change scenarios show an increase in temperature and unreliable rainfall in the 21^{st} century, which will have negative impacts on agricultural production, especially in Africa where it translates to food insecurity (Engelbrecht *et al*., 2015; L'Heureux *et al*., 2017; Usman and Reason, 2004). For instance, climate change projections identify the following impacts on grass biomass: increase in biomass and pasture due to increased surface temperatures and carbon dioxide concentrations in the atmosphere, an increase in drought incidences resulting in reduced dry matter yield; and high rainfall intensity resulting in nutrient leaching, particularly nitrogen (Thornton *et al*., 2009).

Southern Africa has an arid to semi-arid climate with erratic rainfall and rangeland managers and farmers rely on rainfall for agricultural production (Nicholson *et al*., 2018). Agriculture contributes to the primary sector of the economy and livelihoods, particularly in rural areas (Louw *et al*., 2006; Notenbaert *et al*., 2009). Consequently, the changes in rainfall patterns in recent decades have caused a substantial decrease in agricultural production. A case in point was the 2015/16 to 2017/18 summer rainfall season in southern Africa, which impacted the agricultural sector severely. Livestock production areas experienced extremely high temperatures resulting in negative impacts on livestock conditions and mortality (Archer *et al*., 2021).

Livestock production is crucial to rangeland managers and farmers in the rural areas for livelihoods and sustenance (Cecchi *et al*., 2010; Erb *et al*., 2012; Herrero *et al*., 2013; Kruska *et al*., 2003; Thornton *et al*., 2009). Livestock graze on pasture throughout the year and require nutrition to remain productive and bring in profit for rangeland communities. However, pasture availability fluctuates seasonally and is affected by many factors, including grazing pressure, grassland management and prevailing species, as well as rainfall and temperature conditions (Mupangwa *et al*., 2016). Rangeland managers and farmers do not have the adaptive capacity to cope with climate variability impacts and therefore require support from the government and researchers to utilize natural resources sustainably and enhance their capacity.

In the 21st century, new techniques and algorithms are required to address food security challenges and provide solutions for agriculture (Moulin *et al*., 1998; Goel *et al*., 2021). Early warning systems, climate and weather forecasting are some of the approaches that are employed to predict forage and minimize climate risk (Moeletsi *et al*., 2013; Grimmond *et al*., 2020; Goel *et al*., 2021; Masupha *et al*., 2021). South African institutions including the South African Weather Service (SAWS), Council for Scientific and Industrial Research (CSIR) and the Universities of Cape Town and Pretoria are running operational models for seasonal forecasting research (Landman, 2014). The use of model simulations, remote sensing and GIS technologies coupled with the collection of field samples for monitoring veld condition has yielded positive outcomes (Archer, 2004; Hunt *et al*., 2003; Vanderpost *et al*., 2011; Wessels *et al*., 2007). For instance, in South Africa, the Umlindi newsletter published by the ARC is used for monitoring agrometeorological conditions every month to enhance agricultural productivity (ARC-SCW, 2022).

Pastoralists, farmers and land managers can use tailored seasonal forecasts to inform on-farm decisions including scheduling grazing periods, stocking and destocking, burning of the veld, vaccination as well as buying of livestock feed and protein supplements (Archer *et al*., 2021; Maluleke *et al*., 2019). However, low adoption of scientific developments has been noted in many cases, the reasons for which centre around trust issues between scientists and end-users, interpretation – and thus relevance – of the information, and the dissemination platforms that are utilized. There is a need to improve communication capacity, and advances learnt from the

COVID-19 pandemic on communication platforms such as Zoom, Microsoft Teams, SMSs, e-mail, YouTube, Skype and media can be adopted (Nielsen *et al*., 2020).

Studies show various attempts by scientists, rangeland managers and the farming community to adapt to climate extremes (Archer *et al*., 2021; Ash *et al*., 2012; Cobon *et al*., 2017; Thornton *et al*., 2009). However, very few have considered a review of rangeland uses in agriculture, highlighting challenges and innovative strategies to date. Thus, this literature review aims to summarize the various uses of rangelands, highlighting their importance, and provide guidelines to farmers, extension officers, researchers, policy-makers and rangeland managers on innovative strategies for sustainable production. Suggested solutions for sustainable management of natural resources are summarized below per challenge. The adoption of the strategies in this review can assist in enhancing adaptive capacity, which will increase agricultural productivity. Additionally, this review can serve as a baseline for future studies focusing on rangeland uses and challenges.

2.2.2. Methodology

The literature used in this review was obtained by searching various scientific databases including Google Scholar, Scopus, Web of Science and Science Direct. The keywords that were used to filter literature pertinent for this study include: rangeland uses, food security in rangelands, grazing for livestock, challenges facing rangelands, climate change and variability, land degradation, rangelands management and sustainable rangeland production. Subsequently, the review was structured into sections and subsections.

The keywords selected had to be part of the article’s title, abstract or keywords. In Google Scholar, for instance, the first 10 pages were filtered and ranked by relevance. The search process was strictly selecting articles and reviews written in the English language. Global coverage was also considered in the screening of pertinent material. The literature that was downloaded includes peer-reviewed articles, books, book chapters, conference proceedings, unpublished reports and dissertations. Ultimately, 90 articles were included as part of the review.

2.2.3. Rangeland uses

Food security

Food security is a key concern globally and more so in sub-Saharan Africa and south Asian countries (Cooper *et al*., 2008; Vermeulen *et al*., 2012). Agriculture contributes to the primary sector of the economy and livelihoods, particularly in rural areas (Notenbaert *et al*., 2009). Therefore, rangelands should be managed sustainably to ensure that food will be available for all people, rich and poor, accessible, utilizable and stable in production (Thornton, 2010; Erb *et al*., 2012). The world is experiencing challenges related to food insecurity as rangelands are experiencing accelerated degradation due to the high demand for natural resources (Foran *et al*., 2019). This pressure to supply goods and services to the growing population has left rangelands in a dire state, which has further led to poverty and economic impacts in many rural areas that are dependent on agriculture, most of which is rain-fed. There are many factors leading to food insecurity, including globalization, urbanization, population growth, land tenure reform and climate change (Thornton, 2010; Von Braun, 2010; Shaumarov *et al*., 2012).

The livestock production sector is changing to meet the high demand for natural resources in developing countries (Thornton, 2010; Holechek, 2013). Research shows that these countries are the biggest consumers of meat protein and other meat products (Swanepoel *et al*., 2021; Thornton, 2010; Holechek, 2013; Cobon *et al*., 2017). For instance, during the period 2003-2030, it is estimated that 75% of the growth in livestock production will take place in Asia (Cobon *et al*., 2017). However, Thornton, (2010) argued that developed countries have limited their consumption of meat products to conserve the environment. This high demand leads to misuse of land resources resulting in overgrazing and over-cultivation. Thus, the government has a huge role to play in land reform matters, where farmers and rangeland managers can be given access to land for crop production and growing pasture for livestock (Shaumarov *et al*., 2012). Research and development greatly contributes by assisting farmers to adopt sustainable farming systems (Han *et al*., 2008; McCord and Pilliod, 2022).

Grazing for livestock

Grazers depend on grass biomass for survival, therefore pastoralists and farmers must ensure that good quality forage is located for livestock by choosing the appropriate grazing system (Ash and

Smith, 1996). It is suggested that livestock movements should be guided by rainfall patterns, which are associated with forage production (Ash and Smith, 1996). Grazers feed on palatable grass first and then move to unpalatable grass at a later stage. When pasture becomes unavailable, livestock production decreases which affects livelihoods, translating to the economy.

Research shows that grass biomass production in rangelands around the world is declining due to factors including anthropogenic practices and climate variability (Anderson *et al*., 2018; Dingaan and Tsubo, 2019). For instance, a combination of rainfall variability and grazing impacts on annual above-ground net primary production (ANPP) was evaluated by Koerner *et al*. (2014). Their findings showed that grazing had a greater impact on reducing ANPP growth than rainfall, with ANPP being reduced by more than 40% even with rainfall treatment. Results further showed that species richness was not affected by either grazing or rainfall treatments. This indicates that grass biomass production is influenced by a combination of factors such as soil type, grass species, topography and climatic conditions (Ash and Smith, 1996). Therefore, sustainable management of grass production in rangelands is important for ensuring the continuous availability of pasture for livestock (Schino *et al*., 2003; Thornton *et al*., 2009; Rust and Rust, 2013).

Rainfall variability is also responsible for land degradation (Pickup *et al*., 1998; Archer, 2004; Pachavo and Murwira, 2014). Research and policy have a huge role to play in the sustainability of the ecosystem and conservation of natural resources (Thornton *et al*., 2011). The latter has been achieved through scientific efforts in conducting trials, collecting data and sharing results on various platforms. Similarly, policies have always regulated laws for conserving natural resources in rangelands, although there have been accomplishments and failures in these laws and regulations.

Water

Water is indispensable for the ecosystem in rangelands (Joffre and Rambal, 1993; Gurrieri, 2020). Wetlands, springs, streams and rivers serve the purpose of providing livestock with drinking water as well as sink sites for vegetation growth (Gurrieri, 2020). The growth of vegetation gradually gives back to the ecosystem by improving soil quality and biological organism numbers in the soil (Joffre and Rambal, 1993; Stavi *et al*., 2020). Therefore, in the ecosystem, the sinks are responsible for maintaining good hydrologic conditions. Rangeland managers and farmers use water for various purposes, but the ground surface must not be destabilized in the process. Sustainable management of rangelands will ensure that livestock get drinking water while maintaining the equilibrium in the functioning of the ecosystem (Stavi *et al*., 2020).

Rainfall is important for surface flow, recharging aquifers and vegetation production, and therefore its shortage can result in a remarkable decrease in livestock production (Rufino *et al*., 2011). Agricultural production in many arid and semi-arid parts of the world is dependent on rainfall. In the semi-arid rangelands of southern Africa, low production is normally attributed to unreliable rainfall and low soil moisture levels (Mbatha and Ward, 2010). Therefore, farmers plant seasonal crops, relying on rainfall for good production. But in years of droughts, production is affected negatively. Research shows that water has become a scarce resource, with numerous water sources in southern Africa drying up during prolonged drought conditions (e.g. Malherbe *et al*., 2016; Archer *et al*., 2017). For instance, a 2014/15 to 2017/18 multi-year drought resulted in a drop of 17% in the capacity of dams in the Western Cape Province of South Africa. Wheat production decreased to 47% in 2015/16 and 2017/18, where 586 000 tonnes were recorded in 2017/18, while a significant drop from 1.1 million tonnes was recorded in 2016/17 (Archer *et al*., 2019).

Water and land are projected to become even scarcer in the future (Misra, 2014; Nardone *et al*., 2010; Thornton, 2010). This means that policies should be revised with long-term strategies to conserve water. Additionally, the plans to conserve water should be proactive instead of reactive. This alludes to management strategies that respond to disaster instead of minimizing it.

2.2.4. Challenges facing rangelands

Land degradation

Most rangelands in sub-Saharan Africa are in a degraded state, which leaves farmers faced with great challenges when it comes to finding grazing for small and large livestock alike (Ziervogel *et al*., 2006; Boansi *et al*., 2017; Dingaan and Tsubo, 2019). Due to scarcity of pasture, livestock production has decreased tremendously, ultimately resulting in low income for the farmers (Prowse *et al*., 2015; Renaudeau *et al*., 2012; Thornton, 2010). Signs of degradation include reduced productivity of the soil, bush encroachment and water scarcity. For instance, in most semi-arid and arid rangelands of southern Africa, the invasion of *Vachellia karroo* (previously known as *Acacia karroo*) is a sign of land degradation caused by overgrazing (Tokozwayo *et al*., 2021).

Land degradation has numerous causes including overgrazing, over-cultivation and overpopulation. Communal grazing areas in southern Africa are overpopulated and therefore share land for several uses including settlement, grazing and farming (Beinart, 2000; Palmer and Bennett, 2013). Human and environmental impacts have resulted in land degradation in Syria, where a comparison was made between a fallow and a continuously grazed land by analysing biomass production and species composition (Louhaichi *et al*., 2009). The results showed high biomass production in the fallow land and low biomass in the grazed land. Species composition was also higher in the ungrazed site due to high organic matter content and a more stable soil structure. Therefore, grazing should be managed sustainably to allow for the recovery of vegetation. It is important to note that land degradation causes are sometimes difficult to map out; however, the focus should be on finding ways for minimizing degradation.

Suggested solutions:

- The planting of new grass cultivars that are resilient to climate extremes.
- The restoration of forests to control soil and water erosion.
- The use of fire for management to increase germination density.
- The preservation of good soil structure through the location of water points to minimize soil compaction and erosion.
- Introducing financial incentives for pastoralists and farmers that comply with rules set by the government in efforts to reduce land degradation.
- Monitoring of veld condition using remote sensing technology and big data.
- Using the appropriate grazing system, i.e. continuous or rotation.

Climate variability and change

Climate variability includes extreme events such as droughts, heatwaves, floods and tropical cyclones. The El Niño Southern Oscillation (ENSO), comprising El Niño, La Niña and neutral phases, has been identified as a source of seasonal variability and predictability (Reason, 2002). However, the Indian Dipole and other sea surface temperature patterns have also been said to influence global weather patterns, including those of southern Africa (Reason, 2002; Saji and Yamagata, 2003; Marchant *et al*., 2007; Funk *et al*., 2014). Fluctuations linked with El Niño and La Niña events, among other circulation patterns, are responsible for climate variability (Malherbe *et al*., 2014; Reda *et al*., 2012).

The impacts of climate extremes on agriculture are several and varied (Moeletsi and Walker, 2012; Vogel *et al*., 2019). During periods of drought, the soil water content decreases, affecting the growth and reproductive phases of plants (Manea *et al*., 2016). Malherbe *et al*. (2020) demonstrated that extreme droughts accompanied by extreme heatwaves in the 2015/16 El Niño resulted in the loss of grass biomass in the Kruger National Park of South Africa. The study used an Extreme Climate Index, based on temperature and rainfall derivatives. Validation data, namely the herbaceous biomass dataset and buffalo regional population growth rates, were used to quantify this index (Malherbe *et al*., 2020). Certain grass cultivars and species are more tolerant to dry conditions than others (Swemmer *et al*., 2006). However, rainfall surplus can have negative and positive effects, in that some areas might experience a substantial increase in production while others experience a decrease. Most studies have found that biomass production increases with high rainfall (Silvertown *et al*., 1994; Lohmann *et al*., 2012).

Suggested solutions:

- The participation of the local community in research projects, which is called co-development. For instance, researchers can interpret scientific data for the community.
- The use of machine learning and big data to enhance adaptation to climate extremes.
- The adoption of technical information such as seasonal, climate and weather forecasts. However, it is important that this information is interpreted for relevance to end-users.
- The effective dissemination of information using platforms such as Zoom, SMSs and e-mail.
- The introduction of sustainable farming systems in communal lands.

Governance

Government is responsible for rangeland monitoring and restoration programmes that ensure the sustainability of rangelands (Han *et al*., 2008; McCord and Pilliod, 2022). Policies for protecting rangelands against damage exist and should evolve with rangeland uses (Shaumarov *et al*., 2012; Fernández-Giménez *et al*., 2015). However, in the case of a disaster, governments regulate funding for relief projects after assessment. This system has not always yielded positive results in many rangelands, mainly due to its fragmented approach. Fragmented funding has been known to impede long-term strategic planning as grants are allocated to local government (Foran *et al*., 2019). The drawback of this system is that its design tends to be responsive and not reactive. For instance, during periods of drought, pastoralists, herders and farmers will be provided with forage subsidies after an assessment of the damage (Chang, 2018). These subsidies are aimed at assisting farmers in coping with the harsh conditions and livestock will therefore be fed for a given period. It is advised that safety nets be established to invest funds for disaster management (Han *et al*., 2008).

Monitoring of rangelands condition is broadly employed by the government to get an estimate of veld state and condition (Han *et al*., 2008). Given that many rangelands are degraded, restoration programmes can be introduced, coupled with financial incentives for compliant rangeland managers (Han *et al*., 2008; Louhaichi *et al*., 2016). The introduction of financial incentives has yielded positive results in Syria. This strategy stipulated that herders be given incentives to not planting barley but instead participate in a rehabilitation programme that saw rangelands recovering after a long period. Biomass of 56 kg/ha was reaped compared to 23 kg/ha from barley cultivation (Louhaichi *et al*., 2016). Although rangeland restoration can be a long-term project, it will yield a positive outcome that will increase food production.

Suggested solutions:

- The establishment of centres for cross-breeding plants and stock breeding, as well as research facilities for rangelands.
- The revision of policies and regulations to be more comprehensive.
- Investing in research and development projects to enhance rangeland management.
- Investing in safety nets to evade panic when requests for relief funds are submitted.
- The provision of funds, credit, insurance, skills and knowledge to rangeland managers and communities.
- Financial incentives for rangeland managers that comply with rules can encourage successful initiatives by the government and policy-makers.

- The use of marketing to improve sales of products and income.

2.2.5. Conclusions

This review summarizes rangeland uses in agriculture, including providing food, water and grazing, as well as recurrent challenges around the world. The challenges documented in this review include land degradation, climate variability and change, as well as governance. These challenges have been shown to lower agricultural productivity, which translates to global food insecurity. Suggested solutions for managing natural resources to continue supplying the human population today and for future generations are summarized for each challenge.

In the 21st century, new techniques and algorithms are required to address food security challenges and provide solutions for agriculture. The use of model simulations, remote sensing and GIS technologies coupled with the collection of field samples for monitoring veld condition has yielded positive outcomes. The collection of field samples, although labour intensive, can give indications of available pasture for the upcoming season that can assist farmers to avoid practices that will exacerbate land degradation.

2.3. Current practice and lessons on drought early warning systems

2.3.1. Introduction

The recurrence of drought disasters in many regions around the world has led to the implementation of disaster management strategies, including emphasizing drought early warning systems (DEWS) for drought-sensitive sectors such as agriculture (Hao *et al*., 2017). In recent decades, there has been an increase in the development of web-based DEWS worldwide (Hao *et al*., 2017). Many of these systems operate from continental to local scale (Pulwarty and Sivakumar, 2014). Ideally, a drought early warning system collects, processes, analyses and communicates relevant drought information to reduce potential impacts of impending droughts (UNISDR, 2009a). The basis for the implementation of DEWS is to follow an approach of four components specified by UNISDR (2006) as: (1) knowledge of risk; (2) monitoring and warning; (3) dissemination; and (4) response (Figure 2-1).

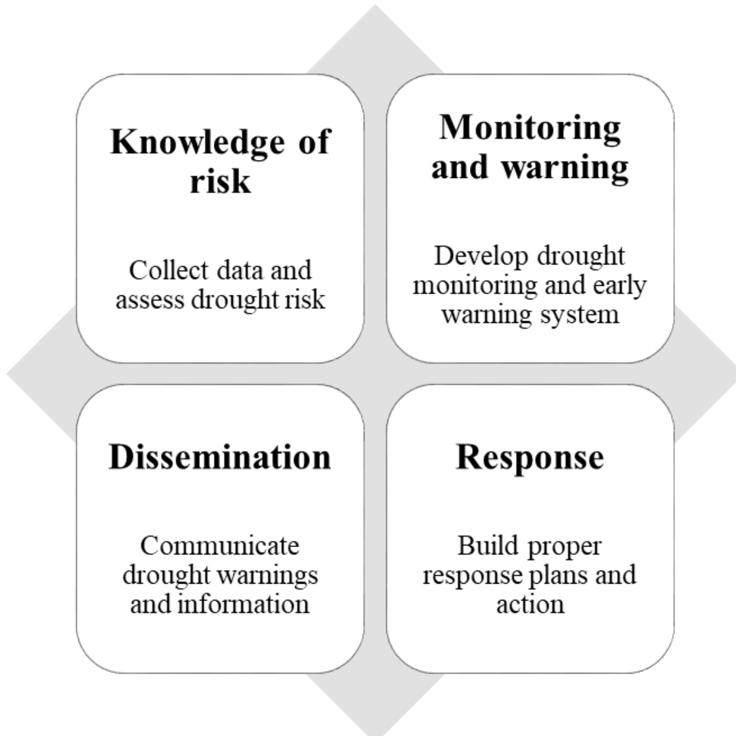


Figure 2-1: Components of a drought early warning system (UNISDR, 2006).

Effective early warning systems embrace all these components and although they may reflect a logical sequence, the components are somewhat interrelated (Hmoudi, 2016). The *knowledge of risk* refers to the risk assessment undertaken to determine an appropriate response ahead of a drought occurrence (Hmoudi, 2016). The widely recognized component is *monitoring and warning*, which requires continuous observations of drought indicators with timely early warning at the centre (UNISDR, 2006). *Dissemination* consists of communicating early warning information to the end-users (UNISDR, 2006), while *response* consists of contingency plans and the capacity of those affected to take action (Basher, 2006). Therefore, to ensure the sustainability of a drought early warning system and its effectiveness to reduce drought-disaster risk, it should be guided by exceptional research, per existing policies and frameworks (Basher, 2006).

Drought early warning systems can improve the agricultural sector's ability to adapt to the increasing frequency, severity and duration of droughts. This is due to the fact that they help to reduce economic losses related to reactive crisis management following drought occurrences

(Hayes *et al*., 2004). Recently, the use of the internet has not only benefited the communication element of DEWS but has also improved drought prediction, monitoring and decision-making by assimilating a variety of tools (Poljansek *et al*., 2017). Thus, the objective of this review was to assess web-based agricultural drought early warning systems with a focus on operational aspects, to identify potential opportunities and challenges for developing a system for South Africa.

2.3.2. Methodology

The review began with an overview of agricultural drought early warning initiatives in Africa, followed by current national resources and capacities in South Africa. Secondly, a state-of-the-art review approach was utilized to examine current web-based agricultural DEWS with emphasis on exploring the various characteristics needed for a successful system. To obtain relevant literature, a Boolean search on Google and scientific databases such as Google Scholar, Web of Science and SCOPUS was applied using the following keywords: agricultural drought early warning system, disaster management, preparedness, drought monitoring tool, early warning systems and web-based early warning system.

Due to the nature of the study, which draws on operational aspects of web-based agricultural DEWS, information was sourced from peer-reviewed articles and grey literature such as early warning system websites, published reports and newsletters, subject to cross-checking. To narrow the scope of the study, established agricultural DEWS were selected based on the following criteria:

- Consist of an operational web portal (Hao *et al*., 2017);
- The main purpose is to provide early warning as opposed to merely monitoring (Kafle, 2017);
- Provide real-time agricultural drought monitoring (Svoboda *et al*., 2002);
- Comprise agricultural drought indices (Łabędzki and Bąk, 2015);
- Should be a product of an established and credible organization (Jacks *et al*., 2010); and
- Operate at a national level or at regional level with information tailored for each country (Funk *et al*., 2019).

Accordingly, the review considered various characteristics as portrayed by the established systems and based on their input to the overall system. These characteristics were listed and grouped according to the four components of an early warning system, given as: (1) knowledge of risk; (2) monitoring and warning; (3) dissemination; and (4) response (UNISDR, 2006). Furthermore, a simple Strengths, Weaknesses, Opportunities and Threats (SWOT) matrix was applied to provide a synthesis of the review. A SWOT analysis is a common context-analysis approach to explore key focus areas for implementing a proposal (Start and Hovland, 2004). Even though this approach is common in strategic management for business (Mandrazhi, 2021), it can broadly find application in environmental studies for the benefit of presenting recommendations in a simple but realistic manner.

2.3.3. Regional agencies responsible for drought early warning for Africa

The African continent continues to experience increasing levels of drought risk and thus, efforts of drought preparedness at a regional scale play an important role in reducing these risks, as drought impacts on agriculture are often widespread, regardless of political borders. Thus, some regional centres have established programmes and thus far made progress in providing climate forecasts as well as drought information to decision-makers (Tadesse, 2016). These regional centres include the following:

- The Famine Early Warning Systems Network (FEWS NET) provides early warning information for monitoring food security in sub-Saharan Africa, Afghanistan, Central America and Haiti (FEWS NET, 2020). FEWS NET provides evidence-based analysis including products specifying food in/security levels, timely alerts on the likelihood of disasters, weather and climate conditions, price markets and food aid (UNEP, 2012). In line with the FEWS NET drought-monitoring effort, a variety of geoinformation products used for monitoring drought are also produced (FEWS NET, 2020). Information on droughts is provided monthly, through bulletins on the FEWS NET website (https://fews.net/).
- The African Centre of Meteorological Applications for Development (ACMAD) is a weather services centre responsible for providing weather and climate information in Africa. Its core priority is to promote sustainable development within the continent as part of national strategies for poverty eradication. To achieve this, the ACMAD focuses mainly on the agricultural, water resources, health, public safety and renewable energy sectors. The ACMAD

oversees training in weather and climate forecasting, drought monitoring and research for the national meteorological services (NSMs) of its member countries (ACMAD, 2019).

- The AGRHYMET Regional Centre is a dedicated agency of the Permanent Interstate Committee for Drought Control in the Sahel (CILSS). Its primary focus is on managing natural resources for enhancing agricultural production and food security within its member countries of the Sahel and West Africa (Traore *et al*., 2014). The centre provides information based on *in-situ* observations, satellite data, crop water requirements and potential yield. It is also involved in capacity building for specialized fields, viz. agrometeorology and hydrology, in the region (Tadesse, 2016).
- The IGAD Climate Prediction and Applications Centre (ICPAC), previously known as the Drought Monitoring Centre – Nairobi (DMCN), has been mandated to promote the mission and objectives of the Intergovernmental Authority for Development (IGAD) system. The ICPAC has thus far demonstrated its capability to mainstream climate information with the focus on reducing related risks, ending drought emergencies and building resilience for climate change, for its eight member countries in the East African region (Tadesse, 2016).
- The Regional Centre for Mapping of Resources for Development (RCMRD) was established in Kenya with support from the United Nations Economic Commission for Africa (UNECA) and the African Union (AU). It is an inter-governmental organization that currently comprises 20 member countries in eastern and southern Africa (Tadesse, 2016). The primary objective of the RCMRD is to produce and disseminate geoinformation and related technological products and services with the focus of promoting sustainable development for its member countries.
- The Southern African Development Community – Climate Services Centre (SADC-CSC) provides operational services for monitoring weather conditions and forecasting climate-related extremes for its 16 member countries in southern Africa. The objective of the SADC-CSC is to enhance preparedness for any disasters related to weather and climate and to ensure the conservation of natural resources. The Drought Monitoring Centre (sub-centre) is an initiative of the SADC-CSC committed to improved drought risk management in the SADC region (SADC, 2020).

2.3.4. Early warning initiatives from Africa

Ethiopia

Drought has over the years affected Ethiopia's agricultural production and consequently led to food insecurity, due to the country's great dependence on subsistence dryland agriculture. Therefore, monitoring of climatic risks, including drought, has become a key component of the country's food production and security measures. In 2008, the Ministry of Agriculture and Rural Development established the Disaster Management and Food Security Sector (DRMFSS), to deal with all matters related to disasters affecting food security (IFRC, 2014). One of the key directorates of the DRMFSS is the Early Warning and Response Directorate (EWRD). The EWRD works in conjunction with the government's Emergency Nutrition Coordination Unit (ENCU), which is mandated to maintain standards of all nutrition studies in the country (Tadesse, 2016). A well-defined coordination structure exists, comprising a wide variety of humanitarian actors including various thematic task forces and sectoral working groups (Tadesse, 2016).

The EWRD collects early warning information regularly from the district level in nine states and one administrative council (IFRC, 2014). Early warnings are distributed every month in two languages, viz. Amharic and English. Early reaction is produced by LEAP (Livelihoods, Early Assessment and Protection Index) software, which was developed to convert agrometeorological data into crop or rangeland estimates used to quantify financial resources needed to scale up the Productive Safety Net Programme (PSNP) in case of a major drought (IFRC, 2014). However, this software is currently used with the country's food security. Examples of available indicators are:

- Drought conditions,
- Crop status,
- Pests and disease outbreaks,
- Water and feed availability (for livestock), and
- Population nutrition status within drought hot spots.

Regarding formal threshold for response, mitigation or recovery, the humanitarian actors meet in a Task Force and jointly agree on the appropriate measures following the publication of forecasts and once the relevant information has been collected and documented (IFRC, 2014). In addition, early warning legislation in Ethiopia only occurs at a national level and is therefore currently not implemented at regional, district and woreda (local) levels. One of the main challenges encountered is that, due to this high level of execution, information has to pass through various channels and thus farmers do not receive it in time (UNDP, 2000). Amongst other concerns, areas that need improvement include that of the Meteorological Department, in which strengthening of station network, data quality, forecasting skill and reliable long-term data is required (Simon, 2019).

Kenya

The recurrence of drought in Kenya has led to the implementation of relevant policies and structures by the government to plan and respond efficiently to the damaging impacts on agriculture, society and the economy (IFRC, 2014). Previously, the drought management system focused on developing contingency plans in the 1980s, followed by the implementation of the Emergency Drought Recovery Project and the Arid Lands Resource Management Project during the early 1990s (Mugabe *et al*., 2019). However, these were short-term and project-based efforts supported by the World Bank (Mugabe *et al*., 2019).

Recently, the Government of Kenya developed the National Drought Management Authority (NDMA), which was established by the National Drought Management Authority Act of 2016 (Republic of Kenya, 2017). This statutory body was mandated to reduce drought risks, end drought emergencies and implement coordination of drought risk management across government bodies and all other stakeholders in the country (Republic of Kenya, 2017). Therefore, this public body serves as a permanent and specialized institution for long-term planning and action.

As part of Kenya's national drought preparedness strategy, the NDMA developed an early warning system to enhance capacity for early response to drought disasters. This system uses a method of comparing remote sensing data and local knowledge with long-term averages and trends. Indicators are then monitored and predictions are produced at a county (district) level every month (IFRC, 2014). Several partners, including the World Food Programme (WFP) of the United Nations, have partnered with NDMA to strengthen their technical capacity (Republic of Kenya, 2017). Available outputs include biophysical, socio-economic, access and utilization indicators.

Moreover, a colour-coded classification has been adopted, in which areas in green, yellow, amber and red are used to provide recommendations on drought conditions to the public.

In addition to early warning improvements, the preparedness strategy includes response and recovery plans. Late response or even failure to react on early warning information may lead to an overdependence on emergency aid and further weaken farmer resilience to drought impacts (Republic of Kenya, 2017). Thus, a contingency planning system still exists, despite challenges such as lack of readily available finance and the weak link between emergency interventions and response time.

Uganda

Uganda is recognized as a disaster-prone country, due to previous occurrences of numerous disasters such as drought, floods, landslides, disaster fires and conflicts (Atyang, 2014). However, the main area significantly affected by severe drought recurrence is the Karamoja sub-region, and other parts of the northern and eastern region (ACTED, 2008). This has necessitated the need for the Ugandan government to implement proactive preparedness and prevention strategies as part of the country's disaster risk management (Atyang, 2014). The preparedness approach identifies the early warning system as a core element of its strategy.

The National Emergency Coordination and Operations Centre (NECOC) was established by the government, with support from the United Nations Development Programme (UNDP), to perform the task of producing timely early warning information (IFRC, 2014). The main purpose of this centre is to generate products and disseminate them efficiently through various platforms, including the National Platform for Disaster Risk Management, District Disaster Management Committees and the public (IFRC, 2014). Amongst some organizations and agencies implementing early warning with varying focus points in Uganda, the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) and Agency for Technical Cooperation and Development (ACTED) are mainly responsible for early warning efforts concerning drought (Atyang, 2014). The MAAIF manages the national process that feeds into the production of the national monthly food security update, while ACTED leads the drought early warning system together with district government officials.

The early warning system managed by the MAAIF is based within the Early Warning Unit (EWU) at the ministry headquarters in Entebbe (Atyang, 2014). The EWU assembles data collected by other units within the ministry. The data is then converted into useful information through an advisory comprising the following indicators: crop yield, livestock production, the status of pests and disease damage, food and livestock prices (Braimoh *et al*., 2018). However, the advisories are disseminated only twice a year using press releases, media channels and local government officials. Another limiting factor is that the early warning system has no feedback mechanism in place for further improvements (Atyang, 2014).

The drought early warning system process entails collecting and analysing data and information needed for drought prediction (ACTED, 2008). The system is supported by ACTED in terms of providing data entry software, backup, field data and information verification, and overall dissemination of early warnings (ACTED, 2008). Figure 2-2 summarizes the procedure for collecting and disseminating this information. Data is collected from the community monthly, utilizing printed forms and mobile phones (Braimoh *et al*., 2018). It is then transformed using the early warning system software and information regarding the status of the drought and its accompanying impacts is compiled.

The system uses 21 indicators within four main sectors, viz. livestock, crops, water and livelihoods, for providing timely messages of upcoming droughts via bulletins. Examples of these indicators include vegetation conditions, rainfall amount, temperature, crop yields and livestock market prices (Atyang, 2014). The bulletins are disseminated to the stakeholders through e-mails, notice boards and meetings. One interesting fact to note is that, at a local level, drama groups are involved in distributing information on upcoming drought conditions by performing sketches that also provide recommended strategies to communities (ACTED, 2008). However, this type of information channel relies on external funding and is therefore not sustainable (Atyang, 2014).

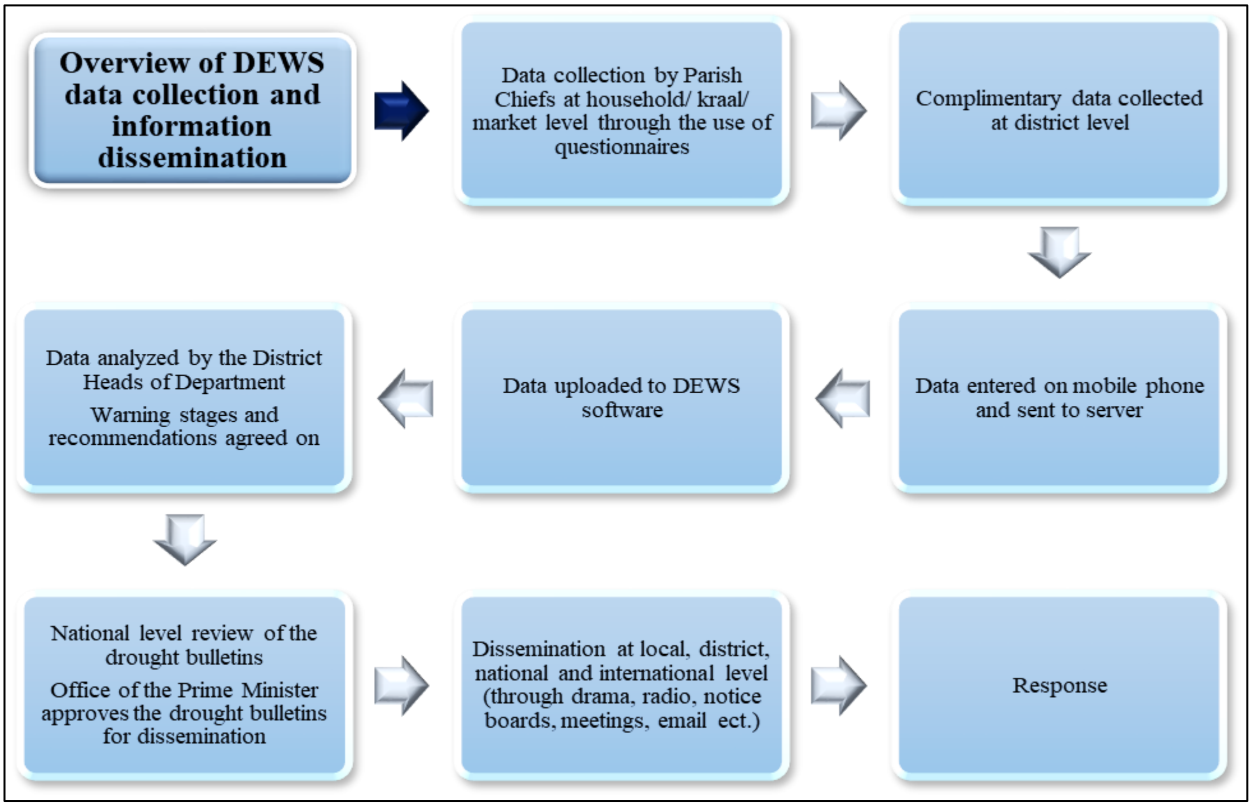


Figure 2-2: Data collection and dissemination process for DEWS in Uganda (ACTED, 2008).

Ghana

The Climate Technology Centre and Network (CTCN), in collaboration with the Water Resources Commission (WRC), UNEP-DHI Partnership and Environmental Protection Agency (EPA), developed and implemented a drought early warning system for the water and agriculture sectors (CTCN, 2017). The main objective was to improve the capacity of Ghana's government to reduce drought risk on both sectors, by developing relevant scientific-based technology (DHI, 2018). The system comprises a web-based portal based on the drought early warning and forecasting portal of the Flood and Drought Management Tools project (CTCN, 2017) (http://www.flooddroughtmonitor.com/home?register=trueandug=CTCN).

The portal consists of components that enable the registered user to access near-real-time drought indices, view and/or download meteorological, vegetation and water time series, identify relevant drought-causing indicators and enable user-defined thresholds for drought assessment (CTCN, 2017). Furthermore, the drought assessment component within the portal allows a user to analyse drought vulnerability and identify drought-stricken regions (CTCN, 2017). Drought information is disseminated through the reporting component, in which users can choose between automated reports or manually develop their preferred reports in various forms, e.g. text, chart, table or image (DHI, 2018).

Tunisia

In Tunisia, a drought management system has been in existence since 1987 (UN-DESA and ESCWA, 2013). However, based on lessons learnt from prolonged severe droughts of the late 1980s and early 1990s, the Ministry of Agriculture and the Ministry of Environment developed a practical guide on how to manage drought and its accompanying impacts on society. These guidelines were issued in 1999 and provide a framework for the process of general drought management including preparedness and response (Verner *et al*., 2018).

The approach of this management system is based on three consecutive steps: (1) announcement, (2) warning and (3) action. The first step entails an assessment based on the various indicators of meteorology, hydrology and agriculture, listing the areas affected by drought, the level of its intensity and the needs assessment for financial support (Verner *et al*., 2018). Concerning agricultural drought, the assessment includes dehydration of olives, observing the status of grasslands and delayed planting, as well as price increases for feed (Verner *et al*., 2018). The relevant departments at districts and specialized committees are responsible for conveying the announcement to the Ministry of Agriculture (FAO, 2018).

The second step involves the communication of the announcement to the minister, who then recommends an action plan to the national committee comprising decision-makers and beneficiaries (UN-DESA and ESCWA, 2013). During the final stage, the aforementioned committee implements and supervises all measures as outlined in the action plan, in cooperation with the relevant district departments and specialized committees, during and after the drought (UN-DESA and ESCWA, 2013). One of the main advantages of this system is that the approach is sustainable and it is supported by the Government of Tunisia (FAO, 2018). However, weaknesses do exist which include delays in decision-making as well as untimely and poor communication between the relevant stakeholders (Verner *et al*., 2018). Moreover, the lack of a forecast component is considered a major weakness within the system (FAO, 2018).

South Africa

In South Africa, policies support agricultural drought preparedness by providing easy access to weather and climate forecasts, as well as agrometeorological information. For agricultural drought risk management, much significance occurred following the implementation of Act No. 57 of 2002: Disaster Management, the National Disaster Management Framework of 2005 and Act No. 16 of 2015: Disaster Management Amendment (Republic of South Africa, 2015). These aforementioned legislative documents guide the procedures of drought disaster management in the country by all levels of government as well as related stakeholders. However, efforts from other responsible institutions remain weak, and at times delayed, due to lack of capacity (human and financial) and low-level intergovernmental collaboration (Midgley and Methner, 2016).

From a scientific capacity, the South African Weather Service (SAWS) is the main mandated government entity responsible for monitoring weather and climate patterns necessary for decision-making (SAWS, 2020). Operationally, SAWS produces and disseminates weather and seasonal climate forecasts (for a period of up to 5 months) regularly through various platforms (Baudoin *et al*., 2017). Once a forecast is issued, relevant government authorities are responsible for disseminating it to minimize potential impacts on agricultural production. Currently, there are various challenges including uncertainties on the usage of information, as to some extent, farmers at a local level may struggle to interpret and understand the information primarily due to the abundant use of technical jargon (Toxopeüs, 2019). Hence, it is important to support local extension services and disaster management centres in their initiative to interpret and promote the appropriate utilization of these forecasts (Andersson *et al*., 2019).

In addition to efforts to disseminate relevant information for drought monitoring in South Africa, the Agricultural Research Council (ARC) developed and implemented a newsletter called Umlindi with the aim of providing near-real-time information on agrometeorological conditions, including rainfall, drought, vegetation and fire, to the agricultural sector and the country at large (ARC-SCW, 2022). The Umlindi newsletter compiles information obtained from scientific research in a simplified manner that decision- and policy-makers, as well as the public, can understand and use. It is disseminated monthly to over 300 direct subscribed users and via the ARC website. Although Umlindi is effective in terms of monitoring drought from onset to recovery, it operates largely in a reactive manner as it uses observed data from the previous month.

A national platform called the National Agro-meteorological Committee (NAC), which is coordinated by the Department of Agriculture, Land Reform and Rural Development (DALRRD) exists in South Africa. The committee holds regular meetings every quarter with a focus on managing agrometeorological risks on agriculture, including drought (DALRRD, 2020a). These meetings serve to present and communicate current agrometeorological conditions and to discuss seasonal forecasts as a form of early warning. The data presented are then converted into useful information through an advisory and disseminated via various platforms such as the DALRRD website and e-mails (DALRRD, 2020a).

2.3.5. Examples of established web-based drought early warning systems

National Integrated Drought Information System

The National Integrated Drought Information System (NIDIS) of the NOAA National Climatic Data Center (NCDC), was developed in a consortium with various agencies (federal, regional, tribal, state and local government), research institutions and the private sector for various sectors in the United States of America (NIDIS, 2020). The system utilizes the following five components to guide drought early warning activities across the country: (i) observation and monitoring, (ii) planning and preparedness, (iii) prediction and forecasting, (iv) communication and outreach, and (v) research and applications. The system consists of a web portal (https://www.drought.gov/drought/) that serves as a hub for integrating this multifunctional approach as well to coordinate the network of key partners.

The web portal contains interactive spatial maps which allow users to customize drought information based on sector, location and period. The U.S. Drought Outlook within the system uses short-, medium- and long-range forecasts of the NOAA Climate Prediction Center to predict impending droughts, based on the well-established U.S. Drought Monitor (Svoboda *et al.*, 2002). In terms of quantifying drought, the outlook uses a similar method to the drought monitor, whereby intensity levels are based on combined information from drought indices, e.g. Palmer Drought Severity Index (PDSI) and Standardized Precipitation Index (SPI), as well as reports on drought impacts from >450 observers across the USA (Pulwarty and Sivakumar, 2014). Other products include impact reports, historical drought information, decision-support tools, resources on drought education and other supporting services on drought-related matters (Pulwarty and Sivakumar, 2014). Monthly maps are disseminated on their website, social media (Facebook, Twitter and YouTube) and to subscribed users.

Intersucho Portal

The Intersucho Portal (https://www.intersucho.cz/) is a web-based platform of the Czech drought monitor, which was developed in 2014 by the Institute of Global Change Research of the Academy of Sciences of the Czech Republic (CzechGlobe), Mendel University in Brno and the State Land Office (Intersucho, 2020). Subsequently, in 2016, a forecasting system was added only for the Czech Republic and Slovakia, to forecast impending agricultural droughts for the improvement of crop production decision-making (Trnka *et al*., 2020). The monitor employs a combination of remote sensing data with a soil water index and climate measurements to monitor drought for Central Europe (Trnka *et al*., 2014).

In general, the Intersucho Portal consists of the following five pillars: (i) present soil moisture conditions; (ii) SoilClim model simulations; (iii) vegetation conditions; (iv) drought forecasts; and (v) weekly expert reports (Intersucho, 2020). The latter was adopted from the USDM framework and currently, the portal encompasses just over 100 active observers who provide weekly reports on the impacts and conditions of drought (Intersucho, 2020). The drought prediction system produces maps based on a detailed ensemble of five forecasting models, showing the likelihood of drought intensity and soil water saturation for the next 10 days (updated daily), as well as long-term drought forecasts for the next 2 and 6 months (updated weekly) (Trnka *et al*., 2020). A graph depicting the development of drought for the previous 2 months and a prognosis of the next 10 days is also given. Other tools based on observed data exist within the portal, including vegetation of permanent crops, water supply in the soil, impacts of drought on vegetation, accumulated stress, impacts on agriculture, deficit of water supply in the soil, impacts on vegetation – Europe and soil moisture index – Europe (Intersucho, 2020).

Famine Early Warning Systems Network

One prominent initiative is the Famine Early Warning Systems Network (FEWS NET) which offers early warning information for monitoring food security in approximately 38 countries in sub-Saharan Africa, Central Asia, Central America and the Caribbean (FEWS NET, 2020). FEWS NET consists of a web-based portal (https://fews.net/) and collaborates with over 20 organizations to provide evidence-based analyses on climate-related risks on food security. Products offered by the network include food security levels, timely alerts on the probability of disasters, weather and climate conditions, a variety of geo-information products, market prices and food aid, using a colour-coded phase classification system (UNEP, 2012). Relevant to agricultural drought, indices utilized by FEWS NET include the SPI, Water Requirement Satisfaction Index (WRSI), Normalized Difference Vegetation Index (NDVI) and Vegetation Health Index (VHI) (FEWS NET, 2020).

The FEWS NET drought early warning system applies a multistage approach, based on several datasets and monitoring tools (Funk *et al*., 2019). For instance, historical observations (e.g. climate and drought), as well as large-scale climate indices, are utilized before the agricultural season commences to map vulnerabilities and identify potential drought-prone regions (Funk *et al*., 2019). Routine field observations from various experts are used to complement satellite-based drought indices and medium-term weather forecasts during mid-season (Magadzire *et al*., 2017). Towards the end of the season, FEWS NET early warning scientists meet to assess drought severity and impacts to refine assessments and provide tailored support to guide humanitarian response plans (Magadzire *et al*., 2017).

The food security-based information is disseminated through monthly bulletins on the FEWS NET website, to subscribed users and on social media (FEWS NET, 2020). Furthermore, FEWS NET consists of various software tools designed for varied functions such as the Early Warning eXplorerLite which allows users to view meteorological, vegetation and snow water time series at varied locations, while the water point map viewer provides information regarding water availability for livestock and human consumption (FEWS NET, 2020).

High Resolution South Asia Drought Monitor

The Indian Institute of Technology – Gandhi Nagar (IIT-GN) and the International Water Management Institute (IWMI) developed the High Resolution South Asia Drought Monitor (https://sites.google.com/a/iitgn.ac.in/high_resolution_south_asia_drought_monitor/) (Aadhar and Mishra, 2017). The monitor provides real-time drought monitoring and forecasting over South Asia as well as on a national scale for India, Pakistan, Bangladesh, Nepal, Bhutan and Sri Lanka using bias-corrected data at a spatial resolution of 0.05° (Aadhar and Mishra, 2017). Maps of current and future meteorological, agricultural and hydrological drought conditions are provided (updated daily) using the following drought indices: SPI, Standardized Soil Moisture Index (SSI) and Standardized Runoff Index (SRI) (Shah and Mishra, 2015).

Outputs based on data generated using the Global Ensemble Forecast System (GEFS) include precipitation forecasts for the next 15 days and drought forecasts (overall and per index) with a 7-day and 15-day lead time. Additional maps highlighting areas where drought could be expected to persist or recover are provided. The monitor also includes soil water and runoff simulations of the Variable Infiltration Capacity (VIC) model to identify areas under severe agricultural and hydrological drought (Shah and Mishra, 2015). These simulations are then quantified against NDVI anomalies and the Drought Severity Index (DSI) (Aadhar and Mishra, 2017).

New Zealand Drought Monitor

The New Zealand Drought Monitor (https://niwa.co.nz/climate/information-and-resources/drought-monitor) is a product of the National Institute of Water and Atmospheric Research (NIWA, 2020). This web-based drought monitoring system combines multiple indices, namely the SPI, Soil Moisture Deficit (SMD), Soil Moisture Deficit Anomaly (SMDA) and Potential Evapotranspiration Deficit (PED), to determine a composite index titled the New Zealand Drought Index (NZDI) (NIWA, 2016) which serves as a measure of drought conditions in the country. The main function of the New Zealand Drought Monitor is to produce real-time interpolated drought maps (updated daily) to a community of drought-sensitive users including farmers, commercial consultants and government ministries (Mol *et al.*, 2017). The monitor contains functions that allow the user to download a data file, access maps per district, and an option to generate time-series based on the NZDI or using individual base indices (NIWA, 2020).

Caribbean Drought and Precipitation Monitoring Network

In the Caribbean, drought prediction and monitoring for sustainable Integrated Water Resources Management (IWRM) is performed through the Caribbean Drought and Precipitation Monitoring Network (https://rcc.cimh.edu.bb/long-range-forecasts/caricof-climate-outlooks/). The main hosts of the network are the Caribbean Institute for Meteorology and Hydrology (CIMH) and the Caribbean Regional Climate Centre (CRCC) of the World Meteorological Organization (WMO) (CRCC, 2020). The Caribbean Drought and Precipitation Monitoring Network publishes current status and projected droughts to provide drought early warnings in the Caribbean (FAO, 2016). This initiative is currently performed through the Caribbean Drought Bulletin that monitors drought conditions at regional and national scales (CRCC, 2020).

The Caribbean Drought Bulletin currently produces monthly drought products utilizing the following indices and indicators: SPI, SPEI, monthly rainfall, mean temperature anomalies and rainfall deciles (CRCC, 2020). Also included are the Drought Alert Maps of the Caribbean Climate Outlook Forum (CariCOF) climate forecasts, comprising impending drought situations with a lead time of 3 (short-term) and 6 (long-term) months (CariCOF, 2019). The bulletin further provides a link to the detailed CariCOF Drought Outlook with drought maps, implications and recommendations on how to mitigate accompanying impacts. Similar to the FEWS NET, the CariCOF meets at the beginning of the rainy and dry seasons to discuss drought issues related to the region and to provide tailored support for risk reduction (CariCOF, 2019).

China Drought Monitoring System

In China, the National Climate Center (NCC) of the China Meteorological Administration coordinates the China Drought Monitoring System (https://cmdp.ncc-cma.net/extreme/dust.php), which is based on real-time data (NCC, 2020). This system monitors droughts for sectors to set up precautionary measures ahead of the disaster (Changhan *et al*., 1998). Drought is monitored using soil water monitoring, remote-sensing data and the comprehensive meteorological drought index (CI), which is calculated using SPI (1-month and 3-month) and potential evapotranspiration (Cheng *et al*., 2018; Pulwarty and Sivakumar, 2014). Based on these indicators, the NCC then produces a China drought monitoring bulletin, intended mainly for government departments, as well as drought monitoring maps which are accessible to the public and updated daily on the NCC website (WMO, 2006).

Poland Agricultural Drought Monitoring System

In Poland, the authority responsible for agricultural drought monitoring and early warning is the Ministry of Agriculture and Rural Development (ADMS, 2020). Following an Act of this ministry, the Institute of Soil Science and Plant Cultivation developed the Agricultural Drought Monitoring System (ADMS) (http://www.susza.iung.pulawy.pl/en/), which is based on monitoring drought and its impacts on various agricultural commodities (Łabędzki and Bąk, 2015). The climatic water balance (CWB) model, together with soil classes, determines agricultural drought risk, which can also be used to identify areas eligible for agricultural insurance payments due to losses caused by drought (ADMS, 2020).

The ADMS infrastructure is based on a web portal consisting of four components: (1) comment from Agrometeorologist; (2) CWB maps; (3) drought hazard maps; and (4) tables for commodities. The comment from Agrometeorologist provides a detailed report of drought conditions after every 10 days, per commodity, for every voivodeship (equivalent to a province) and district. The CWB map component provides a map detailing the climatic water balance index, which is the difference between precipitation and potential evapotranspiration, for a period selected by the user (Łabędzki and Bąk, 2015). The third component includes a feature for generating a map and a table showing potential drought zones (provinces as well as number and percentage of districts), by selecting a year, period and crop type. The commodity tables provide drought risk tables for each commodity, per soil category at every municipality. The platform further includes a distinct feature that displays maps based on remote sensing information, using the NDVI and Apparent Thermal Inertia (ATI) updated every 16 days, starting from 2017 (ADMS, 2020).

2.3.6. Lessons from best practices

Figure 2-3 gives a schematic diagram which entails the key characteristics of established web-based agricultural drought early warning systems, as linked to the key components of early warning systems. Table 2.6 displays the inclusion of these characteristics in the various DEWS: (1) time series, (2) data file, (3) processing, (4) forecast, (5) composite index, (6) impact, (7) field reports, (8) spatial map, (9) interactive map, (10) social media, (11) subscription, (12) user-friendly, (13) contingency plan and (14) feedback. This section explores the meaning of each feature toward the success of web-based agricultural DEWS.

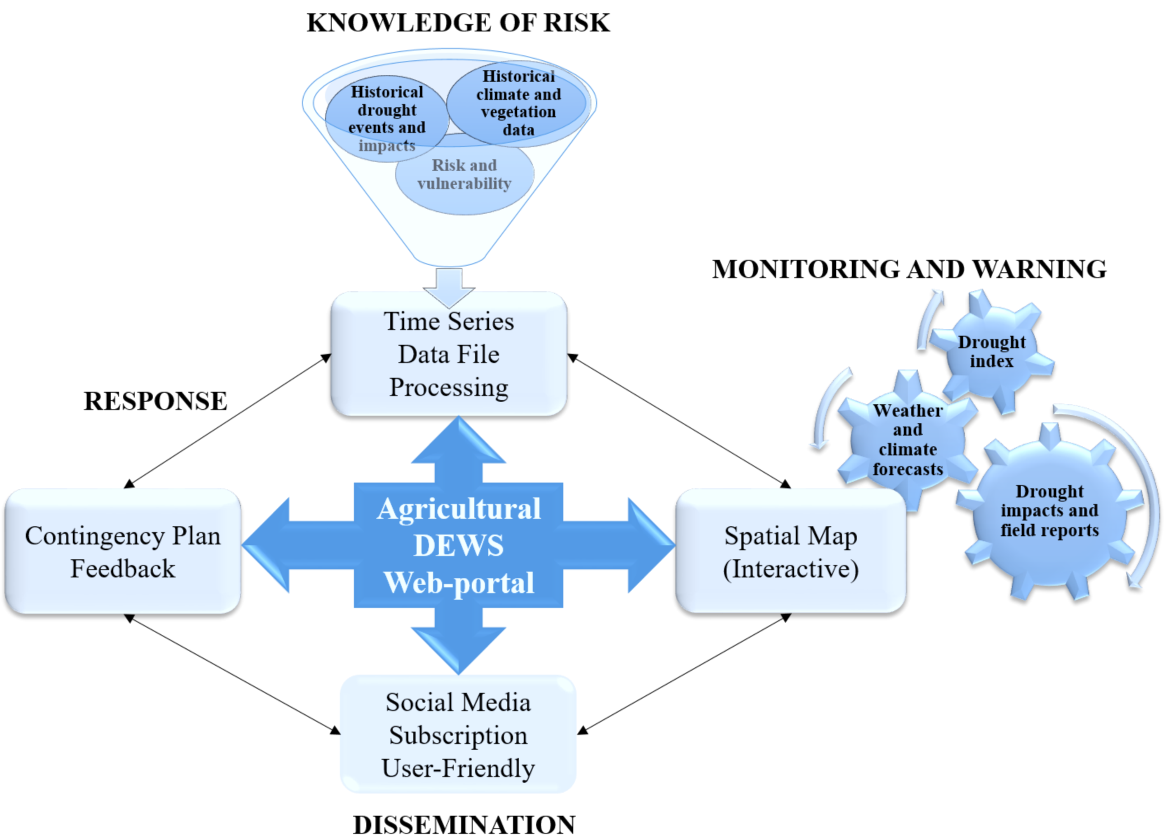


Figure 2-3: Schematic representation of characteristics within a web-based agricultural drought early warning system (DEWS) as given by the four recognized interrelated components of developing an early warning system.

Table 2.6: Characteristics of established agricultural drought early warning systems included in this review.

COMPONENTS OF AN EARLY WARNING SYSTEM	Characteristics	National Integrated Drought Information System	Intersucho Portal	Famine Early Warning Systems Network	High Resolution South Asia Drought Monitor	New Zealand Drought Monitor	Caribbean Drought and Precipitation Monitoring Network	China Drought Monitoring System	Poland Agricultural Drought Monitoring System
KNOWLEDGE OF RISK	Time Series	X	X	X		X		X	
	Data File	X		X		X		X	
	Processing	X		X		X		X	X
MONITORING AND WARNING	Forecast	X	X	X	X		X		
	Composite Index	X	X	X		X		X	X
	Impact	X	X	X			X		X
	Field Reports	X	X	X					
	Spatial Map	X	X	X	X	X	X	X	X
	Interactive Map	X		X					
DISSEMINATION	Social Media	X	X	X					
	Subscription	X		X					X
	User-Friendly	X	X	X	X	X	X	X	X
RESPONSE	Contingency Plan	X		X			X		
	Feedback	X	X	X	X	X	X	X	X

Knowledge of risk

The first characteristic, viz. the provision of time series, was a common feature in the established web-based agricultural DEWS as it was found in five of the eight systems. This characteristic provides the ability to obtain a series of previous drought occurrences, historical climate and vegetation observations at a specified location ordered in time. The usage of historical information directs the process of early warning through various assessments to contextualize current agricultural drought conditions, classify relevant drought-causing indicators and identify agricultural drought-prone regions (Funk *et al*., 2019). Hence it is vital for data within DEWS to be frequently (weekly to monthly) updated.

The second characteristic, found in four of the eight established systems, is the data file. This feature allows users to download data for a specific location. The advantage hereof is that users can download data necessary as inputs on other supplementary tools, such as those of the FEWS NET (FEWS NET, 2020). It was observed that all systems comprising this characteristic also had the processing characteristic, which creates layers of information for any location over a specific period. Users are then able to generate maps depicting potential drought zones by selecting the different layers of information, time and crop type (found only in the ADMS). This feature provides an outstanding opportunity to compare layers for comprehensive vegetation analyses in the context of ongoing climate alteration and increasing drought threats (Magadzire *et al*., 2017). One prominent advantage of having to process without uploading data files is the limitation of any hindrance to the system (normally caused by large datasets), especially in areas with poor internet connectivity (Funk *et al*., 2019).

Monitoring and warning

According to Jacks *et al*. (2010), the main requirement to effective early warnings and response includes timely, accurate forecasts and "nowcasts" (commonly 0-2 hours). However, due to the slow onset nature of agricultural drought, medium-range forecasts (between 3 and 10 days) may be suitable for detecting drought conditions/dry spells in advance and within the season, whereas in most cases, long-term forecasts (a season or more in advance) may not be reliable (Wilhite *et al*., 2000). As shown in Table 2.6, five of the eight systems comprise the forecasting characteristic. These forecasts can provide important information for decision-makers to act accordingly, e.g. put mitigation strategies into place (Pozzi *et al*., 2013).

Limitations in drought forecasting skill serve as a common challenge, particularly deterministic weather forecasts for key elements such as rainfall, temperature and evapotranspiration (Hao *et al*., 2017). This is due to the complex dynamics of the atmosphere and users therefore have to be aware that climate forecasts will always have some kind of uncertainty linked to them (ECMWF, 2021). Meanwhile, DEWS without the forecasting characteristic rely heavily on observed data and thus reduce lead-time upon which to make informed decisions. Moreover, other innovative tools for agricultural drought prediction may be explored. However, Lumbroso (2018) argued in a case study for Uganda that lack of funding hindered the success of operationalizing numerous new and innovative DEWS, thus specifying the need for financial sustainability.

The use of drought indices to monitor the occurrence and impacts of droughts is a common practice across various regions worldwide (Wu *et al*., 2004). Owing to the differing features of drought and the complexity of its impacts on agriculture, it is crucial to use an agricultural drought index or a composite of indices that will capture all essential characteristics. For an early warning system, key indicators for predicting agricultural drought are rainfall-based, vegetation-based and model-based (Senay *et al*., 2014). Six of the eight systems exhibited an approach of combining these indicators into one index (Table 2.6), with the High Resolution South Asia Drought Monitor (Aadhar and Mishra, 2017) and the Caribbean Drought and Precipitation Monitoring Network (CRCC, 2020) using multiple indices, individually.

Another feature important for agriculture is determining the level of drought impact. Systems containing the impact characteristic (found in five of the eight systems investigated) can detail the extent of drought impacts on various agricultural commodities. A good example is the ability of the ADMS to account for soil water deficits that are unable to uphold optimal yields in classifying agricultural drought (ADMS, 2020). This system does not have a forecasting function, yet it provides good practice for monitoring drought conditions for croplands. The system utilizes a function for masking crop areas, determining drought per area, and providing a map and tables signifying the percentage area under drought stress for each commodity. Reporting periods of drought risk analysis are carried out following the country's crop calendar (ADMS, 2020). One common hurdle may include the provision of unreliable/false information due to a lack of empirical testing and evaluation concerning spatio-temporal scales and impacts (Vicente-Serrano *et al*., 2012).

In addition, field observations add to the value of determining drought impacts on agriculture. This approach integrates field observers in monitoring drought from onset to recovery and was adopted by three of the reviewed systems, including the NIDIS (NIDIS, 2020), Intersucho Portal (Intersucho, 2020) and FEWS NET (FEWS NET, 2020). Field observations benefit early warning such that they complement remote sensing and *in-situ* drought indices to determine the level of impact and identify regions requiring direct attention (Funk *et al*., 2019). This should be an automated process, which occurs in combination with the insight of a skilled observer to minimize potential error. However, it is noteworthy that resources may be demanding in terms of labour and financial costs (Quansah *et al*., 2010).

One common characteristic was the ability to visualize areas of concern through a spatial map (Table 2.6). In drought monitoring, spatial mapping plays a key role in revealing the nature and distribution of drought in terms of the areal extent (Tefera *et al*., 2019). Additionally, spatial mapping allows the user to depict variation in drought risk and identify hotspot areas needing urgent attention. All the established systems included in this review displayed this feature and thus serve as an important contribution to web-based agricultural DEWS. Moreover, an improvement to the usage of a spatial map for these agricultural DEWS was the introduction of an interactive spatial map. This characteristic allows the user to select their area of choice and obtain statistics on current and previous droughts. As learnt from the NIDIS (NIDIS, 2020) and FEWS NET (FEWS NET, 2020), the use of an interactive map is essential for web-based agricultural DEWS, making them more efficient and user-oriented (Wilhite *et al*., 2007).

Dissemination

It is essential for DEWS to comprise high capabilities of adapting to emerging communication technology, e.g. smartphones, mobile tablets and social media platforms (Wilhite, 2000). The use of social media for sharing drought early warning information was found in almost all of the systems; however, only three systems, viz. NIDIS (NIDIS, 2020), Intersucho Portal (Intersucho, 2020) and FEWS NET (FEWS NET, 2020), had specific social media accounts. The New Zealand Drought Monitor (NIWA, 2020) and the Caribbean Drought and Precipitation Monitoring Network (CRCC, 2020) shared drought information, together with other services on their host organization’s account. Drought information of the High Resolution South Asia Drought Monitor (Aadhar and Mishra, 2017) was shared on social media through the lead scientist’s account, thus making it less accessible on this particular platform.

The subscription characteristic was found in three systems, whereby users can subscribe and receive early warning information mostly through e-mails. This feature is beneficial as it allows for minimum delay of information delivery to the end-users (Jacks *et al*., 2010). It was further learnt that web-based DEWS should communicate information in a manner that would minimize confusion or misunderstanding, as this would indirectly determine its adoption by the various stakeholders. Currently, in Africa, there is still low confidence in these systems as compared to other parts of the world, including the Caribbean and South Asia (Lumbroso *et al*., 2016). Moreover, all systems were considered user-friendly, as determined by the minimal complication of the web portals and the simplicity of the outputs (using various formats such as maps, text and graphs).

Response

Contingency planning is an important part of the early warning continuum and plans may be revised at any stage. An example of this approach was found on the NIDIS (NIDIS, 2020), FEWS NET (FEWS NET, 2020) and the Caribbean Drought and Precipitation Monitoring Network (CRCC, 2020). Contingency plans are important for agricultural drought early warning as they provide decision-makers with relevant recommendations on the corresponding warnings and enhance their response capacity (Basher, 2006). This leads to the need for building the necessary capacity for various role-players.

Late response or even failure to react to early warning information may result in issues of slow decision-making and procurement processes, which could extend the time in which governments respond to challenging drought impacts (Mugabe *et al*., 2019). It is also important for an early warning system to have a feedback component to allow for corrections and improvements (Atyang, 2014). In general, the established systems have indicated that response from users is a vital characteristic of any web-based agricultural DEWS.

2.3.7. Synthesis

In this section, a simple Strengths, Weaknesses, Opportunities and Threats (SWOT) matrix summarized the findings to inform the development of web-based agricultural DEWS in South Africa, as part of improving agricultural drought disaster preparedness at a national level (Table 2.7). The findings presented here add to previous research by offering a starting point for practitioners to develop operational web-based agricultural DEWS, as well as to identify further improvements on current systems.

Firstly, in South Africa, there have been significant advances in the last two decades concerning policies and frameworks, specifically in promoting a shift from crisis management to disaster risk reduction (Republic of South Africa, 2005). Moreover, despite the fact that real-time agricultural drought monitoring and forecasting are not present, there are strong institutional capacities of climate forecasting, drought monitoring and conducting research. Another key strength in South Africa was the implementation of the NAC, which allowed for a good structure best capable of dealing with agricultural drought preparedness.

Table 2.7: A simple SWOT analysis showing prospects of developing an agricultural drought early warning system for South Africa.

Strengths	Weaknesses
• Policies and frameworks governing drought disaster management • Existence of an established coordination structure • Ability to monitor drought conditions from local to national level • Access to various datasets and products necessary for drought monitoring • Access to advanced technology and information systems	• Forecasts are purely meteorological and agricultural drought prediction methods are not utilized • Uncertainties relating to the usage of drought-related information by farmers • Lack of drought-specific task forces and working groups • Lack of dedicated human resources and secure financial commitments
Opportunities	**Threats**
• Real-time data processing function for a specific location and time • Incorporate weather and climate forecasts in the appropriate agricultural drought indices for better prediction • Use an existing or develop a region-specific composite drought index • Be flexible in terms of mode of communication and send warning messages together with recommendations • Include contingency plans for a realistic strategy for response and recovery	• Risk of false information due to lack of empirical testing and evaluation • Lack of automation and consistent data updates • Outdated resources due to financial limitations • Slow adoption rate due to lack of awareness and capacity building

These factors imply positive prospects of effective web-based agricultural DEWS in South Africa. This would serve as a digital information hub for coordinating agricultural drought information among all stakeholders. It would further improve a continuous conversation on agricultural drought to minimize decision-makers from prioritizing systems (such as funding) during periods of droughts, which is most likely not the correct time to implement drought mitigation measures. Key characteristics should be adopted for collecting data, assessing risk, predicting impending agricultural droughts, disseminating information and improving the capability to respond accordingly.

2.3.8. Conclusions

This literature review considered the status quo in South Africa and addressed various factors on the prospects of applying key lessons for a probable system. Additionally, the review explored external factors, corresponding to opportunities and threats, by learning from established web-based agricultural drought early warning systems around the world. Various characteristics were found among these systems and the most common include, inter alia, the capability to forecast impending drought, comprise a processing functionality and provide the level of drought impact on agriculture.

The least common yet vital characteristics included the integration of field observations, an interactive map and contingency plans. Factors such as the possibility of providing false information due to lack of calibration, slow adoption rate and lack of secure human and financial commitment were viewed as potential hurdles, which should be perceived as modes of opportunity. Accordingly, the study recommended the use of innovative technologies to translate hazard into impact, provide value-added contingency plans and improve stakeholder communication for further developments.

CHAPTER 3. THE ROLE OF POLICY ON AGRICULTURAL DROUGHT EARLY WARNING SYSTEMS

3.1. Introduction

The implementation of early warning systems serves as the foundation for effective drought policy in many nations (FEWS NET, 2020; NCC, 2020; NIWA, 2020; Svoboda *et al*., 2002). These systems have the ability to communicate significant information to end-users within a timely period (UNISDR, 2006). In the policy-making landscape, drought early warning systems (DEWS) contribute as direct inputs to the overall success of disaster risk reduction (Henriksen *et al*., 2018). They enhance the preparedness of any region ahead of a drought, support decision-making during a drought and enable key role-players to implement long-term risk reduction measures following a drought (Van Ginkel and Biradar, 2021). When utilized effectively, DEWS are proactive and can reduce economic losses associated with emergency disaster response and further improve food security, especially in drought-prone regions (Lumbroso, 2018).

South Africa is one of many countries that are susceptible to the frequent occurrence of droughts and the recurrence thereof, which have had adverse implications on the agricultural sector and the vital role it plays in the socio-economic well-being of the country. For example, towards the end of 2014, drought conditions developed over large parts of the country and intensified during the 2015/16 agricultural season (ARC-SCW, 2022). The impacts soon became apparent and by the end of the season, a 40% maize production decline from the preceding 5-year average was recorded (DAFF, 2019). Similarly, livestock production was also affected with animal losses resulting in a reported 15% decrease in the national herd (AgriSA, 2016). This was classified as one of the most severe droughts of the last 100 years, wherein farmers' income sources were reduced (due to crop failure, livestock deaths and destocking) and livelihoods were threatened (Mare *et al*., 2018).

The scale of drought impacts on agriculture varied and by the end of the financial year (March 2016) the government had allocated R198 million to assist affected farmers with feed and drilling of boreholes (DALRRD, 2020b). Nevertheless, the evidence indicated that apart from the meteorologically-based recovery during the subsequent season (ARC-SCW, 2022), the sector had not recovered and thus an additional amount of R212 million was requested to continue implementing the relief and rehabilitation measures (DALRRD, 2020b). Research further confirmed that some areas, viz. the Karoo region and parts of the Eastern Cape, continued to experience a multi-year drought until early 2020 (Archer *et al*., 2021). Subsequently, an amount of R138.5 million was allocated in 2020 for drought relief based on these prolonged impacts (DALRRD, 2020b). This highlights the necessity to reduce economic losses related to reactive crisis management following disaster-drought occurrences by developing proactive management strategies (Mare *et al*., 2018).

To date, the South African government relies heavily on establishing policies for planning and responding to the far-reaching impacts of drought as there has been significant improvement, specifically, in the last two decades concerning these policy documents (Republic of South Africa, 2003). The shared aim of these policies is centred on reducing disaster risk for all concerned, but are they feasible and do they promote effective drought early warning for agriculture?

From a technical perspective, a study by Masupha *et al*. (2021) presented the capacities of various organizations that would benefit the development of an effective DEWS in the country. Moreover, as stated by Seng (2012), one important aspect that will determine whether early warning systems can be sustained is their effectiveness. According to the United Nations Office for Disaster Risk Reduction (UNISDR, 2009b), an effective DEWS is an interactive system that enables drought preparedness by collecting, processing, analysing and communicating information to intended decision-makers. However, the definition by Lassa (2008) focused not only on the technical aspects but on meaningful procedures for those involved (e.g. people-centred systems with triggers and protocols tailored for various users).

Meanwhile, in 2018, South Africa was classified as one of the countries with drought early warning systems that are moderately effective in reducing humanitarian impacts (Lumbroso, 2018). This research bridges major gaps in the implementation of DEWS for agriculture by obtaining perspectives from diverse stakeholders at management level. Three research questions were considered:

i) What are current policy provisions for agricultural drought early warning systems?
ii) What early warning systems does the agricultural sector utilize for drought?
iii) How can policy ensure the effectiveness of agricultural drought early warning systems?

3.2. Methods

The definition of policy was adopted as "a legal document comprising laws, regulations and procedures to guide decision-making" (Chen *et al*., 2014). The work presented in this study examined policy in the context of drought early warning systems for agriculture. The study relied upon document analysis, literature review, and semi-structured interviews to assess processes relating to DEWS. This method has proven in previous research to obtain a great depth of understanding of various topics under investigation, such as drought preparedness (Gutiérrez *et al*., 2014), climate services (Vincent *et al*., 2017) and drought management policy (Ashish, 2019).

Semi-structured interviews were conducted with experts in the agricultural disaster field based on a questionnaire focusing on early warning practice. Due to the exploratory nature of the research, expert sampling – a sub-type of purposive sampling – was utilized to collect the primary data. This non-probability sampling method was selected based on its ability to obtain information from participants who are highly knowledgeable about the research topic and the study area (Helfenbein, 2019). Thus, prospective participants were selected provided that (1) they had proven expertise in disaster-drought and/or agrometeorology, and (2) they were actively involved in drought early warning activities at a high governance and management level. To avoid potential bias, interviews were performed with a sensible balance of participants (21 key informants) representing various provinces and relevant departments. Lastly, policy documents and interviews were evaluated to identify current procedures, recurring lessons and potential barriers considered important for the effectiveness of agricultural drought early warning systems.

3.3. What are current policy provisions for agricultural drought early warning systems?

All key informants mentioned the Disaster Management Act (DMA) of 2002, as amended (DMAA) in 2015, and the National Disaster Management Framework (NDMF) of 2005 as the main national policies regulating disaster risk reduction in the country. As informed by these policies, various sectors – in this case, agriculture and the provinces – are required to utilize them as a basis for developing their own frameworks and plans. Hence participants at national level acknowledged the Drought Management Plan (DMP) of 2005, the Sectoral Disaster Risk

Management Plan (SDRMP) of 2012 and the draft Sectoral Drought Management Plan (SDMP) of 2020 as the key documents for dealing with agricultural disasters.

The review of key policy documents relating to agricultural drought early warning systems at national level revealed that the keyword ‘early warning’ appeared 100 times (Table 3-1). The highest count of this keyword was found in the recently compiled draft SDMP with 37, followed by NDMF with 23 counts, suggesting that early warning systems have gained relevance and are currently being considered a priority in the country. Additionally, the review included other keywords based on the various components of early warning systems (UNISDR, 2009a). For instance, the term ‘vulnerability’ (mentioned 127 times) was included in the document search due to its significance in determining drought-prone regions (Funk *et al*., 2019). This was followed by ‘assessment’ which had the highest total count of 193. These keywords are considered significant in early warning, particularly for the agricultural sector, as they promote knowledge of risk before, during and after a drought disaster.

As informed by the DMA of 2002, the Department of Agriculture, Land Reform and Rural Development (DALRRD) is responsible for monitoring climate conditions, and where disasters are predicted, provinces are required to conduct pre-disaster assessments to monitor and respond accordingly (DAFF, 2012). The DMAA of 2015 further states that disaster risk assessments have to be implemented by identifying and mapping risks, vulnerable areas and communities (Republic of South Africa, 2003, 2015). Thus, mapping, as a factor of risk knowledge, was included in the keyword search as it allows decision-makers to view the areal extent of impending drought conditions to determine priority areas. The only document missing this keyword was the DMA, but it was later included in the amended DMAA. Another important component of early warning is monitoring (UNISDR, 2009a), which refers to the detection of impending and existing drought conditions through relevant indicators for agriculture. According to the SDRMP, it is the DALRRD’s responsibility to enable programmes focusing on continuous monitoring and evaluation of hazards in the provinces (DAFF, 2012).

Table 3.1: Disaster policy (national level) review based on word count of drought early warning system terminologies.

Policy	Early warning (system)	Vulnerability	Assessment	Map	Forecast	Drought indicator	Information system	Dissemination	Awareness
DMA, 2002	1	5	4	0	0	0	2	8	0
DMAA, 2015	6	5	6	6	0	0	0	0	0
NDMF, 2005	23	65	116	29	2	0	4	70	73
SDRMP, 2012	17	20	22	3	2	0	1	13	24
DMP, 2005	16	11	12	5	2	4	1	6	11
Draft SDMP, 2020	37	21	33	7	4	2	3	19	28
TOTAL COUNT	100	127	193	50	10	6	11	116	136

Keywords associated with drought monitoring were searched as ‘forecast’ and ‘drought indicator’ and they were hardly mentioned in the policy documents, with 10 and 6 counts, respectively. The draft SDMP refers to the usage of climate forecasts, together with indigenous and scientific knowledge to identify drought risk (DALRRD, 2020b). Yet, the climatic forecast was commonly mentioned as a prime indicator for disaster-drought, with little evidence of triggers or specific methodology to quantify agricultural drought. Notwithstanding the significant role of forecasts in predicting disasters (Kgakatsi and Rautenbach, 2014), there is an omission in the plans on how they should be utilized with agricultural drought indices to detect the onset, development and recovery of agricultural drought. The plan further anticipates the compiling and utilization of drought indicator maps as part of the sector’s long-term objective.

Monthly advisories that serve as an early warning for disasters should be disseminated by the DALRRD to alert stakeholders to the risks involved (DAFF, 2012). Thus, as stated in the plans, the provincial departments are responsible to establish procedures on how this information will be disseminated. It is stated that communication channels such as TV, radio, libraries, internet, Extension Services points, information days and farmers’ days should be utilized to ensure that information reaches the end-users (DAFF, 2012; DALRRD, 2020b). This information should be archived as both hard copies and electronically. Based on the word count search, the term ‘information system’ was rarely mentioned and yet ‘dissemination’ was stated 116 times, suggesting that key policy documents do recommend communication as a key enabler. However, a study by Kunguma (2020) revealed that existing information systems in the provinces are mainly reactive.

Current policy documents recognize capacity building through public awareness as a vital initiative for disaster risk reduction. Stemming from the SDRMP, education and awareness programmes should not only be prioritized during periods of disaster but more especially during quiet periods, as this might hinder the effectiveness of early warning systems. In addition, the DALRRD has formed early warning committees to coordinate matters relating to agricultural disasters at both national and provincial levels (DALRRD, 2020b). Thus, the adoption of DEWS by end-users should be feasible. The keyword ‘awareness’ was frequently mentioned (136 times) in the current policy documents and this further implies that the emphasis on awareness campaigns and programmes would enhance the response capacity of end-users and the element of feedback through effective systems.

3.4. What early warning system does the agricultural sector utilize for drought?

3.4.1. Sources of drought early warning information

To obtain information on the various sources of drought early warning information, participants' awareness of seasonal forecasts and agricultural products available to them was examined. Figure 3-1A shows that all officials, both at national and provincial levels, were aware of the forecasts issued by the South African Weather Service (SAWS). However, when asked if they understand the forecasts, the majority (73%) said to some extent, while 27% mentioned that they do understand them (Figure 3-1B). Participants that stated they understood the seasonal forecasts to a certain extent mentioned that they often struggle to interpret and understand this information primarily due to the usage of technical jargon relating to the climate models. Another explanation was that these forecasts can be quite tricky, but provinces are part of a national committee that assists with interpreting them.

It was further observed that not all participants were familiar with the agricultural drought monitoring products available. Figure 3-1A shows that 62% said they were aware of these products while the remaining 38% said no. Those who made use of these products mentioned that they mainly utilize drought and vegetation maps from the Umlindi newsletter and the status of dam levels from the Department of Water and Sanitation website. In addition, two officials based in their respective provinces stated that they supplement this information with other technologies such as drones and the second one stated that:

> *"We use our system that is based on climatology maps and in-house surveys that indicate the dependency of farmers on outside assistance for their farming operations. Our system indicates the status of farmers by Municipal area and therefore we can compare areas to each other and prioritize the most vulnerable and thus focus, assistance and awareness can therefore be concentrated on the most vulnerable."*

When asked if all these sources of drought-related information add value to agriculture the participants said yes, the common reason being that they assisted in quantifying impending drought risk. At a national level, it was indicated that the seasonal forecast combined with short- and long-term analysis of agricultural-related indices provide an indication of the spatial pattern of the drought hazard and the probability of rainfall for the agricultural season and thus, they provide a clear picture of areas that need mitigation and relief. Officials at provincial level generally mentioned that they use the products to alert farmers to put measures in place and minimize the prospective impact. However, there was a general concern that farmers do not have access to all the relevant technologies, highlighting that to improve decision-making at a local level, there is room for improvement.

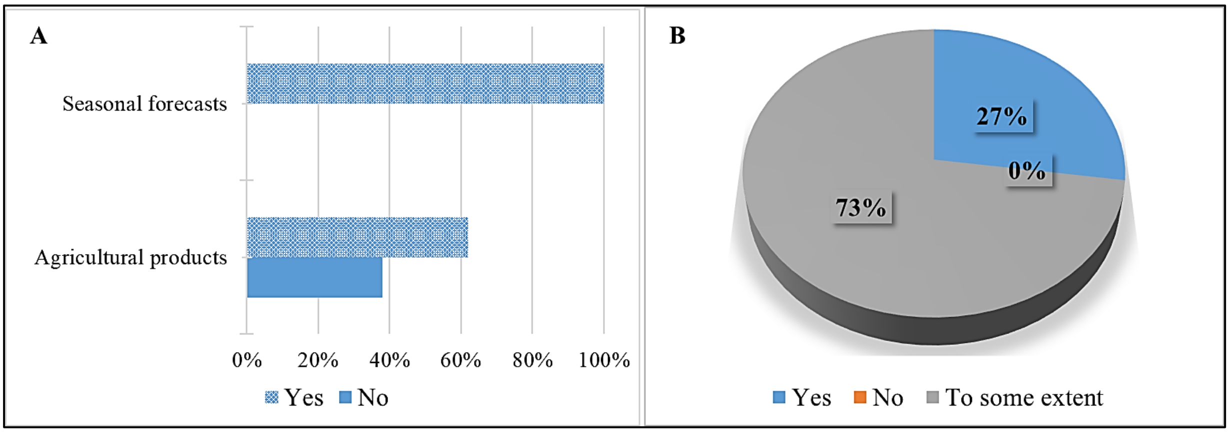


Figure 3-1: Percentage of the usage of various sources for (A) early warning information and (B) participants' knowledge of the seasonal forecasts.

3.4.2. Stakeholder involvement

Based on the survey, the participants listed the following stakeholders as key role-players in planning and managing agricultural drought:

- National and Provincial Disaster Management Centres
- National and Provincial Departments of Agriculture
- Department of Water and Sanitation
- Department of Forestry, Fisheries and the Environment
- National Treasury
- Local Government Municipalities
- South African Weather Service
- Agricultural Research Council
- Academic institutions
- Organized agriculture
- Non-governmental organizations
- General public

Given the diversity of stakeholders and the fact that drought cuts across many sectors (water, agriculture, environment, etc.), survey participants were asked whether there were good working relations among the various role-players. The majority of participants at national level said yes, while officials in the provinces believed that there are no proper working relationships and the most relevant role-players work in silos. One official mentioned that they only come together when drought has been declared, but when it comes to reducing the risk that leads to drought, they are lacking and not being effectively coordinated to do that. It was further suggested that to improve this, there has to be a cross-cutting database system that covers all aspects of drought and government departments should work with academia, the private sector (organized agriculture) and research to create a conducive environment for these role-players to implement the five elements of drought disasters.

3.4.3. Coordination and communication channels

Responses from the National Disaster Management Centre (NDMC) showed that the national office issues a monthly mapped product of the latest SPI and sets the analysis of the SPI against a 3-month baseline for purposes of gauging both the improvement and decline of areas affected by the drought. This is distributed by the National Joint Drought Coordination Committee (NDJCC) every month. The maps are also distributed to all provincial centres (PDMCs). The quarterly National Advisory Forum also tables this product. From the Department of Agriculture it was mentioned that disaster risk reduction sections in provinces cascade information to district coordinators, and at the district level they cascade to local municipalities. It was indicated that the provinces engage farmers through farmer’s days, radio, e-mails, information leaflets and SMSs to convey mitigating factors. The national office also provides organized agriculture with early warning information directly through farmers’ days, etc.

Coordination between different stakeholders involved in agricultural disaster management is fundamental for sharing of information (Pulwarty and Sivakumar, 2014). Thus, participants were asked if there was a clear process for coordination (communication channels with roles) among all relevant stakeholders in terms of drought early warning. There was mutual agreement that all stakeholders are included in the drought-related plans as they clarify the roles and responsibilities of all stakeholders across all stages of drought. This was found to be very clear from the national offices, but there were concerns that in some provinces there are still challenges relating to roles, especially at a local level.

3.5. How can policy ensure the effectiveness of agricultural drought early warning systems?

Literature indicated that policy clearly outlines the responsibilities of stakeholders in terms of managing drought within the agricultural sector (DAFF, 2005). These plans state that although the DALRRD was tasked with managing agricultural drought in the country, responsibilities have to be shared across all levels of government, supported by other relevant stakeholders including the general farming community (DAFF, 2005). This interaction of roles would allow for a cohesive structure best capable of dealing with agricultural drought as a disaster hazard.

The responsibility of implementing the Disaster Management Act is that of the Department of Cooperative Governance and Traditional Affairs (CoGTA), through the National Disaster Management Centre (NDMC) (Republic of South Africa, 2003, 2015). Yet, owing to the multispectral nature of the DMA, the NDMC does not work in isolation and the decision-making processes involve the National Disaster Management Advisory Forum (NDMAF), Intergovernmental Committee on Disaster Management (ICDM) and the relevant Cabinet cluster committee(s) where applicable. In the context of agricultural disasters, the DALRRD is primarily responsible for steering climate change mitigation and adaptation, risk and disaster management for the sector, while shared responsibility lies with the other levels of government, organized agriculture and the larger agricultural community (DALRRD, 2020a).

Based on reviewing of key policy documents, the amended DMA had the lowest count of early warning-related terms, due to its nature. However, it was observed that these documents recognize early warning as a key contributor to achieving the goal of disaster risk preparedness. According to this Act, a clear disaster management plan should be prepared at national and provincial levels and early warning mechanisms should be developed accordingly (Republic of South Africa, 2003, 2015). Officials at provincial level do utilize provincial disaster-related frameworks and plans. However, the findings observed that there were inconsistencies in the type and amount of disaster and drought plans among the various provinces. For example, some officials mentioned that they do not have drought plans but rather utilize provincial disaster management frameworks, while other provinces utilize numerous plans relating to agricultural drought disasters. The findings further showed that certain provinces prefer tailored plans that serve as practical tools due to their respective areas being faced with challenges leading to a shift in disaster risk patterns such as climate change, rapid population growth and land-use changes.

For assessments on agricultural drought risks across the world, the commonly used methods or tools are drought indices, as they provide valuable information with regard to severity, duration and impacts (Mishra and Singh, 2010). These include indices such as the Standardized Precipitation Index (SPI) (McKee *et al.*, 1993), Water Requirement Satisfaction Index (WRSI) (Senay and Verdin, 2003), Normalized Difference Vegetation Index (NDVI) (Rouse *et al.*, 1974) and Vegetation Condition Index (VCI) (Kogan, 1990). Currently, the NDMC uses impact indicators based on SPI (based on meteorological calculations) particularly to inform drought declarations and determine which areas qualify for drought relief.

Additionally, when a drought disaster occurs, assessments (including field verification) should occur from local to national level and declarations are conducted according to the requirements at each level (Disaster Management Act of 2002). Furthermore, the DALRRD relies on seasonal forecasts, drought and vegetation maps as well as dam levels as indicators necessary for early warning. Once these products are issued, relevant government authorities are responsible for disseminating them to the provinces to minimize potential impacts on agricultural production.

Although it is mandatory for the DALRRD to have an efficient and effective early warning system as outlined by the SDRMP and the draft SDMP (DAFF, 2012; DALRRD, 2020b), this current system is not automated and needs a lot of improvement. The dissemination of information must be revamped to include other channels like social media. There are some positives in the system like the high involvement of provincial structures, but the dissemination to local structures remains a concern. The survey findings further revealed that principals should be capacitated on the importance of risk reduction, as most of them neglect early warning and focus more on post-disaster recovery. These reactive methods provide a relief-based mentality instead of promoting a much-needed proactive approach (Wilhite *et al.*, 2014). Moreover, participants stated that policies and strategies must emphasize proactive approaches to drought. Drought should not be treated like other hazards as it has a slow onset that is difficult to address as an immediate emergency.

3.6. Conclusions

Since the publication of the Disaster Management Act (No. 57 of 2002), policies relating to agricultural disasters have emphasized disaster risk reduction. Therefore, drought early warning systems are major contributing factors in ensuring that risk to agricultural systems is always reduced. The work presented here examined agricultural disaster-drought management policy in South Africa regarding early warning systems. The study relied upon reviewing policy documents and assessing the implementation thereof, through stakeholder engagements at national and provincial levels.

The findings revealed that current policies and plans recognize the usage of early warning systems for effective drought preparedness and response. Yet, indicators regarding the implementation showed that officials should be capacitated in terms of available sources of drought early warning information. This should further be complemented with awareness workshops on how to interpret and utilize the available products. It was also revealed that the communication channels do not promote timely warnings based on the current dissemination methods and that there are uncertainties on clear roles at a local level. Thus, is it recommended that the government should prioritize proactive interventions such as innovative early warning systems or improvements on current systems to reduce spending a lot of money on disaster response and recovery.

South Africa has made significant progress concerning institutional arrangements for disaster management as well as their capacity to integrate. The DALRRD and NDMC have established multi-institutional platforms of engagement with key role-players, including farmers. Multiple institutions should be involved in drought early warning to have a pool of resources to enable society to be prepared for drought. However, the following key issues need to be considered: (1) clear guidelines and roles of members should be established, especially at local level; and (2) emphasis should be placed on the use of decision support tools to help guide decision-making, planning and improve response capacities.

CHAPTER 4. COLLECTION OF CLIMATE DATA AND INDICES FOR THE DEVELOPMENT OF A DROUGHT EARLY WARNING SYSTEM

4.1. Introduction

Agricultural drought occurs as a result of a combined effect of anomalies in various processes of the hydrological cycle such as lack of precipitation, high evapotranspiration, low soil moisture, etc., contributing to its potential severity on crops (Van Hoek *et al*., 2019). For example, in field crops, drought stress a few days after planting could result in compromised germination and seedling emergence, while the reproductive phase is considered the most susceptible (Hussain *et al*., 2018). The failure of certain processes such as pollination and dry matter production diminish crop and pasture yield (Prasad *et al*., 2008). In addition, many other responses are triggered at the onset of a drought, highlighting the key role of water in plant cells (Da Silva *et al*., 2013). Thus, rainfall serves as the most essential element for agricultural drought early warning systems. However, rainfall alone specifies meteorological drought, while soil moisture in cropping zones during the growing season is a more direct indicator of agricultural drought (Shukla *et al*., 2014).

While rainfall data may be the most accessible weather element in many regions, other variables such as temperature, evapotranspiration and relative humidity are key in depicting all the features associated with agricultural drought (WMO, 2006). It is important to note that adequate climate data are essential for weather forecasting, drought management and validation of hydrological and crop models. For data-poor regions, with sparse climate data networks, challenges may include limited understanding of local agricultural drought dynamics necessary to calibrate and validate models (Sheffield *et al*., 2018). Data quality implications such as missing data and short length of observations also represent critical challenges in data networks around the world (Wilhite *et al*., 2000).

Weather and climate forecasts are crucially important for an effective drought early warning system. According to Jacks *et al*. (2010), the main requirement for effective early warning is timely, accurate forecasts and "nowcasts" (commonly 0-2 hours). However, due to the slow-onset nature of drought, medium-range forecasts (from 3-10 days) are more suitable for monitoring drought conditions/dry spells within the season. In most cases, long-term forecasts (a season or more in advance) are not very reliable (Wilhite *et al*., 2000). In South Africa, seasonal forecasts are very much driven by the state of the El Niño Southern Oscillation (ENSO) phenomenon and become more unreliable in the absence of a strong signal from the Pacific Ocean.

In addition to *in-situ* observed climate data, earth observation (EO) data may also be applied for monitoring agricultural drought. Over the last few decades, progress on remote sensing methodologies has improved the ability to efficiently monitor drought and address early warning challenges (Nieuwenhuis *et al*., 2015). Historically, *in-situ* weather and climate observations have been widely used for drought monitoring. However, during the late 1990s, a transformation occurred, concurrent with progress on EO satellites (West *et al*., 2019). These satellite-based technologies are equipped with sensors collecting data representing mainly in the optical domain, to provide enhanced remotely-sensed information on drought characterization (Niemeyer, 2008).

Given the scale of agricultural drought, appropriate data sources for monitoring are those that are able to provide low spatial and high temporal resolution data necessary for continuous monitoring in near-real-time (Dalezios *et al*., 2014). Key remote sensing-based (directly estimated and modelled) elements for monitoring agricultural drought can be used for assessing and monitoring the various drought characteristics such as intensity, duration and spatial extent (Su *et al*., 2017). These elements include rainfall, land surface temperature, evapotranspiration, soil moisture and vegetation condition (Senay *et al*., 2014).

One disadvantage of satellite-based methodologies is that water-stressed vegetation only becomes visible once the drought has already developed. However, remote sensing, together with modelling and forecasting can generate timely information on impending drought conditions (Su *et al*., 2017). Moreover, EO technologies play a significant role in monitoring drought, particularly in developing regions with insufficient densities of meteorological and hydrological stations (Sheffield *et al*., 2018). Other recent studies preferred a hybrid of both *in-situ*- and remote sensing-based techniques for a more comprehensive assessment of drought conditions (Sun, 2009; Zhao *et al*., 2011).

Subsequent chapters are restricted to the current study, and provide details on all inputs that are included in the agricultural drought early warning system (ADEWS). The system uses inputs from various available datasets to develop an automated processing service that can compute drought indicators. The input datasets are all obtained from internal data sources at the Agricultural Research Council – Soil, Climate and Water (ARC-SCW). For the purpose of this report, Figure 4-1 depicts a simple flow diagram of the components that form the system, with all the input variables highlighted at the top.

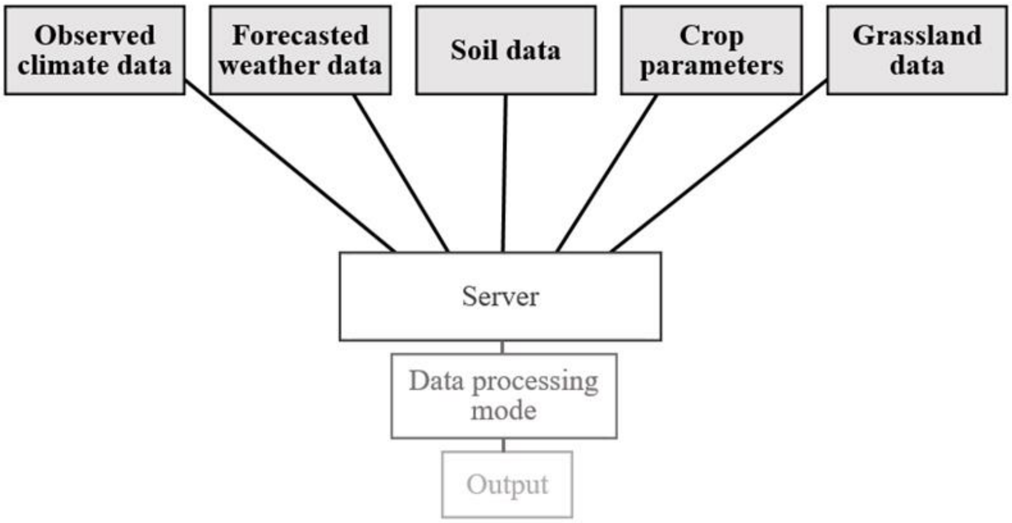


Figure 4-1: Flow diagram of the agricultural drought early warning system, with key inputs at the top.

4.2. Observed climate data

Daily *in-situ* meteorological data are obtained from the ARC-SCW weather station network which consists of over 600 automatic weather stations distributed across all agroclimatic zones in South Africa (Figure 4-2). These stations monitor air temperature, rainfall, relative humidity, solar radiation, wind speed and direction, and the data are stored at hourly temporal resolution (Moeletsi *et al*., 2022). Data are available operationally, with a 24-hour delay, from the ARC-SCW Agri-Climate databank. Calculated indices include evapotranspiration as well as cold and heat units. For the historical climatological datasets, mechanical weather station data are obtained, also from the ARC-SCW Agri-Climate databank, containing historical datasets of rainfall and temperature data. Daily rainfall, minimum temperature, maximum temperature, minimum and maximum relative humidity, wind runs and evaporation data are available from the automatic weather stations. However, most of the mechanical weather station datasets comprise only rainfall or rainfall and temperature data.

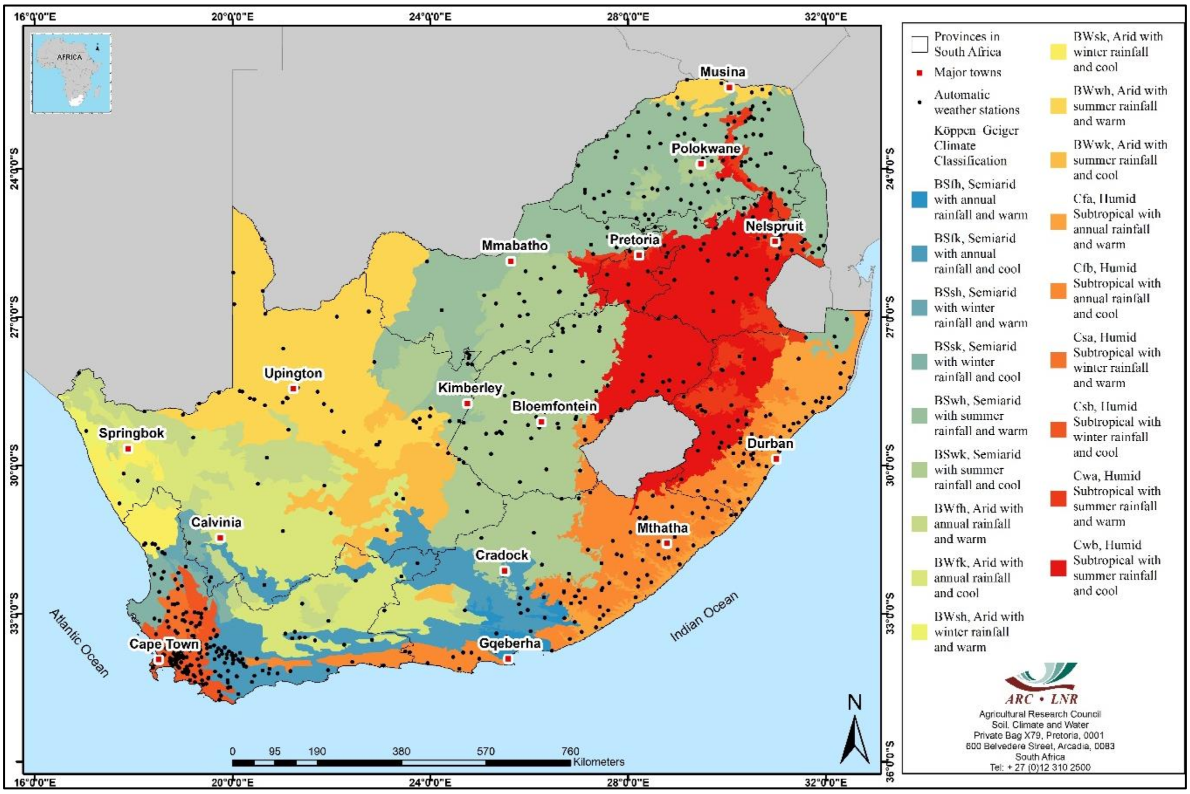


Figure 4-2: Location of ARC-SCW automatic weather stations.

Observed rainfall, temperature, relative humidity and solar radiation data are interpolated into GIS surfaces on a daily basis as the data are received at the ARC-SCW. These interpolated surfaces are then used in the ADEWS instead of having only point data available. The long-term average values, also spatialized, together with satellite-based estimates (Funk *et al*., 2015) in the case of rainfall (Figure 4-3), are used to obtain improved surfaces over and above what is possible through an inverse distance weight interpolation procedure only. In the case of temperature, the long-term average, providing climatological spatial variability, is used to improve on interpolated data (Figure 4-4). Where crop models, grazing models or water balance models are used in the ADEWS, the input data are obtained from the interpolated daily surfaces. This provide more flexibility where modelled data are used but no station data are available in the immediate vicinity.

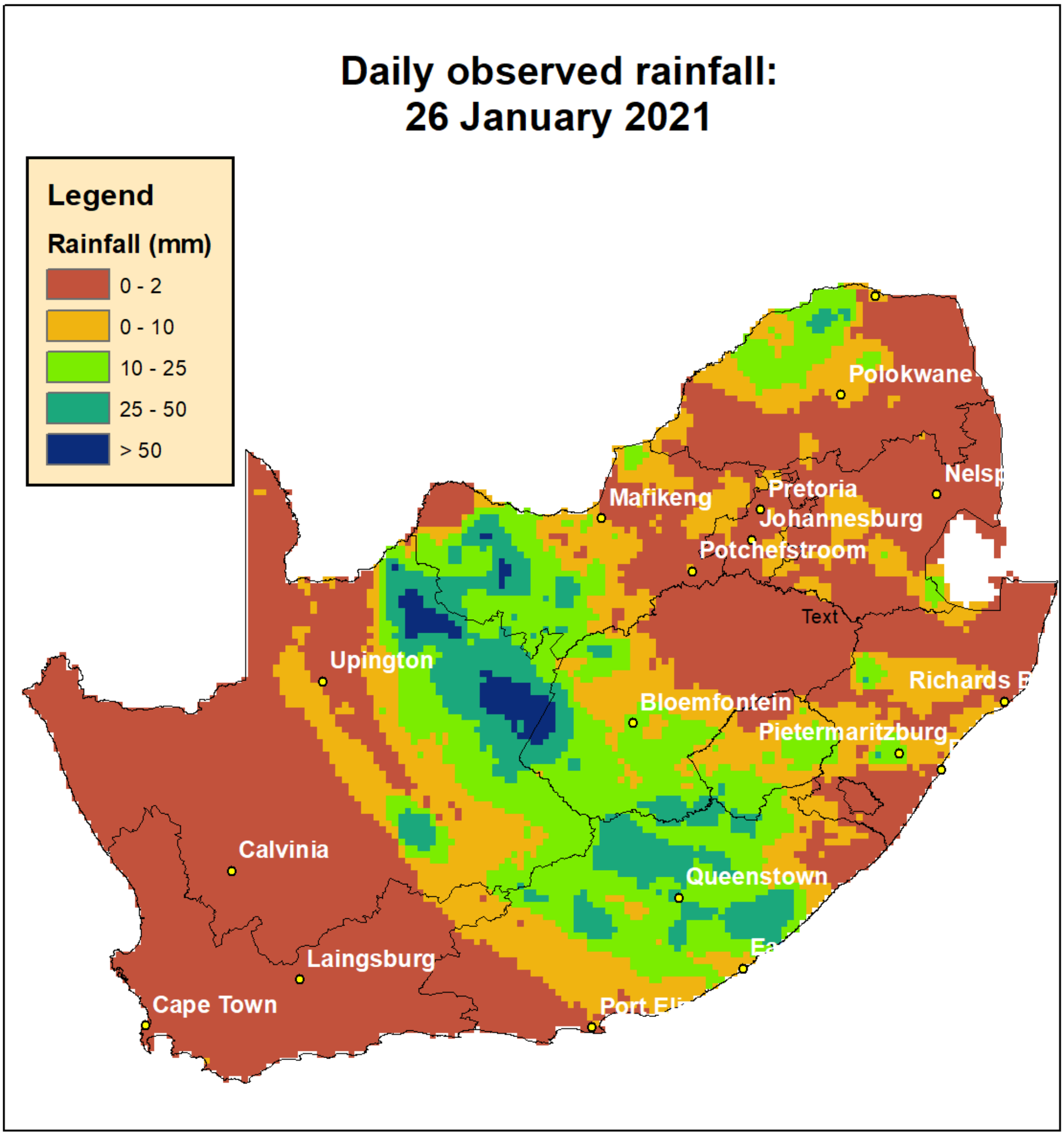


Figure 4-3: Daily rainfall surface for South Africa, obtained through a combination of the data from the ARC-SCW automatic weather station network and satellite-based rainfall estimates.

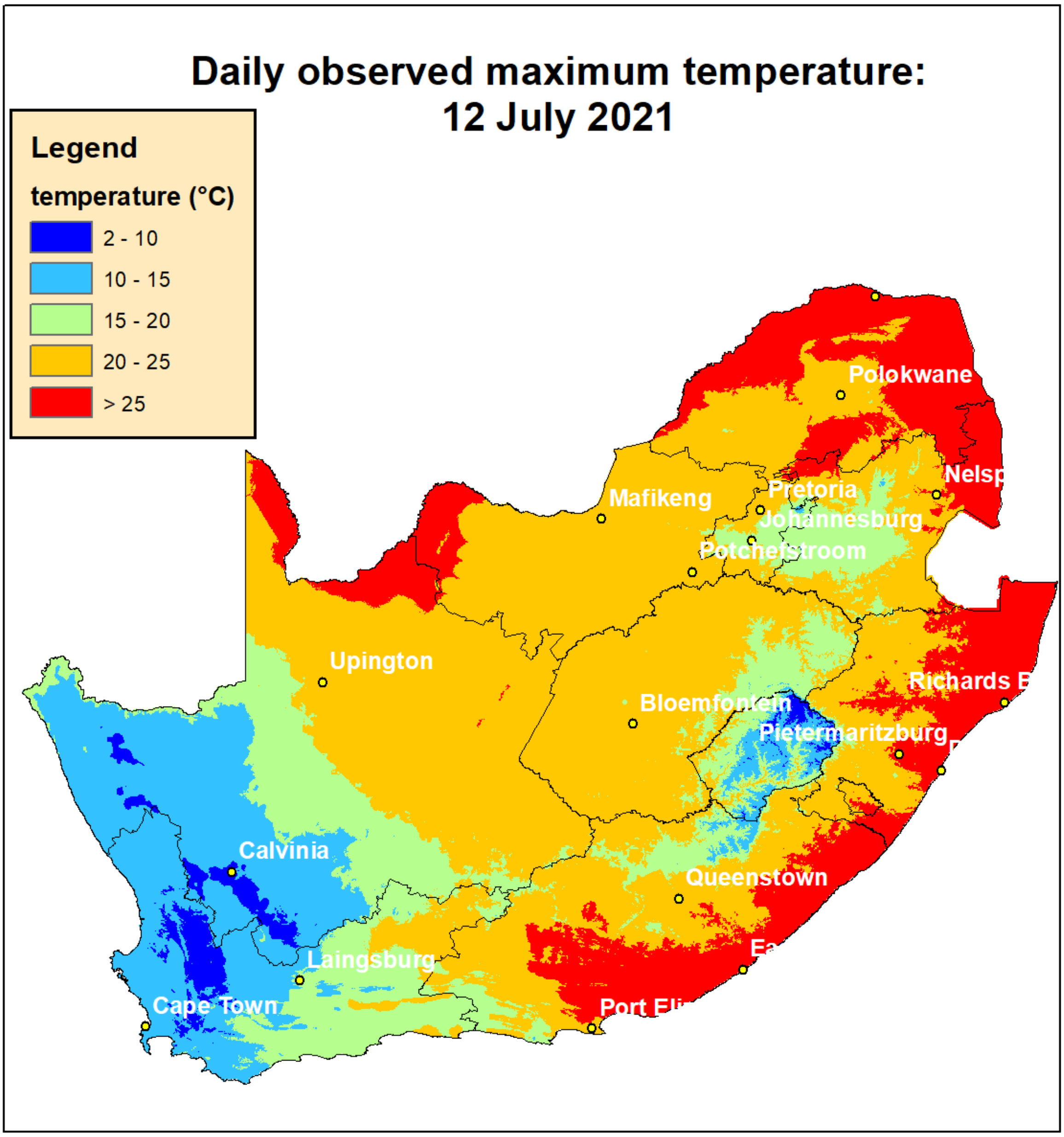


Figure 4-4: Daily maximum temperature surface for South Africa, obtained through a combination of the data from the ARC-SCW automatic weather station and an existing long-term average maximum temperature climatology GIS surface developed earlier.

4.3. Estimated data

Evapotranspiration is an important variable in drought monitoring as it describes water availability and the rate at which the water is consumed by both crops and the soil (Vicente-Serrano *et al*., 2010). Climatic variables that can explain this process include temperature, relative humidity and wind speed (Allen *et al*., 1998). Due to the unavailability of evapotranspiration data from most stations, specifically prior to the year 2000, the present study calculated reference evapotranspiration (ETo) based on the Hargreaves method (Hargreaves and Samani, 1985). This method requires geographic coordinates of each station together with minimum and maximum air temperature as inputs.

The Hargreaves method has been demonstrated to significantly reduce sensitivity to error in climatic inputs, as it calculates ETo as a function of minimum and maximum air temperature and extra-terrestrial radiation (Hargreaves and Allen, 2003). Moreover, previous studies have applied this method as the best alternative for determining evapotranspiration in large-scale studies where relative humidity, vapour pressure deficit, wind speed or solar radiation data were missing (Droogers and Allen, 2002; Masupha and Moeletsi, 2018; Moeletsi *et al*., 2013; Trambauer *et al*., 2014). Hargreaves and Samani (1985) give the following equation for the Hargreaves method:

$$\mathrm{ET0} = 0.0023 \times \mathrm{Ra} \times \mathrm{TD}^{0.5} (\mathrm{Tm} + 17.8) \quad \text{(Eq. 4.1)}$$

where:

$ET0$ = Daily reference evapotranspiration

TD = Difference between maximum and minimum temperatures

Tm = Average monthly temperature

Ra = Water equivalent of the extra-terrestrial radiation in mm/day, given by:

$$\mathrm{Ra} = \frac{1440}{\pi} (\mathrm{G_{sc}}.\, \mathrm{d_r})[\Psi_s \sin(\varphi) \sin(\delta) + \cos(\delta) \sin(\Psi_s)] \quad \text{(Eq. 4.2)}$$

where:

G_{sc} = Solar constant (0.0820 MJ/m^2/min)

d_r = Inverse relative distance from earth to sun, given by: $d_r = 1 + 0.033\cos\left[\frac{2\pi(JD)}{365}\right]$

JD = Julian day of year

Ψ_s = Sunset hour angle (rad)

δ = Solar declination (rad), given by: $0.409\sin\left(2\pi.\frac{JD}{365} - 1.39\right)$

φ = Latitude of location

To convert MJ/m^2/d to mm/d, multiply the MJ/m^2/d value by 2.43.

The agricultural drought early warning system will automatically simulate drought index on a daily basis and reflect changes. These changes will be determined by water requirements per crop type. Moreover, crop factor (Kc) values, necessary as adjustment factors for the crop water requirement per growing stage, differ throughout the agricultural season (Allen *et al.,* 1998; Martin *et al.*, 2000). Thus, in order to determine the Kc values, the single Kc approach developed by Allen *et al*. (1998) was applied which comprises three steps:

1. Determine the total growing period of each crop.
2. Determine the various growth stages of each crop.
3. Determine the Kc values for each crop for each of the growth stages.

The first step refers to the period (in days) from planting to the last day of harvest. It is primarily dependent on the type and variety of crop, climate and planting date. The total growing period is highly dependent on local crop varieties but, for the purpose of this study, three periods, viz. short, medium and long, were analysed respectively. Step 2 requires the total growing period to be divided into 4 growth stages: (i) initial stage, (ii) development stage, (iii) mid-season stage and (iv) late season stage. The third and final step is to determine the crop factors by obtaining values (for *initial* and *end*) from Allen *et al*. (1998) and adjusting them according to local climatic conditions. Thereafter, intermediate Kc values are linearly interpolated to obtain the Kc during the whole growing period. The adjustment entailed reducing the values by 0.05 if the relative humidity is high and the wind speed is low (i.e. RH > 80% and u < 2 m/sec), with the opposite applying when humidity is low and the wind speed is high (i.e. RH < 50% and u > 5 m/sec). table 4-1 shows average Kc values per growth stage for various major field crops.

Table 4.1: Examples of Kc values for various major field crops (Allen *et al*., 1998).

Type of Crop	**Initial stage**	**Development stage**	**Mid-season stage**	**Late-season stage**
Barley/Oats/Wheat	0.35	0.75	1.15	0.45
Grain/small	0.35	0.75	1.10	0.65
Maize, grain	0.40	0.80	1.15	0.70
Millet	0.35	0.70	1.10	0.65
Potato	0.45	0.75	1.15	0.85
Sorghum	0.35	0.75	1.10	0.65
Soybean	0.35	0.75	1.10	0.60
Sunflower	0.35	0.75	1.15	0.55

4.4. Forecasted climate data

In order to improve the chances of early detection of potential drought, short- to medium-term weather forecast data for South Africa are included in the ADEWS. Towards this end, the Conformal Cubic Atmospheric Model (CCAM) was installed to produce 6-day forecasts in operational mode at a spatial resolution of 16 km. The model is launched every 24 hours, based on the observed data provided by the Global Forecast System (GFS – https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs), which is operational at the ARC-SCW.

Multiple near-surface variables are produced and the following are used as surrogates for the equivalent observed elements:

- Daily maximum temperature
- Daily minimum temperature
- Daily total rainfall
- Daily total potential evapotranspiration
- Daily total solar radiation

Figure 4-5 and Figure 4-6 show the forecast for temperature and rainfall, respectively, produced at 06:00 SAST on 13 January 2021 for later the same day. It is based on input data by 02:00 SAST from GFS.

The output data for the variables listed above are extracted automatically from the forecast output files for use in subsequent algorithms in the ADEWS. The forecast data are used specifically in the crop and grazing modelling components of the ADEWS. The daily forecast data for 6 days ahead are used together with the observed data which are the interpolated station observations in these models. Inclusion of the forecast data shortens the response time of the crop and grazing modelling output to the current weather conditions.

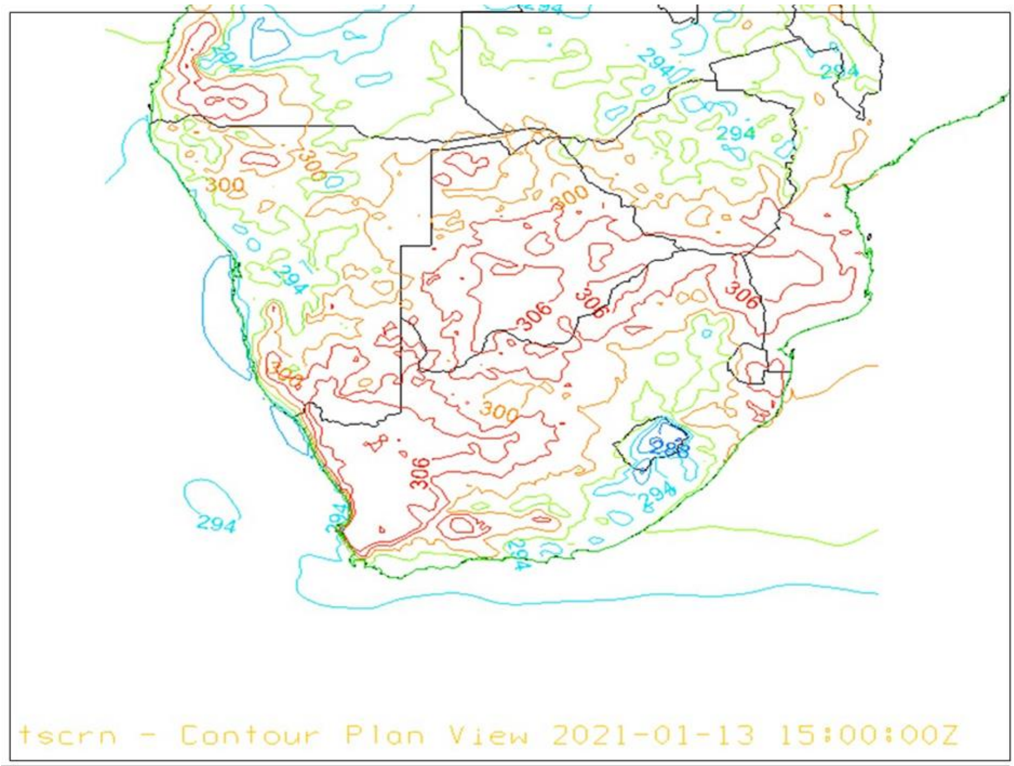


Figure 4-5: Forecast for screen temperature (° Kelvin), produced at 06:00 SAST on 13 January 2021 for 15:00 SAST the same day.

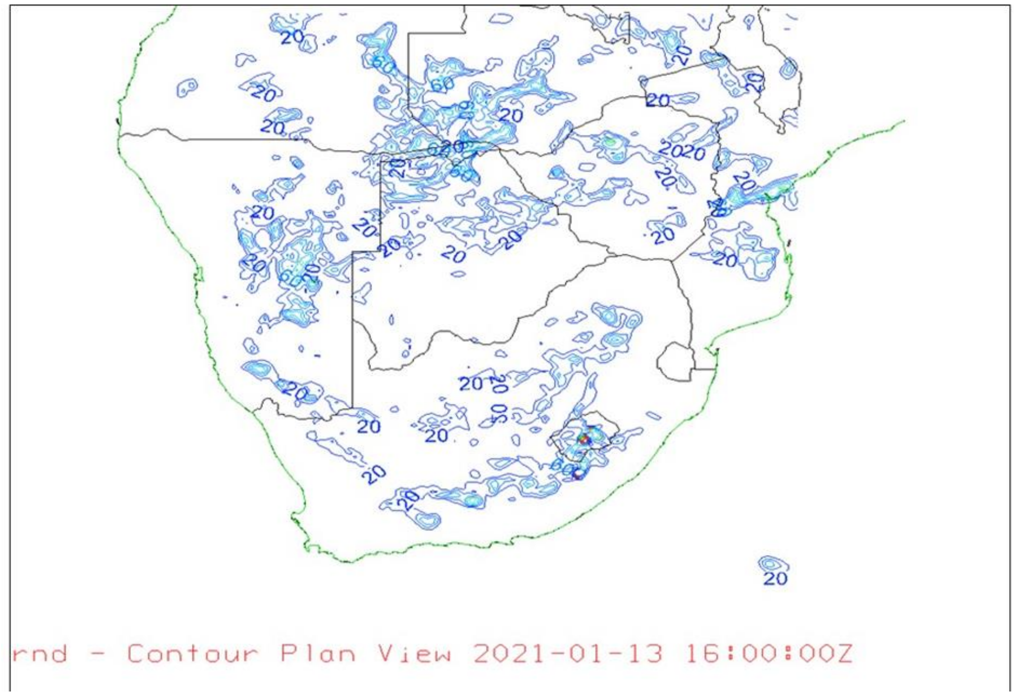


Figure 4-6: Forecast for total rainfall (mm) by 16:00 SAST on 13 January 2021, produced at 06:00 SAST the same day.

4.5. Remote sensing data

Earth observation data used in the ADEWS is based on the Normalized Difference Vegetation Index (NDVI) which quantifies vegetation activity or density by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs). The NDVI is used widely as an indicator of drought stress. Multi-day (typically 10-16 days) composites of NDVI images are commonly used, where the daily images are combined using the so called MVC (Maximum Value Composite) products to eliminate at least partially the effects of cloud cover and perturbing atmospheric artefacts. Several indices are derived from NDVI data for drought monitoring purposes at the ARC-SCW. These are based on various metrics of the NDVI in relation to a long-term archive and can relate information relevant to short periods and also long periods where cumulative products are used.

The ARC-SCW Coarse Resolution Imagery Database (CRID) is used to store historical and near-real-time EO data, including various archives of historical and operational NDVI data. Datasets in this database are used operationally for drought monitoring, with most consisting of coarse spatial resolution data (250 m to 1 km). With regard to temporal resolution, the datasets are specifically aimed at environmental monitoring at relatively high temporal resolution of 10 days up to 16 days depending on the specific satellite sensor.

Currently, the main dataset used for monitoring is the Moderate Resolution Imaging Spectroradiometer (MODIS – https://modis.gsfc.nasa.gov/) dataset from the TERRA and AQUA platforms, with an archive starting in 1999. For the ADEWS, the current dataset used and updated operationally is the 500 m MODIS NDVI dataset consisting of 16-day composites and therefore also a temporal resolution of 16 days. The vegetation monitoring products in the ADEWS are all derived from the MODIS NDVI dataset. Contingency plans are in place so that when the MODIS sensor is decommissioned, another already existing vegetation monitoring data archive in the CRID is available. Specifically, an equivalent dataset is maintained based on data obtained from the Visible Infrared Imaging Radiometer Suite (VIIRS – https://www.earthdata.nasa.gov/learn/find-data/near-real-time/viirs).

4.6. Soil data

Soil data are obtained from the ARC-SCW Soil Information System. Fundamental soil parameters required include texture, soil water-holding capacity, organic carbon, drained upper limit, wilting point, bulk density and soil nitrogen. The soil data are especially important and incorporated in the crop modelling, grazing modelling, and calculation of the Water Requirement Satisfaction Index (WRSI). As an example, Figure 4-7 presents soil water-holding capacity in South Africa. The product was derived earlier from a large number of soil samples collected over several years by the ARC-SCW.

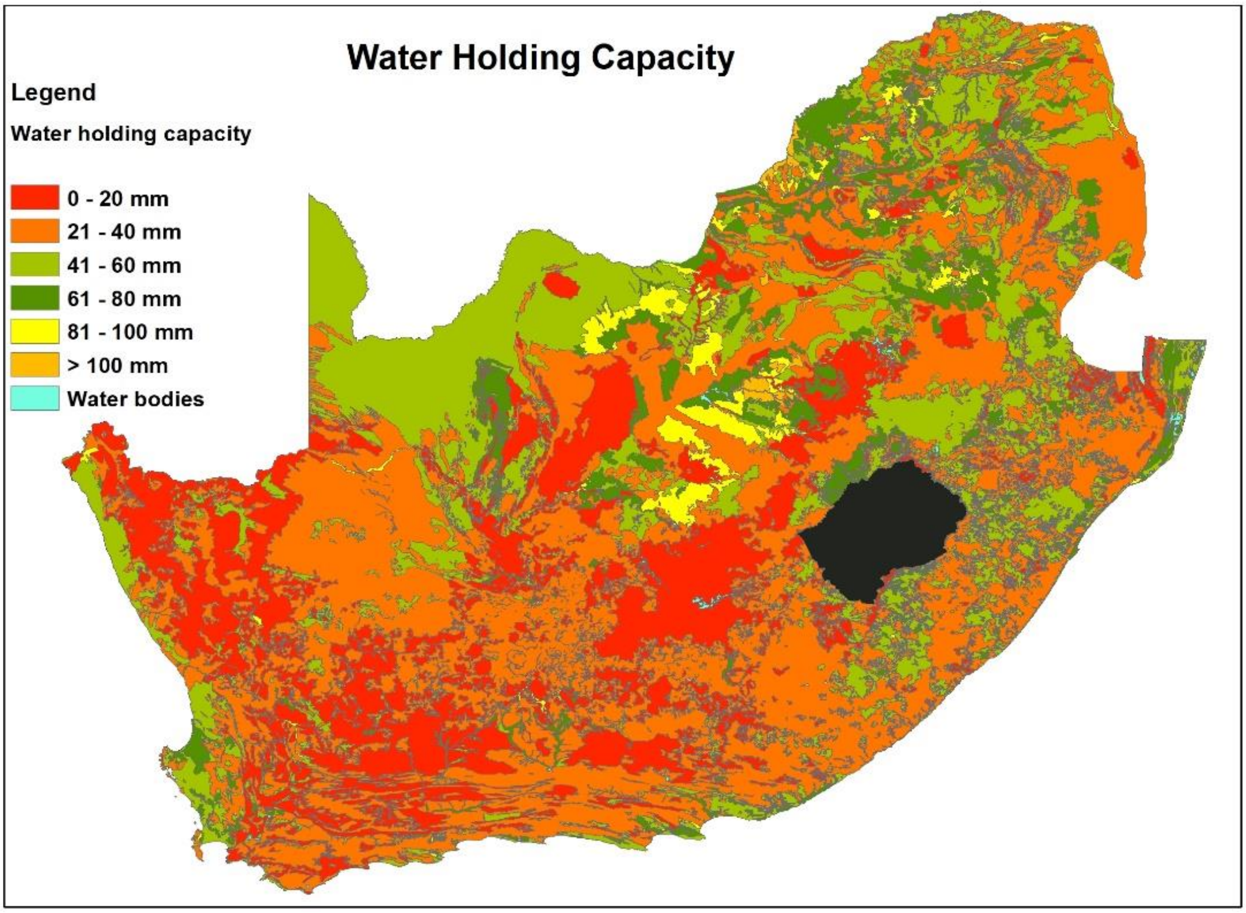


Figure 4-7: Water-holding capacity in South Africa, given by class.

4.7. Selected drought indices

This section provides an overview of the drought indices available in the ADEWS. These are for the most part general drought indices, but also applicable in identifying agricultural drought, noting their flexibility to highlight long-term drought situations, specific seasonal anomalies or recent trends. These are all calculated from the input data described in previous sections. Over and above the indices described here, simple monitoring information is also available in the ADEWS. This is the total monthly rainfall for up to the previous calendar month, providing someone with knowledge about a specific area with information regarding developing situations. For more recent, short-term conditions, the 10-day accumulated rainfall totals at the locations of ARC-SCW automatic weather stations, as recorded by those stations, are also provided. These offer additional information of the most recent conditions that may not yet be reflected in indices based on monthly data.

4.7.1. Standardized Precipitation Index

The Standardized Precipitation Index (SPI – McKee *et al.*, 1993) is based solely on rainfall data. Since rainfall data is more widely available and has longer historical records than for other variables, the availability of an index based on rainfall provides better spatial detail and better historical context. The SPI provides an indication of the rainfall situation for a specific period in the context of the historical record, and is not only based on the relation with a specific metric (e.g. long-term average). It is calculated by fitting the available long-term rainfall data to a Gamma probability distribution, which is then transformed to a normal distribution so that the mean SPI for the location and desired period is zero. The use of a time series of at least 30 years of rainfall data is advised for the successful determination of the parameters of the Gamma distribution from the monthly rainfall data. The index assigns a single numeric value to the precipitation that can be compared across regions with markedly different climates. That is due to the standardization of the SPI which allows the index to determine the rarity of a specific drought event within the climatological context of any climatic region. The SPI has been selected by the WMO as a key meteorological drought indicator (Hayes *et al*., 2011).

Based on various accumulations of monthly rainfall values (e.g. 3-month, 6-month, etc.), the index value can give an indication of the intensity of meteorological, agricultural or hydrological drought due to its temporal flexibility. It can also detect wet and dry events occurring simultaneously at different time scales (e.g. a wet month within a dry 2-year period). The 1-month SPI is a short-term value and can be important during the growing season as an indicator of soil moisture and crop stress. At the 3-month time scale, the index reflects short- and medium-term moisture conditions while also providing a seasonal estimation of precipitation. At the 6-month time scale, the SPI becomes a very important indicator of seasonal conditions with regard to drought stress in crops and grazing. At 12 months and longer, the SPI will only show wet or dry conditions if the shorter-term SPI values for the period are indicating a trend. At these longer time scales, stream flow and reservoir levels are well correlated with the index and it becomes an indicator for hydrological drought.

In the ADEWS, the SPI is calculated at different time scales (1-, 3-, 6-, 12- and 24-month periods) per quaternary catchment, allowing discrimination between potential agricultural and hydrological impacts. It is based on a dataset of monthly rainfall values per quaternary catchment, derived from historical and recent interpolated monthly rainfall GIS layers updated operationally at the ARC-SCW.

4.7.2. Water Requirement Satisfaction Index

The Water Requirement Satisfaction Index (WRSI – Frere and Popov, 1979; Allen *et al*., 1998) was developed to specify the extent to which water requirements of a seasonal crop have been dis/satisfied. The index is an indicator of crop performance based on the availability of water to the crop during a growing season, with the yield at the end of the growing season linearly related to the index value. The weather-related variables used in the WRSI model are precipitation and potential evapotranspiration (PET). These input variables are available at the ARC-SCW as they are part of the dataset of GIS climate layers obtained by interpolating the observed/calculated values at each of the automatic weather stations on an operational basis every day. While the rainfall value is recorded at each station, the PET value is calculated at each station from hourly data and is available on the Agri-Climate databank together with daily rainfall data, for each station per day in near-real-time.

The WRSI is the ratio of seasonal actual crop evapotranspiration (AET_c) to the seasonal crop water requirement, which is equal to the potential crop evapotranspiration (PET_c):

$$\mathrm{WRSI} = \left(\frac{\Sigma \mathrm{AETc}}{\Sigma \mathrm{PETc}}\right) * 100 \qquad \text{(Eq. 4.3)}$$

The relationship between evapotranspiration and crop evapotranspiration is given by appropriate crop coefficients (Kc):

$$\mathrm{PETc} = \mathrm{PET} * \mathrm{Kc} \qquad \text{(Eq. 4.4)}$$

Kc values are published by the FAO and are available for a wide variety of crops. The Kc value changes through a growing season (Allen *et al*., 1998; Martin *et al*., 2000) and is also unique to specific crops. In the ADEWS, the WRSI is calculated for three maize cultivar types under dryland conditions over the summer rainfall region of South Africa, namely 140, 120 and 100 days until maturity to represent long, medium and short season cultivar types, respectively. Figure 4-8 shows the Kc value as a function of days since emergence for a 120-day (medium growing season) maize cultivar, together with the equation used in the ADEWS to approximate the Kc value during the calculation of the WRSI for a 120-day maize cultivar.

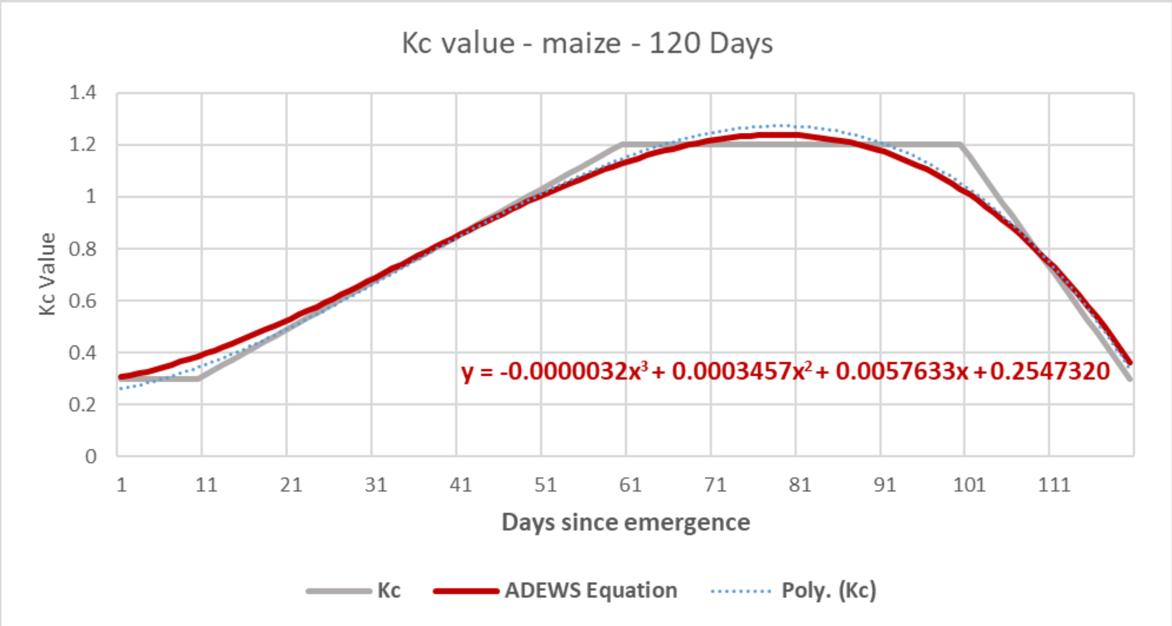


Figure 4-8: Crop coefficient (Kc) for a 120-day maize cultivar (grey line) together with the function used in the ADEWS to update the Kc value throughout a growing season also for a 120-day maize cultivar.

Actual crop evapotranspiration (AETc) represents the actual amount of water withdrawn from the soil and therefore available to the root zone of the plant to be extracted, namely the soil water content (SWC). The upper limit of the SWC is a function of soil water-holding capacity and plant root depth. Its value varies from a minimum of 0 to a maximum equal to the water-holding capacity.

For each time step of the calculation of the WRSI, plant-available water (PAW) is firstly calculated by adding the precipitation during the time step to the SWC from the previous time step. When the SWC falls below a certain critical level (critical soil water level – SWC), AETc becomes less than PETc, indicating water stress. Therefore, AETc is determined as follows:

When PAW >= SWC:

$$\text{AETc} = \text{PETc} \qquad \text{(Eq. 4.5)}$$

When PAW < SWC:

$$\text{AETc} = \frac{\text{PAW}}{\text{SWC}} * \text{PETc} \qquad \text{(Eq. 4.6)}$$

When AETc > PAW

$$\text{AETc} = \text{PAW} \qquad \text{(Eq. 4.7)}$$

The WRSI is updated daily in the ADEWS, calculated using daily interpolated observed rainfall and potential evapotranspiration together with crop coefficients and soil water-holding capacity data per GIS grid point.

4.7.3. Percentage of Average Seasonal Greenness

The Percentage of Average Seasonal Greenness (PASG) is an indicator of relative cumulative vegetation activity over a multi-month period as it is the sum of NDVI values during the period expressed as a percentage of the long-term average over the same period:

$$\text{PASG}_{\text{PnYn}} = 100 * \left(\frac{\text{SG}_{\text{PnYn}}}{\text{XSG}_{\text{Pn}}}\right) \qquad \text{(Eq. 4.8)}$$

where:

$\text{PASG}_{\text{PnYn}}$ = PASG for a specific period in specific year/season

SG_{PnYn} = Accumulated NDVI values for a specific period in a specific year/season

XSG_{Pn}= Long-term average of the accumulated NDVI over the period

This index allows for identification of areas experiencing drought stress over extended periods such as a growing season. The PASG can be used to identify the following:

a) **Drought stress in crops present through the growing season**, especially later during the growing season when the cumulative effect of drought may be important. An example of this would be when crop modelling indicates below-normal yields that might be related to lower rainfall during an extended period in the growing season. The 3-month PASG can be used to assess early-season potential production for maize by January, by reflecting cumulative vegetation activity during the October to December period. Moreover, the summer cumulative PASG (starting from July) can also be used for this, and can also show the potential effect on cumulative vegetation activity by the end of the growing season, as it occurred during the entire summer growing season. Likewise, for winter crops, the 3-month PASG can be used to assess drought impacts during one half of the growing season, while the winter cumulative PASG (starting from January) can identify cumulative stress during the entire growing season by September or October.

b) **Drought-stressed grazing through a growing season.** Similar to the use for crops, the index is useful to consider the cumulative effect on pastures of prolonged dry periods during a growing season. For example, if the grazing modelling component indicates lower productivity than previous years in the time series, the PASG can be used to gain a better understanding of the spatial patterns of stressed areas. If grazing modelling indicates relatively low productivity over part of the North West Province by February, the 3-month PASG or the summer cumulative PASG can be used as additional evidence and a clearer indication of the spatial extent of the stressed areas.

Hydrological drought can be highlighted by the summer or winter cumulative PASG by the end of the relevant water year/growing season. Being able to represent drought stress over a relatively long period, the index can further highlight catchments where drought stress is having a significant long-term effect on vegetation activity and therefore also water levels.

In the ADEWS, the PASG is produced from the 16-day MODIS NDVI composites at a 500 m spatial resolution available in the CRID. It is calculated for a summer (July to June) and winter (January to December) year as well as for a moving 3-month period. Apart from the PASG for the latest month period, the archived data can also be displayed for up to 2 years in the past. For display of current and historical PASG data, the ADEWS has a slider which the user can utilize to interrogate its evolution over time during the 2-year period.

4.7.4. Vegetation Condition Index

The Vegetation Condition Index (VCI) compares the NDVI of a given period with the minimum and maximum computed for the same period from the entire dataset (e.g. for 1-10

January 2023 the NDVI will be compared to the NDVIs for 1-10 January over the entire multi-year period).

$$\mathrm{VCI} = 100 * (\mathrm{NDVIt} - \mathrm{NDVILTmint})/(\mathrm{NDVILTmaxt} - \mathrm{NDVILTmint}) \quad \text{(Eq. 4.9)}$$

where:

NDVIt = NDVI for a specific period

NDVILTmint = Minimum NDVI value over the long-term archive for the specific period

NDVILTmaxt = Maximum NDVI value over the long-term archive for the specific period

The VCI ranges from 0 to 100 with low values corresponding to unhealthy and stressed vegetation while high values correspond to healthy and unstressed vegetation. Different degrees of drought severity are indicated by VCI values below 50%. In the ADEWS, the VCI is produced from the 500 m 16-day MODIS NDVI composites available in the CRID at a 16-day temporal resolution. Apart from the VCI for the latest month period, the archived data can also be displayed for up to 2 years in the past. For display of current and historical VCI data, the ADEWS has a slider which the user can utilize to interrogate its evolution over time during the 2-year period.

4.8. Modelling – crop and grazing

4.8.1. Crop modelling

The Decision Support Tool for Agrotechnology Transfer (DSSAT) (Hoogenboom *et al*., 2010) Crop Environment Resource Synthesis (CERES) Maize model is used to produce estimates of maize yield and various other related variables. CERES-Maize is a daily-incrementing simulation model of maize growth, development and yield (Jones *et al*., 1986). It is the most widely used maize model globally and is the mother-seed of several other maize models such as APSIM. It is a multi-purpose simulation model that can be used, amongst others, for yield forecasting.

The CERES-Maize model simulates maize growth, development and yield and therefore needs to take into account processes such as phenological development, biomass accumulation and soil water balance, together with water use by crops as well as soil nitrogen uptake. The model needs input data describing soil properties such as depth, texture and water-holding capacity.

It also needs data on management practices such as fertilizer strategy, planting density and depth, and planting date. Daily weather data is needed to describe conditions influencing the development of the crop throughout the growing season.

The crop model output in the ADEWS contains information about estimated yields, as simulated using CERES-Maize, during the current production year compared to previous years since 2014, for 75 locations evenly spread over the summer grain production region. The crop modelling section in the ADEWS is intended to focus on a number of crops, and currently the first focus crop is maize over the main production area of the summer rainfall region. The crop simulation output is based both on observed data (as recorded in near-real-time by the ARC-SCW automatic weather station network) and short-range (6-day) forecast using the Conformal Cubic Atmospheric Model (CCAM). At each of the 75 locations for which the simulations are done, daily weather data are obtained from the GIS surfaces of interpolated observed weather data. These include daily rainfall, maximum temperature, minimum temperature and solar radiation data stored in the ARC-SCW Agri-Climate Databank.

Typical management practices for each location, such as regionally specific planting density and planting date, are assumed. Specifically, three planting dates are assumed for each area (location) within the normal planting window for that region. Application of fertilizers is assumed at 60 kg/ha N, a typical fertilizer strategy for dryland cultivation over large parts of South Africa. Soil information such as depth and water-holding capacity is obtained from the ARC-SCW Soil Information System for each simulation location.

Crop model output is not specifically intended to highlight the effects of drought only, but also other weather-related impacts such as temperature extremes and heat units as well as non-weather-related factors such as soil type, planting depth, cultivar type and fertilizer strategy. However, if drought occurs at the sensitive stages of crop development, the simulations will be sensitive to the effect of such stress and will within the context of all other factors adjust the yield estimate to show the drought impact. It therefore makes a meaningful contribution to agricultural drought early warning.

4.8.2. Grazing modelling

The PUTU VELD model was refined from previous versions of the PUTU model (Fouché, 1992). It is a dynamic and deterministic model and also incorporates physical and biological processes. It has been calibrated to simulate rangeland production over the central parts of South Africa around Bloemfontein (Snyman, 2013). The model simulates the growth and development of climax grasses, i.e. grasses that grow in favourable soil and climatic conditions and are perennial. The model uses daily meteorological data and a two-layered description of soils.

The PUTU VELD model has been converted into FORTRAN coding language at the ARC-SCW in order to afford researchers the opportunity to make adjustments, automate procedures and include various data types from different sources (Odendaal, 2018). It simulates and produces output on a daily basis beginning on 1 July and ending on 30 June. The weather input variables are daily total rainfall (mm), minimum and maximum temperatures (°C), reference evapotranspiration (mm) and sunshine duration (h). As previously stated, in the ADEWS the weather data are obtained from the interpolated daily GIS surfaces for rainfall, minimum and maximum temperatures and evapotranspiration. The sunshine duration input variable is calculated from solar radiation (interpolated from automatic weather station data), point latitude and Julian date.

Model simulations are done for 309 evenly spaced points across the eastern half of South Africa, covering the main grazing areas too. Because the weather input variables are obtained from interpolated GIS daily weather surfaces, the location of these evenly spaced points are not determined by the location of weather stations.

The outputs of the PUTU VELD model include the following: dry matter production (kg/ha) reached on a certain date; maximum dry matter production (DMPmax) (kg/ha) and the date that it occurs (Dtp); number of moisture stress days (MSD); the reserves (kg/ha) on 1 July; and the residual production on 1 July (from which LSU can be calculated). In the ADEWS, the simulated current maximum dry matter production reached by the current date is compared to the simulated maximum value by the same date during previous growing seasons since 2011. The ranking of the value for the current growing season relative to the previous seasons is produced as output and can be displayed in the ADEWS.

In order to improve the lead time to identify hotspots, the ADEWS makes use of modelled weather data by CCAM. The same elements are used as those that are observed inputs – only the modelled equivalents. The ADEWS uses 6-day forecast data with hourly output summarized to daily values.

4.9. Conclusions

Input data to calculate ADEWS products are all collected and archived or in some cases produced at the ARC-SCW. The products are based on operationally collected and archived meteorological data originating from the ARC-SCW automatic weather station network as well as EO data from the ARC-SCW CRID. Using these datasets, operationally updated at the ARC-SCW, guarantees future availability of ADEWS products (indices) and sustainability of the system.

The ADEWS products range from being generic, aimed at monitoring meteorological drought, to commodity specific. While most are aimed at assessing developing drought situations, the inclusion of multi-day forecast data provides a measure of forward-looking capability and may in some cases shorten the potential response time to developing situations. The system is currently operational, but functionality will be expanded in future and certain monitoring products will be refined going forward.

CHAPTER 5. DEVELOPMENT OF AN AGRICULTURAL DROUGHT EARLY WARNING SYSTEM

5.1. Introduction

This chapter describes the characteristics, use and programming of the Agricultural Drought Early Warning System (ADEWS). The ADEWS is a web-based Graphical User Interface with the following address: https://www.drought.agric.za. Users can identify drought-affected areas and drought intensity in a GIS environment using multi-disciplinary datasets. For user-determined locations, automated messages can be received to keep them informed of the latest developments regarding drought at these points of interest.

The chapter also provides details about the various components of the ADEWS and how they have been developed. Due to the heterogeneity of the input data and contributing components to the system, several programming languages are used to obtain the complete set of components that make up the system. These include Python, html scripting language, leaning also on the predetermined scripts made available by the Leaflet library to complement the programming in html for the ADEWS.

5.2. User interface

The ADEWS website (https://www.drought.agric.za) is open to the public and can be accessed by any registered user. The landing page is shown in Figure 5-1. Before being able to make use of the ADEWS, users must register by completing the registration fields and providing the following information: full name, e-mail address, user name and password. Registration is immediate and they can then use the login tab to provide their registered details and proceed to the main page (Figure 5-2). The ADEWS main page, upon logging in, contains:

- The ADEWS main menu, containing the various drought monitoring components, on the left.
- The most recent 12-month Standardized Precipitation Index (SPI) for South Africa displayed on the main map.
- A secondary GIS menu on the top right where the user can choose to display various orientation layers such as administrative boundaries and towns. The user can also choose between the ESRI maps as background or satellite-derived true colour images.

- A slider bar for the opacity of displayed layers located beneath the secondary GIS menu to the right. In this instance, the user can use the slider to change the opacity of the 12-month SPI layer.
- A colour scale / legend for the layer that is being displayed, at the bottom right.

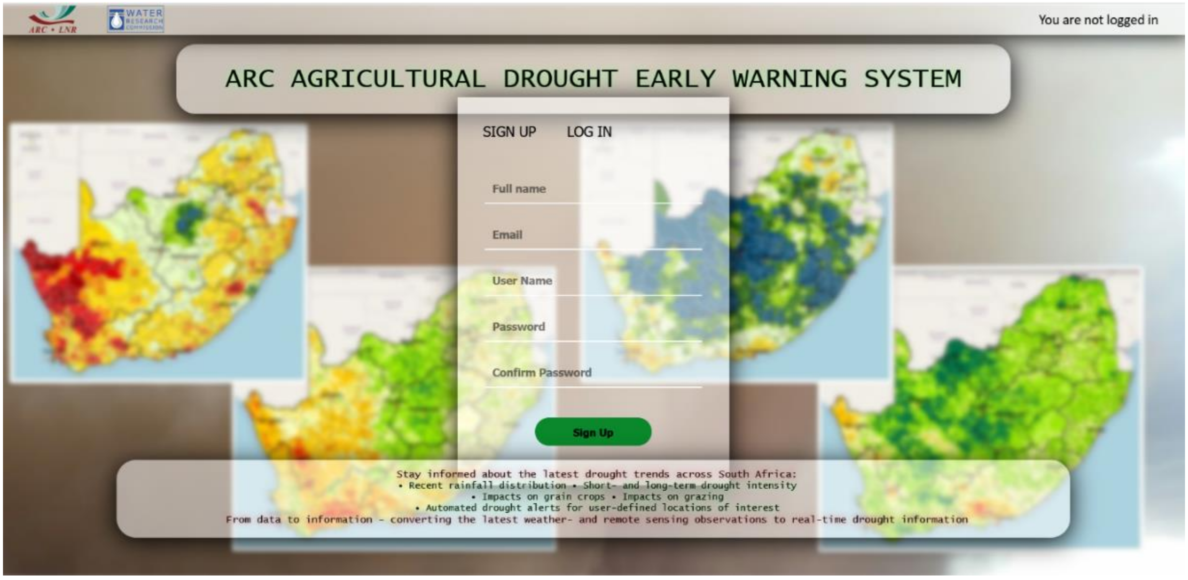


Figure 5-1: Landing page of the Agricultural Drought Early Warning System (ADEWS).

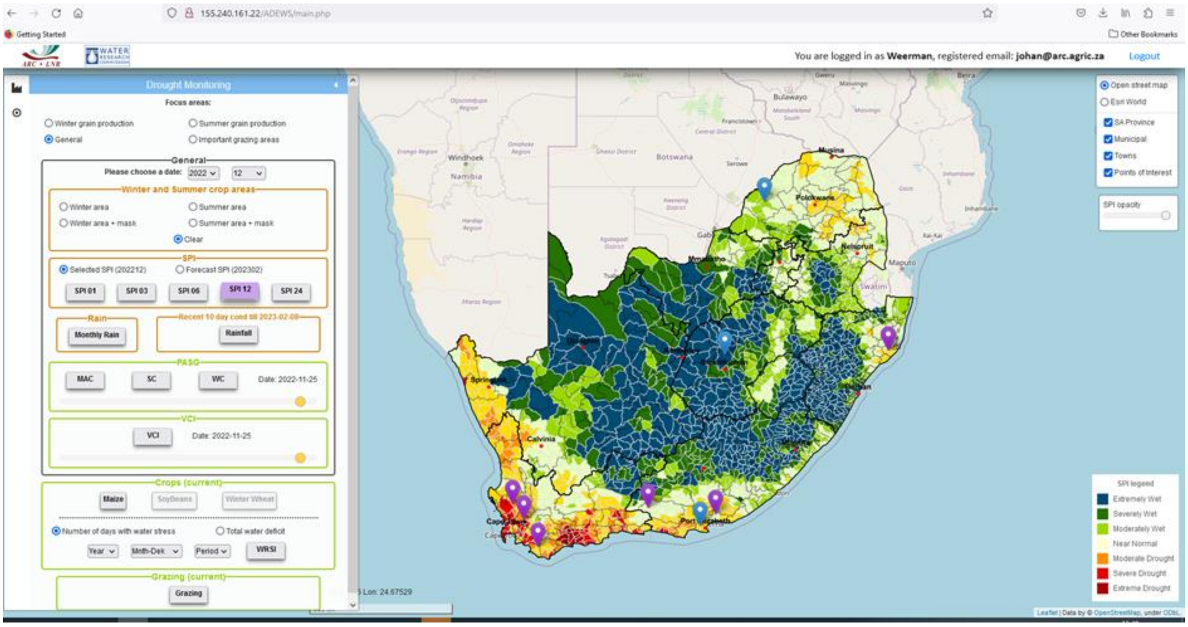
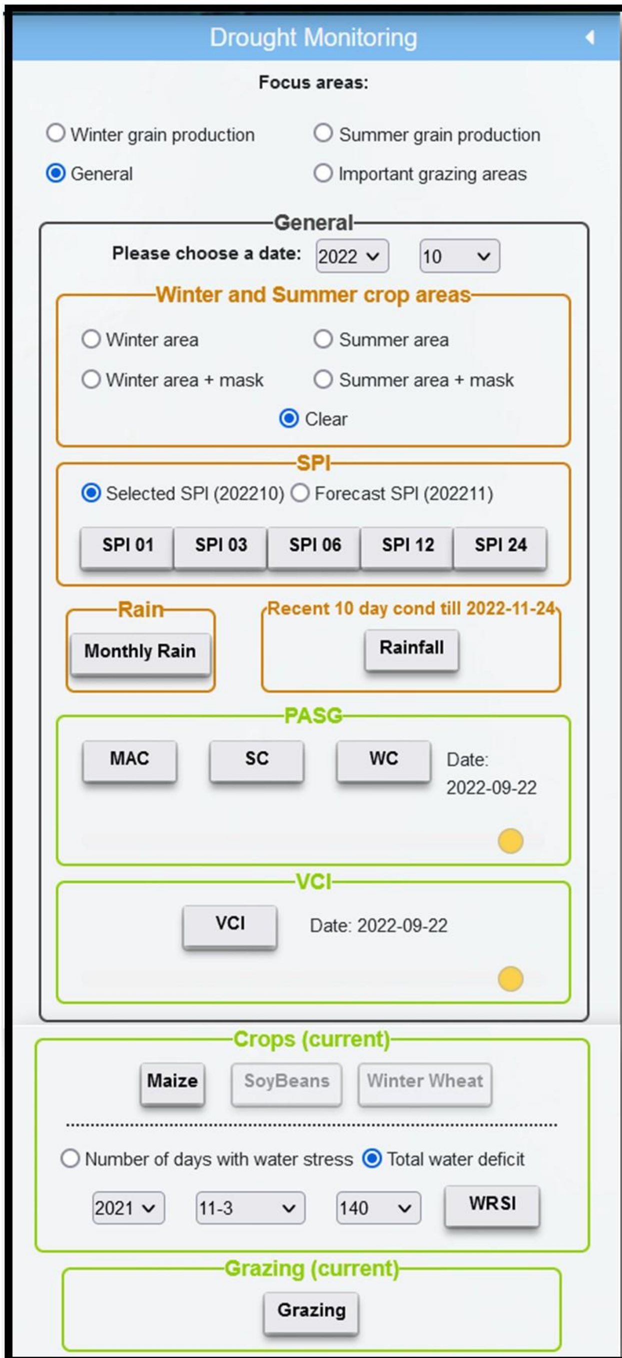


Figure 5-2: The ADEWS main page layout.

The ADEWS has pan and zoom functionality as is typical of GIS-based systems. Figure 5-3 gives a description of the various components contained in the main Drought Monitoring menu.



Focus areas: These selectable options are used to guide the user by enabling and disabling certain aspects of the DEWS

General: This section contains drought monitoring indices that are useful for all purposes, depending on the selected date and the time period over which the index is calculated selectable options are used to guide the user by enabling and disabling certain aspects of the DEWS

Select year / Select month: These drop-down menus allow the user to specify a specific month for which to view the various SPI and PASG layers.

SPI: Standardized Precipitation Index. The user can choose an SPI layer to display, based on the period length selected (1/3…/24) and the date selected at the top. When Forecast SPI is selected, the date is limited to the current month because the forecast is operationally updated as the current month progresses.

PASG: Percentage of average seasonal greenness. With the end date selected at the top, the user can choose to display the Moving Average Cumulative (3-month—MAC), Summer Cumulative (SC—starting in July) or the Winter Cumulative (WC—starting in January) PASG ending in the selected month.

VCI: Vegetation Condition Index. Using the slide bar, the user can animate and display any 10-day layer.

Crops: The user can display the current simulated expected **yield**, relative to the previous years since 2014, for the crop indicated. The **WRSI** for specific planting windows can also be viewed.

Grazing: The user can display the current simulated grass production, relative to the previous years at the same time of the growing season, since 2014.

Figure 5-3: The ADEWS main Drought Monitoring menu, with a summary for each component on the right-hand side.

Information on each component of the main Drought Monitoring menu is provided when the user hovers the cursor over any item (Figure 5-4). Under the General section, the first option available is for displaying the SPI. Here, the user can select the relevant date for which the index must be displayed via a drop-down menu. Furthermore, various relevant period lengths (number of months over which the rainfall is accumulated for the index to be calculated) can be selected. These are: 1, 3, 6, 12 and 24-month periods. The SPI is displayed with the appropriate legend, a classification to identify various theoretical intensities of drought or wetness, calculated using the index. In the example shown in Figure 5-5, the user displays the 12-month SPI ending in December 2022.

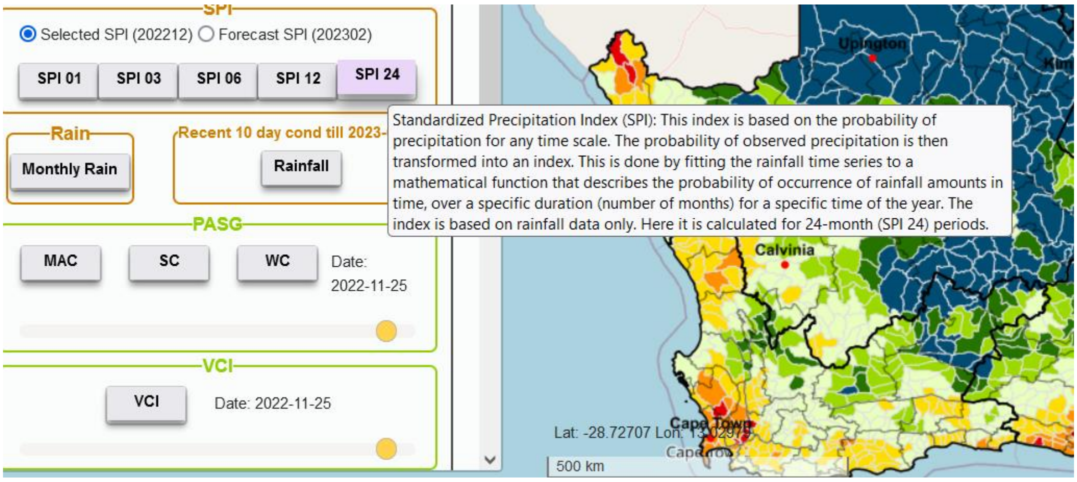


Figure 5-4: An information box appears when the user moves the cursor over the SPI 24 button, without activating it. Such pop-up boxes appear when the user moves the cursor over any of the menu items.

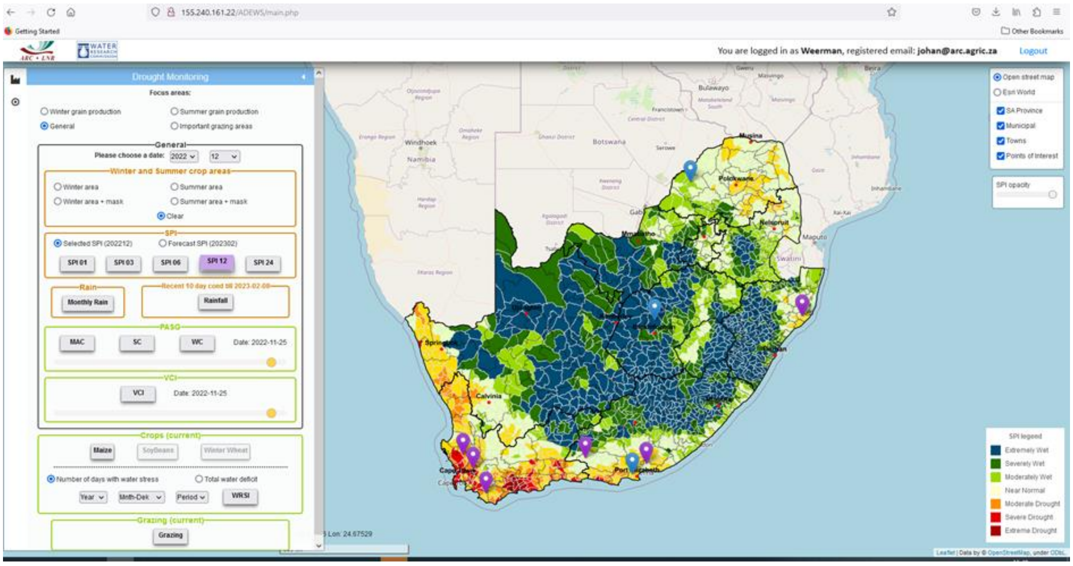


Figure 5-5: 12-month SPI by December 2022, displayed when the user selects the SPI 12 button while the date selector at the top is set to 2022/12. The markers displayed on the map are the points of interest chosen by the user (displayed because the points of interest tick mark in the top right menu is activated).

The next item under the General section in the ADEWS main menu is Rain. This provides the user with knowledge of typical rainfall totals for specific months in a specific region and an indication of recent rainfall values. Upon clicking the Monthly Rain button, a map of rainfall for the month selected in the date selector is displayed (Figure 5-6).

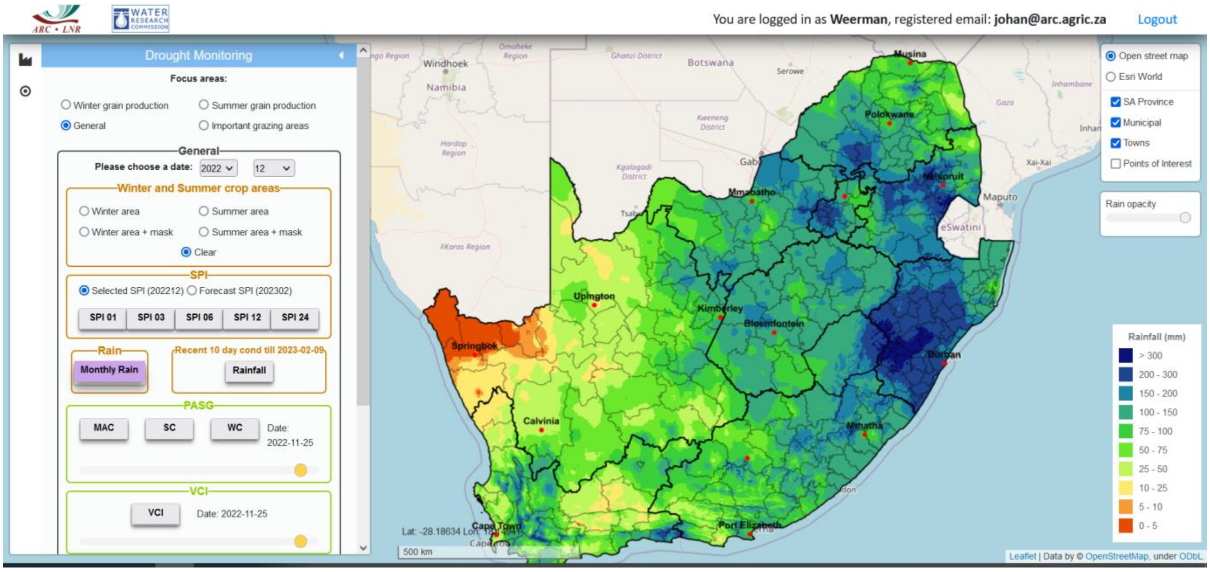


Figure 5-6: Monthly total rainfall in mm for December 2022, displayed when the user clicks on the Monthly Rain button while the date selector at the top is set to 2022/12. The markers for points of interest are not displayed because the points of interest tick mark in the top right menu is inactive.

To the right of the Monthly Rain button, the user can click on the Rainfall button to display the most recent 10-day rainfall total up to the date as indicated, per station point for all operational ARC-SCW weather stations (Figure 5-7). The colour of the station points is linked to the total accumulated rainfall at that point. When the user select any of the station points, a pop-up information box provides the station name and total accumulated rainfall figure.

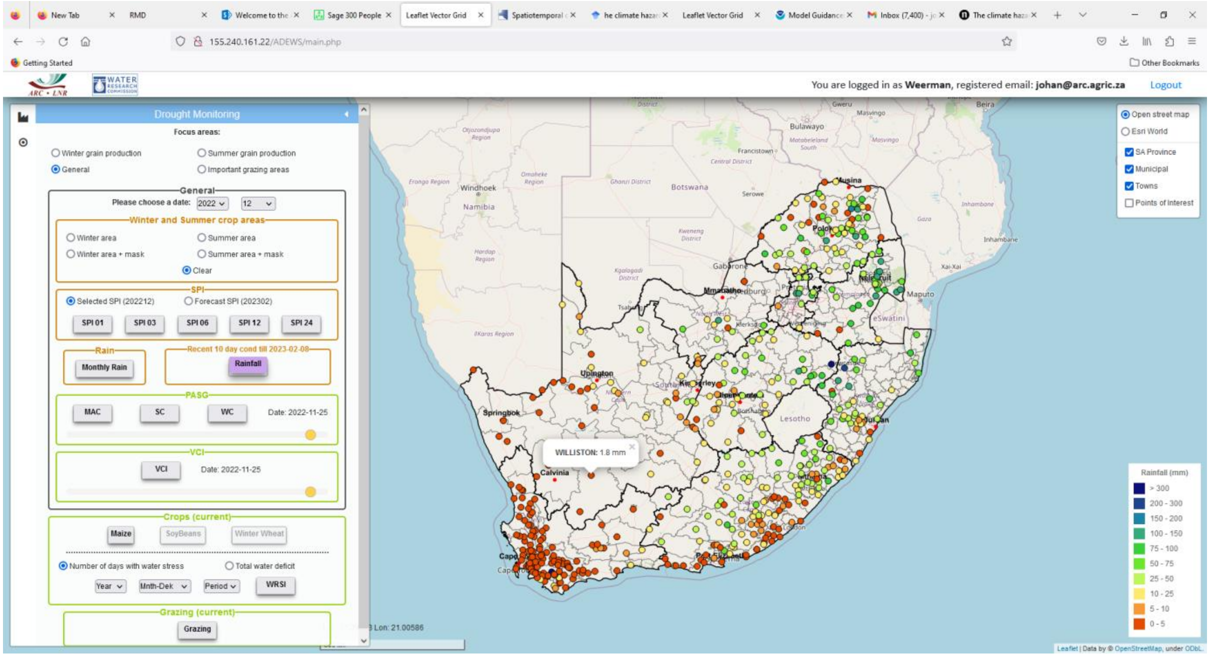


Figure 5-7: 10-day accumulated rainfall by 6 February 2023, as indicated on the main Drought Monitoring menu. The legend at the bottom right is associated with the colours of the points representing weather stations. When the user selects any of the station points on the map, the station name and 10-day accumulated rainfall total for that specific station is displayed, such as for Williston in the example.

The next items in the General section of the ADEWS main Drought Monitoring menu are the EO-based vegetation monitoring products. The Percentage of Average Seasonal Greenness (PASG) section contains three buttons for the three pre-determined accumulation periods:

MAC = Moving average 3-month cumulative

SC = Summer-year (July to June) cumulative

WC = Winter-year (January to December) cumulative

The slider at the bottom of the PASG section can be used to change the date by which the specific PASG selected is displayed (Figure 5-8).

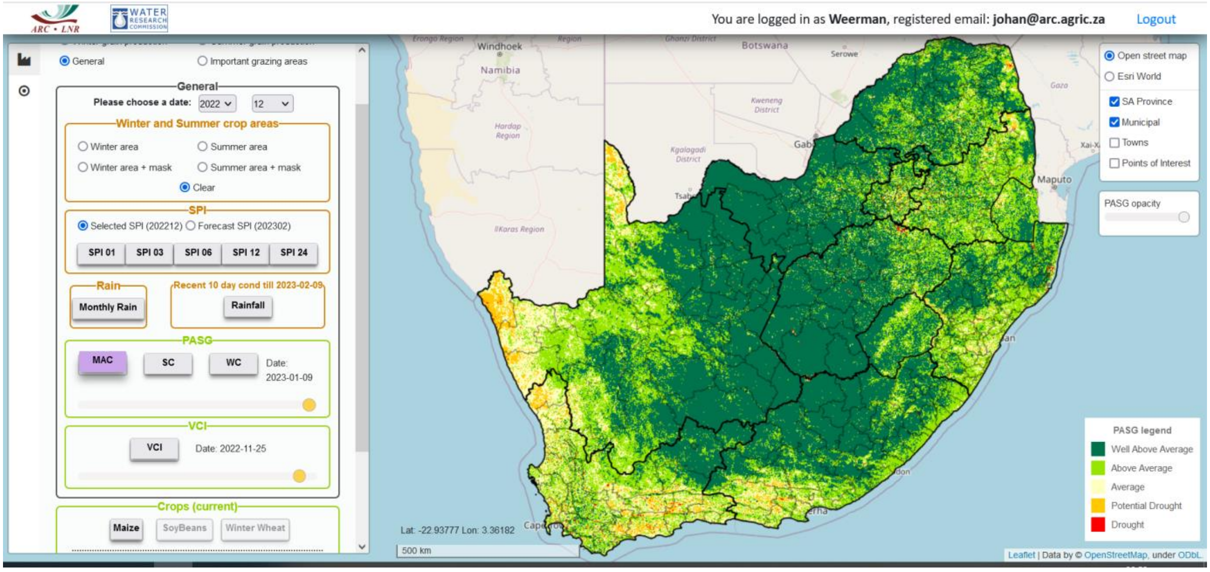


Figure 5-8: Moving average cumulative PASG by 9 January 2023, displayed when the user selects the MAC button in the PASG section while the slider is located at 2023-01-09.

The Vegetation Condition Index (VCI) is also located under the General section of the main Drought Monitoring menu. The VCI is displayed when the user activates the VCI button, for a specific date determined by the slider at the bottom of the section (Figure 5-9).

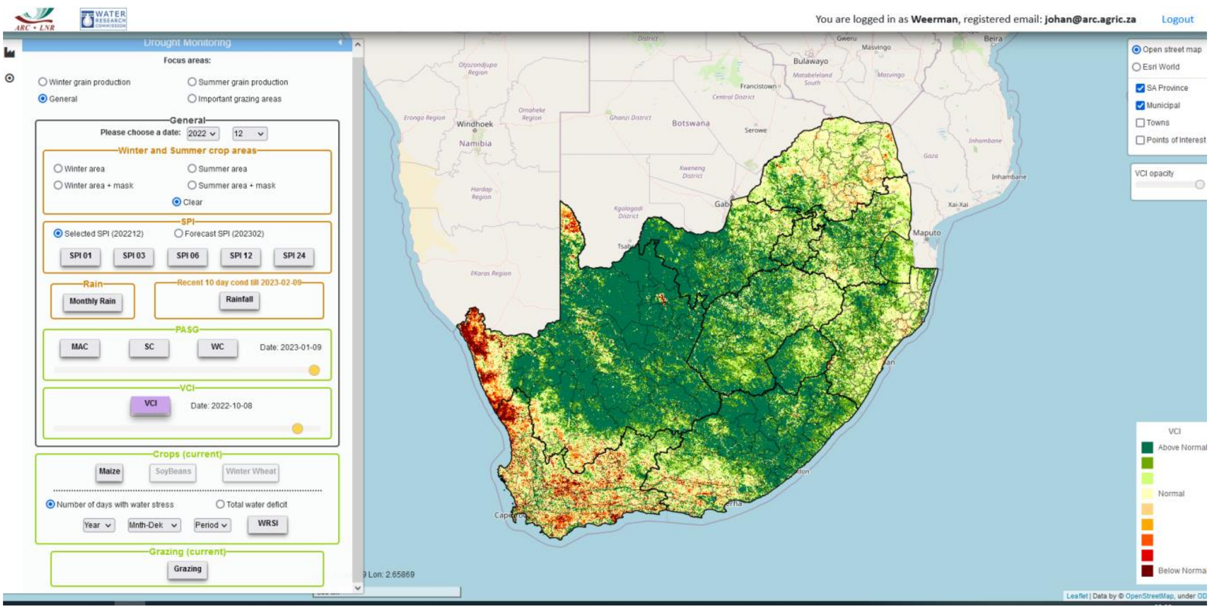


Figure 5-9: VCI by 8 October 2022, displayed when the user selects the VCI button while the slider is located at 2022-10-08.

While typical panning and zooming functionality is available, both the winter and summer crop area masks can be used so that the system will automatically zoom to that specific region while also masking out other areas (Figure 5-10).

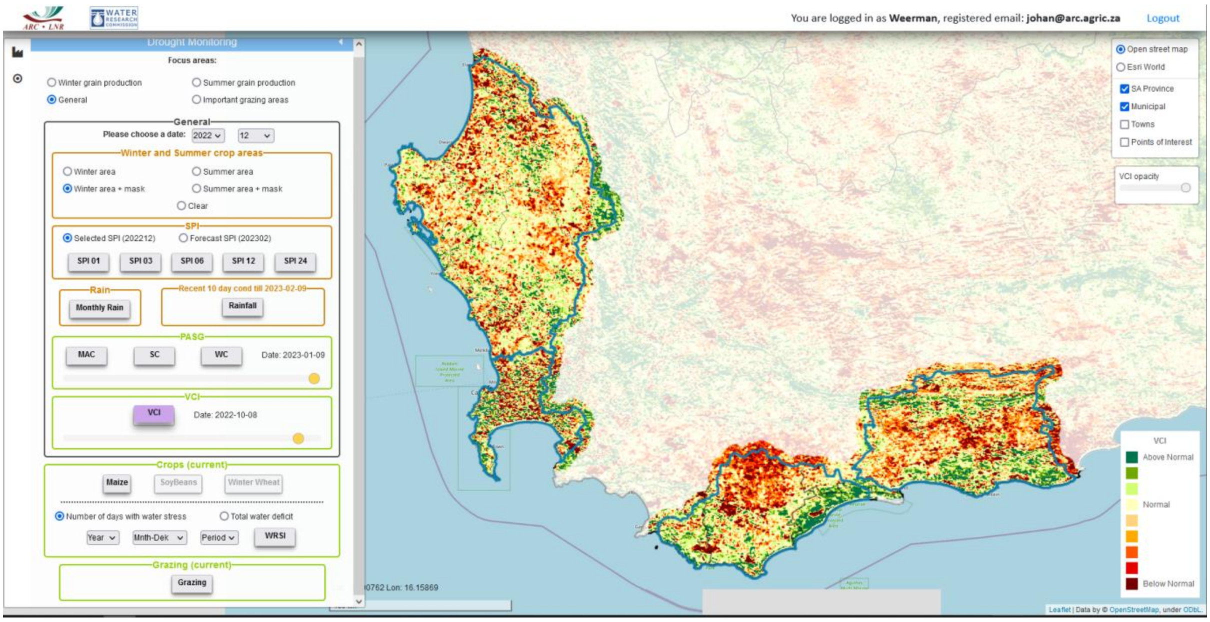


Figure 5-10: VCI by 8 October 2022, displayed when the user selects the VCI button while the slider is located at 2022-10-08, together with selecting the winter area and mask radio button in the Winter and Summer Crop Areas section within the General section of the main Drought Monitoring menu.

The following two sections focus on crops and grazing, respectively. Products associated with crops or grazing are located outside and below the General monitoring section in the ADEWS main Drought Monitoring menu. Under the Crops section, the user can select the Maize button to see the yield estimates for 75 points spread evenly across the main summer grain production region (Figure 5-11), for the current summer, compared to previous summers since the dry 2014/15 summer.

The colours of the points on the map correspond to the ranking of this year's yield estimate to that of previous years. These estimates are available from February for the current summer, the same month during which the Crop Estimates Committee provide their first estimate for maize yields and production. The DSSAT CERES-Maize model simulations only commence at this stage of the summer growing season when a reasonable amount of observed data are available.

When the user selects any of the modelling points on the map, a bar graph appears to the bottom left, indicating the yield estimates for the previous summers and current summer at that point.

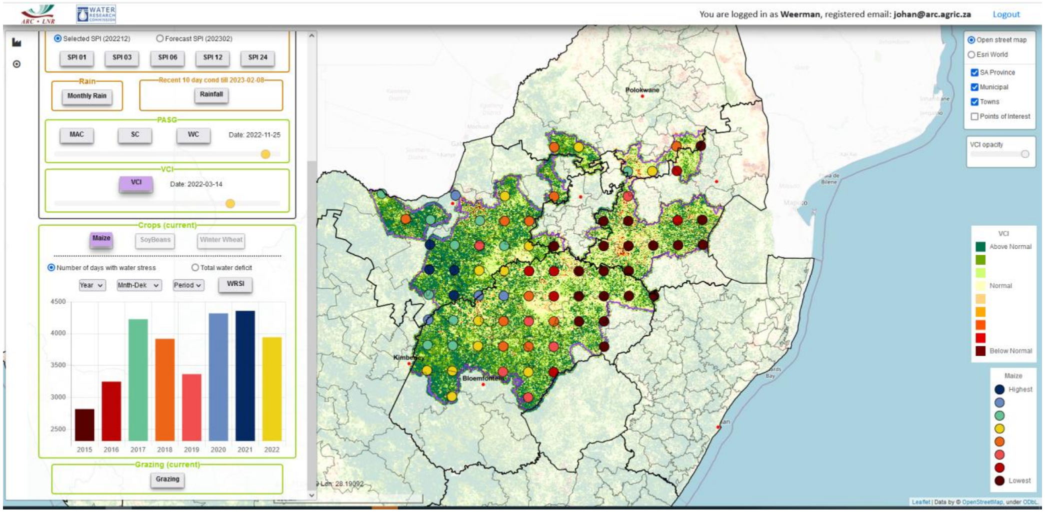


Figure 5-11: Maize yield estimates for the current summer relative to the previous summers since 2014/15. The colours correspond to the ranking of this year's yield estimate to that of previous years, as indicated in the legend. The summer crop area and mask radio button is selected to guide the focus to the summer crop area specifically.

The second item in the Crops section is the Water Requirement Satisfaction Index (WRSI). The user can select to view the number of days with stress according to the algorithm, or the WRSI value, by selecting the appropriate radio button. The user then has to select the cultivar type, having a choice between 100, 120 and 140-day growing season cultivars. The user also needs to select the planting date for which the WRSI must be displayed. These range from early October to early January. Figure 5-12 shows the number of days with drought stress calculated for a 120-day growing season cultivar, planted during the first 10 days of November 2022.

For each cultivar type, the ADEWS also provides a summary of the best possible outcome for a specific growing season, as identified by selecting the appropriate planting year and selecting Composite for the planting period (Figure 5-13).

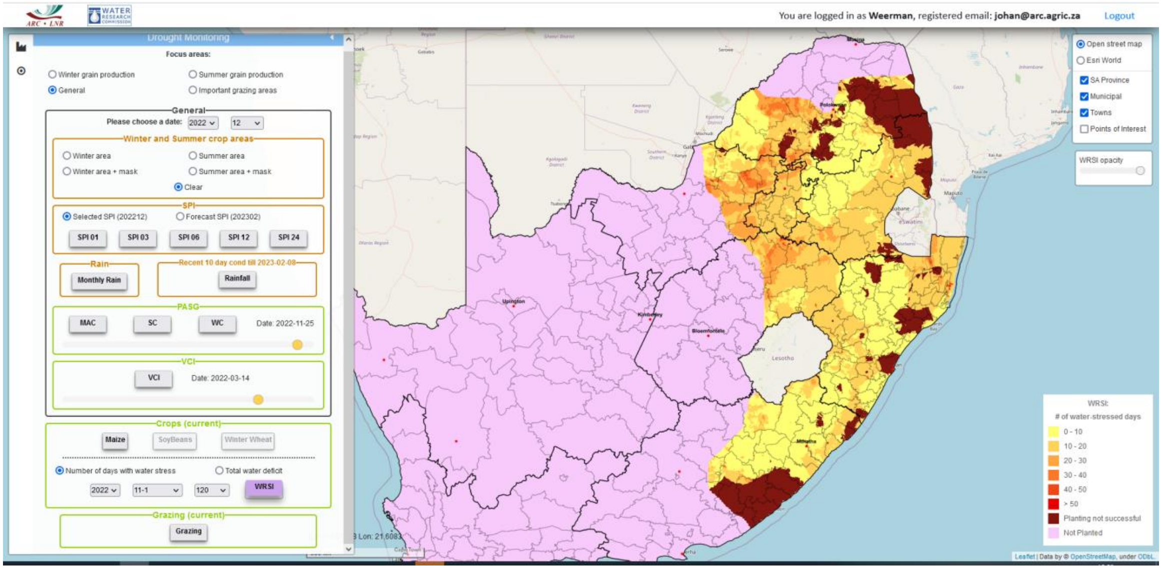


Figure 5-12: Number of days with water stress calculated according to the WRSI, for maize planted during the first 10 days of November 2022. Areas falling outside the planting window for the specific period are indicated in light purple. Areas where the first 10 days of November fall inside the planting window but where, according to the rainfall data, planting was unlikely due to persistent dry conditions, are indicated in maroon (planting not successful).

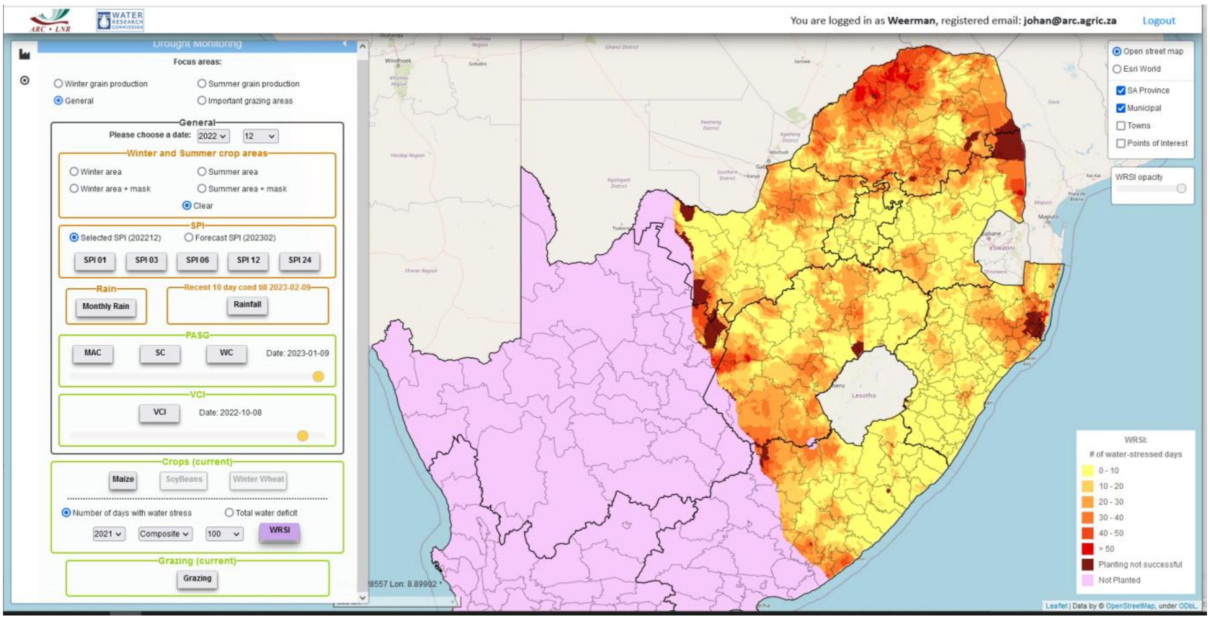


Figure 5-13: Minimum number of days with water stress calculated according to the WRSI, for a 100-day growing season maize cultivar planted during any of the planting periods from October 2021 to January 2022. Areas where dryland maize is not planted are indicated in light purple. Areas where some of the periods fell within the climatological planting window, but where dry conditions would not allow successful planting, are shown in maroon.

The rainfall-based and NDVI-based indices provide a good indication of the conditions with respect to pastures in the relevant areas. In the ADEWS, however, the user can also investigate conditions as it relates to grass cover specifically. The grazing component shows the modelled grass cover currently (updated operationally) with respect to conditions during the previous 10 years. This is the last section, at the bottom of the main Drought Monitoring menu. When the user selects the Grazing button, an image is displayed for the central to eastern parts of the country of relative grazing conditions as ranked by comparing the modelled grass production at that stage with those for the previous years by the same date (Figure 5-14).

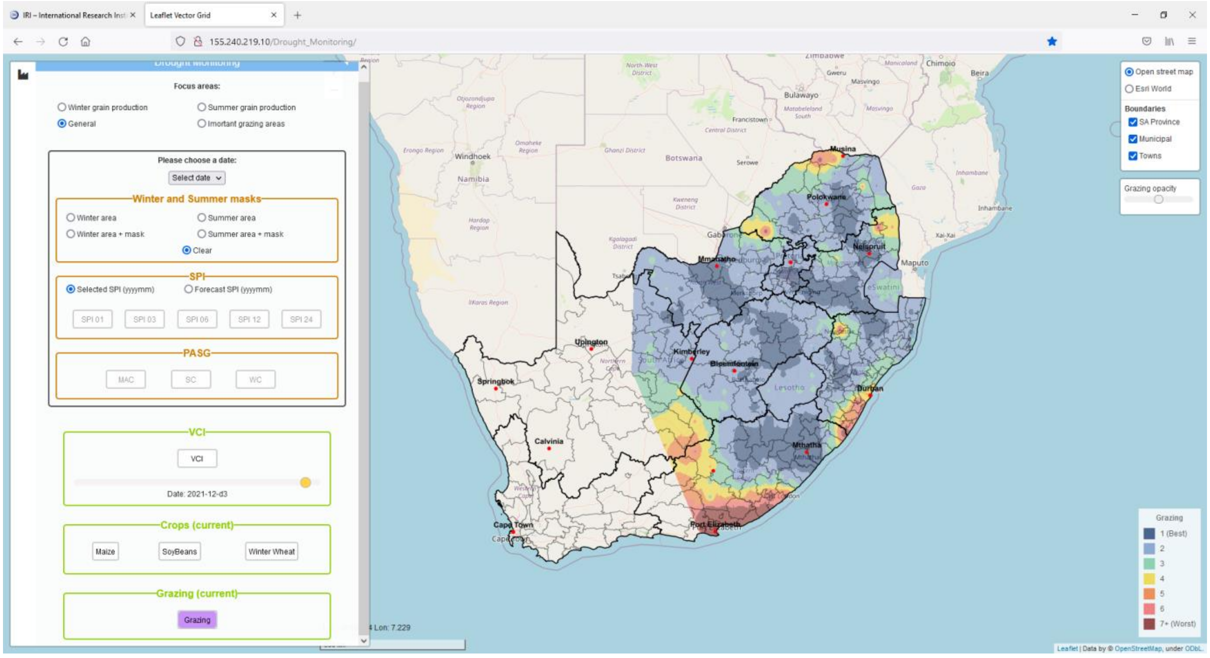


Figure 5-14: Grazing conditions relative to previous years by late December 2021. Higher (lower) values indicate better (worse) conditions than in previous years since 2014.

At the top left of the main Drought Monitoring menu, the user can select the radio button icon, which will open the area of interest section where the user can select points of interest for which automated e-mails will provide updated information regarding the latest drought developments.

5.3. Automated early warning e-mails

ADEWS users can identify specific points of interest and choose whether they would like to receive automated e-mail alerts on a weekly basis for all or a subset of the identified points of interest (Figure 5-15). For the points selected and activated for e-mail alerts, the user receives an automated weekly e-mail containing drought indicator information (Figure 5-15).

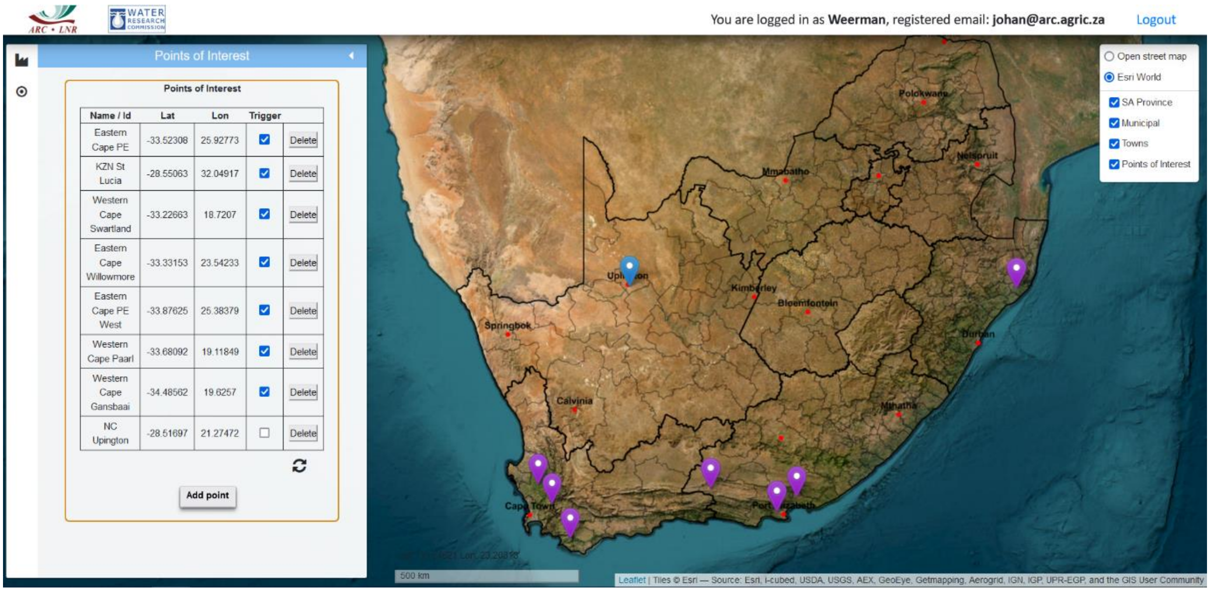


Figure 5-15: Point selection interface for locations of interest. In the table on the left, the user can choose to receive automated e-mails for all or a subset of the points (points selected for e-mail alerts are displayed in purple and unselected points in blue). The user can also choose to delete certain points in the table.

To: Johan Malherbe <Johan@arc.agric.za>
Subject: ARC Drought Monitor automated alert

Dear Weerman,

You are receiving this email because you opted for notifications on the following marker(s):
Western Cape Swartland

Drought information for: **Western Cape Swartland**
According to the rainfall data at the ARC, at the following location: Western Cape Swartland (lat: -33.22663 lon: 18.7207), at shorter time scales (6 months), recent Severe Drought conditions (SPI06 = -1.66) may likely have negative impacts on current dryland cultivation and grazing. Cumulative vegetation activity since January further indicates significantly drought-stressed vegetation in the vicinity (PASG = 86.5%). Furthermore, recent vegetation activity is indicative of a potential continuation of the stressed conditions (3-month PASG = 96.2%).
Summary:
24-month SPI by 2022-10: -0.25
6-month SPI by 2022-10: **-1.66**
3-month SPI by 2022-10: **-1.36**
PASG since January by 2022-10-24: **86.5%**
3-month PASG by 2022-10-24: **96.2%**

Kind Regards
ARC Drought Monitoring team

Figure 5-16: Automated e-mail alert for points selected by a user in the ADEWS, providing updated drought information according to the drought indicators used in the ADEWS.

5.4. Programming of the system

Most of the input data into the ADEWS are in GIS format, e.g. GeoTiff or ESRI Grid or ESRI Shapefile. Due to the heterogeneous datasets as well as algorithms and scripts from various coding languages incorporated, several programming languages are used to obtain the complete set of components constituting the system. These include Python and html scripting language, leaning also on the predetermined scripts made available by the Leaflet library to complement the programming in html for the ADEWS.

5.4.1. Programming of the SPI component

The coding for this component is predominantly in Python. It encompasses the creation of rainfall data per quaternary catchment, the calculation of the SPI from the monthly rainfall data, storage of the SPI data in a GeoServer, as well as the user interaction to display the SPI data in the ADEWS.

Utilizing a Shapefile consisting of polygons representing quaternary catchments, the monthly rainfall (Malherbe *et al*., 2016), as per monthly rainfall grid developed by the ARC-SCW and operationally kept up to date, is summarized to obtain an average value per quaternary catchment polygon. These procedures are coded in Python. From this point, the summarized values are added to an existing table of historical monthly rainfall values since 1920, to create a table of monthly rainfall totals from January 1920 until the relevant focus period (in an operational system, this is the latest month for which data exist). The acquired table of monthly rainfall values is used in a SPI calculating program, called by Python, to obtain the SPI values per quaternary catchment, for each relevant period length, over the entire time series.

The table with SPI values per quaternary catchment is joined with an existing Shapefile, in order to obtain a final, new, appropriately named Shapefile for the latest month containing the calculated SPI value per period length for the month. Finally, the SPI Shapefile is placed in the ADEWS GeoServer, where similar Shapefiles for previous months are also kept, so that users can display the SPI data. The final SPI value, based on the rainfall of a specific month, is usually only available by about a week after the month ends. This creates a rather long delay to obtain the latest conditions according to the rainfall situation. For this reason, the ADEWS gives the user the opportunity to calculate the SPI for the current month. The user can also choose to display the forecasted SPI expected by the end of the current month. The procedure to obtain the SPI value for the current month in advance is summarized as follows:

The daily rainfall, based on a combination of satellite-derived rainfall estimates and ARC-SCW automatic weather station data for the month to date, in GIS form, is accumulated from the start of the current month. The number of days for which observed data are available is calculated, as well as the number of days left in the remainder of the month. Using the balance between the number of days of observed data and the number of days remaining until the end of the month, the balance of the long-term average rainfall per grid point is added to the accumulated rainfall, to obtain an estimate of the expected rainfall for a specific month. The estimate for the monthly total improves towards the latter part of the month, and the user is afforded the opportunity to create an idea of the drought situation that will be represented by the SPI about a week after the month comes to an end. In order to further improve the rainfall estimate for the month, the 7-day rainfall forecast will also be included on a daily basis in future (this is work in progress).

Utilizing a Shapefile consisting of polygons representing quaternary catchments, the estimated total monthly rainfall is summarized to obtain an average value per quaternary catchment polygon.

The rest of the procedure to obtain SPI values of various period lengths for the current month is similar to calculating the SPI per quaternary catchment, described above. The procedure to calculate the forecast monthly rainfall is done in Python. When the user selects a specific SPI to display by choosing the date and period length, the relevant SPI Shapefile is retrieved from the GeoServer and the SPI value is displayed per quaternary catchment with the appropriate colour scheme. The coding for these procedures is done in Python and html scripting language, relying also on predetermined scripts in the Leaflet library.

5.4.2. Programming of the vegetation components

The VCI is developed within the ARC-SCW Coarse Resolution Imagery Database (CRID) outside the ADEWS environment using automated Python scripts. The index is produced by a script that applies the following basic algorithm:

- NDVIAX – Long-term Average NDVIA)/(Long-term Standard Deviation of NDVIA) where A is the specific period, i.e. 1-10 Jan, x is the current year

Thereafter, it is imported into the GeoServer of the ADEWS.

The PASG is produced within the CRID using automated Python scripts, after which it is ingested into the ADEWS. The index is produced by a script that applies the following basic algorithm:

- [(NDVIAx …+ NDVIZX)/(Long-term average cumulative NDVIAtoZ)] * 100 where A is the starting period (i.e. 1-10 Jan), Z is the end period (i.e. 20-31 March) and x is the current season (year)

The VCI and PASG layers are imported into the ADEWS GeoServer from the ARC-SCW internal file structure, using automated Python scripts. When a user activates the PASG through choosing a specific date, the image is displayed in the ADEWS using the correct colour scheme, predefined in the GeoServer. A similar methodology is followed when the user presses the VCI button and toggles the sliding bar.

5.4.3. Programming of the crop component

This coding for this component happens mainly in Python and the output displayed by the user is a result of the simulation by a crop model based on observed weather data and soil data, with management options and more described in the model. For the maize component, model simulations are performed for 75 points spread evenly across the main crop production region in the summer rainfall area.

Daily rainfall, maximum temperature, minimum temperature and solar radiation data from the ARC-SCW Agri-Climate databank are interpolated. The resulting daily GIS surfaces for each variable are archived in a file structure, with data in this format available since 2014. For each data point, an automated Python script extracts the daily data and writes it out to a text file that is compatible with the crop model. In a separate process, the CCAM forecast in NetCDF format is archived in a file structure. An automated Python script also extracts the daily rainfall, maximum temperature, minimum temperature and solar radiation per point from the NetCDF forecast file, for the following 6 days. The text file for weather input data for the crop model simulation, as created by the Python script, is shown in Appendix 4.

The CERES-Maize model is called through an automated Python script to perform the crop simulations for each point, for which a batch processing file has been created. The batch processing file identifies a number of simulations to be performed for each point – currently six per growing season, starting in 2014/15. The six simulations comprise an early and a late planting date and three cultivar types (short, medium and long growing season cultivars). The resulting output file following the simulation for a specific point is shown in Appendix 5.

An automated Python script extracts the yield data for each simulation and year for each point from the output file, including the simulated yields for the current growing season. The simulated expected yield per growing season since 2014/15, calculated from the output of the six simulations per growing season, is calculated in a Python script (Appendix 6).

The estimated yield per point, per growing season, is stored in the GeoServer using an html script (Appendix 7) from where it is displayed in the ADEWS, with an assigned colour representative of its ranking relative to previous seasons in terms of simulated yields.

5.4.4. Programming of the grazing component

The coding for this component is done in Python, invoking also a grazing model coded in Fortran. The input data are all in GIS format – an interpolation of ARC-SCW weather station data for a number of variables used in the model. The model is run for 309 points spread evenly across the central to eastern parts of South Africa, as the model is used to estimate grass production. Daily rainfall, maximum temperature, minimum temperature, solar radiation and potential evapotranspiration data from the ARC-SCW Agri-Climate databank are interpolated and the resulting daily GIS surfaces for each variable are archived in a file structure. Using Python coding, the daily data values for each variable are extracted for each of the 309 evenly distributed points over the central to eastern parts of South Africa.

Again using Python coding, the extracted variables per point are placed in a separate weather input file per point, per summer-year (July to June) for the period of data availability (since 2011). The weather input file is compiled in such a manner that the format allows the ingestion into the grazing model (PUTU VELD). An example of the weather input file is shown in Appendix 8. The weather input file, per point and per summer year is updated on a daily basis to include the latest observed data. The coding for the PUTU VELD model is in FORTRAN (Appendix 9 gives an overview of the components of the simulations as it appears in the FORTRAN script). The code is launched and completes the model simulation for all 309 points, based on the historical weather data including the latest additions as the process of ingesting new data into the weather input files occurs on a daily basis.

The simulations performed by the PUTU VELD script generate two separate output files per point, per year, namely a daily output file and a seasonal summary. A section of the daily output file for one growing season at one point location is shown in Appendix 10. One of the output variables is Total Production. The daily Total Production values per point and per year are extracted by an automated Python script from the yearly output files, per point, and placed into one summary file with daily values of Total Production for all the years with available data, per point. An example of such a file is shown in Appendix 11. Using a Python script, the current Total Production value is ranked relative to the values for the same date during previous years. The ranking, per point, is interpolated to obtain a map showing the distribution of above-normal and below-normal grazing conditions across the central to eastern parts of South Africa.

5.4.5. Programming of the WRSI component

The coding for this component is in Python using open source gdal libraries. The algorithm for the WRSI considers for planting the overlap of historically calculated planting window as it progresses from east to west over the summer rainfall region with the rainfall during the current summer to determine successful planting. The input data are all in GIS format – an interpolation of ARC-SCW weather station data for a number of variables used in the model. The process is as follows:

- Ingest existing long-term average planting window layer, relevant to a specific date, starting from 1 October to 10 January.
- Calculate the total rainfall, as represented by the daily rainfall totals of interpolated rainfall data from the ARC-SCW Agri-Climate databank for the previous 5 days.
- Allow 10 days in order to consider the rainfall for the subsequent 10 days.
- Calculate the total rainfall, as represented by the daily rainfall totals of interpolated rainfall data from the ARC-SCW Agri-Climate databank for the subsequent 10 days.
- Determine the overlap area where total rainfall for 5 previous and 10 subsequent days both exceed 25 mm where the planting window is active for the specific day.
- Create a composite of all daily successful planting areas during a specific 10-day window.
- For each pixel in successful planting area for the planting dekad, set the water balance equal to the water-holding capacity of the soil.

- Start in the middle of the planting dekad and, for each day, calculate the difference between rainfall for the day and the potential evapotranspiration for the day, modified as per maize crop coefficient which is variable, according to the dynamic crop coefficient. The potential evapotranspiration is a GIS surface for the day, similar to the rainfall for the day, interpolated from ARC-SCW Agri-Climate databank data.
- For each day up to 140 (or 120 / 100) calculate the difference in rainfall and crop evapotranspiration (Rain – ETCrop), and add to the water balance, which is limited to the water-holding capacity of the soil.
- Whenever water balance is negative, add the daily difference between rainfall and potential crop evapotranspiration to the WRSI value (starting from 0 at the beginning of the growing season). Also, keep count of the days during which the negative WRSI becomes more negative.
- Continue the process on a daily basis for the entire growing season to obtain the final value by the end of the growing season, per pixel, for maize planted during a specific planting window.

5.5. Conclusions

This chapter provided an overview of the functionality of the ADEWS by detailing the characteristics of the Graphical User Interface as well as pointing out the early warning e-mail messaging. It also described the coding of the system and demonstrated the use of various coding languages to develop the complete ADEWS system.

While various indices are available in the ADEWS and which the user encounters in the Graphical User Interface, information pop-up boxes provide context to the available products and guide the user on their correct use. With 2 years of archived data and products available, the date drop-down menu as well as the sliders for the EO products allow interrogation of the evolution of drought conditions. The PASG as well as the SPI provide further flexibility by being available for various accumulation periods. Over and above the more generic drought monitoring products, there are currently also commodity-specific products. These are intended to be expanded so that the ADEWS will provide drought information on a broader range of specific commodities.

The ADEWS is currently available as a website. However, given the wide range of potential users of the drought information contained in the system, a natural next step will be to investigate the possibility of developing an App which would make the potential reach of the system much larger.

CHAPTER 6. STAKEHOLDER ENGAGEMENT TO TEST ADEWS

6.1. Introduction

In South Africa, agricultural droughts have significant environmental and socio-economic consequences (Botai *et al*., 2016; Archer *et al*., 2019). Often, the root cause of these impacts is a lack of accurate and comprehensive information available for decision-makers to plan accordingly (Andersson *et al*., 2019). To address this issue, many regions worldwide have implemented drought early warning systems (DEWS) to provide relevant drought information that can help mitigate potential impacts across drought-sensitive sectors, including agriculture (Pulwarty and Sivakumar, 2014).

Accordingly, the Agricultural Research Council (ARC) has developed a new Agricultural Drought Early Warning System (ADEWS) to support the organization's strategic objectives of promoting sustainable ecosystems and natural resources, as well as enhancing the resilience of agriculture to climatic hazards. This web-based system offers registered users free access to a wide range of products based on data obtained from the ARC's automatic weather station network and Coarse Resolution Imagery Database (CRID), which is an in-house database of historical and near-real-time satellite imagery used for environmental monitoring. The ADEWS provides daily updates on drought conditions across South Africa, using monitored and forecasted data and also enables users to receive weekly updates and alerts for specific locations.

Central to the success of DEWS is the detection, quantification and monitoring of droughts, which requires the use of tools that can provide quantitative information on various aspects of droughts such as duration, severity, frequency, spatio-temporal patterns and impacts. However, if authorities and communities at risk are not engaged in the process, the interventions and responses concerning hazards are likely to be insufficient (Rogers and Tsirkunov, 2011). According to a report by Climate-ADAPT (2022), DEWS should be evaluated in collaboration with their users to ensure that the information provided is tailored to the users' needs and that appropriate measures are taken in response to the information provided. This signifies the importance of stakeholder involvement in the development and design process of DEWS, as given by this report.

6.2. Methodology

Prior to testing the newly developed ADEWS (https://www.drought.agric.za/) with external stakeholders, the project team performed an internal trial run, via Microsoft Teams, to establish its functionality in relation to their expectations as users, and constructive feedback was provided. Subsequently, the ADEWS was tested through workshops with relevant stakeholders for scientific knowledge, functionality, relevance and ease. The primary goal of these workshops was to evaluate whether the system satisfies the anticipated standards for improving early warning efforts in the agricultural sector of South Africa.

The first workshop was held at the ARC-NRE in Pretoria on 13 September 2022, attended by 16 participants from the Agrometeorology, Geoinformation Science, Water Science and ICT divisions (Figure 6-1). The second workshop was held in Vanderbijlpark on 13 December 2022 with 23 members of the National Agro-meteorological Committee (NAC) (Figure 6-2). The NAC comprises officials from the national Department of Agriculture, Land Reform and Rural Development (DALRRD), Provincial Departments of Agriculture (PDAs), Provincial Disaster Management Centres (PDMCs) and other institutional structures, such as the ARC and South African Weather Service (SAWS).

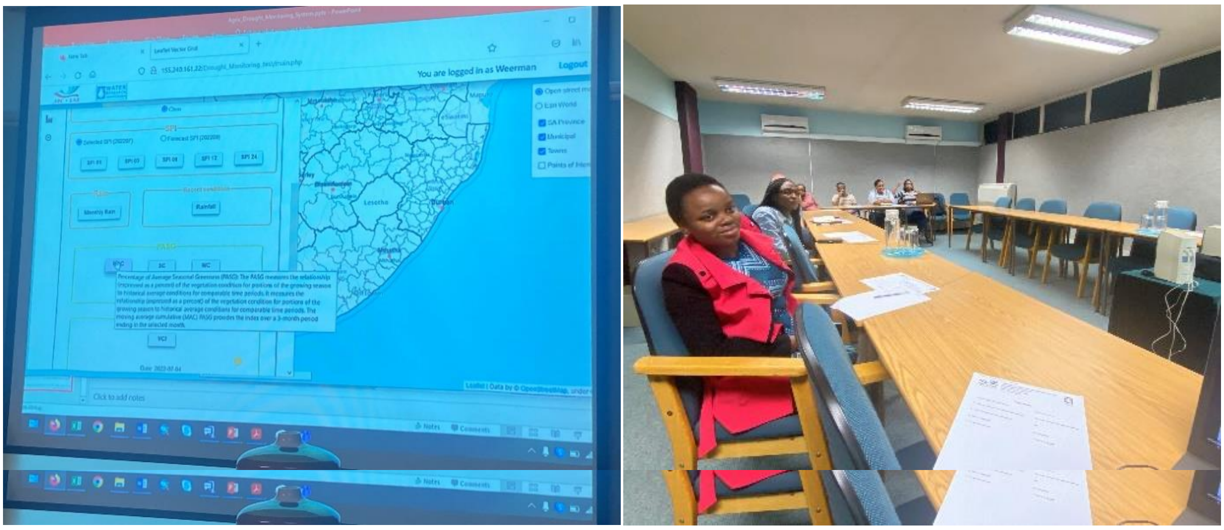


Figure 6-1: ADEWS workshop at ARC-NRE on 13 September 2022.

The workshops began with an introduction and purpose of developing a drought early warning system for the agricultural sector. This was followed by a brief overview of the functions and indices available in the new ADEWS. Demonstrations were performed and the participants assessed the overall presentation and the system by means of a questionnaire.

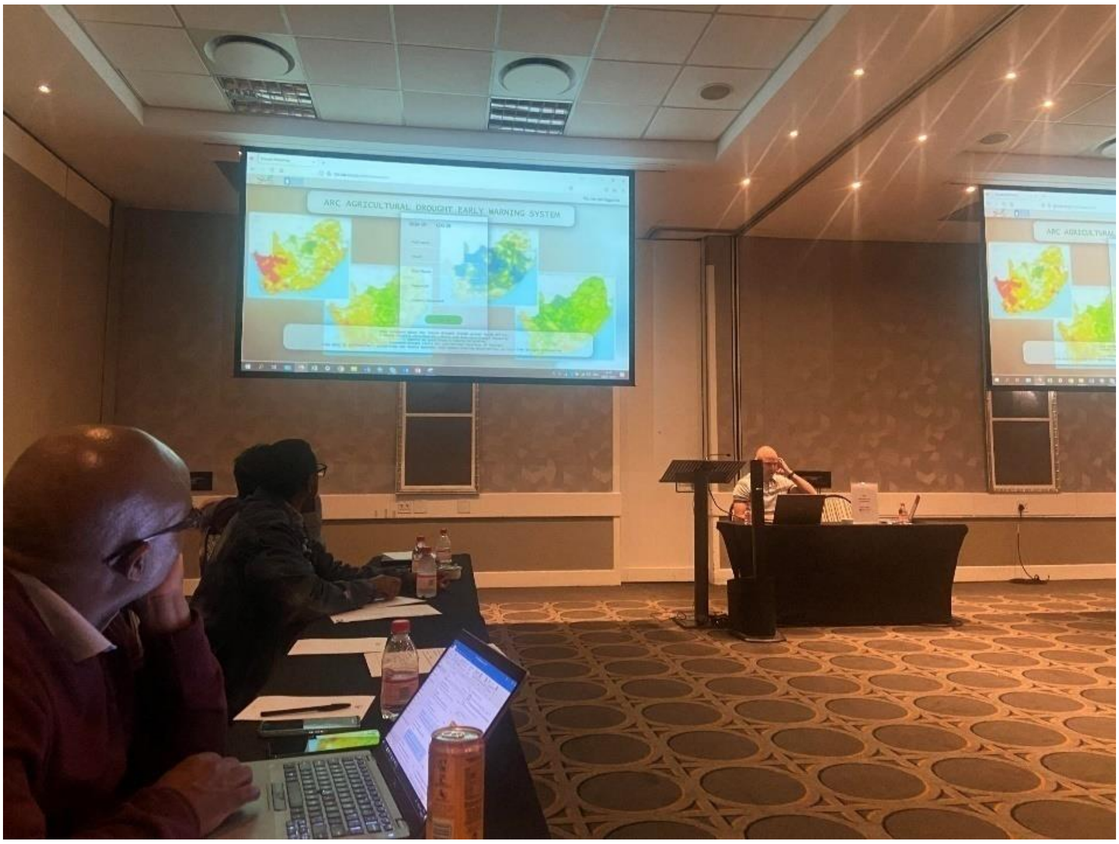


Figure 6-2: Testing of the ADEWS with members of the NAC in Vanderbijlpark,

6.3. Results

6.3.1. Internal trial run

The feedback from participants demonstrated that the landing page only showed a Google map without any information (e.g. current drought conditions). It was recommended that the landing page should show current drought conditions with a clear legend indicating drought monitor categories. Navigating was not easy as it took a bit of time to find/locate relevant information especially for external users. It was further suggested to have separate drop-down menus for year and period for date selection.

When assessing the forecast component of the ADEWS, participants were satisfied with its functionality. One person highlighted that indices may be simple for a scientist, but not for an average user who might not have background information (e.g. not everyone understands what are the SPI, PASG, VCI and how they work). Thus it was recommended to provide a brief description of each index. In addition, a suitable index or indicator especially for croplands and not only vegetation (e.g. VCI) and meteorological indices (e.g. SPI) was recommended. Furthermore, to avoid confusion, yield should specify the type of crop under consideration. It would be ideal to have the level of impact on various agricultural commodities.

6.3.2. External workshops

Participants were asked to rate their satisfaction regarding the demonstration of the ADEWS. The majority (71%) who participated in the first workshop indicated that they were satisfied, while the remaining 29% were neutral (Figure 6-2A). Moreover, Figure 6-2B shows that 86% of the participants rated the ADEWS itself as good, while 14% indicated that the system was very good. Thus, in general, participants were satisfied with the workshop and the system, with certain aspects requiring improvement, e.g. inclusion of trend analysis, typology, composite index and plans for sustainability.

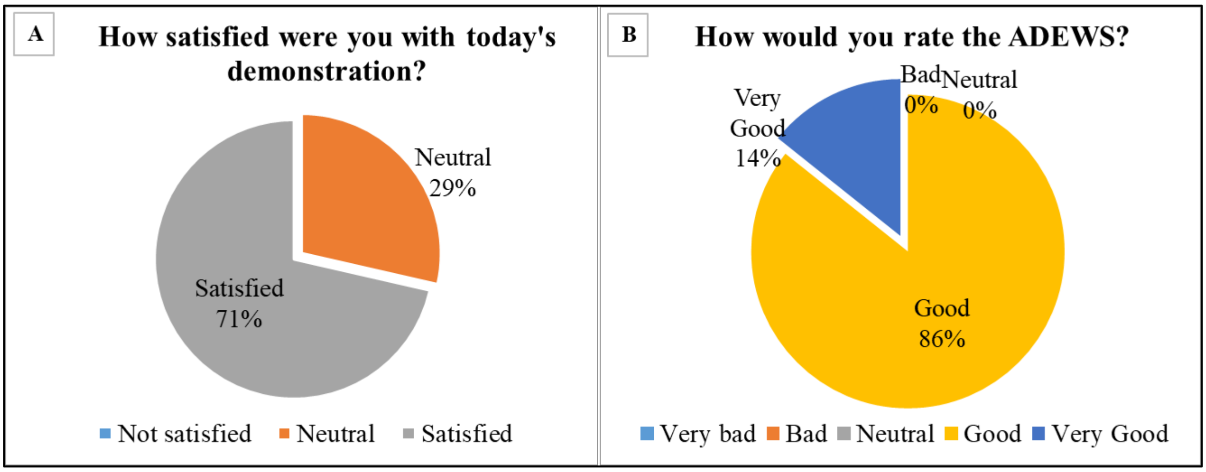


Figure 6-3: Feedback on user satisfaction during the first workshop concerning (A) the demonstration and (B) the ADEWS itself.

When asked to rate the overall demonstration of ADEWS during the second workshop, 87% of the participants were satisfied, with 13% being neutral (Figure 6-4A). Meanwhile, 69% of the participants said that the ADEWS was good and 22% found it to be very good (Figure 6-4B).

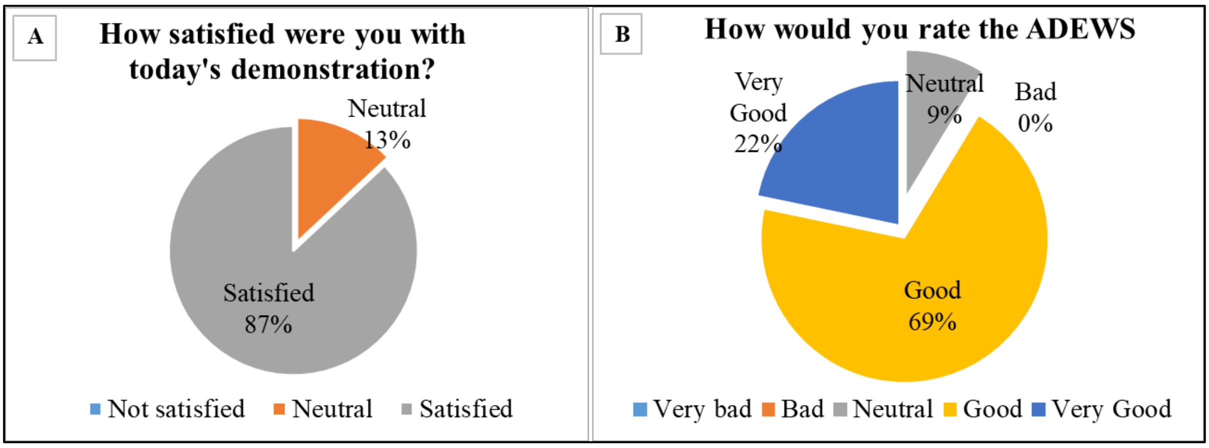


Figure 6-4: Feedback on user satisfaction during the second workshop concerning (A) the demonstration and (B) the ADEWS itself.

Participants mentioned that they would potentially utilize the system to:

- Give guidance, especially regarding what to plant for crop production farmers and help with information for planning.
- Assist researchers and technicians for planning purposes and drought monitoring.
- Generate and disseminate timely and meaningful early warning information regarding disaster risk.
- Reduce the economic impact of climatic hazards.

Participants further indicated that the ADEWS should be inclusive and sensitive to the different sources of vulnerability. Other functions can only be added after the system has been tested on the ground to rate whether it covers all the critical aspects related to climate and the environment. It was further indicated that the inclusion of functions such as invasive plants monitoring, migratory pest information, livestock conditions and medium-term drought forecasting would be beneficial as added functions in the ADEWS.

6.4. Recommendations

During the workshops, participants were asked to identify areas that needed improvement and they indicated that farmers and agricultural advisors need to be capacitated on the ADEWS. It was also recommended to make the system available offline, due to network challenges in some regions. According to the participants, the inclusion of ideal planting dates, cultivar choices, dam levels and historical drought data should be considered. Furthermore, the system might be too difficult for farmers to understand and use, hence, further improvements on public understanding and reducing the resolution would make it more user-friendly. It was also noted that the system has the potential to be expanded and aligned with other systems within the Southern African Development Community (SADC) region.

6.5. Conclusions

This chapter indicated the value of active stakeholder participation in ensuring the effectiveness of drought early warning systems. The consensus was that the ADEWS is a very good system that will help farmers and other stakeholders make informed farming decisions. Feedback from the workshop participants was essential to determine factors such as the usability of the system and expectations from users, serving as a likelihood for adoption. The importance of adopting the ADEWS is that it will enhance the capacity of all agricultural stakeholders, particularly policy- and decision-makers, agricultural organizations, farmers, banks and the general public in ensuring the success of shifting from crisis to risk management. It is therefore recommended that the developers address the comments in order to improve and sustain the system.

CHAPTER 7. IMPROVING THE EFFECTIVENESS OF DISASTER RISK REDUCTION ON THE MANAGEMENT OF AGRICULTURAL DROUGHT

7.1. Introduction

Disaster-drought, a persistent climate feature of South Africa, has long caused significant limitations on agricultural productivity that mainly affects vulnerable communities and the country's economy (Archer *et al*., 2019; Botai *et al*., 2016). Unlike other climate-related disasters, disaster-droughts are commonly not immediately evident, they could last for long periods and usually end within 12-36 months (DAFF, 2005). The ability of a region to prepare for and respond effectively to the effects of drought depends on several factors, including biophysical elements such as soil characteristics and crop systems, and socio-economic factors like social behaviour and economic growth. Furthermore, human activities such as land use and cropping systems contribute to the onset of human-induced drought.

The United Nations Office for Disaster Risk Reduction (UNISDR, 2009a) notes that a disaster-drought may result from inadequate pre-disaster readiness, rather than solely from a water deficit. The complex relationship between the direct cause of droughts such as insufficient rainfall and indirect factors such as inappropriate land use practices can complicate effective risk management efforts (Bergman and Foster, 2009; Cai *et al*., 2017). Therefore, it is crucial to implement efficient disaster management strategies to minimize the impact of drought in any region. In fact, the continuous disaster management cycle, consisting of four stages, viz. mitigation, preparedness, response and recovery, can be employed for effective drought management (NDMC, 2013). These stages can be carried out before, during and after a drought event to prevent or reduce its impact and facilitate recovery from any damage. However, it is important to acknowledge that droughts cannot be avoided entirely.

The term *mitigation* involves making efforts aimed at minimizing the impact of drought, whether caused by humans or other factors, with the ultimate goal of reducing the risk, exposure and vulnerability of affected communities (Republic of South Africa, 2003). Drought *preparedness* refers to all the measures and resources that institutions use to ensure that communities are equipped to deal with the impacts of drought (Bazza, 2014), while drought *response* strategies aim to minimize the impact of drought during and after its occurrence.

Generally, these strategies, as outlined by Wilhite (1996), include providing livestock feed, offering low-interest loans and grants, providing fuel and human food subsidies, and transporting water to affected areas.

The process of *disaster recovery* involves restoring physical and social systems to their pre-disaster state once the immediate impacts of the disaster begin to decrease and eventually end (Khan *et al*., 2008). In the case of a drought, successful recovery would involve a season of above-normal rainfall to restore soil moisture and improve crop and pasture yields (Ruehr *et al*., 2019). However, it is notable that a comprehensive recovery approach must also take into account good governance and effective management practices to achieve sustainable long-term recovery (Raikes *et al*., 2019).

Disaster risk *governance* involves collaboration among different actors and the use of policies and legal frameworks to coordinate strategies, rather than relying solely on government decision-making (Bressers *et al*., 2016). Disaster risk *management* is the systematic planning and implementation of policies and strategies essential for reducing the risks associated with disasters (UNISDR, 2009b). Slow or complicated decision-making can result in failure to fully recover from drought, as well as delays in achieving ecosystem equilibrium and building resilience, as pointed out by Ng and Yap (1993) and Eludoyin *et al*. (2017). Therefore, it is crucial for governments to have clear policies that ensure their various departments respond to drought effectively and minimize its impact on society.

According to Pradhan *et al*. (2017), effective planning and policy implementation are essential for improving performance and providing feedback for policy- and decision-makers. The general aim of policy documents is to reduce the risk of disasters for all parties involved. Therefore, this study aimed to evaluate the effectiveness of policy[1] related to agricultural drought management in South Africa. The project focused on: (1) exploring legal documents guiding drought management, (2) assessing the experiences of government officials managing disaster-droughts on agriculture, and (3) identifying achievements and constraints in managing droughts. The findings of the study can be used to provide recommendations to enhance current policies and programmes aimed at reducing future agricultural drought impacts in South Africa.

[1] **Policy:** an official document that contains laws, rules and regulations, used as a basis for decision-making (Chen *et al*., 2014).

More broadly, the analysis may be useful in identifying gaps and proposing appropriate measures for other regions facing drought risk.

7.2. Methodology

The research adopted a qualitative research approach, where data was collected from both primary sources (i.e. interviews) and secondary sources by assessing formal drought documentation. Previous studies have utilized qualitative methods to understand data from participants in their natural environment and identify areas that require attention (Chen *et al*., 2014; Fontaine *et al*., 2014; Vincent *et al*., 2017). As the research was exploratory in nature, the primary data was collected using expert sampling, which is a type of purposive sampling. This method was chosen because it allows the researcher to gather information from participants who are highly knowledgeable about the research topic and the area being studied (Helfenbein, 2019). It is important to note that expert sampling is a non-probability sampling method. Thus, the study identified individuals who met two specific criteria. Firstly, they had to demonstrate established knowledge in disaster-drought and/or agrometeorology. Secondly, they were required to be actively engaged in disaster-drought activities at a high level of governance and management.

To ensure diversity in the sample, a total of 21 key informants were interviewed telephonically from various provinces and relevant government departments: three from the national Department of Agriculture, Land Reform and Rural Development (DALRRD), one from the Department of Water and Sanitation (DWS) and three from the National Disaster Management Centre (NDMC), while nine officials represented the Provincial Departments of Agriculture (PDAs) and five represented the Provincial Disaster Management Centres (PDMCs). This approach aimed to prevent any potential biases in the data collection process.

A semi-structured questionnaire was utilized and included questions that focused on three areas: (i) planning for drought-related disasters, (ii) reducing the risk of disasters, and (iii) managing drought in general (see Appendix 12). The overall effectiveness of policy was measured based on indicators that were adapted from a previous study by Pradhan *et al*. (2017). These indicators are presented in Figure 7-1 and highlight important aspects of policy, including existing documents, implementation, intervention outcomes, and policy improvement based on feedback.

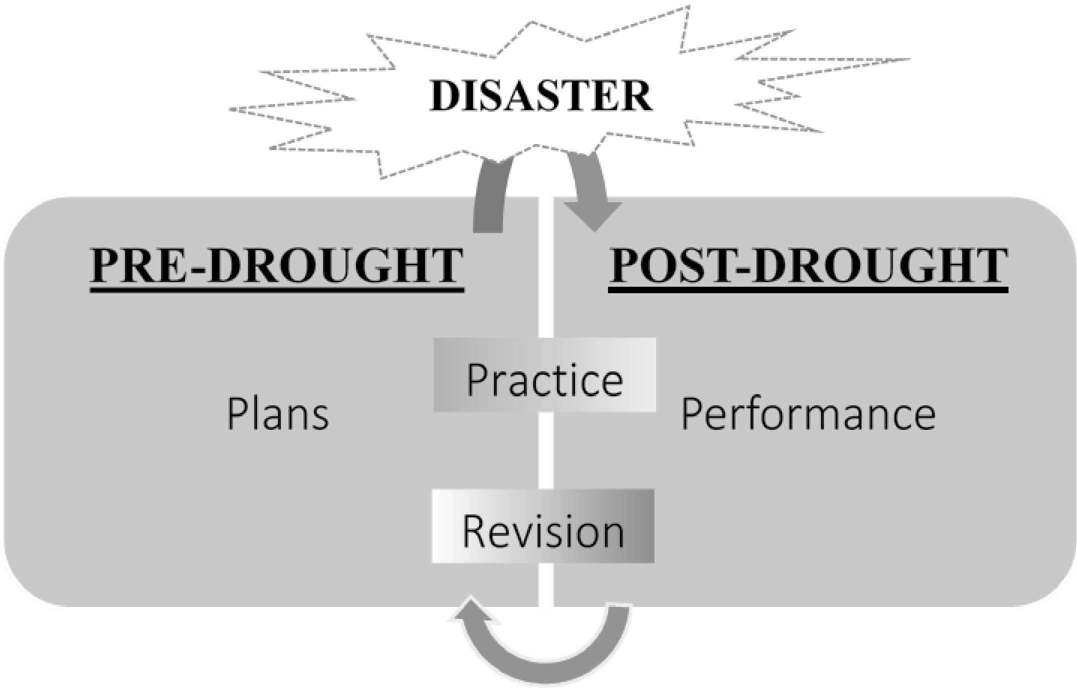


Figure 7-1: Modified framework for assessing policy effectiveness for managing disaster-droughts.

The survey questions presented in Table 7.1 aimed to examine the content of policies and measures that have been undertaken and/or are currently being implemented at national and provincial levels. To better understand the guiding principles and practices, secondary sources were analysed. The data was obtained mostly from literature review, government reports and policy documents on agriculture and disasters – accessed online from major databases (the Department of Higher Education and Training's accredited journals database, Scopus, Web of Science, and Science Direct) using appropriate keywords.

Additionally, government and international reports, conference proceedings and other research papers were acquired from physical and electronic document repositories. While most documents were purposefully searched, others were obtained from survey participants through e-mails and, in some cases, through informal conversations with colleagues. By reviewing these documents, important information and key lessons were extracted.

Table 7.1: Specific questions based on various key indicators of drought policy effectiveness used in this study.

Indicators	Specific questions
Plans	• Are you aware of any drought-related policies / plans / frameworks / formal documentation for South African agriculture? If yes, list them. • How do you access the various drought documents?
Practice	• In your experience, what disaster risk-reduction measures have you taken? Provide evidence and refer to the years when drought was declared a disaster for your area. List according to *Prevention, Mitigation, Preparedness, Response, Recovery* and *Rehabilitation*. • Do the various measures incorporate local information? Explain
Performance	• Were the disaster risk-reduction measures listed effective? Explain and include the evaluation processes. • What mechanisms do you use to evaluate how the various strategies relate to reducing societal vulnerability?
Revision	• Are post-drought assessments included in the plan/s? If yes, what is the procedure? • Are the drought-related policies dynamic / static? If dynamic, how often are they revised?

7.3. Results

7.3.1. Outline and knowledge of policies that govern agricultural disaster-droughts

The development and modification of policies related to drought risk management in South Africa have shown positive progress over time. Before 1990, national drought risk management mainly focused on commercial farmers and the inclusion of various stakeholder groups, but the establishment of the National Consultative Drought Forum in 1992 reflected a more inclusive approach to policy formulation (Wilhite, 2000). In 1995, the National Drought Management Committee was formed to promote and integrate public participation in disaster management at a national scale. However, it is noteworthy that the Constitution of the Republic of South Africa (1996) is the supreme law of the country, comprising the primary rules that constitute the country and its institutions. According to this law, disaster management is regarded as a functional area of concurrent national and provincial legislative competence, guided by applicable policies (South African Government, 1996).

Following these developments, the South African government aligned with international trends in disaster risk management by consulting with stakeholders and drafted legislation, leading to the publication of the Disaster Management Act (DMA) in 2002 (Republic of South Africa, 2003). Participants in the current study recognized this Act as the main guiding policy for disaster-drought management. While the DMA has provided a solid foundation, certain aspects of the policy framework require further consideration. For instance, the Agricultural Risk Insurance Bill, stemming from the Act, primarily focuses on emergency response activities after the impact of disasters, which are more on post-impact activities rather than proactive risk reduction (Wilhite *et al*., 2005).

In 2005, the National Disaster Risk Management Framework (NDMF) was introduced, emphasizing proactive measures to reduce vulnerability in disaster-prone areas, communities, and households (Republic of South Africa, 2005). The framework comprises four key performance areas (KPAs), along with three enablers that aid in achieving the objectives set out within these KPAs (Republic of South Africa, 2005). Survey participants further mentioned other policy documents that were only relevant to their level of governance. For instance, officials at national level mentioned that they follow the NDMF for guidelines, while those responsible for agricultural disasters included the Drought Management Plan (DMP), Sectoral Disaster Risk Management Plan (SDRMP) and draft Sectoral Drought Management Plan (SDMP) (DAFF, 2012; DALRRD, 2020b).

The DMP outlines responsibilities of the national DALRRD in terms of managing drought within the agricultural sector. The plan further states that although the department was tasked with managing agricultural drought in the country, responsibilities have to be shared across all levels of government, supported by other relevant stakeholders including the general farming community (DAFF, 2005). This interaction of roles allows for a cohesive structure best capable of dealing with agricultural drought preparedness. However, efforts from other responsible institutions remain weak, and at times hindered due to lack of capacity (human and financial) and low level intergovernmental collaboration (Midgley and Methner, 2016).

The SDRMP and draft SDMP were developed to promote a risk-reduction approach to drought risk management, specifically on reducing economic loss, vulnerability and protection of the environment (DAFF, 2012; DALRRD, 2020b). As mandated by Parliament, provincial organs of government should develop and implement disaster management policy frameworks and plans as line functionaries (Republic of South Africa, 2003, 2005, 2015; South African Government, 1996). According to the survey, two of the seven provinces that participated mentioned that they have their own drought plans, while the rest depended on the provincial disaster management frameworks and seasonal contingency plans.

Survey participants were questioned on the accessibility of the various policy documents. As depicted in Table 7.2, an equal percentage (19%) of participants responded that the documents are obtainable through various platforms or are available exclusively online. Two participants stated that some documents were not accessible, referring to draft documents that were not yet approved and the terms of reference documents that are utilized internally.

Table 7.2: Accessibility of disaster-drought related policy for agriculture based on survey results. (*n* = 21)

	Hard	**Soft**	**Hard, Soft**	**Hard, Soft, Not accessible**	**Online**	**Online, Hard**	**Online, Soft**	**Online, Hard, Soft**
Number of responses	2	1	3	2	4	2	3	4
Percentage	10%	4%	14%	10%	19%	10%	14%	19%

7.3.2. Disaster risk reduction measures to manage drought on agriculture

Survey participants were asked about the measures taken in terms of mitigation, preparedness, response and recovery to gather information on the various initiatives implemented at their governance level. Officials referred to the most recent (e.g. 2015, 2019) and ongoing interventions when listing disaster risk reduction (DRR) measures following the declaration of drought as a disaster in their respective jurisdictions. Different strategies were observed among national and provincial departments, with national interventions primarily focusing on providing funding for projects while the implementation of measures takes place at the provincial level.

The policy context recognizes prevention and mitigation as crucial factors in achieving the goal of disaster risk reduction (Republic of South Africa, 2005). Consequently, when seeking financial assistance from national or provincial organs of state, consideration is given to whether prevention and mitigation measures were implemented, and if not, the reasons for their absence (Republic of South Africa, 2005). Additionally, an assessment should be made as to whether the disaster could have been avoided or minimized through the implementation of such measures and whether it was reasonable to expect their implementation under the given circumstances. Participants often combined prevention and mitigation, while acknowledging the challenges in completely preventing drought by stating that despite efforts to enhance vulnerability awareness, prior risk knowledge and understanding drought patterns, it is ultimately impossible to prevent drought entirely.

The study findings revealed that pre-disaster interventions related to prevention and mitigation focused on improving infrastructure, conducting awareness campaigns and drilling boreholes (Table 7.3). Preparedness measures included the development of management plans, monitoring drought indicators for early warning and creating a farmer database. The overall goals of preparedness measures are to enhance the resilience of vulnerable systems, forecast drought occurrences well in advance and enable an effective response to drought (Bazza, 2014; Bureau and Policy, 2019).

According to Wilhite (1996), the implementation of pre-disaster plans can reduce community vulnerability to drought by improving their coping mechanisms. In the past, many countries prioritized crisis management, such as drought relief, without proactively enhancing their drought plans, which ultimately increased vulnerability to drought disasters. This proactive approach to improving the coping abilities of affected communities can be implemented before, during, or after a drought disaster.

According to Wilhite (1996), the implementation of a pre-disaster plan can reduce a community's vulnerability to drought by enhancing their coping mechanisms. In the past, many countries primarily focused on crisis management and drought relief rather than proactively improving their drought plans, resulting in increased vulnerability to drought disasters (FAO, 2019; Wilhite, 1996). This proactive approach to strengthening the capacity of affected communities to cope with drought can be implemented before, during, or after a drought disaster (Buchanan-Smith, 2001; Do Amaral Cunha *et al*., 2019; Van Zyl, 2006).

Table 7.3: Pre-disaster measures relating to agricultural drought at national and provincial levels of government.

Level of government	Prevention and Mitigation	Preparedness
National	• Convene Disaster Management Technical Task Team on a quarterly basis to report on the progress of managing water related risks. • Developed drought dashboard on the National Integrated Water Information Programme that was operational since 2019. • Conduct assessments to obtain prior risk knowledge and who is most vulnerable. • Reflect on previous disaster-droughts, analyze what went wrong and provide the necessary information to the various officials in provinces. • Facilitated funding to support farmers with boreholes and dam scooping interventions through national DALRRD and PDAs.	• Development and implementation of Disaster Management Plan. • Update contingency plans for disaster risks (i.e. floods, drought, water pollution and critical dams). • Ensuring hydrological instrumentation is well equipped and operational. • Conduct seasonal preparedness workshops. • Utilize seasonal forecasts and agricultural drought monitoring products from SAWS and ARC, respectively. • Based on the 2015/16 drought we had been monitoring from the preceding season (2014/15). • Participate in meetings with committees at provincial level.
Provincial	• Provide fodder support to farmers. • Drilling of boreholes. • Fencing. • Seed provision. • Invasive alien clearing. • Livestock watering. • River protection structures. • Maintain earth dams. • Pilot study of planting pasture to supply farmers during the winter season. • Convey the necessary information through awareness campaigns. • Desilting of dams.	• Work closely with relevant stakeholders. • Develop applicable policies and strategies. • Build staff capacity. • Create a farmer database. • Conduct revolving awareness campaigns to prepare farmers. • Send early warning information through bulk SMS directly to farmers' phones. One province currently has 10588 farmers registered. • Installation of weather stations across the province. • Convey information through local radio stations.

Drought response is clearly covered in the strategic objectives of policy pertaining to the agricultural sector, with the aim of "enhancing the ability to offer efficient emergency relief during disasters, to combat poverty and foster sustainable development in the country". In the event of a disaster, organs of state are required to gather information from all stakeholders and activate appropriate steps in the contingency plans to support and facilitate response measures (DAFF, 2012; DALRRD, 2020b). Participants at national level mentioned that they provide funding for provinces to initiate relief support such as the provision of feed, pellets, salts and phosphorus (Table 7.4).

Table 7.4: Measures relating to the post-disaster phase as carried out by the various departments at both national and provincial levels.

Level of government	Response	Recovery
National	• Initiate relief programmes. • Monitor the various projects to check progress per the business plan provided. • Facilitate funding to support farmers with feed for livestock. • Gazette water restrictions. • Re-prioritization of funds to water services authorities for water tankers, drilling of boreholes, augmentation projects, raising of dam walls and installing JoJo tanks in water-scarce communities.	• Provide funding through long-term grant. • A business plan is provided with an implementation plan and the NDMC monitors the various projects to check on progress. • Facilitate funding to support farmers with the eradication of alien invasive plants and fodder bank development.
Provincial	• Provide support to farmers as soon as possible. • Conduct monitoring and evaluation of the disaster. • Provide feed, pellets, salts, phosphorus, etc. • Awareness campaigns. • Relief programmes. • Procurement of fodder. • Prioritize the budget to assist farmers to procure livestock feed (bales, pallets) and water tanks.	• Ongoing communication with farmers and relevant stakeholders. • Maintenance of database of all farmers in the region. • Seed project to provide farmers with seeds in areas experiencing drought. • Planting of indigenous vegetation. • Strengthening fodder production. • Improve infrastructure through maintaining boreholes, dam scooping and reconstructing dam walls that collapsed. • Remove invasive alien plants together with LandCare. • Fencing.

According to the survey participants, during disaster-droughts there was a committee that held meetings quarterly at which members reported on the ground conditions. The department utilized the reports to consult with relevant parties to initiate support. At this time, farmers would also begin to submit requests for assistance. Provinces would then send out assessment forms to farmers to fill in and submit to their respective extension advisor, and based on the information obtained, the department would conclude on the affected areas. This step is essential as it determines the facilitation of funding to support those that have complied. Thus, communities that implemented risk reduction measures and were most affected based on little resources, received priority. It was further noted that officials at the national department monitored the various projects to identify progress according to the respective business plans.

The phase immediately following a drought is particularly challenging as the extent of damage and resource losses guides decisions on short-term recovery and also determines long-term recovery plans for affected communities (Monteil *et al*., 2020). Once a drought situation has been brought under control, the PDAs should carry out the following post-disaster activities: conduct assessments to determine the damage caused and assistance required; offer recovery services and monitor the implementation process; compile post-disaster reports; and provide restoration and rehabilitation to those affected (Republic of South Africa, 2005). Policy further states that it is critical to emphasize awareness programmes during this period to provide education on the realities of climate variability, the status of natural resources and vulnerability. To ensure a successful drought recovery, officials maintained continuous communication with key role-players, updated farmer information and provided the necessary relief (Table 7.4).

The recovery phase is crucial because it determines the potential impact of future disasters and presents an opportunity to implement measures to reduce their likelihood (Republic of South Africa, 2003). Therefore, this phase can be viewed as an opportunity to shift the focus from emergency response to recovery, with the aim of building a more resilient society (Haile *et al*., 2020; Moatty and Vinet, 2016). Moreover, there was a general consensus that the various DRR measures incorporated local information. For example, an official at provincial level stated:

> *"We do incorporate local information in a sense of engaging directly with farmers to identify their needs. Some of them assist us with indigenous knowledge because most of them are more experienced than us."*

The various provinces carry out risk assessments that involve interacting with farmers as well as performing bi-annual veld assessments. Moreover, in the case of disaster-drought, assessments are conducted beforehand in order to request funding where the needs of farmers are documented. Thus, funding would then be acquired based on these needs. However, there was a concern from one of the participants that their area includes a large percentage of communal farmers and thus, awareness campaigns on the various DRR measures should be structured for communal farming systems.

7.3.3. Perception concerning performance of various DRR interventions

After the participants listed their interventions they were asked about the effectiveness of their strategies and the evaluation process employed. The responses to this question were varied. Some participants who answered positively mentioned that evaluation was carried out informally through continuous assessments with the farmers. However, another official highlighted that evaluation should not be an internal process and suggested involving external members such as the Monitoring and Evaluation directorate and auditors. Figure 7-1 illustrates that 32% of the participants believed the measures were effective, despite the absence of a formal evaluation process. They explained that evaluation was conducted informally through continuous assessments with the farmers. Additionally, a participant at provincial level emphasized the practice of holding debriefing sessions after each disaster to identify lessons learned and areas for improvement. The information gathered during these meetings would provide insights into the effectiveness of the various interventions.

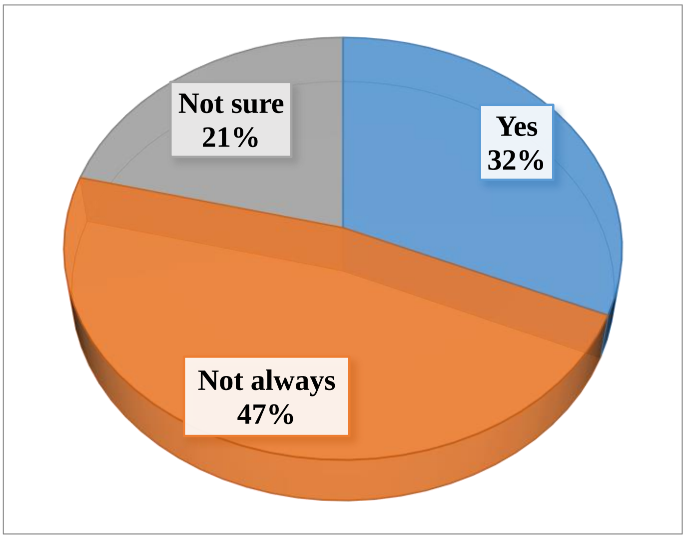


Figure 7-2: Perceived effectiveness of the various disaster risk reduction interventions.

The findings revealed a lack of consistency in the evaluation process, with some relying on informal assessments and others recognizing the importance of involving external entities for a more comprehensive evaluation. This inconsistency raises concerns about the reliability and validity of the evaluation outcomes. To strengthen the evaluation aspect of disaster risk reduction initiatives, it is recommended that a formal evaluation framework be established, outlining clear guidelines and procedures for assessing the effectiveness of interventions. This framework should include the involvement of external experts and stakeholders to provide an unbiased and thorough evaluation. By adopting a systematic and comprehensive evaluation approach, policy-makers and implementers can gain valuable insights into the success and shortcomings of the interventions, enabling them to make evidence-based decisions and further improve disaster risk reduction strategies.

The highest percentage (47%) of participants responded that their interventions were only effective to a certain extent as in most cases the situation was too adverse and thus it was very difficult to measure the effectiveness of the measures. There were other factors such as the infestation of alien invasive species that also contributed to the failure of certain measures. Another common problem according to the survey was increased dependency on government, whereby farmers expected to be assisted with maintenance even after the respective projects have been concluded, thus negatively affecting the effectiveness of the interventions.

The survey findings highlighted a number of concerns regarding the response measures and evaluation of strategies. It was revealed that following the normal supply chain procedure would lead to delays in implementing response measures, allowing the damage to escalate. This issue was particularly pronounced in resource-poor provinces with a limited number of experienced suppliers available. Additionally, approximately 21% of participants expressed uncertainty about the effectiveness of the measures. While many believed that the interventions had the potential to be effective, they often fell short due to the magnitude of the needs outweighing the limited assistance provided.

Participants pointed out various limitations in the implementation of the interventions. One significant challenge was the difficulty of reaching all affected communities adequately. For instance, due to limited financial resources, departments were only able to provide a small number of resources (e.g. five round bales) to farmers with a larger number of cattle. This blanket approach, where the same type of assistance was provided to all, regardless of their specific circumstances, was identified as another limitation. In addition, some participants acknowledged that many interventions were still in their early stages and would require further assessment over the coming years through research, assessments, monitoring and evaluation.

When questioned about the availability of a formal mechanism to evaluate how the various strategies contributed to reducing societal vulnerability, it was found that such an approach was generally lacking. Instead, officials relied on informal methods such as conducting monitoring visits, engaging beneficiaries and asking informal questions during awareness campaigns to gather vulnerability information. In one province, officials monitored commodity price fluctuations to gain insights into vulnerability, especially when locally produced commodities had to be imported. Another province planned to conduct surveys to determine the impact of interventions, while officials from a third province collaborated with organized agriculture and other departmental programmes to gain a better understanding of the societal position of farming communities.

7.3.4. Revision of agricultural disaster-drought related policies

The survey aimed to determine if post-drought assessments were included in participants' plans and whether they assisted in the revision process. The findings revealed that the majority of participants (41%) confirmed the inclusion of post-drought assessments, while 30% stated otherwise, and the remaining 29% were unsure. Those who confirmed the inclusion of post-drought assessments highlighted their integration into continuous risk assessments. Notably, one province had a dedicated Drought Management Task Team (DMTT) that utilized post-drought working groups to conduct on-the-ground assessments of drought conditions (Western Cape, 2016). An official explained that post-disaster assessments, documented as back-to-office reports, were conducted in collaboration with the Provincial Disaster Management Centre (PDMC) once the allocated funding was utilized.

To gain understanding into the use and revision of policy documents, participants were asked about the dynamic or static nature of their current plans. Generally, officials emphasized that all government policies were dynamic and subject to necessary amendments. Among those responsible for agricultural disaster management at provincial level, respondents expressed the ideal need for frequent plan revisions, but acknowledged that this was not always the reality. On the other hand, informants at national level emphasized that policy documentation was continuously revised, with a particular focus on contingency plans. An official explained that:

"Contingency plans are reviewed every season. Formal documentation is revised when necessary, for example, due to climate change or other factors such as departmental changes affect how and when to revise the policies, as it is critical to align them with the new mandate."

It was observed that officials recognized the need to revise internal frameworks and plans more frequently than formal documents, but they were uncertain about the specific time frame for such revisions. Responses varied, with some suggesting annual revisions, while others mentioned 2- or 3-year intervals. Only one respondent provided a more detailed explanation, stating that revisions of disaster management plans should adhere to the standards outlined in the Disaster Management Act and the Disaster Management Framework. According to this respondent, Level 1 plans should be revised 3 years after approval and Level 2 plans 2 years after approval, while Level 3 plans (the final ones) can be revised annually.

There was a general consensus that formal documentation might take longer to revise. Additionally, factors such as the nature of the drought, location, environment and climate were mentioned as considerations in determining the revision frequency. For example, one province updated their Drought and Water Scarcity Management Plan in 2016, which was a revision of the previous version from 1998. The decision to update the plan was driven by the recurring nature of drought disasters and their significant impacts. In this case, the relevant sector departments initiated a process to develop a multi-sectoral, integrated approach for updating the plan. It was also highlighted that Standard Operating Procedures and any other disaster plans should be reviewed on an annual basis.

7.4. Discussion

The research findings provided empirical evidence that the effectiveness of disaster-drought related policy is guided by its implementation through various programmes and projects. In general, South Africa largely follows the Disaster Management Act (Act No. 57 of 2002) as amended (Disaster Management Amendment Act No.16 of 2015) for all matters concerning disasters, including drought (Republic of South Africa, 2003, 2015). Serving as a subordinate, the National Disaster Management Framework of 2005, as amended, guides the procedures and implementation of disaster management in the country by all levels of government as well as related stakeholders (Republic of South Africa, 2005).

According to policy, the various sectors and spheres of government are responsible for formulating their frameworks and plans (Republic of South Africa, 2005). The survey revealed that out of the seven participating provinces, two stated that they have their own drought plans, while the others relied on the provincial disaster management frameworks and contingency plans designed for specific seasons. This emphasizes the importance of enforcing accountability in the provinces to enable the selection of appropriate policy measures based on the type of hazard and the unique physical characteristics of the local area (Garcia and Fearnley, 2012).

The overall effectiveness of policy was assessed by evaluating the various DRR measures in accordance with current policy at national level as well as in the different provinces. While the survey indicated some positive efforts in implementing pre-disaster measures and recognizing the importance of prevention and mitigation, it also highlighted the challenges of fully preventing drought and the need for a more proactive approach to DRR (Figure 7-3).

Common interventions included establishing fodder banks, drilling boreholes and erecting fencing to prevent overgrazing. Infrastructure projects like earth dam construction, provision of water tanks and fencing were tangible interventions. While borehole projects are unquestionably valuable, certain key individuals have suggested that they could be more effective if they were managed properly. For instance, some boreholes were drilled but not equipped, resulting in significant setbacks. However, it is essential to provide training and capacity building to local communities and stakeholders to facilitate sustainable practices to ensure the longevity and effectiveness of implemented measures (Haigh *et al.*, 2018).

Generally, DRR measures are crucial components of drought policies in many countries to alleviate the effects of drought (FAO, 2019). It was further depicted that there was some overlap between interventions, emphasizing important measures for reducing vulnerability to the impacts of drought. This indicated that certain measures such as seed and fodder production projects can serve as short-term recovery efforts while also being maintained as long-term mitigation measures. However, in many cases, particularly in least developed and developing countries like South Africa, interventions may promote a dependency syndrome (Wilhite, 1996). According to the survey, this was predominant in subsistence and emerging farming communities. A study in Iran produced comparable findings, with this conduct leading to distrust among those who did not qualify or receive assistance (Keshavarz *et al.*, 2013).

Therefore, it is necessary to implement capacity building programmes for vulnerable farming communities alongside drought relief efforts to decrease their reliance on the government.

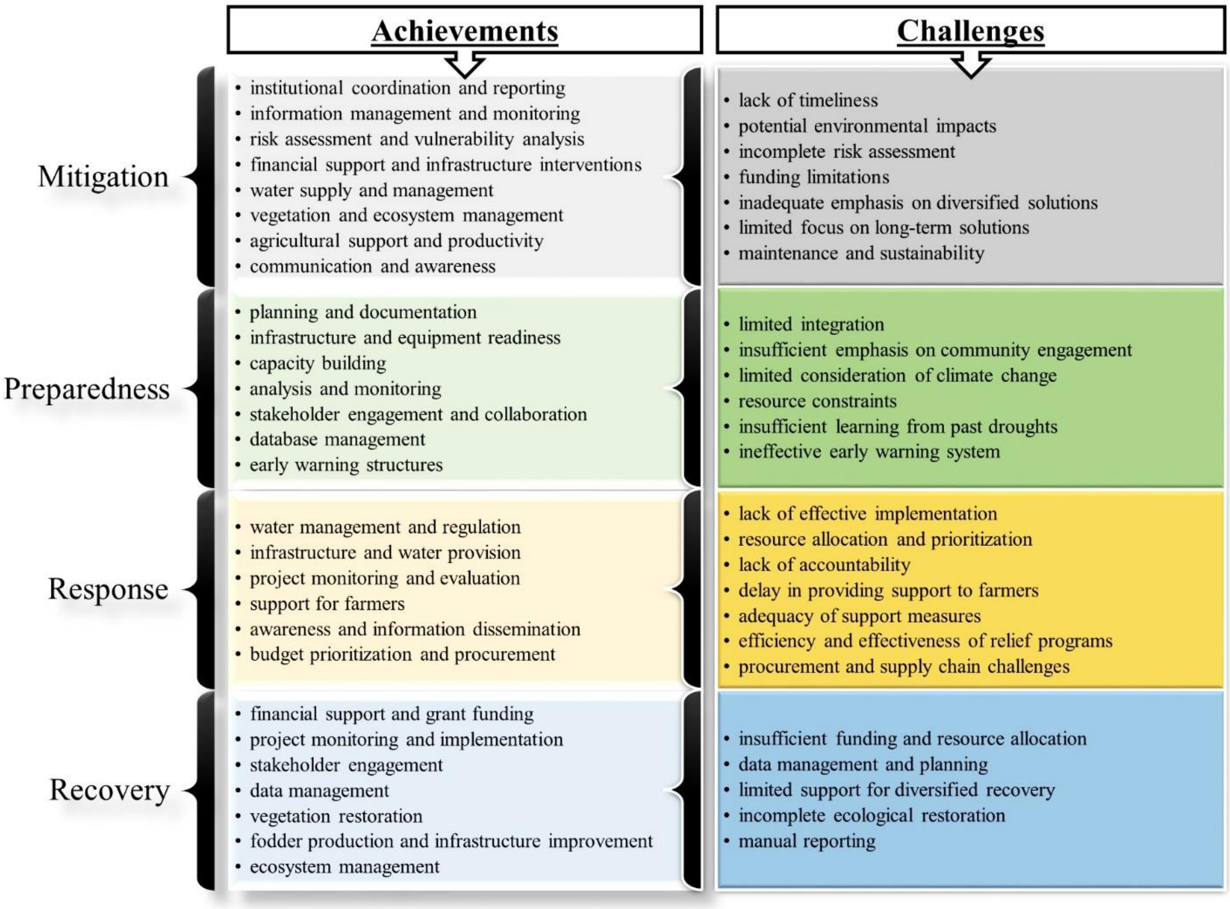


Figure 7-3: Prevailing themes on the various DRR measures and associated limitations.

Officials have noted some limitations when it comes to putting the necessary policies into practice (Table 7.5), including inadequate attention being paid to communal farmers and challenges arising from lengthy supply chain and procurement processes during disaster-droughts. In addition, officials revealed that despite using scientific research to inform their interventions, there was no established system in place to assess the effectiveness of the different strategies and how they contribute to decreasing societal vulnerability. This highlights gaps in policy concerning the efficacy and lasting viability of measures even beyond the completion of project implementation phases.

Table 7.5: Identified lessons and tailored recommendation for improving disaster-drought policy in South Africa.

Indicators to measure effectiveness	Observed limitations	Proposed points of action
Plans	• Limited development of provincial drought plans. • Accessibility challenges of policy documents.	• Encourage all provinces to develop and implement their own comprehensive drought plans. • Provide multiple and user-friendly platforms for sharing policy documents at all spheres of government.
Practice	• Lack of emphasis on proactive risk reduction. • Challenges in resource allocation and budget prioritization. • Delay in providing support. • Inadequate planning and implementation. • Resource constraints and limited focus.	• Strengthen the implementation of pre-disaster plans. • Establish clear timelines and deadlines for the development and implementation of drought plans. • Allocate funds based on identified risks and the potential environmental impacts of drought. • Emphasize long-term planning. • Prioritize maintenance and sustainability. • Explore innovative financing mechanisms and public-private partnerships to overcome resource constraints. • Enhance learning from past droughts. • Invest in the development and enhancement of robust early warning systems for droughts. • Promote accountability. • Ensure ecological restoration.
Performance	• Difficulty in measuring effectiveness. • Lack of consistency in evaluation process. • Lack of formal mechanisms for evaluation. • Delays in response measures. • Discrepancies in allocating assistance.	• Enhance adequacy of support measures. • Adopt digital technologies and automated reporting systems. • Conduct research to evaluate the outcomes and effectiveness of drought interventions. • Involve external experts and stakeholders in the evaluation process. • Tailor assistance programmes to the specific needs and circumstances. • Streamline the supply chain procedure to expedite the implementation of response measures.

Indicators to measure effectiveness	Observed limitations	Proposed points of action
Revision	• Inconsistency in including post-drought assessments. • Uncertainty and inconsistency in plan revision frequency. • Lack of clarity on plan revision criteria.	• Establish clear guidelines and procedures for conducting post-drought assessments and integrating their findings into the revision process. • Define a specific time frame for revising internal frameworks and plans. • Rationalize the revision process for formal documentation to ensure timely updates and alignment with changing circumstances.

Through monitoring and evaluation of current DRR measures, critical information can be obtained for future use. This is another contributing factor to the effectiveness of policy as it allows for determination of how the various measures can be utilized to serve those in need, as opposed to applying the umbrella approach. Furthermore, post-drought assessments were not given priority and thus information on past droughts, the level of impacts and the measures that assisted to lessen the impacts were not properly documented. These findings raise concerns about the effectiveness of the evaluation process and the lack of a standardized approach for assessing the impact of strategies on reducing societal vulnerability. Establishing a formal evaluation mechanism that incorporates systematic data collection and analysis would provide more reliable insights into the effectiveness of interventions.

Keeping records of important information on the various characteristics of each drought might be useful for planning purposes, including deciding on the type of interventions to implement, based on good practice (Bergman and Foster, 2009). According to the study, all this information is collected and stored in the various government offices as hardcopy reports. This underlines the need to develop an electronic system for drought information. Bandyopadhyay *et al*. (2020) highlighted the importance of realizing and accepting that drought cannot be addressed using the same approach as other natural hazards. Therefore, this electronic information system would address matters relating to agricultural drought and would benefit the sector immensely by ensuring that crucial information does not get lost due to factors such as incorrect filing or even fire. Moreover, technological advancements would improve the efficiency, accuracy and timeliness of data collection and reporting during the disaster management phases.

The uncertainty concerning the revision of policy documents also presents a challenge. Findings related to the revision of the various policy documents indicated that although officials were aware of the dynamic nature of these documents, generally, many of them were unsure of the revision period. At national level it was found that contingency plans must be revised bi-annually and yet there might be a concern at the provincial level. This step of the planning process, therefore, needs to be emphasized, as authorities can review the effectiveness of their current drought plans and revise as necessary (Fontaine *et al*., 2014).

Other factors that might have influenced the success of policy through implementation include the high frequency and prolonged nature of agricultural disaster-droughts. According to Beraki (2019), the intensity of droughts has increased (seasonally and annually) since the 1950s and the duration and frequency of droughts have started to increase since the 1980s. This implies that if the frequency of droughts increases, areas with long drought recovery times are more likely to suffer a new drought event before fully recovering from the previous one (Liu *et al*., 2020). Thus, it is essential to integrate climate change projections and scenarios into long-term planning processes for drought.

The occurrence of drought-induced disasters demands prompt attention from multiple stakeholders, as and when they occur. However, this might not be the appropriate time to initiate disaster risk reduction measures. Additionally, it is easy to overlook the impact of drought once rainfall resumes, which results in neglecting the fact that certain areas continue to suffer from disaster-drought effects for extended periods (Bergman and Foster, 2009). This emphasizes the significance of pre- and post-disaster planning to achieve efficient disaster risk reduction.

7.5. Conclusions

Considering South Africa's high exposure and vulnerability to agricultural disaster-drought, it was necessary to embark on a study concerning how this disaster is being managed in the country. The study focused on reviewing policy documentation and a survey to obtain the holistic nature of laws and interventions aimed at reducing drought impacts on agriculture. Knowledge of the various policy documents from national to provincial level was provided. Accordingly, these documents were examined to identify how they contribute to addressing the pre- and post-disaster phase of the disaster management cycle, concerning agricultural drought.

According to the research findings, South Africa is implementing disaster-drought policies throughout the country, but there are still some limitations. These include a lack of updates to drought plans, imbalanced allocation of resources, the absence of a formal and dependable system to document information on past drought impacts, and the lack of an appropriate mechanism to assess the effectiveness of different interventions. These drawbacks result in delayed response, recovery, and successful planning after droughts. Therefore, to ensure that developed policies are utilized to their full potential, it is crucial to guarantee that operational procedures, skilled personnel and other essential resources are available and functioning during and after disaster-droughts.

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APPENDICES

Appendix 1: Capacity building

The project addressed capacity building for students and permanent ARC staff members. Students were recruited via the ARC Professional Development Programme (PDP). They are registered at a number of universities in South Africa and are supervised by academics in partnership with ARC researchers. The university lecturers that we are collaborating with are Prof. M. Tsubo (Tottori University, Japan) and Dr. W.T. Tesfuhuney (University of the Free State). The following Doctoral and Masters students are registered under the project:

***Student*: Ms. Teboho Elisa Masupha**
Institution: University of South Africa
Topic: Development of an agricultural drought early warning framework for South African croplands
Level: PhD
Supervision: Dr. M.E. Moeletsi, Prof. M. Tsubo

***Student*: Ms. Phumzile Maluleke**
Institution: University of South Africa
Topic: Impacts of climate variability on livestock production in the Limpopo Province
Level: PhD
Supervision: Dr. M.E. Moeletsi; Prof. M. Tsubo

***Student*: Ms. Vuwani Makuya**
Institution: University of the Free State
Topic: Analysis of drought on major maize production areas in South Africa
Level: MSc
Supervision: Dr. W.T. Tesfuhuney, Dr. M.E. Moeletsi, Dr. Z. Bello

***Student*: Ms. Tshimangadzo Rasifudi**
Institution: University of KwaZulu-Natal

Topic: Analysis of hydro-meteorological drought using drought indices and the SWAT model in the Vaal River Catchment

Level: MSc

Supervision: Ms. K.T. Chetty, Dr. M.E. Moeletsi

Appendix 2: Project output dissemination

- One peer-reviewed scientific article was accepted for publication:

  Masupha, T.E., Moeletsi, M.E. and Tsubo, M., 2021. Prospects of an agricultural drought early warning system in South Africa. International Journal of Disaster Risk Reduction, 66, 102615. https://doi.org/10.1016/j.ijdrr.2021.102615

- Two abstracts were submitted and accepted for presentation at a conference:

  Name: 35th Annual Conference of the South African Society for Atmospheric Sciences
  Date: 8-9 October 2019
  Venue: Riverside Sun, Vanderbijlpark

  Conference papers:
  i. Title: Seasonal effects of rainfall on rangelands in the Limpopo Province
  Authors: Maluleke, P., Moeletsi, M.E. and Tsubo, M.
  ii. Title: Agricultural drought preparedness and systems in South Africa: A review
  Authors: Masupha, T.E., Moeletsi, M.E. and Tsubo, M.

- One abstract was submitted and accepted for presentation at a virtual conference:

  Name: International Conference on Dryland Agriculture
  Date: 21-23 July 2020
  Venue: Virtual (Zoom)

  Conference paper:
  Title: Agricultural drought risk with reference to future maize production in the north-eastern regions of the Limpopo Province, South Africa
  Authors: Masupha, T.E. and Moeletsi, M.E.

- Three abstracts were submitted and accepted for presentation at a conference:

  Name: 36th Annual Conference of the South African Society for Atmospheric Sciences
  Date: 31 October-1 November 2022
  Venue: Global Change Institute, University of the Witwatersrand, Johannesburg

  Conference papers:
  i. Title: Observed climate variability in the Limpopo Province
  Authors: Maluleke, P., Moeletsi, M.E. and Tsubo, M.
  ii. Title: Assessing the governance context of agricultural drought disasters in a changing climate
  Authors: Masupha, T.E., Moeletsi, M.E. and Tsubo, M.

iii. Title: The Agricultural Drought Early Warning System
Authors: Malherbe, J., Masupha, T.E., Moeletsi, M.E. and Beukes, P.J.

- Three abstracts were submitted and accepted for poster (1) and oral (2) presentation at a conference:

  Name: Fifth National Global Change Conference (GCC5)
  Date: 30 January-2 February 2023
  Venue: University of the Free State, Bloemfontein

  Conference papers:

  i. Title: Role of policy on the effectiveness of agricultural drought early warning systems in South Africa
  Authors: Masupha, T.E., Moeletsi, M.E. and Tsubo, M.

  ii. Title: Analysis of meteorological and hydrological droughts in the Vaal River Catchment
  Authors: Rasifudi, T., Chetty, K.T. and Moeletsi, M.E.

  iii. Title: Drought impacts on maize yield in the Free State province between 1990-2020.
  Authors: Makuya, V., Tesfuhuney, W.T., Moeletsi, M.E. and Bello, Z.

- Two abstracts were submitted and accepted for poster presentation at a conference:

  Name: African Climate Development Initiative-Early Career Researchers (ACDI-ECR) Conference
  Date: 8-10 March 2023
  Venue: University of Cape Town, Cape Town

  Conference papers:

  i. Title: Analysis of hydro-meteorological drought using drought indices and the SWAT model in the Vaal River Catchment
  Authors: Rasifudi, T., Chetty, K.T. and Moeletsi, M.E.

  ii. Title: Planting dates and adaptation strategy for rainfed maize under climate change
  Authors: Makuya, V., Tesfuhuney, W.T., Moeletsi, M.E. and Bello, Z.

Appendix 3: Project data management plan

The Agricultural Research Council (ARC) and the Water Research Commission (WRC) recognise the importance of knowledge sharing to maximize the impact of the research outcomes. To ensure efficient management of the data generated by the completed research project on the development of a drought preparedness framework for South Africa, a data management plan has been implemented, as this is crucial for ensuring the accessibility and utilization of the knowledge generated.

The newly developed Agricultural Drought Early Warning System (ADEWS) is accessible through a web-based platform located at https://www.drought.agric.za/. It relies on comprehensive and multidisciplinary datasets and indices pertaining to specific agricultural commodities. The project team will ensure that the research data, including datasets from the ADEWS, are properly documented, organized and preserved at the ARC. By utilizing both monitored and forecasted data, the system also offers registered users the opportunity to access diverse products and generate maps illustrating historical and anticipated drought conditions for any location and time frame across South Africa. This will enable future researchers to validate and build upon the findings, encouraging continued advancements in drought preparedness and sustainable water resource utilization in agriculture.

To facilitate knowledge sharing, the project team aims to contribute to the scientific community by publishing research findings in peer-reviewed scientific publications. These articles will provide a comprehensive account of the project's methodology, results and conclusions, ensuring that the research contributes to the existing body of knowledge and is accessible to a wider audience of researchers, policy-makers and practitioners. The project team also recognizes the importance of developing future researchers and professionals in the field. As such, the project's outcomes will be integrated into study dissertations / theses, allowing the students to explore specific aspects of the research in depth and contribute to the knowledge base.

Furthermore, the project team plans to disseminate the findings through various channels, such as conferences, workshops and seminars to engage with stakeholders from academia, government departments, agricultural communities and other relevant organizations. This will provide opportunities for interactive discussions, presentations and knowledge exchange, allowing participants to benefit from the research outcomes and share their experiences and insights. To reach a broader audience, popular articles and policy briefs will be developed. These articles will present the research outcomes in a concise and accessible manner, targeting stakeholders such as farmers, extension workers and policy-makers. By providing practical information and actionable recommendations, these articles will support informed decision-making and promote the adoption of drought preparedness measures.

Appendix 4: Text file for weather input data for the crop model simulation, as created by the Python script

```
*WEATHER DATA : CUST

@ INSI      LAT     LONG  ELEV
  CUST  -26.700   27.000  1350
@DATE  SRAD  TMAX  TMIN  RAIN
14001  33.8  27.5   8.7   0.0
14002  32.3  29.3   9.4   0.0
14003  30.5  28.3  13.2   0.0
14004  29.5  28.4  11.3   0.0
14005  27.9  29.9  10.4   0.0
14006  18.5  28.6  15.7   0.0
14007  23.6  27.9  15.4   0.0
14008  27.7  25.4  13.2   0.0
14009  23.8  27.8  15.4  10.4
14010  30.5  29.7  14.8   0.0
14011  19.8  28.1  15.0   8.9
14012  23.5  28.1  14.2   0.0
14013  29.9  30.1  11.6   0.0
14014  23.2  26.7  13.4   0.0
14015  23.5  29.6  15.0   0.0
14016  33.2  29.1  12.4   0.0
14017  30.6  30.4  10.3   0.0
14018  32.3  28.4   7.7   3.8
14019  24.3  28.5  14.5  10.9
14020  25.4  27.3  13.1   0.3
14021  23.8  26.4  13.1   0.0
14022  28.9  27.1  13.1   0.0
14023  24.3  28.6  14.9   0.0
14024  22.0  30.0  14.7   1.5
14025  25.9  27.5  14.1   0.0
14026  17.7  22.6  14.8   0.0
14027  13.6  23.3  14.8   0.5
14028  26.0  27.2  16.2   0.0
14029  21.8  28.5  15.5   2.3
14030  15.4  29.3  15.8  29.2
14031  13.0  24.5  16.4  17.0
14032  18.2  26.0  15.5   0.0
14033  18.0  28.8  16.6   3.3
14034  14.4  21.9  15.4   0.0
14035  22.5  27.5  15.1   0.0
14036  24.1  28.4  15.1   4.1
```

Appendix 5: Output file following the crop simulation for a specific point

!IDENTIFIERS........................								EXPERIMENT AND TREATMENT.........		SITE INFORMATION...........			DATES...						DRY WEIGHT, YIELD AND YIELD COMPONENTS				
@ RUNNO	TRNO	R#	O#	P#	CR	MODEL...	EXNAME..	TNAM.....................		FNAM....	WSTA....	SOIL_ID...	SDAT	PDAT	EDAT	ADAT	MDAT	HDAT	DWAP	CWAM	HWAM	HWAH	BWAH
1	1	1	1	1	MZ	MZCER047	TEST1404	Sim1		TESTING1	POTC1408	CBAN840001	2014001	2014315	2014322	2015026	2015095	2015095	-99	10005	3423	3423	0
2	1	1	1	1	MZ	MZCER047	TEST1404	Sim1		TESTING1	POTC1408	CBAN840001	2015001	2015304	2015311	2016007	2016066	2016066	-99	9375	3158	3158	0
3	1	1	1	1	MZ	MZCER047	TEST1404	Sim1		TESTING1	POTC1408	CBAN840001	2016001	2016304	2016309	2017011	2017078	2017078	-99	10384	3943	3943	0
4	1	1	1	1	MZ	MZCER047	TEST1404	Sim1		TESTING1	POTC1408	CBAN840001	2017001	2017304	2017309	2018016	2018083	2018083	-99	4768	1441	1441	0
5	1	1	1	1	MZ	MZCER047	TEST1404	Sim1		TESTING1	POTC1408	CBAN840001	2018001	-99	-99	-99	2018349	2018349	-99	0	0	0	0
6	1	1	1	1	MZ	MZCER047	TEST1404	Sim1		TESTING1	POTC1408	CBAN840001	2019001	2019307	2019312	2020017	2020083	2020083	-99	9241	3232	3232	0
7	1	1	1	1	MZ	MZCER047	TEST1404	Sim1		TESTING1	POTC1408	CBAN840001	2020001	2020306	2020312	2021013	2021078	2021078	-99	9710	3869	3869	0
8	2	1	1	1	MZ	MZCER047	TEST1404	Sim2		TESTING1	POTC1408	CBAN840001	2014001	2014315	2014322	2015010	2015065	2015065	-99	9755	4859	4859	0
9	2	1	1	1	MZ	MZCER047	TEST1404	Sim2		TESTING1	POTC1408	CBAN840001	2015001	2015304	2015311	2015357	2016040	2016040	-99	8052	4059	4059	0
10	2	1	1	1	MZ	MZCER047	TEST1404	Sim2		TESTING1	POTC1408	CBAN840001	2016001	2016304	2016309	2016359	2017045	2017045	-99	9283	4641	4641	0
11	2	1	1	1	MZ	MZCER047	TEST1404	Sim2		TESTING1	POTC1408	CBAN840001	2017001	2017304	2017309	2017364	2018052	2018052	-99	6449	2798	2798	0
12	2	1	1	1	MZ	MZCER047	TEST1404	Sim2		TESTING1	POTC1408	CBAN840001	2018001	-99	-99	-99	2018349	2018349	-99	0	0	0	0
13	2	1	1	1	MZ	MZCER047	TEST1404	Sim2		TESTING1	POTC1408	CBAN840001	2019001	2019307	2019312	2019365	2020052	2020052	-99	9557	4522	4522	0
14	2	1	1	1	MZ	MZCER047	TEST1404	Sim2		TESTING1	POTC1408	CBAN840001	2020001	2020306	2020312	2020364	2021051	2021051	-99	9290	4760	4760	0
15	3	1	1	1	MZ	MZCER047	TEST1404	Sim3		TESTING1	POTC1408	CBAN840001	2014001	2014315	2014322	2014362	2015042	2015042	-99	6653	3303	3303	0
16	3	1	1	1	MZ	MZCER047	TEST1404	Sim3		TESTING1	POTC1408	CBAN840001	2015001	2015304	2015311	2015348	2016022	2016022	-99	5084	2261	2261	0
17	3	1	1	1	MZ	MZCER047	TEST1404	Sim3		TESTING1	POTC1408	CBAN840001	2016001	2016304	2016309	2016346	2017022	2017022	-99	5725	2679	2679	0
18	3	1	1	1	MZ	MZCER047	TEST1404	Sim3		TESTING1	POTC1408	CBAN840001	2017001	2017304	2017309	2017350	2018028	2018028	-99	4890	2088	2088	0
19	3	1	1	1	MZ	MZCER047	TEST1404	Sim3		TESTING1	POTC1408	CBAN840001	2018001	-99	-99	-99	2018349	2018349	-99	0	0	0	0
20	3	1	1	1	MZ	MZCER047	TEST1404	Sim3		TESTING1	POTC1408	CBAN840001	2019001	2019307	2019312	2019353	2020031	2020031	-99	6783	3273	3273	0
21	3	1	1	1	MZ	MZCER047	TEST1404	Sim3		TESTING1	POTC1408	CBAN840001	2020001	2020306	2020312	2020352	2021029	2021029	-99	6892	3352	3352	0
22	4	1	1	1	MZ	MZCER047	TEST1404	Sim4		TESTING1	POTC1408	CBAN840001	2014001	2014350	2014356	2015058	2015129	2015129	-99	10032	3518	3518	0
23	4	1	1	1	MZ	MZCER047	TEST1404	Sim4		TESTING1	POTC1408	CBAN840001	2015001	2015350	2015355	2016054	2016133	2016133	-99	11189	3967	3967	0
24	4	1	1	1	MZ	MZCER047	TEST1404	Sim4		TESTING1	POTC1408	CBAN840001	2016001	2016350	2016355	2017058	2017154	2017154	-99	11669	4999	4999	0
25	4	1	1	1	MZ	MZCER047	TEST1404	Sim4		TESTING1	POTC1408	CBAN840001	2017001	2017350	2017360	2018066	2018118	2018118	-99	7034	1838	1838	0
26	4	1	1	1	MZ	MZCER047	TEST1404	Sim4		TESTING1	POTC1408	CBAN840001	2018001	2018365	2019006	2019072	2019159	2019159	-99	9088	4396	4396	0
27	4	1	1	1	MZ	MZCER047	TEST1404	Sim4		TESTING1	POTC1408	CBAN840001	2019001	2019350	2019355	2020058	2020135	2020135	-99	8918	4537	4537	0
28	4	1	1	1	MZ	MZCER047	TEST1404	Sim4		TESTING1	POTC1408	CBAN840001	2020001	2020350	2020356	2021058	2021150	2021150	-99	11448	5053	5053	0
29	5	1	1	1	MZ	MZCER047	TEST1404	Sim5		TESTING1	POTC1408	CBAN840001	2014001	2014350	2014356	2015043	2015105	2015105	-99	9864	5144	5144	0
30	5	1	1	1	MZ	MZCER047	TEST1404	Sim5		TESTING1	POTC1408	CBAN840001	2015001	2015350	2015355	2016039	2016093	2016093	-99	9676	4879	4879	0
31	5	1	1	1	MZ	MZCER047	TEST1404	Sim5		TESTING1	POTC1408	CBAN840001	2016001	2016350	2016355	2017041	2017101	2017101	-99	9673	5355	5355	0
32	5	1	1	1	MZ	MZCER047	TEST1404	Sim5		TESTING1	POTC1408	CBAN840001	2017001	2017350	2017360	2018044	2018109	2018109	-99	8700	4764	4764	0
33	5	1	1	1	MZ	MZCER047	TEST1404	Sim5		TESTING1	POTC1408	CBAN840001	2018001	2018365	2019006	2019055	2019119	2019119	-99	8090	4614	4614	0
34	5	1	1	1	MZ	MZCER047	TEST1404	Sim5		TESTING1	POTC1408	CBAN840001	2019001	2019350	2019355	2020041	2020104	2020104	-99	8888	5107	5107	0
35	5	1	1	1	MZ	MZCER047	TEST1404	Sim5		TESTING1	POTC1408	CBAN840001	2020001	2020350	2020356	2021039	2021097	2021097	-99	10073	5236	5236	0
36	6	1	1	1	MZ	MZCER047	TEST1404	Sim6		TESTING1	POTC1408	CBAN840001	2014001	2014350	2014356	2015028	2015076	2015076	-99	7514	3682	3682	0
37	6	1	1	1	MZ	MZCER047	TEST1404	Sim6		TESTING1	POTC1408	CBAN840001	2015001	2015350	2015355	2016025	2016067	2016067	-99	6261	2864	2864	0
38	6	1	1	1	MZ	MZCER047	TEST1404	Sim6		TESTING1	POTC1408	CBAN840001	2016001	2016350	2016355	2017026	2017076	2017076	-99	6887	3311	3311	0
39	6	1	1	1	MZ	MZCER047	TEST1404	Sim6		TESTING1	POTC1408	CBAN840001	2017001	2017350	2017360	2018032	2018083	2018083	-99	6567	3138	3138	0
40	6	1	1	1	MZ	MZCER047	TEST1404	Sim6		TESTING1	POTC1408	CBAN840001	2018001	2018365	2019006	2019045	2019092	2019092	-99	6240	2612	2612	0
41	6	1	1	1	MZ	MZCER047	TEST1404	Sim6		TESTING1	POTC1408	CBAN840001	2019001	2019350	2019355	2020027	2020074	2020074	-99	7137	3682	3682	0
42	6	1	1	1	MZ	MZCER047	TEST1404	Sim6		TESTING1	POTC1408	CBAN840001	2020001	2020350	2020356	2021030	2021079	2021079	-99	5738	2471	2471	0

This output file contains 42 simulation results, i.e. 6 simulations for each of the 7 years. TRNO refers to the treatment number or specific simulation. Other important fields include the date fields: start – SDAT, planting – PDAT and emergence – EDAT. The weight at harvest is contained in the HWAH column and is the value used for the yield estimate.

Appendix 6: Coding to calculate the expected yield per growing season since 2014/15, calculated from the output of the six simulations per growing season in the model simulation output file per simulation point

```
defModel_txt_read(dbfoutfile, Modeltxt, station):
    List = {}
with open(Modeltxt, 'r') as read:
allLines = read.readlines()

heading = allLines[3].split()
key = heading[18]
List[key] = {}



for line in allLines[4:]:
        if not str(int(line.split()[12][:4])+1) in List[key]:
List[key][str(int(line.split()[12][:4])+1)] = {}
        if not line.split()[8] in List[key][str(int(line.split()[12][:4])+1)]:
            List[key][str(int(line.split()[12][:4])+1)][line.split()[8]] = {}
ifint(line.split()[21]) == 0:
            List[key][str(int(line.split()[12][:4])+1)][line.split()[8]] = 2000
else:
            List[key][str(int(line.split()[12][:4])+1)][line.split()[8]] = int(line.split()[21])


values = []
for key in List['HDAT']:
if key[:4] == '2015':
            value_2015 = (List['HDAT'][key]['Sim1'] + List['HDAT'][key]['Sim2'] +
0.5*List['HDAT'][key]['Sim3'] + \
                0.5*List['HDAT'][key]['Sim4'] + List['HDAT'][key]['Sim5'] +
List['HDAT'][key]['Sim6']) / 5
values.append(value_2015)
print '2015', value_2015
```

```
for key in List['HDAT']:
if key[:4] == '2016':
        value_2016 = (List['HDAT'][key]['Sim1'] + List['HDAT'][key]['Sim2'] +
0.5*List['HDAT'][key]['Sim3'] + \
            0.5*List['HDAT'][key]['Sim4'] + List['HDAT'][key]['Sim5'] +
List['HDAT'][key]['Sim6']) / 5
values.append(value_2016)
print '2016', value_2016

for key in List['HDAT']:
if key[:4] == '2017':
        value_2017 = (List['HDAT'][key]['Sim1'] + List['HDAT'][key]['Sim2'] +
0.5*List['HDAT'][key]['Sim3'] + \
            0.5*List['HDAT'][key]['Sim4'] + List['HDAT'][key]['Sim5'] +
List['HDAT'][key]['Sim6']) / 5
values.append(value_2017)
print '2017', value_2017

for key in List['HDAT']:
if key[:4] == '2018':
        value_2018 = (List['HDAT'][key]['Sim1'] + List['HDAT'][key]['Sim2'] +
0.5*List['HDAT'][key]['Sim3'] + \
            0.5*List['HDAT'][key]['Sim4'] + List['HDAT'][key]['Sim5'] +
List['HDAT'][key]['Sim6']) / 5
values.append(value_2018)
print '2018', value_2018

for key in List['HDAT']:
if key[:4] == '2019':
        value_2019 = (List['HDAT'][key]['Sim1'] + List['HDAT'][key]['Sim2'] +
0.5*List['HDAT'][key]['Sim3'] + \
            0.5*List['HDAT'][key]['Sim4'] + List['HDAT'][key]['Sim5'] +
List['HDAT'][key]['Sim6']) / 5
values.append(value_2019)
```

```
print '2019', value_2019

for key in List['HDAT']:
if key[:4] == '2020':
        value_2020 = (List['HDAT'][key]['Sim1'] + List['HDAT'][key]['Sim2'] +
0.5*List['HDAT'][key]['Sim3'] + \
             0.5*List['HDAT'][key]['Sim4'] + List['HDAT'][key]['Sim5'] +
List['HDAT'][key]['Sim6']) / 5
values.append(value_2020)
print '2020', value_2020

for key in List['HDAT']:
if key[:4] == '2021':
        value_2021 = (List['HDAT'][key]['Sim1'] + List['HDAT'][key]['Sim2'] +
0.5*List['HDAT'][key]['Sim3'] + \
             0.5*List['HDAT'][key]['Sim4'] + List['HDAT'][key]['Sim5'] +
List['HDAT'][key]['Sim6']) / 5
values.append(value_2021)
print '2021', value_2021

values.sort()
value_color = len(values) - (values.index(value_2021)+1) + 1

results = dbf.Dbf(dbfoutfile, new=False)
for i in List:
rec = results.newRecord()
rec["Station"] = station
rec["Lat"] = RealStationList[station]['Lat']
rec["Lon"] = RealStationList[station]['Lon']
rec["y2015"] = value_2015
rec["y2016"] = value_2016
rec["y2017"] = value_2017
rec["y2018"] = value_2018
rec["y2019"] = value_2019
```

```
rec["y2020"] = value_2020
rec["y2021"] = value_2021
rec["color"] = value_color
rec.store()
results.close()
```

Appendix 7: Coding to store the estimated yield per point, per growing season in the GeoServer using an appropriate colour scheme

```
<?xml version="1.0" encoding="UTF-8"?>
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xmlns="http://www.opengis.net/sld"
xmlns:ogc="http://www.opengis.net/ogc"
xmlns:xlink="http://www.w3.org/1999/xlink"
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<FeatureTypeStyle>

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```
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</StyledLayerDescriptor>
```

Appendix 8: Weather input file for PUTU VELD created by Python script

3021 2244 0000 AAA BB DEC 2021

DAY	MAXT	MINT	RAIN	EVAP	SUN	AVET
1	37.0	21.0	0.0	6.0	26.0	29.0
2	38.0	21.0	0.0	6.0	26.0	29.5
3	39.0	21.0	0.0	6.0	26.0	30.0
4	38.0	24.0	3.0	6.0	24.0	31.0
5	31.0	20.0	33.0	2.0	6.0	25.5
6	33.0	18.0	0.0	4.0	20.0	25.5
7	33.0	21.0	1.0	3.0	13.0	27.0
8	27.0	20.0	0.0	2.0	8.0	23.5
9	29.0	19.0	2.0	2.0	10.0	24.0
10	36.0	19.0	4.0	5.0	43.0	27.5
11	37.0	21.0	0.0	6.0	43.0	29.0
12	38.0	22.0	1.0	6.0	25.0	30.0
13	37.0	21.0	14.0	5.0	22.0	29.0
14	33.0	20.0	0.0	4.0	19.0	26.5
15	34.0	19.0	0.0	5.0	43.0	26.5
16	34.0	19.0	18.0	3.0	14.0	26.5
17	26.0	21.0	0.0	2.0	9.0	23.5
18	29.0	22.0	5.0	2.0	10.0	25.5
19	29.0	21.0	1.0	3.0	12.0	25.0
20	32.0	22.0	5.0	3.0	15.0	27.0
21	33.0	22.0	1.0	4.0	21.0	27.5
22	37.0	23.0	0.0	5.0	24.0	30.0
23	39.0	25.0	0.0	5.0	23.0	32.0
24	30.0	22.0	6.0	2.0	6.0	26.0
25	30.0	21.0	0.0	4.0	18.0	25.5
26	33.0	21.0	0.0	4.0	21.0	27.0
27	36.0	22.0	0.0	5.0	24.0	29.0
28	36.0	23.0	2.0	5.0	23.0	29.5
29	37.0	24.0	0.0	5.0	25.0	30.5
30	35.0	22.0	0.0	5.0	23.0	28.5
31	35.0	24.0	3.0	4.0	20.0	29.5

3021 2244 0000 AAA BB JAN 2022

DAY	MAXT	MINT	RAIN	EVAP	SUN	AVET
1	34.0	22.0	11.0	4.0	19.0	28.0
2	26.0	20.0	1.0	3.0	16.0	23.0
3	28.0	19.0	0.0	3.0	15.0	23.5
4	34.0	19.0	0.0	5.0	23.0	26.5
5	37.0	21.0	0.0	5.0	24.0	29.0
6	39.0	21.0	23.0	5.0	20.0	30.0
7	27.0	21.0	5.0	2.0	11.0	24.0
8	32.0	21.0	0.0	4.0	20.0	26.5
9	32.0	22.0	0.0	4.0	18.0	27.0
10	34.0	21.0	0.0	5.0	24.0	27.5
11	31.0	22.0	0.0	5.0	21.0	26.5
12	32.0	22.0	0.0	4.0	17.0	27.0
13	34.0	22.0	0.0	5.0	21.0	28.0
14	32.0	23.0	3.0	4.0	17.0	27.5
15	33.0	22.0	5.0	4.0	20.0	27.5

Appendix 9: Overview of the components of the PUTU VELD simulation as it appears in the Fortran simulation script

```
!
! *******************************************************************
! * PROGRAM TO COMPUTE AND TABULATE POTENTIAL CO2-ASSIMILATION AND *
! * POTENTIAL DRY MATTER GAIN IN G/M**2/DAY OVER A PERIOD OF 365   *
! * DAYS ON A DAILY BASIS                                          *
! *******************************************************************
!     DIAGRAM OF ALL PLANTPARTS AT ANY GIVEN STAGE OF GROUTH
!     ======================================================
!                        I CA                                  ##
!                 DEAD   I  LIVE                               ##
!     ******     ******  I  ********                           ##
!     *    *<-X4-* GD *<-X8-* GL   *---R5---I                  ##
!     *    *     ******  I  ********        I                  ##
!     *    *             I                  I                  ##
!     *    *             I                  I                  ##
!     *    *             I                  I                  ##
!     *    *             I                  I                  ##
!     *    *     ******  I  ********        I                  ##
!     *    *<-X5-* CD *<-X9-*  CL  *---R4---I                  ##
!     *    *     ******  I  ********        I                  ##
!     *    *             I                  I                  ##
!     * TR *             I                  I                  ##
!     *    *             I                  I                  ##
!     *    *             I                  I                  ##
!     *    *     ******  I   *******     *******    *******    ##
!     *    *<-X7-* BD *<-X2--* BL  *-R1--* RES *<---* DMG *    ##
!     *    *     ******  I   *******     *******    *******    ##
!     *    *             I                  I                  ##
!     *    *             I                  I                  ##
!     *    *             I                  I                  ##
!     *    *     ******  I   *******        I                  ##
!     *    *<-X6-* SD *<-X1--* SL  *---R2---I                  ##
!     ******     ******  I   *******        I                  ##
!     DA                 I                  I           BA     ##
!     ----------------------------------------------------     ##
!     DB                 I                  I           BB     ##
!                        I                  I                  ##
!                        I                  I                  ##
!                        I                  I                  ##
!                        I                  I                  ##
!                ******  I   *******        I                  ##
!                * RD *<-X3--* RL  *---R3---I                  ##
!                ******  I   *******                           ##
!                        I                                     ##
!                        ICB                                   ##
!                        I                                     ##
!
!
!     KEY:
!         DMG=THE DAYS DRY MATTER GAIN (KG CARBOH./HA/DAY)
!         GD =GRAIN DEAD              GL =GRAIN LIVING
!         CD =CLUM DEAD               CL =CLUM LIVING
!         BD =LEAVES DEAD             BL =LEAVES LIVING
!         SD =STUBBLE DEAD            SL =STUBBLE LIVING
!         RD =ROOTS DEAD              RL =ROOTS LIVING
!         TR =TRASH DEAD              RES=CARBOHYDRATE RESERVES
!         DA =ABOVE GROUND DEAD       BA =ABOVE GROUND BIOMASS
!         DB =ROOT DEAD               BB =ROOT BIOMASS
!         D=DA+DB=TOTAL DEAD          B=BA+BB=TOTAL BIOMASS(STANDING BIO)
!         CA=ABOVE GROUND STANDING CROP
!         CB=BELOW GROUND STANDING CROP
!         ' =STANDING CROP-SUMMATION OF ALL MASS
!
```

Appendix 10: Section of the daily output file for one growing season at one point location produced by the PUTU VELD simulation

JDA	BCL	BCD	BBL	BBD	BSL	BSD	TP	PPROD	TPROD	BCON	AL
360	0	48.5	18.6	51	0.8	1454.8	118.1	177.1	295.3	8	0.4
361	0	48.5	18.6	51.1	0.8	1454.8	118.2	171.4	289.6	8	0.4
362	0	48.5	18.7	51.1	0.8	1454.8	118.2	165.7	283.9	8	0.4
363	0	48.5	18.7	51.1	0.9	1454.8	118.3	160	278.3	8	0.4
364	0	48.5	18.7	51.1	0.9	1454.8	118.3	154.3	272.6	8	0.4
365	0	48.5	18.7	51.1	0.9	1454.8	118.4	148.6	266.9	8	0.4
1	0	48.5	18.7	51.2	0.9	1454.8	118.4	142.9	261.2	8	0.4
2	0	48.5	18.7	51.2	0.9	1454.8	118.4	137.1	255.5	8	0.4
3	0	48.5	18.7	51.2	0.9	1454.8	118.4	131.4	249.9	8	0.4
4	0	48.5	18.8	51.2	0.9	1454.8	118.5	125.7	244.2	8	0.4
5	0	48.5	18.8	51.2	1	1454.8	118.5	120	238.5	8	0.4
6	0	48.5	18.8	51.2	1	1454.8	118.5	114.3	232.8	8	0.4
7	0	48.5	18.8	51.3	1	1454.8	118.6	108.6	227.1	8	0.4
8	0	48.5	18.8	51.3	1	1454.8	118.6	102.9	221.4	8	0.4
9	0	48.5	18.8	51.3	1	1454.8	118.6	97.1	215.8	8	0.4
10	0	48.5	18.8	51.3	1	1454.8	118.7	91.4	210.1	8	0.4
11	0	48.5	18.8	51.3	1	1454.8	118.7	85.7	204.4	8	0.4
12	0	48.5	18.9	51.4	1.1	1454.8	118.7	80	198.7	8	0.4
13	0	48.5	18.9	51.4	1.1	1454.8	118.7	74.3	193	8	0.4
14	0	48.5	18.9	51.4	1.1	1454.8	118.8	68.6	187.3	8	0.4
15	0	48.5	18.9	51.4	1.1	1454.8	118.8	62.9	181.7	8	0.4
16	0	48.5	18.9	51.4	1.1	1454.8	118.8	57.1	176	8	0.4
17	0	48.5	18.9	51.5	1.1	1454.8	118.9	51.4	170.3	8	0.4
18	0	48.5	18.9	51.5	1.1	1454.8	118.9	45.7	164.6	8	0.4
19	0	48.5	18.9	51.5	1.1	1454.8	118.9	40	158.9	8	0.4
20	0	48.5	18.9	51.5	1.1	1454.8	118.9	34.3	153.2	8	0.4
21	0	48.5	18.9	51.5	1.1	1454.8	118.9	28.6	147.5	8	0.4
22	0	48.5	18.8	51.5	1.1	1454.8	118.8	22.9	141.7	8	0.4
23	0	48.5	18.8	51.6	1.1	1454.8	118.8	17.1	136	8	0.4
24	0	48.5	22.4	51.6	0	1454.8	122.5	11.4	133.9	8	0.4
25	0	48.5	27.5	51.6	0	1454.8	127.6	5.7	133.3	8	0.4

26	0	48.5	27.6	51.6	0.1	1454.8	127.7	0	127.7	8	0.6
27	0	48.5	27.5	51.7	0.1	1454.8	127.7	0	127.7	8	0.6
28	0	48.5	27.5	51.7	0.2	1454.8	127.7	0	127.7	8	0.6
29	0	48.5	36.1	51.7	2.5	1454.8	136.3	0	136.3	8	0.5
30	0	48.5	39	51.8	5.7	1454.8	139.3	0	139.3	8	0.7
31	0	48.5	39.1	51.8	6.1	1454.8	139.4	0	139.4	8	0.8
32	0	48.5	39.2	51.8	6.4	1454.8	139.6	0	139.6	8	0.8
33	0	48.5	47.3	51.9	15.5	1454.8	147.7	0	147.7	8	0.8
34	0	48.5	55.6	51.9	33	1454.8	156	0	156	8	0.9
35	0	48.5	58.1	52	41	1454.9	158.6	0	158.6	8	1.1

Key:

Variable	Explanation	Value	Unit
JDA	Julian days		d
BCL	Culms living expressed in terms of BCOVER		
BCD	Culms dead expressed in terms of BCOVER		
BBL	Leaf mass at the present of basal cover		kg/ha
BBD	Leaves dead expressed in terms of BCOVER		
BSL	Stubble living expressed in terms of BCOVER		
BSD	Stubble dead expressed in terms of BCOVER		
TP	Biomass production		kg/ha
TPROD	TP + TPROD		kg/ha
PPROD	Residual production of previous summer		
BCON	Growth rate of the leaves		kg/ha/d
AL	Leaf area		ha

Appendix 11: Total production values per point and per year, extracted by an automated Python script from the yearly output files, per point

JDAY	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
353	74.8	84.7	206	184.8	150.2	139.9	119.2	97.4	90.3	117.9	233.8
354	74.8	84.8	206	184.8	150.1	139.9	119.2	97.4	90.3	117.9	233.8
355	74.8	84.8	206	184.9	150.1	140	119.2	97.5	90.3	117.9	233.9
356	74.7	84.9	206.1	184.9	150.1	140	119.3	97.5	90.3	118	233.9
357	74.7	84.9	206.1	185	150.3	140.1	119.3	97.6	90.2	118	234
358	74.7	85	206.1	185	150.2	140.1	119.3	97.6	90.3	118.1	234
359	74.8	85	206.2	185	150.2	140.1	119.4	97.6	90.3	118.1	234
360	74.9	85	206.2	185.1	150.6	140.1	119.4	97.7	90.4	118.1	234.1
361	74.9	85.1	206.3	185.1	150.7	140	119.4	97.7	90.4	118.2	234.1
362	74.8	85.1	206.3	185.2	150.7	140.1	119.5	97.8	90.4	118.2	234.1
363	75.6	85.2	206.3	185.1	150.7	140.1	119.5	97.8	90.4	118.3	234.2
364	75.6	85.2	206.3	185.1	150.6	140	119.5	97.8	90.3	118.3	234.2
365	75.6	85.3	206.3	185.2	150.7	140	119.6	97.9	90.3	118.4	234.3
1	75.5	85.3	206.4	185.1	150.7	140	119.6	97.9	90.2	118.4	234.3
2	75.5	85.3	206.4	185.2	151.2	140.1	119.6	97.9	90.2	118.4	234.3
3	75.5	85.3	206.4	185.2	151.2	140.1	119.7	97.9	90.2	118.4	234.4
4	75.4	85.4	206.5	185.2	151.2	140.1	119.7	98	90.2	118.5	234.4
5	75.4	85.4	206.5	185.3	151.1	140.1	119.7	98	90.2	118.5	234.4
6	75.4	85.4	206.5	185.3	151.1	140.1	119.7	98	90.1	118.5	234.5
7	75.3	85.5	206.6	185.3	151.1	140.1	119.8	98.1	90.1	118.6	234.5
8	75.3	85.5	206.6	185.4	151.2	140	119.8	98.1	90.1	118.6	234.5
9	75.2	85.5	206.6	185.4	154.6	140	119.8	98.1	90	118.6	234.5
10	75.2	85.6	206.5	185.4	155.8	140	119.9	98.2	90	118.7	234.6
11	75.2	85.6	206.5	185.5	156.2	140	119.9	98.2	89.9	118.7	234.6
12	75.1	85.6	206.5	185.5	156.2	139.9	119.9	98.2	89.9	118.7	234.6
13	75.1	85.6	206.4	185.5	156.2	139.9	119.9	98.3	89.9	118.7	234.7
14	75.1	85.7	206.4	185.5	156.2	139.9	119.9	98.3	89.8	118.8	234.7
15	75	85.7	206.4	185.6	156.8	139.8	120	98.3	89.8	118.8	234.7
16	75	94.4	206.4	185.6	163.8	139.8	120	98.4	89.8	118.8	234.8
17	75.6	104.5	206.3	185.6	167	139.8	120	98.4	89.7	118.9	234.8
18	76.5	109.7	206.3	185.6	171.7	139.7	120.1	98.5	89.7	118.9	234.8

Appendix 12: Survey questionnaire

The purpose of this questionnaire is to get insight into the drought management process and the effectiveness of policies implemented to deal with agricultural drought in South Africa.

Supplementary material

This supplementary material provides definitions of the various terms used in the questionnaire. [DOUBLE CLICK ON THE ICON BELOW].

Supplementary material 042021.docx

Interviewer information

Name: …………………………………………………………………………………………………

Date: ………………………………………………………………………………………………..

Starting time: ……………………………………………………………………………………

Finishing time: …………………………………………………………………………………..

SECTION A: GENERAL INFORMATION

Name of organization									
Level of governance	National ☐			Provincial ☐			District ☐		
Name of Province (**if applicable**)	GP ☐	NW ☐	FS ☐	NC ☐	WC ☐	EC ☐	KZN ☐	L ☐	MP ☐
Name of District (**if applicable**)									
Designation (position)									
Experience (**in drought management**)	<2 years	2-5 years	6-10 years	11-15 years	>15 years				

1. What are the responsibilities of your organization in relation to drought management for agriculture? And what are your roles?

Responsibilities of organization	**Roles of official**
•	•
•	•
•	•
•	•
•	•

SECTION B: INTRODUCTION ON DROUGHT MANAGEMENT PLANS

2. Are you aware of any drought-related policies / plans / frameworks / formal documentation for South African agriculture?

Yes	
No	

If yes, list them

……………………………………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

…………………………………………………………………………………………

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3. How do you access the various drought plan documents? Tick what is appropriate

Online	
Hard copy	
Soft copy	
Not accessible	

4. Who are the relevant stakeholders involved in the drought planning process?

…………………………………………………………………………………………

…………………………………………………………………………………………

…………………………………………………………………………………………

…………………………………………………………………………………………

………………………………

5. Are the drought plans dynamic / static?

Dynamic	
Static	
Not sure	

If dynamic, how often are they revised?

…………………………………………………………………………………………

…………………………………………………………………………………………

………………

SECTION C: INSIGHT ON DROUGHT DISASTER RISK-REDUCTION

6. List the years / seasons in which drought was declared a disaster (only specify for your area / level).

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…………………………………………………………………………………………

…………………………………………………………………………………………

……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………
………………………………………………

7. In your experience, what disaster risk-reduction measures have you taken? Provide evidence and refer to the years when drought was declared a disaster for your area.

List according to ***Prevention, Mitigation, Preparedness, Response, Recovery and Rehabilitation***.

Disaster element	Risk-reduction measure
Prevention	• •
Mitigation	
Preparedness	
Response	
Recovery and Rehabilitation	

8. Based on your answer in the previous question, do the various measures incorporate local information?

Yes	
No	
Not sure	

Explain

……………………………………………………………………………………………
……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

………………………………………

9. Were the measures listed in Question 7 effective?

Yes	
No	
Not sure	

Explain and include the evaluation processes.

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

………………………………

10. What mechanisms do you use to evaluate how the various mitigation strategies relate to reducing societal vulnerability?

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……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

………………………………

11. What mechanisms do you use to assess end-user uptake on drought mitigation and preparedness strategies? Explain and provide evidence

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……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

………………………………

12. In the drought management plan/s that you use, how is drought monitored? And, what are the triggers or thresholds for agricultural drought?

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……………………………………………………………………………………………

…………………………………………………………………………………………………

…………………………………………………………………………………………………

………………………………

13. Are you aware of the various seasonal forecasts that are being used to assist in predicting drought?

Yes	
No	

If yes, specify the ones you use.

…………………………………………………………………………………………………

…………………………………………………………………………………………………

…………………………………………………………………………………………………

………………………

14. Based on question 14, do you understand the seasonal forecasts?

Yes	
No	
To some extent	
N/A (Answered no in #13)	

15. Are you familiar with any agricultural drought monitoring products available?

Yes	
No	

If yes, specify.

…………………………………………………………………………………………………

…………………………………………………………………………………………………

…………………………………………………………………………………………………

…………………………………………………………………………………………………

………………………………

16. In your opinion, do seasonal forecasts and drought monitoring products add value to drought early warning in the agricultural sector?

Yes	
No	
To some extent	
Not sure	

Explain

…………………………………………………………………………………………

…………………………………………………………………………………………

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………………………………

17. Describe the drought early warning system that you use. Include how it reaches the end users.

…………………………………………………………………………………………

…………………………………………………………………………………………

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…………………………………………………………………………………………

………………………………

18. In the drought documentation, is there a clear process for coordination (communication channels with roles) among all relevant stakeholders in terms of drought early warning?

Yes	
No	
Not sure	

Explain

…………………………………………………………………………………………

…………………………………………………………………………………………

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………………………………

19. How do you determine the timing of drought response? Is there a system with thresholds to trigger the start and end of drought assessments for response initiatives? Explain

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…………………………………………………………………………………………

…………………………………………………………………………………………

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………………………………

20. What method do you use to delineate affected areas? And how do you determine who qualifies for relief assistance? Explain

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………………………………

21. Are post-drought assessments included in the plan/s?

Yes	
No	
Not sure	

If yes, what is the procedure?

…………………………………………………………………………………………………

…………………………………………………………………………………………………

…………………………………………………………………………………………………

…………………………………………………………………………………………………

………………………………

22. Is there a system to compile and publish statistical information on historical drought impacts?

Yes	
No	
Not sure	

If yes, provide evidence

…………………………………………………………………………………………………

…………………………………………………………………………………………………

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SECTION D: VIEWS ON AGRICULTURAL DROUGHT MANAGEMENT

23. Rate the disaster elements in accordance to the current agricultural drought management in the country, **based on priority**.

1 = Very weak, 2 = Weak, 3 = Average, 4 = Strong, 5 = Very Strong

Element	**Human resources**	**Financial resources**	**Overall priority**
Prevention			
Mitigation			
Preparedness			
Response			
Recovery and Rehabilitation			

24. Based on the previous question, what could be done to improve the weak elements(s)? Explain

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………………………………………………………………………………………………
………………………………………………………………………………………………
………………………………………………………………………………………………
………………………………

25. Do you receive enough support from your department with regard to addressing drought? Explain

………………………………………………………………………………………………
………………………………………………………………………………………………
………………………………………………………………………………………………
………………………………………………………………………………………………
………………………………

26. Do you think the current drought management for agriculture in South Africa is proactive or reactive?

Proactive	
Reactive	
Not sure	

27. What do you think are the most important factors for facilitating paradigm shifts in drought plans and management? E.g. from reactive to proactive

…………………………………………………………………………………………

…………………………………………………………………………………………

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………………………………

28. Drought cuts across many sectors (water, agriculture, environment, health, etc.) Do you think there is appropriate working relations among the government departments and other stakeholders (private, academia, research, etc.)?

Yes	
No	
Do not know	

If not, what needs to be improved?

…………………………………………………………………………………………

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………………………

29. Based on the previous question, what role can research play in order to assist in addressing drought and its impacts on agriculture?

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………………………………

THANK YOU FOR PARTICIPATING IN THIS SURVEY. YOU ARE WELCOME TO COMMENT OR ASK QUESTIONS.

SUPPLEMENTARY MATERIAL

This supplementary material provides definitions of the various terms used in the questionnaire.

Term	Definition
Drought	A period of prolonged precipitation deficiency, relative to the statistical average of an area.
Agricultural drought	A period when soil moisture is insufficient to meet crop water requirements during the growing season and thus, resulting in a decline in agricultural production.
Disaster	A progressive or abrupt, widespread or localized extreme event, which causes pronounced damage to the well-being of the environment, humans and the economy.
Disaster-drought	Gradual deterioration of grazing land and crop failure due to precipitation deficiency. Disaster-droughts could last very long, but usually end within 12 to 36 months.
Proactive approach	Action taken to control an expected occurrence or situation.
Reactive approach	Action taken after a situation has occurred.
Prevention	Actions aimed at reducing or eliminating the impact of future hazard events, by avoiding the hazard or strengthening resistance to it.
Mitigation	Measures aimed at reducing the risk, impact or effects of a disaster or threatening disaster situation.
Preparedness	The strengthening of capabilities at all levels in preparedness to improve response to, and recovery from future threats (to the sector) and to reduce their potential negative impact on livelihoods.
Response	The provision of assistance and/or intervention during or immediately after a disaster to meet the life preservation and basic subsistence needs of those affected.
Recovery and Rehabilitation	Decisions and actions taken after a disaster with a view to restoring living conditions of the stricken community, while encouraging and facilitating adjustments to reduce disaster risk.