ASSESSING THE INTEGRATION OF FOURTH INDUSTRIAL REVOLUTION TECHNOLOGIES INTO DROUGHT EARLY WARNING SYSTEMS FOR AGRICULTURAL DISASTER RISK MANAGEMENT

by

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I declare that the above thesis is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

I further declare that I submitted the thesis to originality checking software and that it falls within the accepted requirements for originality.

I further declare that I have not previously submitted this work, or part of it, for examination at Unisa for another qualification or at any other higher education institution.

E.T. Masupha
SIGNATURE

July 2024
DATE

DEDICATION

I dedicate this work to my academic journey, which has been filled with newfound purpose and self-understanding. Through hours of research, challenges faced, milestones achieved, lessons learned, and moments of reflection, I have grown stronger and more committed to my personal and academic growth. I also acknowledge that I couldn't have done it alone, and that fills me with so much gratitude for the support I received. Thus, may this thesis serve as a reminder of my journey and inspire me to embrace the endless potential that lies ahead.

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ABSTRACT

The agricultural sector, particularly in developing countries, is highly vulnerable to drought occurrences, which often result in substantial socio-economic losses. In southern Africa, drought frequency has tripled over the last six decades and is projected to worsen due to climate change. This underscores the critical importance of effective drought early warning systems (DEWS), essential for enhancing preparedness before a drought, facilitating decision-making during drought conditions, and enabling stakeholders to implement long-term risk reduction measures following a drought. Therefore, the present study aimed to develop a conceptual framework for a DEWS that integrates modern technologies to enhance its functionality and impact within the context of the fourth industrial revolution (4IR).

The research adopted a conceptual approach, employing both empirical and non-empirical methods. These included qualitative analysis, a scoping review, the application of Toulmin's model of argumentation, and a metric-based approach utilizing South Africa as a case study. Primary data were collected through purposive sampling, with key informants interviewed between June 2021 and April 2022 using a semi-structured questionnaire. Secondary data collection and analysis involved a rigorous process of Boolean keyword searches, bibliometric analysis, and content evaluation.

The survey revealed positive advancements in the development of relevant policies such as the Disaster Management Act No. 57 of 2002, yet identified significant concerns regarding localized planning and implementation, particularly across provinces. Notably, there was a lack of tailored drought plans in five of the seven participating provinces and 68% of participants expressed uncertainty regarding the effectiveness of current measures. Main factors included disparities in resource allocation, early warnings not tailored to farmers' characteristics, overreliance on government support, and utilizing manual methods for documenting field reports. To address these challenges, the study proposed a proactive approach including pre-disaster plans that emphasize mitigation, improving implementation efficiency, building capacity, and establishing formal review mechanisms to enhance the effectiveness of strategies. This approach will therefore establish a conducive environment essential for implementing innovative DEWS effectively.

According to the bibliometric analysis, the integration of 4IR technologies into drought research began in 2015, with significant contributions from China and the United States. However, the relationships derived from the co-occurrence of keywords predominantly focused on data collection and processing, lacking comprehensive emphasis on all fundamental components of DEWS. Therefore, employing Toulmin's model of argumentation, the study established applicable links between 4IR technologies and DEWS, resulting in the development of eight interconnected modules. Modules such as smart data networks and advanced analytics presented the use of the Internet of Things, robotics, and big data analytics to enhance real-time data collection and monitoring. The study revealed that artificial intelligence plays a significant role in generating accurate forecasts, tailored warning alerts, and enabling interactive communication. Furthermore, the use of extended reality can enable users to simulate drought scenarios, interact with data, and evaluate the impact of various measures for improved decision-making.

The study further assessed South Africa's current agricultural drought early warning system to determine its effectiveness and feasibility for adopting the 4IR-based DEWS framework. The findings revealed a significant gap in that while the system is proficient in quantifying and monitoring drought, it lacks prioritization of field reports, interactive mapping, and enhancing the response capabilities of agricultural stakeholders. Therefore, the implementation of smart weather stations, unmanned aerial vehicles, and connected wearable devices ensures a more localized and timely collection of data, including weather, crop, irrigation, and farm management activities, to generate tailored information. Moreover, transitioning from current static web pages to Web 3.0 functionalities can facilitate intelligent processing, dissemination, and decision-making among farmers, extension officers, cooperatives, researchers, and policymakers. However, overcoming limitations such as high initial costs, and limited technical expertise, is crucial. Thus, to fully realize the potential of this proposed framework and achieve a more effective, sustainable approach to agricultural drought management, further research, practical implementation, and policy amendments are essential.

Key terms: Agricultural drought monitoring, Artificial intelligence, Big data, Disaster response, Early warning systems, Fourth industrial revolution, Machine learning, Qualitative research, Internet of Things sensors, Unmanned aerial vehicles.

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LIST OF ABBREVIATIONS

3D	**Three-dimension**
4IR	**Fourth Industrial Revolution**
ACMAD	**African Centre of Meteorological Applications for Development**
ACTED	**Agency for Technical Cooperation and Development**
ADEWS	**Agricultural Drought Early Warning System**
ADMS	**Agricultural Drought Monitoring System**
ADO	**African Drought Observatory**
AI	**Artificial Intelligence**
ARC	**Agricultural Research Council**
BDA	**Big Data Analytics**
CariCOF	**Caribbean Climate Outlook Forum**
CWB	**Climatic Water Balance model**
DEWFORA	**Drought Early Warning System for Africa**
DEWS 4.0	**Fourth Industrial Revolution-based Drought Early Warning System**
DEWS	**Drought Early Warning System**
DRMFSS	**Disaster Management and Food Security Sector**
EWRD	**Early Warning and Response Directorate**
FEWS NET	**Famine Early Warning Systems Network**
GIS	**Geographic Information System**
IoT	**Internet of Things**
KPI	**Key Performance Indicator**
MAAIF	**Ministry of Agriculture Animal Industries Fisheries**
NAC	**National Agro-meteorological Committee**
NDMA	**National Drought Management Authority**
NDVI	**Normalized Difference Vegetation Index**
NIDIS	**National Integrated Drought Information System**
NL	**National-level departments**
NOAA	**National Oceanic and Atmospheric Administration**
NZDI	**New Zealand Drought Index**

PL	**Provincial-level departments**
SADC-CSC	**Southern African Development Community - Climate Services Centre**
SAWS	**South African Weather Service**
SPI	**Standardized Precipitation Index**
UAV	**Unmanned Aerial Vehicle**
Web 3.0	**Semantic Web**
Web 4.0	**Intelligent Web**
WRSI	**Water Requirement Satisfaction Index**
XR	**Extended Reality**

CHAPTER 1. INTRODUCTION

1.1. Research background

The agricultural sector, especially in developing nations, is one of the most vulnerable sectors to the occurrence of extreme weather, climate, and water-related disasters, with more than 2 million fatalities and global economic losses exceeding 4.3 trillion US dollars between 1970 and 2021 (WMO, 2023). Sub-Saharan Africa, reported nearly 17% of these disasters during the same period, with drought and famine accounting for the greatest number of deaths, especially in the eastern and the horn of Africa (WMO, 2023). In southern Africa, the frequency of droughts has tripled over the last six decades due to the impact of climate change (Yuan *et al.*, 2018), thus exposing this region to the prospect of future droughts characterized by increased frequency, intensity, and duration (Rusca *et al.*, 2023). This is expected to have negative impacts on crop yields and prices (Anderson *et al.*, 2019), thereby aggravating food insecurity, impeding economic growth, and creating new cycles of poverty in vulnerable regions (Dhanya and Geethalakshmi, 2023).

South Africa is among numerous countries prone to frequent drought occurrences which has led to detrimental impacts on agriculture (Archer *et al.*, 2019; Botai *et al.*, 2016). For example, during the 2014/15 agricultural season, drought conditions emerged across significant areas of the summer rainfall region, intensifying during the subsequent 2015/16 season (ARC, 2017). The impacts thereof became evident by the end of the season, with maize production decreasing by 40% (DAFF, 2019), livestock losses amounting to 15% (AgriSA, 2016), and the government allocating R198 million for assistance by March 2016 (DALRRD, 2020b). This was classified as one of the most severe droughts of the century, in which farmers' income sources were reduced and livelihoods were threatened (Mare *et al.*, 2018).

Subsequently, the winter rainfall region experienced severe to extreme drought conditions during the 2016/17 season (ARC, 2017) and consequently contributed negatively to the production of wheat. Research further confirmed that certain areas such as the Karoo region and parts of Eastern Cape province continued to experience a multi-year drought until early 2020 (Archer *et al.*, 2022) and an amount of R138.5 million was allocated in 2020 for drought relief based on the prolonged impacts (DALRRD, 2020b). According to Archer *et al*. (2022), this specific drought was considered unique and it revealed the disastrous impact of droughts, particularly on the agricultural sector.

Throughout history, drought has captured considerable attention, yet providing a precise definition for this phenomenon remains challenging. Generally, drought definitions vary widely due to differences in types, characteristics, and impacts (Rajsekhar *et al.*, 2015). It is widely known that drought often originates from a deficiency in precipitation—meteorological drought, and the longer this deficit persists, the greater the likelihood of other types of drought occurring (Cai *et al.*, 2017) as shown in Figure 1-1. For instance, agricultural drought is linked to periods of meteorological drought that lead to decreased soil moisture levels, essential for optimal crop growth (Ding *et al.*, 2021). According to Malherbe *et al*. (2016), this may occur within approximately three months, following apparent impacts on crops.

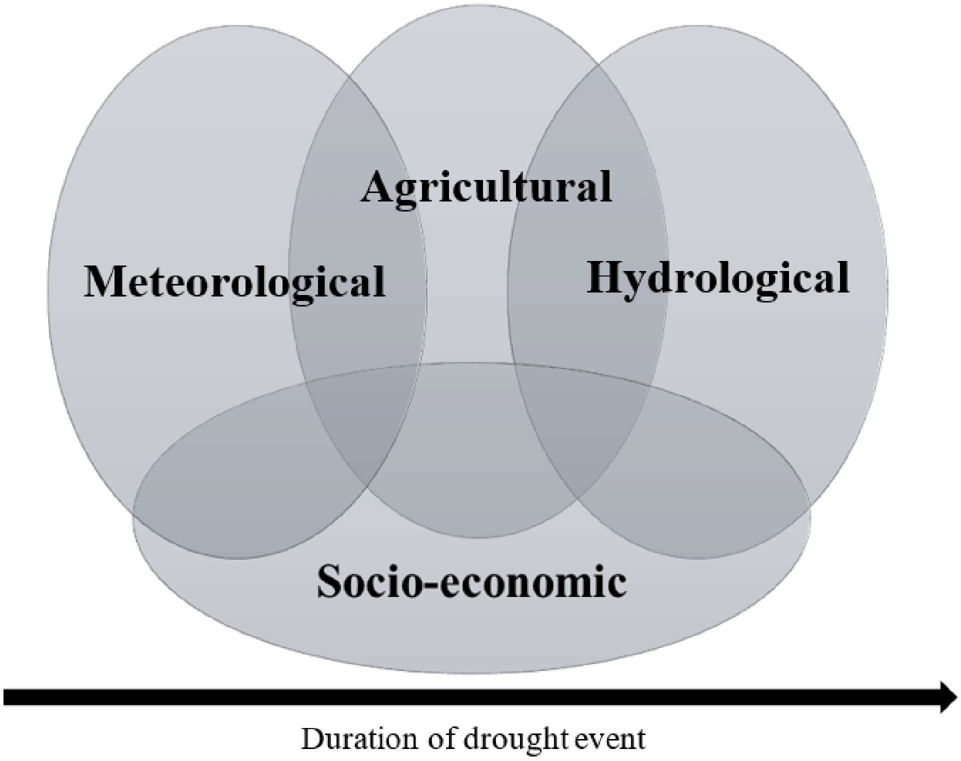

Figure 1-1: The interaction of drought types as a function of time (Crocetti *et al*., 2020).

Agricultural drought has a domino effect through various processes within the hydrological cycle, including insufficient precipitation, high evapotranspiration, and reduced soil moisture, thereby intensifying its effects on crops (van Hoek *et al*., 2019). In field crops, even a few days of drought stress post-planting can compromise germination and seedling emergence, with the reproductive phase being particularly vulnerable (Hussain *et al.*, 2018). This vulnerability arises from the potential failure of critical processes such as pollination and dry matter production, leading to reduced grain formation and ultimately limiting crop and pasture yields (Sehgal *et al.*, 2018). Moreover, the onset of drought triggers numerous other responses, emphasizing the pivotal role of water in plant cells (da Silva *et al.*, 2013). Consequently, the diverse reactions of crops to drought impacts depend on factors such as the duration of the drought, crop type, and developmental stages (Hussain *et al.*, 2018).

Hydrological drought, which typically manifests after a period of six to 12 months, is marked by a notable deficiency in both surface and subsurface water resources (Crocetti *et al.*, 2020). This scarcity imposes significant implications on hydrological systems, intensifying the complexities associated with water availability and management within agricultural systems and ecosystems (Van Loon, 2015). Conversely, socio-economic drought emerges when any of the three physical types of droughts begin to affect the economy or society at large (Shi *et al.*, 2018). A study by Vogel and van Zyl (2016) further described drought as a 'wicked problem and challenge', attributing this to the complex interplay of biophysical, socio-economic, and political factors. Whereas Crausbay *et al*. (2017) proposed ecological drought as intermittent periods of reduced water availability, driving ecosystems past vulnerability thresholds, and thus affecting ecosystem services and feedback loops in natural or human systems.

Another facet of this complex phenomenon is the human influence, involving factors such as land use and cropping systems, which can induce drought. This implies that a growing human population may increase the demand for specific economic resources, potentially intensifying the societal impacts of drought (Cai *et al.*, 2017). In addition, a drought is classified as a disaster when the lack of rainfall begins to impact human activities, including food security, health, and overall quality of life—aligning with socio-economic drought (Cunha *et al.*, 2019). Thus, understanding the nature of drought, its diverse impacts, and the complexities associated with its definition is essential for developing effective mitigation and adaptation tools such as early warning systems (Chivangulula *et al.*, 2023). These systems have been implemented in disaster management strategies in many regions around the world to mitigate risks in drought-sensitive sectors such as agriculture (Hao *et al.*, 2017).

1.2. Overview of South Africa as a case study area

South Africa is a country located in the southern region of the African continent (between 22°S to 35°S latitude and 17°E to 33°E longitude), covers a land area of 1 219 602 km^2 and is divided into nine provinces (GCIS, 2021). The country has a diverse range of climatic conditions, from arid in the western region to humid subtropical in the east, with semi-arid conditions prevailing in much of the northern and central interior (Figure 1-2). This variation is primarily influenced by the country's geographical location, altitude, and position between the Atlantic and Indian Oceans (Davis-Reddy and Vincent, 2017). The northern and western regions experience the highest temperatures, while the elevated areas are cooler (GCIS, 2021). Annual rainfall ranges from <400 mm in the west to >1000 mm in the east (ARC, 2023). However, substantial fluctuations in rainfall occur commonly throughout the year, as the Intertropical Convergence Zone interacts with other regional atmospheric circulation patterns (Daron, 2014).

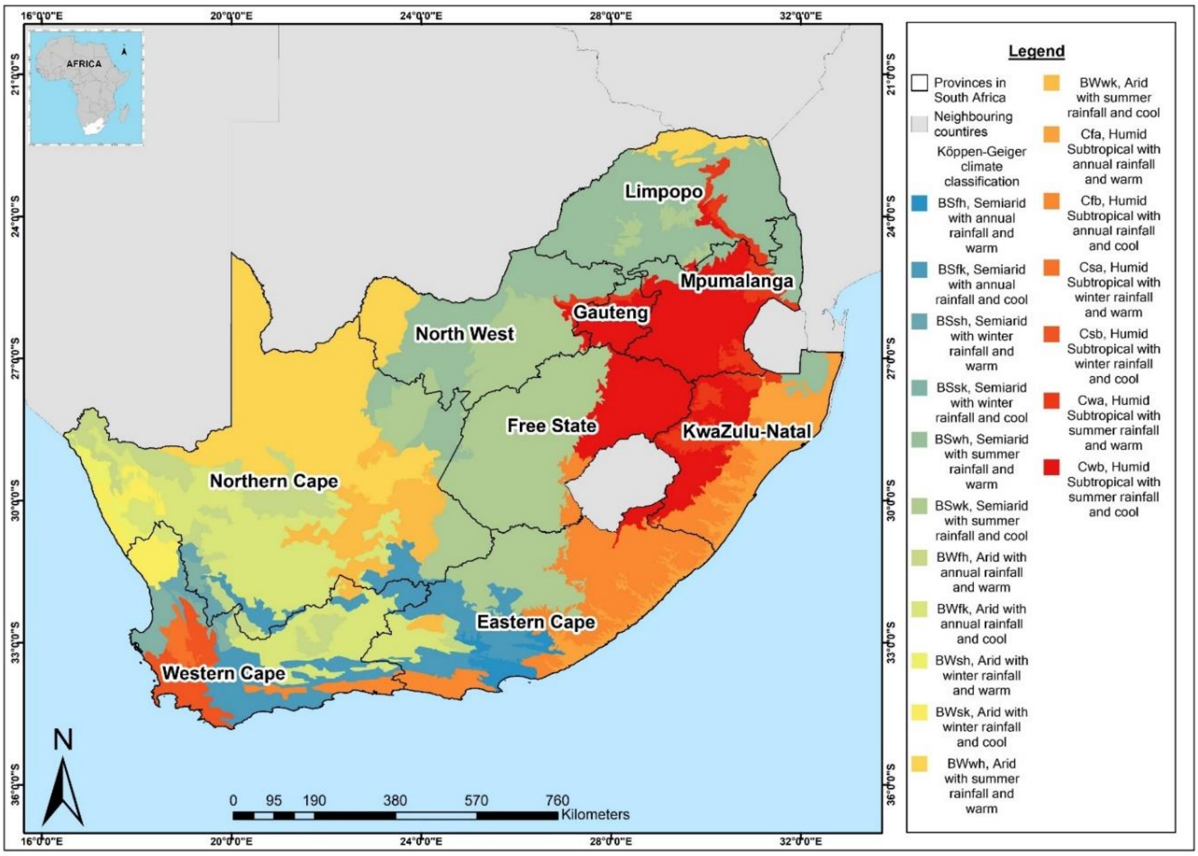

Figure 1-2: Location of the case study area—South Africa, and its climate classification based on the Köppen classification (Köppen, 1936), updated by (Peel *et al.*, 2007).

Based on South Africa's high climatic variations (Figure 1-2), the country's agriculture is very diverse. Activities range from cattle ranching and sheep production, respectively, in the Savanna biome and the Nama-Karoo, to the intensive crop and mixed farming systems in the summer and winter rainfall regions (Republic of South Africa, 2020). Crop production serves as a vital source of food security and a contributor to gross value – mainly through commercial farming (about 90% of total output) (DAFF, 2019). The more small-scale systems are scattered around the country and poorly organized, thus making it difficult to quantify (Mthembu, 2013). However, they contribute toward employment even though they are commonly poorly resourced (DAFF, 2019). Meanwhile, approximately 22% of households (mostly in rural areas) practice subsistence farming (Mthembu, 2013).

1.3. Problem statement and objectives

1.3.1. Problem statement

South Africa, like several other countries, faces recurrent droughts that frequently escalate into disasters. In response, the South African government has implemented policies aimed at planning for and managing these disasters (Republic of South Africa, 2003, 2015). For the agricultural sector, much significance occurred following the implementation of the National Agro-meteorological Committee (NAC), which was established under the Disaster Management Act No. 57 of 2002, as amended by Act No.16 of 2015, with the mandate to develop and implement early warning systems for risk management (DALRRD, 2020a). This committee is composed of members from various directorates within the department of agriculture, land reform and rural development, nine provincial departments of agriculture, the Agricultural Research Council (ARC), and the South African Weather Service (SAWS) (Cerfonteyn, 2016).

In terms of technical capacity, the SAWS, which is the primary government entity tasked with monitoring weather and climate patterns, issues a seasonal climate forecast every month (SAWS, 2020). Simultaneously, the ARC, serving as the principal agricultural research institution in the country, disseminates a monthly newsletter named the Umlindi, providing near real-time information on observed rainfall, drought, vegetation, and agricultural-related fires (Maake *et al.,* 2023). Upon the publication of the seasonal forecast and the Umlindi, the directorate overseeing the NAC, namely, climate change and disaster risk reduction, collates this information along with reports from various provinces to create an advisory, distributed in a portable document format via the department website and emails (DALRRD, 2020a).

Subsequently, the relevant government officials disseminate this advisory to the agricultural community, including farmers, aiming to mitigate potential risks to agricultural production (Cerfonteyn, 2016). However, despite these efforts, the detrimental impacts of drought persist as a significant threat to agricultural production across the country, raising concerns not only about the multifaceted nature of drought but also about the effectiveness of disaster risk management. Therefore, the first research question emerged as follows:

i. How effective is South Africa's drought policy in ensuring disaster risk reduction for the agricultural sector?

In disaster risk management, a drought early warning system (DEWS) is considered one of the most important mechanisms around the globe to alleviate drought impacts due to its ability to communicate significant information within a timely period (Pulwarty and Sivakumar, 2014). According to a report by Lumbroso (2018), the DEWS in South Africa were classified as moderately effective in mitigating humanitarian impacts. This could be attributed to several factors, including uncertainties surrounding the utilization of seasonal forecasts. At the local level, farmers may encounter difficulties in interpreting and understanding the information, primarily due to the extensive use of technical terminology (Toxopeüs, 2019). Additionally, while the Umlindi effectively disseminates relevant information for drought monitoring in the country, it primarily operates reactively, relying on observed data from the previous month.

Recently, the ARC developed a web-based system named the Agricultural Drought Early Warning System (https://www.drought.agric.za/), which provides improved access to a wide range of drought-related products utilizing observed and forecasted data for any location in South Africa. This system incorporates features of both Web 1.0 (static web pages) and Web 2.0 (subscription to receive email notifications), prevalent during the second and third industrial revolutions, respectively (ADEWS, 2023). Yet, its suitability and relevance in the context of the fourth industrial revolution (4IR) are subject to examination. Since the introduction of the 4IR around 2010, scholars have gained significant interest in exploring the applications of its technologies and how they can be utilized to bring about positive change (Munawar *et al.*, 2022). Yet, there has been little effort to explore how these technologies could be utilized to enhance the effectiveness of DEWS in a constantly evolving technological and climatic landscape. Therefore, a second research question emerged:

ii. To what extent can the implementation of a 4IR-based DEWS contribute to the advancement of drought early warning capabilities for agriculture?

1.3.2. Objectives

The main aim of this study was to develop a conceptual framework integrating the technologies of the 4IR into DEWS to provide practical solutions for the effective management of agricultural drought disasters.

The specific objectives were:

1) Assess the effectiveness of disaster risk reduction policies in South Africa to facilitate the adoption of an innovative DEWS within the agricultural sector.
2) Review the existing DEWS to determine strengths and weaknesses to identify opportunities for improved efficiency.
3) Investigate the integration of 4IR technologies within the framework of DEWS with a focus on identifying points of synthesis, challenges, and transformative impacts.
4) Evaluate the feasibility of integrating a 4IR-based DEWS framework into the current agricultural system of South Africa.

1.4. Thesis outline

This thesis consists of six chapters, outlined as follows:

- CHAPTER 1: INTRODUCTION provides background information on the research, an overview of the study area, and presents the problem statement and objectives.
- CHAPTER 2: ASSESSING THE EFFECTIVENESS OF AGRICULTURAL DROUGHT MANAGEMENT POLICIES IN SOUTH AFRICA presents the role of policy effectiveness in enhancing agricultural disaster-drought management, as a foundation for a 4IR-based ADEWS in South Africa.
- CHAPTER 3: REVIEW ON AGRICULTURAL DROUGHT EARLY WARNING SYSTEMS FOR DISASTER RISK REDUCTION explores drought early warning

systems worldwide to learn from successful practices and identify opportunities for innovative systems.

- CHAPTER 4: CONCEPTUALIZING TECHNOLOGIES OF THE FOURTH INDUSTRIAL REVOLUTION INTO DROUGHT EARLY WARNING SYSTEMS presents the conceptual framework for developing 4IR-based drought early warning systems for various applications.
- CHAPTER 5: APPLICATION OF THE FOURTH INDUSTRIAL REVOLUTION-BASED DROUGHT EARLY WARNING SYSTEM FRAMEWORK IN SOUTH AFRICA focuses on demonstrating the feasibility of integrating the developed framework into the existing system in South Africa.
- CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS provide the synthesis of the research, recommendations, contribution to knowledge, and the way forward.
- APPENDICES including a list of publications, conferences, and materials for the study are provided at the end.

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CHAPTER 2. ASSESSING THE EFFECTIVENESS OF AGRICULTURAL DROUGHT MANAGEMENT POLICIES IN SOUTH AFRICA

This chapter has been submitted for publication and is currently under review in: Progress in Disaster Science (see Appendix 1: Publications)

Abstract

Using a qualitative research approach at both national and provincial levels, this chapter delved into the effectiveness of agricultural drought management policies in South Africa. Key informants provided insights into various policies and their implementation to mitigate risks in the country. The survey highlighted that only two out of seven provinces had their own drought plans, with others relying on existing disaster frameworks. At the national level, policy implementation primarily focused on funding projects for risk reduction and compliance monitoring, while provincial efforts emphasized farmer projects, awareness campaigns, risk assessments, and resource allocation. However, the study found that these measures were not always effective, with 68% of participants lacking confidence in their efficacy. The study further identified certain limitations hindering the effectiveness of policy, including imbalances in resource allocation, procurement delays, and limited capacity in human resources. Although a significant majority of participants (62%) utilized online platforms to access policy documents, a notable contrast emerged as 59% reported manually documenting field assessment reports, filed in hardcopy format. Thus, to ensure the optimal utilization of developed policies, the study recommended a comprehensive strategy outlining the development of local plans, integration of modern innovations, and investment in formal evaluation mechanisms. This strategy will enhance the efficiency of policy for improving resilience in the agricultural sector during drought disasters. In a broader context, the analysis can be valuable in identifying gaps and suggesting appropriate measures for other regions experiencing drought risk.

2.1. Introduction

The complex relationship between the direct causes of drought 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). The United Nations Office for Disaster Risk Reduction (2009), denotes that a drought disaster may result from inadequate disaster management, rather than solely from a water deficit. By definition of the Disaster Management Act, 2002, of South Africa, a disaster is a progressive or abrupt, widespread or localized extreme event, which causes pronounced damage to the well-being of the environment, humans, and the economy (Republic of South Africa, 2003). In practice, effective disaster management can be carried out by utilizing the continuous cycle (Figure 2-1), which involves four steps, viz. response, recovery, mitigation, and preparedness (United Nations, 2016). These steps may occur before, during, and after a disaster, to prevent it (although not entirely preventable), reduce its impacts, or recover from potential damages.

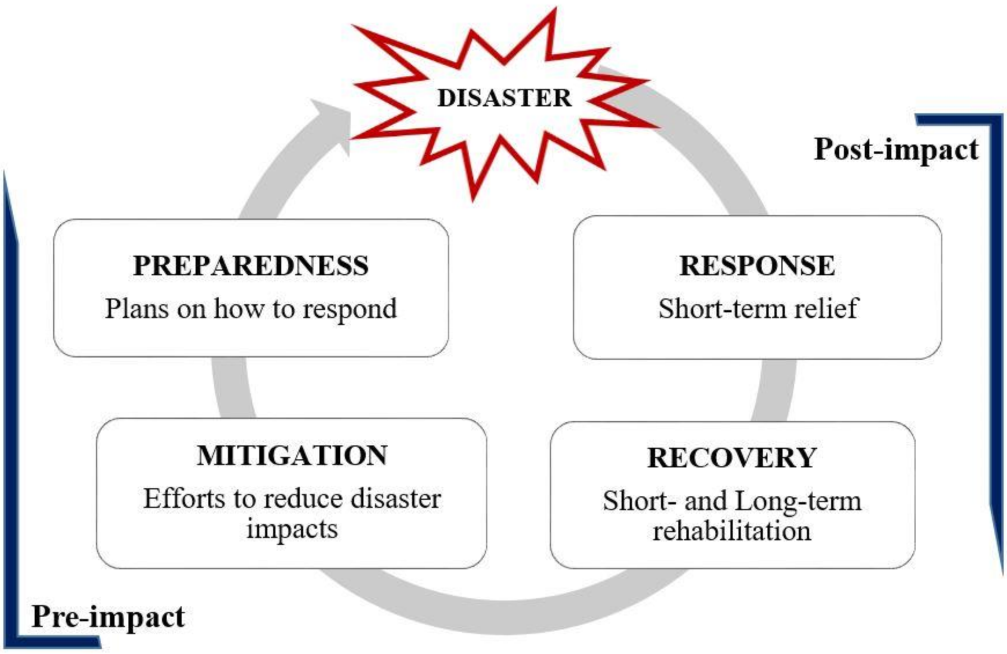

Figure 2-1: The disaster-management continuum model (United Nations, 2016).

Generally, the disaster management steps do not occur separately, and at times, they overlap due to the intensity of the disaster (Khan *et al.*, 2008). Concerning drought on agriculture, 'response' refers to immediate actions taken following the direct impacts, e.g. 1) provision of livestock feed; 2) introduction of low-interest loans and grants; 3) provision of fuel subsidies;

4) provision of human food subsidies; 5) provision and transportation of water to affected sites (Haigh *et al.*, 2019). 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). This period determines the potential impacts of the next drought occurrence and creates a state where measures may be applied to reduce the probable impact of a similar event from occurring (Republic of South Africa, 2003). Therefore, this phase may be perceived as a 'window of opportunity', as it allows stakeholders to shift focus from response to recovery of a more resilient society (Moatty and Vinet, 2016; Haile *et al.*, 2020).

For agricultural purposes, successful recovery would imply sufficient rainfall to restore ample soil water and ultimately improve crop and pasture yields (Ruehr *et al.*, 2019). The term 'mitigation' involves taking efforts aimed at minimizing the impact of drought, whether caused by humans or other factors, with the ultimate goal of lowering the risk, exposure, and vulnerability of affected communities (Republic of South Africa, 2003). While, disaster 'preparedness' refers to actions taken before a disaster to anticipate, respond to, and recuperate from the probable impacts (United Nations, 2016). This step deals with all resources and efforts that are undertaken by institutions to ensure that communities are equipped to deal with the impacts of drought (Bazza, 2014).

The three main purposes of 'preparedness' include (Bazza, 2014; Bureau and Policy, 2019): 1) to predict drought occurrences in advance; 2) to ensure effective drought response, and; 3) to enhance coping mechanisms. Slow or complicated decision-making in policy implementation can lead to delays in drought recovery and rehabilitation, making it difficult to manage drought effectively. Hence, utilizing Drought Early Warning Systems (DEWS) can serve as a transitional link between pre- and post-disaster phases, providing decision-makers with the necessary time to prepare for and manage the potential impacts of the next drought (Pozzi *et al.*, 2013). Accordingly, this chapter aimed to assess the implementation of disaster policies at the managerial level for reducing agricultural drought risk, as an enabler of a conducive environment essential for implementing innovative DEWS.

2.2. Methodology

2.2.1. Materials

The research adopted a qualitative approach, where data was collected from both primary sources (i.e., interviews) and secondary sources through the assessment of formal drought documentation. Given its empirical nature, this approach emphasized collecting data from participants in their natural environments, allowing for the identification of key areas that required attention, as learned in previous research (Chen *et al.*, 2014; Fontaine *et al.*, 2014; Vincent *et al.*, 2017). The sampling method employed was expert sampling, a purposive non-probability technique, which allows for the selection of participants based on their specific expertise in the relevant field. This method was chosen because it ensures that the sample consists of individuals who are highly knowledgeable about the research topic and the area being studied (Helfenbein, 2019). Hence, not all individuals in a population had a chance of being selected for the sample.

To ensure comprehensive representation, the study aimed to gather information from participants who met two specific criteria. Firstly, they had to demonstrate established knowledge of drought disasters and/or agrometeorology based on their work positions. Secondly, they were required to be actively engaged in drought disaster activities at a high level of governance and management. A preliminary sample size was established, considering the need for detailed information and the specific expertise required. However, some potential participants were unable to participate due to scheduling conflicts, while others declined for reasons such as time constraints or other commitments. Therefore, adjustments were made to the participant list as interviews progressed to ensure that robust representation of expertise was maintained. Ultimately, responses were obtained from participants at the National level (NL) and Provincial level (PL), excluding two provinces.

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, one from the Department of Water and Sanitation, and three from the National Disaster Management Centre, while nine officials represented the Provincial Departments of Agriculture and five represented the Provincial Disaster Management Centres. The demographic characteristics of participants are presented in Table 2-1.

Table 2-1: Demographic characteristics of key informants

Gender	**Frequency (%)**
Male	10 (48)
Female	11 (52)
Level of occupation	
Senior-level	13 (62)
Mid-level	8 (38)
Level of governance	
National	7 (33)
Provincial	14 (67)
Work experience	
≤5 years	3 (14)
6 - 10 years	7 (33)
11 -15 years	9 (43)
>15 years	2 (10)

The survey was conducted from June 2021 to April 2022, based on a semi-structured questionnaire that included questions on (i) planning for drought-related disasters, (ii) reducing the risk of disasters, and (iii) managing drought in general (Table 2-2). These questions aimed to examine the content of policies and measures that have been undertaken and/or are currently being implemented at national and provincial levels.

Table 2-2: 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, 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 the drought-related policies dynamic/static? If dynamic, how often are they revised? • Are post-drought assessments included in the plan/s? If yes, what is the procedure?

2.2.2. Analysis

A thematic analysis was performed on a software called ATLAS.ti Version 22 (https://atlasti.com/product/whats-new-in-atlas-ti-22/). The steps on how the data were analyzed are discussed below:

i. **Data preparation:**
   - Imported audio recordings, transcriptions, and additional notes into ATLAS.ti.

ii. **Initial coding:**
   - Performed initial open coding to identify patterns.

iii. **Thematic development:**
   - Organized codes into categories to create a structured coding system.
   - Identified overarching themes.
   - Refined and defined themes.

iv. **Analysis and interpretation:**
   - Created memos to record thoughts, interpretations, and potential connections between codes and themes.

Policy effectiveness was measured based on indicators that were adapted from a previous study by Pradhan *et al*. (2017). These indicators are presented in Figure 2-2 and highlight important aspects of policy, including existing documents, implementation, intervention outcomes, and policy improvement based on feedback. To better understand the guiding principles and practices, secondary sources were analyzed. 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. Moreover, by synthesizing findings from a diverse range of sources, a comprehensive understanding of the factors contributing to the establishment of conducive environments for innovative drought early warning systems was achieved. This systematic approach served as a foundation for the development of effective drought early warning systems, fostering resilience and preparedness in the face of drought challenges in agriculture.

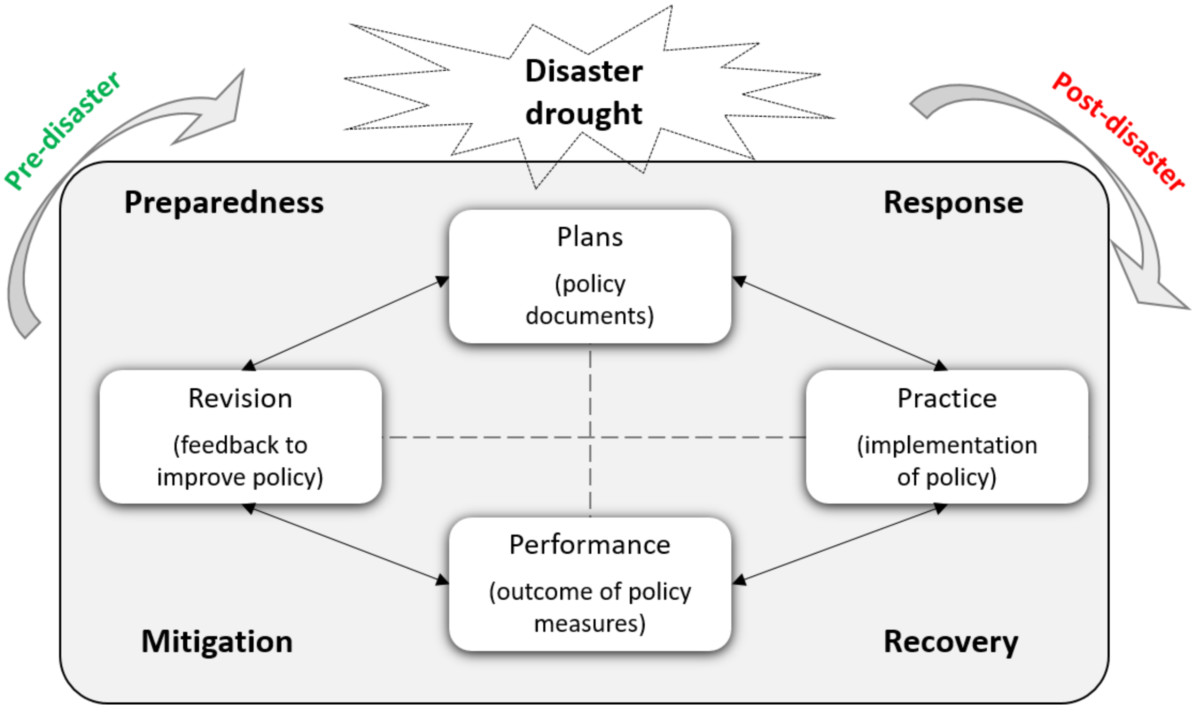

Figure 2-2: Indicators for assessing policy effectiveness of agricultural drought-related policies at national and provincial levels. Adapted and modified from Pradhan *et al*. (2017).

2.3. Results

2.3.1. Access to policy documents

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. The policies have shown positive progress over time. Before 1990, national drought risk management mainly focused on commercial farmers and the inclusion of various stakeholder groups. However, the establishment of the National Consultative Drought Forum in 1992 reflected a more inclusive approach to policy formulation (Wilhite, 2000). To date, participants in this study recognized the Disaster Management Act (Act No. 57 of 2002) as amended (Disaster Management Amendment Act No.16 of 2015) for all matters concerning disasters (Republic of South Africa, 2003, 2015).

Serving as a subordinate of this Act, the National Disaster Management Framework of 2005, as amended, guides the procedures and implementation of disaster management by all levels of government, including related stakeholders (Republic of South Africa, 2005). In the context of managing drought within the agricultural sector, the Drought Management Plan, Sectoral Disaster Risk Management Plan, and draft Sectoral Drought Management Plan were identified as the primary legislative documents (DAFF, 2012; DALRRD, 2020c). Moreover, provincial government organs are tasked with developing and implementing disaster management policy frameworks and plans as part of their core functions (South African Government, 1996; Republic of South Africa, 2003, 2005, 2015). Yet, according to the survey, two of the seven participating provinces indicated the existence of their drought plans, with the remainder relying on provincial disaster management frameworks and seasonal contingency plans.

The accessibility of policy documents guiding the management of agricultural drought disasters is key to ensuring the utilization of government structures and resources put in place. The accessibility, and the understanding of the content through conducting regular training workshops is fundamental in the management of agricultural drought disasters. Survey participants were questioned on the accessibility of the various policy documents. As depicted in Figure 2-3, the impact of the digital era is evident, with 19% of participants relying solely on online platforms, while the majority (43%) indicated that policies are accessible both online and in traditional hard and soft copy formats. Although not fully utilized, this implies a somewhat shift towards modern digital methods. 24% of participants indicated a method of accessing policies both in hard and soft copy formats. Conversely, 4% exclusively accessed policies in a soft format, while 10% preferred hard copy formats, indicating a sustained reliance on conventional documentation methods.

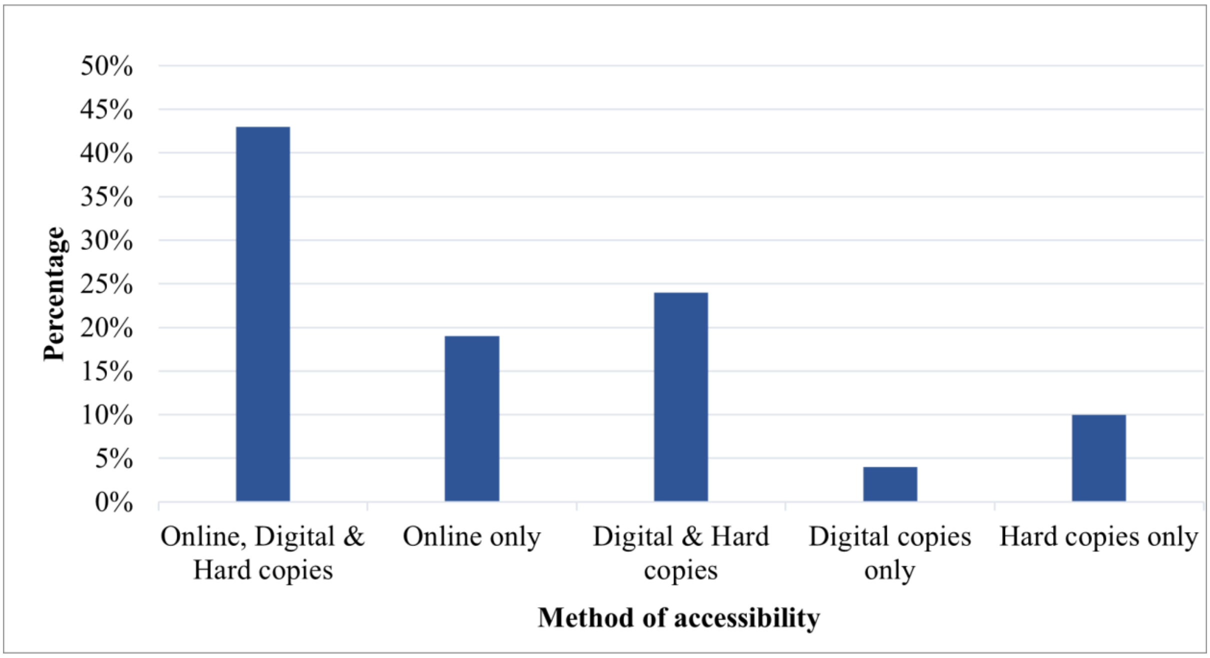

Figure 2-3: Accessibility of drought-related policy for agriculture by key informants. (n = 21).

2.3.2. Disaster risk reduction measures to manage drought in agriculture

Survey participants were questioned on their initiatives across mitigation, preparedness, response, and recovery phases, in their respective jurisdictions. Officials drew on recent and ongoing interventions, especially following the declaration of drought as a disaster (e.g., 2015, 2019). Study findings revealed that at the national level (Table 2-3), pre-disaster interventions related to mitigation were marked by strategic coordination, planning, and provision of resources to the affected provinces. The presence and regular meetings of disaster-related technical task teams provided a cohesive approach when managing drought risks, while the financial support enabled the implementation of projects for reducing future drought risks. Prevailing themes for preparedness measures included planning, infrastructure maintenance, utilizing seasonal forecasts, and drought monitoring indices for early warning and building capacity.

According to the survey participants, it is ultimately impossible to prevent devastating drought impacts entirely, despite efforts to enhance vulnerability awareness, prior knowledge, and understanding of drought patterns. Thus, planning is essential as it will ensure proper response in the event of a drought disaster. Participants at the national level mentioned that they provide funding for provinces to initiate relief support such as the provision of feed supplements for livestock and installation of tanks in affected communities (Table 2-3). For a successful recovery, it was further noted that officials at the national departments monitor the various projects to identify progress according to the respective business plans.

Table 2-3: National disaster risk reduction efforts as reported by key informants in a survey between 2021 and 2022 in South Africa.

Element	Theme	Examples of participants' responses
Mitigation	• Coordination	• Convene the disaster management technical task team every quarter to report on the progress of managing water-related risks.
	• Information management	• Development and maintenance of a drought dashboard.
	• Historical reflection	• Conduct assessments to obtain prior risk knowledge and vulnerability. • Reflect on previous disaster droughts, analyze what went wrong, and provide the necessary information to the various officials in provinces.
	• Resource provision	• Facilitation of funding to support farmers with boreholes and dam scooping interventions through national and provincial departments.
Preparedness	• Planning	• Development and implementation of a Disaster Management Plan. • Update contingency plans for disaster risks (e.g., floods, drought, water pollution, and critical dams).
	• Infrastructure maintenance	• Ensure hydrological instrumentation is well-equipped and operational.
	• Early warning	• Utilize seasonal forecasts and drought monitoring indices.
	• Capacity building	• Conduct seasonal preparedness workshops. • Organize multi-stakeholder meetings with committees at the provincial level.
Response	• Emergency response	• Initiate relief programs. • Gazette water restrictions.
	• Funds allocation	• Facilitate funding to assist farmers with livestock feed. • Re-prioritize funds for water tankers, drilling of boreholes, augmentation projects, raising of dam walls, and installing tanks in water-scarce communities.
Recovery	• Financial support	• Provide funding through a long-term grant. • Facilitate funding to support farmers with the eradication of alien invasive plants and fodder bank development.
	• Monitoring and evaluation	• Monitor various projects to check progress per the business plan provided.

Provincial efforts during the pre-disaster phase (Table 2-4) were characterized by tangible implementation and capacity building. Practical interventions, including the facilitation of funding for farmers and specific projects, highlighted a commitment to promote drought disaster mitigation. In terms of preparedness, stakeholders' collaboration was a focal point, highlighting the importance of working closely with relevant partners to enhance collective readiness. The maintenance of a detailed farmer database per region emerged as a strategic measure, to ensure who to target in the event of a drought disaster. In addition, one official mentioned the installation of weather stations contributed to improving monitoring and early warning capabilities in their province.

Table 2-4: Interventions to reduce drought disaster risk at the provincial level in South Africa as given by key informants during a survey in 2021 and 2022.

Element	Theme	Examples of participants' responses
Mitigation	• Farmer projects	• Provide fodder support to farmers. • Seed project. • Planting pasture to supply farmers during the winter season. • Projects on invasive alien clearing.
	• Infrastructure development	• Fencing. • Drilling of boreholes. • Livestock watering. • Desilting of dams.
	• Environmental conservation	• Projects on invasive alien clearing. • River protection structures.
	• Community engagement	• Convey the necessary information through awareness campaigns.
Preparedness	• Stakeholder collaboration	• Work closely with relevant stakeholders. • Maintenance of a database of all farmers per region.
	• Infrastructure	• Installation of weather stations.
	• Early warning	• Conduct revolving awareness campaigns to prepare farmers. • Convey information through local radio stations. • Send early warning information through bulk short message service directly to farmers' phones.
Response	• Resource allocation	• Provide relief to farmers as soon as possible. • Provide feed, pellets, salts, phosphorus, etc. • Prioritize the budget to assist farmers in procuring livestock feed (bales, pallets) and water tanks.
	• Risk assessments	• Conduct monitoring and evaluation of the disaster.
	• Awareness	• Conduct awareness campaigns.
Recovery	• Communication	• Ongoing communication with farmers and relevant stakeholders.

	• Infrastructure maintenance	• Improve infrastructure by maintaining boreholes, dam scooping, and reconstructing dam walls that collapsed. • Provide fencing material for farmers.
	• Land rehabilitation	• Remove invasive alien plants. • Planting of indigenous vegetation. • Seed project to provide farmers with seeds in areas that experienced drought.

Furthermore, early warning initiatives included creating awareness campaigns to prepare farmers and utilizing local radio stations in some areas. In one province, a method of sending bulk short message service directly to farmers' phones was utilized for the timely dissemination of early warning information. However, it was mentioned that the information provided was not tailored to the specific characteristics and requirements of farmers. Instead, it was generalized, assuming that most farmers have both livestock and crops, thus failing to account for variations in agricultural practices and priorities among different farming households. During the response phase, the results showed that during droughts, resource allocation, risk assessments, and awareness campaigns were given priority. The allocation of funds aimed at supporting farmers with essential resources such as livestock feed, bales, pallets, and water tanks. However, there was a concern regarding the imbalanced allocation of resources during this phase as one official mentioned:

> *"For example, you may find that the allocated funds enable us to provide only five round bales per farmer, distributed equally. However, this distribution may not be reasonable, as it may not meet the needs of a farmer with 100 cattle, who may require more"* (PL4).

Furthermore, as depicted in Table 2-4, provincial drought recovery measures showed that communication with farmers and stakeholders remained ongoing for responsive support. Infrastructure maintenance involved including boreholes and reconstructing dam walls, providing fencing material, and undertaking land rehabilitation. These interventions are often aligned with mitigation efforts, and one official mentioned that the merging of the two is particularly driven by the shortage of human resources within the institution, compelling the consolidation of efforts to optimize resource utilization.

The study further revealed how participants perceive the prioritization of individual disaster risk reduction components based on governance level (Figure 2-4). Overall, the scores indicate that the response component was prioritized higher than the other components, reflecting an average to strong level of priority. National participants rated all components higher than their provincial counterparts. This implies that individuals in national governance roles are more likely to prioritize measures, possibly due to the broader implications of their decisions and responsibilities at the national level. However, the consistently lower ratings for preparedness, mitigation and recovery at provincial level indicate a potential gap in awareness regarding their proactive role in disaster risk reduction.

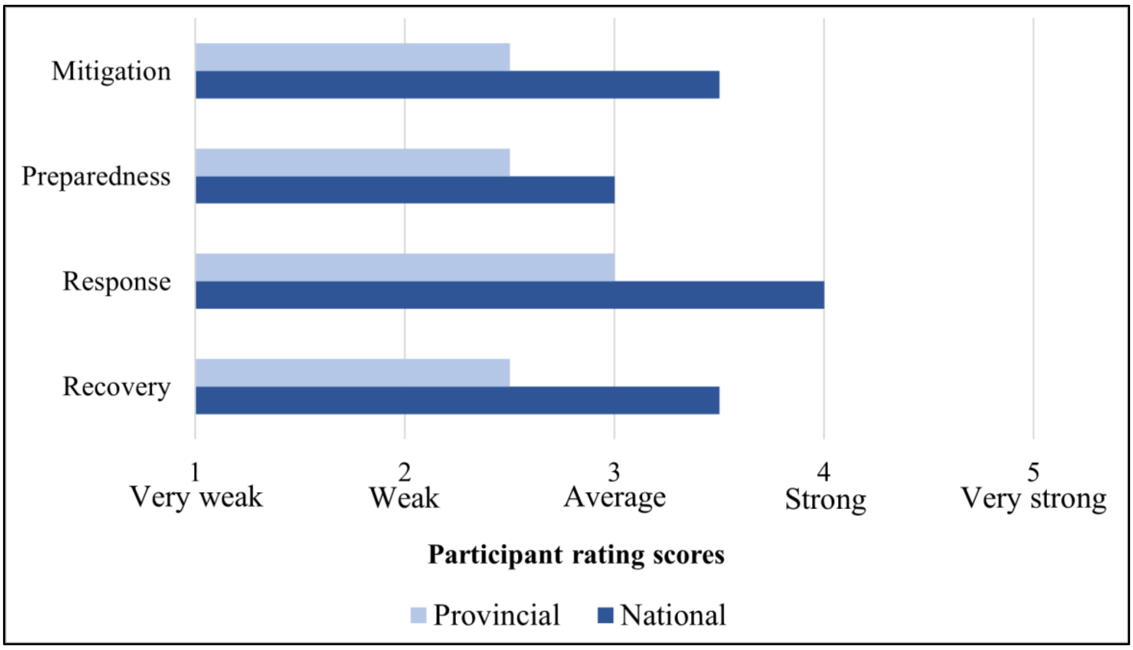

Figure 2-4: Rating scores of components in disaster risk management by key informants during a survey in 2021 and 2022.

The median scores for each component were compared across work experience categories to identify patterns and differences in prioritization among the various participants (Table 2-5). Results revealed that as work experience increased, particularly among those with over 15 years in the field, participants tended to rate components higher than participants with lesser work experience. This could be attributed to the fact that they have a deeper understanding of disaster risk reduction measures gained from practical exposure. Meanwhile, for those with less than five years of experience, the ratings were relatively low, averaging around 2.5 to 3.0, suggesting probable barriers restricting their understanding and engagement in drought disaster management.

Table 2-5: Participant rating scores of disaster risk reduction components per work experience.

Experience level	Mitigation	Preparedness	Response	Recovery
< 5 years	2.5	2.5	3.0	2.5
6-10 years	3.0	3.0	3.5	3.0
11-15 years	3.5	3.0	4.0	3.5
> 15 years	4.0	3.5	4.0	4.0

2.3.3. Performance of the various drought risk reduction interventions

The participants were asked about the effectiveness of their strategies and the evaluation process employed. The responses to this question varied a lot from one participant to another. Some participants mentioned that evaluation was conducted informally through continuous assessments with the farmers. However, other officials highlighted the importance of monitoring and evaluation as well as the involvement of external stakeholders in such an exercise. Figure 2-5 illustrates that 32% of the participants believed the measures were effective, although some relied on informal assessments and others mentioned the importance of involving external entities for a more comprehensive evaluation.

The highest percentage (47%) of participants responded that the interventions were only effective to a certain extent as in most cases the drought conditions were too adverse and thus it was difficult to measure the effectiveness of the measures. Approximately 21% of participants expressed uncertainty about the effectiveness of the measures. While some 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. A common limiting factor was increased dependency on the government, whereby farmers expected to be assisted with maintenance even after the respective drought relief projects had been concluded, thus negatively affecting the effectiveness of the interventions. Moreover, factors such as funding and procurement processes have been identified as obstacles to achieving efficiency as they often result in inadequate support and late response. Provincial-level officials were most likely to mention this in their responses, with some alluding that:

"It is unfortunate that our department lacks equitable funding, meaning we do not receive provincial funding directly for disaster response, instead, we rely on allocations from the national office. Even if we were to receive this funding and an allocation is made for drought response, but no drought occurs in that given year, we will face difficulties in accounting for those funds" (PL4).

"We have initiated discussions with the provincial treasury to seek assistance in establishing an emergency procurement process" (PL10).

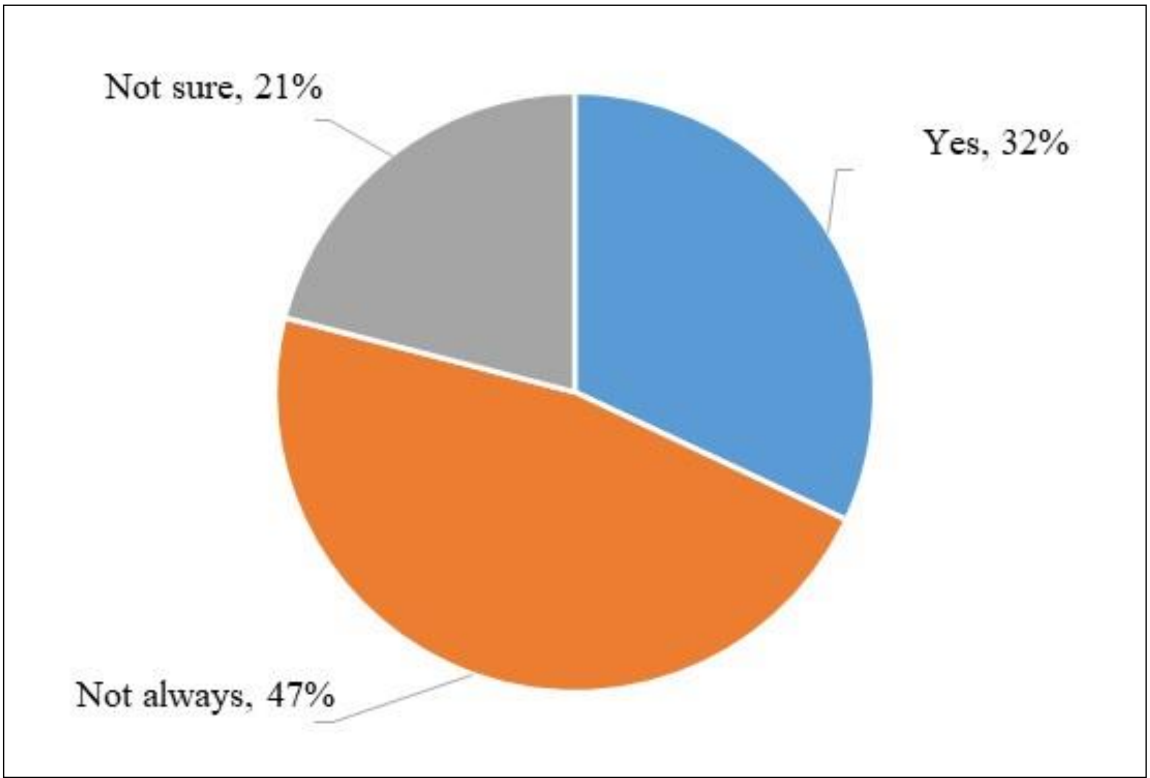

Figure 2-5: Perceived effectiveness of various disaster risk reduction interventions based on a national and provincial survey in South Africa.

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. In one province, officials monitored commodity price fluctuations to gain insights into vulnerability, especially when locally produced goods needed to be substituted by imports. While officials in some of the provinces collaborated with organized agriculture and other departmental programs to gain a better understanding of the societal position of farming communities.

2.3.4. Revision of agricultural drought-related policies

To gain an understanding of the revision of policy documents, participants were asked about the flexibility of their current policy documents. Generally, officials emphasized that all government policies were dynamic and subject to necessary amendments. Among those responsible for agricultural disaster management at the provincial level, participants expressed the ideal need for frequent plan revisions but acknowledged that this was not always the reality. On the other hand, informants at the 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"* (NL1).

It was noted that officials recognized the need to revise internal frameworks and policies 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 mentioning 2- or 3-year intervals. Only one respondent provided a more detailed explanation, stating that:

> *"Revisions of disaster management plans need to adhere to the standards outlined in the Disaster Management Act and the Disaster Management Framework. Accordingly, Level 1 plans need to be revised 3 years after approval and Level 2 plans 2 years after approval, while Level 3 plans can be revised annually"* (NL2).

There was a 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 its drought-related 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.

The survey further aimed to determine if post-drought assessments were included in participants' policy documents and whether they assisted in the revision process. The findings revealed that most participants (41%) included post-drought assessments, while 30% stated otherwise, and the remaining 29% were unsure. Those who confirmed the inclusion of these assessments highlighted their integration into continuous risk assessments. Currently, all this information is collected and stored in different government offices as hardcopy reports. Moreover, post-disaster assessments in one province are conducted in collaboration with the Provincial Disaster Management Centre as part of our Disaster Risk Reduction program.

2.4. Discussion

2.4.1. Synthesis of agricultural drought policy implementation in South Africa

Generally, drought risk reduction measures are crucial components of drought policies in many countries to alleviate the effects of drought (FAO, 2019). Thus, Figure 2-6, displays an illustration of the interconnected components and themes within agricultural drought management in the country. Herein, the national mitigation efforts serve as the foundation for preparedness at the national level, with strategies then translated into specific provincial mitigation activities. This is in alignment with policy, recognizing pre-disaster measures as a crucial phase in achieving the goal of disaster risk reduction (Republic of South Africa, 2005).

Once a drought disaster is declared, the response phase is activated at both levels, addressing immediate requirements, and promoting a coordinated approach. The policy specifies that the organs of the 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, 2020c). Affected farmers are required to submit requests for assistance and this will initiate processes such as assessment of conditions for relief measures. The priority of government structures is to assist the poorly resourced farmers due to their vulnerability status during disasters. However, when seeking financial assistance from national or provincial departments, consideration is given to whether prevention and mitigation measures were implemented, and if not, the reasons for their absence (Republic of South Africa, 2005).

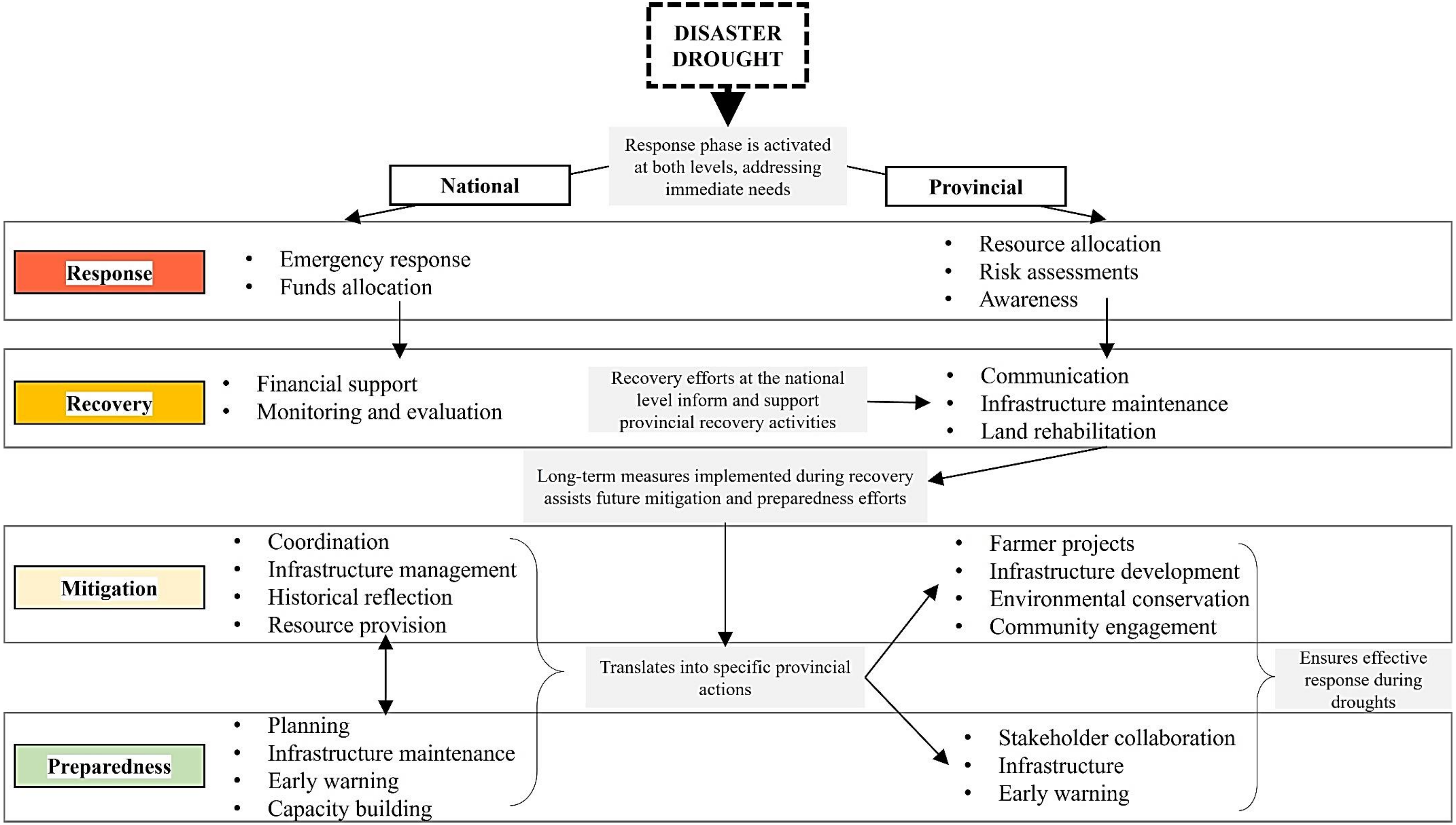

Figure 2-6: Schematic illustration of how the agricultural sector manages disaster drought, as reported by key informants in South Africa.

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 provincial officials are supposed to carry out the following post-disaster activities (Figure 2-7): 1) conduct assessments to determine the damage caused and assistance required; 2) offer recovery services and monitor the implementation process; 3) compile post-disaster reports; and 4) provide restoration and rehabilitation to those affected (Republic of South Africa, 2005). Therefore, this phase determines the potential impact of future disasters and presents an opportunity to implement measures to reduce their likelihood (Republic of South Africa, 2003).

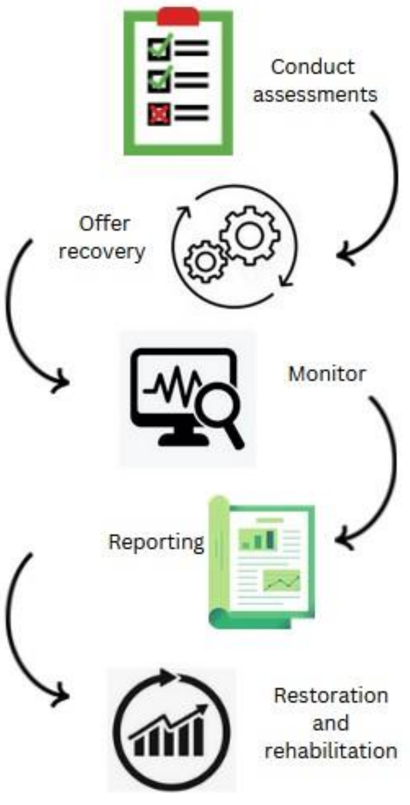

Figure 2-7: Important post-disaster activities that ensures recovery.

2.4.2. Approach for addressing challenges in policy implementation

The current survey identified several challenges in the implementation of agricultural drought-related policy. There were a notable absence of tailored drought plans at the provincial level, emphasizing the need for localized planning to ensure accountability and the selection of appropriate policy measures based on local hazards and physical characteristics. To address this, implementing a localized planning framework is essential. Another challenge was the overreliance of farmers on government support. In many cases, particularly in least-developed and developing countries, government interventions may promote a dependency syndrome (Farny, 2016). 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 establish programs focusing on building self-reliance for farming communities.

Based on the survey, officials often faced challenges of lengthy supply chain and procurement processes during drought disasters, necessitating a more modernized approach to policy implementation. Integrating technologies such as blockchain, which functions as a safe transactional database, can improve supply chain processes, ensuring speed, trust, transparency, and efficiency (Beck *et al.*, 2017). Furthermore, the lack of an established system to assess the effectiveness of policy interventions and their contribution to decreasing societal vulnerability raises concerns about the overall effectiveness of the current measures. To address this hurdle, the implementation of a formal evaluation mechanism, incorporating systematic data collection and analysis, is crucial for gaining reliable information about the impact of strategies on communities. This builds upon the findings of Gutiérrez *et al*. (2014) in Brazil, indicating that this approach implies long-term effectiveness in mitigating socio-economic impacts during future drought conditions.

The study emphasizes the importance of a proactive approach to drought management by implementing pre-disaster plans that focus on enhancing coping mechanisms. Monitoring and evaluation of current drought risk reduction measures, together with post-drought assessments, provide critical information for future planning, ensuring a more targeted and effective approach to addressing the impacts of drought on society (Fontaine *et al.*, 2014). This approach, whether implemented before, during, or after a drought disaster, strengthens community resilience and reduces vulnerability (Buchanan-Smith, 2001; Van Zyl, 2006; Do Amaral Cunha *et al.*, 2019). Therefore, these findings highlight the need for a practical plan of action (Figure 2-8), including localized planning, streamlined policy implementation, capacity-building, and the establishment of formal evaluation mechanisms to enhance the effectiveness of drought management strategies. It is further recommended that future studies extend this focus to explore more localized or specific contexts to gain comprehensive insights.

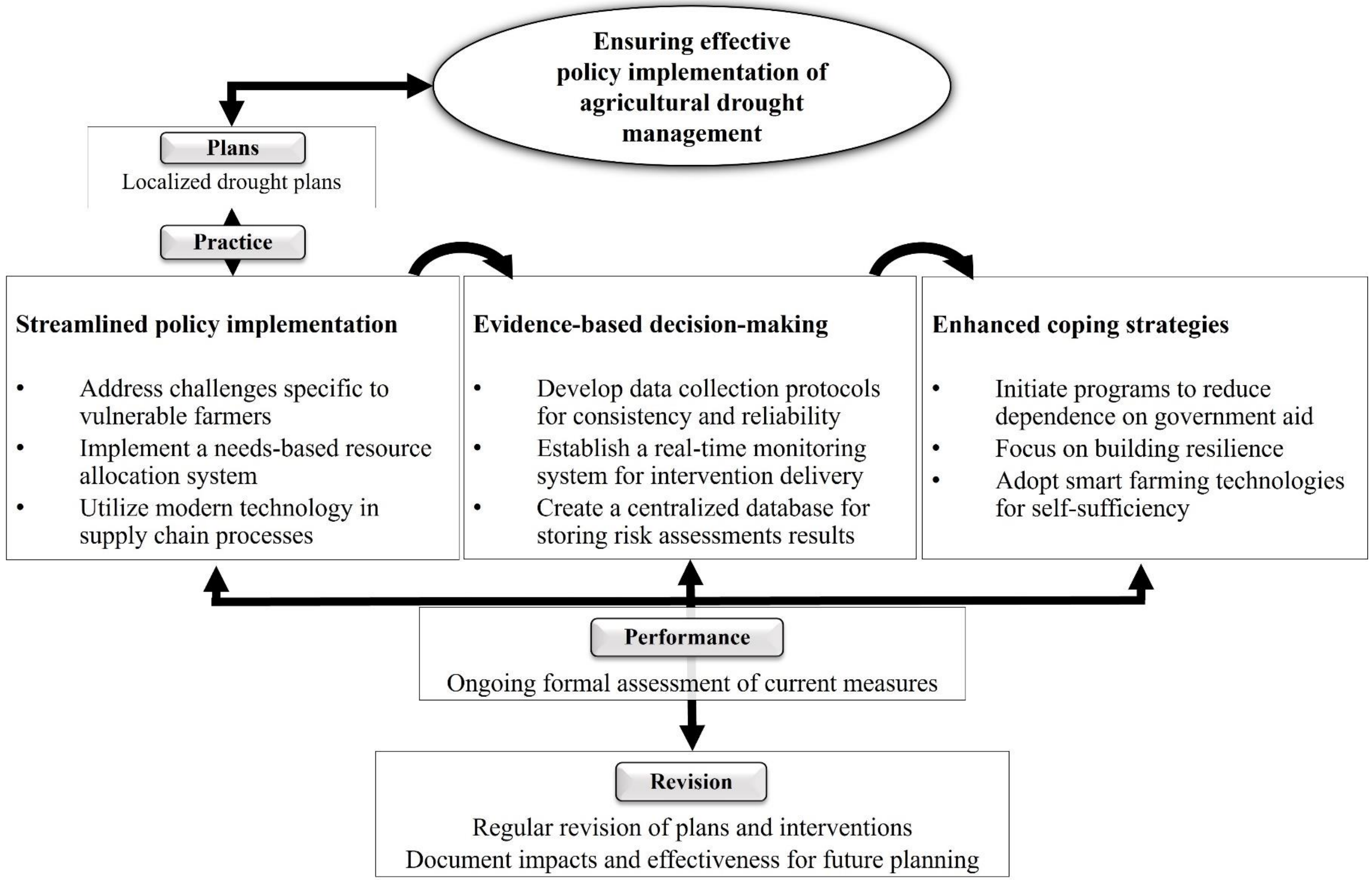

Figure 2-8: Framework to overcome challenges on current agricultural drought policy implementation in South Africa.

2.4.3. Implications for integrating innovation into disaster-drought policy

Drought early warning systems, renowned for their ability to provide crucial information mitigating potential impacts in drought-sensitive sectors, have seen a global surge in development, creating opportunities for innovation during the 4IR era (Masupha *et al.*, 2021). However, the successful adoption of these systems depends on their integration within socio-economic contexts, existing governance structures, and policies of any region (Rogers and Tsirkunov, 2011). This study focused on policy as the principal guide, containing laws, rules, and regulations crucial for decision-making (Chen *et al.*, 2014). The overall effectiveness of the policy was assessed by evaluating the various drought risk reduction measures based on current policy at the national and provincial levels.

The policy landscape in the country has shown positive progress over time by aligning with international standards, such as the Sendai Framework for disaster risk reduction, emphasizing proactive measures to reduce vulnerability in disaster-prone areas (Republic of South Africa, 2005; Aitsi-Selmi *et al.*, 2015). This implies a promising start in creating a conducive environment to adopt innovative interventions. Moreover, the continuous revision of policies, particularly at the national level, reflects adaptability and promotes an environment for exploring and implementing cutting-edge solutions for drought risk reduction. However, the uncertainty surrounding the revision of policy documents at the provincial level poses a potential challenge. Emphasizing this process becomes crucial, as authorities can review their current drought policies, and make necessary improvements (Fontaine *et al.*, 2014). This indicates that acknowledging limitations in policy implementation also presents an opportunity for innovative 4IR frameworks.

The impact of the digital era was evident in this study, as participants have incorporated the use of online platforms for accessing various policy documents, although some revealed a continued dependence on traditional documentation approaches. Yet, the survey further revealed that field assessment reports were documented manually and filed in hardcopy format, underlining the need to develop an electronic system for drought information. Therefore, a 4IR-based system would ensure accessibility and ensure that crucial information does not get lost due to factors such as an incorrect filling system leading to misplacement, or even in the event of a fire. According to Bergman and Foster (2009), keeping records of important information on the various characteristics of each drought in an accessible manner is useful for planning purposes, including deciding on the type of interventions to implement, based on good practice.

The various disaster risk reduction interventions, marked by stakeholder coordination and resource provision suggest potential areas for improvement through innovation. This includes factors such as planning and investing in resources for advanced technologies in smart data collection, real-time monitoring, and digital dissemination (Abdullah *et al.*, 2017; Zahra *et al.*, 2018). The policy implementation at the provincial level, specifically, the continuous stakeholder engagements further create opportunities for technological solutions to enhance response capabilities tailored to address regional needs. In addition, this is a contributing factor to the effectiveness of policy as it allows for the determination of how the various measures can be utilized to serve those in need, as opposed to applying the umbrella approach. Francis *et al*. (2021) explored this integration, revealing promising outcomes for rural communities. The absence of a formal mechanism for evaluating the undertaken risk reduction measures further highlights a gap in developing innovative methodologies to improve the effectiveness of interventions.

2.5. Conclusions

The main objective of this chapter was to evaluate the effectiveness of agricultural drought management policies in South Africa. Through a qualitative research approach, the study offered empirical evidence regarding the implementation of these policies at managerial levels of governance. Findings revealed positive advancements in the development of relevant policies, with the majority of participants accessing these documents through both online platforms and traditional formats. However, there was a lack of tailored provincial drought plans, necessitating the need for localized planning frameworks.

The survey further discovered some exemplary efforts in implementing disaster risk reduction measures, as well as the roles of officials at the various levels. Consequently, the success of these interventions provided a foundation for the integration of innovation into existing frameworks, ensuring more effective and adaptable drought management strategies. However, challenges were noted in the current approach, such as uncertainties in resource allocation and the absence of a formal mechanism for evaluating interventions, and the overreliance of farmers on government support. Therefore, to ensure that developed policies are utilized to their full potential, it is crucial to implement a comprehensive strategy. This involves developing local plans, optimizing policy responses, investing in capacity-building initiatives, and establishing formal evaluation mechanisms. This approach will promote good governance, and efficient policy implementation and strengthen disaster risk reduction for a more resilient agricultural sector against drought disasters. Consequently, it will create an enabling environment for the adoption of emerging innovations.

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CHAPTER 3. REVIEW ON AGRICULTURAL DROUGHT EARLY WARNING SYSTEMS FOR DISASTER RISK REDUCTION

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Abstract

In recent years, significant scientific and institutional initiatives have focused on developing agricultural drought early warning systems within disaster risk reduction programs. To conduct a scoping review, a Boolean keyword search was performed on Google and scientific databases like Google Scholar, Web of Science, and SCOPUS. This search aimed to gather information from peer-reviewed articles and grey literature such as websites, reports, and newsletters, subject to crosschecking. The findings revealed that certain African countries employ early warning systems to notify farmers about impending drought conditions. Ethiopia's experience highlighted the importance of an established coordination structure involving various task forces and working groups. Kenya emphasized the necessity of response and recovery plans to ensure effective preparedness. However, areas requiring improvement were identified, including enhancing the weather station network and data quality in Ethiopia, addressing the lack of readily available finance for recovery in Kenya, and addressing the use of unsustainable message channels at the local level in Uganda. Furthermore, established web-based agricultural drought early warning systems revealed characteristics, such as the ability to forecast, preference selection functionality, and information on drought impacts on agriculture. Less common but vital characteristics included integrating field observations, interactive maps, and contingency plans. Factors such as the risk of providing false information due to lack of calibration, slow adoption rates, and insufficient human and financial commitment were recognized as potential obstacles, which should be perceived as opportunities for improvement. Consequently, the study recommended utilizing innovative technologies to improve the functionality and effectiveness of warning systems.

3.1. Introduction

The rising frequency and severity of drought events globally present profound challenges to agricultural sustainability, socio-economic stability, and ecosystem protection (Crausbay *et al.*, 2017). In efforts to manage drought, through a series of collaborative actions in various drought-prone regions, drought early warning systems (DEWS) have been integrated into disaster risk reduction, climate change adaptation, and humanitarian initiatives (Cowan *et al.*, 2014). Hence, the implementation of these systems continues to serve as the foundation for effective drought policy in many nations (Svoboda *et al.*, 2002; FEWS NET, 2020; NCC, 2020; NIWA, 2020). This is due to their ability to 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).

The DEWS are commonly employed to effectively address challenges posed by the various forms of drought. They are defined as integrated and interactive systems designed to facilitate drought management by collecting, processing, analyzing, and disseminating information to decision-makers, thereby supporting timely and appropriate responses (United Nations, 2016). The conceptual framework (Figure 3-1) underlying DEWS relies on four fundamental components outlined by the United Nations (2016): (1) knowledge of risk, (2) monitoring and warning, (3) dissemination, and (4) response. Therefore, efficient implementation of DEWS necessitates integrating these components and acknowledging their interdependence.

The recommended terminology relating to these components is given as follows (United Nations, 2016): (1) The knowledge of risk involves conducting risk assessments to determine appropriate responses before a drought event, (2) The monitoring and warning entails continuous observation of drought indicators and utilization of early warning thresholds to generate warnings, (3) Dissemination involves the strategic communication of information to ensure that it reaches its intended audience effectively, and (4) Response includes planning and actions taken by individuals in response to drought warnings.

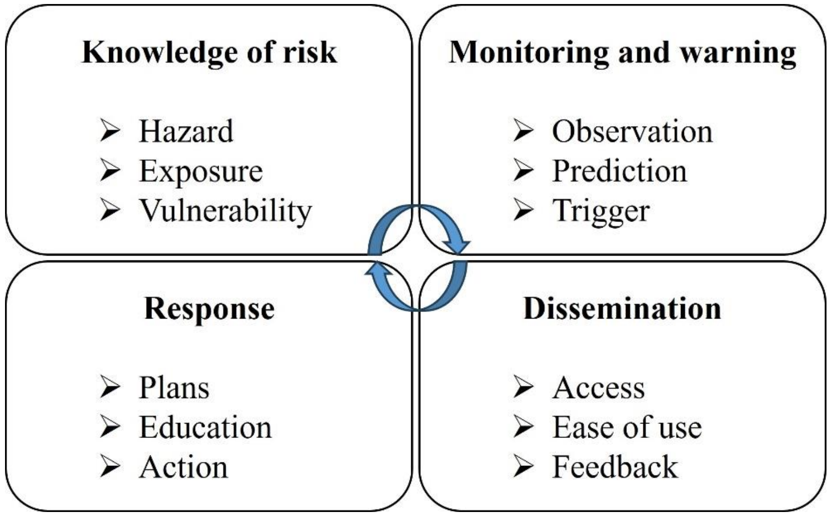

Figure 3-1: Fundamental components of a drought early warning system (United Nations, 2016).

Ideally, when utilized effectively, a DEWS can reduce humanitarian impacts and economic losses associated with emergency response (Lumbroso, 2018). Various initiatives from developed countries have implemented DEWS for agriculture and demonstrated how their systems effectively monitor droughts and issue timely warnings (Svoboda *et al.*, 2002; NCC, 2020; NIWA, 2020). Many of these systems are currently available and they provide valuable information in various regions, based on near real-time quantification of drought conditions (Zink *et al.*, 2016).

Historically, professionals conveyed drought-related data to stakeholders based on written reports (Henriksen *et al.*, 2018). However, the evolution of information and communication technology during the third industrial revolution began to shape the development of web-based DEWS, integrating dashboards and advanced technologies to enhance the efficiency and accessibility of drought monitoring and warning (Pozzi *et al.*, 2013; Hao *et al.*, 2014). This advancement has not only improved communication capabilities but has also refined drought prediction, monitoring, and decision-making processes through the integration of a diverse range of tools and technologies (Poljansek *et al.*, 2017). Thus, the objective of this chapter was to review current agricultural DEWS with a focus on operational aspects, to identify potential opportunities and challenges for enhanced practices.

3.2. Methodology

In addressing the objective, the analysis began with a review of agricultural drought early warning initiatives in Africa. Secondly, a scoping review approach was utilized to examine current web-based agricultural DEWS with an 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 keywords: agricultural drought early warning system, disaster management, disaster 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 systems' websites, published reports, and newsletters, subject to crosschecking. To narrow the scope of the study, established agricultural DEWS were selected based on the following criteria:

i. Consists of an operational web portal (Hao *et al.*, 2017);
ii. The main purpose is to provide an early warning as opposed to merely monitoring (Kafle, 2017);
iii. Provide real-time agricultural drought monitoring (Mladenova *et al.*, 2020);
iv. Comprise of agricultural drought indices (Łabędzki and Bąk, 2015);
v. Should be a product of an established and credible organization (Jacks *et al.*, 2010); and
vi. Operate at a national or 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. Furthermore, a synthesis of the results and further recommendations were provided.

3.3. Agricultural drought early warning initiatives from Africa

3.3.1. Recent web-based initiatives

In Africa, a few examples, operating on a continental scale are available. On a continental scale, recent examples include, (1) the African Drought Observatory (ADO), (2) the Drought Early Warning System for Africa (DEWFORA) project, and (3) the African Drought Monitor and Forecast System (UNESCO 2014) (Valentini *et al.*, 2015). The ADO, which was developed based on lessons from the European Drought Observatory comprises a web-based Map Viewer, in which users can retrieve historical, near-real-time, and seasonal drought information (Valentini *et al.*, 2015). This system also provides a retrieval feature and visualization of baseline maps such as the Köppen-Geiger climate classification, land cover, soil classes, water resources, and socio-economic indicators (Valentini *et al.*, 2015). The DEWFORA was established mainly to advance drought indicators and to improve drought monitoring in Africa for all water-dependant sectors (Iglesias *et al.*, 2014). Various meteorological, hydrological, and agricultural warning thresholds were determined and one building block of this project was the utilization of monthly and seasonal forecasting systems from the European Centre for Medium-Range Weather Forecasts to predict impending droughts (Pozzi *et al.*, 2013).

The African Drought Monitor and Forecast System, developed by Princeton University in collaboration with the Intergovernmental Hydrological Programme, monitors and forecasts drought at various spatio-temporal scales (Sheffield *et al.*, 2014). The aim was to combine remote sensing data with climate forecasts and agricultural models to predict and monitor agricultural drought (Zink *et al*). The system comprises a web-based tool called The African Flood and Drought Monitor that is available in various languages (UNESCO 2014). Key functions of this monitor include (1) the ability to visualize and interact with region-specific data, (2) the provision of historical, near-real-time, and forecast data for multiple drought indices, (3) a feature that allows a user to download and process data, and (4) the systems run on a 0.25° spatial resolution (Sheffield *et al*. 2014). Another notable feature of this monitor is that it provides detailed plots of the climate and hydrological conditions through a point functionality, where a user can click on the map and obtain data for their area of choice (UNESCO 2014). The system comprises five parts, viz. climatology, real-time, near-real-time, seasonal, and climate change.

3.3.2. Regional agencies responsible for drought early warning

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 (Stanke *et al.*, 2013). In general, regional centers are essential for providing critical information on predicted drought, as well as impacts on crops and livestock for proper planning, especially in regions where drought has previously led to poor harvest, food shortages, and a weakened economy (Quansah *et al.*, 2010). Thus, some regional centers have established programs and thus far made progress in providing climate forecasts as well as drought information to decision-makers (Tadesse, 2016). These centers include:

i. 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 geo-information 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/).

ii. African Centre of Meteorological Applications for Development (ACMAD) is a weather services center 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 center 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 of its member countries (ACMAD, 2019).

iii. The AGRHYMET Regional Center is a dedicated agency of the Permanent Interstate Committee for Drought Control in the Sahel. Its primary focus is on managing natural resources to enhance agricultural production and food security within its member countries of the Sahel and West Africa (Traore *et al.*, 2014). The center 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).

iv. The IGAD Climate Prediction and Applications Centre, previously known as the Drought Monitoring Centre-Nairobi has been mandated to promote the mission and objectives of the Intergovernmental Authority for Development system. The center has thus far demonstrated its capability to mainstream climate information with a 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).

v. The Regional Center for Mapping of Resources for Development was established in Kenya with support from the United Nations Economic Commission for Africa and the African Union. It is an inter-governmental organization that is currently comprised of 20 member countries in Eastern and Southern Africa (Tadesse, 2016). The primary objective of the center is to produce and disseminate geo-information and related technological products and services with the focus of promoting sustainable development for its member countries.

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-center) is an initiative of the SADC-CSC committed to improved drought risk management in the region (SADC, 2020).

3.3.3. Tunisia

In Tunisia, a drought management system has been in existence since 1987 (UN-DESA and ESCWA, 2013). However, based on lessons learned 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 (Verner *et al*). These guidelines were issued in 1999 and they 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, viz. (1) Announcement (2) Warning (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 olives dehydration, observing the status of grasslands, delayed planting as well as price increases for feed (Verner *et al.*, 2018). The relevant departments in districts and specialized committees are responsible for conveying the announcement to the Ministry of Agriculture (FAO, 2018).

The second step involves the communication of this 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 post the drought (UN-DESA and ESCWA, 2013). One of the main advantages of this system is that the approach is sustainable and it is greatly supported by the Government of Tunisia (FAO, 2018). However, weaknesses do exist, and they 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).

3.3.4. 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). This early warning directorate works in conjunction with the government's Emergency Nutrition Coordination Unit, which is mandated to maintain standards of all nutrition studies in the country (Tadesse, 2016). A well-defined coordination structure exists, and it comprises 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 using two languages, viz. Amharic and English. Early reaction is produced by the 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 in case of a major drought (IFRC, 2014). However, this software is currently used with the country's food security. Examples of available indicators include:

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

Regarding the 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, such that it is currently not implemented at regional, district, and woreda (local) levels. One of the main challenges encountered includes 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 the station network, data quality, forecasting skills, and reliable long-term data, are required (Simon, 2019).

3.3.5. 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 regions (ACTED, 2008). This has necessitated the need for the Government of Uganda 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 was established by the Government, with support from the United Nations Development Programme, 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 organisations and agencies implementing early warning with varying focus points in Uganda, the Ministry of Agriculture Animal Industries Fisheries (MAAIF) and, the 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, whilst the ACTED leads the Drought Early Warning System (DEWS) together with district government officials.

The early warning system managed by the MAAIF is based within the early warning unit at the ministry headquarters in Entebbe (Atyang, 2014). This unit assembles data collected by other units within the ministry. The data is then converted into useful information through an advisory, comprising of the following indicators: crop yield, livestock production, the status of pests and disease damage, and food and livestock prices (Braimoh *et al.*, 2018). However, the advisories are disseminated twice a year using press releases, media channels, and local government officials. Another limiting factor is that the early warning system does not have any feedback mechanism in place for further improvements (Atyang, 2014).

The process of DEWS entails collecting and analyzing data and information needed for drought prediction (ACTED, 2008). The system is supported by the ACTED in terms of providing data entry software, backup, field data and information verification, and overall dissemination of early warnings (ACTED, 2008). Figure 3-2 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). The data is transformed using the DEWS software and information regarding the status of drought and its accompanying impacts is then compiled.

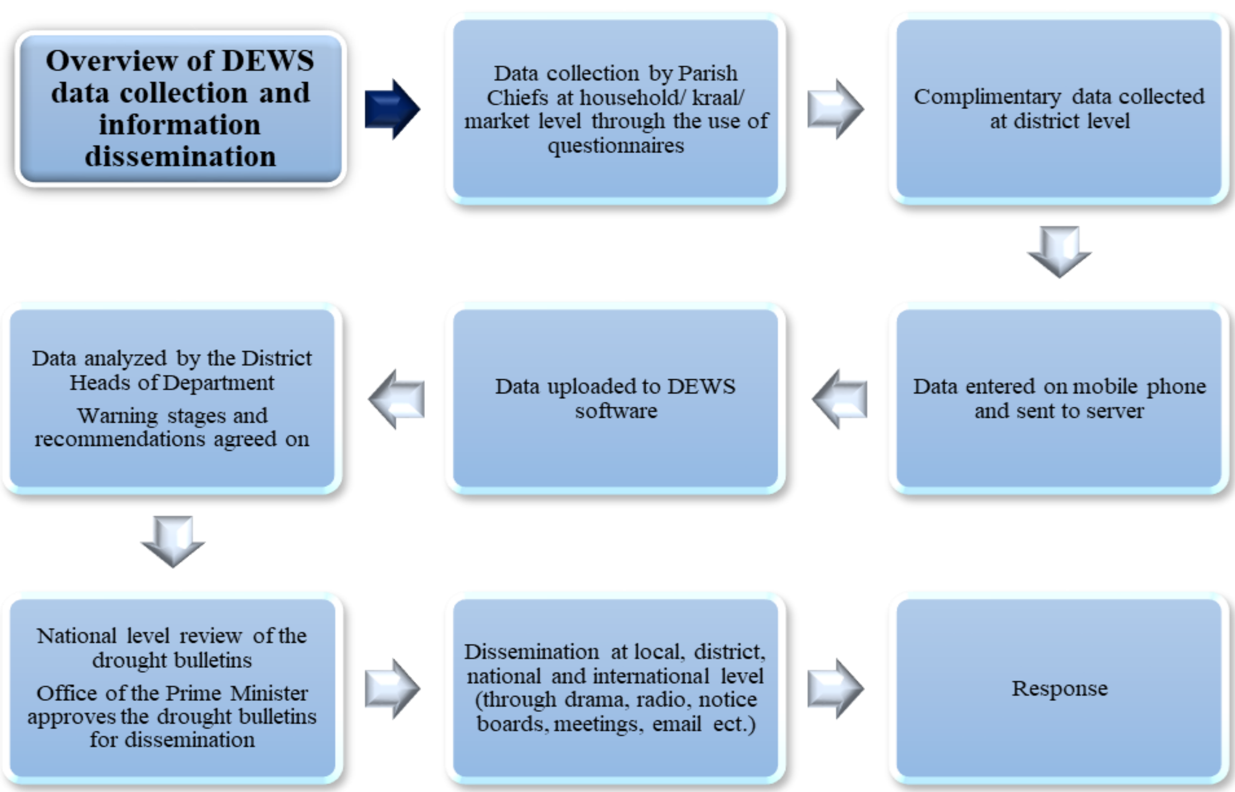

Figure 3-2: Data collection and dissemination process for DEWS in Uganda (ACTED, 2008).

The system comprises 21 indicators within four main sectors, viz. livestock, crops, water, and livelihoods for providing timely messages of upcoming droughts employing 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 emails, notice boards, and meetings. One interesting fact to note is that, at a local level, drama groups are involved in distributing information on the upcoming drought conditions by performing sketches that also provide recommendation strategies to communities (ACTED, 2008). However, this type of information channel relies on external funding and is therefore not sustainable (Atyang, 2014).

3.3.6. Ghana

The Climate Technology Centre and Network in collaboration with the Water Resources Commission, the UNEP-DHI Partnership, and the Environmental Protection Agency, 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 in both sectors, by developing relevant scientific-based technology (DHI, 2018). This system (http://www.flooddroughtmonitor.com/home?register=true&ug=CTCN) consists of a web-based portal based on the Drought Early Warning and Forecasting Portal of the Flood and Drought Management Tools project (Figure 3-3) (CTCN, 2017).

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. word, text, chart, table, or image (DHI, 2018).

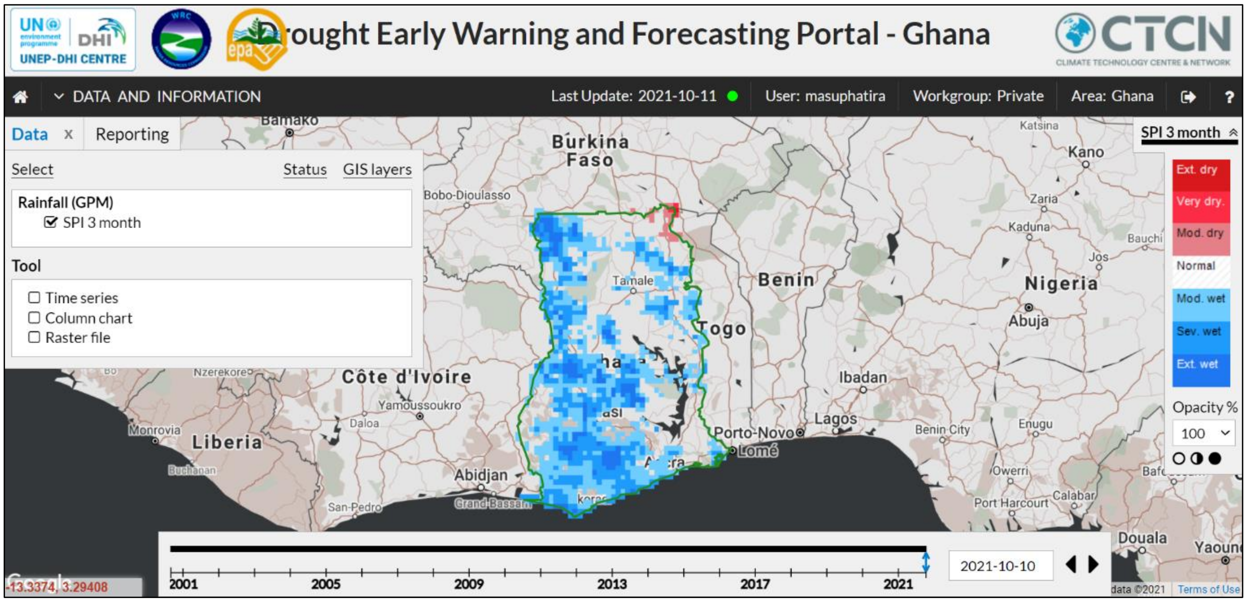

Figure 3-3: Screenshot of the Ghana drought early warning and forecasting portal interface (CTCN, 2017).

3.3.7. 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 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 of the United Nations, have partnered with NDMA to strengthen their technical capacity (Republic of Kenya, 2017). Available outputs include biophysical indicators, socio-economic indicators, access indicators, and utilization indicators.

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 (Figure 3-4). In addition to early warning improvements, the preparedness strategy includes response and recovery plans. Late response or even failure to react to 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 a lack of readily available finance and the weak link between emergency interventions and response time.

<table>
<tr><td>Normal</td><td>Alert</td><td>Alarm</td><td>Emergency</td></tr>
<tr><td>All environmental Agricultural and pastoral indicators are within the seasonal ranges</td><td>Meteorological drought indicators move outside seasonal ranges</td><td>Environmental and at least two production indicators are outside Long term seasonal ranges</td><td>All Environmental, Metrological and Production indicators are outside normal ranges.</td></tr>
<tr><td colspan="4">Recovery:
The drought phase must have reached at least Alarm stage. Recovery starts after the end of drought as signaled by the environmental indicators returning to seasonal norms; local economies starting to recover</td></tr>
</table>

Figure 3-4: A screenshot of the early warning colour coded thresholds for drought in Kenya (NDMA, 2019).

3.4. Established web-based drought early warning systems

3.4.1. National Integrated Drought Information System

The National Integrated Drought Information System (NIDIS), of the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center, was developed in consortium with various agencies (federal, regional, tribal, state, and local government), research institutions, and the private sector to develop a national drought early warning information system 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, viz. (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 as coordinating 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 and Standardized Precipitation Index (SPI), as well as reports on drought impacts from >450 observers across the United States (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, X – formerly known as Twitter, and YouTube) and to subscribed users.

3.4.2. Intersucho Portal

The Intersucho Portal (https://www.intersucho.cz/) is a web-based platform for 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 in Central Europe (Trnka *et al.*, 2014).

In general, the Intersucho Portal consists of five pillars: (a) present soil moisture conditions; (b) SoilClim model simulations; (c) vegetation conditions; (d) drought forecasts; and (e) weekly expert reports (Intersucho, 2020). The latter was adopted from the U.S. Drought Monitor 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 predictions 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 for 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; cumulated stress; impacts on agriculture; deficit of water supply in the soil; impacts on vegetation – Europe; and soil moisture index – Europe (Intersucho 2020).

3.4.3. 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). The 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 to 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 the DEWS include SPI, Water Requirement Satisfaction

Index (WRSI), Normalized Difference Vegetation Index (NDVI), and Vegetation Health Index (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, e.g. the Early Warning eXplorer Lite 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).

3.4.4. High Resolution South Asia Drought Monitor

The Indian Institute of Technology – Gandhi Nagar 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, and Standardized Runoff Index (Shah and Mishra, 2015).

Outputs based on data generated using the Global Ensemble Forecast System 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 also provided. The monitor also includes soil water and runoff simulations of the Variable Infiltration Capacity model to identify areas under severe agricultural and hydrological drought (Shah and Mishra, 2015). These simulations are then quantified against the Normalized Difference Vegetation Index anomalies and the Drought Severity Index (Aadhar and Mishra, 2017).

3.4.5. 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, viz. the SPI, Soil Moisture Deficit, Soil Moisture Deficit Anomaly, and Potential Evapotranspiration Deficit to determine a composite index titled the New Zealand Drought Index (NZDI) (NIWA, 2016). The index 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) for 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).

3.4.6. Caribbean Drought and Precipitation Monitoring Network

In the Caribbean, drought prediction and monitoring for sustainable Integrated Water Resources Management 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 and the Caribbean Regional Climate Centre of the World Meteorological Organization (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 which 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, Standardized Precipitation Evapotranspiration Index, monthly rainfall, mean temperature anomalies, and rainfall deciles (CRCC, 2020). Also included are the Drought Alert Maps of the Caribbean Climate Outlook Forum's (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).

3.4.7. China Drought Monitoring System

In China, the National Climate Center 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, which is calculated using SPI (1-month and 3-month) and potential evapotranspiration (Pulwarty and Sivakumar, 2014; Cheng *et al.*, 2018). Based on these indicators, the center then produces (1) a China drought monitoring bulletin, intended mainly for government departments, and (2) drought monitoring maps, accessible to the public (WMO, 2006). The latter are available and updated daily on the convenient website in Chinese.

3.4.8. 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) comments from agrometeorologists; (2) CWB maps; (3) drought hazard maps; and (4) tables for commodities. The comment from the agrometeorologist provides a detailed report of drought conditions 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 the Apparent Thermal Inertia updated every 16 days, starting from 2017 (ADMS, 2020).

3.5. Lessons from best practices – potential opportunities and common challenges

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

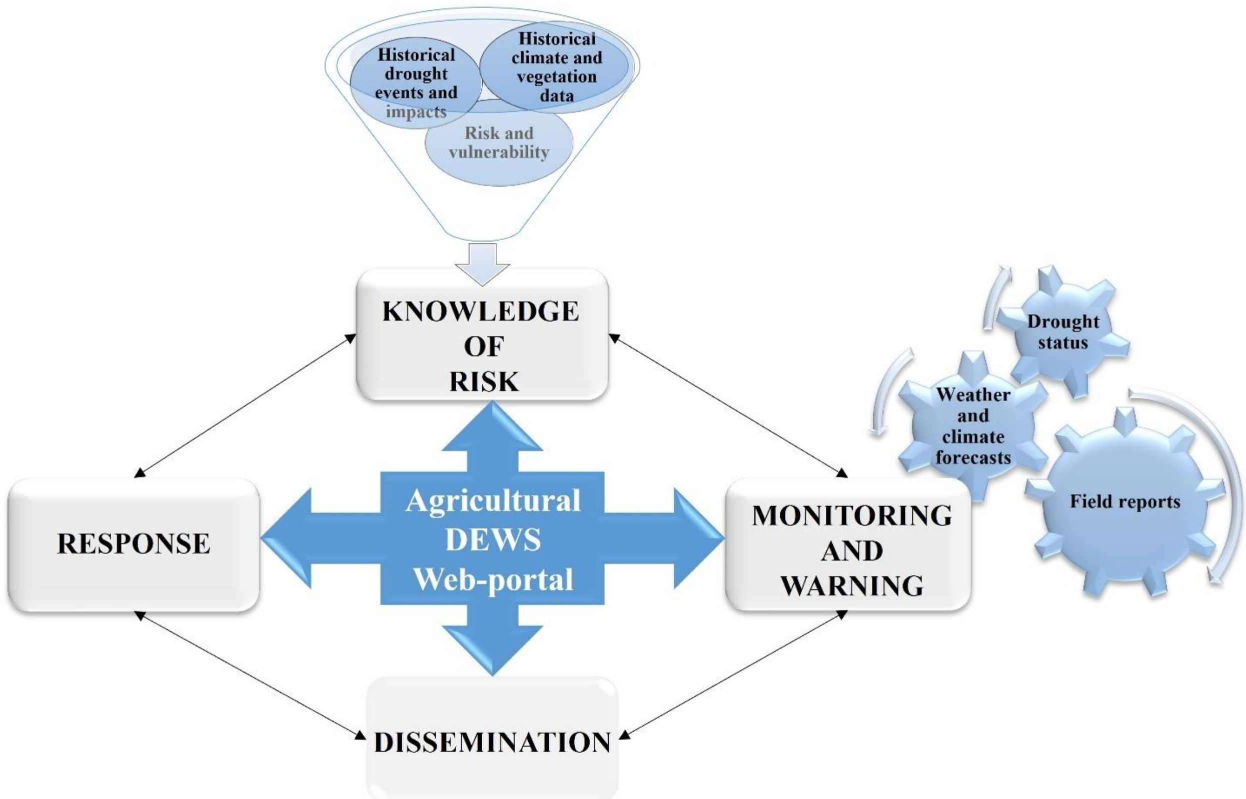

Figure 3-5: Schematic representation of characteristics within a web-based agricultural DEWS as given by the four recognized interrelated components of developing an early warning system.

Table 3-1: Characteristics of established agricultural drought early warning systems included in this review

Fundamental components	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	Composite index	x	x	x		x		x	x
	Impact	x	x	x			x		x
	Time series	x	x	x		x		x	
Monitoring and warning	Spatial map	x	x	x	x	x	x	x	x
	Interactive map	x		x					
	Field reports	x	x	x					
	Forecast	x	x	x	x		x		
Dissemination	User-friendly	x	x	x	x	x	x	x	x
	Subscription	x		x					x
	Preference selection	x		x		x		x	x
	Data file	x		x		x		x	
	Social media	x	x	x					
	Feedback	x	x	x	x	x	x	x	x
Response	Contingency plan	x		x			x		

3.5.1. Knowledge of risk

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 (1) rainfall-based; (2) vegetation-based; and (3) model-based (Senay *et al.*, 2014). Six of the eight systems exhibited an approach of combining these indicators into one index (Table 3-1), 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 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).

Another 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 data within DEWS need to be frequently (weekly – monthly) updated.

3.5.2. Monitoring and warning

One common characteristic was the ability to visualize areas of concern through a spatial map (Table 3-1). 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 variations in drought risk and identify hotspot areas needing urgent attention. All the established systems included in this review displayed this feature and thus served as an important contribution to web-based agricultural DEWS. Moreover, an improvement to the usage of a spatial map was the introduction of an interactive spatial map, which allows the user to select their area of choice and obtain statistics on current and previous droughts (NIDIS, 2020). As learned from the NIDIS (NIDIS, 2020) and the FEWS NET (FEWS NET, 2020), the use of an interactive map is essential for web-based DEWS, making them more efficient and user-oriented.

Field observations contribute significantly to assessing the impact of drought 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 in 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 errors. However, it is noteworthy that resources may be demanding in terms of labour and financial costs (Quansah *et al.*, 2010).

According to (Jacks *et al.*, 2010), the main requirement for effective early warnings and response includes timely and accurate forecasts. However, due to the slow onset nature of agricultural drought, medium-range forecasts (between 3 to 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 be reliable for planning (Feng *et al.*, 2020). These forecasts can provide important information for decision-makers to act accordingly, e.g. put mitigation strategies into place (Pozzi *et al.*, 2013). As shown in Table 3-1, five of the eight systems comprise the forecasting characteristic.

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 thus, users 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.

3.5.3. Dissemination

All systems' web pages 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). The subscription characteristic was found in three systems, whereby users can subscribe and receive early warning information mostly through emails. This feature is beneficial as it allows for minimum delay of information delivery to the end-users (Jacks *et al.*, 2010). It was further learned 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).

Another characteristic, found in five of the eight established systems, is the preference selection 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). However, 50% of the systems consisted of a feature that allows users to download data files 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).

For improved dissemination, DEWS needs to comprise high capabilities of adapting to emerging communication technology e.g. smartphones, mobile tablets, and social media platforms (Wilhite, 2000). The use of sharing drought early warning information on social media 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 their 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 organizations' accounts. While, drought information from 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. 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 feedback from users is a vital characteristic of any web-based agricultural drought early warning system.

3.5.4. Response

A delayed or inadequate response to early warning information can lead to slow decision-making and procurement processes, which may extend the time it takes for decision-makers to address the challenging impacts of drought (Mugabe *et al.*, 2019). Thus, active contingency planning is an important part of the early warning continuum. 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. An example of this approach was found in the NIDIS (NIDIS, 2020), FEWS NET (FEWS NET, 2020), and the Caribbean Drought and Precipitation Monitoring Network (CRCC, 2020).

3.6. Conclusions

The findings presented 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. Key characteristics should be adopted for collecting data, assessing risk, predicting impending agricultural droughts, disseminating information, and improving the capability to respond accordingly. 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 (Funk *et al.*, 2019). Hence, institutions and authorities with complementary resources need to collaborate to provide comprehensive drought monitoring and share financial commitments.

Ideally, a web-based agricultural DEWS should communicate information in a simplified manner through a variety of methods, to ensure minimum delay in delivery and to improve usefulness (Jacks *et al.*, 2010). These may include various formats (interactive maps, text, and graphs), through media as a communication channel (internet, radio, television, social media, etc.), and state-of-the-art information technologies for enhanced interconnection among all components of the system. It was further observed that effective agricultural DEWS comprise contingency plans for a realistic disaster risk reduction strategy (Basher, 2006). These plans add value to the proactive nature of DEWS in such that they minimize loss as opposed to responding to loss (Smit and Skinner, 2002).

Potential challenges, to be anticipated when developing web-based agricultural DEWS, should be acknowledged. These include the risk of false information where the system was not tested and the lack of dedicated human resources and secure financial commitments. It is therefore important to invest in human capacity so that authorities and other stakeholders can be more engaged in agricultural drought communication. Similarly, the need for financial investment in emerging innovative DEWS or improvements on current systems should be emphasized, also, as the cost might be far less than that of disaster response and recovery (Seng, 2012).

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CHAPTER 4. CONCEPTUALIZING TECHNOLOGIES OF THE FOURTH INDUSTRIAL REVOLUTION INTO DROUGHT EARLY WARNING SYSTEMS

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Abstract

Guided by Toulmin's model of argumentation, this chapter examined and proposed a conceptual framework for the underexplored subject of fourth industrial revolution-based drought early warning systems (DEWS 4.0). Eight interconnected modules were identified to demonstrate how incorporating innovative technologies can enhance traditional systems. It was depicted that predictive analytic techniques, incorporating machine and deep learning, ensure accurate drought forecasts. The use of the Internet of Things, unmanned aerial vehicles, and big data analytics can facilitate real-time monitoring of weather, soil moisture, streamflow, and groundwater data. While, natural language processing, a subset of artificial intelligence, can analyze data from unstructured sources (social media, news, reviews), essential for processing comprehensive drought information, thus, improving alert generation, dissemination, and interoperability. Furthermore, the use of extended reality can enable users to simulate drought scenarios, interact with data, and evaluate the impact of various measures on responses and preparedness. This framework can be applied in real-world contexts, demonstrating efficacy in optimizing resource use across diverse sectors such as agriculture, water, and the environment. However, overcoming limitations, including high initial costs, Internet connectivity inconsistencies, the need for skilled personnel, and possible technology fatigue, is essential. To fully realize DEWS 4.0's potential and achieve a more effective, sustainable approach to drought management, further research, practical implementation, and policy development are necessary.

4.1. Introduction

The emergence of drought early warning systems (DEWS) can be traced back to the 1980s, a period marked by severe famines in Sudan and Ethiopia that highlighted the urgent need to prevent and anticipate future food disasters (Kim and Guha-Sapir, 2012). Their main purpose was to provide evidence-based assessments to assist relief agencies and government decision-makers in managing these humanitarian disasters (FEWS NET, 2023). Over time, DEWS has evolved to incorporate a wider range of information and services, making them more accessible and available to end-users (Kafle, 2017). Since their conception, the integration of remote sensing in DEWS improved their ability to describe vegetation activity, with the potential to detect and monitor agricultural droughts (Bokusheva *et al.*, 2016). This was due to the fact that Earth observation satellites had been advancing and satellites equipped with sensors primarily in the optical domain had been developed, resulting in improved remotely sensed information for drought characterization (Niemeyer, 2008).

Before the year 1995, DEWS tended to be reactive in nature, by focusing on monitoring and response after a drought event had occurred (Cowan *et al.*, 2014). Common to these systems was the inclusion of drought indices that employ ground-based meteorological variables, such as rainfall, temperature, evapotranspiration, and soil water content, obtained from weather stations (Wang *et al.*, 2015). Moreover, warnings based on measured meteorological elements or field reports were proven to be ineffective primarily because they were subjective and not available on time, prompting the need for improved forecasting (Kumar *et al.*, 2021). As a result, advancements in computer modeling and data analysis enabled DEWS to incorporate a wider range of factors, such as climate variability, socio-economic conditions, and land use patterns into their forecasts (FEWS NET, 2020; NIDIS, 2020).

During the 2000s, improvements in emerging knowledge and technical tools that enable the assessment of risks, predictions, and warnings started developing momentum (UNISDR, 2006). These improvements were largely attributed to enhanced scientific knowledge of natural hazards (Basher, 2006), together with the utilization of modern information and communication technologies of the 'Digital Age' (Datta, 2021). This allowed for more web-based DEWS (Hao *et al.*, 2017), with effective communication of information through the internet and remote devices such as cell phones and laptops. Following this period, enormous amounts of data were generated and consumed regularly across all industries, thus, creating a foundation for the Fourth Industrial Revolution (4IR), also referred to as Industry 4.0 (Datta, 2021).

The 4IR technologies are making a significant impact on all areas of study, with industrial applications being redefined and technology advancing in every sector (World Economic Forum, 2017). For instance, the use of 4IR technologies has shown to be effective in the water and sanitation sector by improving stakeholder engagement and reducing financial costs by eliminating the need to build or use physical versions of modeled resources (Stankovic *et al.*, 2020). David *et al*. (2022) established that 4IR technologies have an impact on the water, energy, and food nexus, leading to the adoption of cleaner production methods and resource management strategies. Moreover, these technologies have shown great potential in automated data analytics (Sebestyén *et al.*, 2021), converting raw data into useful information (Gubbi *et al.*, 2013), and enhancing real-time decision-making (Sun and Scanlon, 2019).

Recently, disaster management has been identified as an area with promising potential and research into the use of 4IR technologies (Zahra *et al.*, 2018; Shahat *et al.*, 2020; Munawar *et al.*, 2022). Specifically, there has been a rising effort to improve early warning for rapid disasters requiring emergency response (Shah *et al.*, 2019). Yet, concerning drought, which tends to have a gradual onset, there is a lack of research connecting the application of these technologies to early warning systems. Therefore, this chapter provided a comprehensive assessment of the prospects, challenges, and implications that may arise. Through a logical examination of the technological landscape and its potential impact on drought early warning, the research targeted to pave the way for practical implementations and strategies that enhance the overall efficiency of DEWS in addressing related risks and vulnerabilities.

4.2. Methodology

The research followed a conceptual approach to generate theoretical perceptions by employing Toulmin's model of argumentation (Figure 4-1). This model offers a systematic approach to examining and constructing logical arguments based on three main components: claim, grounds, and warrant (Toulmin, 2003). Extensive research has been conducted utilizing Toulmin's model in various fields, including education (Mardiati *et al.*, 2023), where the argumentation skills of students discussing socio-scientific issues, such as viruses, were analyzed. This study revealed that while students excelled in collaborative oral arguments, achieving a high-quality level, their individual written arguments exhibited weaknesses in providing evidence and rebuttals. In environmental science, the model was applied to highlight the ethical implications of ecological debt and the need for equitable responsibilities (Rice, 2009). Furthermore, Shahat *et al.* (2020) employed a conceptual framework for smart disaster governance, incorporating Toulmin's structured argumentation. The study emphasized the integration of Internet of Things technologies to enhance disaster resilience, demonstrating the model's relevance in framing arguments around complex socio-technical issues. These examples illustrate the versatility of Toulmin's model in facilitating discussions across various sectors.

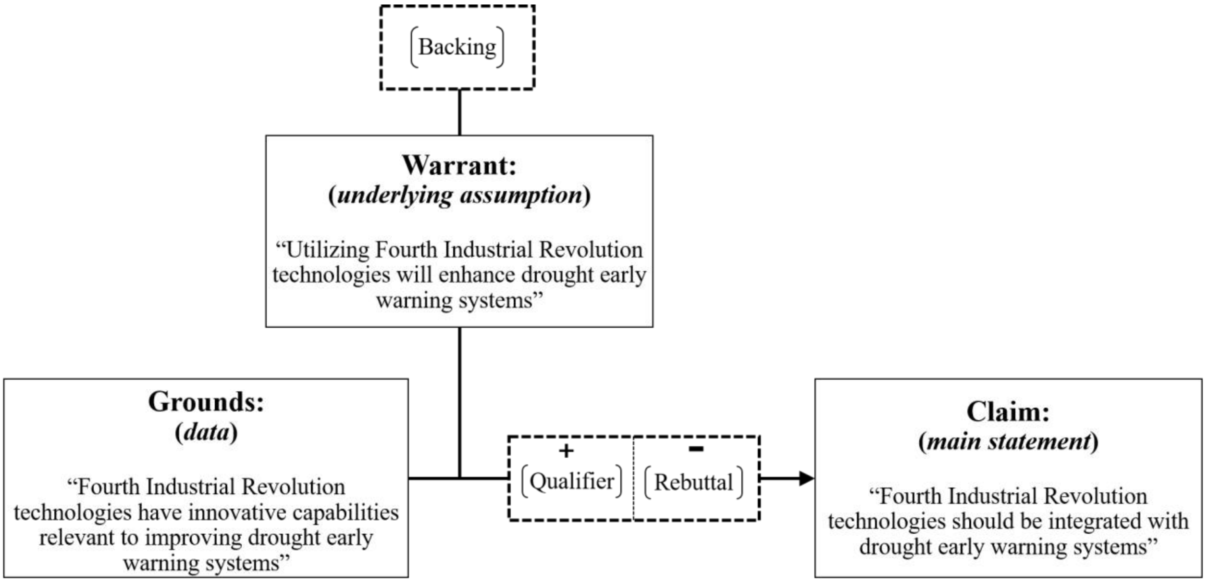

Figure 4-1: Framework applied to analyze and construct the argument for an integrated 4IR-based DEWS, according to Toulmin's model of argumentation (Toulmin, 2003).

The model suggests that a claim, which is the main proposition being presented, is warranted when it is supported by the appropriate grounds (Oh, 2014). Here, the claim was that "4IR technologies should be integrated with DEWS." The grounds were established to demonstrate that these technologies have innovative capabilities relevant to improving DEWS. The warrant provided the logical reasoning and explanation for the connection between the grounds and the claim. The remaining components of the model are additional evidence that supports the warrant (backing), the degree of certainty of the claim (qualifier), and the opposing viewpoints that challenge the claim (rebuttal) (Toulmin, 2003).

To establish the grounds, a bibliometric analysis was conducted by reviewing studies that discuss existing theories and concepts related to 4IR technologies and DEWS. A rigorous process of retrieving literature through a Boolean search was applied to published journal articles, conference proceedings, books, and book chapters held in the Web of Science database. The search used the following query: "fourth industrial revolution OR digitization OR cybersecurity OR blockchain OR virtual reality OR UAV [unmanned aerial vehicle] OR unmanned aircraft systems OR remotely piloted aircraft system OR 3D printing OR smart cities OR drones OR Industry 4.0 OR quantum computing OR robotics OR deep learning OR artificial intelligence OR IoT [Internet of Things] OR Big data OR cloud computing OR machine learning OR disruptive technologies OR 4IR OR Unmanned aerial vehicles OR micro air vehicles OR small unmanned aircraft systems OR web 3 OR cyber physical systems OR 5G (Keywords) AND drought (Title)".

The search produced 297 documents that were extracted and imported into VOSviewer v. 1.6.19 software (https://www.vosviewer.com/), which is designed for analyzing and visualizing bibliometric data (Jan van Eck and Waltman, 2013). The extracted data were analyzed to identify the most prominent research focusing on the co-occurrence of keywords within the scientific literature pertaining to 4IR and DEWS. For an inclusive analysis, the next step was to search for keywords leading to the identification of all relevant technologies. Both logic and inductive reasoning techniques were utilized to form the warrant. Logic reasoning relies on rules of validity and employs a systematic process to ensure the accuracy of conclusions, while inductive reasoning provides a structured framework for integrating and analyzing evidence to guide the development of a new concept (Hayes *et al.*, 2010). Therefore, modules of a 4IR-based drought early warning system (DEWS 4.0) were identified based on existing DEWS components (United Nations, 2016), 4IR technologies, and innovative requirements. Finally, the benefits and challenges were collated to illustrate the degree of certainty and limitation of the claim.

4.3. Results

4.3.1. Research trends

Figure 4-2 represents the temporal evolution and spatial distribution of publications that integrated components of 4IR with drought-related topics. It can be observed that this integration, began in 2015, with only three published papers. The research began to gain interest and by 2019, the number of publications reached a total of 42. Thereafter, there was a consistent growing trend in the research focus, with the year 2023 producing up to 82 publications. Implying that the increasing frequency and severity of drought events, together with their significant socio-economic and environmental impacts (Li *et al.*, 2009), have highlighted the necessity for innovative and effective solutions. Thus, resulted in an increasing interest and recognition amongst the scientific community to examine the potential benefits offered by 4IR technologies in addressing and mitigating the drought challenges.

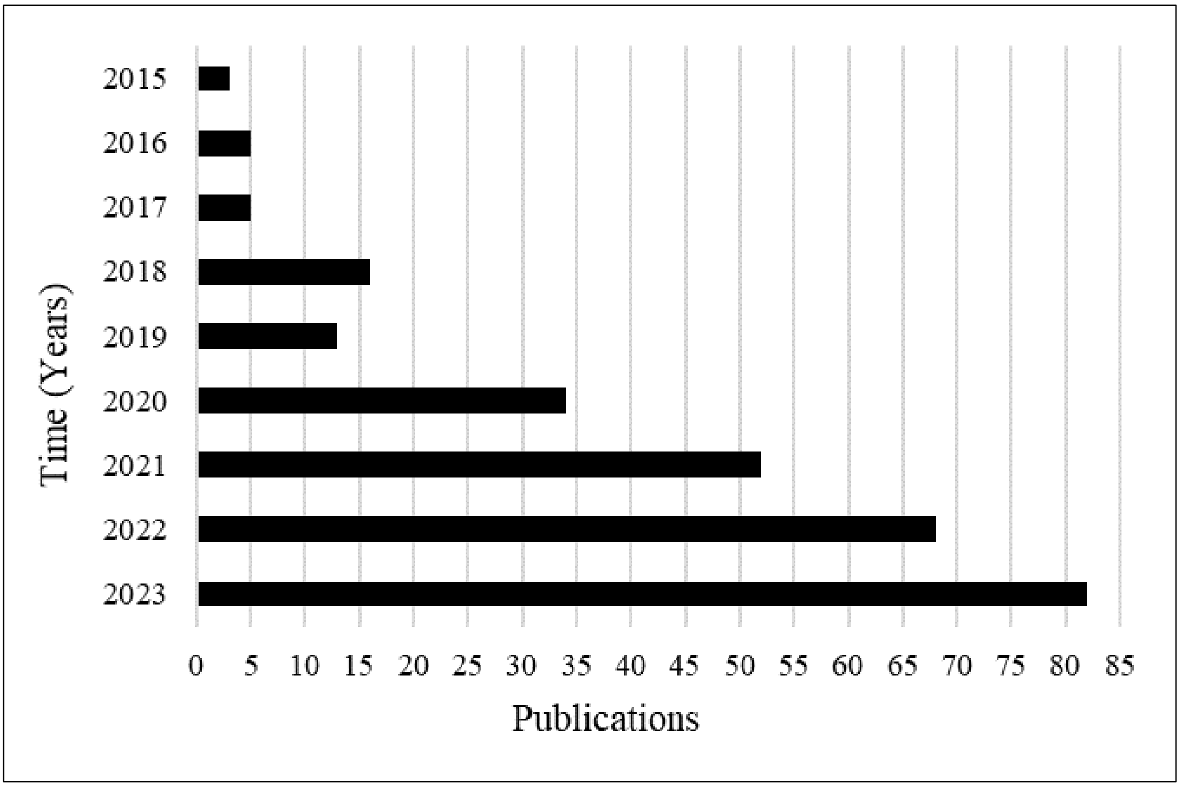

Figure 4-2: Research trends on publications relevant to integrating 4IR to drought-related topics.

Concerning the distribution of research publications across different countries, varying levels of research output were observed (Figure 4-3). Notably, some countries have shown a particularly strong commitment to this research area, while others have demonstrated a developing interest. China, with a significant number of 79 publications (27 %), stands out as one of the leading contributors that displays substantial interest and reflects a proactive approach to exploring the potential benefits of 4IR technologies in addressing drought challenges. This was followed by The United States of America, with 51 publications, illustrating a robust research presence in this area. India, contributed 16%, with 47 publications, and thus also showed notable research activity in this area of interest.

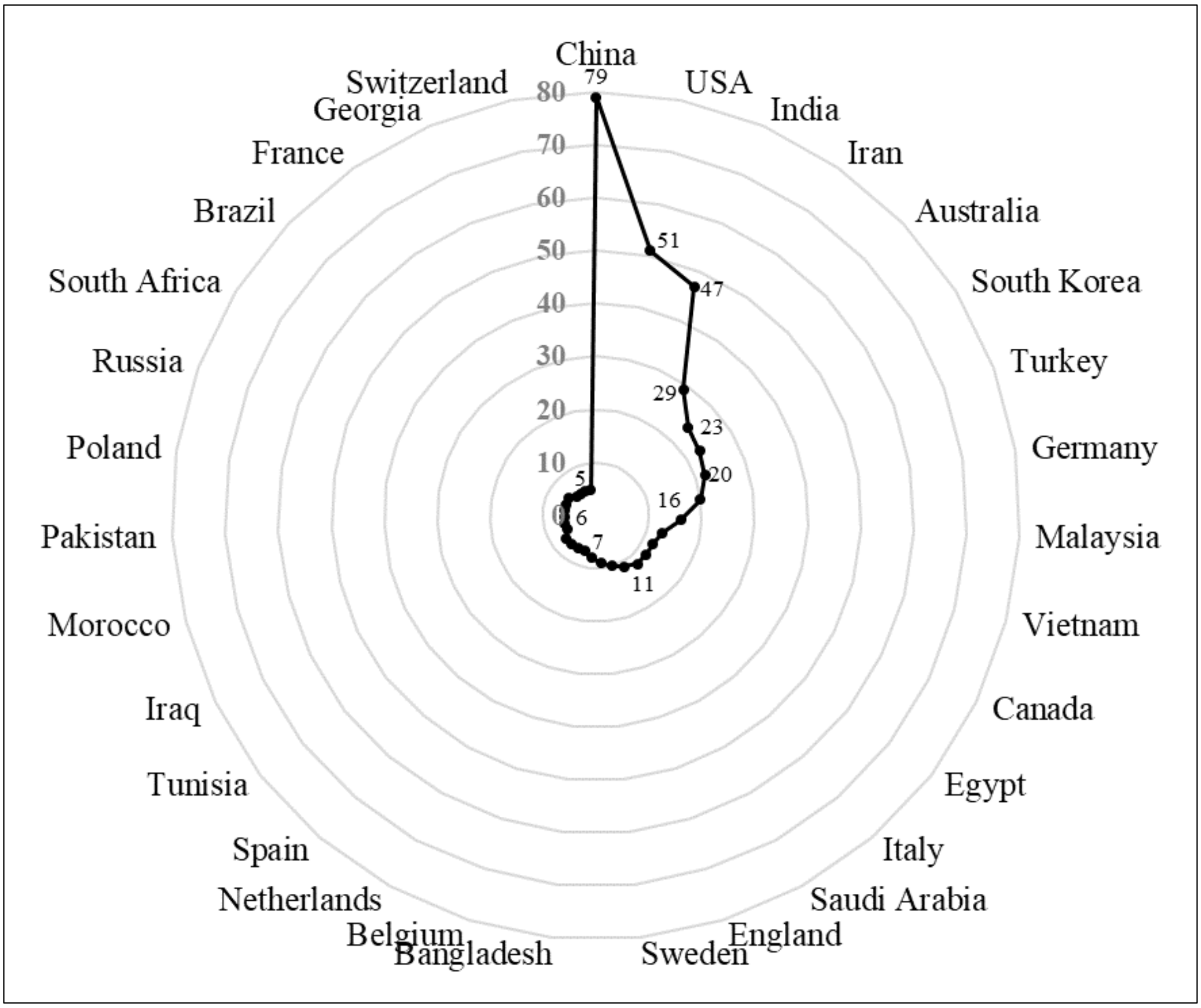

Figure 4-3: Research trend on applying 4IR to drought-related topics per country.

Iran, Australia, South Korea, and Turkey have shown comparable levels of research output, each with 29, 24, 23, and 22 publications, respectively. While the research output from the remaining countries, including Malaysia, Italy, Belgium, Morocco, South Africa, Georgia, and others may be comparatively lower (<20 publications), their involvement demonstrated a growing awareness and recognition of the potential benefits offered by 4IR technologies in the context of drought. It further indicated a need to explore and utilize innovative approaches to enhance their understanding and response to drought challenges. Moreover, this variation in research output across the globe may be attributed to factors such as research priorities, technological readiness, funding availability, and regional contextual differences (Lumbroso *et al.*, 2016). Nonetheless, the collective engagement and growing interest from researchers in different countries underline the global recognition of the significance of integrating 4IR components in addressing and mitigating the challenges associated with drought, thus, laying the foundation for developing 4IR-based DEWS.

4.3.2. Mapping technology requirements to DEWS

To identify patterns and trends, the research density map (Figure 4-4) displays distinct patterns in research focus, where red represents high density and blue indicates low density. In the high-density category, the research areas prominently included keywords such as machine learning, drought, prediction, remote sensing, deep learning, and river-basin. These topics indicated a strong emphasis on utilizing advanced computational techniques and data-driven approaches to address drought-related challenges. The incorporation of remote sensing technologies further highlighted the focus on utilizing satellite imagery and sensor data for monitoring and assessing drought conditions.

In contrast, keywords with a low-density included cloud computing, internet of things (IoT), fog computing, UAV (Unmanned Aerial Vehicle), grain yield, drought stress, and climate change. These topics reflected a consideration of emerging technologies and their potential implications for drought management. The inclusion of fog computing and UAV suggests the investigation of innovative data processing and collection approaches in remote or challenging areas (Campos-Vargas *et al.*, 2020). Additionally, the focus on grain yield, drought stress, and climate change indicates research efforts aimed at applying 4IR technologies to understand the impacts of drought on agricultural productivity and the larger context of climate change.

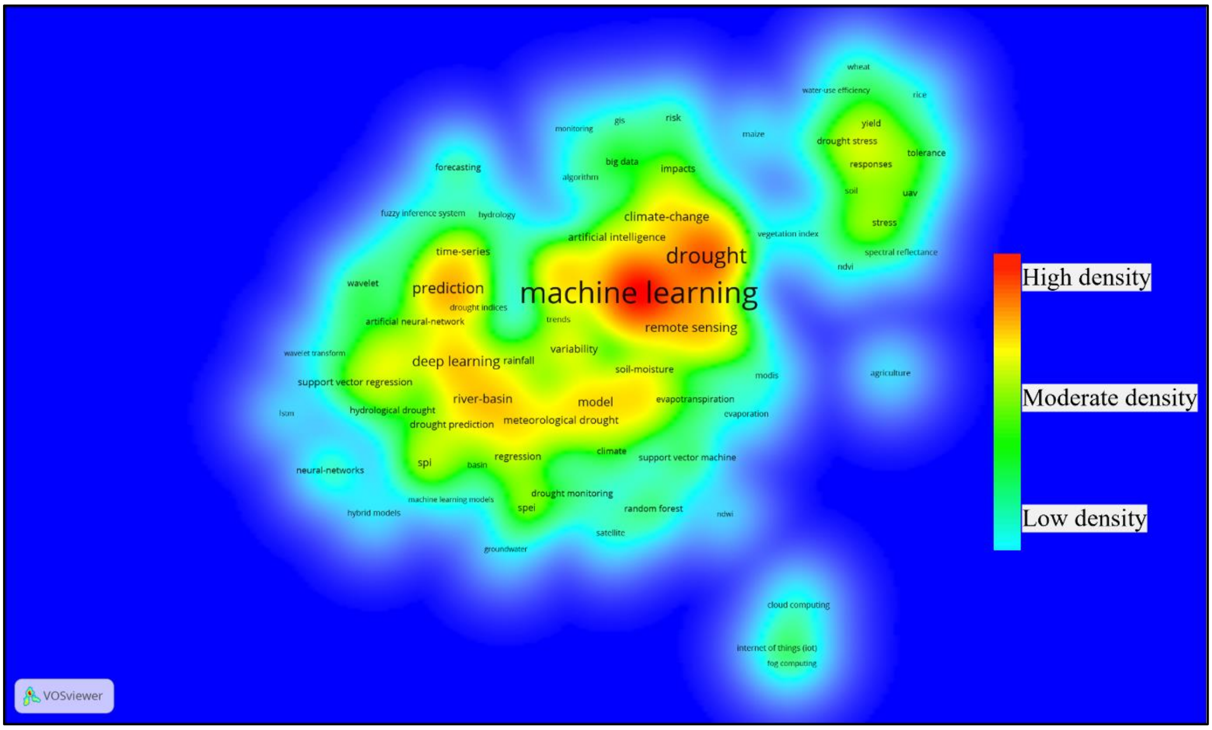

Figure 4-4: Density map on drought research related to the application of 4IR components.

As shown in Figure 4-5, the analysis revealed four clusters formed according to relationships between keywords, and in this context, the keywords had a high degree of similarity or co-occurrence based on the underlying data. Generally, it can be observed that within the analysed dataset, keywords like machine learning, drought, prediction, remote sensing, and climate change appeared prominently, reflected by their larger circle sizes. Cluster 1, revolved around understanding and managing drought-related challenges in agricultural and climatic contexts. Given by 46 keywords, this thematic area focused on research related to crops, vegetation, water stress, and climate change. It comprised keywords such as big data, monitoring, drought stress, yield, water-use efficiency, and spectral reflectance. It also comprised methodologies like machine learning, geographic information systems, remote sensing, and UAVs.

Cluster 2 consisted of 35 keywords and primarily focused on the prediction, trends, time-series, forecasting, and application of artificial intelligence techniques, such as artificial neural networks, deep learning, fuzzy inference systems, and support vector regression, for modeling and forecasting drought events. Moreover, it displayed the implementation of these algorithms in hydrology research, with a particular emphasis on keywords like river basins and groundwater. Meanwhile, the formation of cluster 3 was based on the connections between 16 keywords related to drought indicators. This cluster was formed around research concentrating on keywords like soil moisture, evapotranspiration, random forest, and climate.

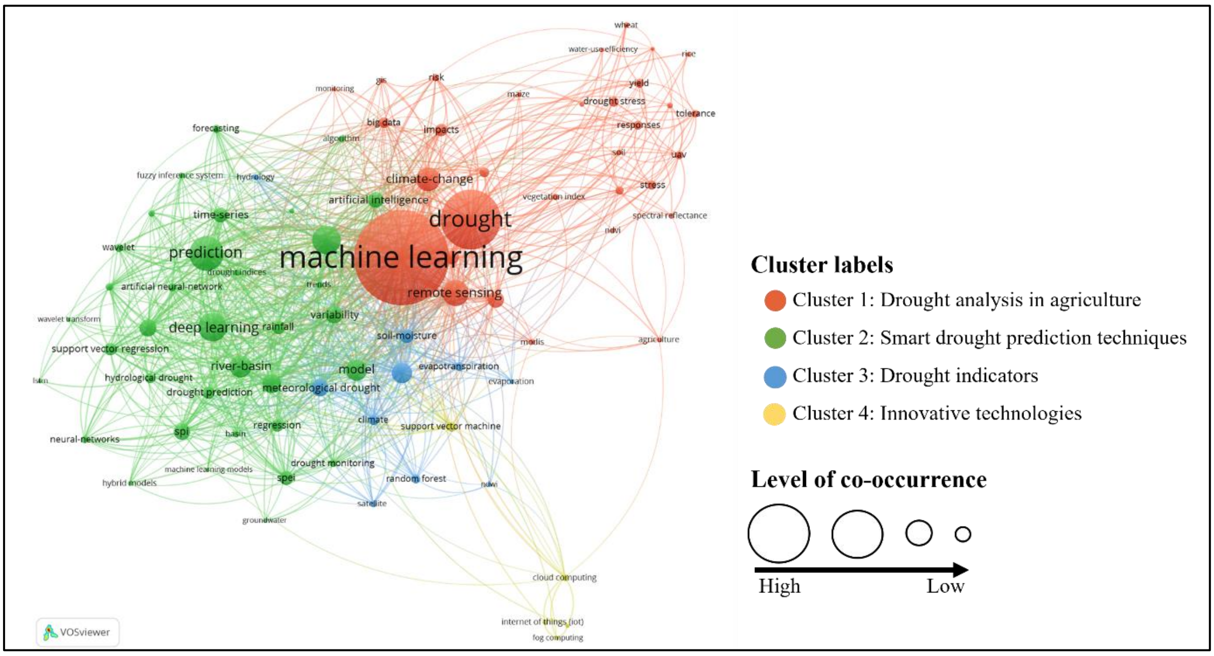

Figure 4-5: Key research themes based on publications concerning 4IR on drought.

Cluster 4, characterized by five keywords, focused on exploring the relationships among cloud computing, fog computing, support vector machine, and IoT specifically in the realm of drought management. The distance between the lines connecting the keywords indicated that this cluster had comparatively weaker relationships or similarities with other clusters. This implies a scarcity of research on the comprehensive integration of these technological elements within drought management practices. Although certain advancements do exist (Johnson *et al.*, 2020; Kaur and Sood, 2021; Sundararajan *et al.*, 2021), these results also suggest a potential avenue for further research to address drought-related challenges innovatively.

The bibliometric analysis revealed that the connections between concepts related to the application of 4IR technologies in DEWS were dispersed and highly biased towards data collection, analysis, and prediction, with agriculture and hydrology being the dominating areas of application. Thus, the selection of applicable technologies was informed by a systematic literature review, involving modifications at different stages to thoroughly align the characteristics of each technology with the requirements of an effective DEWS, as outlined in the literature (Garcia and Fearnley, 2012; Lumbroso, 2018; Calvel *et al.*, 2020). The following technologies were found suitable based on their relevance to meeting the specified requirements: IoT, big data analytics (BDA), cloud computing, artificial intelligence (AI), robotics, nanotechnology, extended reality (XR), and blockchain (Table 4-1).

i. **Internet of Things (IoT):** IoT refers to a technology in which objects or devices like computers, smartphones, industrial machinery, or vehicles can communicate data in real-time via internet-connected instruments (Shanneb, 2018). Typically, these sensors are wirelessly interconnected and collaboratively collect and transmit data from different environments through Bluetooth, short-range communication, and networks, automatically without human assistance (Gubbi *et al.*, 2013). IoT finds vast applications across industries, from environmental monitoring to smart homes and industrial automation, making it an essential technology of the 4IR (Gubbi *et al.*, 2013; Malhotra *et al.*, 2019; Marcu *et al.*, 2019).

ii. **Big Data Analytics (BDA):** BDA is a technology that utilizes advanced computational techniques, statistical methods, and analytical algorithms to handle and analyse large datasets, to detect correlations and trends within them (Shah *et al.*, 2019). It often benefits from the vast amount of data available, with its main aim being to enhance data value and accessibility for decision-making (Munawar *et al.*, 2022). The spectrum of available BDA techniques is wide and common methods include data mining, machine learning, analytical, and statistical tools, therefore, it is vital to recognize that the choice of analytics should align with the particular problem under investigation (Gaffoor *et al.*, 2020).

iii. **Cloud Computing:** Cloud computing has revolutionized the Information Technology industry, providing flexibility, scalability, and accessibility to a wide range of users and applications (Xiong *et al.*, 2017). It refers to the technology responsible for providing access to computing resources, storage, and software applications over the internet (Zhao *et al.*, 2018). Instead of relying on local servers or personal computers, cloud computing provides access to computing resources, storage, and software applications over the internet, known as the cloud (Farooq *et al.*, 2019). This allows organisations or individuals to scale their technological infrastructure easily and cost-effectively, as they can maximize the cloud provider's resources and pay for what they use.

Table 4-1: Relevance of 4IR technologies necessary for developing DEWS 4.0

Technology		Relevance	Key attributes	
i.	**Internet of Things**	Automated exchange of data among objects through sensor networks, without human intervention (Gubbi *et al.*, 2013).	• Sensor integration • Connectivity • Data collection • Remote monitoring	• Automation • Security • Scalability
ii.	**Big data analytics**	Management of large volumes of data (Shah *et al.*, 2019).	• Velocity • Volume • Value	• Variety • Veracity
iii.	**Cloud computing**	Access and utilization of resources hosted on remote servers managed by a cloud service provider (Farooq *et al.*, 2019).	• Scalability • Storage and backup • Security	• Cost-effective • Accessibility • Collaboration
iv.	**Artificial intelligence**	Enables intelligent systems capable of learning, reasoning, and making decisions based on data and experiences (Haenlein and Kaplan, 2019).	• Automation • Predictive analytics • Robustness • Scalability	• Transparency • Adaptability • Cognitive abilities • Continuous learning
v.	**Robotics**	Perform tasks autonomously or in collaboration with humans, through intelligent mechanisms and algorithms (Lynch and Park, 2017).	• Sensing and perception • Physical interaction • Intelligent control • Safety and robustness • Coverage	• Adaptability • Autonomous task implementation • Speed • Precision and accuracy
vi.	**Nanotechnology**	Enables the development of innovative materials and applications at the nanoscale with profound implications (Jha, 2018).	• Size and scale • Miniaturization • Innovative properties • Interdisciplinary	• Enhanced surface-to-volume ratio • Precision and control • Sustainability
vii.	**Extended reality**	Provides users with the ability to interact with computer-generated content within a real-world context (Cárdenas-Robledo *et al.*, 2022).	• Physical and virtual fusion • Real-time interaction • Spatial mapping and tracking	• 3D visualization • Multi-user collaboration • Cross-platform compatibility
viii.	**Blockchain**	Ensures secure and transparent record-keeping across various applications (Maesa and Mori, 2020).	• Decentralization • Transparency • Security	• Consensus mechanism • Privacy • Traceability

iv. **Artificial Intelligence (AI):** AI is a problem-solving, reasoning, learning, and decision-making technology that involves the development of computer systems and algorithms designed to replicate human intelligence (Haenlein and Kaplan, 2019). It includes various subfields that aim to create intelligent machines capable of performing tasks that typically require human intelligence, such as deep learning, natural language processing, and machine learning (Abid *et al.*, 2021). The latter, for example, creates algorithms that empower computers to recognize patterns in data and make predictions or decisions without the need for rule-based programming (Lecun *et al.*, 2015). This makes AI a versatile, and adaptable technology applicable for various applications across industries.

v. **Robotics:** Robotics is a technology that focuses on the design, building, and operation of robots – physical machines capable of performing tasks autonomously or semi-autonomously (Lynch and Park, 2017). A modern example of this technology is UAVs, which are equipped with remote sensing technologies to collect data during flights, either under remote control or along a pre-programmed route (Campos-Vargas *et al.*, 2020). These UAVs can rapidly survey wide regions, through cameras, Light Detection, and Ranging and hyperspectral sensors to provide valuable aerial data in three-dimensional (3D) visualisation (Zhou *et al.*, 2020).

vi. **Nanotechnology:** Nanotechnology refers to a multidisciplinary field of science, engineering, and technology that pertains to designing and developing materials or devices at the nanoscale level, typically with structures smaller than 100 nanometers (Kamarulzaman *et al.*, 2019). At this tiny scale, the materials can display unique properties such as quantum confinement, where the behaviour of electrons is restricted within certain energy levels (Neikov and Yefimov, 2019). Thus, resulting in distinctive optical, electronic, and magnetic characteristics, which may find practical applications in technologies like quantum dots for displays and quantum computing (Jha, 2018).

vii. **Extended Reality (XR):** XR is an inclusive term that refers to all forms of virtual, augmented, and mixed reality technologies that merge the physical and virtual worlds to provide an enhanced experience of reality (Xi *et al.*, 2023). These technologies are able to overlay digital information, such as images, text, or 3D objects, onto real-world environments (Cárdenas-Robledo *et al.*, 2022). However, XR exceeds photorealism or 3D representations as it enables users to experience a sense of place comparable or even identical to the real world (Çöltekin *et al.*, 2020). Thus, allowing for more realistic and interactive experiences.

viii. **Blockchain:** A blockchain is a secure and distributed transactional database that relies on cryptography and a consensus mechanism, often referred to as 'a ledger for digital events' (Beck *et al.*, 2017). This technology initially gained popularity in the context of cryptocurrencies like Bitcoin, however, its potential ranges from supply chain management to identity verification and smart contracts (Maesa and Mori, 2020). Blockchain's distinctive feature from traditional data storage on central servers is that it addresses concerns such as data security due to unencrypted servers and the need for multiple authorities to function simultaneously (Bhushan *et al.*, 2020).

4.3.3. Interconnected modules

As outlined by the United Nations, all four fundamental components of DEWS—knowledge of risk, monitoring and warning, dissemination, and response—must be fully embraced to ensure the system's effectiveness (United Nations, 2016). By considering these components and drawing from the capabilities of the applicable 4IR technologies, potential links were identified to illustrate their integration (Figure 4-6).

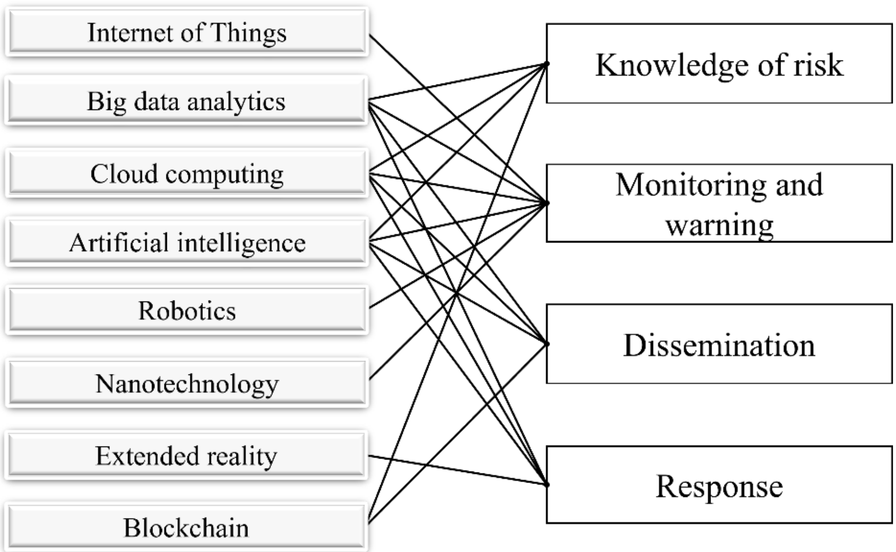

Figure 4-6: Potential relationships between the fundamental components of DEWS and the technologies of the 4IR.

Subsequently, a conceptual framework comprising eight DEWS 4.0 modules was constructed (Figure 4-7). In this context, a module refers to a distinct element within a system that serves a specific function or performs a particular task. The following section describes each of the modules to demonstrate their ability to address drought challenges and show the various technologies, processes, and intended outcomes to fulfill the objectives of the overall system. The modules were given as: (1) advanced analytics, (2) digital archive, (3) smart data networks, (4) predictive modelling, (5) data-driven alerts, (6) interactive communication, (7) scenario planning, and (8) adaptive learning.

- **Module 1: Advanced analytics**

The advanced analytics module is essential for analyzing historical and real-time data to gain an understanding of drought severity (Zargar *et al.*, 2011), patterns, trends, and potential impacts for risk and vulnerability assessments (Guo *et al.*, 2021). This module emphasizes the application of innovative algorithms to combine data into integrated sets and remove errors and outliers to facilitate analysis. The BDA techniques can identify patterns, correlations, and anomalies that may not be apparent through traditional data-processing methods (Gaffoor *et al.*, 2020), playing a significant role within the advanced analytics module by handling the substantial computational requirements of data analysis and processing (Shah *et al.*, 2019), and thus enabling effective data integration, pattern recognition, and anomaly detection.

The use of AI techniques, such as machine learning and deep learning (Chen *et al.*, 2018), can be directly integrated into the advanced analytics module to model droughts and identify trends and anomalies. Natural language processing, a subset of AI, can process human language to extract insights from unstructured data sources such as social media feeds, news articles, and user reviews (Nadkarni *et al.*, 2011). Traditionally, high-performance computing required specialized on-premises infrastructure with powerful hardware and dedicated resources (Xuan *et al.*, 2015). Now, cloud computing can provide the high-performance computing and storage capabilities needed for processing such big data (Mateescu *et al.*, 2011), benefiting DEWS 4.0 by enabling efficient and timely data analysis.

- **Module 2: Digital archive**

Given the vast amount of data that will be generated in the system, the digital archive module provides a comprehensive repository of historical data, including drought occurrences, impacts, and responses, facilitating a profound understanding of drought dynamics, and enabling effective mitigation strategies. The capacities of 4IR technologies, especially via the functions of BDA, AI, cloud computing, and blockchain, can benefit the gathering, compiling, and retrieval of diverse datasets related to drought. By employing BDA and AI algorithms, this module ensures that DEWS 4.0 can automatically identify and categorize data to generate comprehensive metadata on important details such as location, date, and drought severity levels. This would allow users to efficiently navigate, retrieve, and explore historical drought records, not only relying on traditional search parameters but also benefiting from the system's ability to adapt and learn over time. The adaptive learning function ensures that the archiving process remains dynamic, incorporating evolving patterns and trends in drought data, propelled by the advanced analytics module. Moreover, the automated process eliminates the need for manual input, significantly reducing the potential for errors and ensuring a consistent and standardized dataset.

Another key aspect of this module is the use of cloud computing, which provides the necessary infrastructure for data processing and storage (Kaur and Sood, 2021). The flexibility of cloud technology allows fluxes in data volume, enhances accessibility of historical records, and further promotes collaborative efforts among stakeholders, by securely interacting with the data from diverse locations and devices. In such situations, a blockchain enables the security and transparency of historical records, by verifying and tracing changes in the data (Bhushan *et al.*, 2020). For instance, if multiple users, each contributing valuably to the system, need to collaborate, the cloud infrastructure would facilitate seamless sharing and retrieval of archived data, while blockchain technology ensures that data is cryptographically secured within a decentralized registry, preventing unauthorized changes.

- **Module 3: Smart data networks**

The smart data networks module provides a network of interconnected sensors and devices to facilitate activities such as collecting, storing, and retrieval of drought-relevant data. These activities are accomplished by various technologies, including the IoT, robotics, nanotechnology, and cloud computing, to enhance data collection and storage. Through strategically positioned IoT sensor nodes, real-time data describing soil moisture, weather, streamflow, and groundwater levels can be collected (Zahra *et al.*, 2018).

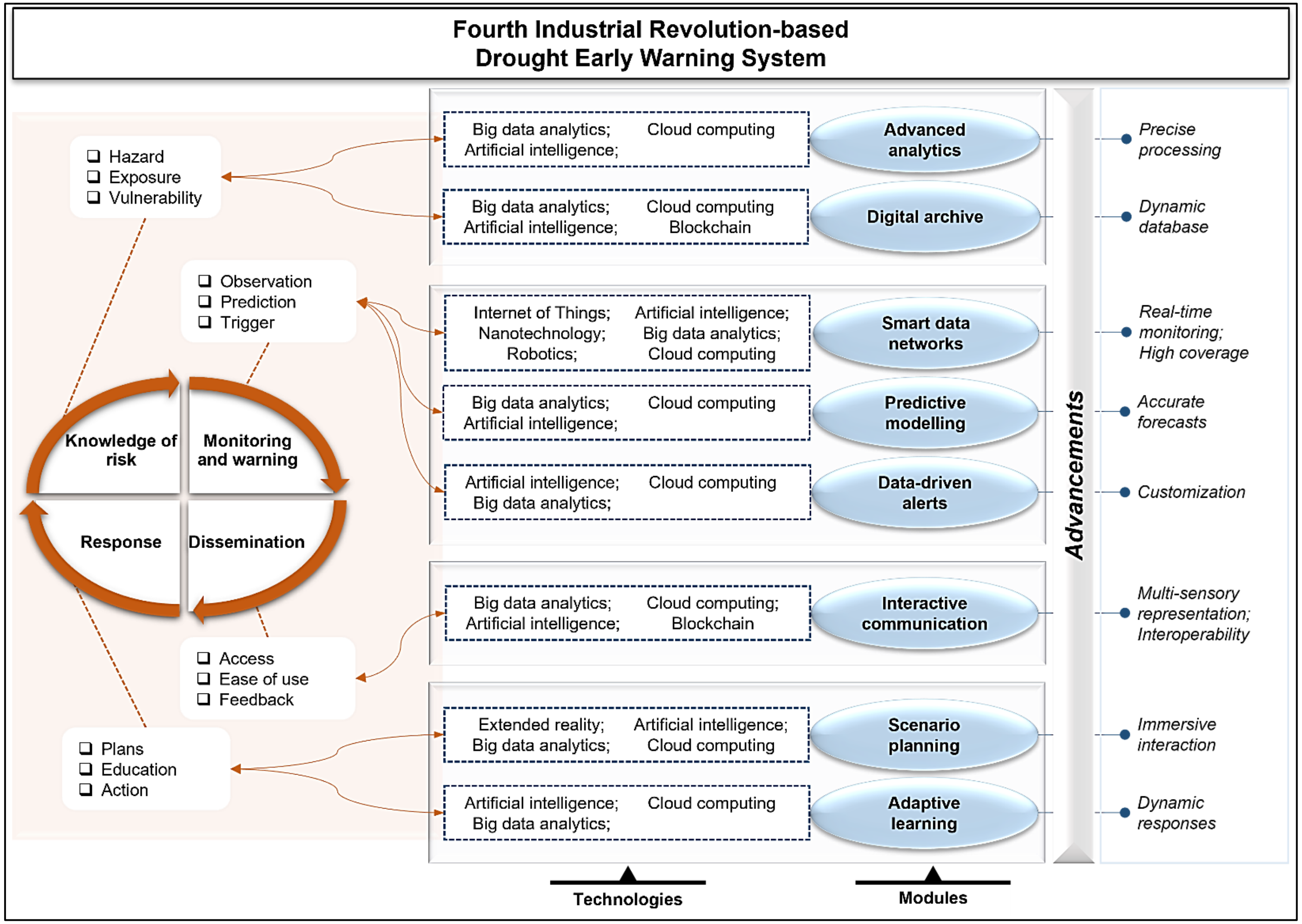

Figure 4-7: Conceptual framework of DEWS 4.0 outlining the various modules and their contributing technologies with respect to the four main components of DEWS.

Connected wearable devices equipped with environmental sensors can be used by various stakeholders to collect localized data to centralized systems such as IoT platforms, cloud computing services, or dedicated monitoring centers. (Moustafa *et al.*, 2015). Moreover, nanosatellites equipped with nanosensors can capture high-resolution images to collect valuable data on vegetation health, land cover, and water resources (Jha, 2018). These sensors, either used individually or integrated with IoT sensor nodes, offer sensing capabilities with improved sensitivity, selectivity, and miniaturization (Neikov and Yefimov, 2019).

To maximize data collection capabilities, UAVs, a subfield of robotics, will play a significant role. Equipped with remote sensing technologies, UAVs offer high spatial resolution and real-time data collection, enabling efficient data collection from remote or inaccessible areas (Nhamo *et al.*, 2020). Moreover, through deep learning and cognitive computing algorithms of AI (Chen *et al.*, 2018), DEWS 4.0 can automatically identify specific objects within images or videos to assist decision-makers in monitoring and assessing the impact of drought events. This expansion of coverage and data type will increase the overall amount of data to be processed and transmitted for DEWS 4.0. Thus, the collected data will need to be wirelessly transmitted to a cloud-based platform for further processing and analysis.

Cloud computing offers scalable and cost-effective storage and computing resources, ensuring efficient handling of large volumes of data (Avram, 2014). After the collection and processing, the use of BDA becomes crucial, allowing the system to continuously store and analyze incoming data streams from various sources (Kaur and Sood, 2021). This ability allows the system to provide real-time updates on drought conditions by detecting significant changes in the indicators of drought onset, severity, and end, as well as potential risks during a drought.

- **Module 4: Predictive modeling**

The predictive modeling module uses predictive analytics techniques to develop accurate drought predictions. Predictive models are developed by using AI techniques, including machine learning and deep learning, which identify complex patterns for accurate forecasts (Kaur and Sood, 2020). The model development process involves using algorithms such as regression models (Smith, 2018), support vector machines (Yang *et al.*, 2019), random forests (Chen *et al.*, 2012), and neural networks (Shin and Jose, 2000) to predict or estimate drought conditions based on available data. For instance, with AI, DEWS 4.0 can analyze historical rainfall, temperature, and river flow data to predict water availability and anticipate water shortages swiftly by continuously learning from real-time data.

By processing large datasets using BDA and cloud computing, the predictive modeling module can create predictive models and forecasting algorithms that consider diverse datasets. Cloud computing provides the necessary computational power and storage capacity to handle the extensive data-processing and model-training requirements of predictive modeling. This integration of real-time model analysis and cloud computing capabilities ensures that DEWS 4.0 can respond swiftly to changing environmental conditions and provide accurate and dependable predictions.

- **Module 5: Data-driven alerts**

The data-driven alerts module allows for the generation of customized drought warning alerts. Although the module is founded on the functionalities of drought forecasting and monitoring, at its core, it uses the capabilities of 4IR to enhance the accuracy, speed, and personalization of these alerts. Integrating innovative technologies such as AI, BDA, and cloud computing, ensures that stakeholders receive real-time, tailored alerts that can be used for effective drought response and mitigation efforts. The application of AI techniques such as machine learning allows the system to continuously process real-time data from various sources and identify early indicators of drought onset, severity, and end, as well as potential risks during a drought, which can then be used to generate alerts.

To enhance the alert generation process, cognitive computing techniques can be used to process unstructured data sources. By incorporating this technology, DEWS 4.0 can automatically analyze real-time data and extract information relevant to drought management. To further personalize recommendations, the module integrates machine learning algorithms to categorize users into different segments based on their characteristics and historical interactions with the system. This deep understanding of the social and environmental impacts of drought enriches the customized alerts with valuable human context and sentiment analysis (Sangaiah *et al.*, 2020). However, the large volumes of real-time data generated will require robust BDA techniques to efficiently process, analyze, and obtain significant information. Here, cloud computing will play a key role in providing the necessary computational power and storage capacity (Zhao *et al.*, 2018) to ensure the timely delivery of real-time alerts and eliminate delays in responses to evolving drought conditions.

- **Module 6: Interactive communication**

The interactive communication module is another critical component within DEWS 4.0, utilizing the capabilities of the 4IR to modernize the presentation and understanding of drought information. Through innovative technologies, it extends beyond visuals, as it can employ a combination of audio, and tactile visual elements to create multi-sensory representations such as interactive maps and voice-activated query systems to enhance the user experience by maximizing the impact of wide-ranging representations. By utilizing BDA, this module can effectively transform complex data into informative visuals such as dynamic maps, charts, and graphs that display real-time and predictive drought information (Abdullah *et al.*, 2017). Going beyond visuals, AI offers the module advanced image recognition and natural language processing capabilities, allowing the system to categorize and interpret images, extract information from textual data, and structure it in a way that can be conveyed through speech.

The use of cognitive computing also provides language-translation capabilities, ensuring that DEWS 4.0 can automatically translate text or speech from one language to another (Gudivada *et al.*, 2019). This facilitates the processing of multilingual data, providing real-time translations that allow users to make informed decisions regardless of language barriers. The module's use of an application programming interface (API), in conjunction with cloud-based systems and other technologies, acts as a link for data sharing and collaboration between stakeholders, enabling them to acquire and incorporate drought information into their own platforms or software systems. Thus, a blockchain can serve as a trusted platform for data sharing, making collaboration more efficient by verifying the authenticity of the shared data (Bhushan *et al.*, 2020). Furthermore, blockchain-based smart contracts can be used to govern data-sharing agreements.

- **Module 7: Scenario planning**

The scenario planning module visualizes drought-related data to allow stakeholders to simulate drought scenarios, interact with the data, and assess the impact of different measures on responses and preparedness. It connects a range of innovative technologies, including XR, BDA, AI, and cloud computing. XR, comprising virtual reality and augmented reality, is a key

4IR technology that offers interactive visualizations in 3D and contextual environments (Xi *et al.*, 2023). By examining different scenarios, decision-makers can identify the most vulnerable areas, assess resource allocation needs, and implement timely interventions to mitigate the effects of drought on their regions.

The module further benefits from the use of BDA and AI techniques to process complex datasets and identify patterns within data, enhancing the accuracy and relevance of the generated scenarios (Kaur and Sood, 2021). The system's cloud-based infrastructure ensures continuous collaboration, while an API facilitates data exchange between systems, enhancing the interoperability of the scenario planning module with the other modules and systems. Through cognitive computing, the system can efficiently process large volumes of unstructured data, saving time for decision-makers who need up-to-date information.

- **Module 8: Adaptive Learning**

The adaptive learning module uses advanced algorithms to enable DEWS 4.0 to continually enhance its performance and accuracy through self-adjustment and self-optimization. This innovative approach allows the system to adapt its strategies and responses dynamically, increasing its efficiency in mitigating the impacts of drought. It further ensures that stakeholders receive training that suits their specific requirements. Key 4IR technologies that directly contribute to the success of the adaptive learning module include AI, BDA, and cloud computing. The integration of AI and BDA techniques allows the module to learn from historical data for continuous improvement. For example, after every drought, the module gathers data on user responses, and the algorithms identify the most successful and efficient strategies for each region, creating a knowledge base of best practices.

Although adaptive learning is common in the field of education (Muñoz *et al.*, 2022), it has significant potential applications in DEWS 4.0 for enhancing the learning and response capabilities of stakeholders. The AI plays a crucial role in this process, as it allows the module to personalize training programs for end-users, decision-makers, and other stakeholders involved in drought responses. Furthermore, cloud capabilities ensure that stakeholders can receive training regardless of their location (Chung and Park, 2016). The application of cognitive computing allows for the analysis of qualitative data, such as surveys or impact feedback forms, to identify recurring themes related to specific drought response measures, which may also be crowdsourced. This technology enhances the module's ability to understand and learn from stakeholders' interactions.

4.4. Discussion

4.4.1. Potential applications

The DEWS 4.0 framework is aimed at significantly improving how drought is managed within drought-sensitive sectors in any region, thus revolutionizing the field of DEWS during the 4IR era. When compared to previous industrial revolutions, the 4IR provides important technological improvements such as speed, precision, and automation (David *et al.*, 2022). Various cases were considered to demonstrate the framework's promising potential applications across diverse fields with its advanced data integration, analytical, and communication capabilities (Figure 4-8). These fields include sustainable agricultural practices, water resource management, climate resilience, biodiversity conservation, and disaster management. For instance, by using machine learning techniques such as gradient boosting and outlier detection techniques to predict soil water requirements, Campos *et al*. (2020) identified significant savings (56.4%–90%) in irrigation water requirements, displaying the technologies' impact on accurately optimizing water usage for agricultural practices.

Another potential application involves the monitoring of groundwater levels, river, and reservoir systems through a network of strategically placed sensors and gauges along water bodies (Hui and Rahmat, 2022). In Florida, Gong *et al*. (2016) demonstrated the use of real-time data and advanced modeling techniques to predict groundwater levels one, two, or three months in advance, while a smart flood early warning system in Malaysia forecasted flood conditions within 9 hours of the flood's occurrence to facilitate proactive management strategies (Munawar *et al.*, 2022). This demonstrates the potential to enhance disaster management interventions such as preparedness and response strategies by empowering stakeholders with actionable information (Abid *et al.*, 2021).

Ecosystems can also benefit from DEWS 4.0's accurate data-driven analytics for targeted conservation efforts. By conserving critical habitats, national parks could utilize this innovative system to identify regions where water sources for wildlife are dwindling, enabling rangers to set up water points to prevent animal casualties as a form of adaptation (Bodmer *et al.*, 2018).

For climate change resilience, Dewitte *et al*. (2021) demonstrated the transformative potential of AI in revolutionizing weather forecasting, climate monitoring, and prediction. The framework guidelines offer practical applications for implementing DEWS 4.0 in the real-world context of drought prediction, monitoring, and response (Figure 4-9). However, the actual outcomes of DEWS 4.0 will vary depending on the implementation and integration of the system within existing governance structures, policies, and socio-economic contexts (Rogers and Tsirkunov, 2011).

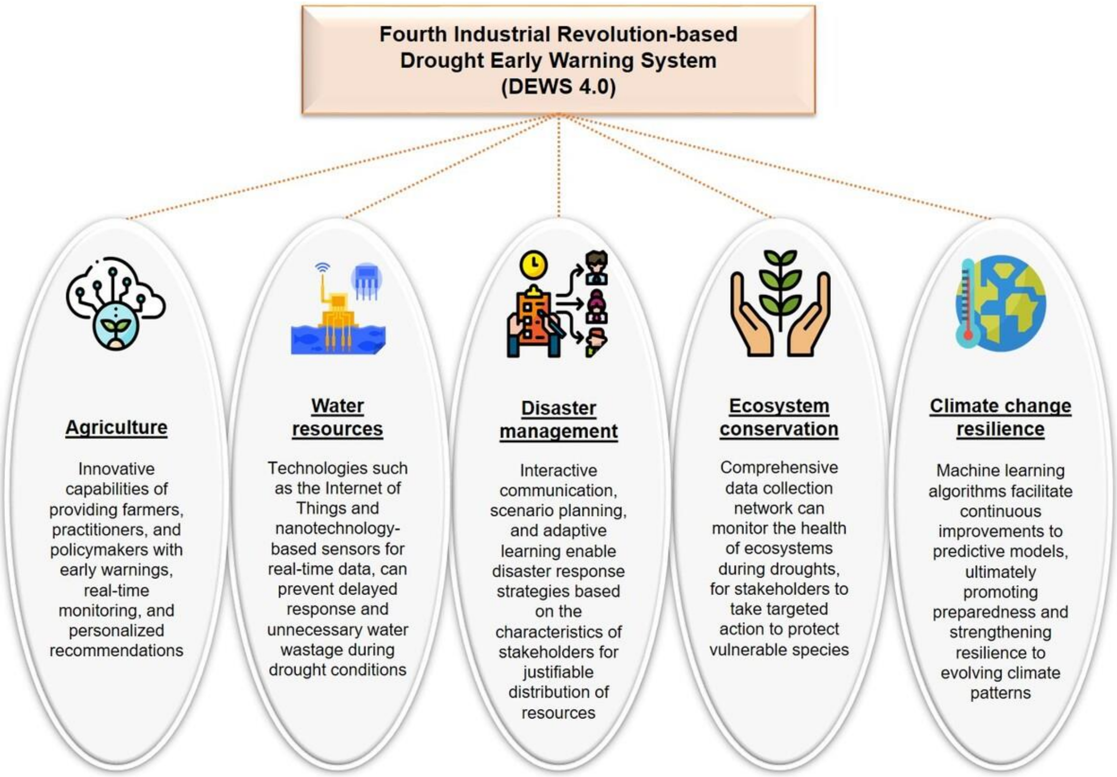

Figure 4-8: Applications of DEWS 4.0 in various sectors.

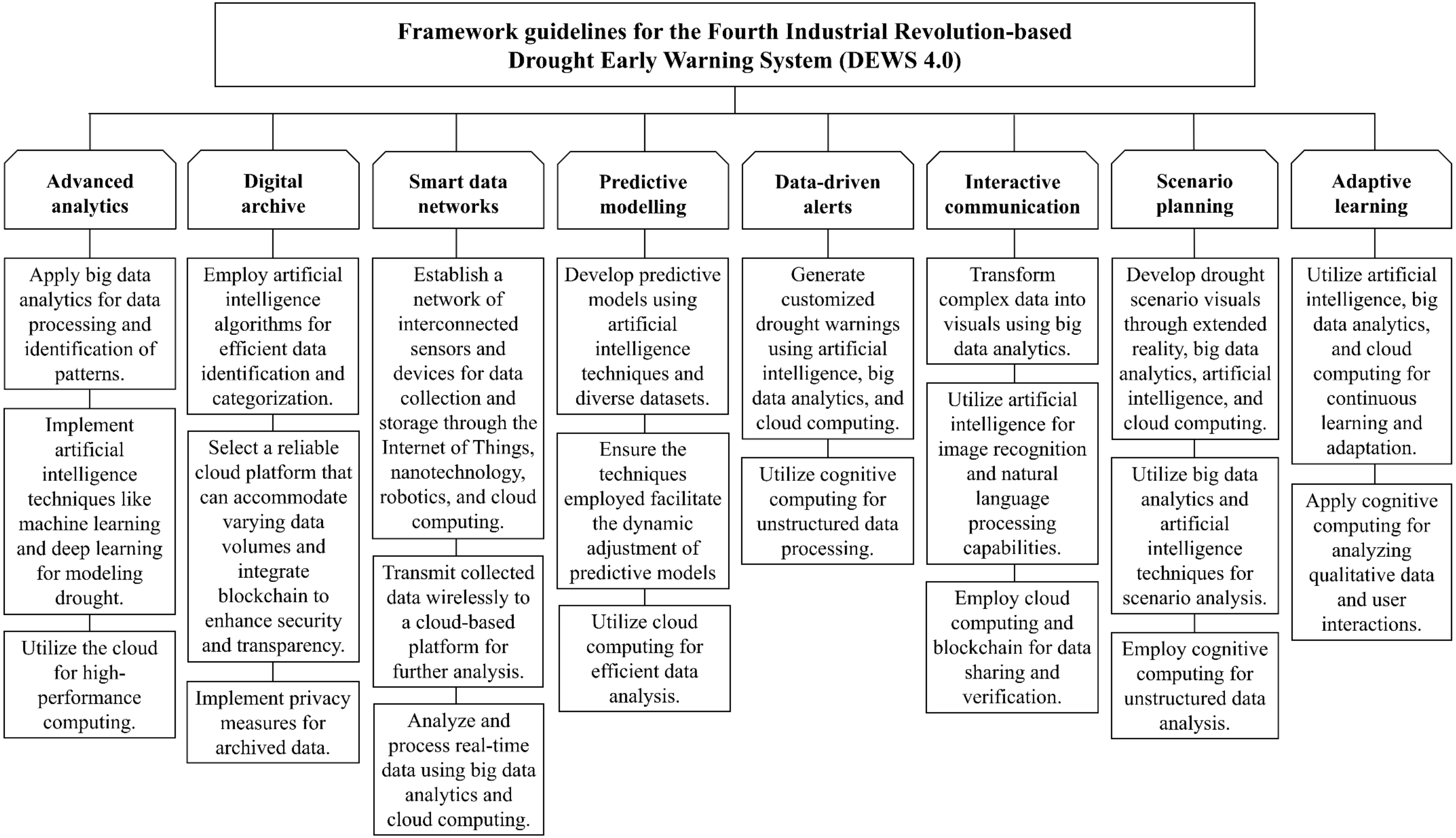

Figure 4-9: DEWS 4.0 framework guidelines for application.

4.4.2. Benefits and limitations

During the shift from traditional DEWS to DEWS 4.0, there will likely be significant advantages and challenges to overcome (Table 4-2). One advantage lies in the advanced skills in data collection, analytics, and the integration of information that improves precision, real-time monitoring, and more accurate alerts. Moreover, the potential system can provide personalized recommendations based on data from various sources. For instance, in an agricultural context, the system can utilize machine learning algorithms to analyze historical crop yield data, soil characteristics, weather patterns, and market prices to provide farmers with tailored recommendations.

Table 4-2: Potential benefits and challenges of implementing DEWS 4.0

Module	Benefits	Challenges
Advanced analytics	Advanced analysis with reduced human error.	Need for skilled data scientists.
Digital archive	Dynamic techniques for collecting, storing, and accessing historical data.	Complexities in ensuring the integrity and preservation of long-term data.
Smart data networks	Enhanced sensor integration and automation for early drought detection.	Equipment maintenance and network discrepancies.
Predictive modeling	Improved forecasting accuracy.	Increased operational costs.
Data-driven alerts	Consistent and tailored alerts.	Complexities in processing and understanding crucial information.
Interactive communication	Interoperability and practical access to information.	Inconsistencies in internet connectivity, digital literacy, and technology fatigue.
Scenario planning	Accurate and timely interventions to mitigate drought effects.	High initial costs and limited technical expertise, potentially delay module use.
Adaptive learning	Targeted response allocation and enhanced capacity building.	May overlook emerging strategies owing to the use of historical information.

The manner in which drought information is represented serves as a key benefit for the system (Jacks *et al.*, 2010), as it employs methods that increase accessibility to a variety of users, including individuals with visual impairments or those who cannot read and write. Adaptive learning features within the DEWS 4.0's framework allow decision-makers to continuously improve their skills and adapt to evolving information. While its API and blockchain capabilities can promote knowledge sharing among the various modules, platforms, and stakeholders, without compromising the information and further benefiting those with limited knowledge and access to advanced technology.

Through the scenario planning module, users can interact with various simulations, making it a dynamic and experiential approach to plan response strategies. It allows users to prepare for a wide range of potential drought scenarios, including flash onsets with limited lead times or prolonged events by developing resilient strategies regardless of the complexity of the condition. This approach not only enhances response capabilities but also minimizes the risks associated with unforeseen challenges. Therefore, adequate training and support would be necessary for all stakeholders.

It is important to note that there may be challenges when utilizing the framework and these include potential pressures on computational resources and operational costs (Xuan *et al.*, 2015). Hence, due to the necessary access to high-performance computing and the implementation of efficient data processing strategies, notable investments in infrastructure and skilled personnel should be prioritized. Furthermore, cybersecurity measures must form an integral component of applying the framework to protect sensitive information (Datta, 2021). Another possible limitation lies in the inconsistencies of Internet connectivity due to unequal infrastructure development and socioeconomic factors. Even in regions where the network is considered reliable, receiving alerts through multiple channels can overwhelm users with a lot of messages. Therefore, ensuring equitable scalability during droughts remains a critical challenge that DEWS 4.0 must address. Policy frameworks should advocate for a balanced approach, wherein technological advancements blend with human-driven responses. Such a holistic approach would lay the foundation for a more resilient, responsive, and sustainable system.

4.5. Conclusions

By presenting strong grounds (a solid foundation that warrants acceptance or consideration of a claim), a DEWS 4.0 framework was developed based on Toulmin's model of argumentation. The framework comprises eight modules that offer a systematic and adaptable approach for incorporating 4IR technologies into DEWS and ensuring that these technologies can be customized to specific contexts and challenges. This proposed framework suggests advanced skills in data collection, analytics, and computational techniques to improve the precision of real-time monitoring for more accurate drought forecasting. Moreover, the adaptive learning capabilities allow the system to provide personalized recommendations based on the analysis of data from various sources. In addition, its AI capabilities increase accessibility to a variety of users, including those with visual impairments or those who cannot read and write.

The API and blockchain capabilities of DEWS 4.0 promote knowledge sharing among the various modules, other systems, and stakeholders, without compromising the information. Through the scenario planning module, users can interact with various simulations, making it a dynamic and experiential approach to planning response strategies. As outlined, the framework guidelines serve as practical tools for real-world applications across various sectors, highlighting its potential to significantly enhance drought preparedness and contribute to a more sustainable and resilient society. However, capacity building will be necessary to maximize the benefits and overcome resistance to new technologies. Future research should investigate the practical implementation of this framework to fully recognize its potential for effective drought management.

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CHAPTER 5. APPLICATION OF THE FOURTH INDUSTRIAL REVOLUTION-BASED DROUGHT EARLY WARNING SYSTEM FRAMEWORK IN SOUTH AFRICA

This chapter has been submitted for publication and is currently under review in: Computers and Electronics in Agriculture (see Appendix 1: Publications)

Abstract

This chapter assessed the Agricultural Drought Early Warning System (ADEWS) in South Africa as a foundation for enhancing its functionality to operate within the context of the fourth industrial revolution (4IR). The evaluation utilized a metric-based approach tailored for early warning systems for climate-related disasters. A content analysis of the system's website was conducted, supplemented by verification from a research report of the system. Consequently, 27 key performance indicators were categorized according to the fundamental components of drought early warning systems and computed through a ratio-based approach in RStudio. Results indicated that the most prominent indicators were associated with the monitoring and warning component, scoring 71%, and dissemination, scoring 67%. The knowledge of risk component showed partial presence, with limitations stemming from the absence of a composite drought index, vulnerability assessment, and trend analysis, whereas the response component was absent. Thus, advancements were recommended to integrate 4IR technologies to fill the identified gaps and introduce new functionalities for improved effectiveness. These include the adoption of smart weather stations and unmanned aerial vehicles to enhance data collection and monitoring capabilities, transitioning to cloud-based hosting for advanced infrastructure, and aligning dissemination protocols with the principles of Web 3.0 for more intelligent interconnections. Furthermore, a decision support element was proposed to assist stakeholders in improving resource allocation, and other management activities, to enhance agricultural productivity and profitability.

5.1. Introduction

The agricultural sector, especially in developing nations, is one of the most vulnerable sectors to the occurrence of drought, with losses exceeding 29 billion US dollars within the 10 years from 2005 to 2015 (FAO, 2019). The growing vulnerability to drought events has increased the impact of drought-related disasters on many communities (Farhangfar *et al.*, 2015). South Africa is no exception, as recurring droughts have adversely led to reduced productivity in major crop and livestock areas, affecting the country's socio-economic well-being (AgriSA, 2016; DAFF, 2019). These droughts occur approximately every 5 to 10 years (DALRRD, 2020d), with a study by Malherbe *et al*. (2016) revealing an increasing frequency of droughts of varying magnitudes from 1980 to 2014.

There is a growing global concern that the occurrence, severity, and duration of droughts may increase as a consequence of climate change and observed rises in extreme weather events (Santos *et al.*, 2014). Thus, necessitating the need to reduce economic losses related to reactive crisis management following drought occurrences by developing proactive management plans, including the implementation of drought early warning systems (DEWS) (Mare *et al.*, 2018). As learned in Chapter 2, several drought-prone regions around the world have implemented DEWS as a major contributing strategy in ensuring drought risk reduction. Systems such as the Famine Early Warning Systems Network (FEWS NET, 2020) and the National Integrated Drought Information System (NIDIS, 2020) incorporate functionalities such as interactive spatial mapping for improved communication, interpretation, and decision-making. This enhances the efficacy of disseminating significant information based on region-specific data to reduce potential impacts on drought-sensitive sectors (UN, 2006).

Based on global efforts and drawing valuable lessons from various international experiences, the Agricultural Research Council in South Africa developed the Agricultural Drought Early Warning System (ADEWS) in 2023. This system, aimed at enhancing the country's resilience to drought events, utilizes a combination of rainfall, vegetation, and model-based data to offer near-real-time drought monitoring and forecasting across the country (ADEWS, 2023). The products generated and disseminated within the system are selected to identify the onset, intensity, and extent of drought, with a focus on highlighting impacts on specific areas of the agricultural sector (Moeletsi *et al.*, 2023).

Following the development of this system, a report by Moeletsi *et al*. (2023) detailed its evaluation with various stakeholders to assess its ability to meet user expectations and to provide constructive feedback for improvement. It was indicated in the report that factors, such as incorporating ideal planting dates, cultivar choices, dam levels, and historical drought information, should be incorporated into the system. Further suggestions were made to address concerns regarding the need to make it user-friendly, as well as its potential for expansion and alignment with other systems in the Southern African Development Community region (Moeletsi *et al.*, 2023). Thus it remains uncertain whether the ADEWS is in line with the fundamentals for establishing effective early warning systems as specified by the United Nations (2016), and whether it can be optimized to align with the characteristics of the current technological environment.

According to Sättele *et al*. (2015), quantifying the effectiveness of early warning systems is essential for demonstrating their impact as risk reduction measures. Moreover, enhancing the design and operation of these systems necessitates a comprehensive assessment of their reliability and effectiveness (Leal de Moraes, 2023). For instance, Lellyett *et al*. (2022) demonstrated the potential of this approach by identifying technical and communication advances within specific areas of climate and weather science to enhance drought early warning systems in Australia. Similarly, Braimoh *et al*. (2018) utilized a comparable approach to assess limitations and opportunities for improving food security early warning systems in Eastern and Southern Africa. The present chapter aims to expand on existing methodology by integrating modern solutions to strengthen the holistic structure of drought early warning systems, crucial for enhancing resilience against drought-related disasters. Thus, the objective was to quantify the effectiveness of the ADEWS through a metric-based approach and explore innovative improvements through the characteristics of the 4IR-based DEWS framework as developed in CHAPTER 4.

5.2. Methodology

Focusing on the case study of South Africa, a content analysis of the ADEWS website https://www.drought.agric.za/ was conducted to evaluate the functional characteristics of the system. Currently, the ADEWS operates on a three-tiered architecture given as follows (Figure 5-1):

- The first tier constitutes a data collection layer supported by *in-situ* and remote sensing data. This layer is specifically designed to handle diverse data formats, indicating enhanced adaptability to changing data landscapes.
- The second tier is a data processing and archiving layer capable of integrating various data sources and generating drought information on a local server. It ensures that the information generated is accurate, reliable, and ready for dissemination.
- The third tier is an information dissemination layer accessible through personal computers and mobile devices, catering to two types of users—mobile and web service users. Moreover, the email notification system ensures timely information delivery for effective communication and decision-making.

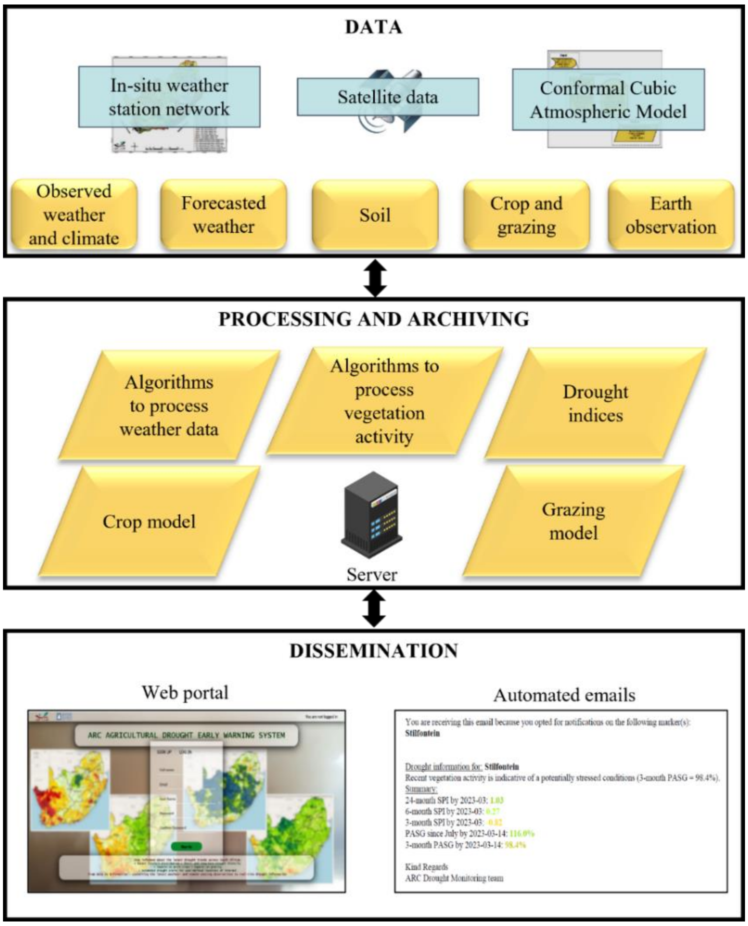

Figure 5-1: The logical architecture of the ADEWS (Moeletsi *et al.*, 2023).

The assessment was based on a modified methodology proposed by Leal de Moraes (2023), employing a metric process which incorporates key performance indicators (KPIs) aligned with the fundamental components of any system, viz.: (1) Knowledge of risk; (2) Monitoring and warning; (3) Dissemination; and (4) Response. The first step was to identify appropriate KPIs considering the many factors that influence the determination of which indicators are necessary for an effective Drought Early Warning System (DEWS). The basis for these indicators was established in Chapter 3 through a review and analysis of existing systems (see Table 3-1). Thus, to enhance inclusivity in the selection process, data was collected from secondary sources, including the websites of established systems, reports, and published material sourced from major databases such as Google Scholar, Web of Science, Scopus, and Science Direct.

The selection criteria involved a systematic approach to ensure that all relevant indicators were considered, reflecting both the operational needs of the DEWS and alignment with best practices. Numerous indicators were identified, and those specifically related to agriculture were selected, resulting in a total of 27 KPIs (Table 5-1). These KPIs were systematically grouped, ensuring that each indicator aligned with fundamental components of early warning systems. The indicators were not evenly distributed due to varying levels of emphasis placed on different components. Some components had a higher concentration of indicators compared to others, but this does not imply their overall significance; rather, it reflects the specific needs and complexities of each component.

Table 5-1: A summary of the key performance indicators utilized in this study to evaluate the effectiveness of the Agricultural Drought Wearly Warning System (Author's construct).

Fundamental component	Key performance indicator
Knowledge of risk	Hazard detection
	Impact
	Composite index
	Vulnerability index
	Hotspot
	Trend analysis
	Time series
	Historical database
Monitoring and warning	Observational network
	Field report
	Forecast
	Spatial map
	Interactive map

	Spatio-temporal resolution
	Warning threshold
Dissemination	Platform
	User-friendly
	Preference selection
	Data file
	Subscription
	Communication channel
	Warning message
	Feedback
	Social media
Response	Contingency plan
	Reporting action taken
	Capacity building

To examine the presence of each selected KPI in the ADEWS, a comparative analysis was conducted on the website, and the report of the system. A ratio-based approach was employed in RStudio (v. 2023.09.0), with each present KPI being assigned a count of one and absent indicators treated as zero. The method involved dividing the number of present indicators by the total number of KPIs and then multiplying by 100 to express the result as a percentage. This percentage signifies the degree of representation that the system achieves within the larger set of KPIs per fundamental component. Thereafter, a scale modified form Leal de Moraes (2023) and Ernesto (2018), was utilized to rate each fundamental component (Table 5-2). Finally, the next step was to synthesize the modules of DEWS 4.0 with the existing architecture of ADEWS and address potential gaps, modify existing protocols, and introduce new elements where necessary.

Table 5-2: Representation scale for key performance indicators within early warning systems (Ernesto, 2018; Leal de Moraes, 2023)

Percentage (%)	**Description**
0 – 20	Not present
21 – 40	Partially present
41 – 60	Moderately present, with major gaps
61 – 80	Moderately present, with minor gaps
81 – 100	Adequately present

5.3. Results

5.3.1. Evaluation metrics

The schematic representation of each component's magnitude from ADEWS is illustrated in Figure 5-2. Overall, the ADEWS displays a noticeable skew towards specific components. The results indicate a partial presence of knowledge of risk, scoring 38%, indicating significant gaps. This aligns with the absence of indicators related to the vulnerability index, hotspots, and trend analysis, suggesting potential shortcomings in the system's comprehensive assessment capabilities. For monitoring and warning, ADEWS displays a moderately present status at 71%, with minor gaps, indicating a solid foundation with room for improvement, especially in aspects like early warning thresholds.

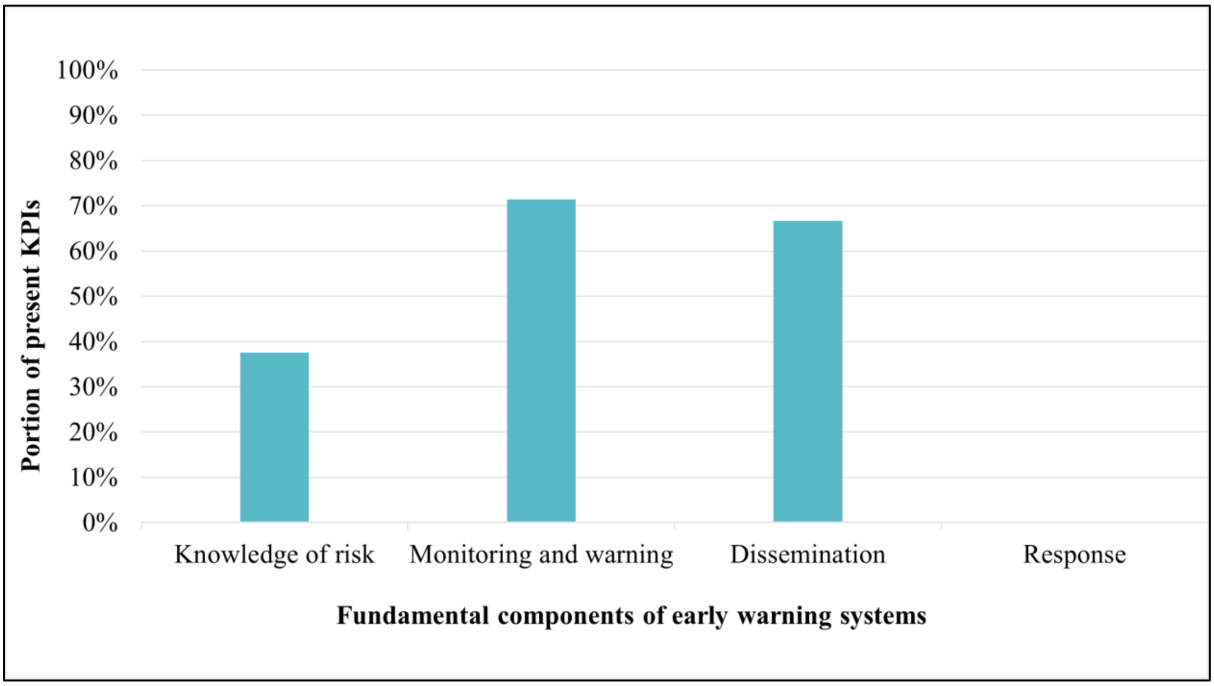

Figure 5-2: The scale of each fundamental component as represented in the ADEWS.

The dissemination component scored 67%, indicating a moderately present status with minor gaps, like the monitoring and warning component. While the most substantial gap observed in the ADEWS was in the response component, scoring 0%, suggesting its absence. This indicates the critical need to include messages containing response actions for responding to warnings, planned actions for post-drought scenarios, and the provision of instructional manuals to educate users on how to effectively utilize the system (Hmoudi, 2016).

- **Knowledge of risk**

In terms of the knowledge of risk component (Table 5-3), the system utilizes numerous *in-situ* and remote sensing-based drought indices derived from data collected by automatic weather stations and historical Geographic Information System (GIS) layers. To identify potential risks in agriculture, the water requirement satisfaction index represents crop performance, based on the satisfaction of water requirements for seasonal crops (Senay and Verdin, 2003).

Table 5-3: Evaluation outcome of the ADEWS based on the knowledge of risk component

Fundamental component	Key performance indicator	Presence	Application within the system
Knowledge of risk	Hazard detection	1	Utilizes various drought indices calculated from observed data and historical records.
	Impact	1	Various indices focus on crop and vegetation activity to indicate prolonged drought stress and provide information on agricultural impacts.
	Composite index	0	-
	Vulnerability index	0	-
	Hotspot	0	-
	Trend analysis	0	-
	Time series	0	-
	Historical database	1	Maintains records of drought-related data dating back to the previous five years.

The Percentage of average seasonal greenness and vegetation condition index are based on vegetation activity, proving beneficial for the summer growing season when vegetation is most active (Heim, 2002). The inclusion of modeling components, such as crop modeling using the Decision Support System for Agrotechnology Transfer CERES-Maize model and grazing modeling with the PUTU VELD model, enhances ADEWS' ability to assess drought impacts on agricultural productivity for both crops and grassland. However, these indices are utilized individually rather than being aggregated into a composite drought index, similar to the United States Drought Monitor (Svoboda *et al.*, 2002) and the New Zealand Drought Index (NIWA, 2016).

Another limitation of the ADEWS is its capacity to assess vulnerability and identify hotspot regions based on historical data, thus, limiting the system's ability to measure drought risk in various regions. Without such assessments, the system may overlook crucial information on localized areas at high risk and fail to provide an understanding of potential impacts on vulnerable populations (Guo *et al.*, 2021). It was further observed that the system lacks functionality to provide drought trends and time series, yet, it maintains a historical database, including drought-related data spanning the previous five years. This data can be utilized as a proxy for understanding past drought events, allowing improved decision-making and response planning.

- **Monitoring and warning**

In the evaluation of the monitoring and warning component (Table 5-4), one notable characteristic of the ADEWS was its observational network, which encompasses multiple datasets. The primary source of collecting data is the weather station network consisting of over 600 automatic weather stations monitoring air temperature, rainfall, relative humidity, solar radiation, wind speed, and direction, and the data are stored at hourly temporal resolution (Moeletsi *et al.*, 2022). The observed data are interpolated into GIS layers and then applied in the ADEWS, avoiding reliance solely on point data.

Table 5-4: Monitoring and warning evaluation outcome of the ADEWS

Fundamental component	Key performance indicator	Presence	Application within the system
Monitoring and warning	Observational network	1	Employs inputs from various datasets to develop an automated processing service that can compute drought indicators.
	Field report	0	-
	Forecast	1	Short- to medium-term weather forecast data are included in the system.
	Spatial map	1	Utilizes a spatial map with a colour scale legend to display drought severity.
	Interactive map	0	-
	Spatio-temporal resolution	1	Computes drought indicators for the country per quaternary catchments at various time scales.
	Warning threshold	1	Provides warnings based on individual drought indices.

The system further employs satellite data, consisting of both meteorological variables and vegetation factors. Suitable remote sensing systems are those that can provide up to low spatial and high temporal resolution data necessary for continuous monitoring (Dalezios *et al.*, 2014). In the ADEWS, vegetation indices are produced from 16-day moderate-resolution imaging spectroradiometer composites at a 500 m spatial resolution. However, the system's ability to validate its findings with real-time ground data (Sun *et al.*, 2017) is limited by the absence of field reports, which provide valuable information on localized drought impacts on agricultural systems.

Another important characteristic of the ADEWS is the drought forecasting function. The system utilizes the conformal cubic atmospheric model, initiated every 24 hours in operational mode with a spatial resolution of 16 km to generate 6-day forecasts. However, this temporal resolution may be suitable for detecting short-term drought conditions within the season rather than capturing the broader progression of agricultural drought. Forecasts tailored to the growing season could offer farmers more time to develop effective drought mitigation strategies (Feng *et al.*, 2020), especially considering South Africa's variation in seasonal rainfall patterns, which impact specific crop growing seasons (e.g. October - April).

In terms of visualizing drought conditions, the ADEWS employs a spatial map accompanied by a colour scale legend to illustrate drought severity. However, without interactive features, users are unable to perform spatial queries or explore temporal trends, thus restricting their ability to customize the display and analyze the data in depth (Smith, 2016). Although the system demonstrates a spatio-temporal resolution characteristic by computing drought indicators across quaternary catchments at various time scales, the system still requires additional improvements to reach its full potential. Another area requiring improvement is the warning threshold characteristic necessary for generating drought warnings. Presently, the system issues warnings based solely on individual drought indices, neglecting the combination of both biophysical and socio-economic indicators to determine predefined levels of alert.

- **Dissemination**

The ADEWS provides a portal, accessible through a web-based graphical user interface, offering a convenient platform for users to interact with the system (Table 5-5). Yet, as indicated by a system testing report (Moeletsi *et al.*, 2023), users found navigation challenging, as it took extra time to locate relevant information, portraying the system as less user-friendly. It was further observed that users have the capability to create a map layer based on preferences, such as drought index and time, but they are unable to download or export a data file containing the required information. The website requires users to register for access and upon logging in, a communication channel is established in the system wherein users receive automated daily emails containing relevant drought indicator information. Users can identify specific points of interest and choose whether they would like to receive automated e-mail alerts for drought indicator information of the identified points of interest.

A gap was noted in warning messages, as the system currently sends messages focusing on observed conditions and lacks a feature for issuing warnings based on forecasted drought. This limitation has the potential to delay users from making timely and informed decisions in response to impending drought conditions (Funk *et al.*, 2019). It was further observed that although there is a provision for user feedback, allowing users to respond to emails for system improvements, the website lacks clarity on how to reach the developers or those responsible for system maintenance and updates. Additionally, the ADEWS lacks a social media presence, limiting communication channels between users and the system's responsible individuals.

Table 5-5: Dissemination evaluation outcome of the ADEWS

Fundamental component	Key performance indicator	Presence	Application within the system
Dissemination	Platform	1	The system is available as a web-based graphical user interface.
	User-friendly	0	-
	Preference selection	1	The user can generate a map layer based on their preferred indices for a given time.
	Data file	0	-
	Subscription	1	Free subscription for receiving emails about drought conditions at preferred locations.
	Communication channel	1	Subscribed users receive automated daily e-mails containing drought information.
	Warning message	1	Messages include a summary of outputs given by various drought indices.
	Feedback	1	Users can respond to emails for feedback on system improvements.
	Social media	0	-

- **Response**

The evaluation of the ADEWS revealed a significant gap in the response component, with the system currently lacking indicators for planned response actions, feedback on actions taken, and capacity building (Table 5-6). This implies a critical need for improvement to enhance the efficiency of the system in building the response capacity of those affected.

Table 5-6: Response evaluation outcome of the ADEWS

Fundamental component	**Key performance indicator**	**Presence**	**Application within the system**
Response	Contingency plan	0	-
	Reporting action taken	0	-
	Capacity building	0	-

5.3.2. Improvements of the ADEWS using 4IR technologies

The overall evaluation of ADEWS highlighted gaps in fundamental components. Thus, proposed adjustments to the current architecture and flow of the system (Figure 5-3) demonstrate how it can operate effectively within a 4IR-based environment through the foundational modules of DEWS 4.0 (see CHAPTER 4). Moreover, an additional tier, known as decision support, was introduced to address the lacking functions of the response component. Collectively, these advancements significantly enhance the capabilities of the system by addressing identified gaps, improving existing functionalities, and introducing new features.

- **Data**

In its current operational state, the ADEWS efficiently collects data from weather stations and satellites to assess data. To enhance data management, DEWS 4.0 suggests the integration of smart weather stations into its infrastructure. These stations employ a network of interconnected Internet of Things (IoT) sensors and cloud-based platforms to collect, analyse, and disseminate real-time weather data (Bella *et al.*, 2023). Moreover, employing IoT soil sensors in farms and drought-prone areas can enhance real-time monitoring of soil moisture levels and fill gaps in regions historically lacking soil moisture data (Johnson *et al.*, 2020). Moreover, the integration of Unmanned Aerial Vehicles (UAVs) with advanced remote sensing capabilities that can focus on smaller, targeted agricultural areas (Munghemezulu *et al.*, 2023) presents a significant advancement for the monitoring capability of the ADEWS.

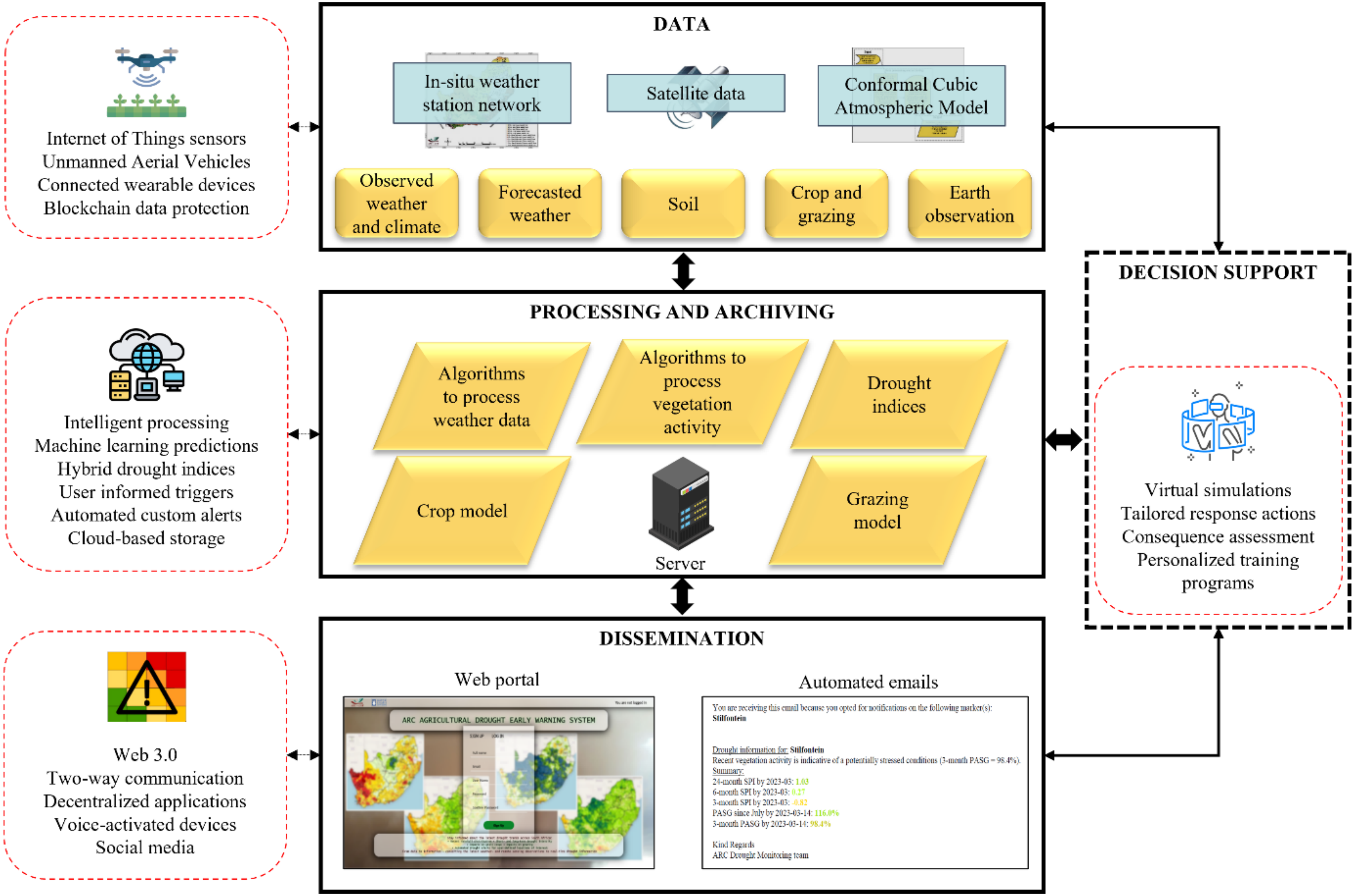

Figure 5-3: Proposed adjustments to the ADEWS architecture for effective operation in a 4IR-based environment.

The combination of *in-situ*, satellite, IoT- and UAV-based data collection will ensure more localized, and timely information, thereby improving ADEWS's capacity to assess agricultural drought conditions. In addition, technologies such as connected wearable devices can be utilized to collect user and farm reports, crucial for informing drought risk modeling. This can rectify the defect in functionality by integrating socioeconomic indicators with changes in agricultural production, specific to the regions under consideration (Schiraldi and Roundy, 2016). This enhancement would empower ADEWS to stay current with evolving drought conditions, affected populations, and other essential factors crucial for identifying hotspots, vulnerable areas, and communities.

To achieve advanced security measures for data protection, integrating encryption algorithms based on widely accepted standards into data management workflows would serve as an important feature in securing sensitive information (Bhushan *et al.*, 2020). To ensure transparency and tamper-resistant records while ensuring data integrity, the capabilities of blockchain technology should be utilized. Furthermore, it is essential for systems with advanced technological components, such as the proposed 4IR-based ADEWS to undergo regular security audits and susceptibility assessments, utilizing reputable cyber security tools.

- **Processing and archiving**

A proposed improvement in the infrastructure of the ADEWS involves transitioning from its localized hosting to cloud-based hosting, utilizing the capabilities of the digital archive module of DEWS 4.0. Complementing this shift, cloud-based hosting will require the integration of high-performance computing to accelerate data processing and analysis (Mateescu *et al.*, 2011). For example, with graphics processing units and parallel processing, the system can significantly enhance computational resources, supporting 4IR-based algorithms necessary for data processing. Furthermore, the integration of big data analytics (BDA) should be considered to establish a secure and efficient environment for managing the substantial volume of data generated by the ADEWS.

Currently, the ADEWS processes input data in GIS formats like GeoTiff, ESRI Grid, or ESRI shapefile, utilizing Python and HyperText Markup Language scripting languages. Practically, programming enhancements within the 4IR environment should optimize these existing languages and scripts. Adapting Python scripts to handle data from IoT sensors and UAVs would ensure compatibility with the proposed improvements. Refining codes, incorporating the latest features from the Leaflet library, and implementing algorithms such as machine learning, capable of recognizing trends and patterns in historical data (Shen *et al.*, 2021), the system can be trained to detect and correct anomalies in the data automatically.

To improve hazard detection, which is currently performed by drought indices (Zargar *et al.*, 2011), technologies of the 4IR introduce artificial intelligence (AI). This technology can be utilized to refine the current indices for developing hybrid drought indices, which assimilate multiple indicators from a combination of both *in-situ* and remote sensing-based drought sources (e.g. Sun, 2009; Zhao *et al*., 2011). This evolution exceeds conventional methods, addressing limitations in accurately capturing and representing the complexity of drought dynamics across various ecosystems (Adnan *et al.*, 2023). In addition, for precise agricultural drought prediction, the ADEWS can incorporate machine learning algorithms, to analyse complex relationships among multiple variables based on historical and climatological data (Rhee *et al.*, 2016).

Research has demonstrated the importance of defining significant threshold levels through operational indices for users to have a better understanding of the various characteristics of drought (Mannocchi *et al.*, 2004). In an agricultural context, the utilization of continuous learning capabilities enabled by AI and cloud computing can enhance the ADEWS' early warning thresholds based on predicted, observed, and user-provided data. This dynamic functionality would therefore ensure that the system remains responsive to changing conditions and diverse agricultural and socio-economic landscapes.

- **Dissemination**

To function in a 4IR environment as a decentralized and interconnected system, the ADEWS should operate on both the backend and frontend, aligning with the principles of Web 3.0 (Figure 5-4). The Web 3.0, often referred to as the Semantic Web, is characterized by improved interoperability, machine-to-machine communication, and decentralized architectures (Gan *et al.*, 2023). While Web 4.0—the Intelligent Web is still in its conceptual phase (Jain, 2023), the functionalities of Web 3.0 are applicable to facilitate two-way communication through various channels and contrast the current static webpage of the ADEWS, which provides a one-way communication method. For instance, as the ADEWS creates personalized accounts for users, offering drought-related information for their regions, 4IR advancements can enable them to input local data such as crop, irrigation, or farm management activities to generate tailored information.

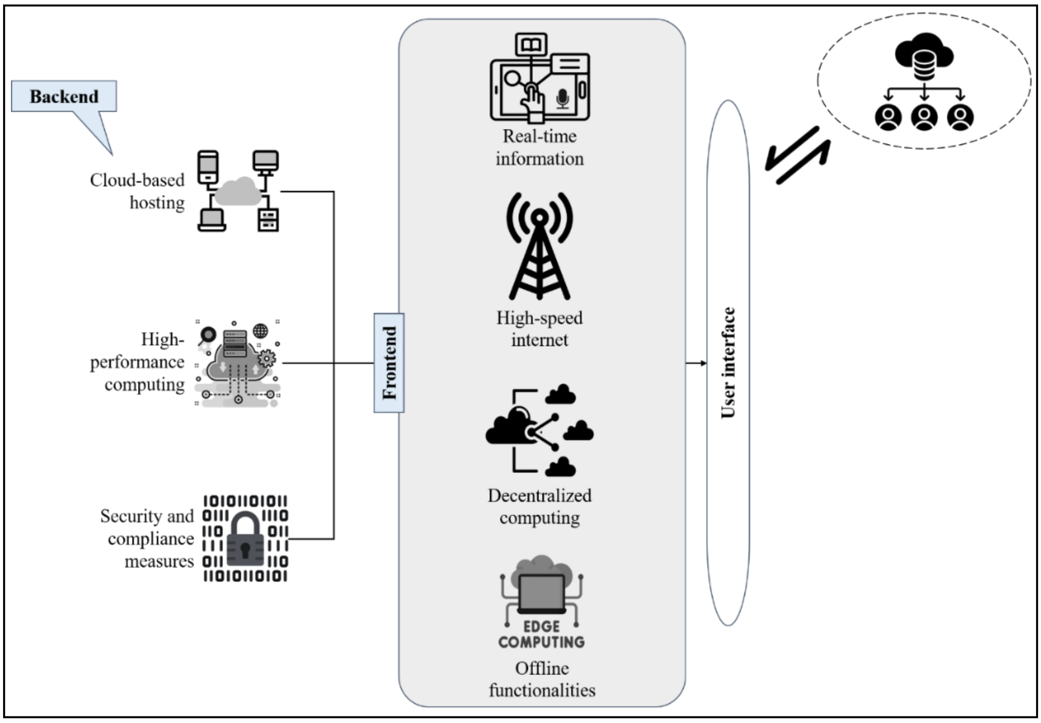

Figure 5-4: Requirements for the infrastructure of a 4IR-based agricultural drought early warning system.

In addition to the current email notifications method, a decentralized mobile application for farmers and other stakeholders can deliver personalized drought alerts, allowing users to input real-time observations, and provide a user-friendly interface (Rivera, 2016). Furthermore, integrating with smartwatches or other wearables is another option that would enable users to receive alerts directly on their wearables and provide feedback through simple interactions. Sending concise drought alerts via text messages is a widely accessible method, even in areas with limited internet connectivity, thus 4IR can enable users to respond with simple keywords or codes (Silva Souza *et al.*, 2017). For users who prefer auditory information, implementing voice-activated systems would allow users to enquire about drought conditions verbally and receive spoken updates, which can be particularly useful in rural areas. Furthermore, linking the ADEWS with social media platforms, would enhance its capabilities to deliver alerts through preferred channels and aggregating user-generated content for improved situational awareness.

It is noteworthy that network requirements for real-time data exchange are crucial for reliable dissemination (Kaufmann and Peil, 2020). Thus, different connectivity technologies like Wi-Fi, cellular, and low-power wide-area networks can be utilized for smooth communication and data exchange among sensors and devices (Bella *et al.*, 2023). To address network constraints, particularly in remote areas, the ADEWS can explore the integration of decentralized computing and offline functionalities for users to input data, receive alerts, and engage with the system locally. Technologies such as edge computing can allow certain processing tasks to be performed on users' devices and reduce dependency on continuous network connectivity (Ye, 2021). This implies that in regions with intermittent or no network access, users can actively participate in the system, with their data seamlessly integrated once network connectivity is re-established.

- **Decision support**

Decision support involves providing practical recommendations, and relevant information to guide stakeholders in making informed choices regarding response and mitigation strategies (Calvel *et al.*, 2020). The previous elements of the ADEWS form the basis for decision support, as their main functions are to detect and communicate potential drought risk information to agricultural stakeholders. Yet, based on the ADEWS evaluation, specific functionalities related to decision support, including response and mitigation strategies, as well as capacity building were absent. Hence, capabilities of adaptive learning, data-driven alerts, interactive communication, and scenario planning modules of the DEWS 4.0 can be suggested as practical advancements to bridge the gap between the identified drought risks and the necessary actions to be taken.

In a situation where the system detects a decline in soil moisture levels and predicts a drought event, it can utilize AI algorithms to generate specific actions such as adjusting irrigation scheduling or implementing water conservation measures. These recommendations would be disseminated to end-users through interactive communication channels, encouraging active participation from farmers and other decision-makers. User input serves as an important factor during this process, as it can enable the decision support element to tailor its responses based on new data and ensure that response and mitigation strategies align with the specific requirements of users and the dynamic nature of drought events.

The scenario planning module of DEWS 4.0 similarly offers a promising role in decision support strategies. It introduces the use of AI, BDA, and extended reality (XR) to simulate various drought-related scenarios specific to agriculture. Through XR devices, users can virtually assess the consequences of different interventions, such as modifying planting dates, to minimize risk and improve productivity (Çöltekin *et al.*, 2020). This can further be extended from the farmer to policy-making level where decision-makers can assess the effectiveness of various mitigation interventions for proper resource allocation. Moreover, stakeholders involved in drought management in South Africa can benefit from this technology when preparing and evaluating their contingency plans (see CHAPTER 2).

To enhance capacity building, technologies of the 4IR enable targeted information delivery by generating personalized training programs based on historical drought data and user interactions. This would contribute to the users' capacity to respond effectively to drought situations throughout different phases of occurrence (Twomlow *et al.*, 2008). Additionally, the interactive communication module can facilitate continuous interaction among diverse stakeholders to participate in discussions through features like real-time messaging systems (Kaufmann and Peil, 2020). For example, a farmer experiencing prolonged drought conditions in a specific region can share observations and encourage collaborative engagement with other users. Through application programming interface and blockchain abilities, the ADEWS can further be integrated with existing databases and complement systems for users to have access to comprehensive information necessary for informed decision-making (Jung *et al.*, 2020).

5.4. Conclusions

This study aimed to evaluate the extent to which the operational ADEWS in South Africa has implemented the fundamental components of an effective early warning system, serving as the foundation for its enhancement into a 4IR-based system. Through a metric-based approach, the results revealed a notable emphasis on monitoring and warning, as well as dissemination components within the ADEWS. However, the knowledge of risk component was only partially present, while the response component was largely absent. The current architecture and flow of the system were improved through the capabilities of 4IR technologies as guided by the DEWS 4.0 framework. This included utilizing technologies such as IoT, AI, BDA, and cloud computing to improve precision in drought risk assessment, prediction, and delivery of real-time, customized warning messages tailored to its users. Adaptive learning from continuous user interactions further enables the system to adapt and evolve to user requirements during drought events.

Transitioning from the static web pages, with limited interactivity to the prospective implementation of Web 3.0 can facilitate more intelligent interactions within its operation and between users. This will provide an environment conducive to interoperability, artificial intelligence, machine learning, decentralized technologies, blockchain, and enhanced privacy and security measures. Furthermore, a new tier called decision support was proposed to the current architecture, particularly targeting to improve the response component. This addition aims to build the capabilities of users in developing various response and mitigation strategies, through capabilities of adaptive learning, customized alerts, interactive communication, and scenario planning.

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CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary of main findings for each research objective

Objective 1: Assess the effectiveness of disaster risk reduction policies in South Africa to facilitate the adoption of an innovative DEWS within the agricultural sector.

- The survey demonstrated that two out of the seven participating provinces reported having their drought plans, while the remaining provinces depended on provincial disaster management frameworks and seasonal contingency plans.
- A significant majority of participants (62%) incorporated online platforms to access various policy documents, with 38% still relying on traditional methods.
- At the national level, drought policy interventions were mainly focused on providing funding to support projects related to disaster risk reduction and monitoring the various projects for compliance.
- Prevailing themes for drought disaster risk reduction at the national level included planning, coordination, funds allocation, resource provision, early warning, monitoring, and evaluation.
- Participants at the provincial level indicated the following prevailing themes for drought disaster risk reduction: farmer projects, awareness campaigns, early warning, risk assessments, infrastructure, and resource allocation.
- A lack of confidence in the effectiveness of the implemented measures was highlighted by 68% of participants. Factors such as unsustainable farmer projects, dependency on government aid, and the absence of a formal evaluation for interventions were identified as obstacles to achieving efficiency.
- Limitations in policy implementation further included factors such as early warnings not tailored to farmers' characteristics, imbalances in resource allocation, delays in response due to lengthy procurement processes, and limited capacity in human resources.
- The flexibility of policies indicates the adaptability required to introduce innovation. Continuous stakeholder engagement also presents opportunities for technology to enhance the ability to tailor information to meet stakeholder needs. The manual documentation of field reports, reported by 59% of survey participants, marks a promising beginning for the introduction of digital methodologies.

Objective 2: Review the existing DEWS to determine strengths and weaknesses to identify opportunities for improved efficiency.

- The review revealed that various drought-prone regions around the world have implemented drought early warning systems (DEWS) to prepare, respond, and mitigate the impacts of drought on vulnerable sectors.
- Eight operational web-based DEWS, primarily focused on agriculture, were identified, revealing a total of 14 varying characteristics collectively, with disparities in presence across the different systems.
- Among the eight systems, six demonstrated the capability to quantify and monitor drought based on multiple indicators through a composite drought index.
- More than 60% of the systems were found to utilize climate and weather forecasting for predicting future droughts, with the remaining systems issuing warnings based on observed conditions.
- Displaying drought conditions via a spatial map was common across the systems. However, only the National Integrated Drought Information System and the Famine Early Warning Systems Network featured interactive drought maps.
- Dissemination of drought information via social media was observed in only three systems.
- The lack of integrating field observations to model and monitor drought, interactive maps for enhanced visualization, and contingency plans to build response capacity were identified as gaps within most established systems.

Objective 3: Investigate the integration of 4IR technologies within the framework of DEWS with a focus on identifying points of synthesis, challenges, and transformative impacts.

- Bibliometric analysis revealed that research publications integrating components of 4IR into drought-related topics began in 2015 with only five, but experienced a rapid increase, reaching 82 publications in 2023 alone.
- China and the United States have demonstrated a focused investment in understanding and utilizing 4IR technologies to enhance drought management, contributing to 79 and 51 publications, respectively since 2015. Countries such as Malaysia, Belgium, Morocco, South Africa, and Georgia had less than 20 publications.

- The connections between keywords related to the application of 4IR technologies in drought research were widely distributed and displayed a strong emphasis on data collection, analysis, and prediction, with agriculture and hydrology being the dominating areas of application.
- Guided by Toulmin's model of argumentation, a framework of eight interconnected modules introducing 4IR technologies to enhance drought early warning capabilities was proposed.
- Technologies such as artificial intelligence (AI), big data analytics (BDA), and cloud computing were integrated into all modules, while the incorporation of the Internet of Things (IoT), nanotechnology, robotics, blockchain, and extended reality (XR) enhanced specific modules.
- Integrating IoT-based sensors and unmanned aerial vehicles (UAVs) can improve real-time monitoring of biophysical indicators, while natural language processing can analyze data from unstructured sources such as textual formats, facilitating the prediction of drought months in advance.
- Utilizing advanced analytical capabilities driven by machine learning and deep learning techniques can result in savings of over 50% of irrigation water.
- The application programming interface and blockchain capabilities promote knowledge sharing while ensuring data security, and users can further engage with various simulations through XR devices to enhance the development of response strategies.

Objective 4: <u>Evaluate the feasibility of integrating a 4IR-based DEWS framework into the current agricultural system of South Africa</u>.

- The evaluation metrics of the Agricultural Drought Early Warning System (ADEWS) in South Africa indicated a bias toward monitoring, warning, and dissemination components. The knowledge of risk component showed partial presence, while the response component was absent.
- Results indicated that the ADEWS currently lacks several critical functionalities, including the ability to assess vulnerability and trends, integrate field reports, incorporate an interactive map, and provide users with the ability to download necessary data files.

- Additional gaps were identified in the system's dissemination process, characterized by static web pages that are not user-friendly and a lack of alternative access methods such as social media platforms.
- The integration of 4IR advancements into the current architecture of the ADEWS highlighted the potential of utilizing a combination of smart sensors and devices for collecting more localized data. This data can then be processed by refining the existing Python scripts to effectively manage big data.
- Transforming existing agricultural drought indices into hybrid models and integrating AI and cloud computing technologies to refine early warning thresholds will effectively capture and portray the multifaceted nature of drought dynamics across different agroclimatic regions.
- Research findings suggest that, in contrast to the current webpage of the ADEWS, Web 3.0 enables two-way communication across various channels, thereby enhancing interoperability, and machine-to-human interaction, and supporting offline functionalities necessary for regions with limited network access.
- A 4IR-based decision support tier was introduced to mitigate the limitations identified within the response component.

6.2. Recommendations

The current study provided evidence indicating that the drought early warning system tailored for the agricultural sector in South Africa requires improvement. While there were positive aspects to policy implementation for drought risk reduction, significant challenges were observed. Furthermore, the current web-based system indicated several limitations in aligning with the principles of the 4IR. It was revealed that the use of 4IR technologies can be incorporated into DEWS for enhanced functionality, ultimately leading to high efficacy in terms of managing drought risk.

The case study on utilizing these technologies on the current ADEWS of South Africa further showed the framework's potential feasibility to significantly enhance its capabilities by addressing identified gaps, improving existing functionalities, and introducing new features. Therefore, to implement the proposed 4IR-based drought early warning system framework—DEWS 4.0, the first requirement would be to strengthen the system's infrastructure by investing in high-performance computing resources including specialized hardware, software, and cloud computing services. Another necessity includes sourcing expertise in blockchain development, smart contract programming, and cryptographic protocols for upgrades in networks, and security measures.

To enhance agricultural drought hazard detection and monitoring, this study recommends investment in IoT sensors and UAVs. In addition, access to diverse and reliable data sources, such as historical records and real-time sensor data, should be established through partnerships with relevant organizations to facilitate knowledge of drought risk for any region. Given the vast amount of data generated through smart sensors, the study emphasizes implementing specialized software tailored to applying algorithms that integrate datasets and remove errors or outliers to facilitate analyses. Hence, the necessity of expertise in machine learning and AI for data pre-processing, training, and application of models for drought risk assessments.

Improved communication supporting real-time dissemination of warning alerts and advisories through multiple channels requires investment in network upgrades and partnerships with telecommunication providers, technology developers, and communities to develop user-friendly interfaces and feedback mechanisms. Creating personalized engines to deliver tailored information to stakeholders is a key part of an innovative system. Therefore, implementing strategies like scenario planning needs expertise in extended reality to develop appropriate models and user interfaces for different users. Moreover, conducting stakeholder engagements to provide training on these decision-support tools necessitates the formulation of training material, workshops, outreach programs, and ongoing technical support.

Based on these requirements, it is therefore imperative to formulate a transformative strategy that will evaluate feasibility based on available resources, processes, and capabilities needed to support scalability. Furthermore, given the unique social, economic, and environmental challenges in South Africa, it is essential to prioritize technological advancements that will serve the well-being and requirements of end-users, including farmers, cooperatives, extension officers, agricultural equipment manufacturers, and policymakers. Therefore, further research is required to evaluate the agricultural sector’s readiness to embrace this innovative approach, while ensuring that the system is user-centric and effective.

6.3. Research contribution to knowledge and practice

This research makes a substantial contribution to the field by addressing a critical subject in agricultural disaster management by enhancing the effectiveness of drought early warning systems to mitigate risks, particularly during the 4IR era. The study developed a conceptual framework that demonstrated advancements in data collection, processing, and transformation of drought-related data into useful information. Interactive communication technologies were introduced to facilitate access to information on personal devices, overcoming time, visual, or network constraints. In addition, the proposal of a decision support element based on the capabilities of BDA, AI, cloud computing, and XR offered stakeholders valuable tools to optimize resource allocation and streamline management activities. This approach is expected to contribute to advancements in the management of drought-related disaster risk reduction.

Merging the framework's innovative capabilities with established systems would create a network that offers a comprehensive and robust approach to drought preparedness. By focusing on evaluating the performance and impact of current DEWS for agriculture, the research not only fills a crucial gap in the literature but also offers practical implications for policymakers and practitioners. Adopting this framework can serve as a benchmark for an integrated drought-information hub and thereby empowering decision-makers to transition from crisis management to proactive risk management.

Furthermore, the study's findings offered novel recommendations to improve current South African policy implementation, reducing future drought impacts on agriculture. Owing to its reliance on universally accepted components, this study has broader implications, making it applicable in various regions globally facing similar challenges with agricultural drought. Therefore, it serves as an instrument for identifying inconsistencies in implementing drought policy and formulating effective measures tailored to address drought risk in diverse regions. Overall, this study demonstrated a high level of originality, depth, and methodological precision, making it a noteworthy addition to the academic literature on agricultural disaster management.

6.4. Future research

The scope of this study was limited to 4IR technologies as key enablers for transitioning the traditional DEWS into an innovative system. Due to the limited scientific knowledge of implementing 4IR in this field, this was a conceptual approach and deliberately excluded technical elements such as computer programming and hardware, necessary for the physical design phases, particularly since a prototype and full implementation of a newly conceptualized system may be resource-intensive and time-consuming. Moreover, the conventional benchmarking approach against best practices was found to be constraining.

Future research should focus on investigating the technical requirements of implementing the framework, considering the practical challenges and opportunities identified in this study. Pilot projects can be initiated in selected regions to test the framework's functionality, identify potential challenges, and gather feedback from end-users before scaling up implementation efforts. Moreover, for integration with current systems, analyses such as proof of concept studies, user experience surveys, and impact assessments could effectively compare the new framework's effectiveness and provide empirical evidence of improvements in performance. Over time, conducting a comparative analysis across different regions and sectors, along with longitudinal studies tracking the implementation and outcomes of the DEWS 4.0 framework, would enhance our understanding of its long-term impacts and sustainability.

In the context of South Africa, maintaining a balance between technology and potential users should be addressed by investigating the diverse requirements of stakeholders through baseline assessments. This will align with the standard procedure of developing effective DEWS, emphasizing the significance of including end-users to ensure that the information provided is tailored to their needs and that appropriate measures can be taken in response to the information provided. For instance, drought-prone regions could be prioritized for water conservation technologies, while smallholder farmers might benefit from improved infrastructure to enhance market access. Targeting specific agricultural systems, such as maize production in the Free State or fruit farming in the Western Cape, would allow for the development of tailored strategies that address unique local challenges. Thus, conducting cost-benefit analyses would also be necessary to evaluate the economic efficiency of the different approaches suggested in the framework.

APPENDICES

Appendix 1: Publications

1) Peer reviewed publications:
    - **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,p.102615. https://doi.org/10.1016/j.ijdrr.2021.102615
    - **Masupha, T.E.,** Moeletsi, M. E., Malherbe, J., Maluleke, P., & Beukes, P. J. (2023). Agricultural drought preparedness framework for South Africa. In L. Myeni, M. Moeletsi, & T. Fyfield (Eds.), CLIMATE-SMART AGRICULTURE: Evidence-based Case Studies in South Africa (p. 334). Retrieved from https://www.academia.edu/105616505/Evidence_based_Case_Studies_in_South_Africa
    - **Masupha, T.E.**, Moeletsi, M.E., and Tsubo, M., 2024. A transformative framework reshaping sustainable drought risk management through advanced early warning systems. iSCIENCE, https://doi.org/10.1016/j.isci.2024.110066

2) Manuscripts under review:
    - **Masupha, T.E.**, Moeletsi, M.E., and Tsubo, M. Assessing the effectiveness of agricultural drought management policies through implementation in South Africa. Submitted in: Progress in Disaster Science.
    - **Masupha, T.E.**, Moeletsi, M.E., and Tsubo, M. Employing a metric to quantify the effectiveness of an agricultural drought early warning system in South Africa. Submitted in: Computers and Electronics in Agriculture.

3) Popular article:
    - **Masupha, T.** and Moeletsi, M., 2023. More planning needed for droughts. Cape Times, p.4. Accessible online: https://www.iol.co.za/capetimes/opinion/more-planning-needed-for-droughts-9449d07f-62ec-424b-8e23-085af474cab1

4) Other publications produced during my candidature:
    - Mpandeli, S., Nhamo, L., Moeletsi, M., **Masupha, T.**, Magidi, J., Tshikolomo, K., Liphadzi, S., Naidoo, D. and Mabhaudhi, T., 2019. Assessing climate change and

adaptive capacity at local scale using observed and remotely sensed data. Weather and Climate Extremes,26,p.100240. https://doi.org/10.1016/j.wace.2019.100240

- Nhamo, L., Van der Walt, M., Moeletsi, M.E., Modi, A.T., Kunz, R., Chimonyo, V.G.P., **Masupha, T.**, Mpandeli, S., Liphadzi, S., Molwantwa, J. and Mabhaudhi, T., 2022. Optimal production areas of underutilized indigenous crops and their role under climate change: Focus on Bambara groundnut https://doi.org/10.3389/fsufs.2022.990213

- Moeletsi, M.E., **Masupha, T.E.**, Malherbe, J., Maluleke, P. and Beukes, P.J., 2023. Development of an agricultural drought preparedness framework for South African croplands and grasslands. WRC Report No. 2968/1/23.

- Maake, R., Malherbe, J., **Masupha, T.**, Chirima, G., Beukes, P., Roffe, S., Thompson, M. and Moeletsi, M., 2023. The Umlindi Newsletter: Disseminating Climate-Related Information on the Management of Natural Disaster and Agricultural Production in South Africa. Climate, 11(12), p.239.

5) Conference presentations:

- **Masupha, T.E.**, Moeletsi, M.E., and Tsubo, M. *Agricultural drought preparedness and systems in South Africa: A review*. The 35th Annual Conference of the South African Society for Atmospheric Sciences, 8 – 9 October 2019, Vanderbijlpark, South Africa.

- Malherbe, J, **Masupha T**, Moeletsi, ME, Beukes PJ. *The Agricultural Drought Early Warning System*. The 36th Annual Conference of the South African Society for Atmospheric Sciences, 31 October 2022 – 01 November 2022, University of the Witwatersrand, South Africa.

- **Masupha, T.E.**, Moeletsi, M.E., and Tsubo, M. *Role of policy on the effectiveness of agricultural drought early warning systems in South Africa*. Fifth Global Change Conference, 30 January – 2 February 2023, Bloemfontein, South Africa.

- **Masupha, T.E.**, Moeletsi, M.E., and Tsubo, M. *Utilizing innovative technologies to enhance drought prediction and management for South Africa's agriculture*. 24th WaterNet/WARFSA/GWP-SA Symposium, 25 – 27 October 2023, Zanzibar, Tanzania.

6) Awards

- **Teboho Masupha** - Outstanding presentation within the Water, Land, Energy, and Agriculture sub-theme at the 24th WaterNet/WARFSA/GWP-SA Symposium held at Hotel Verde Zanzibar, Tanzania on 25 – 27 October 2023, for a paper titled 'Utilizing innovative technologies to enhance drought prediction and management for South Africa's agriculture'.

Appendix 2: 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

<table>
<tr><td>Name of organisation</td><td colspan="9"></td></tr>
<tr><td>Level of governance</td><td colspan="3">National ☐</td><td colspan="3">Provincial ☐</td><td colspan="3">District ☐</td></tr>
<tr><td>Name of Province
(if applicable)</td><td>GP
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<tr><td>Name of District
(if applicable)</td><td colspan="9"></td></tr>
<tr><td>Designation (position)</td><td colspan="9"></td></tr>
<tr><td rowspan="2">Experience
(in drought management)</td><td><2 years</td><td colspan="2">2 – 5 years</td><td colspan="2">6 – 10 years</td><td colspan="2">11 – 15 years</td><td colspan="2">>15 years</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
</table>

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

……………………………………………………………………………………………

……………………………………………………………………………………………

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).

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

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

…………………………………………………………………………………………………

…………………………………………………………………………………………………

…………………………………………………………………………………………………

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?

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………………………………………………………………………………………………

………………………………………………………………………………………………

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

Yes	
No	
Not sure	

If yes, provide evidence

………………………………………………………………………………………………

………………………………………………………………………………………………

………………………………………………………………………………………………

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

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

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?
…………………………………………………………………………………………………
…………………………………………………………………………………………………
…………………………………………………………………………………………………

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