A CRITICAL REVIEW OF DROUGHT RESEARCH: PHYSICAL CHARACTERISTICS, PERCEPTIONS, ADAPTATION STRATEGIES AND PRACTICES

Technical Report to the

WATER RESEARCH COMMISSION

by

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1 INTRODUCTION

1.1 Background and rationale

Recent droughts that occurred in the Southern African region (2015-2017) exacerbated issues of water scarcity and equitable water allocation. The drought which started in 2015 was a result of the combined effects of a severe drought and a strong ENSO (El Niño Southern Oscillation) event (Baudoin et al., 2017). This has resulted in some South African Provinces being declared disaster areas (e.g. KwaZulu-Na), declines in harvest being experienced which resulted in the necessity to import crops, heavy water restrictions being put in place to cope with dwindling water resources and the need to adapt to the "new normal" of water scarcity. These severe droughts appear to constantly 'surprise' the country despite the fact that South Africa is susceptible to such a hazard (Bruwer, 1993). The first detection of El Niño conditions in the Tropical Pacific in 2015, months before the impacts were observed, provided governments with the earliest possible warning of likely adverse impacts on water supply and food production. Notwithstanding the warning signs and the notable disaster risk legislation (the National Disaster Management Act, DMA 2002), it seems that early warnings about a likely severe drought did not catalyse the swift implementation of risk preparedness measures that it should (Baudoin et al., 2017).

This delayed reaction is of concern within the context of future climate change across the region and the increasing drought frequency. The most recent fifth Assessment Report (AR5) of the Inter-governmental Panel on Climate Change (IPCC, 2014) projected increase in temperature and changes in precipitation patterns with an increase of extreme events (e.g. floods and droughts) in southern Africa. These climatic changes, along with population increase, the need for economic growth and job creation, may result in risks of compounded stress on water resources, terrestrial and marine ecosystems, reduced crop productivity, livelihood and food security, as well as increase in vector- and water-borne diseases. In view of the impending impacts of climate change, it is important to recognize the different ways of characterizing drought and the potential impacts associated with each type of drought. This will facilitate the early detection of drought and subsequently the development and implementation of appropriate mitigation and adaptation measures.

In South Africa, studies of past drought management have indicated a trend to focus on relief and emergency support, instead of implementing proactive policy and management (Baudoin et al., 2017). An in-depth examination of drought concepts, drought indices and their definitions, prediction and forecasting methodologies, drought monitoring techniques, information tools, etc. was required to inform vulnerability to drought and risk management tools. The recent droughts that occurred in the southern African region (2015-current) and the projected impacts of climate change provided motivation for an examination of this nature to highlight drought vulnerability in southern Africa and to inform the development of management initiatives (mitigation and adaptation).

1.2 Objectives

This short project attempted to address this challenge by consolidating national and international knowledge on i) physical characteristics of drought, ii) community behaviour and practices under drought situations, and iii) drought mitigation and adaptation options. The aims of the project are:

- To analyse state-of-the-art knowledge on anticipating and preparing for droughts
- To investigate changes of community behaviour and practices under drought situations

- To review drought mitigation and adaptation options.

1.3 Outputs and outcomes of the project

The equity in water allocation as natural resource and human right is governed by the National Water Act (1998). The issues around water allocation are exacerbated during drought periods when rights and priorities to water access, volumes and frequency of water allocation, water management, administration and prices, as well as fairness in water allocation are only some of the questions to deal with. This project proposed to contribute to transformation and redress of water allocation by providing a better understanding of the physical characteristics of drought, analysing social and cultural behaviour in relation to drought, and reviewing available mitigation and adaptation options for combating drought. Drought mitigation and adaptation options also provide mechanisms for sustainable utilization of water resources. Sustainable development solutions are dependent on water availability and demand, with drought mitigation and adaptation mechanisms playing a key role.

The project is not envisaged to directly empower communities because it provides a review of research on drought. However, the consolidated review may provide the basis and the knowledge that will empower communities to mitigate and adapt to drought. There is large scope for informing policy and decision-making based on the body of knowledge that has already been produced nationally and internationally. This refers both to the uptake of definitions, concepts and terminology related to drought, the consideration of socio-cultural behaviour and the drive for implementation of mitigation and adaptation options.

It was envisaged that the main outputs of the project are:

- A technical review report on the current knowledge on drought (physical characteristics of drought, community behaviour and practices under drought situations, drought mitigation and adaptation options, recommendations for the research strategy).
- A policy brief.
- A paper in a popular magazine.

The main outcomes of the project are consolidated knowledge on national and international research on drought to inform the development of a Water Research Commission (WRC) strategy for future research and implementation of drought mitigation and adaptation options in water scarcity-stricken communities. In this way, the project contributed to human capacity development in the water and science sectors. New products and services for economic development were not planned, except for a consolidated review of mitigation and adaptation options that could provide innovative products and services that can be rolled out to society.

1.4 Structure of the report

This report reviews current knowledge on drought nationally and internationally, including physical characteristics of drought, community behaviour and practices under drought situations, drought mitigation and adaptation options, and recommendations for the WRC research strategy. Based on the aims and objectives of the project, the report is articulated to answer the following research questions:
Question 1: What are the definitions of drought and related concepts and terminology?
Question 2: What are the historic and projected climatic and drought trends?
Question 3: What are community behaviour and practices under drought?
Question 4: What are the prospects of drought mitigation and adaptation?

A systematic review is employed in the compilation of the technical report with recommendations on identified research gaps to feed into the WRC research strategy. The systematic review in this project made use of available material related to drought most relevant to southern African conditions and it identified knowledge gaps or areas requiring further research. This report is therefore structured around the 4 focused research questions:

i) Drought definitions and concepts,
ii) Historic and projected climatic and drought trends/impacts,
iii) Community behaviour and practices under drought, and
iv) Mitigation and adaptation options to drought.

2 METHODOLOGY

A wealth of literature exists on the subject matter of drought. Literature required therefore to be searched in a structured and systematic manner. Systematic reviews are different from traditional literature reviews because they aim to identify all studies (published and unpublished) that address a specific question, and their methodology has been developed to minimize the effect of selection, publication and data extraction bias (Nightingale, 2009). The methods used to identify studies for inclusion in systematic reviews have been developed specifically to identify the negative studies that might be published in low impact journals or within conference proceedings, which are not indexed in the bibliographic databases, but which might balance the results of the more easily identified positive studies (Nightingale, 2009).

A good systematic review might achieve most or all of the following (Cooper, 2003):

- Establish to what extent existing research has progressed towards clarifying a particular problem.
- Identify relations, contradictions, gaps, and inconsistencies in the literature, and explore reasons for these (e.g. by proposing a new conceptualisation or theory which accounts for the inconsistency).
- Formulate general statements or an overarching conceptualization.
- Comment on, evaluate, extend, or develop theory.
- Provide implications for practice and policy.
- Describe directions for future research.

Systematic reviews are characterised by being objective, systematic, transparent and replicable. Altering the protocol of a systematic review can introduce bias and should only be made if absolutely necessary. They involve a systematic search process to locate studies which address a particular research question, as well as a systematic presentation and synthesis of the characteristics and findings of the results of this search. The criteria for inclusion and exclusion in the review are objective, explicitly stated and consistently implemented such that the decision to include or exclude particular studies is clear to readers, and another researcher using the same criteria would likely make the same decision (Baumeister, 2013).

An example of systematic literature review can be found in Taylor and Adams (2013) in their investigation of the drought impacts on Lake St Lucia in KwaZulu-Natal. They used the following sources of information: newspapers, scientific publications, reports, minutes of meetings, presentations, photographs and images, informal casual photos, formal fixed point photos, oblique aerial photos, vertical imagery and databases. In the meta-data description, they included the sources of information, quality and biases, quantity, method of storage, ownership and copyright.

The information required to achieve the objectives of this study was sourced from relevant local and international literature and classified into groups in order to quality-control the source of information as a criterion for the search:

i) WRC reports (WRC databases and publications);
ii) Peer-reviewed publications (search engines of scholarly articles such as Scopus, with preference towards review papers);

iii) Grey literature (unpublished articles, conference presentations, project reports, etc.) and popular articles (magazines such as the Water Wheel, newspapers and other media outlets).

The review was based on 4 focused research questions around: i) drought definitions and concepts, ii) historic and projected climatic and drought trends/impacts, iii) community behaviour and practices under drought, and iv) mitigation and adaptation options to drought. For each of these four research questions, suitable keywords were narrowed down:

i) (Definition OR Concepts) AND Drought research AND South(ern) Africa
ii) (Historic drought OR Predicted drought OR Projected drought) AND Drought research AND South(ern) Africa
iii) (Community behaviour OR Community practices) AND Drought research AND South(ern) Africa
iv) (Mitigation OR Adaptation) AND Drought research AND South(ern) Africa

The search was further arranged based on water use sectors: domestic, agricultural, industrial and mining, recreational. Particular attention in the literature search was given to the focal point of this research project, namely previous research conducted by WRC, and recommendations and research gaps identified for future research.

The time frame for the search was ideally since 1997 up to now. The Kyoto Protocol, an extension of the United Nation Framework Convention for Climate Change, was signed in 1997 by governments as a commitment to reduce greenhouse gas emissions, which is inextricably linked to global climate. This period also encompasses the establishment of Millennium Development Goals (2000) and Sustainable Development Goals (2012) that are profoundly linked to climate.

Given the nature and the objectives of the topic, no primary data was collected or analysed. The review was of a qualitative nature according to the set criteria and classifications, and no statistical or meta-data analysis was conducted. The literature review ultimately provided current best available knowledge related to drought in southern Africa to guide decision-making and management practices.

3 DEFINITION OF DROUGHT AND RELATED CONCEPTS AND TERMINOLOGY

3.1 Introduction

This Chapter of the report responds to:

Question 1: What are the definitions of drought and related concepts and terminology?

This research question aims at providing the definition, and explaining physical characteristics, concepts and terminology related to drought. Drought is usually defined as an unpredictable imbalance of water availability caused by prolonged low precipitation of uncertain frequency, duration and intensity; however, many definitions exist in the literature. These include definitions of drought physical characteristics, drought indices (e.g. standard precipitation index, ratio of rainfall and potential evaporation, etc.), as well as concepts and terminology such as drought vulnerability and resilience, drought hazard and disaster, water scarcity and shortage, aridity and desertification. Different disciplines may also define drought based on different indicators and indices (rainfall patterns for meteorological drought, river flows for hydrological drought, groundwater levels for groundwater drought, soil moisture for agricultural drought, profits for economic drought, etc.), as well as depending on the type of impacts (e.g. on a specific economic sector, environment, social impacts on specific communities, etc.). This Chapter consolidates the definitions, concepts and terminology related to drought.

3.2 Drought concepts and terminology

Drought is a result of a natural but temporary imbalance of water availability caused by the lack of precipitation and high temperatures. Whereas temperature trends and increases are more predictable, precipitation is dominated by climatic variability. Dry conditions develop for different reasons and therefore there are several definitions of drought. The effects of the lack of water for watering (mainly agriculture), business activity (e.g. food industries) and cooling (e.g. power plants) are believed to be the most relevant (Jahn, 2015). Wilhite and Glantz (1985) uncovered more than 150 published definitions of drought. A drought is considered to be a temporary period of natural water scarcity, which is a feature of climate, and persisting long enough to result in problems such as crop damage or water supply shortages (Pereira et al., 2009). Ncube (2017) proposed the definition of Van Zyl (2006): "drought in South Africa is a prolonged, abnormally dry period when there is insufficient water for users' normal needs". Schulze (2011a) provided a glossary of definitions related to climate change and weather extremes. Ncube and Lagardien (2015) and Jordaan (2017) provided a glossary of definitions related to drought, risk, vulnerability and resilience, and related terminology. Different types of drought vulnerabilities, such as economic, environmental and social were discussed by Jordaan (2017).

The frequency of occurrence, duration and intensity of a drought is influenced by over-use of water and over-population. It usually follows periods of persistent lower-than-average precipitation of uncertain frequency, duration and intensity (Pereira et al., 2009). Droughts occur in nearly all types of climate and they are characterized by four properties, namely:

- Timing
- Intensity
- Duration
- Aerial extent

Relevant questions to the definition of drought were posed by Zucchini and Adamson (1984): When does a drought begin and end? What is its definition in terms of duration and severity? What is its risk of occurrence? How long before recovery from a state of deficit occurs and what is the risk that drought will last another season?

In an effort to bring some order to monitoring drought, the definitions were grouped into four basic categories: meteorological, hydrological, agricultural and socio-economic. The first three categories track drought as a physical phenomenon. The last category deals with drought as a supply-and-demand problem, through the impacts of water over-use. These definitions usually specify the beginning, end and degree of severity of drought by comparing the precipitation over a certain time period to a historical average. In addition, drought vulnerability is accounted for through the socio-economic context. According to Pereira et al. (2009):

- Meteorological droughts are characterised by the occurrence of reduced precipitation compared to the long term average for a particular region.
- Agricultural droughts are characterised by insufficient available water, e.g. soil moisture, during the growth stages of crops, which often results in a reduction in yield.
- Hydrological droughts, which is often linked to meteorological droughts, refers to persistently abnormally low water volumes in streams, reservoirs, rivers, aquifers, etc.
- Socio-economic droughts occur when the water demand exceeds the available supply, which causes enormous problems for populations and societies. This often results in insufficient available water for the production of food and for alleviating hunger and poverty. The lack of water also affects the development of industries, urban growth, tourism sector, etc.

As drought research and monitoring evolved, other categories emerged. These include ecological drought and anthropogenic drought:

- Ecological droughts impact on ecosystems and the “natural capital” they provide to human communities in terms of ecosystem services, e.g. quality regulation, waste treatment, erosion prevention, and recreation (Crausbay et al., 2017).
- Anthropogenic droughts refer to water shortages caused and modified by human processes (Van Loon et al., 2016).

It is also important to clearly define and distinguish between the terms adaptation, resilience and vulnerability, as they are strongly related to drought. In its 5th assessment report (IPCC, 2014), the IPCC defines adaptation as “the process of adjustment to actual or expected climate and its effects”, vulnerability as the “propensity or predisposition to be adversely affected”, whereas resilience is the “capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation”. Therefore, a resilient system is less vulnerable than a non-resilient system, but this relation does not necessarily imply symmetry, and hence vulnerability is not the opposite of resilience (Gallopín, 2006).

In general, there is a requirement for well-understood, accepted and adopted terminology. Ziervogel et al. (2009) reported the issue that climate forecast results and terminology are not always correctly interpreted and understood.

Box 1: Common terminology and definitions related to drought	
Terminology	**Definition**
Drought	Natural but temporary imbalance of water availability caused by the lack of precipitation and high temperatures
Meteorological drought	Occurrence of reduced precipitation (e.g. <70%) compared to the long term average for a particular region (Bruwer, 1993)
Agricultural drought	Prolonged insufficiency of available water, e.g. soil moisture, during the growth stages of crops, which often results in a reduction in yield (Pereira et al., 2009)
Hydrological drought	Persistently abnormally low water volumes in streams, reservoirs, rivers, aquifers (Pereira et al., 2009)
Anthropogenic drought	Water shortage caused and modified by human processes (Van Loon et al., 2016)
Ecological drought	Drought impacting on ecosystems and the "natural capital" they provide to human communities in terms of ecosystem services, e.g. quality regulation, waste treatment, erosion prevention, and recreation (Crausbay et al., 2017)
Socio-economic drought	Water demand exceeding the available supply causing damage to population, economy and society (Pereira et al., 2009)
Drought vulnerability	Degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of drought (adapted from Schulze, 2011a)
Economic vulnerability	Vulnerability of the economy of communities, towns, districts and different sectors in a specific area (Jordaan et al., 2017)
Environmental vulnerability	Susceptibility of the environment, and more specifically the vegetation, to the impact of a severe drought (Jordaan et al., 2017)
Social vulnerability	Vulnerability of society and local community to the negative impacts of a severe drought (Jordaan et al., 2017)
Drought resilience	Ability to absorb and recover from a hazardous event such as drought (adapted from Schulze, 2011a)
Drought adaptation	Set of measures and practices that aim at lessening the adverse impacts through adjustments in natural and human systems to extreme events such as drought
Drought mitigation	Anthropogenic intervention directed at the cause of a phenomenon (e.g. reduce the causes and enhance the sinks in relation to the occurrence and intensity of extreme events such as drought)

3.3 Drought indexes

WRC reports and scientific publications

Research on drought funded by WRC dates back several decades, when a study on the occurrence and severity of drought in South Africa was conducted (Zucchini and Adamson, 1984). They referred to the Palmer Drought Index as the most widely applied classification system for drought. However, they also underlined that a generic cast-in-stone definition of drought is senseless. This is because drought depends on the water requirements of water consumptive activities. Different water users have different water requirements and drought for one user may not be the same for another user. Consequently, Zucchini and Adamson (1984) developed a rainfall probability distribution model to assess the risk of drought rather than using a drought index. The impact of rainfall occurrence was expressed based on the secondary process of interest and associated users (e.g. crop yield, reservoir storage, soil moisture storage, water table level, streamflow, etc.).

Ncube (2017) conducted a desktop review in the nine provinces of South Africa to identify the current knowledge on drought and occurrence, as well as national and provincial government interventions, including Early Warning Systems, Climate Advisory Services, and Indigenous Knowledge Systems. In this project, eight different types of drought were identified: seasonal drought, periodic drought, disaster drought, false drought, premature drought, prolonged drought, green drought and financial drought. Four basic categories of drought were identified as: meteorological drought, agricultural drought, hydrological drought and socio-economic drought. On the other hand, drought impacts were classified as agricultural, economical, socio-economic and environmental.

A comprehensive list of drought indices applicable depending on the context, sectors and vulnerability, was presented by Jordaan (2017). Jordaan (2017) reported the outcomes of a workshop on indices and warning systems for drought with the participation of representatives from major relevant organizations (World Meteorological Organization WMO, United Nations Convention to Combat Desertification UNCCD, National Oceanic and Atmospheric Administration NOAA, United States Department of Agriculture USDA), where it was agreed that not one drought index fits all needs, but the Standard Precipitation Index (SPI; McKee et al., 1993) should be used to characterize meteorological drought around the world (UNCCD, 2009).

Global warming is associated with an increase in potential evapotranspiration directly related to surface heating. Vicente-Serrano et al. (2010) proposed an improved Standard Precipitation Evapotranspiration Index (SPEI) in order to account for potential evapotranspiration (PET). The SPI and SPEI represent the number of standard deviations above or below the mean (z-score). Abiodun et al. (2018) reported that Southern African droughts are usually quantified through precipitation anomalies or the Standardised Precipitation Index (SPI). They also recommended to consider the important role of potential evapotranspiration by using the Standardised Precipitation Evapotranspiration Index (SPEI) and well as the dynamics of Regionally Extensive Droughts (REDs) besides localized droughts. Moeletsi et al. (2018) proposed two drought indices – the Standardised Precipitation Evapotranspiration Index (SPEI) and the Water Requirement Satisfaction Index (WRSI) – in a drought assessment study done for the Luvuvhu River catchment (Limpopo Province, South Africa). Values and categorization of SPI and SPEI were summarized by McKee et al. (1993) and reported in Table 3.1

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TABLE 3.1
Values and categorization of Standard Precipitation Index (SPI) and Standard Precipitation Evapotranspiration Index (SPEI) (McKee et al., 1993)

SPI		SPEI	
Value	**Category**	**Value**	**Category**
0 to -0.99	Mild drought	-2.0 and less	Extremely dry
-1.0 to -1.49	Moderate drought	-1.99 to -1.50	Severely dry
-1.5 to -1.99	Severe drought	-1.49 to -1.0	Moderately dry
less than -2.0	Extreme drought	-0.99 to 0.99	Near normal
		1.0 to 1.49	Moderately wet
		1.5 to 1.99	Very wet
		2.0 and more	Extremely wet

Other categories for SPI and SPEI were also adopted in the literature. A detailed description of SPI and SPEI statistical concepts and algorithms is provided by Jordaan (2017). Jordaan (2017) finally proposed indicators and their thresholds for drought monitoring and drought declaration based on international experiences from other countries. In particular, he recommended 10 primary indicators:

- Meteorological indicators
    - Precipitation expressed as percentage of the long-term mean
    - Standardized Precipitation Index (SPI)
    - Standard Precipitation Evapotranspiration Index (SPEI)
- Agricultural indicators through remote sensing
    - Normalized Difference Vegetation Index (NDVI)
    - Vegetation Condition Index (VCI)
    - Percentage of Average Seasonal Greenness (PASG)
    - Soil Moisture Index
- Hydrological indicators
    - Reservoirs / Dams
    - Streamflow Levels
    - Groundwater

Jordaan (2017) also proposed and described five categories of drought – D0 to D4 (dry, moderate drought, severe drought, extreme drought, exceptional drought). These drought indicators, thresholds and categories were proposed for formal adoption in South Africa (Jordaan, 2017).

Research is required on the assessment of the best drought (vulnerability) indicators to use so that improved drought forecasting is possible as vulnerability is context-specific and may not be the same everywhere (Vicente-Serrano et al., 2012, Antwi-Agyei et al., 2012, Blauhut et al., 2016). There is a need to validate the relevance and usefulness of the various drought indicators, especially for the purposes of management decisions (Blauhut et al., 2016). Examples of comprehensive drought indices which consider drought impacts on meteorological, agricultural, hydrological and stream health categories have been researched but lack other aspects of drought including social and economic impacts (Esfahanian et al., 2017). Improvements in the observation and modelling of evapotranspiration and all its forcings at a large scale are still required. This includes knowledge, forcings and model capabilities regarding evapotranspiration, soil moisture and surface water with respect to drought (Trenberth et al., 2013).

Popular literature

The occurrence of drought triggers much interest in popular literature (e.g. grey literature, media, etc.) for communication to the public. It is recognized that drought is a very complex phenomenon with many different direct and indirect impacts (amongst them environmental, socio-economic and political). Thus, the definition of drought diverges according to scientists from different science backgrounds. However, WMO generally defined drought as a prolonged dry period in the natural climate cycle that can occur anywhere in the world: “it is a slow on-set phenomenon caused by a lack of rainfall” (WMO, 2014).

Scientists have simplified the definition of drought by classifying it into different categories. UNCCD (2016) also adopted categories such as meteorological drought, hydrological drought and agricultural drought. A meteorological drought, for example, was simplistically defined as a shortage of rainfall; a hydrological drought occurs when a lack of rainfall continues long enough to empty rivers and lower groundwater tables; agricultural drought begins when lack of water affects crops and livestock, as well as locals’ survival (UNCCD, 2016).

Restuccia (2016) discussed the main causes of drought in an article published on the internet:

- Land and water temperatures – It is theoretically known that abnormal increase in land surface temperatures and surface water temperature results in more water escaping from the surface through the process known as evapotranspiration. Too much evapotranspiration can lead to shortage of water on the land surface.
- Air circulations and weather patterns – Change in large scale air circulation and normal weather patterns like El Niño contribute significantly to drought events. Research shows that eight of the ten strongest droughts in southern Africa since 1900 occurred during the mature phase of El Niño (Rouault, 2015).
- Demand of water and supply – Growth in regional population, agricultural activities and industrial activities can result in a shift of the normal water cycle. This may cause higher demand of water. A study estimates that, from 1960 to 2010, human consumption of water increased the frequency of drought in North America by 25% (Denchak, 2018). This is evidence that any increase in demand might increase the probability of drought.

According to Restuccia (2016), other causes of drought might include reduced soil moisture level and timing of precipitation. Depleted or less soil moisture might lead to less evaporation for cloud formation, whereas precipitation timing refers to a situation where the timing of water doesn’t match the agricultural season; too much water may be available when it is not needed, and too little when it is needed.

4 HISTORIC AND PROJECTED CLIMATIC AND DROUGHT TRENDS AND IMPACTS

4.1 Introduction

This Chapter of the report responds to:

Question 2: What are the historic and projected climatic and drought trends?

This Chapter reviews research on climatic trends/impacts and drought, in particular studies on historic data analyses and future projections in South(ern) Africa. Particular reference is made to climatic variables (rainfall, evaporation and the factors affecting it, namely temperature, radiation, humidity and wind), hydrology (surface flow regimes and water quality as affected by topography, soil and geology, vegetation and land use), groundwater (availability and quality, recharge and storage capacity, groundwater drought), climatic changes, water management aspects (monitoring, forecasting and risk management tools) and impacts on various water use sectors (domestic, industrial, agriculture, recreational). The severity of drought impacts may also be influenced by factors such as unfavourable topography, geology, water demand and supply, population and human activities. A clear distinction is made between climate change (long-term changes associated with global warming) and climate variability (short- and medium-term spatial and temporal oscillations in climatic patterns), and their impacts on drought. Because drought usually attracts attention of affected parties only when it occurs, it was fundamentally important to review methods for recording (monitoring and warning) drought. Research on forecasting, risk management and communication of this unpredictable phenomenon was also reviewed.

4.2 WRC reports

The geographical extent of southern Africa covers different climatic zones, which results in distinct temperature and rainfall patterns and gradients. The climate characteristics are driven by the position of the sub-continent in relation to the global atmospheric circulation patterns, the migration of the inter-tropical convergence zone, the complex topography and the oceanic currents along the coast (Davis-Reddy and Vincent, 2017). These features, along with natural inter-decadal climatic variability (El Niño) and anthropogenic effects of climate change, make the region particularly vulnerable to drought events of increasing frequency.

The unprecedented interest in climatological science, driven primarily by the dramatic impacts of anthropogenic climate change, has triggered research in southern Africa, which is geographically ideal to conduct such studies. This is both because it covers several climatic zones and because some areas are impacted heavily by climatic changes. Research on climatic trends, modelling of climate change and variability in South Africa has therefore been at the forefront of international advances for many years (Hewitson, 2001; Hewitson et al., 2004). The scene for a WRC research agenda on climate change that included drought as a manifestation of climatic variability was set by Green (2008).

Traditionally, most impacts of drought were characterized for the agricultural sector where the effects are more evident and because of the consequences on food production and economy. For example, Moeletsi et al. (2018) carried out a specific-site study to investigate historic and future trends of drought and rainy seasons in the Luvuvhu River catchment with particular reference to maize production. The impacts on the agricultural sector manifest as financial losses, imports of food in the case of shortages caused by drought, job losses and increased unemployment rates, as well as migration of population towards cities. Besides socio-economic impacts, environmental impacts are prominent due to drought such as environmental degradation (land, ecosystem), reduced hydroelectric power generation and recreational potential. The impacts on domestic and industrial water use are less documented in southern Africa, yet, in the event of drought, emphasis on water provision is on domestic, sanitary and industrial use according to the priorities of water allocation in the National Water Act (1998). Environmental allocations (reserves) also play a prominent role in the policy.

Ncube (2017) reported on the history, Early Warning Systems and Disaster Management mechanisms in South Africa, and presented some case studies of drought coping in the world and particularly in southern Africa (Bangladesh, Kenya, Zimbabwe, Botswana, Ethiopia, Namibia and desert regions). According to Ncube (2017), the most common information on drought occurrence in South Africa is when drought is declared as disaster. The lack of monitoring networks hampers scientific knowledge on the characteristics of drought (probability, start, end, duration, intensity). Satellite information can be of great use in order to fill this gap.

Pegram et al. (2010) attempted to use remote sensing information to produce spatial time series of soil moisture over South Africa in support of drought monitoring, amongst others. Soil moisture is one of the most difficult water balance components to monitor because of its variability in space and time. The approach including meteorological data, remote sensing information and hydrological modelling proved rather successful in the production of a countrywide Soil Saturation Index (SSI) in support of drought monitoring. The potential of remote sensing information for monitoring and forecasting weather extremes was therefore demonstrated by Pegram et al. (2010) through the development of a freely available spatial product for soil moisture and other meteorological variables. However, further research is required in order to improve algorithms and validate satellite-based products.

Particular attention was dedicated historically to the downscaling of General Circulation Models (GCMs) to local conditions in order to support water management problem-solving at a more localized scale. This may involve: i) statistical downscaling (large-scale climate features are statistically related to the local climate of a region through historical observations), and ii) dynamic downscaling (a high-resolution dynamic model/module is nested/nudged within a GCM). Downscaling was attempted through Artificial Neural Networks (ANNs) (Hewitson, 1997), statistical downscaling (Landman et al., 2008) or a combination of statistical downscaling and fine resolution Regional Climate Models (RCMs) (Landman et al., 2006). More recently, Hewitson et al. (2014) developed a conceptual model for integrating the climatic data projected with GCMs and RCMs with the socio-economic context of local vulnerability (economic and livelihood activities, infrastructure, services, etc.). The purpose was to screen plausible, defensible and actionable climate change scenarios and projections from the perspective of the users and decision-makers.

Botai et al. (2017) investigated the effects of climate change on the mean and variability of several climate variables, primarily soil moisture. Using analysis with GCMs, they found that the south-western regions of southern Africa will be particularly affected by extreme high temperatures with an expansion of areas of hot extremes, the magnitude and intensity of heat waves will increase, and significant differences in patterns of precipitation (water recycling) may occur depending on vertical water exchange fluxes driven by soil moisture, vegetation and evapotranspiration.

One of the most representative studies in terms of characterization of drought trends was produced by Abiodun et al. (2018). Simulations with GCMs and RCMs projected future increase in drought intensity, area coverage, and frequency over southern Africa under both RCP4.5 and RCP8.5 scenarios (detailed explanations of scenarios can be found in IPCC, 2014). The projections also showed that all-dry drought patterns (dry conditions over the entire southern Africa) would become more frequent in the future, while all-wet drought patterns (wet conditions over the entire southern Africa) would become less frequent, but the frequency of dipole drought patterns (dry conditions over part of southern Africa and wet conditions elsewhere) would remain unchanged.

Results of the project carried out by Abiodun et al. (2018) indicated that model simulations can be improved with more data re-analysis and simulations covering a longer time period, including, i.e. paleo-climate data sets. GCMs are reportedly better performing models than RCMs due to difficulties in downscaling global circulation patterns. This is mainly due to uncertainties in the definition of lateral boundary conditions in RCMs. There is a need for understanding the downscaling of climatic projections to localized processes and for better linkages between GCMs and RCMs. Additionally, there is need to link climate characteristics and future projections to southern African river basins and land use. This will support better decisions on water and land use management (e.g. land cover changes), and mitigation of the impacts of drought. Big Data Analysis methodologies provide an opportunity to downscale regional information to locally relevant water resources management.

Studies on changes in first order climatic variables (e.g. rainfall and temperature) are common because of the need to project global warming effects. However, studies on the impact of these climatic variables on sector-specific indicators are limited. Schulze (2008) set the basis for linking climate change adaptation to integrated water resource management. The sensitivity of socio-economic activities to climate change in South African river catchments was investigated in a follow-up study (Stuart-Hill and Schulze, 2011).

A key study in terms of drought trends was conducted by Schulze (2011a) on short- and long-duration droughts based on GCMs meteorological data and streamflow simulations with the Agricultural Catchments Research Unit's (ACRU) agro-hydrological model. The GCMs results were empirically downscaled to a finer scale spatial resolution to describe the hydrological impacts occurring at more local scales. The results of this study were a comprehensive analysis of projected first-order climate variables, second-order climate derivatives as well as changes in meteorological and hydrological droughts. Part of the research assessed the hydrologically relevant statistics of rainfall in South Africa under projected climate change scenarios to understand the rainfall changes at a regional scale where specific research gaps were identified that need further investigation (Schulze et al., 2011a). Schulze et al. (2011) also identified research gaps in the integration of climate change simulations with agro-hydrological models.

Further advances were achieved by Rautenbach et al. (2017), who employed the Coordinated Regional Downscaling Experiment (CORDEX) Regional Climate Model (RCM) data in combination with the ACRU agro-hydrological model to simulate historical and projected hydrological droughts and floods. The research in this project assessed specifically climate downscaling techniques, including dynamical and statistical downscaling, to simulate streamflow in catchments across South Africa, and project drought and flood hazards as well as their uncertainties. It was found that the hydrological model driven by climate modelling data captured streamflow averages and extremes in a large number of catchments. Findings in terms of changes in droughts and floods revealed that the total annual rainfall is likely to decrease over much of South Africa, with some increases in rainfall towards the equatorial regions; the onset of the rainfall season is projected to occur later over much of the region; more intense rainfall events and longer dry spells are likely to occur; and uncertainties are large across rainfall transitional zones. No general recommendations for further research were made in this report.

Studies have shown that one of the main influencing phenomena causing drought conditions in South Africa is the El Niño, due to the warming of the central and eastern Pacific and the Indian Ocean. The converse of this, La Niña, results in wet spells (Rouault et al., 2008). This is an important research focus area and certain research gaps have been identified (Rouault et al., 2008):

- Why is there no linear relationship between El Niño Southern Oscillation (ENSO) and rainfall variability in South Africa?
- Why are some El Niño events not linked to drought?
- What is the impact of El Niño and La Niña at the catchment scale?
- What is the role of the Antarctic oscillation (AAO) on summer rainfall?
- What is the interaction of ENSO and AAO and how does this affect southern African climate?

The need for dissemination and uptake of climate forecasts was discussed at length by Ziervogel et al. (2009), who found that weather and climatic forecasts are little in use by stakeholder, with some exceptions (e.g. City of Cape Town and Department of Water Affairs and Forestry use forecasts of dam levels and usage demands in order to make decisions). Landman et al. (2014) stressed the importance of high computing capabilities for highly complex models and climate forecasts, the need to analyse modelling, ground and remotely sensed data, and the benefits that forecast applications can provide to stakeholders in various sectors for decision-making.

4.3 Peer-reviewed literature

Climate projections show that Africa is likely to experience significant climatic changes, as extreme drying and warming will occur in most subtropical regions with slight increments in precipitation in the tropics (Adebisi-Adelani and Oyesola, 2014; Christensen et al., 2007; Abegaz and Wims, 2015). The climate change models also estimate that the impacts of climate change would be greater in some regions across Africa than elsewhere in the world (Christensen et al., 2007; Sylla et al., 2016). The major challenge of these climate change models and scenarios for Africa, however, is that they are somehow complicated by uncertainty regarding changes in precipitation. Nearly all models show a drying southern Africa, as well as uncertainty between projections in some regions, particularly West Africa, while reports by the IPCC (IPCC, 2014, 2013) revealed uncertainty about future rainfall patterns in southern Sahara, the Guinea Coast and the Sahel. Precipitation patterns are also expected to differ as a result of climate change, with more frequent drought events predicted for regions that are already arid (IPCC, 2014).

Significantly, the IPCC's First Assessment Report (IPCC, 1990) noted that there was no evidence of an increasing incidence of extreme events over the previous few decades, despite a modest increase in average temperatures since the 1950s. Indeed, some evidence pointed to decreases. With regard to the future, the report noted: "With the possible exception of an increase in the number of intense showers, there is no clear evidence that weather variability will change in the future. In the case of temperatures, assuming no change in variability, but with a modest increase in the mean, the number of days with temperatures above a given value at the high end of the distribution will increase substantially……. The number of very hot days or frosty nights can be substantially changed without any change in the variability of the weather….. If the large-scale weather regimes, for instance depression tracks or anticyclones, shift their position this would affect the variability and extremes of weather at a particular location, and could have a major effect. However, we do not know if, or in what way, this will happen". Despite serious attempts to clarify the situation, the models available in the early1990s were ill-suited to providing estimates of future changes in the frequency, intensity and duration of specific extreme weather events (Hay et al., 2016).

Widespread changes in the instrumental record of extreme weather events such as droughts, heavy precipitation, heat waves and the intensity of tropical cyclones were noted in the IPCC's Fourth Assessment Report, with these changes showing "discernible human influences" (IPCC, 2007). Globally, heavy precipitation indices (maximum 5-day precipitation total and maximum 1-day precipitation total) are projected to increase in all regional domains, even where decreases in mean precipitation are indicated, such as in southern Africa, south Europe/Mediterranean, and central America (Hay et al., 2016).

Long term trend analysis of atmospheric variables such as temperature, rainfall and evapotranspiration have been used extensively as proxies for detecting changes in climate (Kusangaya et al., 2013). The increased frequency of occurrence of extreme events such as droughts, floods and cyclone activity in southern Africa has also been cited as evidence of a changing climate. Most scientists are of the view that the increased frequency of extreme events may be attributable to increasing greenhouse gas (GHG) emissions (Kusangaya et al., 2014).

Temperature extremes are common occurrences and an increasing phenomenon in a changing climate. Climate change can impact temperatures causing extremes by shifting the mean and the temperature probability distribution, increasing variability, where symmetric widening of temperature variability occurs in both warm and cold ranges, and a changed symmetry where the higher order distribution statistics is altered. It is necessary to understand the broader historical and future statistical temperature distribution changes to effectively evaluate its impact on human health, agriculture and ecosystem health (Lewis and King, 2017). Research gaps on this aspect were identified by Lewis and King (2017) as: i) evaluation of models to simulate key climatic processes behind regional-scale extremes, relative to observations; ii) exploration of the physical basis for differences in the behaviour of daily and annual-scale temperatures for insight into differences between inter-annual and intra-annual variability.

Analyses of both remote sensing-derived and observed temperature records in southern Africa agree that over the last decades the region has been experiencing a warming trend (Kusangaya et al., 2014). The basic conclusion from several studies has been that temperatures are rising, with minimum temperatures rising faster than maximum temperatures (Kusangaya et al., 2014). These temperature changes may lead to changing patterns of rainfall, the spatial and temporal distribution of runoff, soil moisture, and groundwater reserves, as well as increase the frequency of occurrence of droughts and floods (Schulze, 2011a).

The general trends in temperature and rainfall over South Africa were described by Davis-Reddy and Vincent (2017). Positive anomalies in temperature are on the increase, whilst total rainfall and number of rainfall days are decreasing in the North and North-East, and increasing in the southern interior. There is strong evidence of the increased number of extreme events, especially high temperature combined with decreased rainfall, which may result in more frequent, intense and widespread droughts over certain parts of southern Africa. However, the links between drought occurrence and the effects of El Niño are uncertain (Davis-Reddy and Vincent, 2017).

While the amount of data available for analysis has increased significantly, there is still a lack of data in regions such as Africa and South America. In many parts of the world, limited availability of high resolution observational data still presents a major constraint on the analysis of extreme weather and climate events. Globally there is a need to ensure free and unrestricted access to daily and sub-daily data. Another significant issue is the general mismatch in the spatial scales between observations that are usually made at point locations and model simulations. The latter are typically interpreted as representing an area of a model grid. The disparity is especially a problem for precipitation extremes, reducing confidence in interpreting and understanding the observed changes in the frequency, intensity and duration of such events (Hay et al., 2016).

4.4 Popular literature

Southern Africa is prone to drought conditions. Between July 1960 and June 2004, there have been 8 summer-rainfall seasons when rainfall in the entire summer-rainfall area has been less than 80% of the average (South African Weather Services, 2019). Drought affects South(ern) Africa regions differently since there are many different climatic zones. The south-western Cape region of South Africa depends mostly on winter rainfall, whilst the north-eastern parts of the country are dependent on summer rainfall. According to Bateman (2018), the south-western Cape region experienced three (2015-2018) years of its lowest rainfall years on record. Droughts close to this magnitude have occurred in the past (for example in the late 1920s, early 1970s, and 2003 to 2004) and led to water shortages in Cape Town (Bateman, 2018).

Continued scientific research is very important to unfold new ideas which can help to defeat the disasters caused by drought. Rouault (2015) suggested the need for more research to assess the effects of El Niño. The two research questions suggested by Rouault are: i) why does El Niño sometimes not lead to drought? ii) why a weak El Niño can trigger a severe drought while a strong El Niño can trigger a less severe drought? Understanding drought in southern Africa, its causes and impacts will help to reduce the damage.

The drought impacts caused by the meteorological drought during 2014-2016 in the Lowveld of South Africa were described by Swemmer (2016). The climatological data showed that the 2014-15 rainfall year was one of the driest on record, with just 255 mm of rain recorded compared to the long-term average of 533 mm with the summer of 2015-16 being even drier. High temperatures exacerbated the impact with cattle dying due to lack of food and water, and required transporting at great costs to different areas. The Mopane worms depended on for food by local people also died before reaching maturity for harvesting and wildlife deaths were reported in the Kruger National Park as vegetation wilted. Certain rivers and freshwater ecosystems in the Lowveld dried up causing fish deaths. The article by Swemmer (2016) reported that research on drought impacts in natural areas (protected and rangelands) were lacking. Drought in savannas, however, had a positive side. Herbivore numbers are regulated and overgrazing is prevented, and longer-term drought can kill trees maintaining a balance with grasslands. In severe droughts, the collection of monitoring data is enabled, which is required to understand the long-term role of climate – and climate change – in controlling natural and semi-natural ecosystems (Swemmer, 2016).

5 COMMUNITY BEHAVIOUR AND PRACTICES UNDER DROUGHT

5.1 Introduction

This Chapter answers the following research question:
Question 3: What are community behaviour and practices under drought?

This research question elaborates on conceptual thinking in relation to drought. Inevitably, droughts are likely to impact the socio-political and economic spheres of affected areas. Although engineering aspects may be key in terms of combating drought, there are also social, environmental, legal, institutional, health, cultural and educational aspects that influence behaviour and practices under drought, the values linked to water that determine priorities for water rights, allocations and pricing, and trans-boundary issues. These issues need to be considered for each local community, urban centre, rural area, user group, and administrative, public and private organizations that are involved in drought response and management. Individual perceptions around climate change and extreme events are related to the language used when communicating scientific results to the public. Climate scientists often use words such as “likely” or “very likely” to communicate results on climate predictions, which was shown to be perceived by the public as scientific uncertainty (Somerville and Hassol, 2011). It is also necessary to show the links between what is perceived by individuals and the physical scientific evidence, rather than allowing these two aspects to remain separate (Lewis, 2016). The manner and language used in communicating information concerning climate change or extreme conditions, such as droughts, to the public is therefore very important.

Different geographical regions may be more environmentally sensitive and communities may be more fragile and therefore more susceptible to drought. Responses to drought may then be different. Research and analyses were done in relation to different water sectors: domestic water use, rainfed and irrigated agriculture, industrial and energy, landscape and recreational water uses. The analysis can also re-classify responses according to urban, peri-urban and rural areas, dry and wet environments, etc. Educational aspects refer to studies on changing people’s attitude towards water and drought. The targets of education and awareness on drought can be children and youth, gender-based, families and communities, type of users (e.g. farmers, industry, water managers, technical staff, professionals and academics). The literature search reviewed research done on these topics for different localities, water sectors and types of environment in order to draw experiences as well as research and innovation gaps on community behaviour and practices, and their responses to drought.

5.2 WRC reports

Whereas droughts are specific climatological/weather events, water scarcity is usually used to describe the general problem of supplying the society/economy with enough water. The main human drivers of water scarcity are increased consumption (not only of water directly), population growth (urbanization) and agriculture (European Environment Agency, 2012). Community behaviour and perception on drought and water scarcity is therefore reflected mainly through impacts on health, safety and economic losses. The impacts of drought have been discussed by Ncube (2017) for different sectors of the economy. In agriculture, these are mainly crop failure and death of livestock. In the environment, these impacts manifest in environmental degradation. Hydrologically, they manifest in reduction of streamflow and groundwater levels. The industrial sector is affected by drought resulting in a general loss of welfare. This results in socio-economic impacts such as loss of income, threat to household food security and even famine. Jordaan (2017) discussed how the choice of coping strategy depends on numerous variables such as access to land, finance, market and information, income, experience, education and extension in particular amongst smallholder farmers.

Rivett et al. (2013) investigated incentives to active community engagement in order to improve drinking water supplies in South Africa. To this effect, Information Communication Technologies (ICTs) could provide opportunities for engaging communities (e.g. water supply information, reporting on leaks, etc.). Rivett et al. (2018) conducted a study on domestic water users in the City of Cape Town to investigate the perception and willingness-to-pay of households towards water measurement and conservation devices, e.g. mobile application DropDrop, as tools to reduce water usage through increased population awareness. The results were relatively successful with recommendations on how to improve the mobile application. However, Chiroro et al. (2014) reported that a household education programme did not generally reduce household water consumption nor improved knowledge, although households increased payments of their water bills and reduced the incidence of non-payment.

Employing principles of behavioural economics have assisted municipalities to manage the demand on utilities such as water in order to encourage a behaviour change in household water consumption (Smith and Visser, 2014). Projects using these principles have employed three behavioural mechanisms to manage demand by using a randomised control trial which includes: raising the salience of the consumer's consumption to themselves, comparing the consumer's consumption to some social norm and providing information about how to consume less. In the City of Cape Town, salience was raised on water consumption by reporting previous consumption in a bar chart or by comparison with a neighbour via a bar chart. Raising the salience decreased water consumption. The study also concluded that simplifying the information communicated was more effective in lowering water consumption. More knowledge is, however, required on employing these strategies over a longer term and using them in combination with other appropriate strategies to manage domestic water demand. More research is required in applying principles of behavioural economics to other areas of water studies, such as designing assessments of water policy. Using randomised control trials will allow the identification and isolation of specific elements in a policy in an efficient and practical manner (Smith and Visser, 2014).

Many options to increase water supply as a buffer to drought periods are known, however the perception of the communities will influence their adoption and sustainability. For example, domestic rainwater harvesting for domestic water supply in areas where municipal water supplies are lacking or inadequate or where groundwater is not an option, was found to be an effective source of water supply. Domestic rainwater harvesting could be promoted as an effective adaptation strategy for achieving water security. However, if potential users of the system are not educated on the benefits and maintenance thereof or do not accept the system as a potential source of useable water, rain water harvesting will remain under-utilised. In a research project conducted by (Mannel et al., 2014) in a low cost housing scheme at Kleinmond, the large majority of the community perceived rainwater as beneficial as it saved them money. The users did not know how to maintain the tanks but were willing to learn. The study concluded that domestic rainwater harvesting was a viable option to water for water supply provided that water treatment takes place and training is provided to communities using rainwater tanks (Van Vuuren, 2016a). Future research should include the challenges of implementing domestic rainwater harvesting systems and the problems that users experience. Research should focus on the development of effective training programmes and associated user manuals that will empower users of the system on operation, management and contamination of rainwater as well as on water conservation and reuse. The use of training manuals will depend on their simplicity in the language

used and therefore research should be inclusive of the communities (research participatory approach) that will utilise them. Research on the financial feasibility of training certain individuals on domestic rainwater harvesting rather than an entire community should be considered (Mannel et al., 2014).
Tapela (2011) provided a definition of "social water scarcity" linking it to political, economic and social power dynamics. People in communities perceive social water scarcity as unmet expectations to fulfil their own water needs that enable them to secure and enhance livelihoods against vulnerability to risks and hazards. Social water scarcity is therefore generally linked to unmet expectations for water services and wasteful water use.

5.3 Peer-reviewed literature

Several studies on community behaviour were also found in peer-reviewed literature. Booysen et al. (2019) reported that the announcements by government and the municipality to enforce water restrictions at various levels and water tariffs had little effect in citizen behaviour response regarding reducing water consumption during the drought period in the City of Cape Town. However, the study showed that the strategy of instilling some level of fear in citizens with a drought disaster plan and the imminent threat of "Day Zero" where taps would run dry, was responsible for the significant behavioural change of citizens regarding reduction in water consumption. It was found important and necessary to implement nationwide communication campaign strategies disseminating information on drought and the consequences thereof, thereby creating a "water culture" (Ortega-Gaucin et al., 2016). Analysing the past communication strategies regarding drought from government spheres and the media to citizen behavioural responses provides important information for the improved future management and communication strategies (Booysen et al., 2019).

Communication strategies on early warning of extreme events or hazards are also important. In some African countries, different agencies have mandates to disseminate warnings or information of extreme climate events, which often results in confusion (Lumbroso, 2018). There is a need to develop a systematic framework to guide or coordinate such institutions including the establishment of coherent messages from the relevant departments for the relevant hazard. A research need was identified to assess how people access and interpret early warning messages, and to document findings and incorporate them into more effective means of dissemination (Lumbroso, 2018).

Campbell et al. (2018) conducted a global study to examine the impacts of heat waves on population health. Based on socio-economic status, population density, acclimatisation capability and physical vulnerability, they concluded that heat waves are likely to be frequent and severe particularly in regions where population is already at high risk of death and illness. It was therefore recommended that research be conducted in particular in those under-represented areas that do not have the resources and capability to implement warning systems, community-accessible prevention strategies and adequate medical care. Incidentally, Campbell et al. (2018) recorded no research on heat waves and human health in Africa.

5.4 Popular literature

Popular literature is often focused on evidence of drought impacts. Drought can generally have both direct and indirect impacts, and they can be classified into three categories, namely economic, environmental and social. Economic impacts are those impacts of drought that cost people (or businesses) money. A few different examples of economic impacts of drought were reported by National Drought Mitigation Centre (2019):

- Farmers might lose money due to loss of crops; farmers will also have to spend most of their money on finding alternative sources of water

- Ranchers may have to spend more money to feed and water for their animals
- Businesses that depend on farming, like companies that make tractors and food, may lose business when drought damages crops or livestock, etc.

Drought can also affect the environment in many ways. Examples of environmental impacts include:

- Losses or destruction of fish and wildlife habitat
- Lack of food and drinking water for wild animals
- Increase in disease in wild animals, because of reduced food and water supplies
- Migration of wildlife
- Increased stress on endangered species or even extinction
- Lower water levels in reservoirs, lakes and ponds
- Loss of wetlands
- More wildfires
- Wind and water erosion of soils

Social impacts of drought are ways in which drought affects people's health and safety. Social impacts include public safety, health, conflicts between people when there isn't enough water, and changes in lifestyle (National Drought Mitigation Centre, 2019). Examples of social impacts include:

- Anxiety or depression about economic losses caused by drought
- Health problems related to low water flows and poor water quality
- Health problems related to dust
- Loss of human life
- Threat to public safety from an increased number of forest and range fires
- Reduced incomes
- People may have to move from farms into cities, or from one city to another
- Fewer recreational activities

6 PROSPECTS OF DROUGHT MITIGATION AND ADAPTATION

6.1 Introduction

Chapter 6 addresses the following question:
Question 4: What are the prospects of drought mitigation and adaptation?

Mitigation is referred to as an anthropogenic intervention directed at the cause of a phenomenon (e.g. reduce the sources and enhance the sinks of greenhouse gases that cause climatic change, or the occurrence and intensity of extreme events such as drought). Adaptation is a set of measures and practices that aim at lessening the adverse impacts through adjustments in natural and human systems to extreme events such as drought. Adaptation measures can be anticipatory or reactive, private and public, autonomous or planned (IPCC, 2014). The literature search provided an overview of the mitigation and adaptation options to drought for different water sectors and users. There is need to search for "new waters", optimize water use and protect water resources in drought-prone areas that could balance the increased demand and societal trends, and end the extreme reliance on surface water resources. This Chapter reviews technological and engineering options available to cope with drought and water scarcity. Mitigation practices include institutional framework and governance, technology development, trade and production patterns, education, awareness and public participation, whilst adaptation includes measures for protection from health impacts and spread of diseases, equitable distribution of water and pricing, changes in population's attitude and socio-cultural behaviour. It is important to differentiate adaptation measures to natural conditions of climatic variability and change, and to anthropogenic conditions such as desertification and poor management.

Drought has usually the most devastating impacts on agriculture because of the effects on the food production chain. The agricultural sector is also one of the most sensitive sectors in the country because of a lack of targeted drought response for agriculture. In a paper by Todorovic and Jovanovic (2019), a large number of adaptation and mitigation practices in agriculture were reported that can aid as response to climate change; many of these practices are applicable as responses to drought. Similarly, many adaptation and mitigation measures are beneficial regardless of climate changes and the occurrence of drought ("no regrets action"; FAO, 2011). It appears that response measures in the agricultural sector have been relatively well researched and many of them are ready for piloting, as compared to other sectors (domestic, industrial, etc.). However, the *South Africa's Water Research, Development, and Innovation (RDI) Roadmap: 2015-2025* (WRC, 2015) stressed the importance of supplying water for domestic use in order to improve human health (Water for People). WRC (2015) also warned about depletion of groundwater resources, especially during droughts, that may impact on the production of food (Water for Food, based on WEF, 2015), on the industry (e.g. slowing down of power generation due to shortages of water for cooling of thermal plants), as well as transboundary water use issues in particular during periods of drought (e.g. Crocodile and Orange transboundary catchments). Ultimately, WRC (2015) stressed the importance of conserving wetlands and biodiversity, where drying water resources may also threaten human livelihoods and settlements (Water for the Environment).

6.2 WRC reports

Amongst the research questions addressed in this project, the largest number of entries were found for WRC projects relevant to drought adaptation, in particular in the agricultural sector, both because of its relevance and because of the linkages with water management, i.e. research on water management in general and adaptation to climate change is also relevant to response and adaptation to drought.

Water resources management

Schulze (2011b) provided a comprehensive guideline document on the development of a strategy for adaptation to climate change for the South African water sector, an initial study on practical adaptation to climate change as well as directions for future research on adaptation to climate change in South Africa's water sector (allocation, demand, use and quality). Besides the need for strengthening of management, information and water infrastructure, the following recommendations for future research emanated from this document:

- Related to second order variables in relation to climate change
    - Changes in irrigation water demand and practices
    - Effects of changed land use patterns on water availability and production
    - Effects of changed water availability on land use patterns
- Related to third order variables in relation to climate change
    - Changes in water demand and supply
    - Changes in water rights and allocation mechanisms
    - Changes in dynamics of water quality responses with consequences on purification costs and human health
    - Impacts on terrestrial and aquatic ecosystems
    - A re-think on water storage, including natural, man-made and virtual storage
    - Impacts on infrastructure in regard to hydraulic design, dam safety, and infrastructure maintenance
    - Integrated Catchment Studies
    - Potential conflicts over shared transboundary rivers
    - Vulnerability of the poor in urban areas, in rural areas and including climate forced migration from other countries to South Africa, or climate-driven rural to urban migration
    - A focus on mountainous areas, ('water towers') that are sensitive/vulnerable to climate change

The document of Schulze (2011a) was followed up by a comprehensive WRC project report on climate change adaptation options in support of policy and strategy implementation (Stuart-Hill and Schulze, 2014).

South Africa lacks an up-to-date national database on hydrology, which puts constraints on many sectors such as biodiversity, agriculture, urban settlements and even human health that rely on climate and water as a key resource. Lack of data and inadequate impact modelling places constraints on the medium to long-term adaptation assessments as there is a lack of understanding of how the current climate impacts on livelihoods and what future impacts will be (Bonsal et al., 2011). Groundwater supplies are particularly important during drought periods and data including allocations, withdrawals and recharge is required. This also requires the development of a total water supply database which includes improved streamflow data, wetlands number and groundwater distribution (Bonsal et al., 2011).

In South Africa very little research focusses on the impact of climate change on groundwater resources. Groundwater sensitivity to drought is dependent on the amount of recharge and the semi-arid western part of South Africa has a low recharge rate, making it more susceptible to drought and increasing the vulnerability of the area. Research gaps identified for the impacts of climate change on groundwater include (Dennis et al., 2013):

- The need for drought impact studies which identifies the impacts on groundwater withdrawal and quality
- Reducing uncertainties in understanding observations and projections of climate change and its impacts and vulnerabilities
- Evaluate social and economic costs and benefits (in the sense of avoided damage) of adaptation, at several time scales
- Improve the integration of climate change modelling and impact modelling
- Timing of the precipitation and thus recharge is very important for the future development of the groundwater. In groundwater modelling, the downscaling methods can directly influence the predicted hydrological fluxes. The testing and evaluation of different downscaling methods with data verification is required along with the application to climate modelling data (Stoll et al., 2011)
- Exploring options for the artificial recharge of groundwater
- Identifying drought resilient aquifers (DWS, 2016)
- The valuation of the groundwater ecosystem services (Bann and Wood, 2012)

Agriculture

Concerning different economic sectors, research on drought adaptation in agriculture is abundant. Plant selection and breeding for drought tolerance is one of the most common adaptation responses to drought in the agricultural sector. De Ronde et al. (1999) conducted research to identify and characterise the genes for anatomical and physiological traits that contribute to drought and heat tolerance (polygenetic traits depending on a combination of traits contributing to tolerance), and to transfer such genes to drought sensitive plants. The study was done on tobacco, potato, cotton and maize and a number of crop-specific recommendations for further research on selection were made. Similarly, Spreeth et al. (2004) studied the selection of some under-utilized species (cowpea, Bambara groundnut and *Amaranthus*) in response to drought. The physiological and morphological basis of drought tolerance were studied on germplasm collected from different locations across South Africa. The main outcome was the development of a selection method for screening a large number of plants. The recommendations were very specific for specific plants, but the methodology could be applied for screening accurately other species. Testing in field trials and implementation was recommended in both projects (De Ronde et al. 1999; Spreeth et al., 2004).

Moeletsi et al. (2018) carried out a drought impact study on maize production in the Luvuvhu River catchment in Limpopo. The study was centred on the manipulation of planting dates and season duration as adaptation strategy to drought. In addition, the selection of the areas to be cultivated with maize in the catchment was given attention for the avoidance of drought impacts. Moeletsi et al. (2018) also recommended sustainable water management measures such as conservation agriculture to mitigate the possible effects of climate variability and extremes under climate change. Moeletsi et al. (2018) developed a decision support tool for drought and flood management in the Luvuvhu River catchment. An important recommendation emanating from their work was to disseminate research and products to officials and community in order to facilitate uptake. In addition, they proposed the introduction of crop varieties and species, as well as agricultural strategies that require less water. They also stressed the importance of weather network data collection and processing, and climate and hydrological predictive modelling at finer resolution.

Ncube (2017) reviewed drought coping and adaptation strategies in dryland cropping systems, irrigation and livestock production across the country with particular reference to smallholder farming. These are summarized in Table 6.1. Intervention strategies include availing affordable inputs to smallholder farmers, increase of extension services, investments in smallholder farming and establishment of programs such as the Comprehensive Agricultural Support Programme (CASP) and the Farmer Support Programmes (FSP). Water conservation strategies such as the development and sustainable utilization of new water resources (e.g. groundwater) is also crucial, including groundwater governance and protection zoning. The establishment of insurance markets is generally within the range of commercial farmers, however less affordable to emerging farmers. Similarly, there is lack of incentive to adopt water conservation and saving measures as a "new normal" in farming (Ncube, 2017).

Indigenous Knowledge Systems (IKS) is referred to the 'place-based knowledge' that is rooted in local cultures and generally associated with long-settled communities, which have strong ties to their natural environments, they are knowledgeable of rain occurrence based on other climatic and environmental factors as well as a myriad of drought adaptation options that have been tried and tested through decades and centuries. Some of these adaptation options, such as rainwater harvesting, use of indigenous plant species, drought-resistant animals, erosion control measures, etc., were discussed in Ncube (2017). IKS are currently promoted and recognized as complementary to scientific measures. A comprehensive report on indigenous knowledge of farmers in the Karoo was compiled by Ncube and Lagardien (2015). Ncube and Lagardien (2015) provided information on how local communities perceive drought, as well as an extensive list of adaptation actions to drought in agriculture based on indigenous knowledge (UNFCCC, 2014), including examples of case studies worldwide.

Prevention measures (e.g. investment in water storage facilities, pre-drought preparation to make water users more resistant to prolonged water shortages) are preferred to mitigation (reactive) measures (e.g. contingency plans to balance water supply and demand, subsidizing agricultural production, importing food, etc.). The current policy is mainly oriented towards relief, so implementation of mitigation and adaptation options is required as a pro-active measure. Educational programmes on drought risks, adaptation and mitigation are also required. Ncube (2017) indicated that the main South African drought management policy gaps are the lack of provision for agricultural water use during drought, although domestic and sanitary use is prioritized. Another important gap was indicated to be the lack of Drought Management Plans in provinces. Debates and fora should be strengthened around drought to address community needs, concerns and priorities, provide dialogue space, and update current institutions and government policies.

TABLE 6.1
Summary of institutional and technical measure of drought coping and adaptation strategies in South Africa (adapted from Ncube, 2017).

Institutional strategies		Affordable inputs to smallholder farmers
		Investment in smallholder farming
		Establishment of programs (e.g. Comprehensive Agricultural Support Programme CASP, Farmer Support Programmes FSP)
		Water pricing and tariffs
		Insurance markets
Technical measures	Dryland cropping systems	Drought-tolerant crops
		Zero tillage
		Multi-cropping and inter-cropping systems
		Introduction of new crop rotations to improve soil fertility
		Mulching
	Irrigated cropping systems	Irrigation system efficiency
		Irrigation scheduling
		Drip irrigation
		Root zone irrigation
		Rainwater harvesting and water storage
		Infrastructure maintenance
	Livestock production	Stocking rates
		Pasture management

Ncube and Lagardien (2015) recommended documentation and dissemination of information on drought, in particular indigenous knowledge. They proposed dissemination of information through workshops, information brochures and decentralization of information using cell phones. Farmers' resilience to drought can be improved through various mechanisms: long-term drought early warning and weather forecast systems; using drought-resistant fodder species and drought-resistant crops; and conservation agriculture. Programmatic support is required to emerging farmers. Ncube and Lagardien (2015) also stressed the importance and benefits of integrating scientific and indigenous knowledge.

In another WRC research project, Jordaan et al. (2017) conducted a study on the vulnerability to drought in the agricultural sector and its communities, more specifically the livestock sector in the Eastern Cape. He underlined differences in drought vulnerability and coping strategies between commercial farmers and communal farmers, and provided guidelines for drought classification and disaster drought declaration.

Jordaan (2017) proposed a number of mitigation and adaptation measures to improve resilience against drought by communal, land reform and commercial farmers as well as other stakeholders in the Eastern Cape, based on seven community capitals (Community Capitals Framework CCF7): i) human, ii) social, iii) cultural, iv) financial, v) infrastructure, vi) environmental, and vii) political. The resulting mitigation and adaptation strategies recommended by Jordaan (2017) include:

- Macro level impacts on adaptive capacity
- Culture, ethics, knowledge, perceptions
- Farm level adaptation
- Adjustment strategies
- Drought avoidance strategies
- Alternative livelihood activities (casual labour and informal trade)
- Food management strategies
- Sale of non-productive items and productive items
- Social networks
- Animal feeding strategies
- Drought insurance
- Coping strategies

Jordaan (2017) recommended research on technologies that promote drought-resistant systems and resilient systems, such as drought-resistant cultivars, alternative agricultural systems, conservative grazing, improved irrigation systems and water harvesting. The areas of research were identified to be the management of common land (due to land degradation and farmers' vulnerability), market access for smallholder farmers (due to long distances and competition), support to land reform beneficiaries, quantification of drought risks (comparisons between different methods and geographic areas, for drought insurance purposes), differentiating thresholds for drought declaration depending on vulnerability (e.g. commercial farmers are less impacted by seasonal droughts compared to smallholders), the definition and calculation of hydrological indices for rivers, dams and groundwater, timeous drought relief and drought support (through improved early warning systems and implemented Drought Management Plans), and psychological stress as contributor to drought vulnerability.

Urban and industrial

Studies in South Africa on planning for climate change adaptation at a local level in rural municipalities showed that Participatory Action Research (PAR) was essential in adaptation strategy planning and implementation. Further gaps identified in this area of research include (Hay and Hay, 2014, Ampaire et al., 2017):

- Exploration of self-help culture building in rural South African communities through PAR processes, especially where risk reduction activities are driven from the top down.
- Exploring the potential impact of hazards such as drought and the risk to specific activities, drawing on the experiential knowledge of villagers.
- Consideration of the difference between risk perception and scientific data in order to ensure effective mitigation and appropriate decisions around land use and resource management.
- Conditions under which climate action platforms add value to contextual policy implementation processes (Ampaire et al., 2017).

Mukhaibir and Sparks (2005) investigated the adaptive capacity of small towns in the Northern Cape to drought. They proposed a number of strategies for adaptation to drought based on supply side management (reduction of leaks, regional water resource planning, local water resource management and monitoring, conjunctive use of surface and groundwater, rainwater harvesting) and demand side management (dry sanitation systems, education programmes, tariff structures, water restrictions). A number of recommendations also emanated from this research, such as pro-active, precautionary, long-term and economically feasible strategies, monitoring for depletion of groundwater, emphasis on demand side management, awareness and training of personnel capacity, as well as a quantitative approach with real costs and water resource data.

Conjunctive use of surface and groundwater appears to be an appealing option for many urban areas (both big cities and small towns) and different sectors in South Africa, given the seasonality of climatic conditions and the increased incidence of drought. Part of this strategy is Managed Aquifer Recharge and Storage (MARS; Murray, 2003) that proved to be successful in a number of instances (DWAF, 2007; Bugan et al., 2016).

Galvin et al. (2015) proposed community based adaptation as a mechanism to translate scientific projections to a meaningful level based on livelihood and vulnerability information. They piloted this methodology in communities in cooperation with scientists and Non-Governmental Organizations (NGOs) in order to exchange knowledge and develop local action plans.

Jack and De Souza (2016) developed a generic Emergency Response Plan for Community Water Systems in rural communities or constrained municipalities where risks and vulnerabilities may occur to the water supply system, amongst others water shortages due to drought.

Vogel et al. (2015) highlighted the importance of the integrated water resources management approach because of the complexity of climate change and climate variability, where adaptation issues cannot be solved solely by individuals or groups, and no single recipe for successful adaptation exists. This was re-iterated by Stuart-Hill et al. (2012), with particular focus on hydrology and environmental impacts. Citizen science is a growing phenomenon in South Africa and globally, in obtaining data relevant to integrated water resource management. The water-food-energy nexus in South Africa is relevant to all levels of society and therefore it is logical that the broader society is involved in the protection of these resources (Graham and Taylor, 2018). Using citizen science could be useful in the collection of monitoring data for drought preparedness and forecasting in South Africa, where monitoring and data gathering is hampered in certain areas due to theft and vandalism of river gauges and monitoring stations (Meissner and Jacobs-Mata, 2016). Citizen science is therefore a means of PAR and a bottom-up approach which means that drought adaptation strategies and the implementation thereof will have the support of local communities which they impact on. More research should focus on training and building capacity in developed tools for citizen science. A scaling-up process should be developed so that the tools and learning processes are applied and accessed on a broader scale (Graham and Taylor, 2018).

Ecosystem services

Pringle et al. (2017) stressed the linkages between human well-being (socio-economic system) and natural systems by investigating insurance as a form of risk management that distributes costs of a natural disaster across a pool of people over time. The importance of naturally functioning ecosystem or ecological infrastructure (in combination with traditional built infrastructure) in mitigating the risks of extreme climatic events such as droughts, floods and other natural disasters is recognized. Pringle et al. (2017) also highlighted that there is disconnect between the scientific base and financial institutions, notably insurance companies that could invest in environmental solutions. This is mainly due to the industry being alienated from environmental risks, the difficulty of putting a price value to environmental risks, natural resources being a public good, the long-term nature of environmental impacts as opposed to annual (or quarterly) financial terms, the burden of imposing incentives that may reduce competitiveness, as well as regulatory barriers. In order to overcome these difficulties, Pringle et al. (2017) proposed the engagement of insurers, the agricultural sector and municipalities as the most directly involved and impacted parties. There is need to actively educate these parties about activities that reduce environmental risk, a better understanding of the requirements of actuarial models, and translating scientific information into relevant financial formats. They proposed testing and implementing various mechanisms to reduce the environmental risk, such as pilot demonstration projects, self-insurance models and green bonds for municipalities (Pringle et al., 2017).

Jordaan (2017) also stressed the importance of insurance as mitigation option through the development of Mean Annual Loss (MAL) and loss functions to calculate what is needed during the good years for coverage during dry years in livestock and maize production in the Eastern Cape. Pegram and Eaglin (2010) analysed the opportunities for shared risk between public and private sectors (in particular corporations) in addressing future water shortage in the economic context of water for growth and development.

Botai et al. (2017) recommended further research on the linkages between soil moisture, evapotranspiration and precipitation patterns (vertical moisture feedbacks into the atmosphere) across South Africa at the resolution of quinary catchments and for suitable time series. This research could support a better understanding of vegetation water stress and the localized occurrence of droughts as a function of soil moisture, soil water retention properties and the evapotranspiration processes (soil evaporation, plant transpiration, evaporation of rainfall intercepted by canopy).

The impacts of drought are often very specific to specific sites. Taylor and Adams (2013) investigated the effects of drought (2001-2012) on the complex ecosystem of Lake St Lucia in KwaZulu-Natal (drying of lake bed, increase of water salinity, sedimentation by water and wind, shape changes of shorelines, changes in habitat and species). The study aimed at describing the drought, management interventions and ecological response to drought. The main recommendations emanating from this study was the need for a holistic monitoring of human activities and human-induced transformation, changes in freshwater supply, water quality, impacts of sedimentation and alien invasive species, as well as a record of management interventions. A good understanding and conceptual model of the processes are essential in order to apply sound management practices. Another important recommendation was that, in order to ensure the holistic view, research should address the full catchment to cover the potential sources of impacts, and it should be run in the long-term to cover wet and dry cycles.

Institutional development and governance

Besides practices, policy and strategies are required as an adaptation measure to drought. Ncube (2017) reviewed current drought polices and response strategies at national and provincial level. The newest policy on disaster management is the White Paper on Disaster Management and the ensuing National Disaster Management Act (DMA Act 57 of 2002). A comprehensive National Drought Management Plan is embedded in this Act. According to this national document, each province is required to draft a Drought Management Plan. However, comprehensive provincial Drought Management Plans exist only for the Western Cape and Northern Cape (Ncube, 2017). The legal framework for Drought Management Plans includes the following national regulations, policies and acts (Jordaan, 2017):

- The Constitution
- The White Paper on Agriculture, 1995
- The White Paper on Disaster Management, 1999
- The Disaster Management Act (57 of 2002)
- The Strategic Plan for Agriculture
- The Conservation of Agricultural Resources Act (43 of 1983)
- National Disaster Management Framework (NDMF, 1995)
- National Drought Management Framework (2008)

This legal framework served to develop a Framework for Provincial Drought Management Plans based on the National Disaster Management Framework (Jordaan (2017) that can be applicable to any level of local government. This framework consists of four Key Performance Areas (KPAs):

- KPA 1: Integrated institutional capacity for drought management
- KPA 2: Drought risk assessment
- KPA 3: Drought risk reduction
- KPA 4: Response and recovery

It includes three Enablers:

- Enabler 1: Information management and communication
- Enabler 2: Education, training, public awareness and research
- Enabler 3: Funding

Effective short-term and long-term water resources plans are crucial policy measures to mitigate drought (Ncube, 2017). These can consist of water-supply oriented measures, water-demand oriented measures and drought impact minimisation measures. The measures related to supply management aim at increasing the available water supplies and storage, whereas those pertaining to demand management aim at improving the efficient use of the available resources (Molden et al., 2001). Water recycling and re-using is another important long-term strategy that can mitigate drought. Similarly, reducing non-beneficial water losses, increasing crop water productivity and allocating water for high value crops are well-known measures in agriculture that were amply discussed in the literature (Perry, 2011, Pereira et al., 2012). Search for "new water" sources should also be complementary part of these measures, such as groundwater development, desalination, and management of rainfed agriculture where sufficient land is available (Ncube, 2017).

Policy and research gaps identified by Ncube (2017) included recommendations on drought response and suggestions on a national drought response strategy for agricultural water use in South Africa. The main gap identified was the transfer of research and technology into practice. To this effect, it was recommended that a holistic approach be used in the implementation of drought adaptation and mitigation, including Early Warning Systems and Indigenous Knowledge Systems; however, this should be adapted to the environmental and socio-economic context, in particular where benefits should reach resource poor farmers. The Early Warning System is mandated to the South African Weather Services though the Weather Service Act (Republic of SA 2001), with the responsibility of weather and climate forecasting and the issuing of severe weather-related alerts. The information is disseminated through the Disaster Management Centre (DMC). Provincial governments are mandated to budget and mobilise funds in order to implement drought management strategies.

Research is required on whether drought adaptation strategies are in place and at what levels, e.g. national or local levels. This will provide information on where vulnerabilities are already identified as well as identify the barriers for implementation of strategies in the future such as insufficient resources, technical capacity or political commitment (Aguiar et al., 2018). The few studies that were completed in other African countries show that when adaptation strategies are in place it is usually at a national level and not at a local level (e.g. city level or small-scale farm level). This also applies to policy related to adaptation initiatives and the role of these adaptation initiatives (Filho et al., 2018, Wossen et al., 2014). There is a requirement that climate change and adaptation initiatives and policies be developed specifically at a local (city or farm scale) level and at a national level (AghaKouchak et al., 2015). Adaptation initiatives are more difficult to implement at a local scale due to barriers such as being under-capacitated, but this can be overcome with minimal need for additional resources by institutions if the initiatives were included in existing programmes (Dube et al., 2014). Baseline studies are however necessary to identify the existing institutional capacity and thereafter to develop training resources for institutional capacity building (Tapela, 2012, Ampaire et al., 2017). A research focus area was identified in the development of a generic framework for climate change adaptation for institutional support to communities. This framework will require that all constraining variables are fully researched and understood for successful implementation and they will include (Dube et al., 2014):

- Comprehensive maps of climate change vulnerability at community level.
- Integration of the top-down approach based on how water access is articulated by the institutions expected to serve communities and the 'bottom-up' approach, where the goals are set out by community members.
- Integration of capacities of communities and institutions. Communities that are exposed to specific climate change impacts have some ability to adapt; in addition, institutions have the capacity to provide some level of support in the process of adaptation.
- Development of toolboxes of possible adaptation measures. These include an inventory of possible adaptation measures, outlining the roles and responsibilities of various institutions, as well as identifying the gaps in the provision of community support.
- Improving policy and legal frameworks for supporting climate change adaptation.

- Development of community reception mechanisms for adaptation measures and community buy-in. An understanding of the dynamics of ownership and empowerment through direct community and institutional involvement is needed to ensure sustainability of developed solutions.

6.3 Peer-reviewed literature

Agriculture

The African continent has been identified as particularly vulnerable to the changing climate due to its envisaged low adaptive capacity and vulnerability (Callaway, 2004). The southern African region is regarded as one of the most vulnerable regions in Africa (IPCC, 2007). Two variables are particularly critical for the agriculture sector: future precipitation patterns and their distribution throughout the year, and the incidence of extreme weather events (IPCC, 2014).

Iglesias and Garrote (2015) provided a comprehensive review on agricultural adaptation strategies to climate change in Europe. As many of the climate change impacts are related to precipitation and extreme weather events, many of these adaptation strategies are also applicable to droughts. Appendix B includes a comprehensive list of agricultural adaptation strategies and measures in response to climate change, as reported in Iglesias and Garrote (2015).

There are diverse opinions in the literature to the effect that rural farmers' knowledge of climate change and their adaptive capacity is insufficient for reliable adaptation. Some scientists also perceive that rural farmers' knowledge is insufficient for rigorous evaluation of planned adaptation (Ayanlade et al., 2017). The recent IPCC report (IPCC, 2014) reveals, however, that local awareness and vulnerabilities are increasingly being incorporated in interdisciplinary, multi-stakeholder assessments. The report of the IPCC and previous studies in Africa have shown the need for assessments of the potential impacts of climate variability/change and for the integration of rural people's awareness of these changes alongside other weather stresses (Heltberg et al., 2009; Mubiru et al., 2015; Nyasimi et al., 2013; Van Griensven et al., 2016; Tschakert et al., 2014).

There is a need for an in-depth study to examine farmers' understanding of extreme weather events, their significant impacts on crop and livestock production, and their strategies for adaptation. Communicating scientific findings to farmers and incorporating their understandings will be very useful in implementing and monitoring strategies which would improve the crop yield not only in Africa but in the other parts of tropical regions. This understanding will enable rural farmers to prepare a local response to the anticipated impacts of climate change (Zake and Hauser, 2014; Nyasimi et al., 2013; Savo et al., 2016; Adimassu and Kessler, 2016).

In the case of climate change impacts on smallholder agriculture, what is apparent is the gap between scientists' analysis of global climate change and rural farmers' awareness. Despite the great advancement of climate science in understanding and dealing with the problem of climate change and its impacts on the agricultural sector at the international level, awareness and the concern for the problem at local levels, especially among the rural farmers in Africa, remains crucial (Ayanlade et al., 2017).

In most research, there is often disconnect between the scientific findings and user requirements. Research linked to drought monitoring, forecasting and adaption, especially using advanced technologies such as satellite remote sensing, may not be easily accessible or useable by the stakeholders required to make decisions. It would be advisable to follow a research participatory or science co-production approach (Olazabal et al., 2018). In this approach the users of the information define their needs, devise means to achieve them and set priorities for drought management and result evaluation (Fraser et al., 2013, Demisse et al., 2018, Galvin et al., 2015). This is also a way to decentralise the institutional arrangement from only government-developed climate risk and adaptation strategies to multi-stakeholders (Baudoin et al., 2017). Future research is required on data dissemination and implementation of developed concepts, data management research and information usability with regards to users' requirements (Demisse et al., 2018). This is also applicable to information related to early warning for droughts and other hazards (Wilhite and Svoboda, 2000). Such an approach will encourage more uptake of the research, create more trust amongst users and assist in future improvements (Olazabal et al., 2018).

Drought early warning systems are available in South Africa but there is a need for more locally relevant and comprehensive early warning systems as greater responsibilities are placed on farmers to plan for drought. As agriculture changes in adaptation to a warmer climate, it is expected that early warning systems change to manage a greater scale of information available, crop varieties and an improved focus on reflecting the needs of especially small-scale farmers (Monnik, 2000). According to Monnik (2000) a composite early warning system should ideally consist of:

1. Meteorological information,
2. Agricultural information,
3. Production estimates,
4. Price trends of food and feed,
5. Availability of drinking water, and
6. Household vulnerability.

The early warning system should include a vulnerability profile, which should include trends in recent rainfall, production, prices, and nutritional status, environmental status, soil fertility, and household status of the areas, to assist decision makers with appropriate responses. The physical aspects of early warning system should provide information on the spatial extent of the drought, duration, time of occurrence of drought in relation to the crop calendar, and severity (Monnik, 2000).

Research showed that drought vulnerability in farming in African countries are linked to socio-economic characteristics or development of a particular region. Further research is required to identify the drivers of socio-economic vulnerability and adaptation mechanisms of farmers in regions at a local scale, which emphasises the need for development of targeted adaptation policies and strategies (Antwi-Agyei et al., 2012, Fraser et al., 2013). Livelihood diversification strategies, including income not related to farming, requires research as well as the socio-economic consequences resulting from a decreased dependence on agriculture during water scarce periods (Antwi-Agyei et al., 2012, AghaKouchak et al., 2015). Methods will also be required to assess the consequences on the environment and socio-economics of these alternative drought strategies (Bonsal et al., 2011).

There is a need for research and development in agriculture toward understanding the interaction between food systems and climate change and so to adopt the value chain concept (Adenle et al., 2017, Solh and van Ginkel, 2014). Although models provide a tool for forecasting and prediction of climate variability for adaptation planning, quantification with scientific data will improve their accuracy (Adenle et al., 2017). The trend in drought adaptation research in the agricultural sector in drylands has moved away from the traditional single research component approach to an agro-ecosystems based approach. This is an integrative and a broader approach which involves all aspects including crops, livestock, rangeland, farming practices, trees, soils, water and policies (Solh and van Ginkel, 2014). Such an approach will allow for science-based solutions to be adapted to other regions that will possibly be affected by drought in the future. It should be noted that an agro-ecosystem approach requires the identification and buy-in from relevant stakeholders and partners who are in agreement on the drought impact to agriculture and livelihoods as well as the type of research impact that is required (Solh and van Ginkel, 2014).

Climate change will cause disruptions to rural agricultural food supply and alternatives such as peri-urban agriculture should receive an increase in research focus as a response to climate change. This includes assessing the value of peri-urban agriculture as a means of food security and additional benefits that could be derived from its establishment. Research showing the linkages between peri-urban agricultural areas and nature for ecosystem services is required. Peri-urban farms occur under the mandate of metropolitan governments often not capacitated to support a farming community and not within the national or provincial government (Haysom et al., 2016). As a result, these farmers will not receive the same support as rural farmers do in terms of reducing vulnerability to climate change. Efforts should therefore focus on integrating peri-urban agriculture into broader agri-food value chain, which are afforded the same protection and support as their rural counterparts (Haysom et al., 2016). The following were identified as possible areas for research (Haysom et al., 2016):

- Assessing the role that specific peri-urban agricultural areas play in their respective regions.
- The extent to which these areas are suitable for strengthening food security under conditions of climate change.
- Identifying and investigating the long-term sustainable management of freshwater resources used for peri-urban agriculture and of urban/peri-urban wetland areas which are critical for re-charge, and address the problems of water pollution.
- Investigating the role of peri-urban agricultural areas in city-wide climate change adaptation and mitigation strategies.
- Investigating and enabling suitable linkages to the green economy as well as climate smart agri-processing possibilities, particularly for smallholder farmers, in peri- urban areas.
- Investigating new marketing channels and new outlets for peri- urban produce.
- Investigating opportunities of value-adding marketing for peri- urban agriculture.

Water resilience to drought and dry spells in agriculture can be sustained by integrating land and water use, and incorporating the role of water in building social and ecological resilience in agricultural landscapes (Falkenmark and Rockström, 2008). However, a research gap exists in understanding the thresholds in agricultural systems. It becomes necessary to distinguish between situations where investment in agricultural development can successfully overcome land degradation (desertification) from situations when only social transformation is an option as the crossing of thresholds leaves no viable options remaining (Falkenmark and Rockström, 2008). Land degradation currently occurs and it is possible to identify solutions at a local scale by individuals or communities, while climate change mitigation is required at global scale. The loss of plant-water availability due to increased runoff, reduction in water-holding capacity through erosion, loss of organic matter and deterioration of soil structure can result in edaphic (soil-related) drought during non-drought years (Herrick et al., 2013). Climate change impact further exacerbates the situation. However, land degradation often results from poor land management long before climate change has an impact. Research into understanding the factors that control land degradation and land potential, including the potential to support multiple ecosystem services, will result in improved resilience to adapt to climate change impacts (Herrick et al., 2013). This will include practices in agriculture such as rain water harvesting to support rain-fed agriculture. This can occur by collecting runoff, improving soil infiltration, land, water and crop management to increase water storage in soils, wetlands and groundwater. All of these practices will lead to increased agricultural production, conservation of biodiversity and promotion of recovery of degraded land (Herrick et al., 2013, Rockström and Falkenmark, 2015). Research on climate change and ecological processes should therefore be complementary (Herrick et al., 2013).

Urban and industrial

Adaptation to climate change in cities is a necessity. Although urban climate change adaptation is a relatively new topic, over recent years significant advances have been made in policy, practice and research on climate change adaptation more broadly, and in urban areas specifically. The Cancun Adaptation Framework, adopted in 2010 under the UN Framework Convention on Climate Change (UNFCCC), establishes that climate change adaptation must be afforded the same level of priority as mitigation to reduce greenhouse gas emissions. The Cancun Adaptation Framework also supports the development of national adaptation plans. In Europe, as of January 2013, 15 Member States have adopted national adaptation plans or strategies (European Commission, 2013a, 2013b).

Though climate change is a global problem often discussed at the national scale, urban areas are increasingly seen as having a distinct role in the climate agenda in terms of both mitigation and adaptation. In addition to global disasters, urban areas have unique climate risks (e.g. urban heat island, impervious surfaces exacerbating flooding, coastal development threatened by sea level rise, etc.) (Doherty et al., 2016). Urbanisation in itself changes the local land surface area as well as the climate in urban areas. The urban climate generally has higher surface air temperature, weaker mean wind speed, and lower relative humidity compared with the suburbs and countrysides, which is referred to as the urban heat island effect (Ren, 2015). The urban climate change is coupled with global and regional climate change that further exacerbates the situation. A research gap identified is in understanding the interactions of multiple drivers in the urban domain in the prediction of urban climate change to benefit urban society and urban development (Ren, 2015).

Drought and people are interlinked and as much as drought impact on people, people influences drought and its severity of impact. The anthropocene (human-influenced) is therefore as responsible in causing drought as natural climate variability. The management of drought is often inefficient since these feedback loops are poorly understood (Van Loon et al., 2016). Urban populations exceed rural populations with cities growing exponentially worldwide. According to the New UN Urban Agenda, urban resilience, climate and environment sustainability and disaster risk management are key issues for urban sustainable development for the next 20 years (Baklanov et al., 2018). Due to high population densities, cities are more sensitive and vulnerable to extreme climatic variations and events (Baklanov et al., 2018) and African cities are under-represented in climate change research and successful adaptation initiatives (Filho et al. 2018). African cities have unique development challenges such as rapid population growth, high levels of poverty and environmental degradation linked to a lack of adequate sanitation infrastructure. Although these issues are not climatic factors, they are drivers of constraint, and add to the vulnerability of African cities in managing and adapting to the impact of climate change and weather extremes (Filho et al., 2018). Research should therefore focus on the socio-economic drivers of risk associated with a changing climate and how current and future city development plans can be integrated with extreme climate mitigation and adaptation strategies (Filho et al., 2018).

The Intergovernmental Panel on Climate Change (IPCC) concluded that human influence has contributed, on the global scale, since the mid-20th century, to the observed changes in the frequency and intensity of daily temperature extremes (Christidis and Stott, 2016). This anthropogenic warming of temperature traditionally was determined using finger-printing analysis but new approaches such as event attribution science (using temperature extreme indices to show statistically significant change) can provide a means of quantifying the causal factors that may alter characteristics of specific extreme events, including droughts. Attribution assessments have been limited to large scale spatial extent and more research is required at smaller local spatial scales as climatic variability may mask the anthropogenic signals. There is also a research need for attribution analysis of rainfall extremes using precipitation indices (Christidis and Stott, 2016). In South Africa, attribution studies focussed on the degree to which the predictability of seasonal forecasts vary from year to year, identification of the causes of such variations as well as the degree to which anthropogenic greenhouse gas emissions have altered the chance of extreme weather months. One such meteorological event attribution product was developed in a WRC project (Lawal et al., 2015). Further research is required to develop it into a product that provides information on the attribution of weather risk, including how the anthropogenic contribution to change compares against other drivers of risk. There is also a need to improve the product and promote its use into Africa and internationally to create further capacity in attribution science (Lawal et al., 2015).

On a local scale, such information will be valuable to adaptive strategy planning by municipalities to manage the risk associated with climatic extremes, and to determine whether management plans for adaptation to climate-induced drought or mitigating the actions that lead to human-induced drought are required (Easterling et al., 2016, Van Loon et al., 2016). With continued anthropogenic impact it is essential that updated information is used in attribution analysis (Christidis and Stott, 2016) and there is a need for the compilation of drought impact databases to assist with the analysis of and relationships between society perception of drought, adaptive strategies and drought impacts (Van Loon et al., 2016). In the long-term, the way in which society responds to drought, natural climate variability and landscapes will alter the baseline against which droughts will be measured. If adaptive and predictive drought management is to be successful, it is essential that research focuses on integrating social and natural sciences to evaluate such change (Van Loon et al., 2016). According to Moser and Ekstrom (2010), adaptation involves changes in social-ecological systems in response to actual and expected impacts of climate change in combination with non-climatic drivers such as demographic change or economic development. To date a large number of cities has neither developed comprehensive adaptation strategies, nor have they implemented respective adaptation measures in order to respond to expected climate change impacts (Cortekar et al. 2016). While examples do a good job in illustrating possible adaptation options and giving impulses for other cities, more detailed and specific information is necessary to transfer the same option to another location (Cortekar et al. 2016).

The basic and applied research need is for interdisciplinary studies to increase the understanding of interactions on spatial and temporal scales between emissions, air quality, and regional and global climates (Dube et al., 2016). In South Africa, the Long Term Adaptation Scenarios (LTAS) project applied scenarios to biodiversity, water, agriculture and health, but the built environment assessments are lacking. The LTAS was used in developing a water sector adaptation guide for local government institutions such as municipalities to address the impacts of climate change. Suggested research linked to this included (Dube et al., 2016):

- Development and implementation of practices that result in greener and more sustainable water and wastewater services system.

- Addressing shortfalls in legislative tools such as the Water and Water Services Acts in providing guidance to climate change response in the water sector. Research opportunities on climate change can be led within local government or other institutions.
- Research is required for new designs or improvement of existing infrastructure that consider climate change impacts and advance opportunities for adaptation since key chemical processes associated with water services will continue to change as the climate changes.
- Development of formal incentivised monitoring programmes encourages the municipalities' response to climate change using a progressive scoring system.
- Local municipalities need to embark on intensive climate change awareness campaigns with the aim of bringing understanding and knowledge to the local people as a forerunner to the introduction of adaptation strategies or implementation.
- A need for research on potable water and wastewater services, which are increasingly being negatively impacted, by secondary and tertiary climate change impacts.

In general, most South African cities are lacking integrated approaches that assess observed or projected impacts of climate change and most related studies focus only on a spatial or sectoral subset of the city as the unit of analysis (Ziervogel et al., 2014). Nature-based solutions are also increasingly being implemented in cities as part of urban planning to combat the impacts of climate change and provide additional benefits (Frantzeskaki et al., 2019). Green infrstructure in urban cities enable enhanced climate adaptation and resilience. The Water Sensitive Urban Design is a good example (Armitage et al., 2014). More research is required on strategic planning and placing of green infrastructure in order to provide optimal benefits for new developments as well as protection, conservation or restoration of existing opportunities (Carter, 2018). These additional benefits may initiate response from a different set of actors to create a process of shared response to adapatation strategies in an urban environment due to the multi-level governance of urban areas (Castán Broto, 2017). Research gaps identified in Frantzeskaki et al. (2019) are summarised as:

- Identifying best practices and the processes through which they can be embedded and upscaled while balancing disservices.
- Increased empirical research on trade-offs, co-benefits and unintended effects of nature-based solutions are required.
- More research on the social and health benefits is required.
- Research on the implementation of nature-based solutions, the effect or alteration of unintended ecosystem service delivery and possible solutions.
- Assessing non-material values of urban nature to reduce climate related risk and develop communication strategies of findings by relevant means in the context of city planning and design.
- Linking quantitative data with qualitative data for making nature-based solutions relevant, desirable, specifically tailored and effective in city environments.
- Developing an understanding of the type of business model that can sustain nature-based solutions over the long term and attract investment.
- Determining the economic value including the return on investment, focussing on the estimated impacts and costs of climate risks and the mitigation/adaptation options required at a city level.

For the water sector, planned interventions must consider both supply side and demand side solutions (Gleick and Palaniappan, 2010). On the supply side, adaptation options involve increases in storage capacity or abstraction from water courses. Demand-side options, like increasing the allocative efficiency of water to ensure that economic and social benefit is maximised through use in higher-value sectors, aim to increase value per volume used and to ensure that quality is maintained (Gleick and Palaniappan, 2010). Research gaps have been identified in climate change impact on water resources and the management thereof in an African context. These were identified by Nkhonjera (2017) and reported in Appendix C.

Ecosystem services

Nature or ecosystem based solutions/approaches such as investing in ecological or natural infrastructure can contribute significantly to water security in times of deficit and therefore be a measure of drought preparedness, adaptation and a provision of ecosystem resilience (Jones et al., 2012, Crausbay et al., 2017). Ecological restoration is focussed on restoring or rehabilitating aspects of natural ecological condition and function to deliver ecosystem services of societal benefit. This also includes ecological engineering where new ecosystems are created, such as wetlands, to provide a regulating service. Approaches to ecological infrastructure restoration has shifted as new approaches to restoring or rehabilitating ecosystems under changing climatic conditions are considered (Colloff et al., 2017). Various research gaps regarding nature/ecosystem-based approaches in the light of a changing climate were highlighted by Jones et al. (2012) and Frantzeskaki et al. (2019), including:

- There is a wide range of potential future climatic conditions and it is unclear as to which specific ecosystem-based approaches would be effective. As there are complex interactions between ecosystem components which influence ecosystem services delivery, there is often a lack of estimated maximum adaptation potential, which can generally be approximated for built structures. Field data, field-testing and collection of new data are therefore required.
- There is uncertaintity as to how climate change will affect an ecosystem’s ability to continue to provide its adaptation services into the future. Research to quantify the magnitude of climate-induced change that a particular ecosystem can endure and still provide its adaptation service, combined with a broad range of future climate change projections, is required.
- With increased destruction of ecosystems globally by threats other than climate change (e.g. invasive species), there is need to understand these threats on the ability of ecosystems to provide an adaptation service.
- Further research is required to identify the combinations of social, ecological and economic contexts where restoration-based ecosystem approaches provide competitive adaptation options.
- Research on the effectiveness of nature-based solutions to drought mitigation and the quantification of their costs and feasibility compared to infrastructure based mitigation techniques is required (Jones et al., 2012, Frantzeskaki et al., 2019, Crausbay et al., 2017).

The effects of human water and land use on environmental water supplies, which is not considered in current drought monitoring or prediction, should be explored. Research that considers human and environmental water needs in an integrative manner in the context of ecosystem services is required to understand the impacts of drought and adaptation to it. It is likely that direct human influence on environmental water supplies will, at times, outweigh the impact of climate change in certain circumstances (Christidis and Stott, 2016). Research on quantifying and separating these aspects are required. By assessing the anthropogenic influences on observed changes in extreme events, benefit can be derived to decision makers by influencing adaptation plans and strategies and providing knowledge to climate services (Christidis and Stott, 2016). There is, however, a need to understand the impact of ecological drought on the ecosystem services that benefit society and how these will change with the impact of drought. Findings from such studies can lead to changes in human perception views from one where humans and nature are competing for water to one where understanding that investing in water for nature also means investing in water for people (Crausbay et al., 2017).

Ecological traits in key biodiversity indicators and ecoystems are good indicators of environmetal change, e.g. linking the life history or physiology of species to drought sensitivity in forests or aquatic ecosystems (Tonkin et al., 2019). Further research is required on such ecological knowledge that would allow manipulation of ecological characteristics to reduce vulnerability to drought situations. This will improve proactive resource management strategies such as prescribed fire and forest thinning practices or releases from reservoirs to support hydrological requirements of riparian trees (Tonkin et al. 2019). This will shed light on the types of ecosystems and at what temporal and spatial scales these strategies are most effective enabling place-based management for identified drought vulnerability (Crausbay et al., 2017). Adaptive river management is necessary in changing environmental conditions so as to assure water supplies. In doing so prevention of species population destruction is achieved leading to resilience. Research on ecological traits in ecosystems through process-based models are required to improve river management to enable the continued provision of ecosystem services (Tonkin et al., 2019). Although necessary, process-based models are not often used in management of rivers due to a lack of species-related data. Long-term data is required, which are associated with long-term funding. However, process-based models have shown that improved future predictions, by understanding sentive ecosystems, are possible saving time and money and reducing the amount of interventions required while limiting or avoiding adverse impacts (Tonkin et al. 2019). The lack of species data could be overcome in the interim by developing simpler process-based models by using data from species with similar life histories and characteristics. The development of analytical methods could extrapolate across gaps in data sets (Tonkin et al., 2019).

Identifying and understanding process and function linked to hydrological ecosystem service provision and the costs associatied with loss thereof due to drought, provides a means of identifying ecological, socio-economic or political thresholds at which to implemement an adaptation option to avoid irreversible losses (Bonsal et al., 2011, Banerjee et al., 2013). Such research information can inform water, drought preparedeness and drought mitigation policies (Banerjee et al., 2013). Although research into ecological drought impacts and ecosystem service is gaining, it will still require governance as the key to implementation (Colloff et al., 2017, Crausbay et al., 2017). In South Africa, species and ecosystem modeling was prioritised, which indicates changes to the key biodiversity indicators (Ziervogel et al., 2014). The data sets are available to apply these models but the high levels of species richness, rarity and unique ecosystem types require the development of integrated assessment approaches so as to enhance relevance for policy formulation and implementation related to land-use and infrastructure planning, and investment decision-making (Ziervogel et al., 2014).

Institutional and governance

The research into drought mitigation and intervention will only be effective in the long-term if it is supported by policy and institutional reform for the effective adoption of new technologies and approaches (Solh and van Ginkel, 2014). However, most policies for risk reduction are based on centralised institutional arrangements, which are based on top-down approaches to risk management and therefore inflexible. In South Africa, the response to drought disasters are guided by the Disaster Management Act (DMA), which is executed by the Department of Cooperative Governance (DCoG), through the National Disaster Management Centre (NDMC). The DMA states that risk management is a shared responsibility and solicits national risk reduction from national, provincial and municipal levels, the private sector and civil society. Essentially, the DMA therefore promotes a decentralised multi-stakeholder process for risk management with a more proactive rather than reactive drought management approach (Baudoin et al., 2017). However, the shortcomings were identified in financial and human resources, heavy bureaucracy and a lack of flexibility. Institutions and institutional arrangements frame the manner in which risk reduction strategies are conceived and implemented by either creating barriers or enabling the long-term resilience of local communities (Baudoin et al., 2017). For example, local municipalities experience difficulty in implementing an adaptation or preparedness strategy as it may not be part of a national strategy and therefore support is weakened or insufficient funds are available. Another difficulty with implementation of such strategies is that the costs are immediately visible but the benefits may only be visible in the future (Aguiar et al., 2018).

Due to this, the proactive side of the DMA is limited to monitoring, reporting on the status of major infrastructures across provinces and municipalities but without implementing the actual drought preparedness interventions (Baudoin et al., 2017). Projects such as the Long Term Adaptation Scenarios (LTAS) make provision for limited national capacity development around climate change but there is a lack of a comprehensive capacity-building program that provides support for adaptation and acts as an intermediary for connecting scientists, policymakers and stakeholder groups (Ziervogel et al., 2014). More research is needed to investigate the causes of the disconnections in the management of disaster risks, both vertically (government scales) and horizontally (outwards across society). Research on the involvement of the private sector or insurance schemes to identify pathways to supplement governmental resources for risk (drought) preparedness and responses is required (Baudoin et al., 2017). Research on the understanding of the current risk preparedness and responses management strategy in South Africa is required to improve the functioning thereof so as to enable effective risk reduction approaches in extreme climate events (Baudoin et al., 2017).

Economic development in South Africa is directly linked to energy generation, which is linked either directly or indirectly to water availability and the environment. Climate change impacts on water availability and variability as well as increasing population growth, will require an integrated approach in management. The water-energy-nexus provides an integrated planning approach, which is in line with the Sustainable Development Goals 6, 7, 8 and 9 (Madhlopa et al., 2016). The National Development Plan advocates plans for industrialisation, which will require efficient energy and water use at a national and regional level of economic development. Research opportunities are therefore becoming available for the development of energy and water efficient initiatives. These initiatives create the opportunity for the development of national water-energy nexus policy that can be used to influence national water-energy nexus initiatives. Water and energy is currently planned as separate entities and there is a need for the development of climate resilient water and energy policies/strategies in the three spheres of government. A paradigm shift is required in the perception of the country's development goals where an integrated water-energy nexus will provide increased economic opportunities and will deliver on social goals (Madhlopa et al., 2016).

Adaptation planning and implementation are lagging in urban environments and cities. This was also illustrated internationally by Aylett (2015). Adaptation efforts by critical government agencies responsible for water, wastewater, health and building codes are only in their infancy. In cities, much of the attention is on the impacts that climate variability has on resources, especially water. However, it is also essential that the governance of these resources are also strengthened to improve urban climate adaptation (planning and response) by understanding the institutional networks of governance and responsibilities (Ziervogel, 2019). Assessments are required in local governments of the capacity and skills required for urban adaptation in response to climate change, where networks have already been made, how they were created and which of the local government actors are still to be engaged (Aylett, 2015, Ziervogel, 2019).

Global climate models (GCMs) projections for southern Africa show increases in rainfall variability and increased intensity of extreme events such as droughts that can lead to desertification. Climate change, drought and desertification are therefore interlinked. The policies and policy instruments that address climate change adaptation strategies, capacity and support, and those policies and policy instruments that address causes and impacts of drought (e.g. desertification), should be analysed to identify mutual areas of policy support (Stringer et al., 2009). More research on developing a broader framework of implementing climate adaptation concurrently with sustainable development plans to reduce vulnerability is required. There is also a need for further research using participatory approaches, involving on-the-ground stakeholders, towards formulating adaptation policy (Stringer et al., 2009).

Regarding climate change predictions, water resources re-allocation seems to be a key adaptation measure to tackle water scarcity problems. However, there are some potential solutions to water allocation problems, such as changes in infrastructure, land use or limitations of irrigation that may not be well accepted by the whole of society (Iglesias et al., 2011) and decision-making processes often can lead to conflicts among different stakeholders. Thus, it is essential to incorporate the interests of the different stakeholders affected by the consequences of these processes, including policy makers, farmers and the public. Within the next decade research on changes in regional extremes is likely to produce “actionable” results that will inform risk reduction interventions. But again this will require careful consideration of uncertainty, and presentation of results in terms that are readily understood by stakeholders (Hay et al., 2016).

The process of identifying, monitoring and evaluating adaptation strategies presents many complications, one of which is tracking adaptation. For example, the mitigation of greenhouse gas emissions by policy implementation can be measured but there are no clear cut methodologies or metrics developed for tracking adaptation. It therefore becomes necessary to develop standards, methodologies, indicators and baselines for assessing progress made in adaptation goals (Araos et al., 2016, Filho et al., 2018, Ziervogel et al., 2014). However, there is a lack of practical experience in implementing adaptation programs linked to long-term climate change and in South Africa this is limited to small scale sectoral or local scale. Although sufficient knowledge has been generated on adaptation strategies and activities in South Africa, these are somewhat poorly documented by the research community. This illustrates the need for transdisciplinary, action-research oriented approaches that follows through from understanding of impacts to vulnerabilities, adaptation and implementation (Ziervogel et al., 2014). Critical gaps in adaptation research and practice were identified by Ziervogel et al. (2014) as:

- Development and testing of approaches that enable integrated and flexible adaptation strategies.
- Improved understanding of the social, political, governance and financial barriers or enablers of adaptation in the South African context.
- How adaptation can address the reduction of poverty and inequality?
- One of the major constraints to implementation of the adaptation strategies is the lack of research relating costs of adaptation measures with suitable financing options. A collaborative research approach is required to develop approaches that support ‘robust’, ‘resilient,’ or

‘adaptive’ decision frameworks that take account of uncertainty (climate and its impacts on the social, political, and economic conditions), and avoid lock-in to particular scenarios.

6.4 Popular literature

It is very important for southern African countries, and individual citizens, to take preventative measures for drought impacts, since drought seems to be a recurring pattern in the region. Drought mitigation remains the responsibility of each and every human being. Three important pillars for enhancing drought resilience and to mitigate drought risks were outlined by UNCCD (2016), including: Drought monitoring and early warning systems; Vulnerability and risk assessment; and Drought risk mitigation measures. The diagram in Figure 6.1 summarizes drought mitigation strategies.

Figure 6.1

Summary of drought preparedness pillars according to UNCCD (2016)

There was a general consensus that the South African government was not well prepared for the drought occurring during 2014-2016 and was further criticized as droughts are a recurring instance in South Africa. The drought impacted on agriculture, electricity generation and the economy in a broader sense. The preparedness action were reactive rather than proactive (Meissner and Jacobs-Mata, 2017). The Department of Water and Sanitation (DWS) manages water resources and during drought periods is responsible for prioritising water supply according to water use by the different sectors with different levels of curtailment of use. The following were identified as lacking in drought management by Meissner and Jacobs-Mata (2017):

- Computer models are used to determine operating rules and require regular updating as the water use requirements changes.

- The DWS has water conservation and demand management strategies in place, which are essential to drought management. However, there is a lack of monitoring data on water use from municipalities, backlogs in infrastructure maintenance and some municipalities have not adopted the water conservation ethos. Refurbishment, operation and maintenance of bulk water supply systems and water distribution systems need to be improved.
- There is a gap at national level between scientists' ability to model the incidence of drought and the incorporation of this information into government and sectoral responses.
- A long-term, national drought policy and strategy to mitigate the risk of future occurrences of drought is required. There is a need for regular science-based mechanisms and monitoring that will deliver timely information to decision-makers and so strengthen risk management measures and preparedness plans, e.g. assessment of the use of groundwater resources, where it is sustainable, to augment water supply.
- Implement collaborative governance spanning the government, major water-use sectors and the broader citizenry is required.
- DWS's Drought Management Unit monitors drought and floods before, during and after such events occur. However only remedial measures are provided.
- Theft and vandalism of weather monitoring stations impacts the ability to gather data and operate an effective flood and drought early warning system.
- Rainfall data, necessary for streamflow assessments, is not freely available and needs to be purchased from the South African Weather Service and the Agricultural Research Council, placing a burden on forecasting budgets and hindering climate change research.

Mwendera (2016) reviewed the options available for drought mitigation through water resource management measures, emphasizing water storage. As drought and water resources are interlinked, the management of drought is essential to national water resources policy and strategies. The article reported proactive planning of water resources management for drought preparation and mitigation. These plans included:

- Long-term actions, oriented to reduce the vulnerability of water-supply systems to drought, i.e. to improve the reliability of each system to meet future demands under drought conditions by a set of appropriate structural and institutional measures.
- Short-term actions, which try to face a particular drought event within the existing framework of infrastructures and management policies.

Long-term actions may need to be supplemented by short-term actions depending on how severe the drought event is, which is equivalent to a drought contingency plan. An optimal water resources plan to alleviate drought will include the following measures:

- Water-supply oriented measures
- Water-demand oriented measures
- Drought impact minimisation measures

Specific actions recommended by Mwendera (2016) are summarized in Appendix D.

Ziervogel (2016) reported on climate change impacts and minimising vulnerability with the Adaptation at Scale in Semi-Arid Regions (ASSAR) project. The aim of this project was to generate future-focused and societally relevant knowledge of pathways to well-being in an attempt to address the lack of information on the best ways to deal with vulnerability to climate change. Case studies used in the project were the northern Namibia's Omusati region and eastern Botswana's Bobonong district in which vulnerability and risk assessment workshops were undertaken. The workshops included multiple stakeholders to create knowledge groups to assess what the pressing issues were to the different livelihood groups in the areas and the best responses to them. Drought was identified as one of the three most important issues and an impact chain was developed in which positive and negative future impacts were assessed. The advantage of these workshops were that the knowledge groups could identify and provide workable solutions that could be implemented at a local or district level scale. It was noted that these solutions were only achievable with the participation of all stakeholders which included local communities, local government and non-governmental organisations with connections to international funding organisations (Ziervogel, 2016).

A number of practical adaptation technologies were proposed by Bertule et al. (2018) for combating droughts (too little water) applicable to all water sectors and referred to categories such as water allocations, water augmentation, water efficiency and demand management, water storage and alternative water sources.

An article published in the Water Wheel (WRC (2009) reported a shift in the focus by the WRC on a more integrated research approach embracing a multi-sectoral, multi-level approach in climate change research. The recommended portfolio consisted of three main thrusts:

- Impacts of climate change:
    - Refinement and communication of climate-change scenarios, projections, information and data
    - Identification and quantification of impacts
- Adaptation to climate change:
    - Enhancing adaptive capacity
    - Delivering (piloting) adaptation actions
- Mitigation of climate change

South Africa has high vulnerability to climate change and it is therefore at risk of becoming food insecure. The Food and Agriculture Organisation’s (FAO’s) latest State of Food and Agriculture Report states productivity of crops, livestock, fisheries and forestry will become increasingly severe in all regions as a result of climate change. The impacts on Sub-Saharan Africa will be greatest due to the heavy reliance on agriculture and adaptation measures in these regions are therefore vital to address vulnerabilities in this sector. This is especially true for smallholder farmers. The FAO reports on economically viable alternative ways in assisting such farmers with adaptation measures to prevent poverty and foo-insecurity. The report states that policies should be developed that remove barriers and obstacles to smallholder farmers to implement adaptation measures successfully. Increased climate funds are needed for climate-smart food production systems. The report further states that adaptation and mitigation of climate change must occur concurrently (WRC, 2016).

Methods have been developed for assessing climate change impact on agriculture, however, uncertainty still remains a key issue. Global climate models, crop models and economic models are used to determine change impact on food crop production and prices (Beletse, 2009). The challenges identified were the limited comparisons between models assessments and the methods did not adequately assess socio-economic impacts or adaptation to climate change. This led to a global network of research scientists called AgMIP (Agricultural Model Inter Comparison and Improvement Project). This project had the aim of evaluating the impacts of climate change on food production and economic status of farmers. One of the projects under the network is the Southern Africa Agricultural Model Intercomparison and Improvement Project (SAAMIIPP) with the objectives of estimating regional-scale food production for different future periods and development scenarios, and identifying field-level adaptation strategies and evaluating economic impacts of climate change on commercial and small-scale farming systems. The SAAMIIPP has managed to build scientific and technical capabilities in response to climate change, advanced scientific knowledge and linked scientific communities with stakeholders. Different food producing regions will be expanded to include various adaptation measures including (Beletse, 2009):

- Early and late maturing crops
- Diversification of farming systems (including alternative crops)
- Ecosystem-based adaptation
- Sustainable land management (such as rainwater harvesting)
- Organic and inorganic fertilisation.

The importance of the agricultural sector in South Africa has focused the attention of climate change impact and vulnerability on this sector. A WRC project (no K5/1882/14) entitled 'Adaptive interventions in agriculture to reduce vulnerability of different farming systems to climate change in South Africa', focused on assessing the vulnerability of crops, rangelands and farming households, and determining whether farming practices can be adjusted or changed (Araujo and Johnston, 2014). Production of crops such as maize could increase if climate change impacts were properly understood but others such as mangos and citrus would decline. The adaptation options available are expensive but crop rotations as well as conservation tillage seems to be the best options to mitigate climate change impacts. (Araujo and Johnston, 2014) also reported that the research was based on climate scenarios and models that require updating when new data and models become available.

Some of the countries in the Southern African Development Community have already taken a step in preparing for future drought. According to the 2018 meeting on Climate Change & Drought Mitigation & Adaptation Strategies (Department of Water and Sanitation and Department of Environmental Affairs), the South African government have already decided to fund the following strategies to prepare for future drought.

- Early warning systems that support local communities and small scale farmers
- Raising climate resilient livestock
- Producing climate resilient rooibos tea
- Climate smart vegetable production
- Investments in water security, and
- Investments in climate proof infrastructure

Bonthuys (2018) reported on a WRC study entitled: "Effects of reduction of wastewater volumes on sewerage systems and wastewater treatment plants." The study focused on the drought in the City of Cape Town and the severe impact it had on the sewerage systems and wastewater treatment works. The low flows due to strict water restrictions resulted in impacts on water quality by increasing the chemical oxygen demand and suspended solids. The findings of the project may only be specific to the City of Cape Town as other municipalities have gravity fed sewers or reticulated networks with large sumps that are likely to experience solids deposition and anaerobic conditions. The main findings from this study were (Bonthuys, 2018):

- Plants with inherent flexibility, such as the ability to take settling tanks and biological nutrient removal systems offline during low flow conditions, and allow for the recycling of effluent within the plant to maintain hydraulic load were able to withstand low flow conditions better than inflexible systems.

- Training of plant managers and operators on mitigation measures is required.
- Lower river flows means that the treated wastewater will make up a larger percentage of the flow in rivers and will therefore contain a larger percentage of contaminants harmful to human health. Communities utilising such rivers should be made aware of this by a consultation process with local industries and municipalities.
- The impact of reducing the wastewater volumes through water saving should not be discounted, as the costs to infrastructure and the environment may outweigh savings if necessary measures are not taken into account.
- New conveyance (piping, pump stations) infrastructure and wastewater treatment plants should be designed to be flexible.
- Flow reductions (drought or demand management) should be planned and phased in to plant management.
- There was a need for a guideline document which was developed in the study.
- Smaller collection systems and flow-based wastewater treatment processes must considered when planning infrastructure for water conserving communities in future.
- Local wastewater treatment facilities may also feed more water reuse plants that need predetermined effluent quality.
- Water conservation programs should be part of any new plant designs.
- There is a need to expand the database of knowledge of the impacts of more plants of different sizes and to understand the effects of low flow conditions on gravity-fed sewers.
- Research should be extended to include more plants from other regions with extended periods of imposed water restrictions due to demand management or drought conditions.

Van Vuuren (2016b) reported an article on research done in the Kruger National Park that emphasises the importance of sustainable water law such as the Ecological Reserve implemented as part of the National Water Act (Act no 36 of 1998). Drought conditions in the Kruger National Park has allowed increased data gathering for improved knowledge on mitigation measures in the future. Previous knowledge provided information to park managers that the park was managed differently during each drought. The management in later years changed to strategic adaptive management principles to allow the natural variability to return. The droughts influenced the various animal populations in different ways. Herbivores were negatively affected due to a lack of grazing area available while carnivores have thrived due to an abundance of food. During the drought period, the main rivers in the Kruger National Park were still flowing as a result of the Ecological Reserve implementation, which allowed the terrestrial and aquatic ecosystem processes to continue despite the low rainfall and high temperatures. This was an improvement as with previous severe droughts in the park these rivers ran dry. Good co-operative governance is also practised between various water users and the Department of Water and Sanitation, Irrigation Boards or Water Use Associations, Water Boards (bulk water supply) and with Mozambique water managers. Park managers are also making use of technology such as social media to communicate in real-time when quick decision-making is required. Hydrological models are used to link decision support systems and climate forecasting systems. This assists in the stakeholder management process of water resources (Van Vuuren, 2016b).

Kotzé (2018) also reported on the Ecological Reserves that were in place on the five main rives in the Kruger National Park and how essential it was to the recovery of the Park after a severe drought period. Rivers were kept flowing due to: a proper communication system with all role players involved; accessible and available flow data; hydrological modelling and water resources accounting systems to inform decisions are necessary; a system to evaluate the results of the decision. The Park experienced increase resilience due to improved management of the landscape to a more natural variability in vegetation growth and water hole availability.

7 CONCLUSIONS

The review done in this short project indicated that terminology related to drought is not always used consistently within the South African research community. A universal definition of drought is not probable because it depends on specific users and sectors. Definitions also diverge amongst scientists from different science backgrounds. However, there is a general consensus that drought can be categorized into 6 categories, namely meteorological, agricultural, hydrological and socio-economic, with the addition of two emerging categories, i.e. ecological and anthropogenic droughts. The physical properties of drought are timing, intensity, duration and aerial extent, along with the frequency of occurrence. Similarly, there is no general consensus on indexes that characterize drought, although it is acknowledged that the primary weather variables involved are precipitation, air temperature and potential evaporation or evapotranspiration. As a result, the most commonly used indexes are the Standardized Precipitation Index (SPI) and the Standard Precipitation Evapotranspiration Index (SPEI). Based on these findings, it appears that a consolidation of drought-related definitions and terminology is required that would lead to the acceptance and adoption by the wide South African scientific community and community of practitioners.

Thanks to its favourable geographic position covering different climatic zones along distinct rainfall and temperature gradients, complex topography, influence of oceanic currents along the coastline and the effects of El Niño Southern Oscillation (ENSO), South African research has developed an advanced capability in global climatic analysis, modelling and predictions. The general trends of South African climate is that positive anomalies in temperature are on the increase, whilst total rainfall and number of rainfall days are decreasing in the North and North-East, and increasing in the southern interior. There is strong evidence of the increased number of extreme events, especially high temperature combined with decreased rainfall, which may result in more frequent, intense and widespread droughts. However, many research gaps have been outlined in the research field of physical climatology, in particular regarding the accuracy and uncertainty of predictions, the downscaling of global and regional predictive models to locally relevant conditions, especially in terms of medium- and long-term forecasting, and the variability of the effects of El Niño.

Studies on community behaviour and perceptions to drought were not common and this field of research needs to be strengthened, in particular amongst the most vulnerable population. Community behaviour and perception on drought and water scarcity are reflected mainly through impacts on economic losses, health and safety. From the economic perspective, research gaps were outlined in the need to include aspects such as access to land, finance, market, income, experience, education and extension services, and communication of information. More research is also required in applying the principles of behavioural economics, political, economic and social power dynamics, institutional development as well as the impacts of drought on human health.

Impacts of drought on various sectors of the economy, society and environment are generally very well documented. Similarly, a myriad of drought mitigation and adaptation strategies and practices are known. However, the main shortfall appears to be in the widespread implementation of drought adaptation and mitigation. Adaptation and mitigation practices to drought were not commonly researched for the domestic and industrial sectors, although much work was done on domestic water supply, sanitation and industrial effluent treatment from the physico-chemical and infrastructural perspectives. They were extensively researched for the agricultural sector, however transfer of technologies was slow and the implementation phase needs to be addressed in future. Collection of data and information appears to be shrinking over time, which impacts on the quality of research and knowledge generated. However, this opens up the opportunity for the adoption of new technologies such as remote sensing, and new approaches such as citizen science, indigenous knowledge systems and drought impacts from the perspective of ecosystem services provision.

Based on the results of this review on research done by WRC and broader, a framework for future research on drought was recommended in order to bridge the knowledge gaps. The framework is structured according to the three main clusters that have been dealt with in this project report:

- Physical climatology
- Community behaviour and perception on drought
- Mitigation and adaptation to drought

A second-level tier includes categories according to the sector impacted (e.g. water resource, agriculture, urban and industrial, ecosystems, institutional development and governance). The two levels are loosely linked to the six categories of drought (meteorological, agricultural, hydrological, socio-economic, ecological and anthropogenic droughts) and the categorization allows to address focused research gaps based on specific fields of research. The framework and findings are summarized in Table 7.1, 7.2 and 7.3 by cluster.

TABLE 7.1
Summary of research gaps identified in the literature for cluster on drought climatological research

Cluster	Research gaps	Research topics	References
Climatological research	Consolidation of drought definitions and terminology for wide acceptance and adoption by scientific community and practitioners	*Definition and calculation of hydrological indices for rivers, dams and groundwater*	-
		Differentiating thresholds for drought declaration depending on vulnerability (e.g. commercial farmers are less impacted by seasonal droughts compared to smallholders)	-
	Requirements for high computing capabilities (for highly complex models in climate modelling, forecasts, ground and remotely sensed data)	-	Landman et al. (2014)
	Strengthening of monitoring networks	*Development of real-time drought monitoring systems using geospatial information (e.g. satellite information)*	-
		Development of citizen science	
	Downscaling (statistical and dynamic) of Global Circulation Models and forecasting models to accurately predict regional and localized impacts of drought	*Definition of lateral boundary conditions in RCMs, better linkages between GCMs and RCMs for downscaling*	Abiodun et al. (2018)
		Spatial downscaling of climate model output at the level of typical quaternary catchments in potentially climate-sensitive areas	Schulze (2005)
		Analysis for more vulnerable and less resourceful areas that were historically under-represented in research	Campbell et al. (2018)
		Validation of downscaled data	-
		Integration of climate change projections and local socio-economic vulnerabilities	-
		Dissemination and uptake of climate modelling and forecasts	Ziervogel et al. (2009)
		Data re-analysis and simulations covering a longer time period, including, i.e. paleo-climate data sets	Abiodun et al. (2018)
		Quantification of the regional feedbacks between climate, land	Schulze et al.

TABLE 7.1
Summary of research gaps identified in the literature for cluster on drought climatological research

Cluster	Research gaps	Research topics	References
		use change, the ocean, fire and aerosols and their effect on climate change projections	(2011)
		Big Data Analysis methodologies	-
	Effects of El Niño Southern Oscillation (ENSO)	*Determining the variability of droughts in relation to the El Niño events*	Rouault et al. (2008)
		Assessment of the impact of El Niño and La Niña at the catchment scale	Rouault et al. (2008)
		The role of the Antarctic oscillation (AAO) on summer rainfall	Rouault et al. (2008)
		Determination of the interaction of ENSO and AAO and how this affects Southern African Climate	Rouault et al. (2008)
	Linking future projections of climate, river basins and land use for improved water and land use management	*Analysis of modelling, ground and satellite-derived data, and model validations*	Abiodun et al. (2018)
		Differentiating and quantifying natural climate variability and anthropogenic climate change impacts	(Nkhonjera, 2017)
		Large scale adoption of validated remote sensing information at high and low resolution depending on the purpose	Pegram et al. (2010)
		Linkages between soil moisture, evapotranspiration and precipitation patterns at the resolution of quinary catchments and long-time series	-
		Projections of impacts on domestic, industrial and energy water use – urban areas	Ren (2015)
		Projection of impacts on ecosystems and ecosystem services	-

TABLE 7.2
Summary of research gaps identified in the literature for cluster on community behaviour and practices under drought

Cluster	**Research gaps**	**Research topics**	**References**
Community behaviour and practices under drought	The effects of socio-psychological, institutional and cultural factors underlying individual perceptions in the context of climate change and drought	*Development of community reception mechanisms for adaptation measures and community buy-in*	-
		Exploration of self-help culture-building in rural South African communities through participatory action research (Hay and Hay, 2014)	Hay and Hay (2014)
		Consideration of the difference between risk perception and scientific data in order to ensure effective mitigation and appropriate decisions	Hay and Hay (2014)
		Exploring the potential impact of hazards such as drought and the risk to specific activities, drawing on the experiential knowledge of villagers	Hay and Hay (2014)
		Conditions under which climate action platforms add value to contextual policy implementation processes	(Ampaire et al., 2017)
	Role of (peri-)urban agricultural areas	*Role of specific (peri-)urban agricultural areas in food security*	(Haysom et al., 2016)
		Role of specific (peri-)urban agricultural areas in freshwater resources and wetlands conservation	Haysom et al. (2016)
		Role of specific (peri-)urban agricultural areas in green economy and climate smart agri-processing	Haysom et al. (2016)
		New marketing channels and new outlets for (peri)-urban produce and agriculture	(Haysom et al., 2016)
	Impacts on human health and safety	*Improving knowledge on the links between climate change extremes, food security, nutrition and health*	(Ziervogel et al., 2014)
		Impacts of drought on human health in Africa (e.g. heat waves)	Campbell et al. (2018)
		Social impacts of drought on human health and safety	(National Drought

TABLE 7.2 Summary of research gaps identified in the literature for cluster on community behaviour and practices under drought			
Cluster	**Research gaps**	**Research topics**	**References**
			Mitigation Centre, 2019)
		Psychological stress as contributor to drought vulnerability	-
	Behavioural economics	*Behavioural economics and management of domestic water demand*	(Smith and Visser, 2014)
	Education, training and empowerment of stakeholders	*Development of toolboxes of adaptation measures for institutions' support to communities*	(Smith and Visser, 2014)
		Developing training resources for institutional capacity building	(Tapela, 2012)
		Community and institutional training programmes on the benefits and maintenance of drought mitigation and adaptation measures (e.g. rainwater harvesting)	(Mannel et al., 2014)
		Development of an upscaling process so that the tools and learning processes are applied and accessed more widely	(Graham and Taylor, 2018)
		Integration of capacities of communities and institutions	-
		Indigenous knowledge systems and integration with science	(Adenle et al., 2017, Chanza and De Wit, 2016)
		ICT technology to engage communities	-
		Citizen science	(Graham and Taylor, 2018)
		Comprehensive maps of climate change vulnerability at community level	(Dube et al., 2014)
		Documentation, communication and dissemination of	Lumbroso (2018)

TABLE 7.2 Summary of research gaps identified in the literature for cluster on community behaviour and practices under drought			
Cluster	**Research gaps**	**Research topics**	**References**
		information on drought, in particular indigenous knowledge	

TABLE 7.3
Summary of research gaps on drought mitigation and adaptation identified in the literature and categorized in different research fields

Cluster	**Research field**	**Research topics**	**References**
Drought mitigation and adaptation	Water resources	*Strengthening of network data collection and processing at fine resolution for drought monitoring*	Moeletsi et al. (2018)
		Conjunctive surface and groundwater use and Managed Aquifer Recharge and Storage (MARS)	DWAF (2007)
		Sustainability of water resources management	-
		Validating the relevance and usefulness of drought indicators	(Blauhut et al., 2016)
		Testing and evaluation of different downscaling methods for water resources management	(Stoll et al., 2011)
		Improvement of early warning systems, especially medium- to long-term drought early warning and weather forecast systems	-
		Search for "new water" sources	-
		Technological development for water sources development, water treatment and re-use	-
		Linkages between land use and water use	Schulze (2011b)
		Water demand and supply	Schulze (2011b)
		Water rights and allocation mechanisms	Schulze (2011b)
		Water infrastructure and storage	Schulze (2011b)
		Trans-boundary catchment management	Schulze (2011b)
		Water-driven population migration	Schulze (2011b)
	Agricultural sector	*Diversification of cropping systems and crops*	Moeletsi et al. (2018)
		Plant selection and breeding	De Ronde et al. (1999); Spreeth et al., (2004)
		Planting dates, cropping season duration and areas of cultivation	Moeletsi et al. (2018)
		Improved land and water management strategies and practices that require less/conserve water	Moeletsi et al. (2018)
		Adoption of indigenous under-utilized crops	-

TABLE 7.3
Summary of research gaps on drought mitigation and adaptation identified in the literature and categorized in different research fields

Cluster	Research field	Research topics	References
		Sustainable agricultural intensification	-
		Integrated agro-ecosystems-based research	(Solh and van Ginkel, 2014)
		Livestock and pasture management	Ncube (2017)
		Application of "no regrets action" adaptation and mitigation measures that are beneficial to agriculture regardless of climate changes	FAO (2011)
		Restoration of environmental degradation	(Shiferaw et al., 2014)
		Establishment of new irrigation infrastructure and rehabilitation of old infrastructure	-
		Investigating the role of peri-urban agricultural areas in city-wide climate change adaptation and mitigation strategies	(Haysom et al., 2016)
		Farm power, mechanization, green energy and postharvest technologies under drought conditions	Adenle et al. (2017)
		Programmatic support for emerging, smallholder farmers and land reform beneficiaries	-
		Education and training	-
		Participatory management	-
		Economic risk mitigation and disaster management	Ncube (2017)
	Urban and industrial	*Research on interactions of multiple drivers in the urban domain in the prediction of urban climate change to benefit urban society and urban development*	Ren (2015); (Van Loon et al., 2016)
		Assessing observed or projected impacts of climate change in the built environment	Dube et al. (2016)
		Development of event attribution science	Lawal et al. (2015)
		Assessments in local governments of the capacity and skills and networks required for urban adaptation	(Aylett, 2015, Ziervogel, 2019)
		Integration of city development plans with drought adaptation strategies	-
		Strategic planning, development and implementation of green infrastructure in cities (e.g. more sustainable water and wastewater services in local municipalities; Water Sensitive Urban Design)	Armitage et al. (2014); (Carter, 2018)

TABLE 7.3 **Summary of research gaps on drought mitigation and adaptation identified in the literature and categorized in different research fields**			
Cluster	**Research field**	**Research topics**	**References**
		Research on potable water and wastewater services	(Dube et al., 2016)
		Development of water and energy efficient initiatives (water-energy-nexus)	(Madhlopa et al., 2016)
		Demand management in urban areas (dry sanitation, pressure reduction, tariff structures, water restrictions)	-
		Reduction of leaks and other losses	-
		Large scale rainwater harvesting	-
		Technology development in renewable sources of energy	-
	Ecosystem services	*Drought impacts on natural areas – protected areas (biodiversity) and rural rangelands*	Swemmer (2016)
		Understanding the mechanisms, processes and indicators of natural droughts in ecosystems and ameliorating the effects of artificial droughts	(Boulton, 2003, Humphries and Baldwin, 2003); (Ziervogel et al., 2014)
		Establishment and conservation of ecological infrastructure	Pringle et al. (2017)
		Quantification and categorization of the hydrological ecosystem services affected by drought	-
		Valuation of ecosystem services to quantify the impacts of drought	(Bann and Wood, 2012)
		Ecological traits that most influence drought sensitivity and adaptive capacity	(Tonkin et al., 2019)
		Development of improved forecasting tools that can project the response of key species, life stages and ecosystems to environmental changes – process-based models	(Tonkin et al., 2019)
		Nature-based solutions to drought mitigation and their feasibility	(Frantzeskaki et al., 2019)
		Integration of ecosystem-based approaches to reduce disaster risk with other measures of risk reduction	(Pearce, 2014)
	Institutional development and governance	*Improving understanding of the current risk preparedness and responses management strategy in South Africa*	-
		Investigating the causes of the disconnections in the management of disaster risks, both vertically (government scales) and horizontally (outwards across society)	(Baudoin et al., 2017)

TABLE 7.3
Summary of research gaps on drought mitigation and adaptation identified in the literature and categorized in different research fields

Cluster	Research field	Research topics	References
		Improved understanding of the social, political, governance and financial barriers or enablers of adaptation in the South African context	-
		Baseline studies to identify the existing institutional capacity	-
		Establishing institutions to assess response to climate change and drought	(Nkhonjera, 2017)
		Developing standards, methodologies, indicators, baselines, and monitoring programmes for tracking adaptation effectiveness, drought forecasting and refining climate models in different sectors (water resources, agriculture, urban and industrial, ecological), including socio-economic aspects	(Aldous et al., 2011); (Esfahanian et al., 2017)
		Development and testing of approaches for integrated and flexible adaptation strategies	-
		Development of both local and national level adaptation initiatives, strategies and associated policies	(AghaKouchak et al., 2015)
		Developing a broader framework of implementing climate adaptation concurrently with sustainable development plans	(Stringer et al., 2009)
		Using participatory approaches towards formulating adaptation policy to bridge the gap between science and users' and practitioners' needs and awareness	(Stringer et al., 2009)
		Improving policy and legal frameworks for supporting drought mitigation and adaptation	-
		Drafting and implementation of provincial and local Disaster Management Plans for timeous drought relief and support	-
		Identifying pathways to supplement governmental resources for risk (drought) preparedness and responses by involvement of private sector/ insurance schemes	-
		Research on links between local governments and networks (e.g. NGOs) in implementation of adaptation	Baudoin and Ziervogel (2017); Woodruff (2018)
		Developing trans-disciplinary and multi-sectoral knowledge networks as a pathway towards improved adaptive capacity	WRC (2009); (Baudoin and Ziervogel, 2017)
		Implications of drought to the food-water-energy nexus	(Madhlopa et al., 2016)

TABLE 7.3 **Summary of research gaps on drought mitigation and adaptation identified in the literature and categorized in different research fields**			
Cluster	**Research field**	**Research topics**	**References**
		Coordination of trans-boundary response to drought	-
		Development of integrated assessment approaches for key biodiversity indicators for enhanced policy formulation and implementation	(Ziervogel et al., 2014)
		Development of formal incentivised monitoring programmes encouraging the municipalities' response to drought using a progressive scoring system	(Dube et al., 2016)
		How adaptation to drought can address the reduction of poverty and inequality	-
		Dissemination of research and products to officials and community in order to facilitate uptake	Moeletsi et al. (2018)
		Drought awareness campaigns with the aim of bringing understanding and knowledge to the local people as a forerunner to the introduction of adaptation strategies or implementation	(Dube et al., 2016)
		Quantification of drought impacts and risks (evaluating social and economic costs and benefits, in the sense of avoided damage of adaptation, at several time scales)	-
		Comparisons between different methods and geographic areas for drought insurance purposes	-
		Pilot demonstration of insurance models	-

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APPENDIX A

SPECIFIC RESEARCH GAPS IN RELATION TO HYDROLOGY AND RAINFALL TRENDS, CLIMATE CHANGE AND AGRO-HYDROLOGICAL MODELLING

(Source: Schulze et al., 2011a)

Rainfall and hydrological responses

- Rate of expected change of rainfall in the first half of this century versus that in the second half of the century
- Shifts in the seasonal timing of rainfall
- Projected changes in extreme rainfall events
- Impacts of projected climate change on other climatic variables, e.g. temperature and potential evaporation
- Explicit assessment of the impacts of projected climate change on hydrological responses through the application of climate scenarios in a hydrological model
- Application of alternative emissions scenarios in climate scenario development to define the full envelope of possible change

Integration of climate change and agro-hydrological models

- Regional feedbacks between climate, land use change, the ocean, fire and aerosols are all currently unknown and their effect on climate change projections should be quantified
- In order to reduce uncertainty and improve levels of confidence in climate projection model outputs, research should focus on using output from a series of global climate models (GCMs) to obtain a probability distribution of, and a level of confidence on, the climate impacts being modelled
- There is a need for detailed actual land use information and information of the water engineered systems (e.g. dams, irrigation and return flows), which would significantly enhance the usefulness of hydrological modelling in catchments where crucial real-world decision are made
- Likely impacts of climate change on flow regimes for all 67 indices of the Hydrologic Alteration (IHA) used to describe ecologically relevant hydrological regimes
- Development of a regionally co-correlated equations, which could provide more regionally relevant results on modelled river water temperatures. A more complex equation could provide an estimated maximum water temperature as current equations are fully reliant on the accuracy of the mean air temperature data only
- Assessing the impacts of projected climate change on the river water temperature parameters to extend to cover southern Africa

APPENDIX B

AGRICULTURAL ADAPTATION STRATEGIES AND MEASURES IN RESPONSE TO CLIMATE CHANGE

(Source: Iglesias and Garrote, 2015)

Table B1. Adaptation measures selected and mechanism behind each option that offsets the potential negative impacts of climate change for agricultural water management.

Table B1. Adaptation measures selected and mechanism behind each option that offsets the potential negative impacts of climate change for agricultural water management.

Adaptation needs	**Measure**	**Mechanism to overcome the impacts of climate change**
I. Improve resiliency and adaptive capacity	1) Implement regional adaptation plans	Enhances effectiveness of adaptation measures
	2) Improved monitoring and early warning	Mitigates consequences of adverse events
	3) Improve coordination planning	Enhances effectiveness of adaptation measures
	4) Innovation and technology	Improves effectiveness of adaptation measures and reduces costs
II. Response to changes in water availability	5) Innovation: water use efficiency	Increases water availability
	6) Improve soil moisture retention capacity	Increases water use efficacy
	7) Small-scale water reservoirs on farmland	Increases water management flexibility at the local level
	8) Improve the reservoir capacity	Increases management flexibility and water availability at regional level
	9) Water reutilisation	Increase water availability
	10) Improve water charging and trade	Decrease inefficient use of water
	11) Re-negotiation of allocation agreements	Improves water use efficiency
	12) Set clear water use priorities	Improves water use efficiency
	13) Integrate demands in conjunctive systems	Increases management flexibility and water availability
III. Response to floods and droughts	14) Create/restore wetlands	Reduces flood peaks
	15) Enhance flood plain management	Reduces flood vulnerability
	16) Improve drainage systems	Reduces extent and duration of flooding Decreases risk of flood damages
	17) Farmers as 'custodians' of floodplains	Decreases risk of flood damages
	18) Hard defences	Reduces flood peaks at the local level
	19) Increase rainfall interception capacity	Improves ergonomic water use efficiency

Table B1. Adaptation measures selected and mechanism behind each option that offsets the potential negative impacts of climate change for agricultural water management.		
Adaptation needs	**Measure**	**Mechanism to overcome the impacts of climate change**
	20) Introduce drought resistant crops 21) Insurance to floods and drought	Decreases economic losses to the farmer
IV. Response to increased irrigation requirements	22) Change in crop and cropping patterns 23) Improve practices to retain soil moisture 24) Develop climate change resilient crops	Decreases economic risk to the farmer Decreases the need of additional water to crops Mitigates impacts of climate change
V. Response to changes in agricultural land use	25) Relocation of farm processing industry 26) Addition of organic material into soils 27) Introduce new irrigation areas	Maintains industrial activity Recovers soil functions Develop new agricultural land
VI. Response to deterioration of water and soil quality	28) Improve nitrogen fertilisation efficiency 29) Soil carbon management and zero tillage 30) Protect against soil erosion	Reduces agricultural diffuse pollution Reduces soil erosion and improves soil water retention capacity Reduces land degradation
VII. Response to loss of biodiversity	31) Increase water allocation for ecosystems 32) Maintain ecological corridors 33) Improve crop diversification	Improves ecosystem services, effective at global level Improves biodiversity with positive global consequences Improves biodiversity

Table B2. Adaptation measures to climate change risks and opportunities.

Responding to the need of adaptation and measures	**Level (1)**	**Category (2)**	**Time scale (3)**	**Technical difficulty (4)**	**Potential cost (5)**	**Potential benefits (6)**	**Benefit to effort ratio (7)**
I. Improving resiliency and adaptive capacity							
1) Implement regional adaptation plans	P	MA	LT	H	M	H	1.15
2) Improved monitoring and early warning	P	MA	MT	M	M	H	1.50
3) Improve coordination planning	P	MA	ST	M	L	H	2.14
4) Innovation and technology	P	MA	LT	H	H	H	1.00
II. Responding to changes in water availability							
5) Innovation: water use	P	MA	MT	M	M	H	1.50
efficiency 6) Improve soil moisture retention	F	T	MT	M	M	L	0.50
capacity 7) Small-scale water reservoirs on	F	I	MT	M	M	H	1.50
farmland 8) Improve the	P	I	LT	H	H	H	1.15
reservoir capacity	P	I	MT	H	H	H	1.25
9) Water reutilisation	P	MA	LT	H	H	H	1.00
10) Improve water charging and trade	P	MA	LT	H	H	H	1.00
11) Re-negotiation of allocation agreements	P	MA	LT	H	L	H	1.36
12)Set clear water use priorities	P	MA	MT	M	L	M	1.25
13)Integrate demands in conjunctive systems							
III. Responding to floods and droughts							
14) Create/restore	F	I	LT	H	H	M	1.00

wetlands							
15) Enhance flood plain management	F	MA	MT	H	H	H	1.07
16) Improve drainage systems	F	I	LT	M	L	M	1.11
17) Farmers as ‘custodians’ of floodplains	P	MA	LT	M	H	H	1.36
18) Hard defences	P	I	LT	H	H	H	1.15
19) Increase rainfall interception capacity	P	I	MT	M	M	H	1.88
20) Introduce drought resistant crops	F	MA	LT	H	M	M	0.77
21) Insurance to floods and drought	P	MA	MT	M	H	H	1.88
IV. Responding to increased irrigation requirements							
22) Change in crop and cropping patterns	F	MA	ST	L	M	M	1.43
23) Improve practices to retain soil moisture	F	MA	MT	M	M	M	1.00
24) Develop climate change resilient crops	P	T	LT	H	H	M	0.67
V. Responding to changes in agricultural land use							
25) Relocation of farm processing industry	P	MA	LT	H	H	H	1.00
26) Addition of organic material into soils	F	MA	ST	L	M	L	0.71
27) Introduce new irrigation areas	P	MA	LT	H	H	H	1.15
VI. Responding to deterioration of water and soil quality							
28) Improve nitrogen fertilisation efficiency	F	MA	ST	L	L	L	1.00
29) Soil carbon management and	F	T	MT	M	M	M	1.00

zero tillage							
30) Protect against soil erosion	F	MA	MT	M	H	L	0.42
VII. Responding to loss of biodiversity							
31) Increase water allocation for ecosystems	P	MA	LT	H	L	H	1.15
32) Maintain ecological corridors	P	MA	LT	H	H	H	1.00
33) Improve crop diversification	F	T	LT	M	M	M	0.91

(1) Farm level (F), policy level (p); (2) agronomic (AG), management (MA), infrastructural (IN); (3) short term (ST), medium term (MT) or long term (LT); (4)-(6) low (L), medium (M) or high (H).

APPENDIX C

RESEARCH GAPS IN CLIMATE CHANGE IMPACTS ON WATER RESOURCES AND MANAGEMENT IN AFRICA

(Source: Nkhonjera, 2017)

- More empirical studies on water management institutions (comparative studies of river basins with different institutions, and their relative effectiveness in mitigating variability, scarcity, water quality degradation) to improve the understanding of water management institution response to climate change.
- Research on natural climate variability and anthropogenic climate change impacts in an integrated approach so that more realistic predictions of hydrological response to the future climate can be obtained.
- Better database management and dissemination of information for water resource managers.
- Improving use of downscaled climate change information for input into hydrological modelling.
- Refining use of earth observation and in situ data to increase understanding and improve prediction of climate change.
- Improving the utility of available model outputs by acknowledging and quantifying compounded predictive uncertainty.
- Uncertainties in projected groundwater recharge that originate in the hydrological models need further exploration.
- Research on impact of climate-driven changes of land use on groundwater recharge (e.g. increased groundwater abstraction lowering groundwater levels and storage).
- Associated costs of higher concentrations of people and infrastructure coupled with extreme weather events need more exploration.
- More research required in river basins where climate change will impact on water demand for agriculture and industry.
- The impacts of climate change, other existing stressors on the hydrological regime and freshwater ecosystems as well changes in water and land management is associated with many uncertainties. Research on a dedicated monitoring programme with specific reference to adaptive management scenarios is required, with the aim of refining implementation with climate model scenario improvements, tracking adaptation strategy effectiveness and changing ineffective strategies (Aldous et al., 2011).
- Understanding the mechanisms and processes of natural droughts in freshwater ecosystems and ameliorate the effects of artificial droughts (Boulton, 2003, Humphries and Baldwin, 2003).
- Climate change adaptation projects in South Africa focussed more on environmental rather than socio-economic issues. Research on methods to conceive trans-disciplinary climate change adaptation projects is required to reduce climate change variability (Baudoin and Ziervogel, 2017).
- Integration of ecosystem-based approaches to reduce disaster risk with other measures of risk reduction, e.g. avoidance of high risk zones, building codes, early warning and evacuation procedures (Pearce, 2014).
- More research should focus on how local governments can use networks (e.g. NGOs) in dealing with shortcomings in terms of technical or operational issues in

developing/implementing adaptation strategies/measures, policies and programs (Baudoin and Ziervogel, 2017, Woodruff, 2018).

- Comparative studies to determine if cities that occur within/utilise networks have stronger climate adaptation plans/capacities than cities outside of networks (Woodruff, 2018).
- Research on developing transdisciplinary knowledge networks as a pathway towards improved adaptive capacity is required (Baudoin and Ziervogel, 2017).

APPENDIX D

SUMMARY TABLES OF DROUGHT ADAPTATION MEASURES AND WATER STORAGE OPTION

(Source: Mwendera, 2016)

Drought adaptation measures related to water resources		
Category	**Short-term**	**Long-term**
Supply management	- Mixing fresh and low quality waters - Exploiting high-cost waters - Over-drafting aquifers - Diverting water from given uses - Decreasing transport and distribution losses - Adjust legal and institutional framework	- Increase water collection and storage opportunities (reservoirs) - Desalination of brackish and saline water - Treatment and reuse of wastewater - Water transfers - Artificial precipitation - Locate potential new resources - Groundwater recharge - Adjust legal and institutional framework
Demand management	- Restricting agricultural uses (rationing, subjecting certain crops to stress) - Restricting municipal uses (e.g. lawn irrigation) - Review operations of reservoirs - Water metering and pricing - Water rationing - Education and awareness creation - Provide permits to exploit additional resources - Provide drilling equipment - Adjust legal and institutional framework - Negotiate transfer between sectors	- Adopting supplementary and deficit irrigation - Water-saving irrigation techniques (drip, sprinkler, etc.) - Incentives to invest in water saving technology - Water recycling - Dual distribution networks for drinking water supply - Inventory private wells and negotiate their public use - Assess vulnerability and advise water users - Adjust legal and institutional framework
Impact minimisation	- Temporary reallocation of water resources (on the basis of assigned use priority) - Restrict uses - Emergency supplies - Public aid to compensate loss of revenue - Tax relief (reduction or delay of payment deadline) - Rehabilitation programmes - Resolving conflicts - Implement set-aside regulations	- Development of early warning system - Reallocation of water resources on the basis of water quality requirements - Use of drought resistant plants - Development of a drought contingency plan - Mitigation of economic and social impacts through voluntary insurance, pricing and economic incentives - Education activities for improving preparedness to drought - Elaborate set-aside regulations

Water storage options		
Storage option	**Benefits**	**Risks**
Natural wetlands	- Water storage is provided as an ecosystem service without the need for costly infrastructure; - Water purification; - Regulation of water flows; - Attenuating floods and droughts; - Sediment and nutrient retention and export	- Excessive utilisation of water in natural wetlands may undermine other ecosystem services
In-field rainwater harvesting	- Generally, low-cost options that can be implemented by individual farmers and communities	- Limited storage, will not provide water for more than a few days without rain; - Farmers with small land holdings may be reluctant to give up some land to serve as donor areas
Groundwater	- Evaporation losses are low or non-existent; - Multiple year storage that is largely decoupled from seasonal variability.	- Requires detailed hydrogeological information to locate wells and estimate yields; - Depending on the geology of the aquifer, the water may contain toxic chemicals (e.g. arsenic)
Ponds and tanks	- Low cost options implementable by communities and non-governmental organizations (NGOs).	- High evaporation losses; - Risk of contamination from surface runoff and livestock; - Risk of siltation; - May provide breeding habitat for disease vectors.
Reservoirs	- Large volume of water which can be used for multiple purposes; - It enables production of electricity; - Can offer protection from floods.	- Requires substantial capital investment; - Displacement of large number of people; - Significant environmental and social impacts arising from changes in river flows; - May provide breeding habitat for disease vectors.