AOSIS

Water Security and Climate Adaptation in Southern Africa

Volume 1

Integrated Transboundary Water-Climate Management Tools

Edited by
Nnenesi A. Kgabi

Water Security and Climate Adaptation
in Southern Africa
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Integrated Transboundary **Water–Climate** Management Tools

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Peer review declaration

The publisher (AOSIS) endorses the South African 'National Scholarly Book Publishers Forum Best Practice for Peer Review of Scholarly Books'. The manuscript was subjected to rigorous two-step peer review prior to publication, with the identities of the reviewers not revealed to the author(s). The reviewers were independent of the publisher and/or authors in question. The reviewers commented positively on the scholarly merits of the manuscript and recommended that the manuscript be published. Where the reviewers recommended revision and/or improvements to the manuscript, the authors responded adequately to such recommendations.

Research Justification

The scholarly theme of the book lends itself to the discipline of earth and atmospheric sciences, with a specific focus on water–climate studies. The book is a scholarly discourse by researchers in the natural sciences, including hydrologists, climate scientists, environmental engineers and water scientists. The purpose of the book is to address the limited complementarity between the water and climate studies, which is crucial in promoting scientific research that informs policy decisions and the implementation of water-security plans.

The chapter contributions were sourced from researchers in the project – 'Water Security and Climate Adaptation in Southern Africa' at the North-West University, and the research chair network linked to the United Nations Educational, Scientific and Cultural Organization (UNESCO) Chair on Sustainable Water Research for Climate Adaptation in Arid Environments, based at the Namibia University of Science and Technology. The chapters were selected to represent water–climate models and policy research conducted in different river basins in arid and semi-arid environments. Therefore, the water–climate management tools highlighted in this book include General Circulation Models (GCMs), Coupled Model Inter-comparison Project Phase 5 (CMIP5), Soil and Water Assessment Tool (SWAT), Africa Flood and Drought Monitor (AFDM), Extreme Precipitation Events (EPEs), R ClimDex, Mixed Strategy Game Models, Standard Precipitation Indices (SPIs), Water Evaluation and Planning (WEAP) System, Penman Calculator and Saturated Volume Fluctuation (SVF).

Four of the nine chapters in this book contain material representing substantial reworking of the primary research and modelling for higher degree studies done at the University of Zambia and the Namibia University of Science and Technology. One chapter is a review of previous studies, and the remaining eight are based on river basin research and modelling projects by researchers from different institutions. As a whole, the book contains more than 50% original content, not published before, and no part of the book has been plagiarised.

Nnenesi A. Kgabi, Unit for Environmental Sciences and Management, Faculty of Natural and Agricultural Sciences, North-West University, Potchefstroom, South Africa

Contents

Abbreviations, Figures and Tables Appearing in the Text

List of Abbreviations

%R	Percentage Recharge
ACCESS1-0	Australian Community Climate and Earth System Simulator
AFDM	Africa Flood and Drought Monitor
Alex	Alex Muranda Livestock Development Centre
C	Cut Off
CDD	Consecutive Dry Days
Cla	Claratal
CNRM-CM5	Centre National de Recherches Météorologiques Climate Model
CORDEX	Coordinated Regional Climate Downscaling Experiment
CORDEX-Africa	Coordinated Regional Climate Downscaling Experiment for Africa
CSV	Comma-separated-values
CUEB	Cuvelai-Etosha Basin
CWD	Consecutive Wet Days
DEM	Digital Elevation Model
Diep	Dieprivier-Namib Desert Lodge
EPEs	Extreme Precipitation Events
Erich	Erichsfelde
ET	Evapotranspiration
FAO	Food and Agriculture Organization
Gan	Ganab
GCM	General Circulation Model

Gell	GellapOst
GHG	Greenhouse Gas
GIS	Geographic Information System
HRUs	Hydrologic Response Units
I	Inflow
IPCC	Intergovernmental Panel on Climate Change
IPSL-CM5A-LR	Institut Pierre Simon Laplace Model Climate Model
ITCZ	Inter-Tropical Convergence Zone
Kari	Karios-Gondwana Canyon Lodge
MAWF	Ministry of Agriculture, Water and Forestry
MIROC5	Model for Interdisciplinary Research on Climate
MPI-ESM-MR	Max Planck Institute for Meteorology Earth System Model
MPI-M-MPI-ESM-LR	Max Planck Institute for Meteorology Earth System Low Resolution Model
MRI-CGCM3	Meteorological Research Institute Coupled Global Circulation Model
Nara	Narais-Duruchaus
NASA	National Aeronautics and Space Administration
NDMC	National Drought Mitigation Centre
NDVI	Normalized Difference Vegetation Index
NMS	Namibia Meteorological Services
O	Outflow
Omat	Omatako Ranch
PET	Potential Evapotranspiration
PGF	Princeton Global Forcings
PGFD	Princeton Global Forcing Dataset
PRCPTOT	Annual Total Wet-day Precipitation
PSDI	Palmer Severity Drought Index
R_n	Net Radiation

R10	Number of Heavy Precipitation Days
R20	Number of Very Heavy Precipitation Days
R95p	Very Wet Days
R99p	Extremely Wet Days
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RH_{mean}	Mean Relative Humidity
RMS	Root Mean Square
RO	Runoff
Rx1	Maximum 1-day Precipitation Amount
Rx5	Maximum 5-day Precipitation Amount
S	Storativity
SADC	Southern African Development Community
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management
SDII	Simple Daily Intensity Index
SMHI	Swedish Meteorological and Hydrological Institute
Sonop	Sonop Research Station
SPEI	Standardised Precipitation and Evapotranspiration Index
SPI	Standard Precipitation Index
SVF	Saturated Volume Fluctuation
Sy	Specific Yield
SWAT	Soil and Water Assessment Tool
T_{mean}	Mean Temperature
Tsu	Tsumkwe Breeding Station
U	Wind Speed
USGS	United States Geological Survey
VIC	Variable Infiltration Capacity
WARMA	Water Resources Management Authority

Wat	Waterberg
Wdk	Windhoek-NBRI
WEAP	Water Evaluation and Planning
Wlo	Wlotzkasbaken
WMO	World Meteorological Organization

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Preface

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Most African countries face water resources stress. This prompts the need to provide reliable access to water of sufficient quantity and quality in the face of increased urbanisation, a changing and unpredictable climate, and economic instability. However, decisions on water supply and climate adaptation continue to be attended on a 'budget allocation' basis, instead of relatively accurate scientific information on the sustainability of available water sources. According to the Southern African Development Community (SADC) (2005), water-resources availability, utilisation and related infrastructure development in the SADC are hampered by significant variability of rainfall in quantity and distribution, which leads to variability in water-resources availability and usage across the region.

Therefore, there is an urgent need to address the water and climate challenges jointly, starting with the development and/or improvement of water–climate management tools suitable for the region. The nature of the region, that is shared transboundary watercourses also contributes to the challenges of water–climate management in the SADC. Thus, in this book, studies conducted on different river basins in South Africa, Namibia, Tanzania (also host to lake basins) and Zambia are used to demonstrate the need for an integrated transboundary water–climate management tools and approach to ensuring water security for key sectors in Southern Africa. (Falkenmark et al. 2007; Falkenmark & Molden 2008):

> Framings of water security that focus on quantity and availability of water are often linked to water security assessment tools. Perhaps

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> the most well-known assessment tool to date combines two indices – for water stress and water shortage – in the measurement of water scarcity. (n.p.)

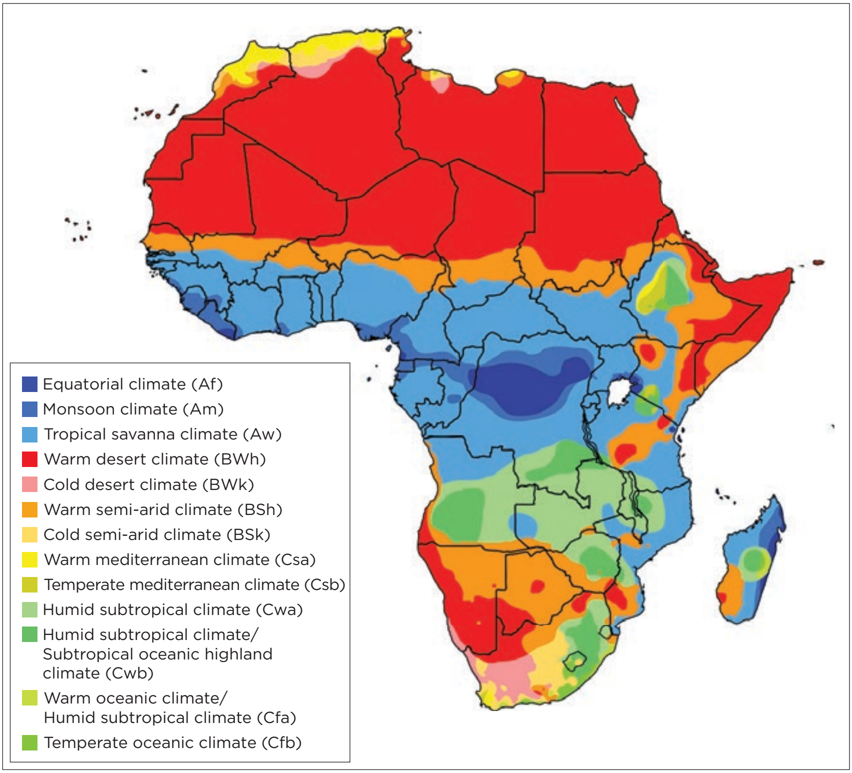
The water stress and water shortage challenges of the SADC are linked to climate variability, mainly temperature and rainfall variability. Thus, the water–climate management tools emphasised in this book take the form of models and policies.

A brief review of the water–climate studies in the SADC showed that most water and climate studies in the region are conducted separately (Brewis et al. 2019) with a few exceptions by Derrick Ngoran et al. (2015), Kusangaya et al. (2014) and Liehr et al. (2017) that seek to address both water and climate jointly. South Africa has carried out most research on water–resource management than any other country in the SADC (Masia & Erasmus 2013; Mckenzie & Wegelin 2009), followed by the impact of climate change (Du Plessis 2017) and groundwater modelling (Abiye 2016). Studies conducted in Namibia (Angula 2010; Jury & Engert 1999; Kluge et al. 2008; Liehr et al. 2017; Mbaiwa 2004; Newsham & Thomas 2011) focus more on the prediction of the impact of climate and water scarcity because of the arid nature of the country. Climate-related studies are most common in Zambia (Hamududu & Ngoma 2019a, 2019b; Mubaya et al. 2010; Mulenga et al. 2017; Mweemba et al. 2015; Umar & Nyanga 2011). Studies on water-resources management and the hydrological modelling of the Kilombero Flood plain (Näschen et al. 2018), the great Ruaha basin (Tumbo & Hughes 2015), the Kihansi catchment (Birhanu 2009) and the Usangu wetland (McCartney et al. 2008) were highlighted in Tanzania. Climate and water studies have also been carried out in Botswana, focusing more on the impact of climate change (Alexander et al. 2013; Saarinen et al. 2012), modelling (Hambira et al. 2011; Milzow et al. 2009; Rahm et al. 2006) and water resources management (Hambira 2007).

One should also note that the effects of climate change, particularly rainfall variability and scarcity are more intense in the most arid countries of the SADC, namely, Botswana and Namibia.

Thus, most chapters in this book used Namibia as a case study because of the high aridity (ref. to Africa map of Köppen climate classification in Figure 0.1) and the fact that the country depends entirely on shared transboundary watercourses for all livelihoods.

Chapter 1 presents an assessment of water–climate studies conducted in Tanzania, a member of the SADC. The study aimed to determine if the research community recognises the interdependence of the water and climate approaches and tools, and the need to bring the two together for understanding and the effective management of the water resources. Therefore, the study assessed the sources and availability of data, and the



Source: Koenker et al. (2019:374).

FIGURE 0.1: Aridity of the African countries.

relevance and effectiveness of water–climate tools in the form of water models, climate models, water–climate models, pathways/ platforms and policies. The focus of the selected studies is also assessed to ascertain the extent to which researchers focus on water, climate, rainfall and hydrology, and whether these are addressed separately or as inextricably linked matters of priority for the SADC.

Several researchers, including Du Plessis (2017), predicted a decrease in both surface and ground supplies as a result of climate variability in one of the SADC countries – South Africa. Du Plessis predicted a temperature rise between 1 °C – 4 °C by 2050 and 3 °C – 7 °C by 2100, and increased evaporation and extreme events (drought and flood) that could affect water resources and rainfall patterns. Considering the evident need to understand the dynamics of our climatic conditions in relation to water availability, we present a study (in ch. 2) focused on modelling the impact of regional climate-change scenarios on the availability of water resources in a semi-arid river basin in South Africa. Statistically downscaled data were derived from General Circulation Model (GCM) simulations of the Coupled Model Inter-comparison Project Phase-5 (CMIP5) and across two greenhouse gas (GHG) emission scenarios known as Representative Concentration Pathways (RCP) 4.5 and 8.5. The Soil and Water Assessment Tool (SWAT) model was run using these data for a period of up to mid-century (2020–2050) and the results were then compared with long-term historical data. The multimodel average showed a possible decrease in precipitation (up to -14%), a decrease in water yield (up to -15%) and an increase in potential evapotranspiration (PET) (up to +10%). The latter is indicative of possible drought spells between rainy events. It is expected that the results from this chapter will assist in the formulation of adaptation strategies that will minimise the negative impact of climate change on available water resources in the SADC region.

However, considerations for the diversity of the Southern African region and the limited data, need to be made when using regional models, as these play a crucial role in the accuracy, reliability and effectiveness of water–climate management tools such as models, plans and policies. In an attempt to address the scarcity of scientific data and contextualised water–climate management tools in Africa, and Southern Africa in particular, the emphasis of Chapter 3 is on evaluating the effectiveness of the Africa Flood and Drought Monitor (AFDM) in providing reliable information for precipitation extremes research, decision making and utilisation by local farmers, and suggesting procedures for making the tool user-friendly for all stakeholders. The AFDM monitors and forecasts meteorological, agricultural and hydrological drought at various temporal and spatial scales. It also has a multi-decadal, historical reconstruction of the terrestrial water cycle against which current conditions can be compared. If properly adapted to the real water–climate challenges of the continent, the tool could contribute to the effective future management of water in Africa.

There is evident dependence on rainfall in the SADC because of the much needed agricultural activities that play an important role in ensuring food security in the region. However, the dependence on rainfall increases the vulnerability of the communities because of climate-induced pressures in the region. A few studies have been conducted using the Standardised Precipitation Index (SPI). These include a modelling study conducted in the Okavango delta (Byakatonda et al. 2016). The study also focused on water availability and predicted an increase in dryness because of a high rate of climatic variability in the SPI. Overall, there is an urgent need for reliable information on precipitation extremes and related hydro-climate data in Southern Africa. Thus, the study presented in Chapter 4 focused on an analyses of trends of extreme precipitation events (EPEs) for two towns in Namibia over a fourteen-year period (2004 to 2017). The R ClimDex tool was used to compute precipitation indices selected to represent the overall precipitation, dry condition, wet condition, and the frequency and intensity of EPEs. All indices of precipitation extremes showed a decreasing trend in the seasonal total rainfall and consecutive wet days, whereas there was an increasing trend in consecutive dry days (CDD). Moreover, we observed a decreasing trend in 1-day maximum rainfall, 5-day maximum rainfall, the intensity of the daily rainfall over 25 mm during the winter and 50 mm during summer, which together may indicate a future decrease in the magnitude and intensity of precipitation events. Clearly, if this trend continues and water security decisions continue to lack scientific backing, Namibian towns may suffer more water stress, which could affect the lives and livelihoods of communities.

Southern Africa is a largely semi-arid and arid region as shown in a map of Africa of Koppen climate classification in Figure 0.1. What all arid regions have in common is a consistent deficit of precipitation, relative to water loss by evaporation, implying that the biological availability of water is very low.

The north to north-western part of the SADC, Namibia in particular, is frequently challenged by water scarcity. There have been concerns for the problems associated with scarcity of water in Namibia in recent years. These problems require an in-depth investigation of the various factors affecting the atmosphere and the contribution of evaporation to moisture for cloud formation and subsequently rainfall.

Therefore, the study in Chapter 5 was focused on developing mixed-strategy game models to contribute to the water–air interaction investigations, needed for generating baseline data on the water-holding capacity of the Namibian atmosphere. The mathematical modelling techniques employed in the project were designed to obtain the optimal meteorological factor values defined by relative humidity, temperature, wind speed and leaf wetness data, obtained from 14 Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) stations, for the years 2012 to 2015. Observation of year-orientation and station-orientation patterns from the data simulations for some of the meteorological factors suggests the need for large data from more stations for further investigation towards identifying generalised patterns for the whole country. The solutions obtained from the mixed-strategy game modelling, implemented via linear optimisation techniques, identified the weather stations and the various months of the year, contributing to the optimal values of the meteorological factors, for the combined 2012–2015 data.

Thus, Chapter 6 presents a study on the assessment of drought occurrence, frequency and intensity which was conducted to address the existing data gaps and fewer scientific studies in Namibia that previously led to anomalies in extreme precipitation projections. The SPI method was used for drought investigation at Ondangwa for 68 years (1950–2018) and Katima Mulilo for 30 years (1987–2018). Normal to intense levels of drought for Katima Mulilo were identified by modelled SPIs, contrary to the Namibia Meteorological Services (NMS) SPIs which implied 'above normal' to flood conditions from 1988 to 2016 and a consecutive 37-months of drought in 2001–2004 (SPI12).

A recent study, conducted in Zambia by Hamududu and Ngoma (2019b), predicted a temperature rise of 1.9 °C by 2050 and 2.3 °C by the year 2100, with a decrease in rainfall, resulting in water shortages (13% lower) by 2100. The study used a combination of the water balance model and GCM to predict future changes in temperature and rainfall. Hamududu and Ngoma (2019b) indicated that more efficiency is required in water management tools to support irrigation during the global climate crisis. Therefore, in Chapter 7, we acknowledge the fact that climate variability has negative effects on water demand for various sectors in the economy. These include the increasing need for irrigation in the agricultural sector because of higher temperatures and reduced rainfall. Therefore, the case of the Middle Kafue basin in Zambia is used to highlight the need to plan and ensure the sustainable utilisation of water resources by using a simulation-based model which was developed during the study. Simulation-based water allocation models which use mass balance principles provide an efficient tool for the sustainable allocation of resources in a river system.

The challenge of increased agricultural irrigation activities and competitiveness in water use caused water stress and conflicts in some catchments in Zambia. Therefore, in Chapter 8, we determine water demand for irrigation and its impact on water availability in two Zambian catchments, Mkushi and Chongwe. The study helped to suggest ways of managing water resources allocation and understanding the environmental flow requirements of the catchment. The study found that the demand for irrigation has been increasing since 1963 causing the flows on the Chongwe River at Chongwe Bridge to cease completely from mid-September to October every year. The study also identified the need for rainfall runoff-model development and scientific studies on effluent release into the catchment's streams, as well as its impact on the hydrology of the catchment.

Thus far, there seems to be a categorical dependence on the 'continually-decreasing' surface water by almost all SADC countries. There is limited research on the impact of climate interaction on the availability of groundwater and the implications of our geological features on access to the alternative water resources. Therefore, the study presented in Chapter 9 aimed to evaluate the recharge and storativity of groundwater with a specific focus on the abstraction potential of the groundwater in the Kuiseb River basin in Namibia. Recharge and storativity were calculated using a programmed Saturated Volume Fluctuation (SVF) method, the November 2001 version for Namibia. Due to the lack of rainfall within the basin, the river does not flow for longer periods but rather for a short time when good rainfall of over 300 mm per year in the upper catchment is recorded. The flow of the Kuiseb River and the recharge of its underground waters depend entirely on the climatic conditions leading to variable rains in the less arid eastern reaches of the basin.

Chapter 1

A review of selected water–climate studies conducted in Tanzania, Southern Africa

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Abstract

Tanzania, like most countries in the Southern African Development Community (SADC), faces the challenges posed by a high degree of water-resource variability, both spatially and temporally. The country is host to lakes, which are dynamic entities and sensitive to climatic and environmental change. Therefore, a secondary review was conducted to assess selected Tanzanian studies for relevance and the effectiveness of water–climate tools in addressing the water–climate challenges faced by the country,

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and the SADC. This study showed that most Tanzanian studies addressed the water and climate aspects separately. Only 30% of the studies could be linked to local adaptation and mitigation strategies, mostly in areas such as sustainable water-resource planning, and lake management and conservation. Also, the model development, verification, simulations, projections, and so on did not necessarily lead to the much needed water–climate output.

Keywords: Water–climate studies; Water–climate management tools; Tanzania.

Introduction

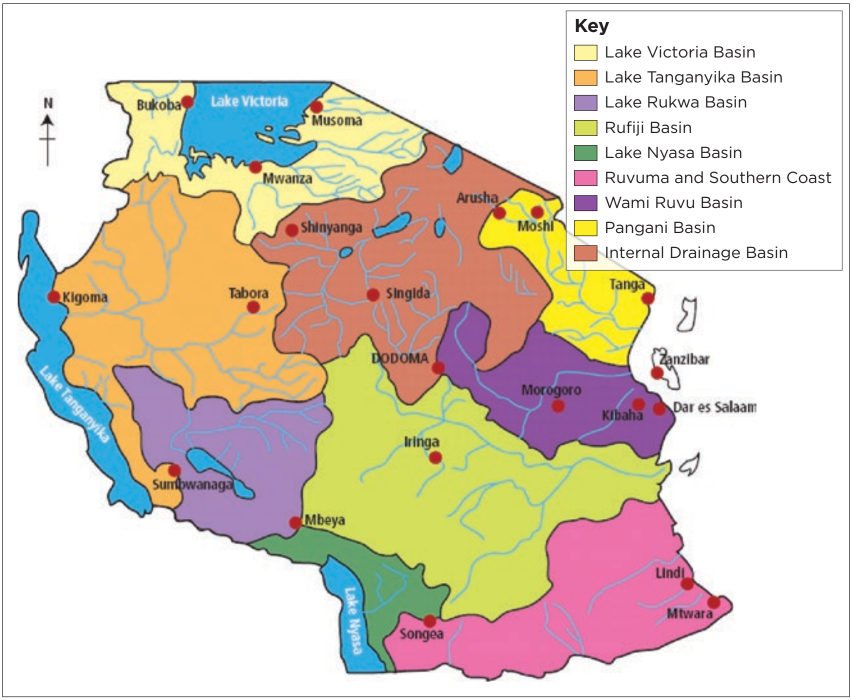
Africa, the world's second–driest continent after Australia, has only 9% of global renewable water resources to support 15% of the global population (UNEP 2010). The lack of water in Africa is further aggravated by rapid population growth and urbanisation (Dos Santos et al. 2017). Aspiration one of the African Agenda 2063 is for the continent to be prosperous, based on inclusive growth and sustainable development.

Sub-Saharan Africa has its own share of problems related to water scarcity. According to the SADC-Regional Strategic Action Plan on Integrated Water Resources Development and Management IV (SADC 2016), Southern Africa is battling with challenges in the form of insecurities related to water scarcity. These are exacerbated by limited financial capacity in an environment of climate-induced pressures and an ever increasing water demand. Approximately 40% of the region's people still do not have access to safe drinking water, whilst about 60% have no access to improved sanitation facilities. It should be noted that water resources availability, utilisation and related infrastructure development in the SADC region are also hampered by significant variability in rainfall, in terms of quantity and distribution, which leads to variability in water resources availability and usage across the region (SADC 2016).

Tanzania is characterised by several 'Lake Basins' (Figure 1.1), which is a unique feature within the SADC as the region is characterised by river basins. The country is also host to one of the oldest lakes in the world. Lakes are dynamic entities and sensitive to climatic and environmental changes (Deus, Gloaguen & Krause 2011). Thus, the country was selected because of the unique water–climate environment and context within the SADC. Also, several researchers, including Andersen (2008), confirm that water resources in semi-arid regions have received less attention because of their complexity and a lack of *in situ* data. Lakes are used to give an indication of the 'balance' (or 'imbalance') (cf. Deus et al. 2011) that may exist between precipitation and other hydrological properties, such as water flow and outflow, including evaporation, and drainage (Deus et al. 2011; Simonsson 2001). 'Lake level fluctuations vary with the water balance of the lake and its catchment and may in certain cases reflect changes in rainfall, evaporation and shallow groundwater resources' (Awange et al. 2008; Deus et al. 2011; Swenson & Wahr 2009). This shows a need for water–climate studies to identify opportunities and guide the planning and development of relevant and effective water–climate management tools.

According to Noel (n.d.), water resources and the performance of the agricultural sector are critical to Tanzania's economy. Annual rainfall levels reported by Luhunga, Botai and Kahimba (2016) in Tanzania range from 534 mm to 1837 mm. Spatial and temporal variations in rainfall can be represented in decreasing order of abundance from the south-western and north-eastern highlands, followed by the semi-arid central Tanzania, which receives seasonal rainfall of not more than 50 mm per month (Luhanga et al. 2016). Thus, it is evident that Tanzania is faced with a challenge of 'spatial' and 'temporal' variability (Rajabu 2007:63–72) in the water resources.

Rotich and Mulungu (2017) reported that the country has been experiencing increases in temperature, which have led to devastating droughts and which contributed to power crises,



Source: United Republic of Tanzania (2007).

FIGURE 1.1: River basins of Tanzania.

decreases in lake levels, lake recessions and the melting of glaciers atop Mount Kilimanjaro during 2006. Moreover, the 10th Tanzania Economic Update (World Bank 2017) reported a decline in renewable per capita freshwater resources over the past 25 years from more than 3000 m^3/person to around only 1600. The decline will likely continue and reach around 1400 m^3/person by 2025, a figure well below the threshold of 1700 m^3/person for water-deficient countries.

The situation confirms the urgent need to develop and implement water–climate management tools or solutions for the country. The report recommends 'investing in data collection and analysis to better equip water management bodies to make decisions', as one of the four key measures towards ensuring that water is well managed (World Bank 2017:n.p.).

Thus, this review aimed to assess selected Tanzanian studies to determine the sources and availability of data or information, relevance and effectiveness of water–climate tools in the form of water models, climate models, water–climate models, pathways or platforms and policies to address water insecurity in Tanzania and Southern Africa. The selected studies were also assessed to ascertain the extent to which researchers put emphasis on water, climate, rainfall and hydrology, and whether these are addressed separately or as inextricably linked matters of priority for the SADC. It was also crucial to determine the extent to which the researchers use previous studies to inform their work, that is, are there studies that follow up and follow through on the water–climate tools, developed by other researchers in the country?

Methods or study approach

A review of articles from selected scientific and open-source literature was conducted. The studies were selected, based on water-resource characteristics, including water source, for example, lakes, rivers or agricultural activity. The challenges faced by the Tanzanian researchers are common to most African countries, that is, limited data, models or scenario uncertainties and lack of information, inaccuracies in downscaling methods, incomplete data series of variable length, unreliable data sets, missing climatic data, lack of information on critical parameters needed to understand the water systems and services, for example, ungauged catchments with unknown inflow, and limited knowledge of the general hydrology of lakes.

Data collection

Convenience sampling was used for the selection of studies to be assessed. The researcher picked the studies that were on top of the Google search engine's output and that were freely accessible (mainly open access). It should be noted that the selection of the studies does not have merit or ranking implications. There is no intended ranking of research conducted in the country. The data were also accessed outside organisational boundaries, mainly from online sources, published research networks and government databases.

The relation of the studies to water sources and/or basins (Figure 1.1) was also considered in the sampling.

Data analysis

The content analysis method for drawing conclusions included observing patterns, themes and trends, making comparisons, building a logical chain of evidence and making conceptual theoretical coherence. The content analysis yielded some descriptive data, giving a detailed picture of the studies conducted on tools related to water–climate in Tanzania.

Only a few studies are being presented in this chapter because of the trends or similarities that were noted; for example, several studies conducted using the Soil and Water Assessment Tool (SWAT) model are not reported because the tool is popular among researchers in Tanzania.

Results and discussion

Water–climate management tools

Table 1.1 gives a summary of the most-studied water–climate tools in Tanzania. Most studies do not consider the existing policies or strategic plans to be developed, improved and/or implemented.

The use of hydrological models indicated in Table 1.1 is consistent with several other studies conducted in Tanzania and the SADC countries; for example, in the hydrological modelling of the Great Ruaha River in Tanzania by applying the Pitman Model to water-resource management, backed by SWAT models (Tumbo & Hughes 2015). The SWAT model is clearly preferred to control water supplies, based on water demand and availability. The SWAT model was used to manage the water supplies of the Kilombero River because of the high water demand created by the Kilimo

TABLE 1.1: Water–climate tools in the selected studies.

Study ID	Area or water source	Water or hydrological models	Climate models	Water–climate models	Pathways or platforms	Reference(s)
1	Lake Nyasa	-	X	-	Emission scenario or RCP 8.5 and RCP 4.5	Luhunga et al. (2018)
2	Little Ruaha River watershed	SWAT	-	-	-	Mbungu and Kashaigili (2017)
3	Tanzania	SWAT	GCMs	-	RCP 8.5	Adhikari et al. (2017)
4	Simiyu River	SWAT	X	-	-	Lubini and Adamowski (2013)
5	Tanzania	-	GCMs		CORDEX program	Luhunga et al. (2016)
6	Lake Manyara	X	-	-	-	Deus et al. (2011)
7	Kikafu River sub-catchment in the Pangani River basin	Crop water model LARS-WG	GCMs	-	A2 emission scenario	Rotich and Mulungu (2017)
8	Lake Babati	A novel-integrated water balance model	-	X	CMIP5	Mbanguka et al. (2016)
9	Lake Manyara catchment	Distributed conceptual hydrological model	-	-	MODIS LST	Deus, Gloaguen and Krause (2013)
10	Mara River basin	SWAT	GCMs	-	-	Dessu and Melesse (2012)

CMIP5, Climate Model Inter-comparison Project 5; CORDEX, Coordinated Regional Climate Downscaling Experiment; GCMs, General Circulation Models; LARS-WG, Long Ashton research station weather generator; MODIS LST, Moderate Resolution Imaging Spectroradiometer Land Surface Temperature; RCP, representative concentration pathways; SWAT, Soil and Water Assesment Tool.

Kwanza Policy in Tanzania, which resulted in a high water demand for irrigation farming in Kilombero Tanzania (Näschen et al. 2018).

The preference for water or hydrological models may be justified. However, according to Cook and Bakker (2012), protection from the risk associated with flood and drought is generally considered a key determinant of water security from an agricultural perspective. However, only the study on Lake Babati, conducted by Mbanguka et al. (2016), was found to address the water and climate models together.

The water–climate focus

The main focus of the water–climate studies is summarised in Table 1.2. Most Tanzanian studies address the water and climate aspects separately. The model development, verification, simulations, projections and so on do not necessarily lead to a water–climate output. Most studies acknowledge the impact of climate on the availability of the water resources; however, the actual work uses some climatic component (mostly rainfall) as input for an existing model. Only one study (study ID 8) was found to satisfactorily bring the water and climate aspects together to develop a sustainable solution.

Water security and related focus

The results presented in Table 1.3 show the focus of most water–climate studies. The inclination towards development and/or assessment of tools for surface water is evident. The inclination towards surface water, although not sustainable, might be reasonable for Tanzania because of the 'many' lake catchments. However, for most SADC countries, the climate–groundwater focus would be crucial.

TABLE 1.2: Main focus of the water–climate studies.

Study ID	Water	Climate	Rainfall	Hydrology	Reference(s)
1	-	X	X	-	Luhunga et al. (2018)
2	-	-	-	X	Mbungu and Kashaigili (2017)
3	-	X	-	X	Adhikari et al. (2017)
4	-	X	-	X	Lubini and Adamowski (2013)
5	-	X	X	-	Luhunga et al. (2016)
6	X	-	-	X	Deus et al. (2011)
7	X (crop water)	-	X	-	Rotich and Mulungu (2017)
8	X	X	X	X	Mbanguka et al. (2016)
9	X	-	-	X	Deus et al. (2013)
10	X	X	-	X	Dessu and Melesse (2012)

TABLE 1.3: Water security and related focus.

Study ID	Surface water	Ground-water	Water demand and/ or utilisation	Water-related economic sectors	Alterna-tive water sources	Reference(s)
1	-	-	-	-	-	Luhunga et al. (2018)
2	X	-	-	X (indirectly: agriculture, rural and urban water, ecology, hydropower)	-	Mbungu and Kashaigili (2017)
3	X	-	-	X (indirectly: agriculture)	-	Adhikari et al. (2017)
4	X	-	-	-	-	Lubini and Adamowski (2013)
5		-	-	X (ultimately: agriculture)	-	Luhunga et al. (2016)
6	X	-	-	X	-	Deus et al. (2011)
7		-	-	Agriculture	-	Rotich and Mulungu (2017)
8	X	X	X	X	X	Mbanguka et al. (2016)
9	X	-	-	-	-	Deus et al. (2013)
10	-	-	-	X (mining sector)	-	Dessu and Melesse (2012)

Studies dealing with the agricultural sector are common in Tanzania. These take the form of simulations.

Actual water–climate research activities

Only a few studies developed models (Table 1.4) for specific catchment areas. Most researchers use existing models and platforms or pathways, which is sensible. However, one would expect the local research community to contextualise and adapt models and/or develop hybrids to address local water problems.

TABLE 1.4: Actual water–climate research activities.

Study ID	Model development	Comparative analysis	Validation and/or testing	Historical trends	Simulations	Projections or predictions	Reference(s)
1	-	X	-	X	X	X (2011–2100)	Luhunga et al. (2018)
2	X	-	X	-	X	-	Mbungu and Kashaigili (2017)
3	-	-	X	-	-	X	Adhikari et al. (2017)
4	-	-	X	-	-	X	Lubini and Adamowski (2013)
5	-	X	X	-	X	X	Luhunga et al. (2016)
6	-	-	-	-	-	-	Deus et al. (2011)
7	-	-	-	-	X	X	Rotich and Mulungu (2017)
8	X	-	X	-	-	-	Mbanguka et al. (2016)
9	-	X	X	-	-	-	Deus et al. (2013)
10	-	-	X	-	X	X	Dessu and Melesse (2012)

Link to global or national or local mitigation or adaptation plans

Only 30% of the studies could be linked to local adaptation and mitigation strategies, mostly in areas such as sustainable water-resource planning, and lake management and conservation. However, there seems to be collaboration (Table 1.5) and sharing of information through (and with) regional programs, networks and databases and government departments or agencies. Also, databases or datasets seem to be the main or widely used source of data for the water–climate researchers.

TABLE 1.5: Sources of information for the Tanzanian studies.

Area	Regional networks or programs	Databases or datasets	National (government agencies or ministries)	Reference(s)
1	CORDEX program	-	-	Luhunga et al. (2018)
2	World Soil Information website (http://www.soilgrids.org/)	(1) WATCH Forcing Data Methodology applied to (2) ERA-Interim data Meteorological Forcing (3) Soil and Terrain Database for Southern Africa	(1) Tanzania Meteorological Agency (2) Rufiji basin Water Board (3) Coarser resolution soil map of Tanzania	Mbungu and Kashaigili (2017)
3	-	-	-	Adhikari et al. (2017)
4	-	-	FRIEND of the Nile Basin	Lubini and Adamowski (2013)
5	-	-	-	Luhunga et al. (2016)
6	-	(1) Tropical Rainfall Measuring Mission amalgamated rainfall product (3B43-V6) (2) MODIS or Terra Satellite Earth Observing System (formerly known as Earth Observing System AM-1 platform)	(1) GRACE satellite project	Deus et al. (2011)
7	Smallholder Systems Innovations in Watershed Management research project – Phase 2 (SSI-2) project	IPCC AR4 (Fourth Assessment Report) scenario data	-	Rotich and Mulungu (2017)
8	-	-	-	Mbanguka et al. (2016)
9	-	GRACE data	-	Deus et al. (2013)
10	-	-	Agriculture	Dessu and Melesse (2012)

CORDEX, Coordinated Regional Climate Downscaling Experiment; FRIEND, Flow Regimes from International Experimental and Network Data; GRACE, Gravity Recovery and Climate Experiment; IPCC, Intergovernmental Panel on Climate Change; MODIS LST, Moderate Resolution Imaging Spectroradiometer Land Surface Temperature; SSI-2, Smallholder Systems Innovations in Watershed Management research project – Phase 2.

Concluding remarks

A review of the studies showed that, although the water and climate challenges are interlinked and the studies for one require the input of data from the other, most water–climate studies in Tanzania seem to be more focused on water and climate models separately. Also, there seems to be a lack of initiatives to link policy, decision making, planning and actual solutions to the studies. Although most studies address the rainfall and temperature issues, the adaptation and/or contextualisation of the modelling studies to the local sectors is lacking to some extent.

Previous studies in Tanzania (Agrawala et al. 2003; Ahmed et al. 2011; Müller et al. 2011) have evaluated the impact of climate change on rain-fed crop production using climate simulation, derived directly from GCMs; however, they are insufficient to detect the huge variations in agricultural output in different regions. This is important because the economy of the country depends heavily on the agriculture sector, which contributes about half of gross production, 30% of export earnings, 65% of raw materials for domestic industries, and employs about 80% of the labour force, whilst facing challenges of climate change and variability (Luhunga et al. 2016).

Assessment of the water–climate studies is crucial for the selection and/or development of suitable models that can be used to predict the impact of climate change on the water resources. In the Tanzanian case, the output of water–climate models may be used in crop models to assess the impact of climate change on the rain-dependent crop production (Luhunga et al. 2016).

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Chapter 2

Impact of climate change on water security in a semi-arid river basin

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Abstract

Recent climate projections suggest a drop of up to 10% in precipitation in most of Southern Africa by 2050. It is estimated

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that by the year 2025, almost one-half of the world population will be living in water-stressed regions. Furthermore, rapid population increase, industrialisation and pollution are putting a strain on the available and diminishing freshwater resources. The main aim of this paper is to model the impact of regional climate change scenarios on the availability of water resources in a semi-arid river basin in South Africa. In this paper, statistically downscaled data were derived from the GCM simulations of the Coupled Model Inter-comparison Project Phase-5 and across two greenhouse gas (GHG) emission scenarios, known as RCP 4.5 and 8.5. The spatial resolution of the dataset is 0.25° × 0.25° (~25 km × 25 km). Six GCMs (climate models) were used for this set of data. The SWAT model was run using these data for a period of up to mid-century (2020–2050); the results were then compared with long-term historical data. Comparison of measured data with simulated historical data showed a strong correlation ($R^2 \geq 0.9$), which is indicative of the reliability of the projected future climate. Varied results were obtained, depending on the type of climate model used, but generally, the trends were similar in most cases. However, the multimodel average showed a possible decrease in precipitation (up to -14%), a decrease in water yield (up to -15%) and an increase in potential evapotranspiration (PET) (up to +10%). The latter is indicative of possible drought spells between rainy events. It is expected that the results of this research will assist in the formulation of adaptation strategies that will minimise the negative impact of climate change in the region.

Keywords: River basin; Global Climate Model; Climate change scenarios; Rainfall; Representative Concentration Pathways; SWAT model; Water yield.

Introduction

Lack of or unreliable water supply for drinking, sanitation and agricultural services, coupled with extreme events such as floods and droughts severely impact most of the world's population in general, and sub-Saharan Africa, in particular. The National Water Resources Strategy of South Africa makes it clear that the water resource is central to development and poverty alleviation (Department of Water Affairs 2013). Yet, decision makers face many challenges in ensuring the sustainable and equitable use of the available water. Some of these challenges are a rapidly growing population, changing economies and climate change.

Climate change projections indicate a future decrease in rainfall, leading to water scarcity in Southern Africa by 2050 (Department of Environmental Affairs 2013). 'Climate projections suggest a drop of up to 10% in precipitation in most of Southern Africa by 2050' (Levina 2006). On a global scale, projections by the World Water Council (2000) confirm that water scarcity for half of the world will occur 25 years earlier (i.e. by 2025).

Temperature variations also play a crucial role in preserving the limited water resources. In South Africa, MacKellar, New and Jack (2014) reported that the past 50 years have been characterised by a general increase in annual temperatures. Future climate extremes have been projected by the Department of Environmental Affairs (2013), confirming an increase in the frequency of high temperatures and relatively less temperature lows.

Also, anthropogenic factors including industrialisation and associated pollution add to 'degradation of water quality' (Bridget et al. 2007) and reduction in fresh water quantities. Further, the anthropogenic factors and population growth affect the sustainability of the water resources, the resilience to climate change and the adaptive capacity of the populations (AMCOW 2012).

Agriculture, mainly commercial farming, is the backbone of South Africa's food security. Rainwater management is central to the agricultural practices of small-scale subsistence farmers (Melesse & Abtew 2016). Therefore, water balance in catchments should be considered in all water and agricultural planning and monitoring activities. According to Melesse and Abtew (2016:n.p.), 'the water balance of any catchment is directly and indirectly influenced by the spatio-temporal variability of land-use and land-cover changes, as well as climate condition'. Land-use changes can result in the modification of crucial hydrological processes, such as runoff, infiltration, evaporation and consequently ground water recharge. Change in land use at the upstream level could bring about a significant on-site effect on water security at the catchment level and off-site effect on downstream users (Woyessa et al. 2006, 2011). Moreover, the effect of climate change could further exacerbate the water security problem through extreme weather conditions, such as drought and flooding. It is therefore important to develop scenarios for possible climate change and to investigate the possible impact of these changes on the hydrological processes and water resources. The main aim of this paper is, therefore, to model the impact of climate change scenarios on water security.

Methods or study approach

Description of the study area

The focus area of this research is a semi-arid river basin in the central region of South Africa (Free State), known as the Modder River basin (Figure 2.1).

The Modder river basin has total area of 1.73 million hectares. It is divided into three sub-basins, namely the Upper Modder, the Middle Modder and the Lower Modder. It is located within the Upper Orange Water Management Area to the east of the city of Bloemfontein. The middle and lower reaches of the Modder river gets its water supply from three reservoirs, namely the Rustfontein and Mockes dams in the east, and by Krugersdrift dam in the west of the city of Bloemfontein. (Woyessa 2019:2).

Biophysical factors

Runoff generation from a specific catchment is affected by biophysical factors, including climate, land use, soil and topography

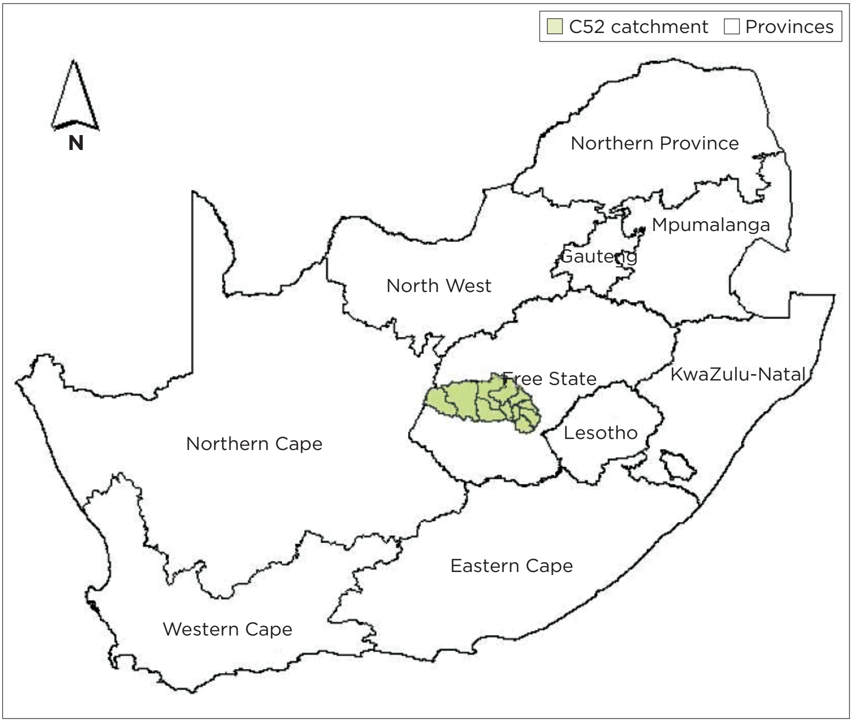


FIGURE 2.1: The study site, the Modder River basin, at the bottom in the box (map not to scale).

(Jain, Kothyari & Raju 2004; Peugeot et al. 1997). The climatic components, particularly rainfall and evapotranspiration (ET) are crucial to water security because of the major impact on the water balance of the catchment. Jewitt et al. (2004) confirmed that rainfall also contributes to an increased runoff whilst high ET reduces the amount of surface runoff, which is considered as blue water.

Similarly, soil properties, such as texture and the infiltration rate affect the amount of surface runoff considerably. For example, high surface runoff is caused by low infiltration rates which is normally the result of soils with a high silt and clay content.

The annual rainfall variation of the study area is given in Figure 2.2. The figure shows a declining trend in annual rainfall, as shown by the straight line. It can be observed that there was a

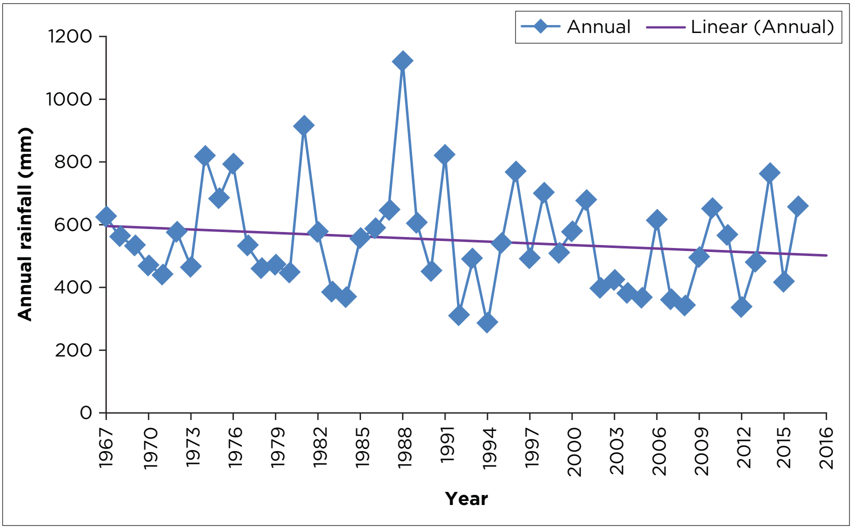


FIGURE 2.2: Long-term annual rainfall (1975–2017).

decline by about 100 mm, according to the trend line. The highest maximum temperature varies between 28 °C and 31 °C, whilst the lowest minimum temperature varies between -1 °C and 1 °C (Figure 2.3).

According to the soil map and geographic information system (GIS) database, obtained from the Institute of Soil Climate and Water, seven soil series are identified in the Modder River basin. The texture of this soil is 100% sandy clay loam (SaClLm) to sandy clay. The Middle Modder River basin is predominantly covered by soil series whose texture predominantly varies from sand to loamy sand. The Lower Modder River basin is largely represented by soil series with a dominant texture of SaClLm.

Land-use or land-cover data were obtained from the Department of Environmental Affairs (2018) of the Republic of South Africa for the period of 1990 and 2014. The summary of the land-use types, as per the class names recognised by SWAT, is given in Table 2.1. The table shows the total area and percentage land-use types, and

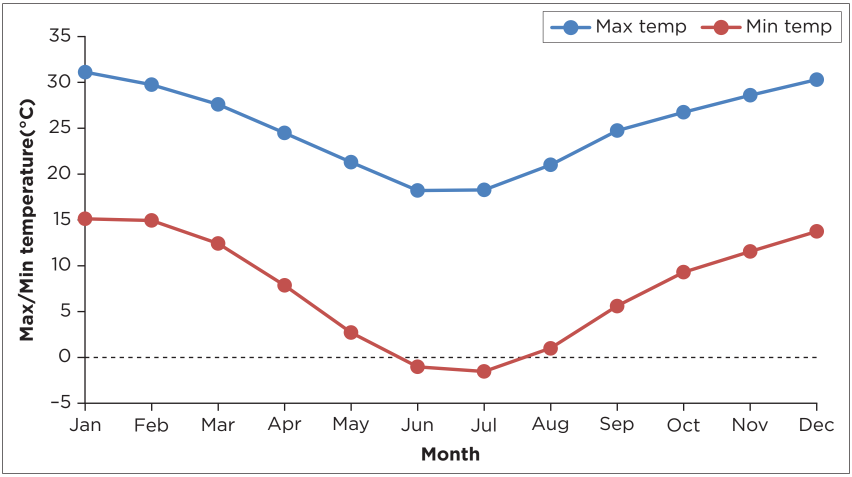


FIGURE 2.3: Mean minimum and maximum temperatures (1975–2005).

TABLE 2.1: Land-use types in the Modder River basin for the years 1990 and 2014.

Land use	1990		2014	
	Area (×1000 ha)	% of watershed	Area (×1000 ha)	% of watershed
Water bodies	51.9	3	34.6	2
Forest	51.9	3	207.6	12
Pasture	1176	68	1072.6	62
Agriculture	397.9	23	363.3	21
Range land	17.3	1	0	0
Urban	34.6	2	51.9	3

Source: Authors' analysis of land-use or land-cover data obtained from the Department of Environmental Affairs (2018).

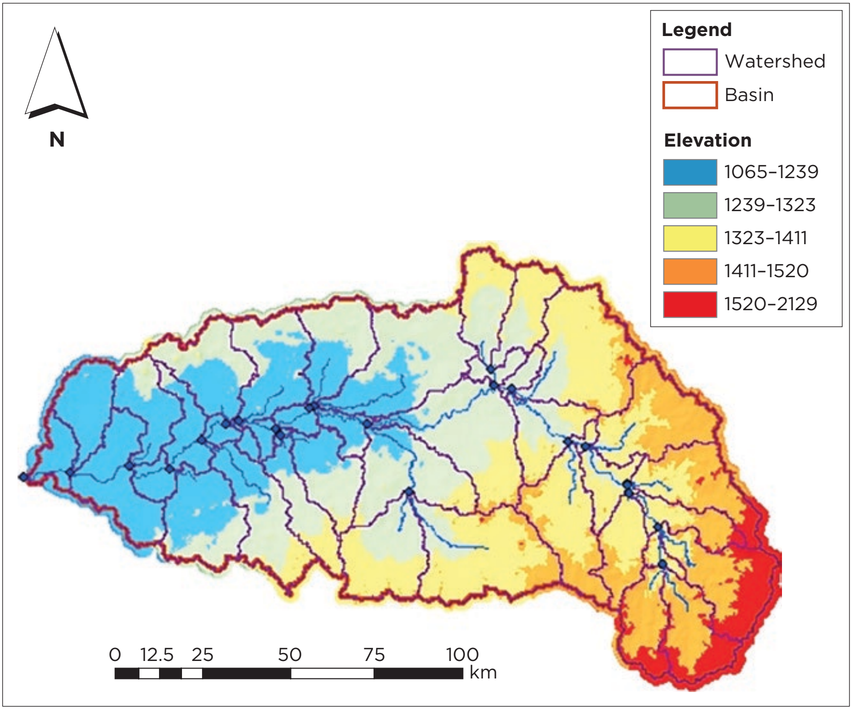
possible changes during this 14-year period. As can be observed from the table, the two major land-use types are pasture and agriculture (84%) showing small changes (decreasing trend) during these two periods. There is also a significant increase in forest cover and a slight increase in urbanisation.

The topographic data or digital elevation model (DEM) for the study area were obtained from the United States Geological

Survey (USGS) Earth Explorer, the Shuttle Radar Topography Mission 1Arc-Second Global (USGS Earth Explorer 2017) with a spatial resolution of 30 m. Figure 2.4 shows the DEM, as well as the stream network of the river basin. The altitude ranges from the lowest value of 1065 m.a.s.l. to the highest of 2129 m.a.s.l.

Climate change modelling

A GCM can provide reliable predictive information on large scales of around 1000 km by 1000 km, covering vastly differing landscapes, with greatly varying potential for floods, droughts or other extreme events. However, Regional Climate Models



Source: Authors' model results obtained, using data from the USGS Earth Explorer and the Shuttle Radar Topography Mission 1 Arc-Second Global (USGS Earth Explorer 2017).

FIGURE 2.4: Digital elevation model of the Modder River basin.

(RCMs) and Empirical Statistical Downscaling, applied over a limited area and driven by GCMs, can provide information on much smaller scales, supporting a more detailed impact and adaptation assessment and planning, which is vital in many vulnerable regions of the world.[1]

For this study, readily available downscaled regional climate data at high resolution were obtained from the National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP). The NASA NEX-GDDP dataset contains downscaled climate scenarios that are derived from the GCM simulations of the Coupled Model Inter-comparison Project Phase-5. The selected GHG emission scenarios, known as RCP, were RCP4.5 and RCP8.5. The dataset has a spatial resolution of 0.25° × 0.25° (~25 km × 25 km). These datasets provide a set of global, high-resolution, bias-corrected climate change projections that can be used to evaluate the climate change impact on processes that are sensitive to finer-scale climate gradients and the effects of local topography on climate conditions on finer scales.[2]

The data were bias-corrected, using an algorithm that compares the GCM output with corresponding climate observations over a common period and uses information, derived from the comparison, to adjust future climate projections so that they are (progressively) more consistent with the historical climate records and, presumably, more realistic in the spatial domain of interest (Raghavan et al. 2018):

> Each of the climate projections includes maximum and minimum temperatures and precipitation for the periods from 1950 through 2005 (Retrospective Run) and from 2006 to 2099 (Prospective Run) on a daily scale. (p. 505)

1. See https://cordex.org/.

2. See https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp.

A subset of six GCMs was selected (Australian Community Climate and Earth System Simulator [ACCESS1-0], Centre National de Recherches Météorologiques Climate Model [CNRM-CM5], Institut Pierre Simon Laplace Model Climate Model [IPSL-CM5A-LR], Model for Interdisciplinary Research on Climate [MIROC5], Max Planck Institute for Meteorology Earth System Model [MPI-ESM-MR] and Meteorological Research Institute Coupled Global Circulation Model [MRI-CGCM3]), which generated daily data of precipitation, and minimum and maximum temperatures for a retrospective run of 30 years (1975–2005) and a prospective run of 30 years (2020–2050). In this study, two GHG emission scenarios (RCP4.5 and RCP8.5) were considered, which are said to be the global model simulations with the highest priority within the Coupled Model Inter-comparison Project – phase 5 (CIMP5).

Hydrological modelling

The hydrological model used in this study was SWAT (Gassman et al. 2007; Mishra et al. 2017):

> SWAT is a basin scale model which operates on a continuous daily time scale. The model is designed to predict the impact of management on water, agricultural chemical and sediment yield in ungauged catchments. It is a physically based model capable of continuous simulation over long time periods. (n.p.)

In the SWAT model, hydrological processes within a catchment are modelled, taking into consideration the weather, soil properties, land 'management' practices and 'surface and groundwater' (Parikh & James 2012:2; cf. Arnold et al. 1998). The catchments are divided into sub-basins based on the outlet points that are selected along the stream network. Each sub-basin is divided into areas having homogeneous soil type, land use, slope and management practices, called hydrologic response units (HRUs), which are defined as '[w]ater yields are calculated for each HRUs and summed up to determine the total sub-basin outputs, which in turn contributes to the total catchment yield output' (Khayyun et al. 2019:n.p.). Hydrologic response units are not spatially defined within sub-basins but represented as percentages of total sub-basin area. Therefore, 'SWAT includes both spatially-distributed parameterization at the sub-basin scale and lumped parameterization at the HRU scale' (Gassman et al. 2007:n.p.).

Applications of the SWAT model to the effects of climate-change and land-management practices on catchment yields have been documented by several studies. These include the studies conducted by Stone et al. (2001), cited in Cousino, Becker and Zmijewski (2015), who used SWAT to predict an overall reduction of the water yield of the Missouri River basin by 10% – 20% during the spring and summer months but an increase of water yield during the fall and winter months in response to doubling atmospheric CO_2 concentrations. Cousino et al. (2015) also used SWAT to model the effects of climate change on water, sediment and nutrient yields from the Maumee River catchment. The study by Cousino et al. (2015) reported that:

> [*M*]oderate climate change scenarios reduced annual flow by up to 24% and sediment yields by up to 26%, while a more extreme climate scenario showed flow reductions by up to 10% and an increase in sediment by up to 11%. (p. 762)

The SWAT hydrological model was applied to simulate the impact of climate change on water- balance components in the Modder River basin, specifically runoff, water yield, ET and PET.

☐ Model setup and input data

The first task of setting up a SWAT model was to acquire all the necessary input data in a format required by the model. The following input data are required by SWAT:

- Digital elevation model: the DEM data with a resolution of 30 m × 30 m were obtained from USGS Earth Explorer. The data were processed using ArcGIS® 10.3.1. These data are key for obtaining the automatic delineation of the watershed by ArcSWAT.
- Land-use map in shape file.
- Soil map in shape file.
- Daily precipitation (of historical and future climate).

- Daily minimum and maximum temperatures (of historical and future climate).

The main aim of running the SWAT hydrological model was to be able to assess the impact of climate change scenarios on water resources, and more specifically on the components of the water balance in the river basin. Thus, it is important to describe in more detail the precipitation and temperatures of future climate as input to SWAT. In the preceding sections, attempts were made to highlight various GCM-driven models and GHG emission scenarios, using two downscaling approaches. Therefore, it should be noted that there were three climate scenarios (historical, RCP4.5 and RCP8.5). The number of combinations of input for the Statistical Downscaling Experiment has six GCM-driven models with three climate scenarios. There were 18 combinations for each of the forms of precipitation and temperature input to this approach.

Model calibration

The model was calibrated during an earlier study in the upper Modder River basin in a quaternary catchment called C52A (Welderufael, Woyessa & Edossa 2013; Woyessa et al. 2011). The calibration result was found to be satisfactory, according to the Nash and Sutcliffe efficiency value of 0.57 for the monthly streamflow calibration, providing a satisfactory correlation between the observed and simulated monthly stream flows.

Results and discussion

Climate change modelling

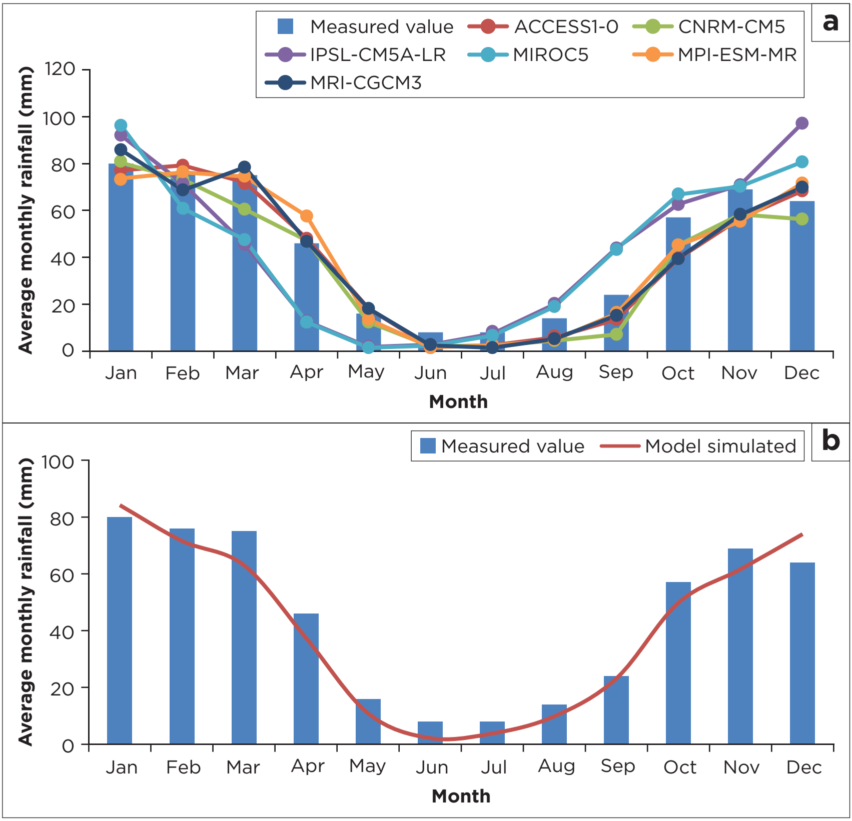
The climate change scenarios (precipitation, and minimum and maximum temperatures) were generated, using six GCM-driven climate models. The temperature change scenario was captured through PET in the next section as outputs of the SWAT hydrological model. In this section, the historical simulation of precipitation by the six GCMs is presented in order to establish how well the models were able to predict historical values.

As described earlier, two groups of data were obtained from NASA's database. These are 30 years of historical climate data (1975–2005) and 30 years of future climate data (2020–2050). The main aim of simulating the historical data as in Woyessa (2019) was to be able to compare the simulated values with climate observations over the same period. The information derived from the comparison can be used to adjust future climate projections, so that they are more consistent with the historical climate records and more realistic in the spatial domain of interest. In this study, an attempted was made to compare the simulated historical rainfall values with the observed (measured) values in the study site. Figure 2.5a presents the monthly averages and the relationships of the six GCM-simulated values and the measured value. It can be seen that the six GCM models predicted the measured values very well. Figure 2.5b shows the multimodel monthly average and the monthly average of the measured values. This figure shows that the multimodel average has a better prediction capacity than when the models are considered independently.

The relationships between the simulated historical values and measured values are better represented using Figure 2.6a and Figure 2.6b. Figure 2.6a shows a strong linear relationship between these two variables for all the six GCMs. It can be observed that there were high R^2 values (0.91–0.95) for all the GCMs, except the two models (IPSL-CM5A-LR and MIROC5), which showed lower R^2 values (R^2 = 0.69). Figure 2.6b shows the relationship between the multimodel simulated and measured monthly average values. A strong relationship between the two variables was demonstrated with a high R^2 value of 0.95. Furthermore, the strong linear relationship between these two variables is found to be very closely aligned with the one-to-one straight line, which is also shown in Figure 2.6b.

Hydrological modelling

The SWAT output provides a detailed analysis of the main water balance components for each of the sub-basins in the watershed. However, for evaluating the impact of climate change scenarios, we shall only be looking at the main water balance components

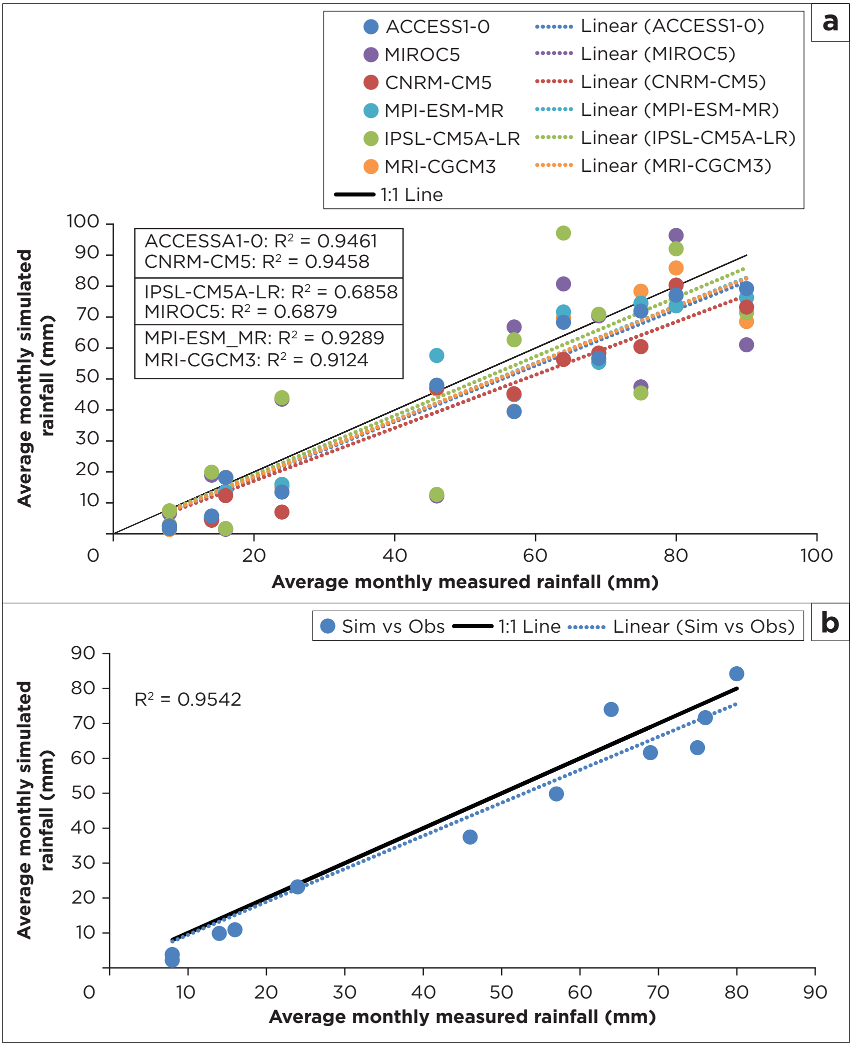


ACCESS1-0, Australian Community Climate and Earth System Simulator; CNRM-CM5, Centre National de Recherches Météorologiques Climate Model; IPSL-CM5A-LR, Institut Pierre Simon Laplace Model Climate Model; MIROC5, Model for Interdisciplinary Research on Climate; MPI-ESM-MR, Max Planck Institute for Meteorology Earth System Model; MRI-CGCM3, Meteorological Research Institute Coupled Global Circulation Model.

FIGURE 2.5: (a) Global Climate Model simulated and measured average monthly rainfall and (b) Multimodel monthly average and measured monthly average rainfall.

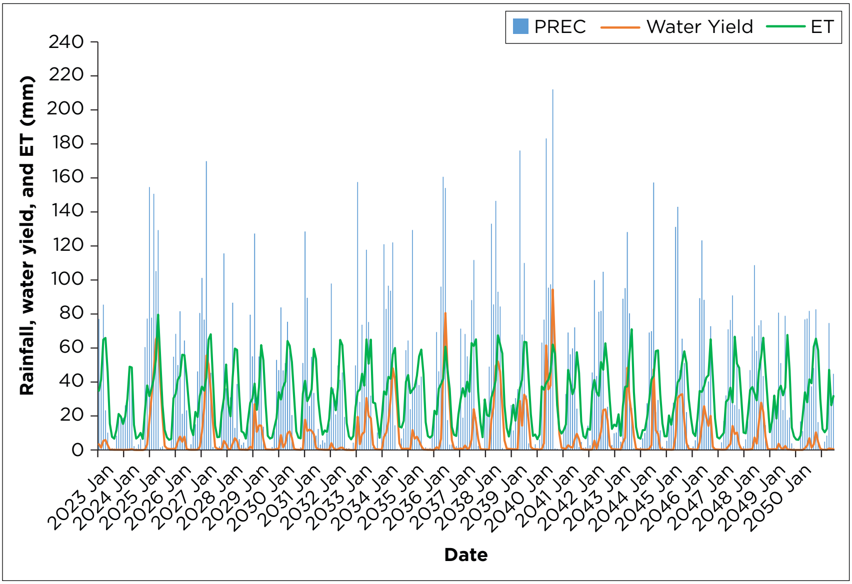
over the entire watershed, namely, rain, surface runoff, water yield, ET and PET, all expressed in millimetres.

Figure 2.7 shows results of the hydrological simulation of monthly average values for rain, water yield and ET under the GHG emission scenario of RCP4.5. From this figure, which is presented for illustration of the SWAT monthly output, it can be observed that there are some extreme monthly values of rain with high water



ACCESS1-0, Australian Community Climate and Earth System Simulator; CNRM-CM5, Centre National de Recherches Météorologiques Climate Model; IPSL-CM5A-LR, Institut Pierre Simon Laplace Model Climate Model; MIROC5, Model for Interdisciplinary Research on Climate; MPI-ESM-MR, Max Planck Institute for Meteorology Earth System Model; MRI-CGCM3, Meteorological Research Institute Coupled Global Circulation Model; Obs, observed; Sim, simulated.

FIGURE 2.6: (a) Measured versus simulated average monthly values of rain using all Global Climate Models and (b) Multimodel average.



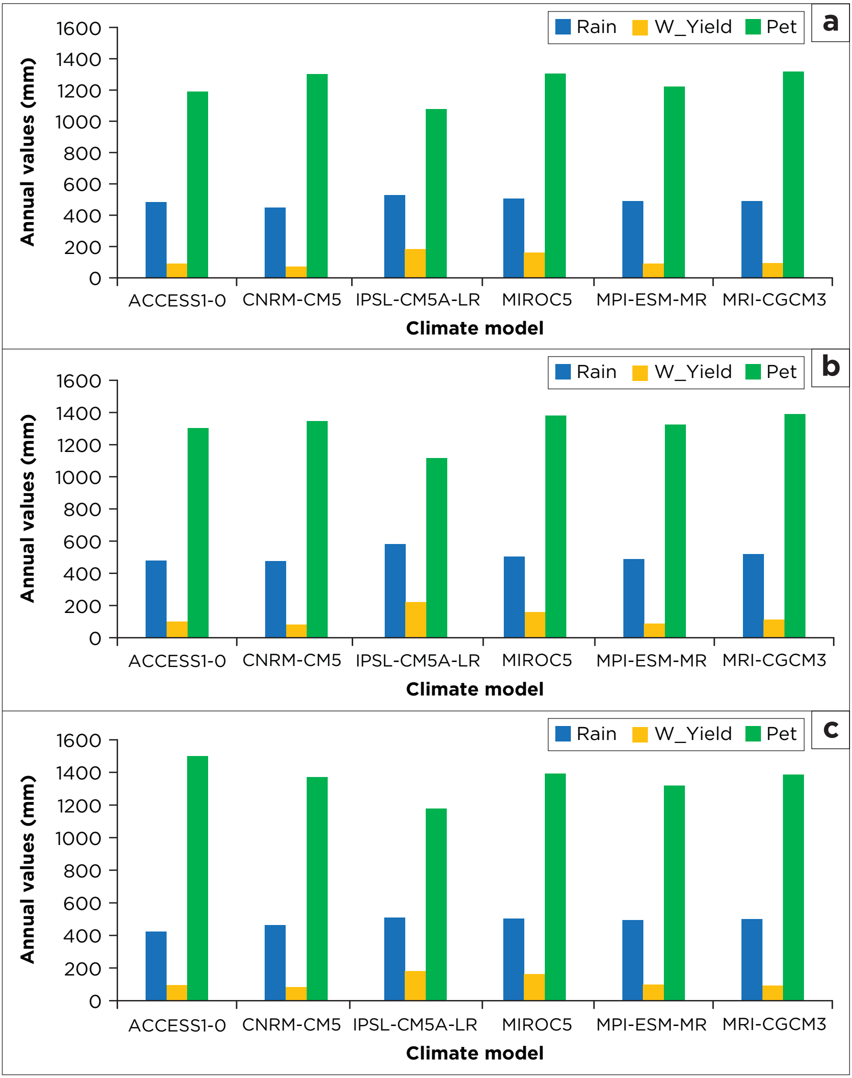
ET, evapotranspiration; PREC, precipitation.

FIGURE 2.7: Average monthly values of rain, water yield and evapotranspiration as simulated by SWAT model based on data from ACCESS1-0 at RCP4.5 (2020–2050).

yield. These events are separated by about 10 years from each other. As indicated in the preceding section, there are 18 combinations of SWAT inputs, which lead to a similar number of outputs. It, then, becomes impractical to present all of them here in such format, hence the need for summarised outputs.

Figure 2.8 presents annual average values of rain, water yield and PET for the three climate scenarios (historical, RCP4.5 and RCP8.5) for four GCM-driven models. It should be noted that the historical data are for the period of 1975–2005, whilst the future climate, where scenarios of RCP4.5 and 8.5 were considered, is from 2020 to 2050 (mid-century).

The presentation of these graphs (Figure 2.8a, Figure 2.8b and Figure 2.8c), next to each other, is done to allow a visual comparison among the different GCMs and between the



ACCESS1-0, Australian Community Climate and Earth System Simulator; CNRM-CM5, Centre National de Recherches Météorologiques Climate Model; IPSL-CM5A-LR, Institut Pierre Simon Laplace Model Climate Model; MIROC5, Model for Interdisciplinary Research on Climate; MPI-ESM-MR, Max Planck Institute for Meteorology Earth System Model; MRI-CGCM3, Meteorological Research Institute Coupled Global Circulation Model; PET, potential evapotranspiration; W_Yield, water yield.

FIGURE 2.8: Average annual values of rain, water yield and evapotranspiration: (a) Historical, (b) Representative Concentration Pathways 4.5 and (c) Representative Concentration Pathways 8.5.

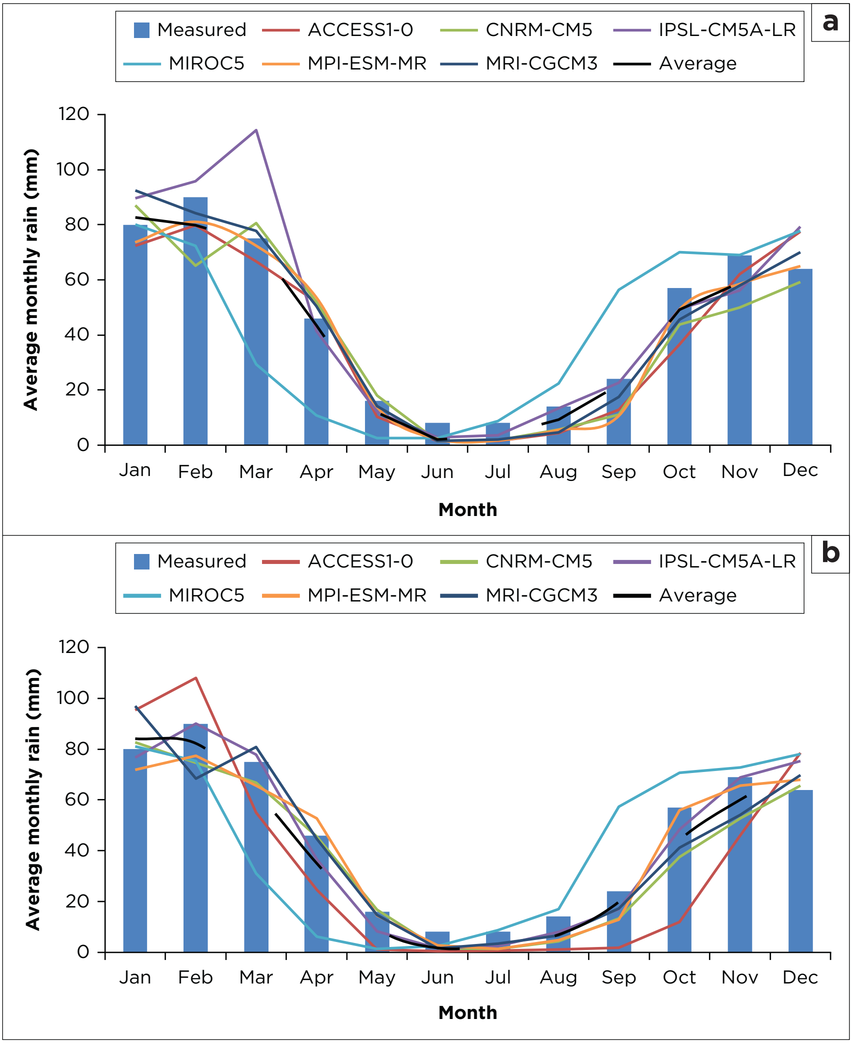
emission scenarios. A quick inspection of these graphs shows that there is a decreasing trend of average monthly rainfall, whereas there is an increasing trend for average monthly PET as one goes from the historical scenario through to the RCP8.5 scenario.

The combined result of the different future climate scenarios, as simulated by the different GCM-driven models, is presented in Figure 2.9a and Figure 2.9b. These figures present comparisons of the average monthly values of future rain with that of the measured rain over the period of 1975–2005. The average monthly future rain, as predicted by the different models, shows a decreasing tendency during most of the months, except for two models that show higher monthly rainfall, compared with the average measured rainfall values. The detailed analysis of the impact of the future climate change on water balance components is presented in a separate section.

A summary of the main water-balance outputs of the watershed, namely, rain, water yield, ET and PET is presented in Figure 2.10. This figure shows the parameters for the three climate scenarios as projected by the six GCM-driven models for the period 2020–2050. Of all the parameters, PET shows a clear increasing trend as one goes from historical through to RCP8.5, indicating a strong influence of the future temperature change, which was captured in the SWAT simulation. The increased PET may also indicate potential dry spells between the rainy events.

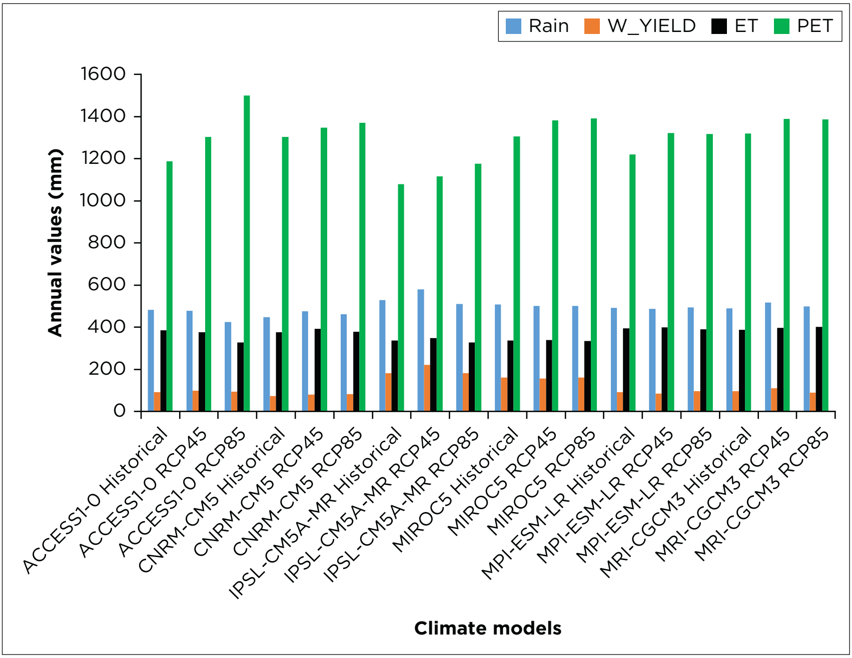
Impact assessment and implications for water security

In the previous sections, attempts were made to highlight the trends of the future rain and temperature and the resultant effect on the main components of the watershed water balance, specifically on water yield (flow of water in the river system) and ET (both actual and potential), as demonstrated using



ACCESS1-0, Australian Community Climate and Earth System Simulator; CNRM-CM5, Centre National de Recherches Météorologiques Climate Model; IPSL-CM5A-LR, Institut Pierre Simon Laplace Model Climate Model; MIROC5, Model for Interdisciplinary Research on Climate; MPI-ESM-MR, Max Planck Institute for Meteorology Earth System Model; MRI-CGCM3, Meteorological Research Institute Coupled Global Circulation Model.

FIGURE 2.9: Comparison of future rain (mid-century) with average measured data: (a) Representative Concentration Pathways 4.5 and (b) Representative Concentration Pathways 8.5.



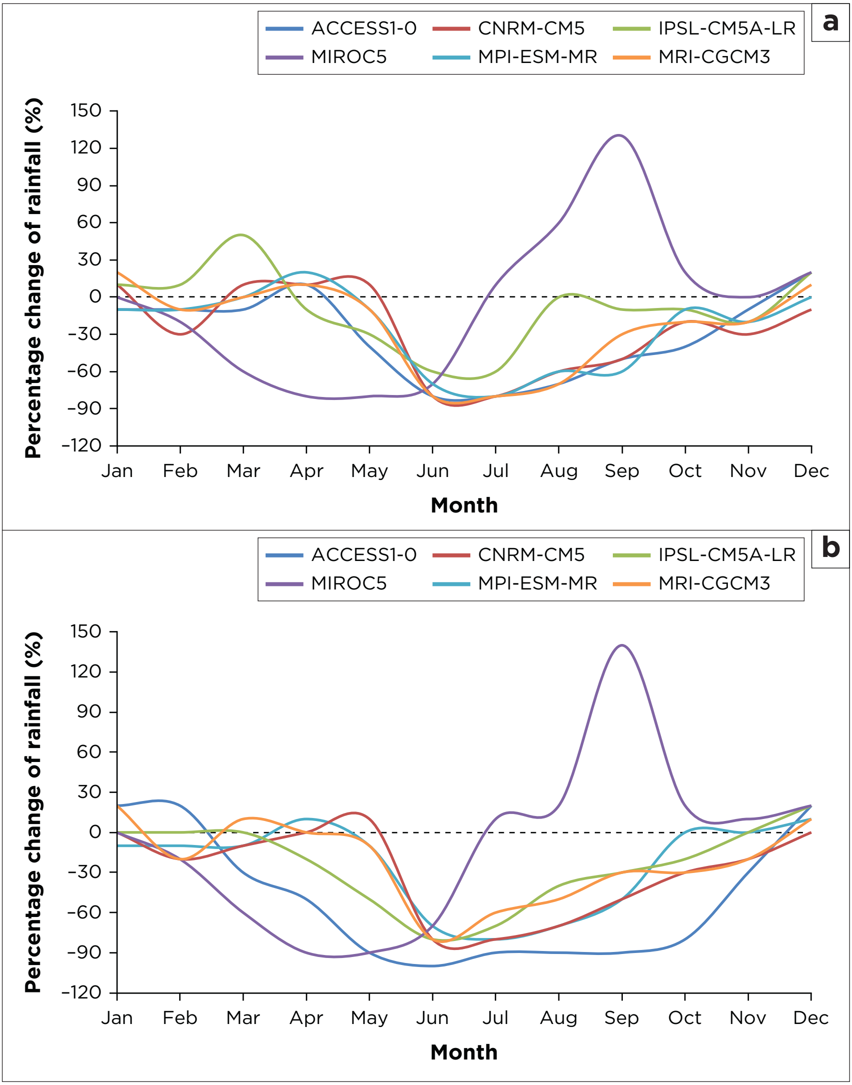
ACCESS1-0, Australian Community Climate and Earth System Simulator; CNRM-CM5, Centre National de Recherches Météorologiques Climate Model; ET, evapotranspiration; IPSL-CM5A-LR, Institut Pierre Simon Laplace Model Climate Model; MIROC5, Model for Interdisciplinary Research on Climate; MPI-ESM-MR, Max Planck Institute for Meteorology Earth System Model; MRI-CGCM3, Meteorological Research Institute Coupled Global Circulation Model; PET, potential evapotranspiration.

FIGURE 2.10: Average annual values of rain, water yield, evapotranspiration and potential evapotranspiration by mid-century.

SWAT modelling. In this section, a detailed analysis of the impact assessment of climate change will be presented together with the quantification of its impact on water security.

☐ Impact of climate change on future rainfall

The GCM-driven models have generated differing results for future rainfall. The average monthly values of the future rain, as predicted by these GCMs, were compared with the average values of the measured rainfall. Figure 2.11a and Figure 2.11b shows the percentage change of average monthly rainfall by mid-century (2050) compared with the historical average of the past 30 years. Most of the GCM-driven models predict a similar pattern of percentage change with



ACCESS1-0, Australian Community Climate and Earth System Simulator; CNRM-CM5, Centre National de Recherches Météorologiques Climate Model; IPSL-CM5A-LR, Institut Pierre Simon Laplace Model Climate Model; MIROC5, Model for Interdisciplinary Research on Climate; MPI-ESM-MR, Max Planck Institute for Meteorology Earth System Model; MRI-CGCM3, Meteorological Research Institute Coupled Global Circulation Model.

FIGURE 2.11: Percentage change of future rain compared with historical values: (a) Representative Concentration Pathways 4.5 and (b) Representative Concentration Pathways 8.5.

the exception of one, that is, MIROC5. This expected trend is similar for both scenarios of RCP4.5 and RCP8.5. The most visible and significant decrease is for the months of May to November.

Figure 2.12a and Figure 2.12b presents the multimodel average monthly percentage change of future rain, compared with historical values. These graphs clearly show the decreasing pattern of rain during the months of the year (except the months of December and January), most significantly during the months

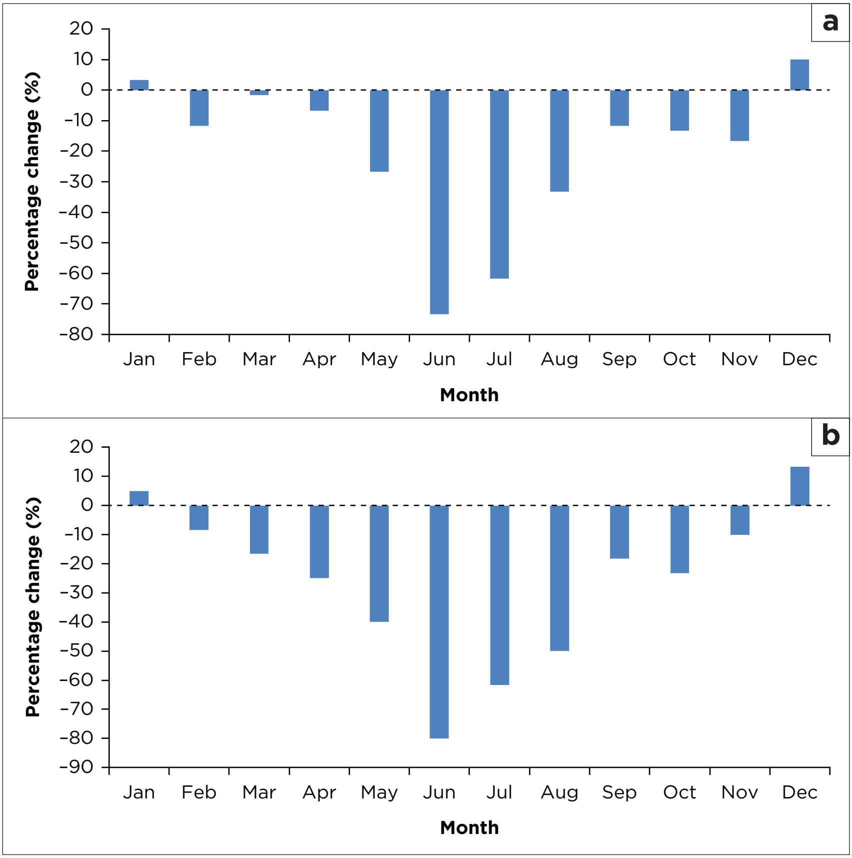


FIGURE 2.12: Multimodel average monthly percentage change of future rain compared with historical values: (a) Representative Concentration Pathways 4.5 and (b) Representative Concentration Pathways 8.5.

of May to August. It also shows that the dry months will become drier, and the normal wet seasons will have less rain. The effect of climate change in reducing rain is more pronounced at RCP 8.5, as shown in Figure 2.11b and Figure 2.12b.

Table 2.2 presents a more detailed picture of monthly percentage change of future rain as compared with historical values for the emission scenario of RCP 8.5. The shaded grids in the table show the magnitude and the month where there will be a reduction in monthly rainfall. As can be observed, almost all GCM-driven models point in the same direction, which is a reduction in monthly rainfall during most of the months of the year.

Impact of climate change on water balance

The projected decrease in rainfall, as described in the previous section, is expected to have an impact on water balance

TABLE 2.2: Percentage change of future monthly rainfall (mid-century) under the scenario of Representative Concentration Pathways 8.5 compared with average observed values (1975–2005).

Month	GCMs						
	ACCESS1-0 (%)	CNRM-CM5 (%)	IPSL-CM5A-LR (%)	MIROC-5 (%)	MPI-ESM-MR (%)	MRI-CGCM3 (%)	Average (%)
January	20	0	0	0	−10	20	5
February	20	−20	0	−20	−10	−20	-8
March	−30	−10	0	−60	−10	10	−17
April	−50	0	−20	−90	10	0	−25
May	−90	10	−50	−90	−10	−10	−40
June	−100	−80	−80	−70	−70	−80	−80
July	−90	−80	−70	10	−80	−60	−62
August	−90	−70	−40	20	−70	−50	−50
September	−90	−50	−30	140	−50	−30	−18
October	−80	−30	−20	20	0	−30	−23
November	−30	−20	0	10	0	−20	−10
December	20	0	20	20	10	10	13

ACCESS1-0, Australian Community Climate and Earth System Simulator; CNRM-CM5, Centre National de Recherches Météorologiques Climate Model; GCMs, General Circulation Models; IPSL-CM5A-LR, Institut Pierre Simon Laplace Model Climate Model; MIROC5, Model for Interdisciplinary Research on Climate; MPI-ESM-MR, Max Planck Institute for Meteorology Earth System Model; MRI-CGCM3, Meteorological Research Institute Coupled Global Circulation Model.

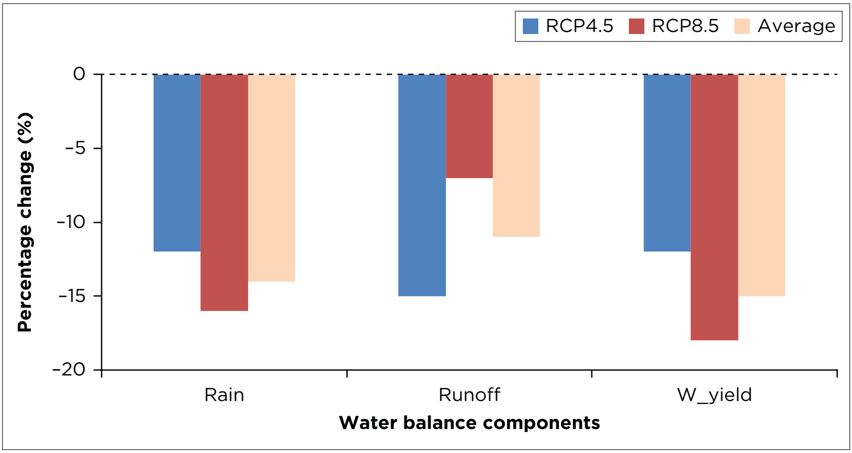
components of the river basin. As shown in the summarised output of the SWAT model, there is a clear indication of an increasing trend of the projected PET by mid-century.

Table 2.3 shows the projected percentage change of PET compared with simulated historical values at RCP8.5. The multimodel average percentage change of PET shows an increase of between 7% and 13% (Table 2.3). This is indicative of potential dry spells between rainy events in addition to a possible decrease in monthly rainfall. Increase in PET coupled with a decrease in rain is expected to impact on runoff generation and subsequently on the water yield in the river basin. Analysis of this downscaling approach, using the multimodel average, shows that there will be a decrease in monthly rain, as shown in Figure 2.11. Similarly, the average water balance components of the watershed, such as rain, surface runoff and water yield, were simulated using SWAT and analysed. The results are presented in Figure 2.13. On average, rain is expected to decrease by 14%, runoff by 11% and water yield by 15%, by the mid-century.

TABLE 2.3: Percentage change of potential evapotranspiration (mid-century) under the scenario of Representative Concentration Pathways 8.5 compared with historical simulated values.

Month	GCMs						
	ACCESS 1-0 (%)	**CNRM-CM5 (%)**	**IPSL-CM5A-LR (%)**	**MIROC5 (%)**	**MPI-ESM-MR (%)**	**MRI-CGCM3 (%)**	**Multimodel average (%)**
January	30	20	-10	10	10	20	13
February	20	10	-20	10	10	10	7
March	10	10	-10	30	10	10	10
April	20	10	0	20	0	10	10
May	20	10	10	0	10	10	10
June	10	10	0	10	10	0	7
July	10	10	10	10	10	10	10
August	20	10	0	20	0	10	10
September	30	20	0	10	10	20	15
October	40	20	-20	10	0	20	12
November	30	20	-20	10	0	30	12
December	20	10	-30	20	10	30	10

ACCESS1-0, Australian Community Climate and Earth System Simulator; CNRM-CM5, Centre National de Recherches Météorologiques Climate Model; GCMs, General Circulation Models; IPSL-CM5A-LR, Institut Pierre Simon Laplace Model Climate Model; MIROC5, Model for Interdisciplinary Research on Climate; MPI-ESM-MR, Max Planck Institute for Meteorology Earth System Model; MRI-CGCM3, Meteorological Research Institute Coupled Global Circulation Model.



RCP4.5, representative concentration pathway 4.5; RCP8.5, representative concentration pathway 8.5.

FIGURE 2.13: Future average water balance components by mid-century (2020–2050).

Conclusion

Investigation of the impact of climate change on water security was conducted in the Modder River basin (central region of South Africa). In this study, a climate change downscaling approach, known as Statistical Downscaling (from NASA), was adopted. This approach was applied using six GCM-driven models. In each of the GCM-driven models, two GHG emission scenarios, namely, RCP4.5 and RCP8.5, were considered. The weather data obtained from the climate change scenarios were used as input for the SWAT hydrological model to simulate the impact of climate change on water and the water balance components of a river basin at mid-century and the end of the century.

The bias-corrected high-resolution downscaled data produced a strong correlation between the historically measured rainfall and the historically simulated rainfall by four of the six models ($R^2 \geq 0.9$), whilst two of them had R^2 of 0.69. The average of the six models showed a strong correlation ($R^2 = 0.95$). The significance of this correlation is that it indicates the reliability of the future climate prediction. The result of (Woyessa 2019):

> [*T*]he hydrological simulation and analysis of climate change data showed that there will be a reduction in rainfall and river basin water balance components under both greenhouse gas emission scenarios, but the effect will be more pronounced under the RCP8.5. (p. 3)

On average, the study revealed the following as a possible impact of climate change by the mid-century:

- rainfall is expected to decrease by 14%
- surface runoff is expected to decrease by 11%
- water yield is expected to decrease by 15%
- PET will increase by 11%.

It is expected that the combined effect of reduced rainfall and increased PET will exacerbate the existing problem of water security in the region.

Acknowledgements

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Chapter 3

Effective utilisation of the Africa Flood and Drought Monitor

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Abstract

Water resources availability, utilisation and related infrastructure development in the SADC are hampered by the significant variability of rainfall in quantity and distribution, which leads to variability in water resources availability and usage across the region. The SADC is highly dependent on rainfall for recharge and a continuous water supply. However, the dependence on rainfall leads to increased vulnerability due to climate-induced pressures. Hence, there is a need for reliable information on precipitation extremes and related hydro-climate data. This study focused on evaluating the effectiveness of the Africa Flood and Drought (AFDM) monitor in providing reliable information for precipitation-extremes-related research, decision making and utilisation by local farmers, and suggesting procedures for making the tool user-friendly for all stakeholders. The AFDM tool combines climate predictions, hydrological models and remote-sensing data to provide useful information on drought and floods in regions where institutional capacity is lacking and access to information and technology prevents the development of systems locally. The tool monitors and forecasts meteorological, agricultural and hydrological drought at various temporal and spatial scales. It also has a multi-decadal, historical reconstruction of the terrestrial water cycle against which current conditions can be compared. If properly adapted to the real water–climate challenges of the continent, the tool could contribute to the effective future management of water in Africa.

Keywords: Africa Flood and Drought Monitor (AFDM); Climate predictions; Hydrological models; Floods; Drought.

Introduction

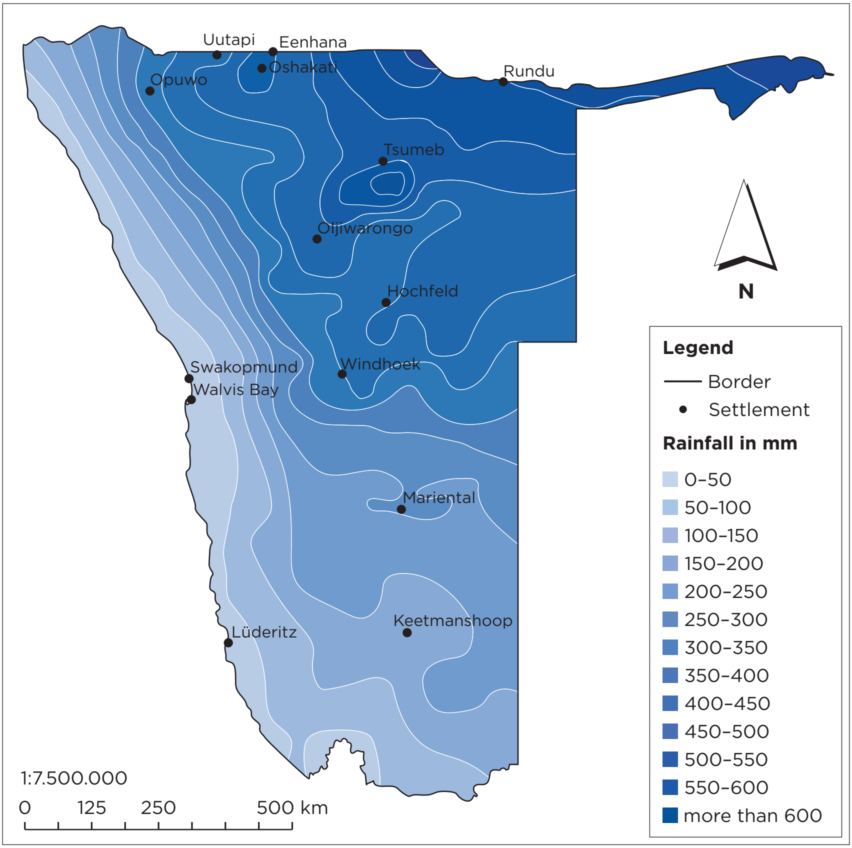
Worldwide, 40% of natural hazards are caused by floods, thus impacting human lives, causing more deaths, property damage and impaired water quality, especially in developing countries (Persendt, Gomez & Zawar-Reza 2015). Moreover, the increasing occurrence and severity of floods, along with water-resource shortage, are the worst hazards to the global ecosystem linked to global warming.

Eckstein (2009) reported that observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences on human societies and ecosystems. Thus, the importance of water–climate tools in ensuring water security is evident because the hydrological cycle is inextricably connected to virtually all sectors of the natural and human environments.

Water resources availability, utilisation and related infrastructure development in the SADC are hampered by significant variability in rainfall regarding quantity and distribution, which leads to variability in water resources availability and usage across the region. The dependence on rainfall increases the vulnerability due to climate-induced pressures. Hence, there is a need for reliable information on precipitation extremes and related hydro-climate data. Figure 3.1 shows the variability of rainfall in Namibia.

Precipitation varies from year to year and over decades, and changes in amount, intensity, frequency and type (e.g. fog vs. rain) affect the environment and society (Trenberth 2011). A consistent decrease in the freshwater resources over the past 49 years, that is, from 9737 mm in 1962 to 2651 mm in 2011, also affects the environment and society (Kgabi & Mashauri 2014).

Many parts of Namibia are experiencing frequent drought occurrences and an increase in frequency of unpredictable flood and drought. In recent years, Namibia has been caught unexpectedly by flood and reoccurring longer durations of drought. For example, the Cuvelai-Etosha basin (CUEB) has been experiencing both floods and drought (Mendelsohn, Jarvis & Robertson 2013; Persendt et al. 2015), and the Zambezi-Kwando-Linyanti Basin is frequently flooded, due to the influence of major rivers and Orange Senqu, and also faces frequent drought.



Source: Ministry of Environment and Tourism (2003).

FIGURE 3.1: Average annual rainfall distribution in Namibia.

In 2006–2007 and 2012–2013, the country observed the onset of rains, which resulted in extreme dryness during the rainfall season, and the increased dryness led to the declaration of a year of drought. The country was also affected by unexpected flooding in the same year (Kapolo 2014). This scenario raised some attention to the understanding of the occurrences of floods and drought and prediction methods used by forecasting bodies within Namibia. Therefore, frequently occurring floods and drought, existing missing data gaps and few studies conducted on the classification of flood and drought in Namibia (Mendelsohn et al. 2013) are significant reasons for assessing the effectiveness of the data provided by forecasting models, and verified based on the results of the AFDM.

The AFDM is a tool developed by UNESCO in collaboration with the Department of Civil and Environmental Engineering, Princeton University, United States of America. The AFDM monitors and forecasts meteorological, agricultural and hydrological drought at various temporal and spatial scales. It also has a multi-decadal, historical reconstruction of the terrestrial water cycle against which current conditions can be compared (ICIWaRM 2018).

The impact of adverse climatic conditions on the water resources (Lötter et al. 2018):

> [*C*]an be exacerbated due to the ineffective use of forecasts, variously relating to the scientific presentation of seasonal forecasts and climate projections, lack of capacity to interpret the findings to suit the needs of different sectors, and challenges in interpreting forecasts in the context of a decision, or combining it with other information sources. (p. 4)

The reliable climate information should form the basis of any water resources related management plan and practice.

Therefore, a verification study on the 20-year (1998–2017) data provided by the AFDM tool for four towns, namely, Windhoek, Katima Mulilo, Keetmanshoop and Walvis Bay, representative of the semi-arid, flood-prone, drought-prone and desert environment, respectively was conducted. This study aimed to assess the effectiveness of the tool in addressing the scarcity of reliable hydro-climate data in Namibia and to determine whether the information provided is 'user-friendly' to the agricultural or farming community.

Methods or study approach

This is a comparative analytical study, which includes both qualitative and quantitative methods.

Study sites

This study focused on four towns (Figure 3.2) representative of four different river basins, namely, Katima Mulilo, Keetmanshoop, Walvis Bay and Windhoek, respectively.

The description of the study sites is given in Table 3.1, with a summary of economic activities and extreme precipitation events (EPEs) experienced.

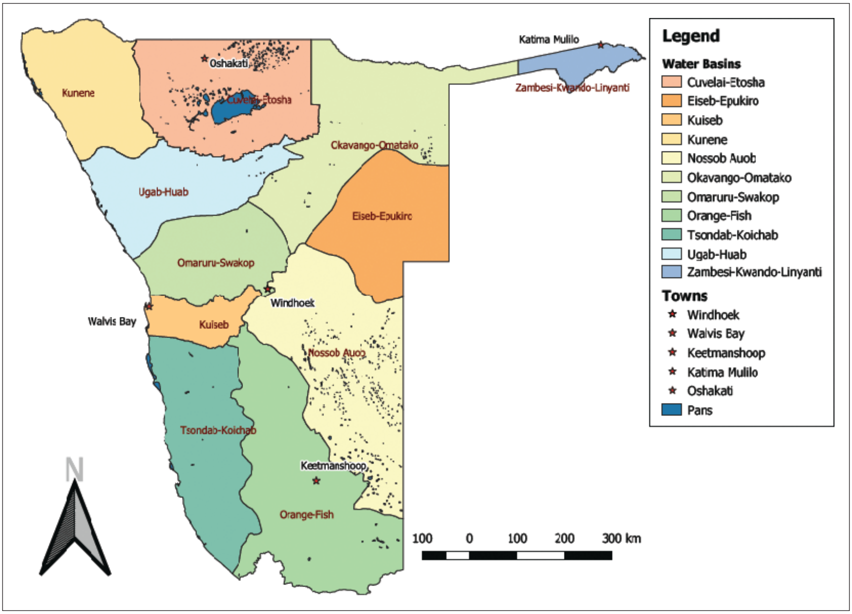


FIGURE 3.2: Map of Namibia showing the selected study sites.

TABLE 3.1: Location of study sites, and the economic and precipitation extremes experienced at the study sites.

Study site (town/region)	Latitude; Longitude	River basin	Population	Economic activities	Extreme precipitation events experienced	Reference
Katima Mulilo (Zambezi)	-17°30’0.00” S 24°16’0.01” E	Zambezi-Kwando-Linyanti	The region has a population of 90 596, and 28 362 in Katima Mulilo	Activities in this region include aquaculture, communal and commercial farming and tourism (i.e. national parks)	Increase in heavy rainfall events (seasonal floods) Increased interannual variability with more intense and widespread weather conditions (i.e. drought)	NSA (2013); IPCC (2007)
Keetmanshoop (Karas)	-26°34’59.99” S 18°07’59.99” E	Orange-Fish	The region has a population of approx. 77 421, and 20 977 in Keetmanshoop	Important hub regarding road and rail traffic in southern Namibia Dominated by commercial farming and important mining activities (i.e. Skorpion Zinc) Tourism (Quiver tree forest)	Average rainfall of 100 mL–200 mL annually and some years without any precipitation	Info Namibia (2018); NSA (2011)

Table 3.1 continues on the next page→

TABLE 3.1 (Continues...): Location of study sites, and the economic and precipitation extremes experienced at the study sites.

Study site (town/region)	Latitude; Longitude	River basin	Population	Economic activities	Extreme precipitation events experienced	Reference
Walvis Bay (**Erongo**)	-22°57’27.00” S 14°30’19.01” E	Kuiseb	The region has a population of 150 809, and Walvis Bay population is approx. 62 096	Activities in the region include mining, fisheries, manufacturing, harbour and tourism	Only little rainfall can be expected, temperatures may rise above 40 °C (extreme arid zone) In this region, cold weather conditions are experienced due to the Benguela Current	NPA (2011) Info Namibia (2018)
Windhoek (Khomas)	-22° 33’ 33.88” S 17° 04’ 59.63” E	Partly situated in Omaruru-Swakop (upper basin) and Kuiseb and Nossob Auob	The Khomas region has a population of approx. 342 141, and 325 858 in Windhoek	The multi-activities of this region include agricultural (farming with crops and animals), industrial, tourism and domestic	Lack of natural water resources due to high arid climatic conditions and negative water balance	NPA (2011)

Data collection and analysis

This study makes use of the hydro-meteorological data for a period of 68 years (1950–2018).

The data will be generated using the AFDM tool, which uses different models that will provide all hydro-meteorological data such as precipitation, temperature, wind speed, soil moisture, stream flow, surface runoff and base flow. Secondary hydro-meteorological data will be gathered from the Ministry of Agriculture, Water and Forestry (MAWF), Meteorological Services of Namibia and other archived published literatures.

Lastly, the effectiveness of the hydro-climatic models and data results from MAWF were assessed by comparing the results obtained from AFDM, against the results obtained from MAWF models and verification of the primary data.

An in-depth assessment of the permutations or data transformations and products of the AFDM was also conducted to understand the complex nature of the tool.

Results and discussion

Comparison of output from Africa Flood and Drought Monitor and the observation data from the National Meteorological Services

The results of AFDM and the Namibia Meterological Services (NMS) for Katima Mulilo, Windhoek, Walvis Bay and Keetmanshoop are presented in Figure 3.3 to Figure 3.6 for precipitation and temperature, respectively.

The rainfall months for Windhoek were not located correctly. Thus, the model results suggested that the area was experiencing winter rainfall most years, yet the rainfall was mostly confined to the period from November to April (with a few years extending

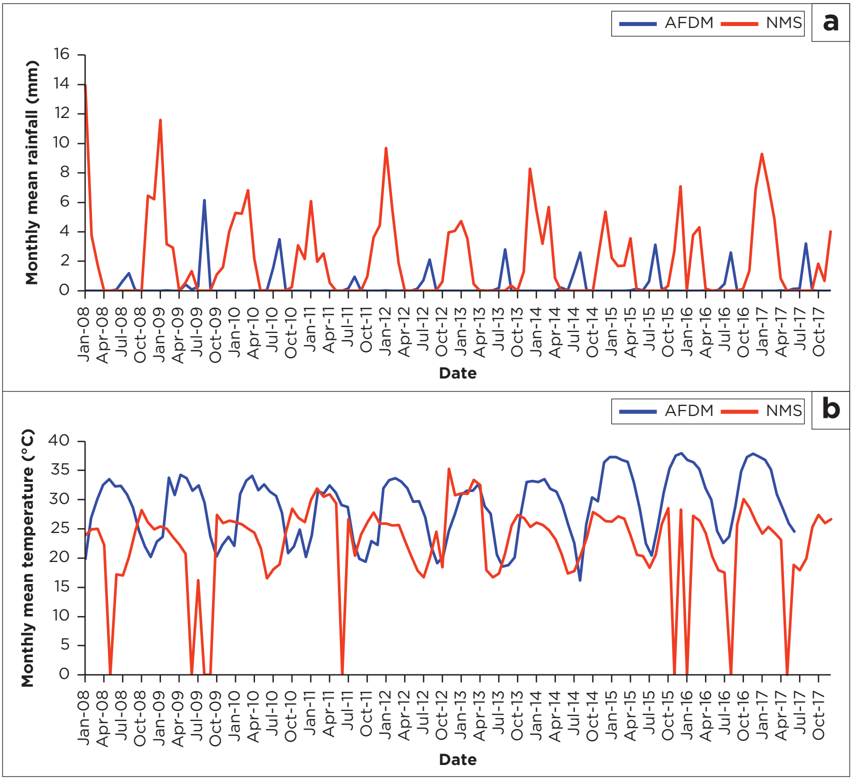


FIGURE 3.3: Africa Flood and Drought Monitor and National Meteorological Services results for Katima Mulilo. (a) Precipitation and (b) Temperature.

to beginning of May) period for the past 20 years. The team noted that (University of Arizona 2018):

> AFDM is based on macro scale hydrologic modelling, ingests available data to provide a real-time assessment of the water cycle and drought conditions, and puts this in the context of the long-term record back to 1950. (n.p.)

However, the scaling and resolution are not necessarily suitable for Namibia and similar countries that have different hydro-climatic settings. This could further suggest the need to use the AFDM data with caution when forecasting EPEs.

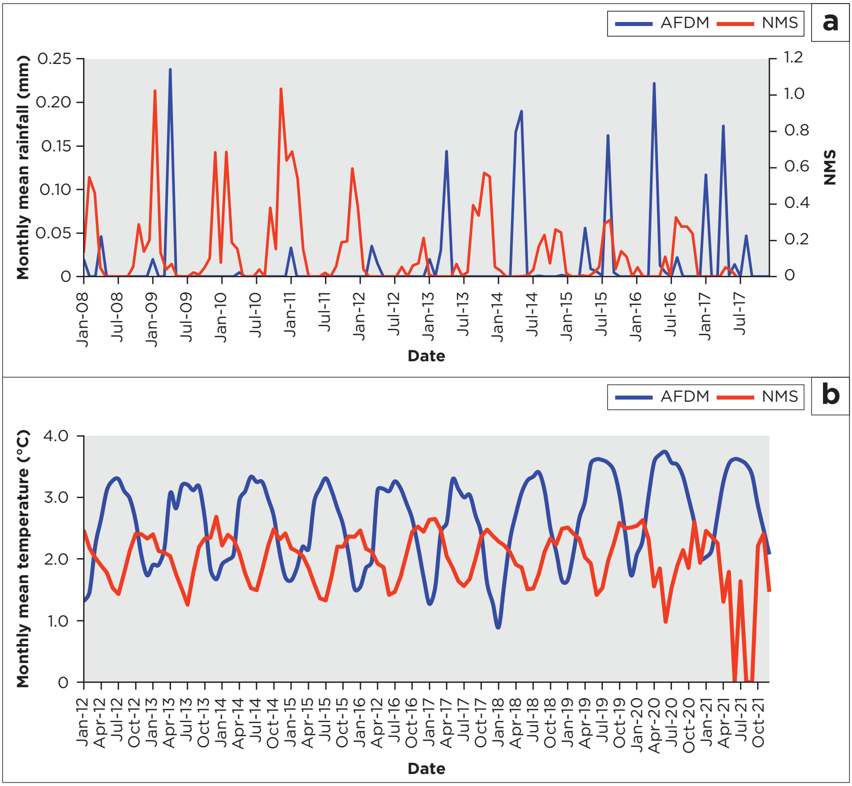


FIGURE 3.4: Africa Flood and Drought Monitor and National Meteorological Services results for Windhoek. (a) Precipitation and (b) Temperature.

The 20-year precipitation data retrieved from the tool revealed a different picture compared with what was observed on the ground. For example, the data from the tool seemed to suggest that Walvis Bay has been experiencing rainfall on a yearly basis over the past 20 years, whereas the town experienced rainfall fewer than five times in the past 55 years.

The data for Keetmanshoop were also not in agreement with ground-based observations and indicated precipitation in the periods where there was none. This implies that the tool does not report only one form of precipitation (rainfall) but combines all

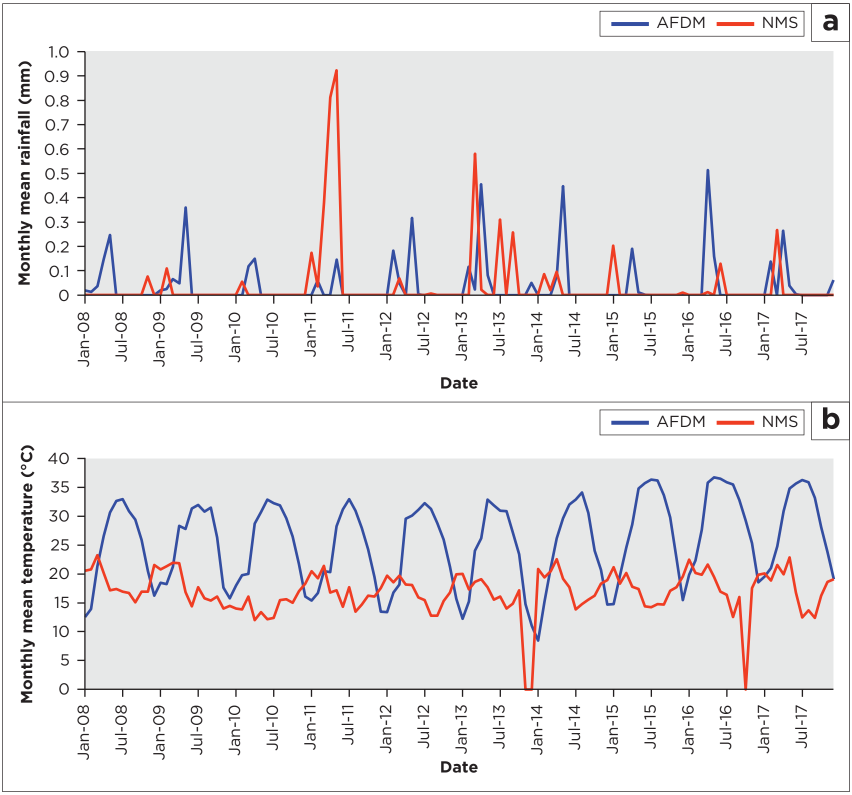


FIGURE 3.5: Africa Flood and Drought Monitor and National Meteorological Services results for Walvis Bay. (a) Precipitation and (b) Temperature.

forms, for example, fog, snow and other potentially precipitable water in the atmosphere.

The following observation may be crucial for effective utilisation of the tool in providing reliable information for precipitation extremes research, decision making and utilisation by local farmers; the AFDM tool presents temperature data in kelvin, and not in degree Celsius, which is commonly used in African countries. Considering the 'technical-literacy' level in our countries, the farmers may not be in a position to always convert the temperature data before use.

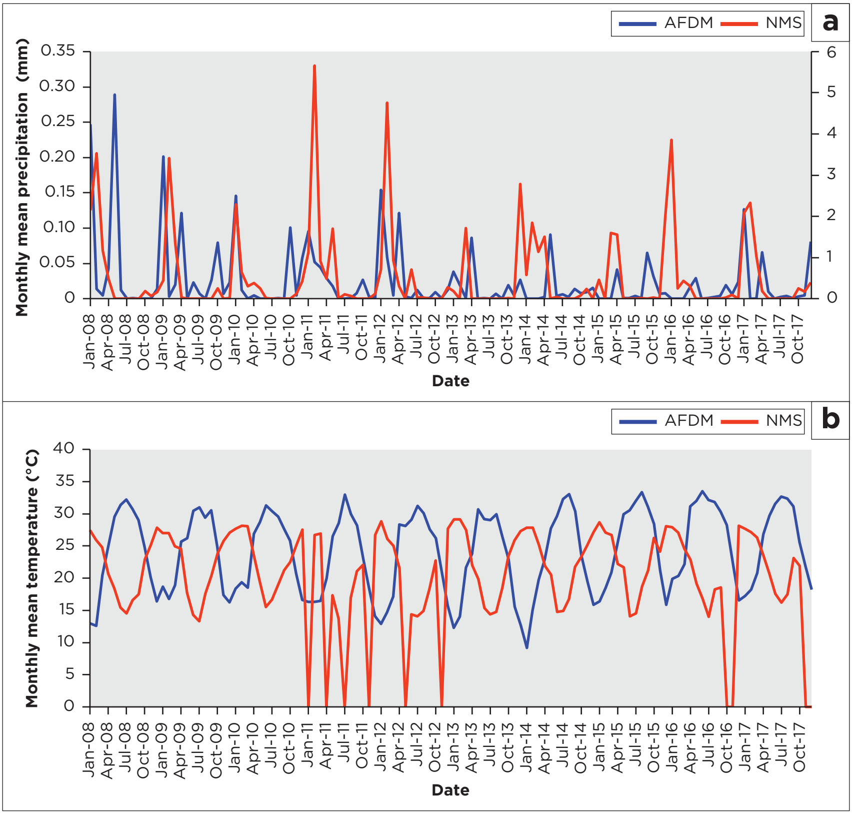


FIGURE 3.6: Africa Flood and Drought Monitor and National Meteorological Services results for Keetmanshoop. (a) Precipitation and (b) Temperature.

The Africa Flood and Drought Monitor data processing or generation process

Figure 3.7a to Figure 3.7f shows the iterations and transformations occurring in the data generation and processing within the AFDM tool. The numbers encircled in blue font show the number or permutations or transformation up to the point indicated.

It is evident that, in its present form, the AFDM tool demands a level of technical know-how, which our farmers and decision

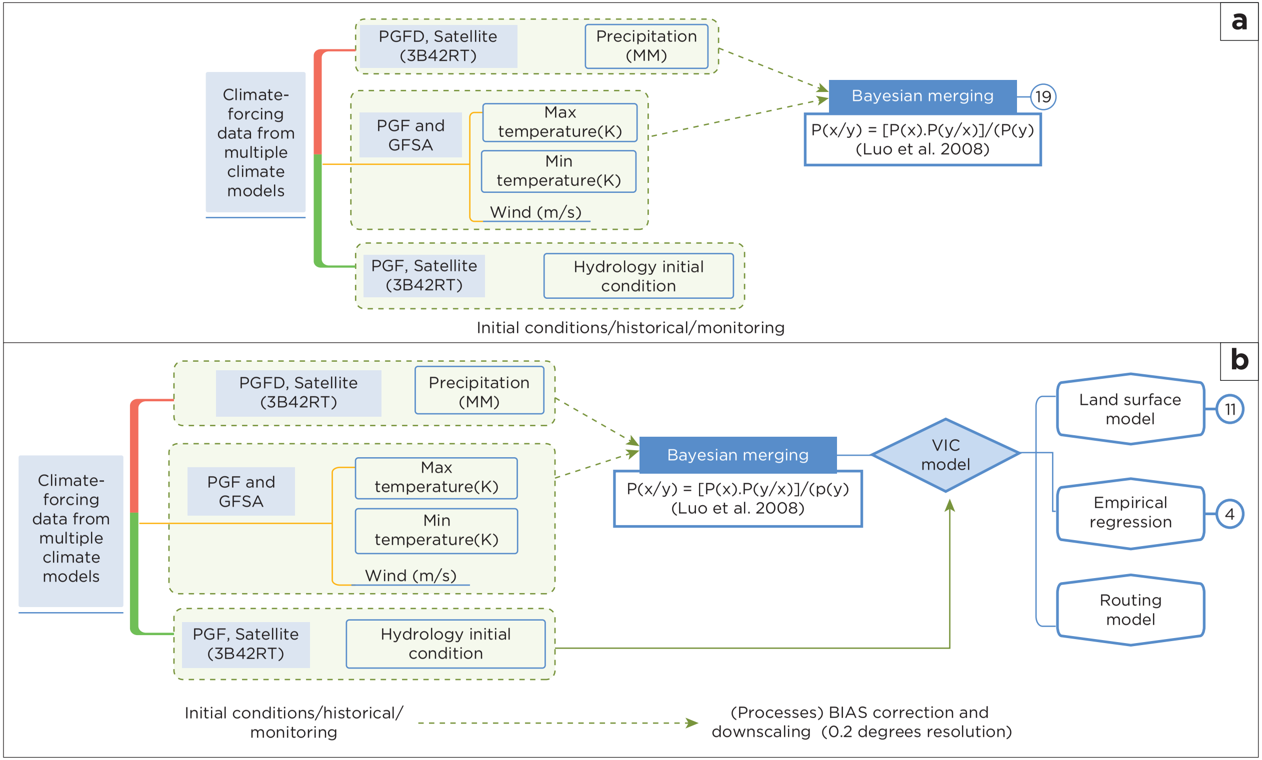


FIGURE 3.7: (a)–(f) Summary of the data processing by using the Africa Flood and Drought Monitor tool.

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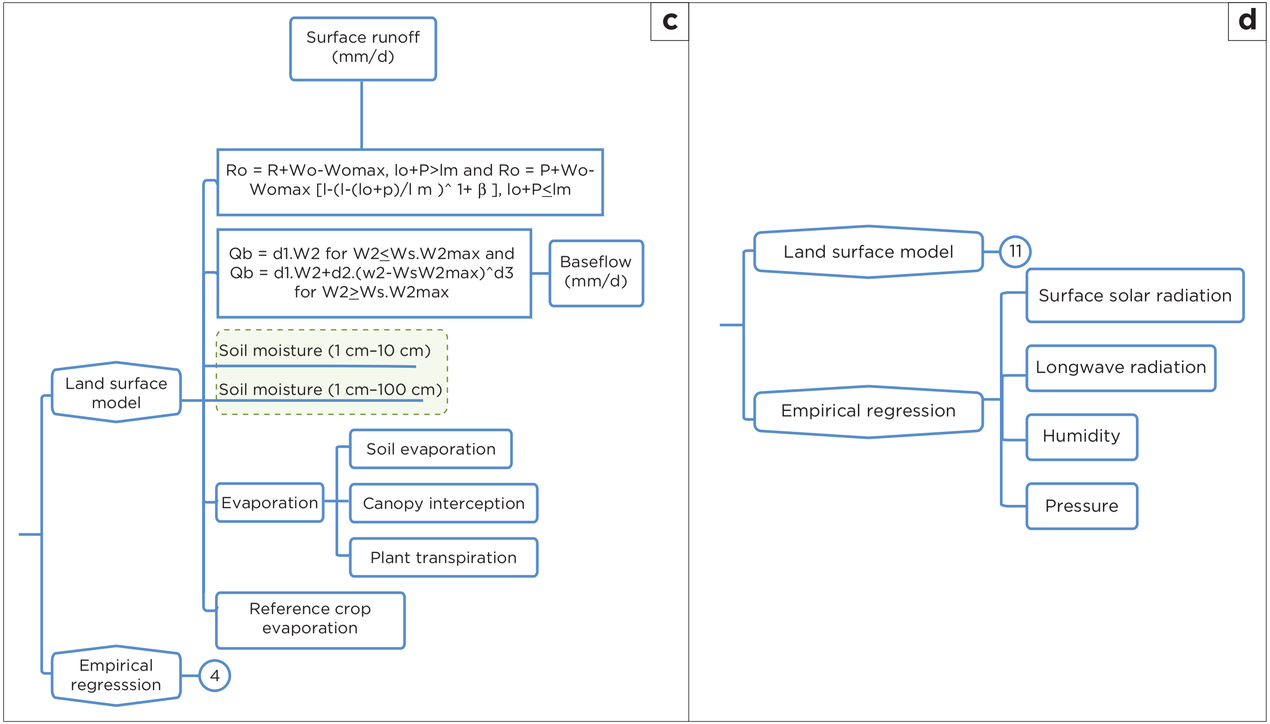

FIGURE 3.7 (Continues...): (a)–(f) Summary of the data processing by using the Africa Flood and Drought Monitor tool.

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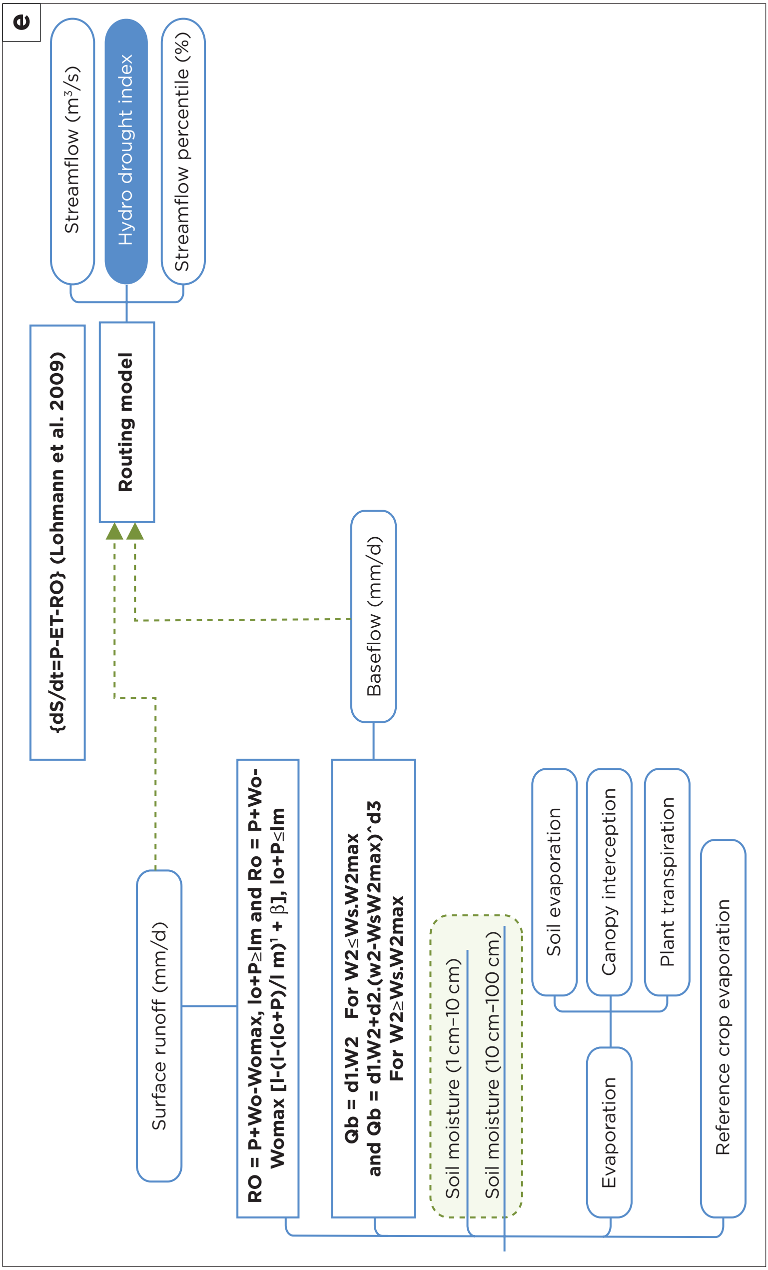

FIGURE 3.7 (Continues...): (a)–(f) Summary of the data processing by using the Africa Flood and Drought Monitor tool.

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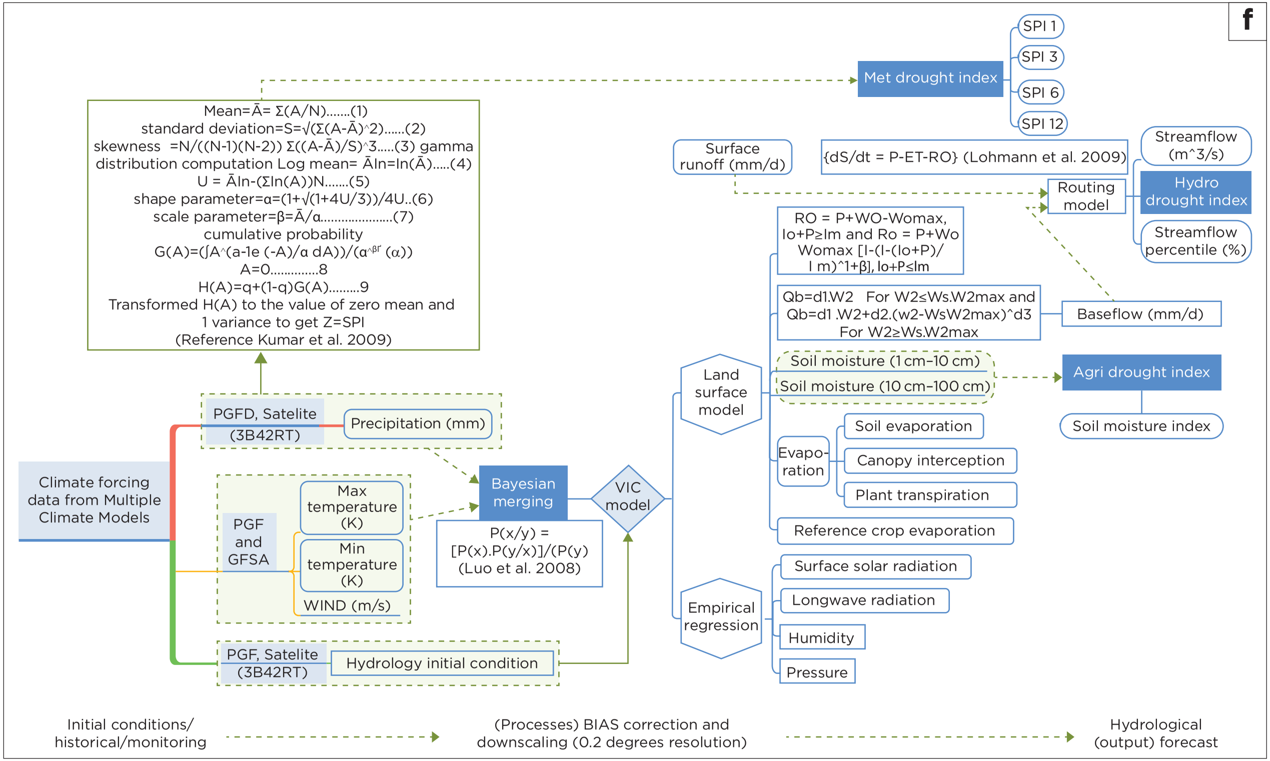


ET, evapotranspiration; PGF, Princeton Global Forcings; PGFD, Princeton Global Forcing Dataset; RO, runoff; SPI, standardised precipitation index; VIC, variable infiltration capacity.

FIGURE 3.7 (Continues...): (a)–(f) Summary of the data processing by using the Africa Flood and Drought Monitor tool.

makers may not necessarily have. It needs to be simplified to the point where any member of the water and agricultural sector can easily use the information provided without having to consult 'technocrats' for interpretation.

Models involved in the information generation and the products

The AFDM tool uses different models and indices to monitor and forecast meteorological, agricultural and hydrological drought. In this study, the Variable Infiltration Capacity (VIC) Hydrological Model used could compute the Standardised Precipitation Index (SPI), Drought Index, and the Normalized Difference Vegetation Index-Moderate Resolution Imaging Spectro-radiometer (Normalized Difference Vegetation Index [NDVI] MODIS-model). These models or indices generate various hydro-meteorological data, such as precipitation, base flow, stream flow, surface runoff, as well as soil moisture and live vegetation, and indicate how the classification of flood and drought will be carried out utilising the indicators and models in classifying occurrences, frequency and intensity.

The AFDM tool produces various products (Table 3.2), such as hydrological indices (soil moisture index, stream flow percentile, surface runoff, base flow, evaporation and reference cop transpiration, Drought Index-Soil Moisture Index, SPI, and stream flow percentile), surface fluxes (net radiation, and net short and long wave radiation) and vegetation products (NDVI percentiles).

Concluding remarks

It is crucial for researchers in the SADC to consider, as implied in the work of Lötter et al. (2018), the types of climate information available, short-term weather forecasts (days), medium-term seasonal climate forecasts (week to months) and long-term

TABLE 3.2: The Africa Flood and Drought Monitor input and output products.

Parameter	Measurement	Description	Data set
Meteorology	Precipitation (mm/day)	Daily total surface precipitation	Satellite precipitation (3B42RT), global forcing data set
	Temperature (maximum, K)	Daily maximum temperature measured at 2 m above the surface	Princeton global forcing and global forecasting system analysis
	Temperature (minimum, K)	Daily maximum temperature measured at 2 m above the surface	Princeton global forcing and global forecasting system analysis
	Wind speed (m/s)	Daily mean wind speed measured 2 m above the surface	Princeton global forcing and global forecasting system analysis
Hydrology	Soil moisture (%) layer 1	Relative soil moisture of the top layer (0–10 cm) calculated from Land Surface Model output	Derived from hydrologic products (VIC)
	Soil moisture (%) layer 2	Relative soil moisture of the second layer (10 cm to ~100 cm) calculated from Land Surface Model output	Derived from hydrologic products (VIC)
	Soil moisture active passive environmental monitoring satellite Soil moisture (m^3/m^3)	Level 3–1 and 3-day composite	Level 3 (1- and 3-day composite)
	Evaporation (mm/day)	The sum of the land surface model's soil evaporation, canopy interception and plant transpiration	VIC hydrologic model (PGF) and (3B42RT)
	Reference crop evaporation (mm/day)		Derived from hydrologic products (VIC)
	Surface runoff (mm/day)	Excess water from the rain, snowmelt or other sources that does not infiltrate due to soil saturation or high intensity but instead flows overland	VIC hydrologic model (PGF) and (3B42RT)
	Baseflow (mm/day)	Portion of the streamflow that comes from the sum of deep subsurface flow and delayed shallow subsurface flow	VIC hydrologic model (PGF) and (3B42RT)
	Streamflow (m^3/s)	Daily basin discharge calculated by putting the baseflow and surface runoff from the VIC Land Surface Model at each grid cell into the velocity-driven spatially continuous routing model	VIC hydrologic model (PGF) and (3B42RT)

Source: Modified from Princeton (n.d.).
NDVI, Normalized Difference Vegetation Index; SPI, standard precipitation indices; VIC, variable infiltration capacity.

Table 3.2 continues on the next page→

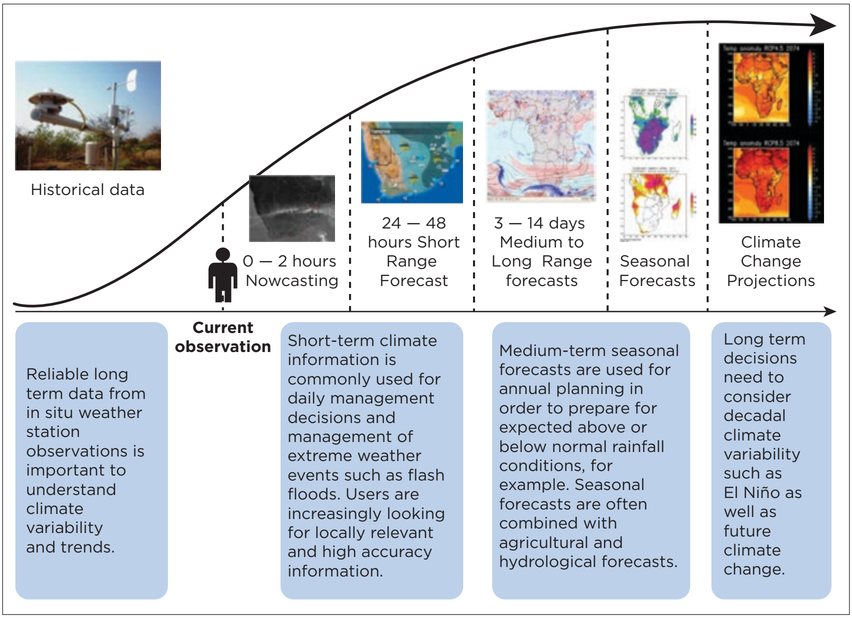
TABLE 3.2 (Continues...): The Africa Flood and Drought Monitor input and output products.

Parameter	Measurement	Description	Data set
Indices (products)	SPI-1, 3, 6, 12	The 1-,3-,6-,12-month standard precipitation index is the number of standard deviations that observed cumulative precipitation deviates from the climatological average at 1, 3, 6 and 12 months	Derived meteorology
	Drought index	A measure of severity of drought in soil moisture – low values indicate drought conditions	Derived meteorology
	NDVI percentile (30-day moving average)	A measure of severity of agricultural drought – low values indicate drought conditions. The 30-day moving average of NDVI is compared with the historical record of NDVI via the empirical cumulative distribution function to determine the percentile	MODIS
	Streamflow percentile (%)	A measure of the severity of hydrological drought – low values indicate drought conditions. Percentile of the simulated discharge at each stream gauge with respect to the historical simulations (1950–2008)	VIC hydrologic model
Surface fluxes (products)	Net radiation (W/m^2)	Difference between incoming and outgoing components of radiation calculated using the VIC Land Surface Model	VIC hydrologic model (PGF) and (3B42RT)
	Net longwave radiation (W/m^2)	Difference between incoming and outgoing components of longwave radiation calculated using the VIC Land Surface Model	VIC hydrologic model (PGF) and (3B42RT)
	Net shortwave radiation (W/m^2)	Difference between incoming and outgoing components of shortwave radiation calculated using the VIC Land Surface Model	VIC hydrologic model (PGF) and (3B42RT)
Vegetation (products)	The NDVI (30-day moving average)	NDVI is a measure of live green vegetation (0–1)	MODIS

Source: Modified from Princeton (n.d.).
NDVI, Normalized Difference Vegetation Index; SPI, standard precipitation indices; VIC, variable infiltration capacity.

climate variability and change (decades) when selecting or developing water–climate tools (Figure 3.8). This includes the AFDM, which clearly needs to be customised or adapted to African environments to ensure availability, accuracy, consistency and reliability of the information generated.

The hydro-climate information is crucial for planning and making sound decisions about water resources management, farming and disaster-risk management. However, this can only be achieved when the tool is adapted to the local environment, as well as the technical or educational level of the local communities. Although the need for the AFDM cannot be overemphasised, it should be noted that the capacity to manage the access and applicability of the hydro-climate services is also crucial for Namibia and the SADC at large.



Source: Davies-Reddy and Vincent (2017).

FIGURE 3.8: Classification of climate data.

Procedures should be put in place to make the tool user-friendly for all stakeholders. These include ensuring the comparability of data to allow the sharing of results between the different stakeholders involved in the water–climate monitoring processes.

Thus, the authors propose the implementation of the 'Usability Index' to determine how well users can learn and use a product to achieve their goals. The same should be used to determine how satisfied users are with the processes. The ISO/IEC 9126-4 Metrics recommends that usability assessments should include effectiveness – the accuracy and completeness with which users achieve specified goals, efficiency – the resources expended in relation to the accuracy and completeness with which users achieve goals and satisfaction – the comfort and acceptability of use.

Acknowledgements

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Data related to rainfall and temperature (maximum and minimum) used for verification of the AFDM tool were provided by the MAWF and the NMS.

Chapter 4

Water security and extreme precipitation indices of selected towns in Namibia

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Abstract

Namibia, like most African countries, is challenged by increasingly stressed water resources and the need to provide reliable access to water of sufficient quantity and quality in the face of increased urbanisation, a changing and unpredictable climate. The need for reliable scientific information on the sustainability of available water sources, including frequency and intensity of precipitation, cannot be overemphasised. This study was aimed at examining trends of EPEs in two towns (Katima Mulilo and Ondangwa) in Namibia over a 14-year period (2004 to 2017). The R ClimDex tool was used to compute precipitation indices, including annual total wet-day precipitation (Prcptot), consecutive dry days (CDD), consecutive wet days (CWD), number of heavy precipitation days (R10), number of very heavy precipitation days (R20), max 1-day precipitation amount (Rx1) and max 5-day precipitation amount (Rx5), simple daily intensity index (SDII), very wet days representing the amount of rainfall falling above the 95th percentile (R95p) and extremely wet days representing the amount of rainfall falling above the 99th percentile (R99p). These indices were selected to represent the overall precipitation, dry condition, wet condition, and the frequency and intensity of EPEs. All indices of precipitation extremes showed a decreasing trend in the seasonal total rainfall and CWD, whereas there was an increasing trend in CDD. Moreover, we observed a decreasing trend in one-day maximum rainfall, five-day maximum rainfall, the intensity of the daily rainfall over 25 mm during the winter and 50 mm during summer, which together may indicate a future decrease in the magnitude and intensity of precipitation events.

Keywords: Extreme precipitation events; Annual total wet-day precipitation; Consecutive dry days; Consecutive wet days; Number of heavy precipitation days; Number of very heavy precipitation days; Max 1-day precipitation amount; Max 5-day precipitation amount.

Introduction

Africa is home to over one-third of the Earth's arid lands (United Nations Environment Programme 1992) and incorporates the largest area of hyper-arid desert. The largest arid areas of Africa straddle the Tropic of Cancer (the Saharan Desert) and the Tropic of Capricorn (the Kalahari, Karoo, and Namib Deserts).

According to Trenberth (2011:n.p.), 'on average, the frequency of precipitation over the global oceans is 10.9%, varying in values 2- to 3-fold higher at high latitudes than in subtropical regions'. The average values over land are less and can be almost zero in deserts (Dai 2000). 'Because evaporation is a continuous process, the intermittency of precipitation means that typical rates of precipitation conditional upon when it falls are 10- to 25-fold larger than for evaporation' (Trenberth 2011:n.p.).

Namibia is not spared from the challenges of aridity, which is characterised by low, variable precipitation and high evaporation. Trenberth (2011) confirmed that precipitation varies from year to year and over decades, and that the changes in amount, intensity, frequency and type of rainfall affects the environment and society.

Therefore, the water scarcity problems experienced by Namibia confirm the need to understand precipitation dynamics at local level. An understanding of the amount, intensity, duration and frequency of precipitation is crucial for planning, design and the utilisation of water augmentation programmes.

Thus, the study aimed to examine the EPEs in terms of the number of wet days and dry days in selected towns in Namibia. The analysis package used in this study was developed by the World Meteorological Organization/Climate Variability and Predictability (WMO/CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI 2013) (Presendt, Gomez & Zawar-Reza 2015). The package was used to calculate 10 standardised indices (annually) to analyse the characteristics of rainfall in order to understand and monitor a changing climate (Persendt et al. 2015).

Identification and validation of EPEs are important as these events are often associated with flood hazards and, ultimately, higher risk of the vector and epidemic diseases, such as malaria and cholera (Anyamba & Tucker 2005). According to Wuensch and Curtis (2010), EPEs play an important role in monitoring and predicting the occurrence of flood disaster events. Furthermore, the evaluation of short- and long-duration precipitation events is critical to our understanding of flooding and its impact on natural and built environments (Persendt et al. 2015).

Moreover, it should be noted that a lack of adequate water supplies could have a significant impact on the ability of people and nations to ensure their economic and social development, as well as maintaining their accustomed standard of living (Persendt et al. 2015).

Methods/study approach

Description of study site

The study sites (i.e. Ondangwa in the CUEB and Katima Mulilo in the Zambezi-Kwando-Linyati basin) in this study (Figure 4.1) were chosen to demonstrate the varied precipitation extreme events, relating to the atmospheric conditions and their impact on water management strategies of the country. Namibia is characterised by alternating floods and drought in the northern regions, and frequent drought in the south.

The R ClimDex tool was used to compute 10 precipitation indices for two towns – Katima Mulilo and Ondangwa.

Data collection and quality control

Rainfall and temperature (maximum and minimum) data used in the study were collected from the MAWF and the NMS.

The data are collected through actual measurements/ observations at the rainfall stations and through Automated

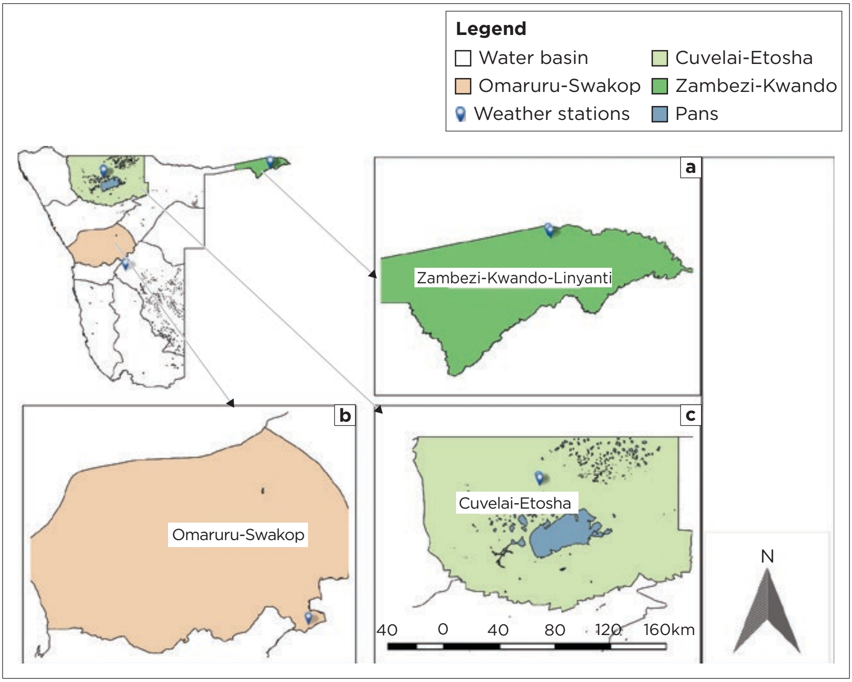


FIGURE 4.1: Location of study sites (towns) with the river basins.

Weather Stations, linked to the software called Meteorological Capturing system (MET cap), installed at the NMS and using cellular technology.

Quality control was done manually, for example any temperature increase of more than 5° within 5 min is cleaned out along with rainfall data as well. The data can be downloaded into a comma-separated-values (CSV) format and converted to Excel for analysis. The rainfall and temperature data in CSV format for this study were collected from the NMS for Katima Mulilo (latitude 17.4833, longitude 24.2667 from 1987 to 2017), Keetmanshoop (latitude 26.5333, longitude 18.1167, from 1970 to 2017), Ondangwa latitude (17.9000, longitude 15.9667, from 2003 to 2017) and Karasburg (Latitude 28.0333, Longitude 18.7500) from 1950 to 2011 rainfall data). Some rainfall data were collected from the MAWF.

The CSV files were converted to Excel format, filtered (replace codes with names), cleaned up (the missing information denoted by stars (****) and (-999) were replaced by zero (0.0). Rainfall data from 1987 to 2003 from the MAWF were merged with rainfall data collected from the NMS (2003–2017) to complete a 20-year (1987–2017) data set for Katima Mulilo. All Excel files were then converted to text files. This was done in preparation for the analysis of the Extreme Precipitation indices with RClimDex software.

Analysis methods

The data collected from the two towns were put into the RClimDex Tool for computation of the 10 precipitation indices.

The original ClimDex software is a Microsoft Excel-based program, developed by Byron Gleason at the National Climate Data Centre that provides an easy-to-use software package for the calculation of the indices of climate extremes for monitoring and detecting climate change (Zhang, Feng & Chan 2018). To resolve the inhomogeneity in the indices series associated with the earlier version, R platform as free and very robust and powerful software for statistical analysis and graphics was employed to develop the current RClimDex tool. The initial version of RClimDex was developed by Xuebin Zhang and Yang Feng at the Climate Research Branch of Meteorological Service of Canada.

The design of RClimDex provides an interface to compute 27 climate extremes indices recommended by the CCI/CLIVAR ETCCDMI (Zhang et al. 2018). The 27 core indices are defined in Zhang and Feng (2004).

The indices generated by the RClimDex tool were analysed, following Zhang et al. (2017). Arithmetic mean values of the indices were used to determine temporal variations of EPEs, arithmetic mean values of the Prcptot were used to assess spatial changes, whilst the cumulative deviation was used as an indicator of abrupt changes in the arithmetic mean values of the indices. The precipitation levels within the time before and after the abrupt changes were assessed, using the student's *t*-test, whilst the Mann–Kendall nonparametric trend test (M-K test) gave an indication of the temporal changing trends and significant levels of precipitation indices.

Description of the indices is summarised in Table 4.1. The indices computed were used to determine the precipitation frequency (R20 mm and R10 mm), intensity (RX1day RX5day, SDII, extremely wet days [R99p] and very wet days [R95p]), duration (CDD and CWD) and amount (Prcptot). Percentile-based indices (very wet days – R95p and extremely wet days – R99p) represent the amount of rainfall above the 95th (R95p) and 99th (R99p) percentiles.

TABLE 4.1: Description of precipitation indices evaluated in the study.

Index	Indicator name	Definition	Units
Prcptot	Annual total wet-day precipitation	Annual total PRCP in wet days (RR ≥ 1mm	mm
CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1mm	days
CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥ 1mm	days
R10	Number of heavy precipitation days	Annual count of days when PRCP ≥ 10 mm	days
R20	Number of very heavy precipitation days	Annual count of days when PRCP ≥ 20 mm	days
Rx1	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
Rx5	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
R95p	Very wet days	Annual total PRCP when RR > 95th percentile	days
R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	days
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP ≥ 1.0 mm) in the year	mm/day

Results and discussion

The results of this study are presented below, focusing on the duration, frequency, extent, intensity and total amount of extreme long-term rainfall. The indicators were confirmed by Presendt et al. (2015) as crucial in identifying past and predicting future hydro-meteorological hazard events (see Myhre et al. 2019).

Temporal variations of extreme precipitation events

The arithmetic mean values of the precipitation indices are presented in Table 4.2 and Table 4.3 for Ondangwa and Katima Mulilo, respectively.

CDD, consecutive dry days; CWD, consecutive wet days; R10, heavy precipitation (annual count of days when PRCP ≥ 10 mm); R20, very heavy precipitation (annual count of days when PRCP ≥ 20 mm); R95, very wet days (annual total PRCP when RR > 95th percentile); R99, extremely wet days (annual total PRCP when RR > 99th percentile); RX1, max 1-day precipitation amount (monthly maximum 1-day precipitation; RX5, max 5-day precipitation amount (monthly maximum consecutive 5-day precipitation); Prcptot, annual total wet-day precipitation (annual total PRCP in wet days (RR ≥ 1mm); SDII, simple daily intensity index (annual total precipitation divided by the number of wet days (defined as PRCP ≥ 1.0 mm) in the year. S.D., standard deviation; SDII, simple daily intensity index; S.E. variance, standard error variance; df, degrees of freedom; *t*, the ratio of the departure of the estimated value of a parameter from its hypothesised value to its standard error.

The cumulative deviation was calculated (Figure 4.2) to assess abrupt changes in arithmetic mean values of the indices.

TABLE 4.2: Mean values for extreme precipitation events in Ondangwa from 2004 to 2017.

Year	CDD	CWD	Prcptot	R10	R20	RX1day	RX5Day	SDII	R95p	R99p
2004	188	6	633.1	14	7	23.3	42.7	13.8	363.8	166.2
2005	248	5	293.3	11	6	7.9	16.2	11.3	43.5	0
2006	71	61	2413.3	80	69	22.3	58.6	24.4	194.6	72
2007	154	4	293.8	9	3	8.6	14.7	8.2	0	0
2008	165	7	686.9	20	13	14.9	33.7	11.3	156.5	0
2009	173	9	815.7	23	12	26.8	45.0	16	367.4	233.2
2010	228	5	537.7	19	8	14.8	29.1	11.7	116	74
2011	205	8	908	30	17	18.4	32.8	14.2	242	0
2012	234	7	556.9	21	9	15.7	28.3	11.4	107.8	65.3
2013	228	4	266.1	10	3	9.0	17.2	7.8	0	0
2014	152	4	381.4	15	3	11.4	21.3	8.5	42.3	0
2015	178	4	299.5	10	4	11.5	20.0	8.3	76.5	0
2016	233	2	265.5	10	3	8.2	16.2	9.2	49.5	0
2017	204	4	348.5	11	6	12.3	20.2	12	56.6	0
Mean	190.1	9.3	621.4	20.2	11.6	14.7	28.3	12.0	129.8	43.6
Count(n)	14	14	14	14	14	14	14	14	14	14
Sum	2661.0	130.0	8699.7	283.0	163.0	205.1	395.7	168.1	1816.5	610.7
S.D.	45.06	14.46	537.85	17.64	16.44	5.84	12.65	4.18	117.36	70.86
S.E. variance	12.0	3.9	143.7	4.7	4.4	1.6	3.4	1.1	31.4	18.9
df	13	13	13	13	13	13	13	13	13	13
t	−9.74743E-16	0	−3.8E-16	-2.1E-16	3.9E-16	8.62E-16	7.95E-16	-8.7E-16	7.48E-16	2.066E-16

Source: Authors' own model results produced using secondary data provided by the MAWF (2018) and the NMS (2018).
CDD, consecutive dry days; CWD, consecutive wet days; prcptot, annual total wet-day precipitation; R10, number of heavy precipitation days; R20, number of very heavy precipitation days; RX1day, maximum 1-day precipitation amount; RX5day, maximum 5-day precipitation amount; SDII, simple daily intensity index; R95p, very wet days; R99p, extremely wet days; S.D., standard deviation; S.E., standard error; df, degrees of freedom; *t*, the ratio of the departure of the estimated value of a parameter from its hypothesised value to its standard error.

TABLE 4.3: Mean values for extreme precipitation events in Katima Mulilo from 1987 to 2017.

Year	CDD	CWD	Prcptot	R10	R20	RX1day	RX5day	SDII	R95p	R99p
1987	209	4	429.9	16	6	13.7	20.7	12.6	103.5	0
1988	143	5	580.5	18	6	17.6	31.6	10.2	176.8	0
1989	187	7	626.4	20	8	16.7	29.5	9.9	112.5	64.3
1990	159	6	435.7	14	7	14.4	24.6	9.7	95	0
1991	207	3	635.7	16	11	20.2	31.2	13.2	240.5	92.5
1992	170	5	374.6	15	5	10.0	18.3	9.1	0	0
1993	164	7	606.5	22	8	13.3	23.3	9.8	42	0
1994	213	6	443.7	15	6	11.6	18.1	10.3	94.5	0
1995	154	6	660.8	20	12	21.9	42.8	15.7	243.5	163.5
1996	245	4	500.4	16	9	15.9	24.4	13.2	130.4	0
1997	148	5	608.1	18	12	17.4	31.5	12.9	101.5	0
1998	192	5	569.2	19	8	12.8	28.6	12.1	153.5	0
1999	228	6	544.6	16	8	18.2	33.2	18.8	293.5	151
2000	131	4	653.7	26	11	14.9	26.7	13.3	67.5	67.5
2001	-	-	-	-	-	-	-	-	-	-
2002	-	-	-	-	-	-	-	-	-	-
2003	1024	2	120.2	4	2	4.5	6.9	8.6	0	0
2004	193	6	734.9	25	11	15.7	33.0	13.4	215.2	0
2005	216	7	697.3	26	14	16.1	36.3	14.8	145	0
2006	182	12	808	29	14	16.6	34.9	11.1	94.1	0
2007	216	4	654.8	21	8	21.3	31.3	12.4	172.9	71.1
2008	232	10	974.8	31	15	19.9	40.8	13.2	288.6	146.6

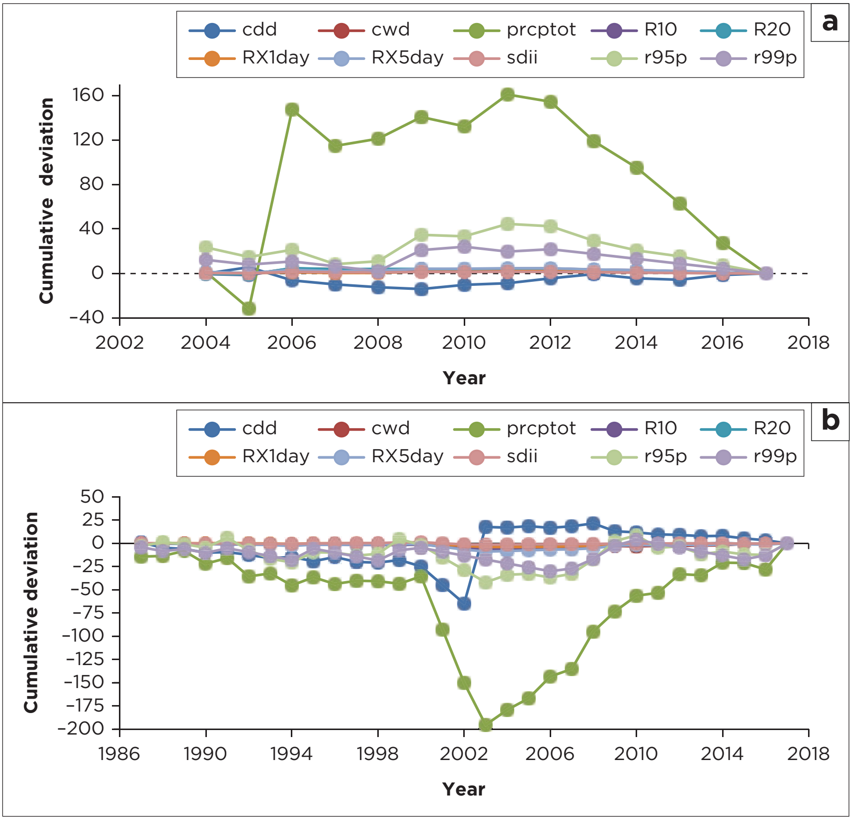
Source: Authors' own model results produced using secondary data provided by the MAWF (2018) and the NMS (2018).
CDD, consecutive dry days; consecutive wet days; prcptot, annual total wet-day precipitation; R10, number of heavy precipitation days; R20, number of very heavy precipitation days; RX1day, maximum 1-day precipitation amount; RX5day, maximum 5-day precipitation amount; SDII, simple daily intensity index; R95p, very wet days; R99p, extremely wet days; S.D., standard deviation; S.E., standard error; df, degrees of freedom; *t*, the ratio of the departure of the estimated value of a parameter from its hypothesised value to its standard error.

Table 4.3 continues on the next page→

TABLE 4.3 (Continues...): Mean values for extreme precipitation events in Katima Mulilo from 1987 to 2017.

Year	CDD	CWD	Prcptot	R10	R20	RX1day	RX5day	SDII	R95p	R99p
2009	114	4	790.5	22	11	23.7	54.9	14.6	330.9	183.5
2010	188	3	742.2	23	14	23.8	35.8	14	197.7	105.6
2011	178	11	605.5	27	8	13.1	25.1	9.8	0	0
2012	196	6	773.7	26	13	17.5	35.6	12.9	147.7	0
2013	186	10	561.7	20	7	11.8	22.1	10.6	49.2	0
2014	203	9	707.8	24	11	18.6	36.2	11.6	162.7	0
2015	172	21	570	13	5	17.4	29.8	9.7	103.5	0
2016	180	11	503.2	17	7	15.0	23.8	12	128.1	84.5
2017	167	9	855.4	25	14	26.1	43.5	13.8	258.9	171.6
Mean	199.9	6.4	573.2	18.8	8.7	15.5	28.2	11.4	133.8	42.0
Count (*n*)	31	31	31	31	31	31	31	31	31	31
Sum	6197.0	198.0	17769.8	584.0	271.0	479.5	874.2	353.3	4149.2	1301.7
S.D.	159.8	4.0	217.9	7.3	3.9	5.9	11.5	3.7	91.7	62.2
S.E. variance	28.7	0.7	39.1	1.3	0.7	1.1	2.1	0.7	16.5	11.2
df	30	30	30	30	30	30	30	30	30	30
t	−6.3862E-17	−1.57989E-16	−6.9139E-16	−1.19582E-15	−3.20403E-16	2.44055E-15	−1.088E-15	−2.296E-15	1.726E-15	0

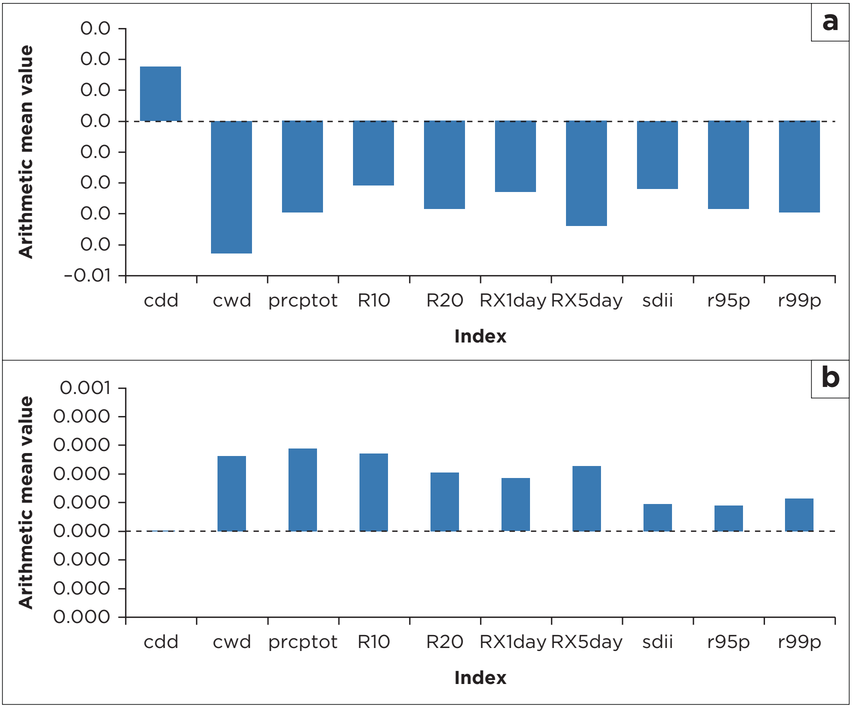
Source: Authors' own model results produced using secondary data provided by the MAWF (2018) and the NMS (2018).
CDD, consecutive dry days; consecutive wet days; prcptot, annual total wet-day precipitation; R10, number of heavy precipitation days; R20, number of very heavy precipitation days; RX1day, maximum 1-day precipitation amount; RX5day, maximum 5-day precipitation amount; SDII, simple daily intensity index; R95p, very wet days; R99p, extremely wet days; S.D., standard deviation; S.E., standard error; df, degrees of freedom; *t*, the ratio of the departure of the estimated value of a parameter from its hypothesised value to its standard error.



Source: Authors' own model results produced using secondary data provided by the MAWF (2018) and the NMS (2018).
cdd, consecutive dry days; cwd, consecutive wet days; prcptot, annual total wet-day precipitation; R10, number of heavy precipitation days; R20, number of very heavy precipitation days; RX1day, maximum 1-day precipitation amount; RX5day, maximum 5-day precipitation amount; sdii, simple daily intensity index; r95p, very wet days; r99p, extremely wet days.

FIGURE 4.2: Cumulative deviation of the extreme precipitation events for (a) Ondangwa and (b) Katima Mulilo.

The mean values of the indices were also subjected to the Mann–Kendal (M-K) test to assess the changing trends and significant levels of precipitation indices as presented in Figure 4.3a and Figure 4.3b.

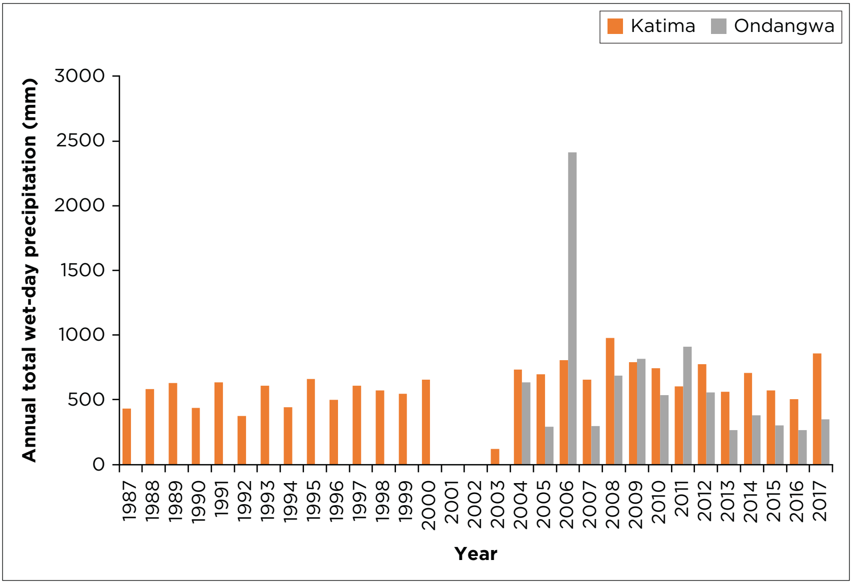


Source: (a & b) Authors' own model results produced using secondary data provided by the MAWF (2018) and the NMS (2018).
cdd, consecutive dry days; cwd, consecutive wet days; prcptot, annual total wet-day precipitation; R10, number of heavy precipitation days; R20, number of very heavy precipitation days; RX1day, maximum 1-day precipitation amount; RX5day, maximum 5-day precipitation amount; sdii, simple daily intensity index; r95p, very wet days; r99p, extremely wet days.

FIGURE 4.3: Mann–Kendal (M-K) test results for indices calculated for (a) Ondangwa and (b) Katima Mulilo.

Spatial variations of extreme precipitation events

The spatial changes were assessed by comparing the Prcptot, that is annual total wet-day precipitation (annual total PRCP in wet days [RR $\geq$ 1mm]) for Katima Mulilo and Ondangwa as presented in Figure 4.4.



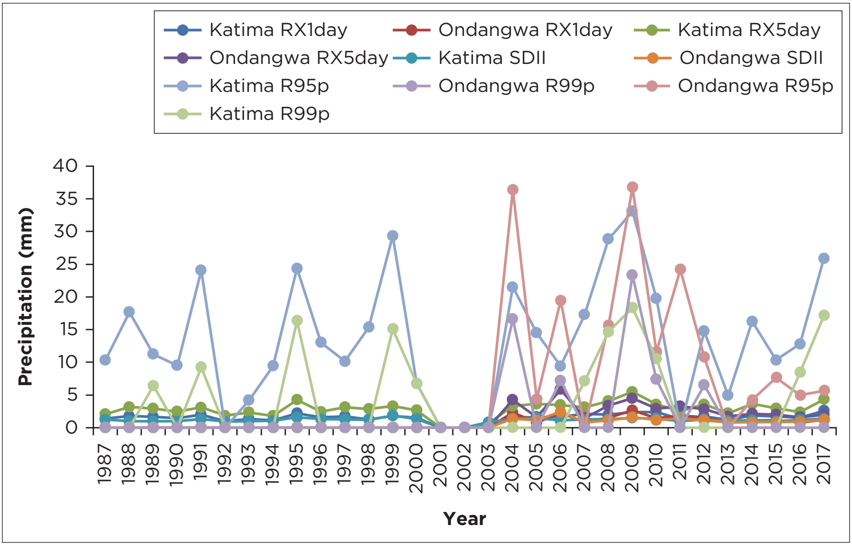
Source: Authors' own model results produced using secondary data provided by the MAWF (2018) and the NMS (2018).

FIGURE 4.4: Annual total wet-day precipitation for Katima Mulilo and Ondangwa.

Precipitation intensity

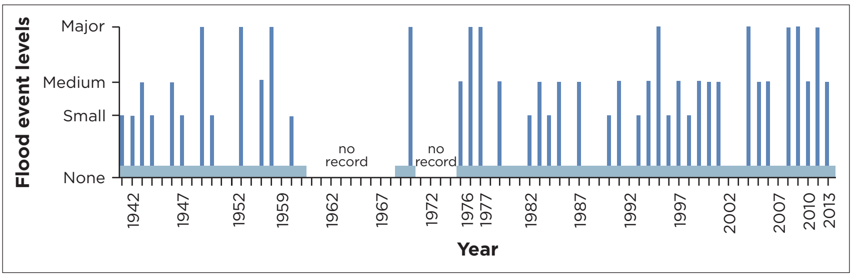
The intensity of precipitation is presented in Figure 4.5, using the monthly RX1day, monthly RX5day, SDII, R95 and R99. The SDII is also described as the total annual precipitation divided by the number of wet days in the year.

Extreme precipitation events play an important role in monitoring and predicting the occurrence of flood disaster events (Wuensch & Curtis 2010). The results from Ondangwa were compared to the actual flood events experienced in the CUEB (Figure 4.6).



Source: Authors' own model results produced using secondary data provided by the MAWF (2018) and the NMS (2018).
RX1day, maximum 1-day precipitation amount; RX5day, maximum 5-day precipitation amount; sdii, simple daily intensity index; r95p, very wet days; r99p, extremely wet days.

FIGURE 4.5: Maximum precipitation indices for Ondangwa and Katima Mulilo.



Source: Persendt et al. (2015).

FIGURE 4.6: Flood (levels) events for Cuvelai-Etosha basin from 1941 to 2013, Northern Namibia.

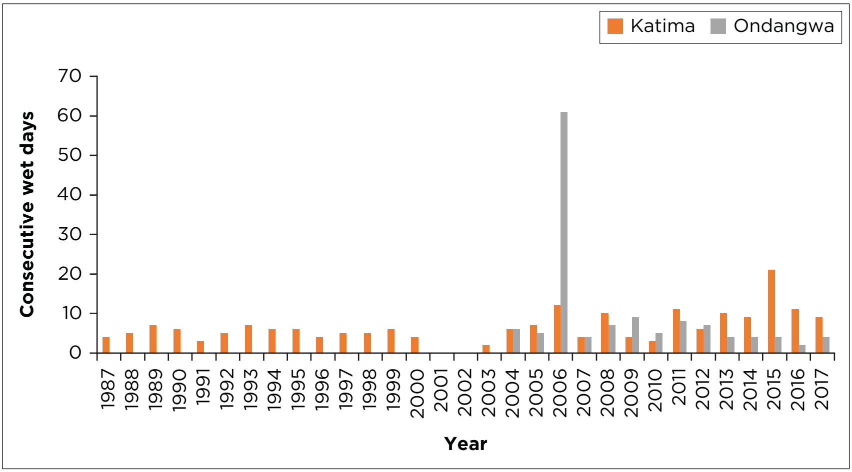
'Evaluation of short and long duration precipitation events is also critical to our understanding of flooding and its impact on natural and built environments' (Persendt et al. 2015; Teegavarapu 2012:269).

Precipitation duration

The duration of precipitation is presented in Figure 4.7 and Figure 4.8 in terms of the number of CWD and CDD in the two towns.

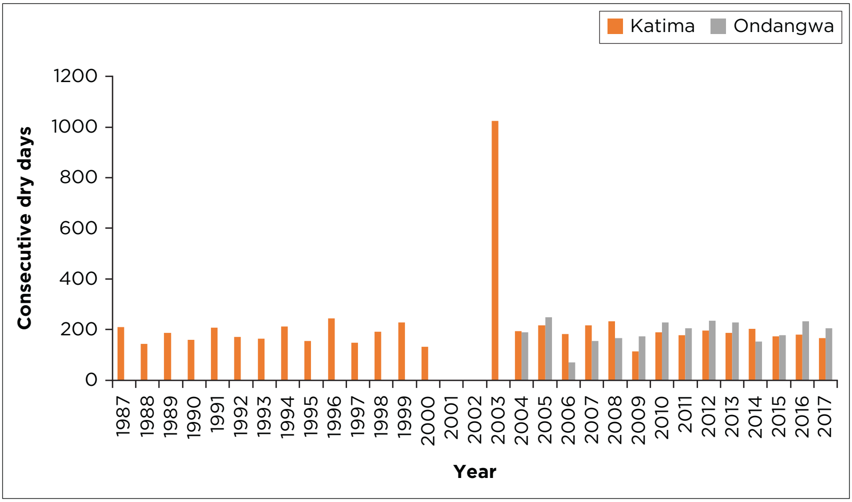
Precipitation frequency

The frequency of precipitation is shown in Figure 4.9 based on the annual count of days of heavy precipitation (R10, i.e. PRCP $\geq$ 10 mm) and the annual count of days of very heavy precipitation (R20, i.e. PRCP $\geq$ 20 mm).



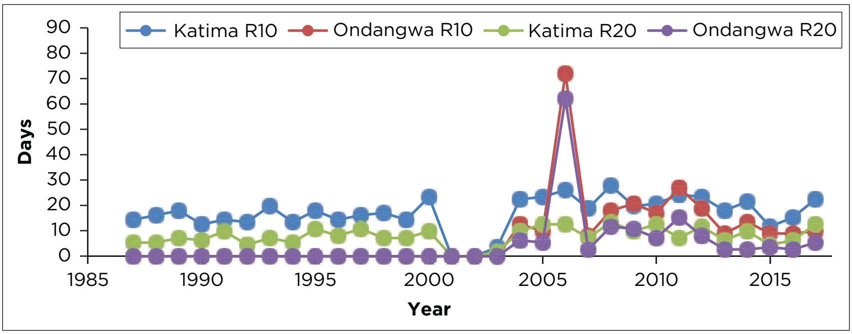
Source: Authors' own model results produced using secondary data provided by the MAWF (2018) and the NMS (2018).

FIGURE 4.7: Consecutive wet days.



Source: Authors' own model results produced using secondary data provided by the MAWF (2018) and the NMS (2018).

FIGURE 4.8: Consecutive dry days.



Source: Authors' own model results produced using secondary data provided by the MAWF (2018) and the NMS (2018).

R10, number of heavy precipitation days; R20, number of very heavy precipitation days.

FIGURE 4.9: Count of heavy precipitation and very heavy precipitation days.

Conclusion

All indices of precipitation extremes showed a decreasing trend in the seasonal total rainfall and CWD, whereas there was an increasing trend in CDD. Moreover, we observed a decreasing trend in one-day maximum rainfall, five-day maximum rainfall, the intensity of the daily rainfall over 25 mm during the winter and 50 mm during summer, which together may indicate a future decrease in the magnitude and intensity of precipitation events. If this trend continues, and water security decisions continue to lack scientific backing, Namibian towns may suffer more water stress, which could affect the lives and livelihoods of communities.

According to Eckstein (2009):

> Reduced precipitation and water flows could enhance droughts and scarcity, thereby diminishing agricultural productivity, endangering public health, impacting migration and settlement patterns, and placing considerable strain on livelihood and social well-being. (p. 426)

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Rainfall and temperature (maximum and minimum) data used for verification of the AFDM tool were provided by the MAWF and the NMS.

Chapter 5

Mixed strategy game models for generating baseline data on the water–air interactions

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Abstract

There have been concerns for the problems associated with scarcity of water in Namibia in recent years. These problems require an in-depth investigation of the various factors affecting the Namibian atmosphere and the contribution of evaporation and moisture to cloud formation.

This study developed mixed strategy game models needed for generating baseline data on the water–climate interactions. The mathematical modelling techniques employed in the project were designed to obtain the optimal meteorological factor values defined by relative humidity, temperature, wind speed and leaf wetness data obtained from 14 Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) stations, for the years 2012 to 2015.

Observation of year-orientation and station-orientation patterns from the data simulations for some of the meteorological factors suggests the need for large data from more stations for further investigation towards identifying generalised patterns for the whole country. The solutions obtained from the mixed-strategy game modelling, implemented via linear optimisation techniques, identified the weather stations and the various months of the year contributing to the optimal values of the meteorological factors, for the combined 2012–2015 data.

Data values for shorter periods (e.g. weekly data instead of monthly data) are needed for each year to obtain useful optimal values to resolve the extremely small and sparsely distributed solutions arising from the application of the game model optimisation algorithm to short-term data for each year.

Keywords: Meteorological factors; Evapotranspiration; Water holding-capacity; Mixed strategy game; Linear optimisation.

Introduction

The arid zones of the world are all characterised by a large deficit of rainfall in relation to the PET and their distribution around the world is governed by the interaction of global atmospheric circulation patterns, the distribution of land and sea, and local topography. (De Pauw et al. 2000:45)

Precipitation in arid areas varies in time because of changing constituents, the most notable of which is water vapour (Trenberth & Smith 2005). According to Tarr (1998), the estimation of future climate changes, resulting from the enhanced greenhouse effect, must take into account the fact that large-scale, naturally-induced changes to the global climate have occurred in the past, and will occur again in future.

Several Southern African countries, including Namibia, have a fair share of aridity, which exasperates extreme climatic conditions and water scarcity. According to Crawford and Terton (2016):

> Namibia experiences precipitations from only the edges of the Southern African rainfall bearing systems. As a result, the country's climate is characterised by aridity and variability with 92% of the land area defined as hyper-arid, arid or semi-arid. (p. 3)

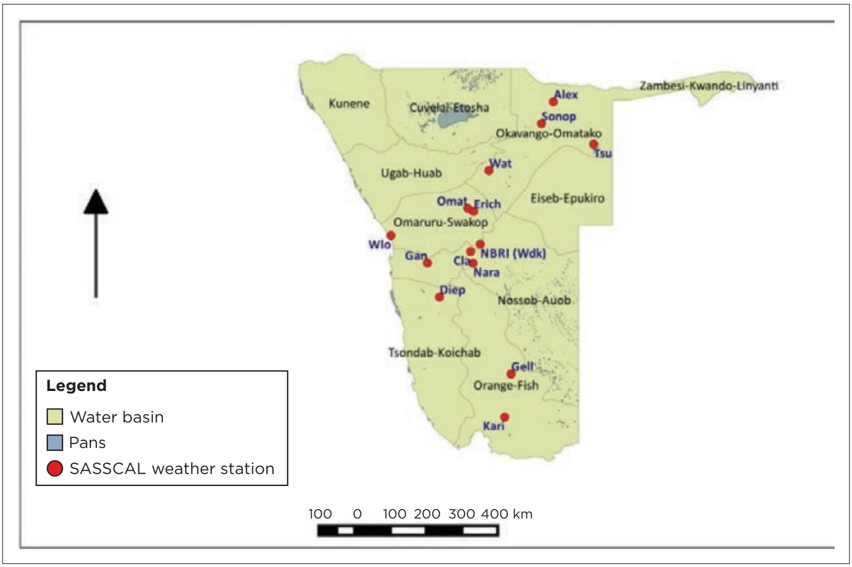
Namibia is characterised by a complex earth-atmospheric interaction system of high temperature, low relative humidity, high evaporation and ET inland; low precipitation, low temperatures and moist air at the Atlantic coast (Namib Desert); high temperatures and frequent floods in the north-east; and high temperatures and alternating floods and droughts in the central-north (Kgabi, Uugwanga & Ithindi 2016).

Climate models disagree on the magnitude and direction of future changes in rainfall for many parts of Namibia; whilst some GCMs project a wetting trend for a given part of the country, others suggest a drying trend (MET 2011). Thus, the study aimed to develop mixed strategy game models needed for generating baseline data on the water–air interactions in the Namibian atmosphere.

Methods/study approach

Modelling of the atmospheric conditions was based on meteorological data for a five-year period (2012–2015), obtained from publicly accessible data, generated by SASSCAL. The relevant meteorological factors considered in this study are wind speed, relative humidity, temperature and leaf wetness.

The SASSCAL weather/research stations (Figure 5.1) used for this study are Alex Muranda Livestock Development Centre (Alex), Dieprivier-Namib Desert Lodge (Diep), Omatako Ranch (Omat), Sonop Research Station (Sonop), Windhoek-NBRI (Wdk), Claratal (Cla), Erichsfelde (Erich), Ganab (Gan), GellapOst



Source: Reju and Kgabi (2018).

FIGURE 5.1: Southern African Science Service Centre for Climate Change and Adaptive Land Management weather station and Water basin.

(Gell), Karios-Gondwana Canyon Lodge (Kari), Narais-Duruchaus (Nara), Tsumkwe Breeding Station (Tsu), Waterberg (Wat) and Wlotzkasbaken (Wlo). The stations, as listed, sequentially coincide with the numbers 1–14 shown in the simulation group of figures from Figure 5.2a to Figure 5.6d.

The weather stations were selected based on the fact that they have been operating for a relatively long time with available data. Moreover, they are distributed along the climatic vegetation of the country.

In our modelling, we considered the months of the year and weather stations as the competitive parameters in a two-player mixed strategy game. Hence in general, we define the following, akin to Reju, Gope and Kanyimba (2012):

- Player 1 strategies = Months of the year.
- Player 2 strategies = Weather stations.
- Payoff = Humidity, temperature and wind speed data values.

Thus our general meteorological factors payoff data is given in Table 5.1.

TABLE 5.1: Meteorological factors payoff table for all the stations.

Weather station	Months	Strategy
Alex	January	f_{11}
	February	f_{21}
	December	f_{m1}
Diep	January	f_{12}
	February	f_{22}
	December	f_{m2}
Wlo	January	f_{n1}
	February	f_{n2}
	December	f_{mn}

Alex, Alex Muranda Livestock Development Centre; Diep, Dieprivier-Namib Desert Lodge; Wlo, Wlotzkasbaken.

In Table 5.1, f_{ij} are the meteorological factor values for month i at station j.

Now for our model, we define the following:

s_j, $j = 1, \ldots 14$ – the weather stations strategies

m_i, $i = 1, \ldots, 48$ – the months of the year strategies [Eqn 5.1]

f_{ij}, – the meteorological factor values

The expected value of the game is given by

$$\text{MFS} = \sum_{j=1}^{14} \sum_{j=1}^{48} f_{ij} m_i s_j \qquad \text{[Eqn 5.2]}$$

where M is the months of the year strategy vector, F, the factor's payoff matrix and S the station strategy vector.

Below are the simulation plots for the meteorological factor values (from the 48-by-14 payoff matrices or tables).

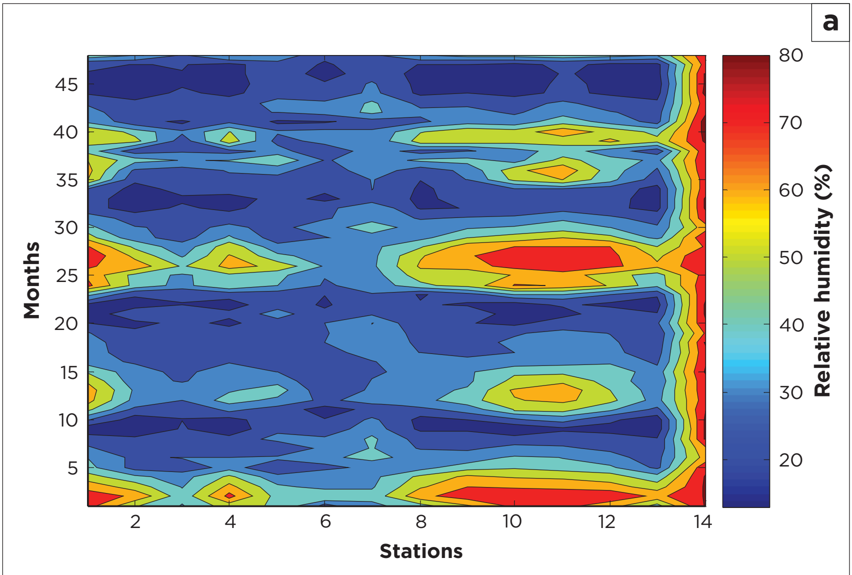
Results and discussion

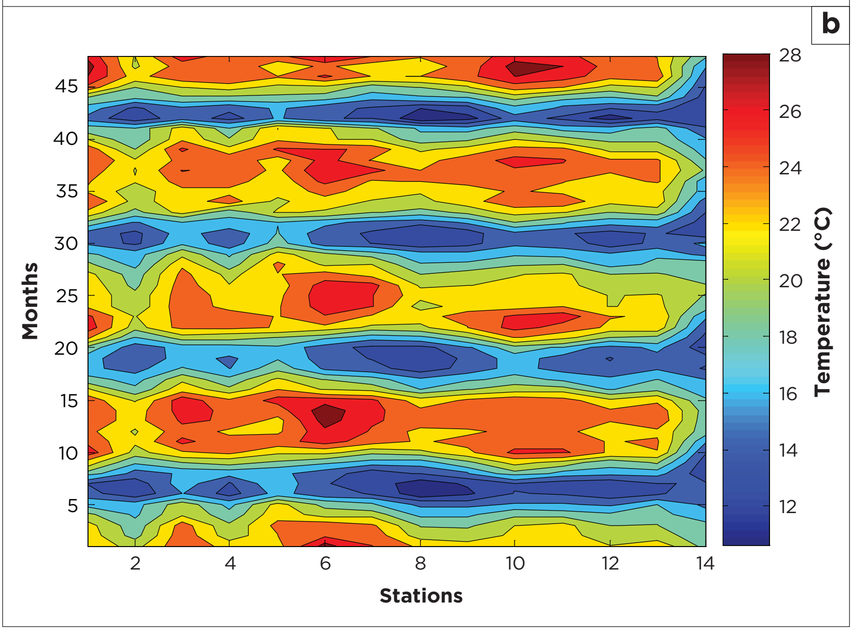
Long-term meteorological factor simulations

The combined long-term humidity, temperature, wind speed and leaf wetness data for the 2012–2015 period are presented in the form of contour plots in Figure 5.2.

Taking a look at the earlier combined simulations, the authors noted that:

1. Higher humidity is observed in the first quarter of 2012 and 2014, around stations Alex, GellapOst, Karios, Narais, Tsumkwe and especially at Wlotzkasbaken.
2. Higher temperature is observed at the end of the year 2012, first quarter of 2013, first quarter of 2014 and the end of 2015, around the stations Omatako ranch, Claratal, Karios, Narais and Tsumkwe.

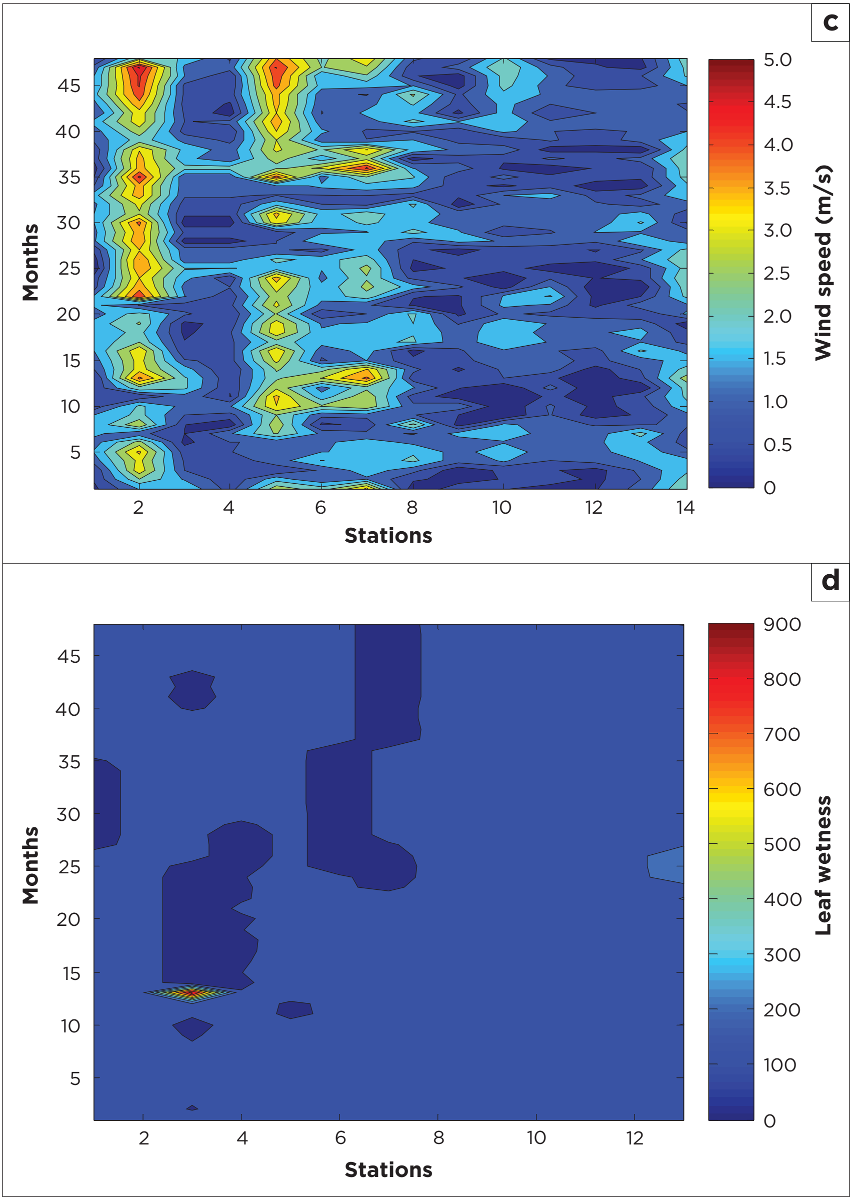




Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

FIGURE 5.2: Long-term meteorological factor simulations for 2012–2015: (a) relative humidity, (b) temperature, (c) wind speed and (d) leaf wetness.

Figure 5.2 continues on the next page→



Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

FIGURE 5.2 (Continues...): Long-term meteorological factor simulations for 2012–2015: (a) relative humidity, (b) temperature, (c) wind speed and (d) leaf wetness.

3. Higher wind speeds seemed to be consistently experienced around stations Dieprivier and Windhoek-NBRI.
4. Very low leaf wetness is observed for the years 2012 to 2015, around all the stations.

Short-term meteorological factor simulations

Results for the short-term (monthly) meteorological factor simulations are presented in Figure 5.3.

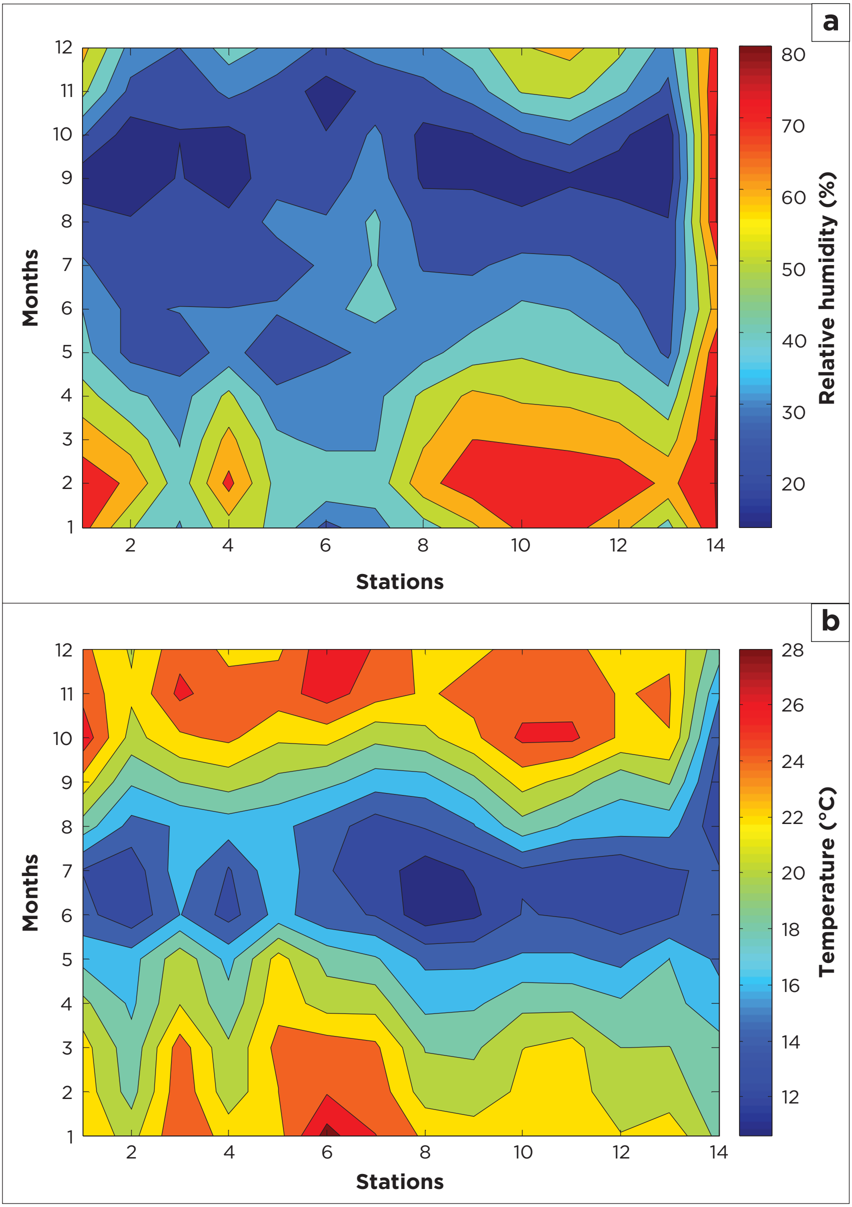
The 2012 plots show that:

1. Higher humidity is observed in the first quarter of the year, around stations Alex, GellapOst, Karios, Narais, Tsumkwe and especially at Wlotzkasbaken.
2. Higher temperature is observed in the first quarter and the last quarter of the year, around stations Omatako ranch, Claratal, Karios, Narais and Tsumkwe.
3. In 2012, higher wind speed is observed in the second quarter and last quarter of the year, around stations Dieprivier and Windhoek-NBRI.
4. Higher leaf wetness is observed in the first quarter of the year and early in October and November, around stations Karios and Wlotzkasbaken.

Figure 5.4a to Figure 5.4d is a presentation of the 2013 contour plots.

The following observations are noteworthy:

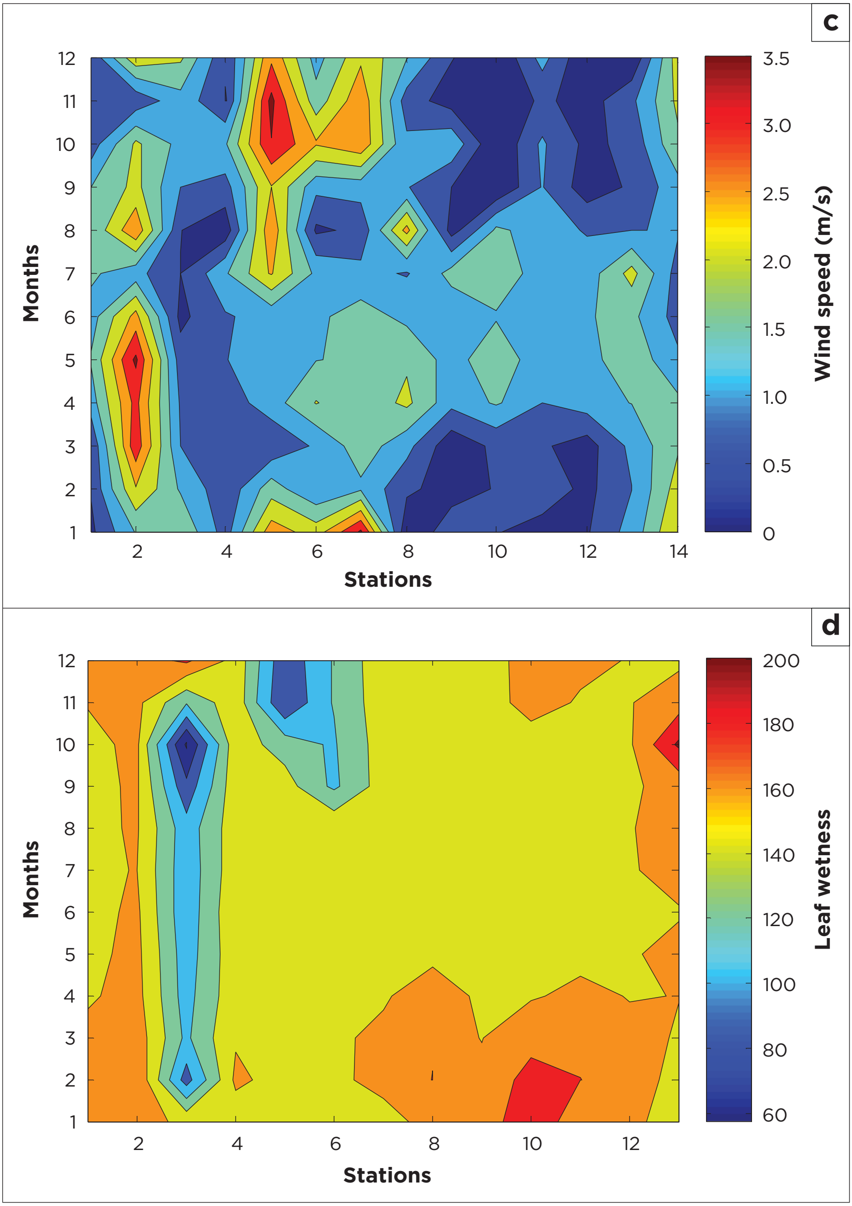
1. Moderate humidity is observed in the first quarter of the year, around stations Alex, Karios, Narais and highly at Wlotzkasbaken.
2. Higher temperature is observed in the first quarter and the last quarter of the year, around stations Alex, Omatako ranch, Claratal, Karios, Narais and Tsumkwe.
3. From the 2013 data, higher wind speed is observed in the first two months and last quarter of the year, around stations Dieprivier, Windhoek-NBRI and Erichsfelde.



Source: Authors' own model results produced using secondary data obtained from the public domain (SASSCAL 2016).

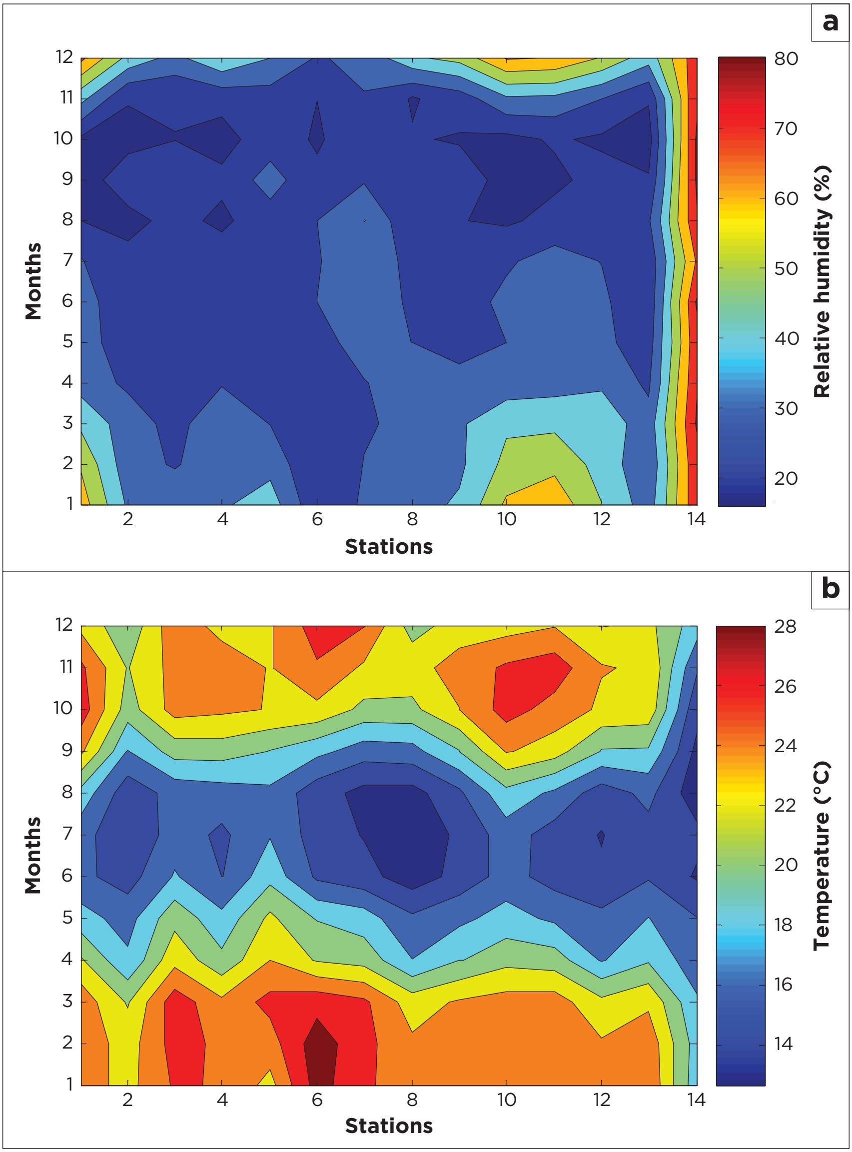
FIGURE 5.3: Monthly meteorological factor simulations for 2012: (a) relative humidity, (b) temperature, (c) wind speed and (d) leaf wetness.

Figure 5.3 continues on the next page→



Source: Authors' own model results produced using secondary data obtained from the public domain (SASSCAL 2016).

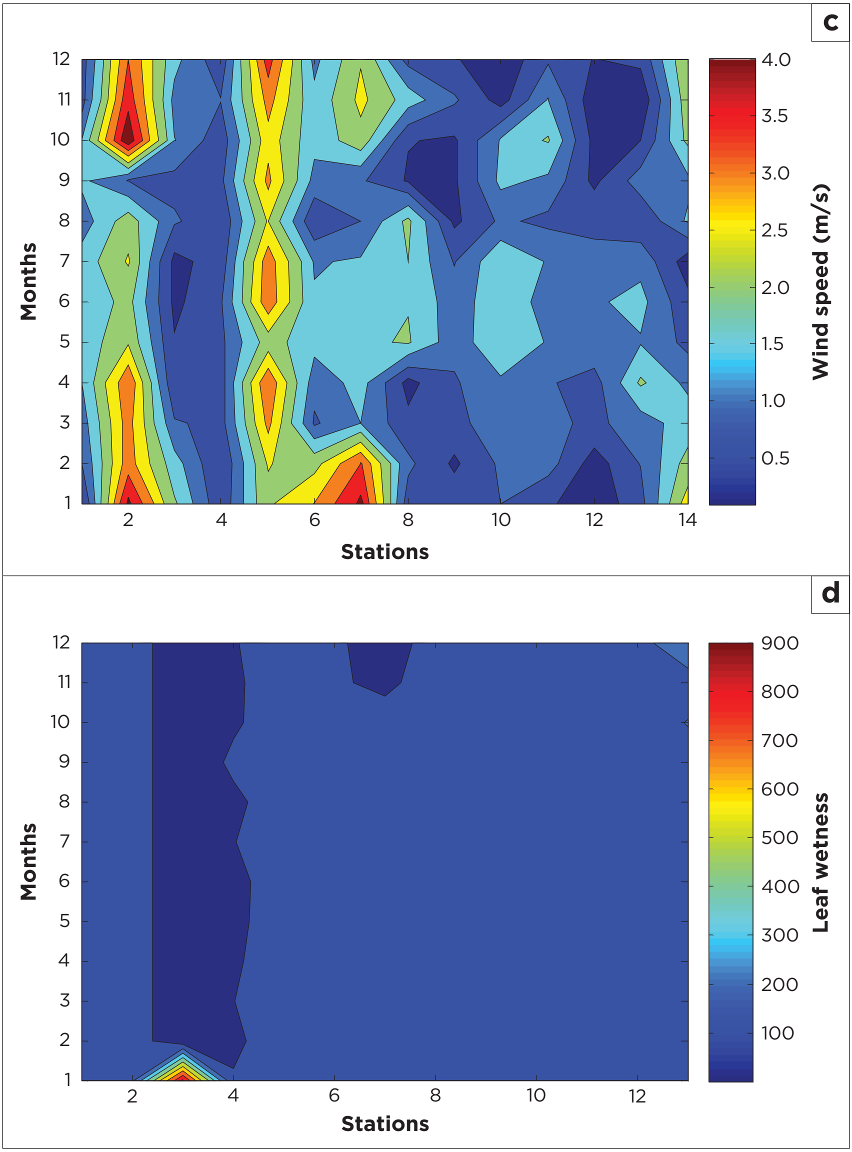
FIGURE 5.3 (Continues...): Monthly meteorological factor simulations for 2012: (a) relative humidity, (b) temperature, (c) wind speed and (d) leaf wetness.



Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

FIGURE 5.4: Monthly meteorological factor simulations for 2013: (a) relative humidity, (b) temperature, (c) wind speed and (d) leaf wetness.

Figure 5.4 continues on the next page→



Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

FIGURE 5.4 (Continues...): Monthly meteorological factor simulations for 2013: (a) relative humidity, (b) temperature, (c) wind speed and (d) leaf wetness.

4. Higher leaf wetness is observed in the first month of 2013, around Omatako Ranch.

The 2014 data are shown in Figure 5.5.

The main observations from the 2014 plots are as follows:

1. Higher humidity is observed in the first quarter of the year, around stations Alex, Karios, Narais, Tsumkwe and especially at Wlotzkasbaken.
2. Higher temperature is observed in the first quarter and the last quarter of the year, around stations Omatako ranch, Karios, Narais, Tsumkwe, but highly in Claratal and Erichsfelde.
3. Higher wind speed is observed in almost in all months, around Dieprivier whilst in July and November for Windhoek-NBRI.
4. Higher leaf wetness is observed in the first quarter of the year, around Wlotzkasbaken.

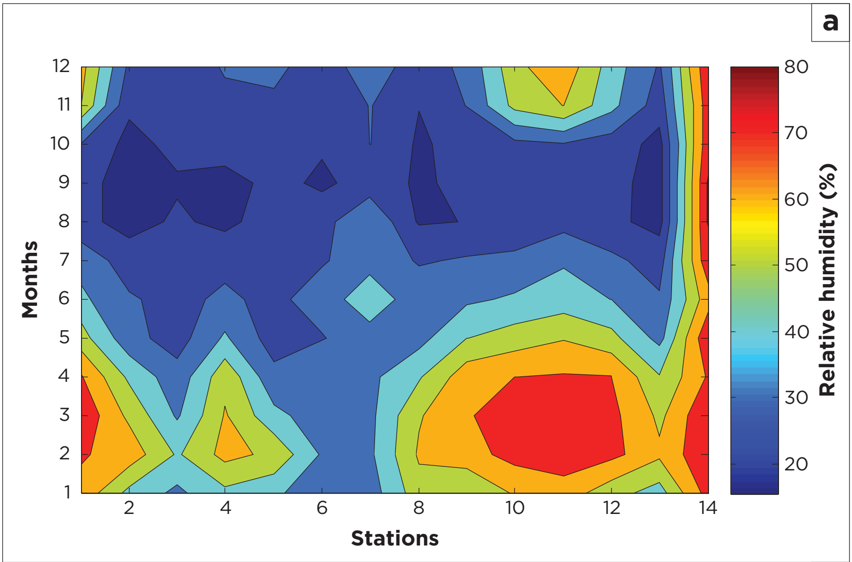
The contour plots for 2015 are presented in Figure 5.6.

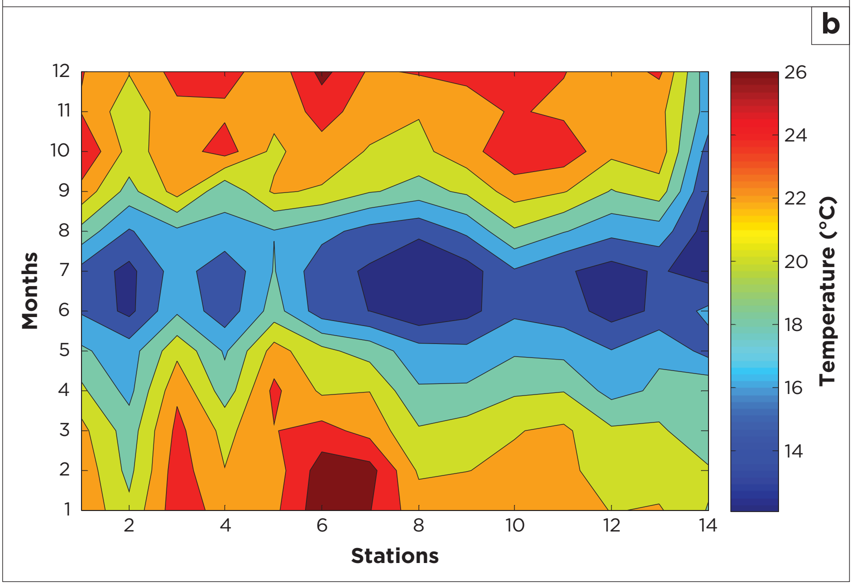
From the 2015 plots, we noted the following:

1. Moderate humidity is observed in March and April, around stations Alex, Karios, Narais, and highly at Wlotzkasbaken.
2. Higher temperature is observed in the first quarter and the last quarter of the year, around stations Alex, Omatako ranch, Claratal, Narais, Tsumkwe and especially in Karios.
3. Higher wind speed is observed in the last half of the year 2015, around stations Dieprivier and Windhoek-NBRI.
4. For 2015, higher leaf wetness is observed in the first third of the year and the last third, around stations Alex, Dieprivier, Windhoek-NBRI, GellapOst, Tsumkwe, Waterberg and Wlotzkasbaken.

Game model optimal solutions

Implementing a game model technique as described by Equation 5.1 and Equation 5.2, we have the following optimal solutions from our mixed strategy models for the combined 2012–2015 data.

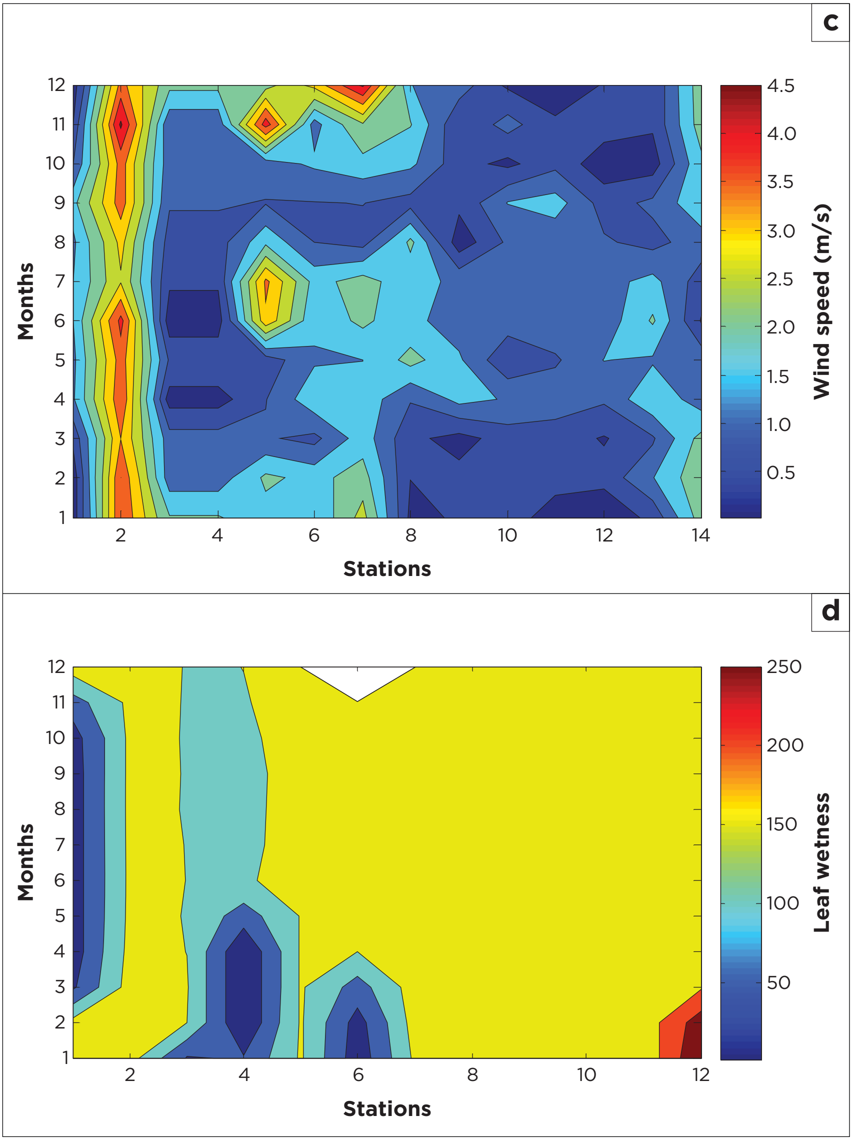




Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

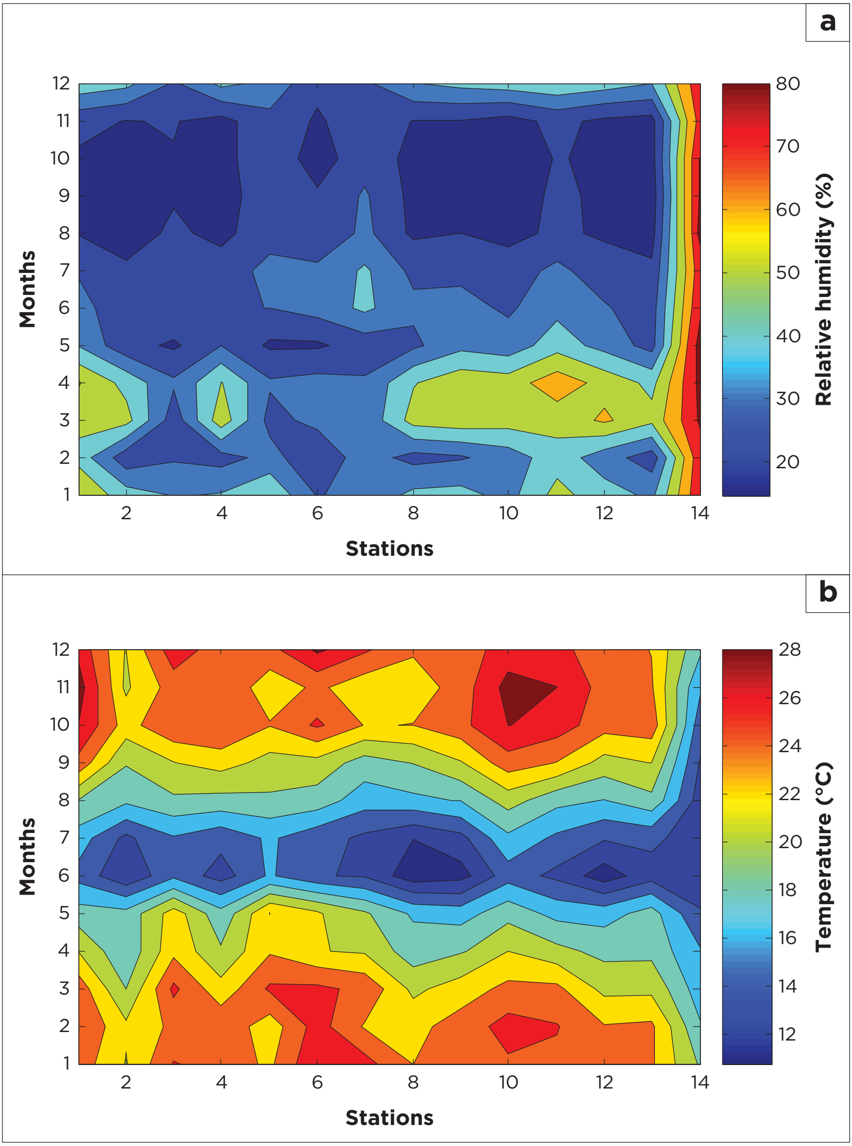
FIGURE 5.5: Monthly meteorological factor simulations for 2014: (a) relative humidity, (b) temperature, (c) wind speed and (d) leaf wetness.

Figure 5.5 continues on the next page→



Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

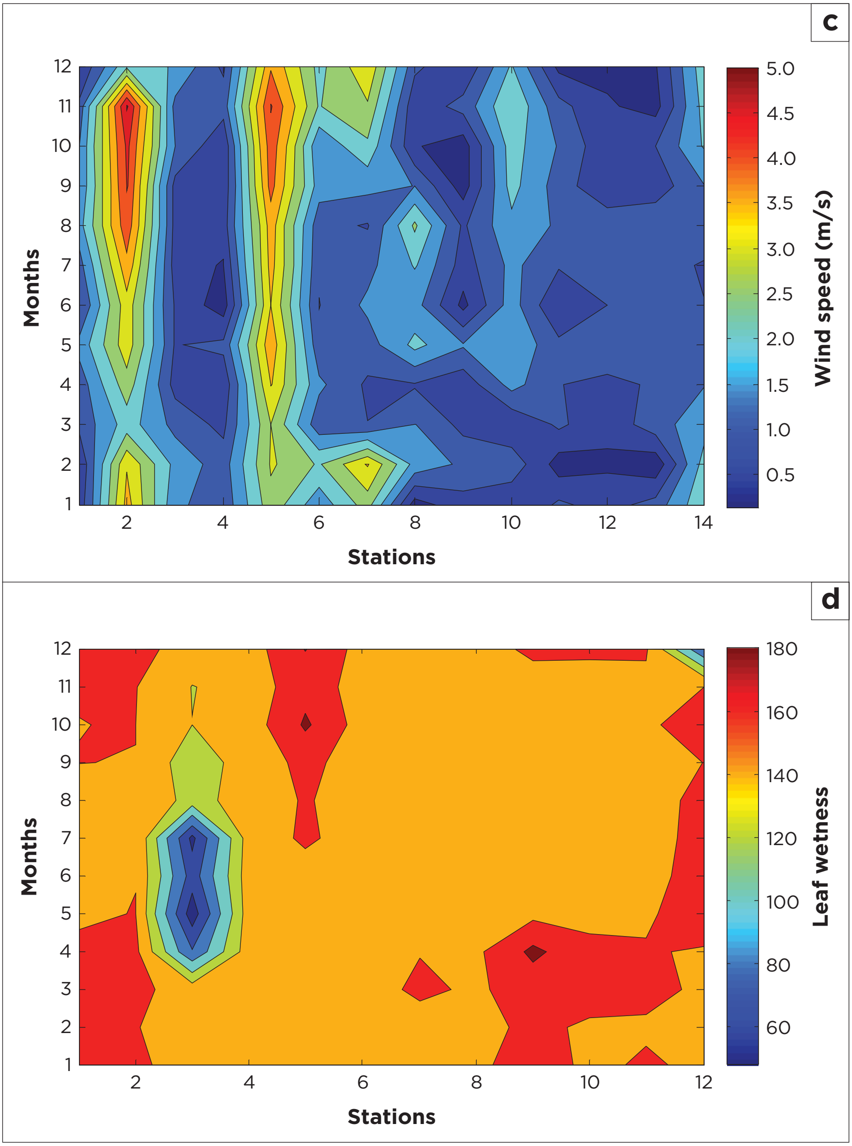
FIGURE 5.5 (Continues...): Monthly meteorological factor simulations for 2014: (a) relative humidity, (b) temperature, (c) wind speed and (d) leaf wetness.



Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

FIGURE 5.6: Monthly meteorological factor simulations for 2015: (a) relative humidity, (b) temperature, (c) wind speed and (d) leaf wetness.

Figure 5.6 continues on the next page→



Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

FIGURE 5.6 (Continues...): Monthly meteorological factor simulations for 2015: (a) relative humidity, (b) temperature, (c) wind speed and (d) leaf wetness.

To solve a larger game, as in our models, a linear optimisation approach is usually employed. The associated linear programming problem for our models for each of the meteorological factor is given as follows to provide the mathematical theory underlying the modelling techniques:

$$\text{Maximise } S_f = \sum_{j=1}^{14} s_j \qquad \text{[Eqn 5.3]}$$

subject to

$$\sum_{j=1}^{14}\sum_{i=1}^{48} f_{ij} \; s_j \leq 1 \qquad \text{[Eqn 5.4]}$$

$$s_j \geq 0 \qquad \text{[Eqn 5.5]}$$

where s_j , $j = 1,2,...,14$ are the weather station strategies and f_{ij} is the meteorological factor values (corresponding to the payoff matrix of the game model).

For the relative humidity model, we have the following optimal solutions:

- $s_2 = 0.0809$; $s_{10} = 0.9191$, where $s_1 = s_3 = s_{13} = s_{14} = 0$.
- $m_2 = 0.9625$; $m_{25} = 0.0375$, where $m_1 = m_2 = m_{13} = m_{14} = m_{47} = m_{48} = 0$.

$$\text{MFS} = \sum_{j=1}^{14}\sum_{j=1}^{48} f_{ij} m_i s_j = 43.4243 \qquad \text{[Eqn 5.6]}$$

The solutions are summarised in Table 5.2.

TABLE 5.2: Relative humidity concentration matrix.

Months	**Weather stations**	**Diep**	**Kari**
	Probabilities	**0.0809**	**0.9191**
February (2012)	0.9625	44.0	43.4
June (2014)	0.0375	27.374	44.837
Game value		43.4243	

Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

Diep, Dieprivier-Namib Desert Lodge; Kari, Karios-Gondwana Canyon Lodge.

For the average temperature model, we have the following optimal solutions:

- s_6 = 0.1764; s_{14} = 0.8206, where $s_1 = s_3 = s_{12} = s_{13} = 0$.
- m_{13} = 0.6994; m_{36} = 0.3006, where $m_1 = m_2 = m_{13} = m_{14} = m_{47} = m_{48} = 0$.

$$\text{MFS} = \sum_{j=1}^{14} \sum_{j=1}^{48} f_{ij} m_i s_j = 20.1497 \quad \text{[Eqn 5.7]}$$

The results are summarised in Table 5.3.

For the wind speed model, we have the following optimal solutions:

- s_3 = 0,2608; s_7 = 0.1875; s_{10} = 0.2727; s_{11} = 0.2420; s_{13} = 0.03071, where $s_1 = s_2 = s_6 = s_7 = s_{10} = s_{14} = 0$.
- m_{17} = 0.0812; m_{32} = 0.1186; m_{35} = 0.0929; m_{36}= 0.0682; m_{40}= 0.6392, where $m_1 = m_2 = m_{13} = m_{14} = m_{47} = m_{48} = 0$.

$$\text{MFS} = \sum_{j=1}^{14} \sum_{j=1}^{48} f_{ij} m_i s_j = 1.1788 \quad \text{[Eqn 5.8]}$$

The summarised results are shown in Table 5.4.

TABLE 5.3: Average temperature concentration matrix.

Months	**Weather stations**	**Cla**	**Wlo**
	Probabilities	**0.1794**	**0.8206**
February (2014)	0.6994	19.4	20.3
January (2015)	0.3006	21.9	19.8
Game value		20.1497	

Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

Cla, Claratal; Wlo, Wlotzkasbaken.

For the leaf wetness, we have the following optimal solutions:

- s_3 = 0,0459; s_4 = 0.2820; s_6 = 0.6621; s_{14} = 0.0100, where $s_1 = s_2 = s_8 = s_9 = s_{11} = s_{13} = 0$.

TABLE 5.4: Wind speed concentration matrix.

Months	Weather stations	Diep	Wdk	Erich	Tsu	Wat
	Probabilities	**0.2608**	**0.1875**	**0.2727**	**0.2420**	**0.0371**
September (2013)	0.0812	0.83	1.23	0.88	1.4	0.39
August (2014)	0.1186	0.75	0.84	0.75	1.16	1.06
November (2014)	0.0929	1.11	0.58	1.11	0.57	0.77
December (2014)	0.0682	2.1	0.6	2.1	0.3	0.5
April (2015)	0.6392	0.81	1.09	0.6	1.02	0.81
Game value			1.1788			

Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

Diep, Dieprivier-Namib Desert Lodge; Wdk, Windhoek-NBRI; Erich, Erichsfelde; Tsu, Tsumkwe Breeding Station; Wat, Waterberg.

- m_1 = 0.6616; m_2 = 0.1130; m_3 = 0.2048; m_{13}= 0.0206, where $m_4 = m_5 = m_{10} = m_{11} = m_{47} = m_{48} = 0$.

$$\text{MFS} = \sum_{j=1}^{14} \sum_{j=1}^{48} f_{ij} m_i s_j = 155.0932 \qquad \text{[Eqn 5.9]}$$

The summarised results are shown in Table 5.5.

It should be noted that the game value for each of the above models is a computed value and lies between the minimum and the maximum values, defined by the observed meteorological factor values for the stations that constitute the optimal strategic weather stations, as presented in Table 5.2 to Table 5.5.

Combined optimal solutions

Table 5.6 is a summary of the optimal values for the meteorological factors determined for the combined 2012–2015 period.

The results of our game modelling technique when applied to the short-term data for each year were not practically useful, as the optimisation algorithm returns extremely small and sparsely distributed solutions. Thus data values for shorter periods (e.g. weekly data instead of monthly data) are needed for each year to obtain useful optimal values.

TABLE 5.5: Leaf wetness concentration matrix.

Months	Weather stations	Omat	Sonop	Cla	Wlo
	Probabilities	**0.0459**	**0.2820**	**0.6621**	**0.0100**
January (2012)	0.6616	165.1	165.9	169.7	152.9
February (2012)	0.1130	180.3	165.0	178.8	153.9
March (2012)	0.2048	178.7	159.3	172.0	159.1
January (2013)	0.0206	153.6	156.0	170.8	190.6
Game value			155.0932		

Source: Authors' own model results produced using secondary data obtained from the public domain (SASSCAL 2016).

Omat, Omatako Ranch; Sonop, Sonop Research Station; Cla, Claratal; Wlo, Wlotzkasbaken.

TABLE 5.6: Summary of strategic game model results.

Meteorological factors	Model optimal values	Contributing stations	Contributing months	Dominant month (with the highest probability)	Dominant station (with the highest probability)
Humidity	43.4243	Dieprivier and Karios	February (2012) and June (2014)	February 2012	Karios (0.92)
Temperature	20.1497	Claratal and Wlotzkasbaken	February (2014) and January (2015)	February 2014	Wlotzkasbaken (0.82)
Wind speed	1.1788	Dieprivier, Windhoek-NBRI, Erichsfelde, Tsumkwe and Waterberg	September (2013), August (2014), November (2014), December (2014) and April(2015)	April 2015	Erichsfelde (0.27)
Leaf wetness	155.0932	Omatako ranch, Sonop Research Station, Claratal and Wlotzkasbaken	January (2012), February (2012), March (2012) and January (2013)	January 2012	Claratal (0.66)

Source: Authors' own model results produced using secondary data obtained from public domain (SASSCAL 2016).

Conclusion

From the foregoing model results, the following conclusions are drawn:

1. A look at the simulations in Figure 5.2a to Figure 5.2c reveals patterns that are dominantly '*year-oriented*' for both humidity and temperature data but '*station-oriented*' for wind speed data. The leaf wetness profiles also follow more of a *station-oriented* pattern as observed in Figures 5.3d, 5.5d and 5.6d.
2. Simulations of humidity data show that higher humidity was observed in the first quarter and in the last two months of each year around several stations such as Alex, GellapOst, Karios, Narais and Tsumkwe, with consistently higher humidity at Wlotzkasbaken. However, the game model results exclude Wlotzkasbaken from the two stations that contributed to the optimal humidity for the combined 2012–2015 data.
3. Simulations of temperature data show that higher temperatures were observed in the first quarter and last quarter of each year, around stations Omatako ranch, Claratal, Karios, Narais and Tsumkwe. The optimal game results identified one of these stations, namely Claratal, as one of the two stations that contributed to the optimal temperature for the four-year period.
4. Simulations of wind speed data show that higher wind speeds were observed in the last quarter of each year, around stations Dieprivier and Windhoek-NBRI. Interestingly, these two stations were also identified as amongst the strategic optimally wind-prone stations from the game model results.
5. Simulation of leaf- wetness data show that higher leaf wetness was observed in 2015, in the first third of the year and the last third, around stations Alex, Dieprivier, Windhoek-NBRI, GellapOst, Tsumkwe, Waterberg and Wlotzkasbaken. There were missing data for leaf wetness at some of the selected stations: Erichsfelde and Karios did not have leaf wetness data for 2014, with Narais also not having data for 2015. Hence these stations were not included in the game model for leaf wetness.

6. As shown in the results from both the game models and data simulations, the optimal values for humidity, temperature, wind speed and leaf wetness occurred mostly in the first quarter and the last quarter of the identified strategic years, representing the rainy seasons.

Identification of the strategic stations and the periods of the year with optimal meteorological values from the game modelling technique provides useful information for monitoring the country's atmospheric conditions.

From the results of our models, the following recommendations are suggested:

1. The game models provide practically useful results only for the combined 2012–2015 period, whilst they result in sparsely distributed solutions when done for each year. It is therefore suggested that further research investigation requires smaller time-interval data (such as weekly data) to investigate annual optimal meteorological values.
2. Since more weather stations have been created, more data from wider distributions across the country are needed to obtain comprehensive information on the atmospheric water–air interaction for the country.
3. Observation of *year-orientation* and *station-orientation* patterns for some of the meteorological data also requires large data from more stations for further investigation towards identifying generalised patterns for the whole country. For example, identifying weather station-oriented patterns for the country will provide useful information for strategic monitoring and planning.

Acknowledgements

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Chapter 6

Analysis of drought frequency and intensity using standard precipitation index

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Abstract

A study on assessment of drought occurrence, frequency and intensity, as well as the effectiveness of the AFDM in monitoring and forecasting drought occurrence and intensity in Namibia was conducted to address the existing data gaps and small number of scientific studies in the country. The SPI method was used for drought investigation at Ondangwa for 68 years (1950–2018) and Katima Mulilo for 30 years (1987–2018). Outputs from the SPI Generator for Namibia meteorological ground-based data (NMS SPIs) were compared to the modelled SPIs from AFDM (online extracted output). For Ondangwa, several no-drought periods were detected from NMS SPIs, whilst periods of drought were detected from modelled SPIs. For Katima Mulilo normal to intense levels of drought were identified by modelled SPIs, contrary to NMS SPIs which implied 'above normal' to flood conditions from 1988 to 2016 and 37 consecutive months of drought in 2001–2004 (SPI12). Contradicting results were observed in 2009 when the modelled SPIs (SPI6) indicated an intense drought (–2), yet NMS SPIs (1, 2, 3, 12) suggested wet conditions (1.2), coinciding with the floods of 2009 in Katima Mulilo. Reliability assessment of the modelled SPIs was performed at 95% (Tcrt = 1.96) confidence interval for SPI (1, 3, 6 and 12) for the two towns and this shows decreased significance differences (ts<tcr) for all timescales suggesting reliable results.

Keywords: Standard precipitation index; Africa Flood and Drought Monitor; Drought classification; Aridity; Drought forecasting.

Introduction

Droughts are climatological hazards exacerbated by climate change. The underlying causes of droughts are long timescale (months or longer) variability of both precipitation and evaporation (Seneviratne et al. 2013; Zwiers et al. 2013). In Namibia, where aridity is normal, precipitation variability over basins between and within seasons is high (Gaughan & Waylen 2012). Namibian climate variability is the result of a combination of its geographical location (Tropic of Capricorn latitude 23.5°), two pressure systems and the Inter-Tropical Convergence Zone (ITCZ). The cold upwelling Benguela Current and the South Atlantic high-pressure systems, both control the moisture availability on the west coast and interior part of the country, the ITCZ seasonal movement brings about wet and dry cycles with rainfall seasons from November to April) (Eckardt et al. 2013; Jokisch, Schulz & Papangelou 2018; Mendelsohn, Jarvis & Robertson 2013).

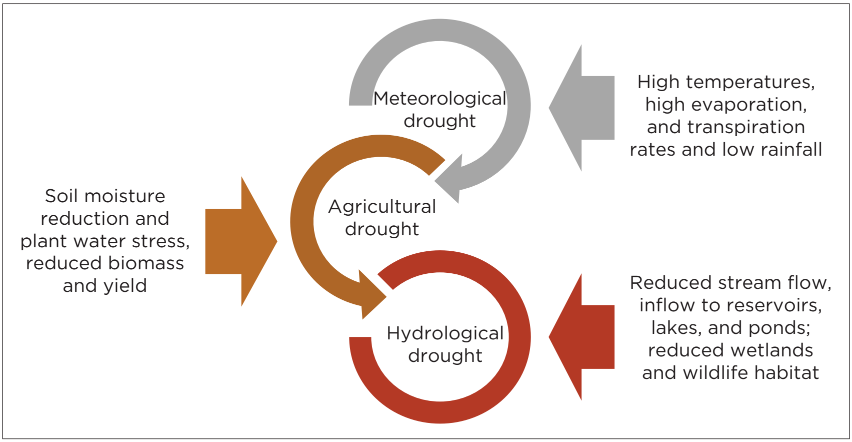
The arid nature of Namibian climate increases vulnerability to droughts occurrence, thus aggravating the water scarcity problem linked to remarkably high evaporation rates (≥ 1650 mm annually) that exceeds rainfall availability. Rainfall gradient decreases from the Eastern North (700 mm) to the Southern West of Namibia (50 mm – 250 mm) (Kgabi, Uugwanga & Ithindi 2016).

Seneviratne et al. (2013) illustrated that the physical science behind drought is not easy to understand because of its complexity from onset, duration of stay and ending. This means that extra caution is required in monitoring and detecting abnormally low rainfall deficits in an arid environment because of the non-conformity of data to the normal distribution. Most data are dominated by below normal to no rainfall and missing data.

There are no single criterion for defining drought, different stakeholders, for example policy makers, water managers, hydrologists, agriculturists and farmers have different criteria for defining drought periods. Moreover, assessment methods and models lead to different ways of defining and classifying drought as a disaster. For example, studies by Seneviratne et al. (2013) and Kgabi et al. (2016) grouped drought into major classes based on the meteorological, agricultural and hydrological aspects.

Meteorological drought occurs because of reduced rainfall, high temperature, high evaporation and strong winds. The prolonged duration of meteorological drought impacts agricultural and plant production because of reduced soil moisture (Shrivastava et al. 2018). Hydrological drought occurs from the reduction of stream flow, water levels in lakes, ponds and wetlands triggering water budgeting, insufficient water to run hydropower plants, unavailable water for irrigation and failure to sustain life in the aquatic environment (Figure 6.1). Thus, the importance of monitoring drought occurrences, frequency and intensity in Namibia is essential for meteorological monitoring and prediction, farming communities in managing livestock and food production before and during drought crises, and for water-related sectors to quantitatively analyse and plan for disaster risk management from early warning systems. This shall result in reduced evacuation and drought disaster relief costs (Adnan et al. 2017).

For decades, various methods for assessing drought occurrences, frequency and intensity have been discovered, tested and are successfully used in several countries worldwide. These methods include SPI (McKee, Doesken & Kleist 1993), Bhalme and Mooley (1980) Drought Index (Bhalme & Mooley, 1980); Palmer Severity Drought Index (PSDI) (Palmer 1965); Palmer Drought Index (Alley 1984); Aridity Anomaly



Source: Adapted from Kgabi et al. (2016).

FIGURE 6.1: Development stages and categories of droughts.

Index; Aridity Index; and Microwave Integrated Drought index (Decile and Standardised Precipitation and Evapotranspiration Index [SPEI], Svoboda & Fuchs 2016).

The evolution of these methods has largely been contributed by improvement in technology ranging from ground observation (manual and automated instruments) to remote sensing/satellite collection of data; improved data collection methods; and technical improvement on data analysis from single rainfall-based methods to multiple, integrated and remote-sensing indicators and indices (Shrivastava et al. 2018; Svoboda & Fuchs 2016; Xia et al. 2018).

It is well known that Namibia is faced with recurring droughts with increased drought-crisis management in recent years; however, there are studies relating to drought occurrence characterised by missing data that have been conducted in the country (Angombe 2012; Botha 1998). Therefore, testing the performance and adoption of the already-tested methods for assessing drought occurrence, frequency and intensity will help bridge the gap in Namibia. This study therefore adopted the SPI method by McKee et al. (1993) to assess drought occurrences, frequency and duration in Namibia. The SPI scales for ranking are indicated in Table 6.1. Zero values are interpreted as normal, negative SPI values as rainfall deficit (drought), and positive SPI

TABLE 6.1: Drought classification.

SPI scale	
SPI values	**Drought scale**
≤-2.0	Extremely dry
(–1.99) to (–1.5)	Severely dry
(–1.49) to (–1.0)	Moderately dry
(–0.99) to (+0.99)	Normal
(+1.0) to (+1.49)	Moderately wet
(+1.5) to (+1.99)	Very wet
>=+2.0	Extremely wet

Source: McKee (1993), cited in Xia et al. (2018).
SPI, standardised precipitation index.

values as surplus rainfall (floods). The intensity of floods and droughts increases with positive and negative values, respectively.

In this context, an assessment study of drought occurrence, frequency, intensity, classification of drought and the effectiveness of the AFDM data source in Namibia is presented, using SPI method in Katima Mulilo and Ondangwa towns. The study used ground-observed rainfall data from the NMS to compute SPIs (1, 3, 6, 12) by utilising the SPI Generator tool from the University of Nebraska and compared to Modelled SPI (1, 3, 6, 12) outputs extracted from the AFDM online tool. The study excludes all other sources of water such as flood waters in Namibia, caused by heavy rains from neighbouring countries such as Congo and Angola.

Methods/study approach

Site description

The study was conducted in the two towns of Ondangwa and Katima Mulilo. Ondangwa town is located within the CUEB in the northern central part of Namibia (17.9000°S, 15.9667°E). The CUEB (Ondangwa – 1080 m) is extremely flat, elevated 1100 m – 1200 m from sea level, with ephemeral water channels, called iishanas. The source of water is from local rains and from perennial Cuvelai and Mui Rivers which originate from Angola to Etosha. Annual rainfall is between 250 mm and 600 mm, high annual temperature (>22 °C) and evaporation rates (2100 mm) which exceed precipitation. Two seasons are known, namely, the rainfall season during summer (October and November to April) and the dry winter season (May to September). This area has been experiencing both floods and droughts.

Main economic activities carried within the area include large-scale irrigation farming of mahangu (millet), tourism and wildlife management in Etosha National Park (Hamutoko, Wanke & Voigt 2016; Mendelsohn et al. 2013).

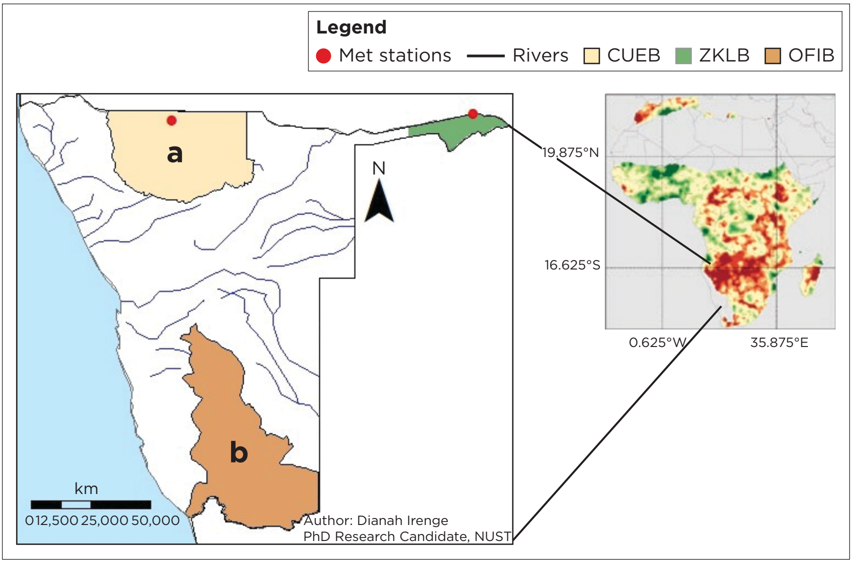
On the other hand, Katima Mulilo town is located within Zambezi-Kwando-Linyanti basin in the north-eastern part of Namibia (17.4833°S, 24.2667°E). The basin extends through the

Zambezi (formally Caprivi) region, having borders with Angola, Zambia, Zimbabwe and Botswana (Figure 6.2). The basin is characterised by the highest annual rainfall (more than 700 mm) in Namibia with the perennial (Zambezi) and ephemeral (Kwando) Rivers as water sources. The major economic activity carried in this town is farming with more than 70% of its inhabitants depending on Zambezi River water (IWRM 2010) (Figure 6.2).

Data collection and analysis

Meteorological services and hydrological units in Namibia

Ground-observed daily precipitation data for both towns were collected from the NMS and the MAWF under Hydrology section for the period of 68 years (1950–2017) for Ondangwa and 30 years (1987–2017) for Katima Mulilo. These data were used to



Source: PCA (2018a).

FIGURE 6.2: (a & b) Study area locations: Cuvelai-Etosha basin and the Zambezi-Kwando-Linyanti basin.

compute SPI-1, SPI-3, SPI-6 and SPI-12) by using the 'SPI Generator' software developed and owned by the National Drought Mitigation Centre (NDMC) at the University of Nebraska (see https://drought.unl.edu/droughtmonitoring/SPI/SPIProgram).

The NMS is the custodian of the meteorological data collection and they oversee all the weather stations within the country, but because of operational challenges some of the data are missing. Some data were also collected from the MAWF. The missing data are a challenge, arising from vandalism and technical issues.

The African Flood and Drought Monitor

A corresponding modelled dataset of SPI-1, SPI-3, SPI-6 and SPI-12 were downloaded from the AFDM as online extracted outputs, from the website (PCA 2018b) for the period of 68 years (1950–2018) for Ondangwa and Katima Mulilo towns.

The AFDM tool was developed and owned by Princeton University. It uses a combination of models and theories that include the VIC hydrological model, the Routing Model and Bayesian theory for bias correction, merging and downscaling of the data to higher resolution (0.25) (Luo & Wood 2008). The AFDM provides meteorological, hydrological, vegetation and indices (SPIs and Streamflow percentiles) products for the monitoring and predicting floods and drought in Africa (Sheffield et al. 2014).

Therefore, this study assessed the drought occurrence, frequency and intensity within Namibia utilising available data from the NMS, MAWF and Modelled AFDM (SPIs) outputs (1950–2018) to address the problem of a few drought assessment studies in Namibia, the problem of missing data and also to evaluate the reliability of data from the AFDM.

The data collected from the NMS and the MAWF were cleaned and merged for both stations. The analysis of primary data was performed using SPI Generator software which uses the SPI computation principles as illustrated by Equation 6.1 –

Equation 6.9, as suggested by Kumar et al. (2009) to produce SPI-1, SPI-3, SPI-6 and SPI-12 outputs with drought duration and drought frequency. On the other hand, SPI outputs were extracted from the AFDM tool. Both results were interpreted according to McKee drought classification scales by McKee as cited by Xia et al. 2018 (Table 6.1). The AFDM data reliability test was performed by using a *t*-test at 95% confidence interval using Excel.

The SPI is a normalised index representing the probability of the occurrence of rainfall when compared to the climatological average. Thus, the number of standard deviation that observed the 1-, 3-, 6- and 12-month cumulative precipitation deviate from climatological average are termed as SPI-1, SPI-3, SPI-6 and SPI-12, respectively.

$$\bar{A} = \sum \frac{A}{N} \qquad \text{[Eqn 6.1]}$$

$$S = \sqrt{\sum (A - \bar{A})^2} \qquad \text{[Eqn 6.2]}$$

$$Skew = \frac{N}{(N-1)(N-2)} \sum \left(\frac{A - \bar{A}}{S}\right) \wedge 3 \qquad \text{[Eqn 6.3]}$$

$$Log\ mean = \bar{A}\ ln = ln\,(\bar{A}) \qquad \text{[Eqn 6.4]}$$

$$U = \bar{A}\,ln - \left(\sum (ln(A)/N)\right) \qquad \text{[Eqn 6.5]}$$

$$Shape\ parameter = \alpha = \frac{1 + \sqrt{1 + \frac{4U}{3}}}{4U} \qquad \text{[Eqn 6.6]}$$

$$Scale\ parameter = \beta = \frac{\bar{A}}{\alpha} \qquad \text{[Eqn 6.7]}$$

Cumulative probability

$$G(A)\frac{\int A^{a-1e\ \frac{-A}{\alpha}dA}}{\alpha\ \hat{}\ \beta\Gamma(\alpha)}\ A=0 \qquad \text{[Eqn 6.8]}$$

$$H\,(A)=q+(1-q)G\,(A) \qquad \text{[Eqn 6.9]}$$

Transforming H (A) to the value of 0 mean and 1 variance gives Z = SPI, where $\bar{A}$ = mean, *A* = summation rainfall, *N* = number of observed precipitation, *S* = standard deviation, *U* = lognormal values, *G (A)* = Gamma distribution and *H (A)* = cumulative probability (equations found in Kumar et al. 2009).

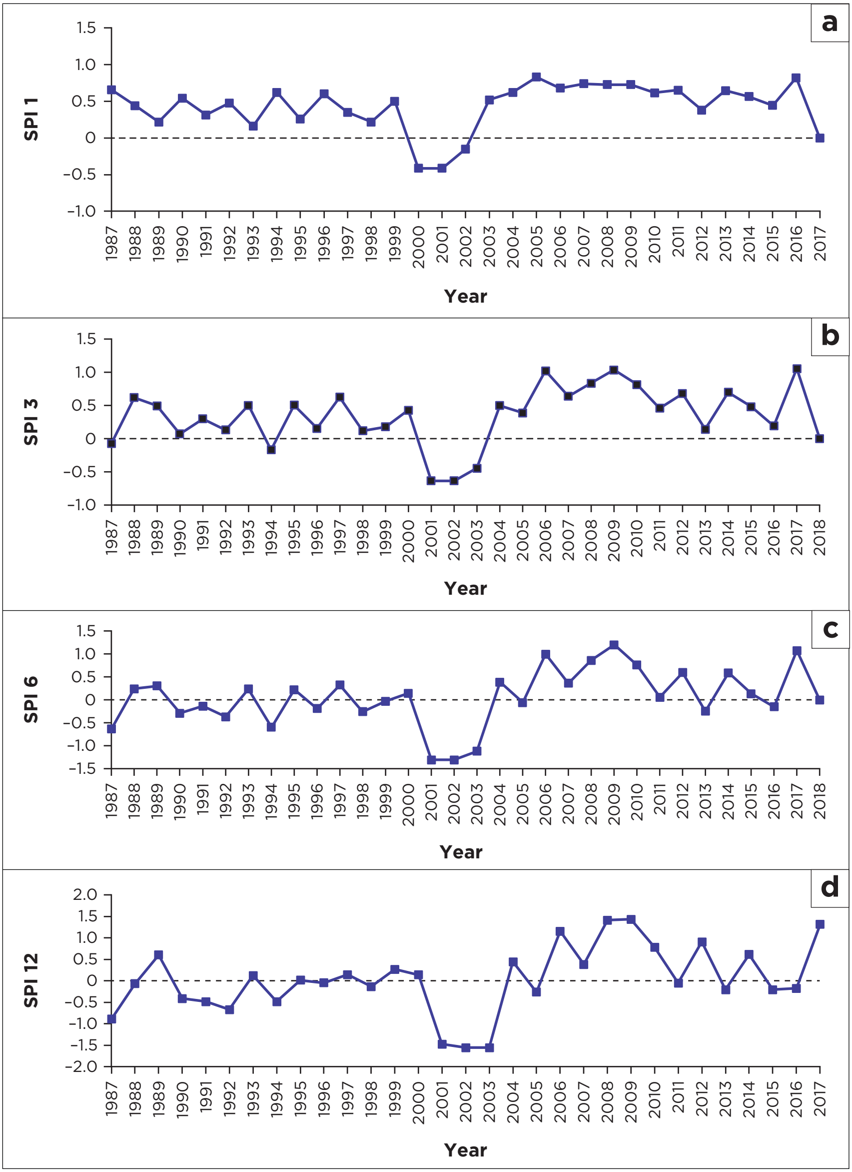
Results and discussion

Drought occurrence, duration and severity

The SPI values, drought durations and frequencies for the two towns produced different drought severity, onsets, ends and peaks (Figure 6.3 and Figure 6.4). The SPI values for Ondangwa town revealed almost no rainfall anomaly towards SPI negative values (-0.4), suggesting non-detection of abnormally low rainfall from the ground-observed data (Figure 6.4a to Figure 6.4d).

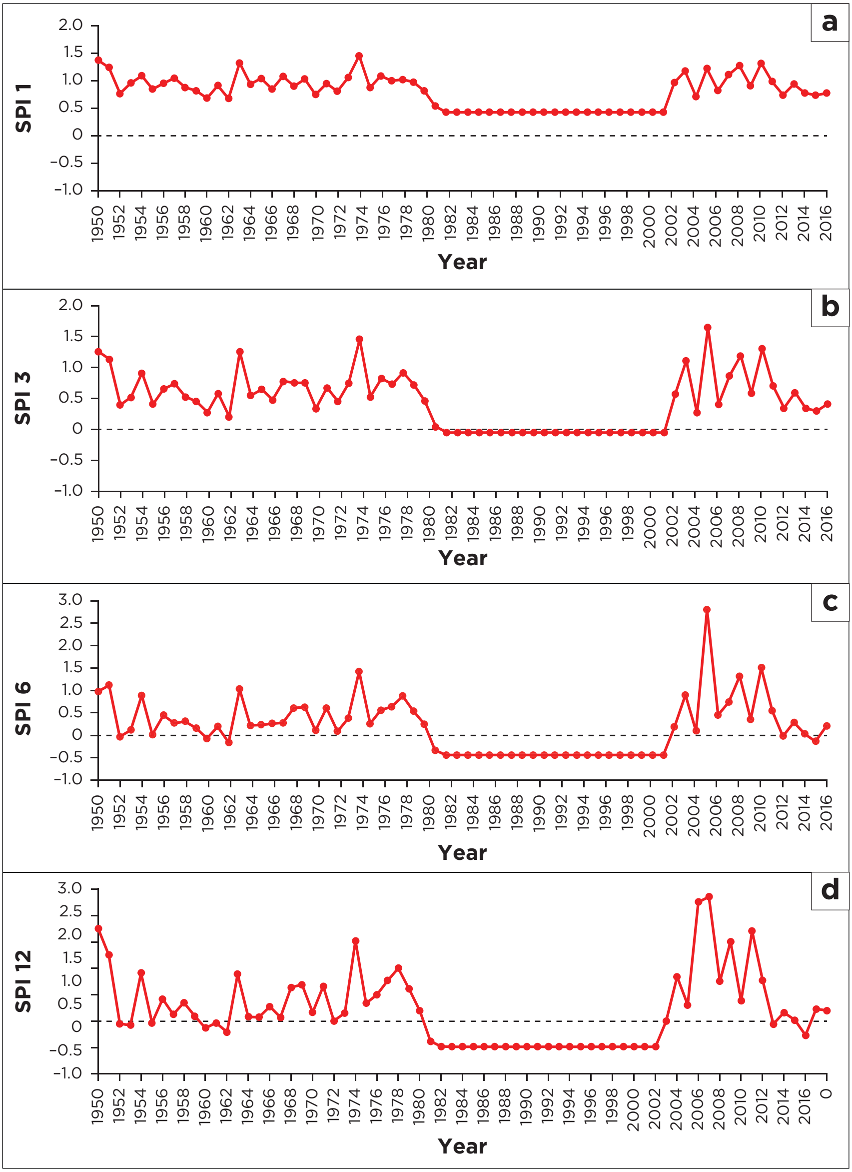
The SPI values for 1-,3-, 6- and 12-month computed for Katima Mulilo town indicate drought occurrences (Figure 6.3) and durations with clear onsets, ends and peaks (Figure 6.5a to Figure 6.5d). Short durations of drought spells started occurring in 1987, 1990, 1992, 1993, 1994, 1995 and 1998. From 1999 to 2004, severe and prolonged drought occurred. These also occurred in 2013 and 2015 as well. Drought levels for Katima Mulilo are relatively moderate to severe, as interpreted in accordance with McKee SPI scales of drought classification (Table 6.1).

Using McKee drought classification scales, the highest drought peak is indicated by SPI-12 peak value of -1.83 (Figure 6.5d) followed by drought peak value of -1.52 for all SPI-1, SPI-3 and



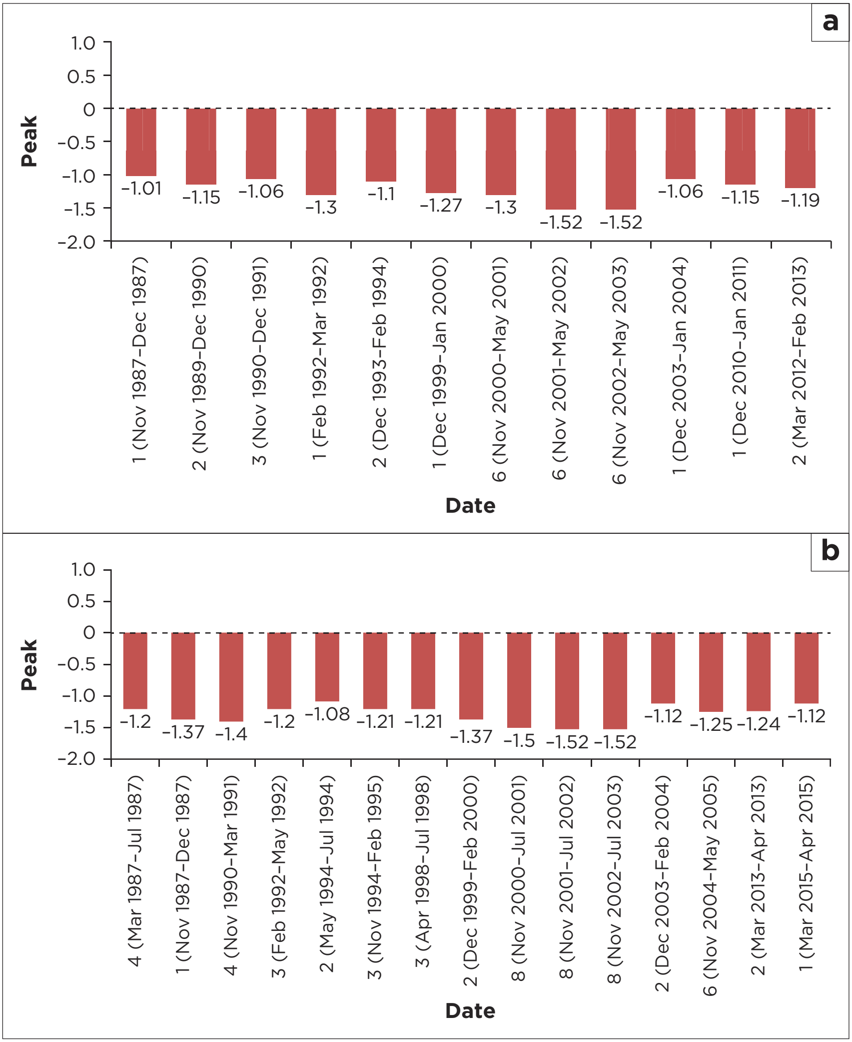
Source: Authors' own model results produced using data generated by the AFDM (PCA 2018c).
SPI, standardised precipitation index.

FIGURE 6.3: Katima Mulilo drought variability time series at (a) SPI-1, (b) SPI-3, (c) SPI-6 and (d) SPI-12 from 1987 to 2018.



Source: Authors' own model results produced using data generated by the AFDM (PCA 2018b).
SPI, standardised precipitation index.

FIGURE 6.4: Ondangwa drought variability time series at SPI-1, SPI-3, SPI-6 and SPI-12 from 1987 to 2018.



Source: Authors' own model results produced using data from the NMS (2018a, 2018b).
SPI, standardised precipitation index.

FIGURE 6.5: Katima Mulilo drought severity at (a) SPI 1, (b) SPI 3, (c) SPI 6 and (d) SPI 12 timescales for ground-observed data (Namibia Meteorological Services).

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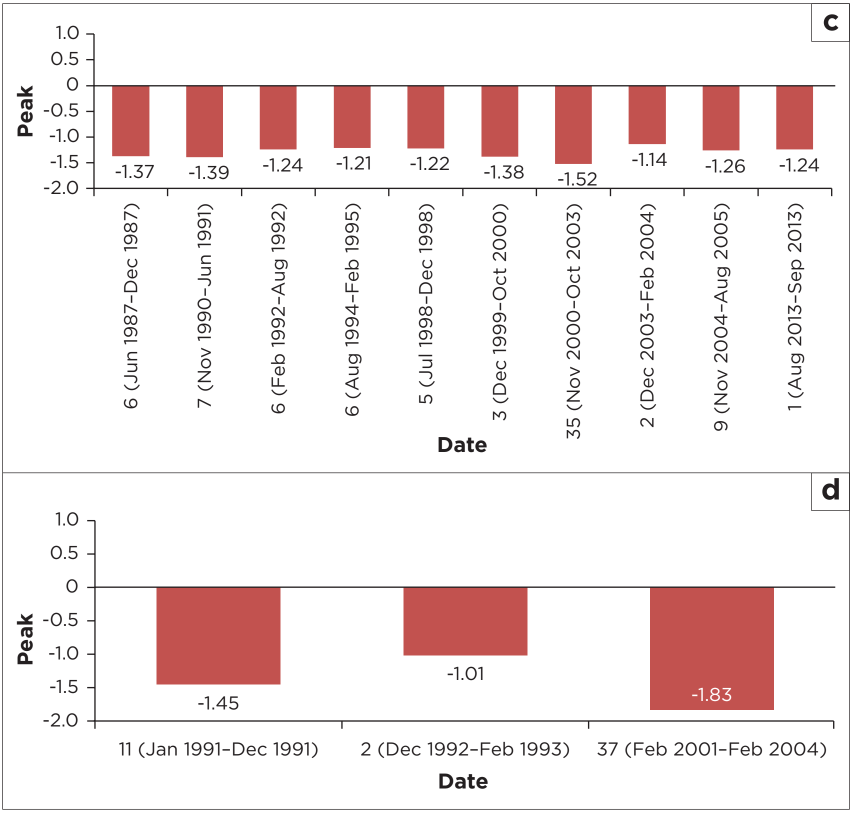


Source: Authors' own model results produced using data from the NMS (2018a, 2018b).
SPI, standardised precipitation index.

FIGURE 6.5 (Continues…): Katima Mulilo drought severity at (a) SPI 1, (b) SPI 3, (c) SPI 6 and (d) SPI 12 timescales for ground-observed data (Namibia Meteorological Services).

SPI-6 (Figure 6.5a to Figure 6.5c). This suggests that Katima Mulilo experienced severe dryness within the study period. Some drought peak values were relatively low and mostly obvious with short timescales SPI-1, -1.01 (Figure 6.5a) and SPI-3, -1.08 (Figure 6.5b). However, the SPI-12, -1.01 (Figure 6.5d) indicated a lower drought peak as well. The prolonged droughts duration in Katima Mulilo were 35 and 37 months for SPI-6 and SPI-12, respectively. It is also noted that most of the extended droughts set on during the time when the rainfall season starts (November) in Namibia. Thus, Katima Mulilo experienced the longest and most severe drought for four consecutive years from 2000 to 2004 (Figure 6.5c and Figure 6.5d).

Drought duration and peaks can be used to detect drought severity and rainfall deficits. Prolonged duration of droughts with high drought peaks result in extreme dryness and widespread long-lasting impacts in an area. Longer drought duration at SPI-1 (6 months), SPI-3 (8 months), SPI-6 (35 months) and SPI-12 (37 months) are characterised by high drought intensities similar to the behaviour of droughts that were found in semi-arid North-eastern Brazil using SPI methods, suggesting that the longer the drought stays, the more severe the impact (Bak & Labedzki 2002; Brito et al. 2017).

Drought classification

Classification of drought in Katima Mulilo from 1987 to the 2018 time series was performed by grouping the SPIs output into two decades, 1987–1997 and 1998–2018. The results in Table 6.2 show a clear decadal drought variability in Katima Mulilo between these two groups. The first decade (1987–1997) is characterised by the short duration of droughts from 1 to 6 months, associated with low-intensity drought peaks for all timescales (1-, 3-, 6- and 12-month SPIs). This type of drought is classified as meteorological drought. In the second decade (1998–2018), annual drought variations are noticed. Prolonged meteorological drought duration from 35 to 37 months at longer SPI scales (SPI-6 and SPI-12) with high intensity (–1.52 and –1.82) are evident and are likely to cause an extreme reduction in soil-moisture levels leading to reduction in plants production and yields. In other ways, the absence of rainfall for a long time reduces river levels and flows and also reduces groundwater recharge and levels, leading to the manifestation of agricultural and hydrological drought (Brito et al. 2017). Therefore, meteorological drought that dominated the period extended to agricultural and hydrological drought between 1998 and 2018 (Table 6.2).

TABLE 6.2: Drought status for Katima Mulilo and Ondangwa as analysed by Standardised Precipitation Index generator.

Study location	Drought scale	SPI 1	SPI 3	SPI 6	SPI 12
Katima Mulilo	Moderately dry	–1.01	–1.08	–1.14	–1.01
	Duration	1 month	2 months	2 months	2 months
	Severe dryness	-1.52	-1.52	-1.52	-1.82
	Duration	6 months	8 months	35 months	37 months
	Standard error	0.3166	0.4390	0.6346	0.7916
Ondangwa	No drought found				

Source: Authors' own model results produced using data generated by the AFDM (PCA 2018b, 2018c).
SPI, standardised precipitation index.

Drought severity is a combination of drought duration (from onset to end) and peak (intensity) from 1987 to 2018.

Drought frequency

Drought frequency is the number of drought events that are identified within a period (1987 to 2018) of data that were collected. Drought frequencies for Katima Mulilo and Ondangwa are presented in Table 6.3 and Figure 6.6. A majority of Katima Mulilo SPI values with higher frequencies are found within the normal climatology class, similar to results identified by Kumar et al. (2009) in Brazil; however, below normal, negative SPI values for SPI-12 (–1.83) were found five times; SPI-12 (–1.7) 29 times and SPI-1, SPI-3 and SPI-6 (–1.5) more than 15 times. Above 0 values (SPI positive values) interpreted as very wet to extremely wet were more frequently represented than SPI negative values. This is because the Zambezi Kwando-Linyanti basin, where Katima Mulilo is located, falls in an area in Namibia characterised by high rainfall, thus drought occurrences are less frequent in this area than floods. On the contrary, Ondangwa's SPIs, with positive values are less frequent at SPI-3, SPI-6 and SPI-12, but more at SPI-1. Although Ondangwa SPI results indicated no drought, the SPI positive values (+1 to +3) with high intensity occur rarely. The SPI frequency distribution of Ondangwa is left skewed. In addition, SPI negative values are also relatively low (Figure 6.6b, Figure 6.6d, Figure 6.6f and Figure 6.6h).

TABLE 6.3: Drought frequencies at SPI-1, SPI-3, SPI-6, SPI-12 for Katima Mulilo town.

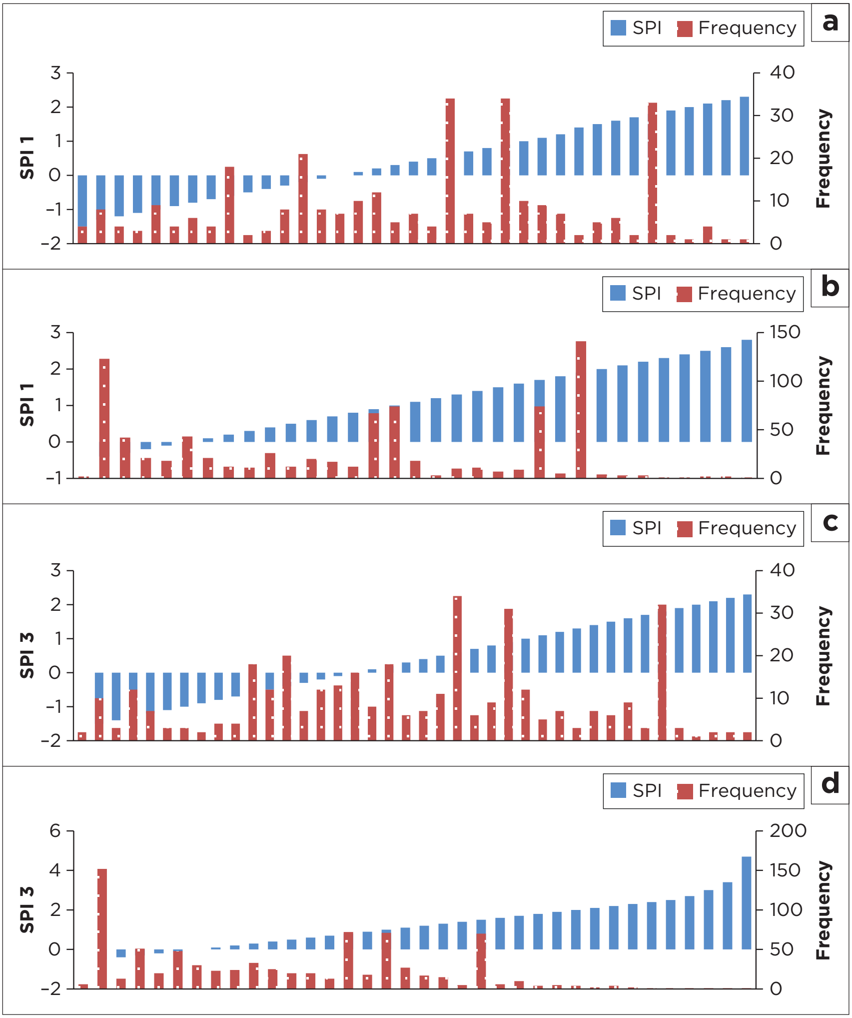
Katima Mulilo location	Index	Drought scale						
		Extremely dry	Severely dry	Normal	Normal	Normal	Very wet	Extremely wet
Katima Mulilo	SPI 1	≤−2	−1.5	−0.5	0	0.5	1.5	≥2
	Frequency	0	4	22	17.5	34	34	1
	SPI 3	−2	−1.5	−0.8	−0.1	0.5	1.8	2
	Frequency	0	10	17	13	34	32	2
	SPI 6	−2	−1.5	−0.52	−0.3	0.6	1.3	2.2
	Frequency	0	19	21	21	7	11	1
	SPI 12		−1.83 to −1.7		0.4	0.2	1.6	2
	Frequency		5 to 29		30	37	6	1

SPI, standardised precipitation index.

Comparison of African Flood and Drought Monitor-modelled Standardised Precipitation Index to Namibia Meteorological Services ground-observed Standardised Precipitation Index from Namibia Meteorological Services

The comparison of annual drought analysis results for Katima Mulilo (1987–2018) and Ondangwa (1950–2018) towns from the model AFDM and ground observation (NMS) are presented below. The graphs (Figure 6.7 and Figure 6.8) were plotted to compare ground-observed SPIs and modelled AFDM SPIs. A significant test for modelled AFDM SPI output was computed by employing normal *t*-test statistical methods as summarised in Table 6.4.

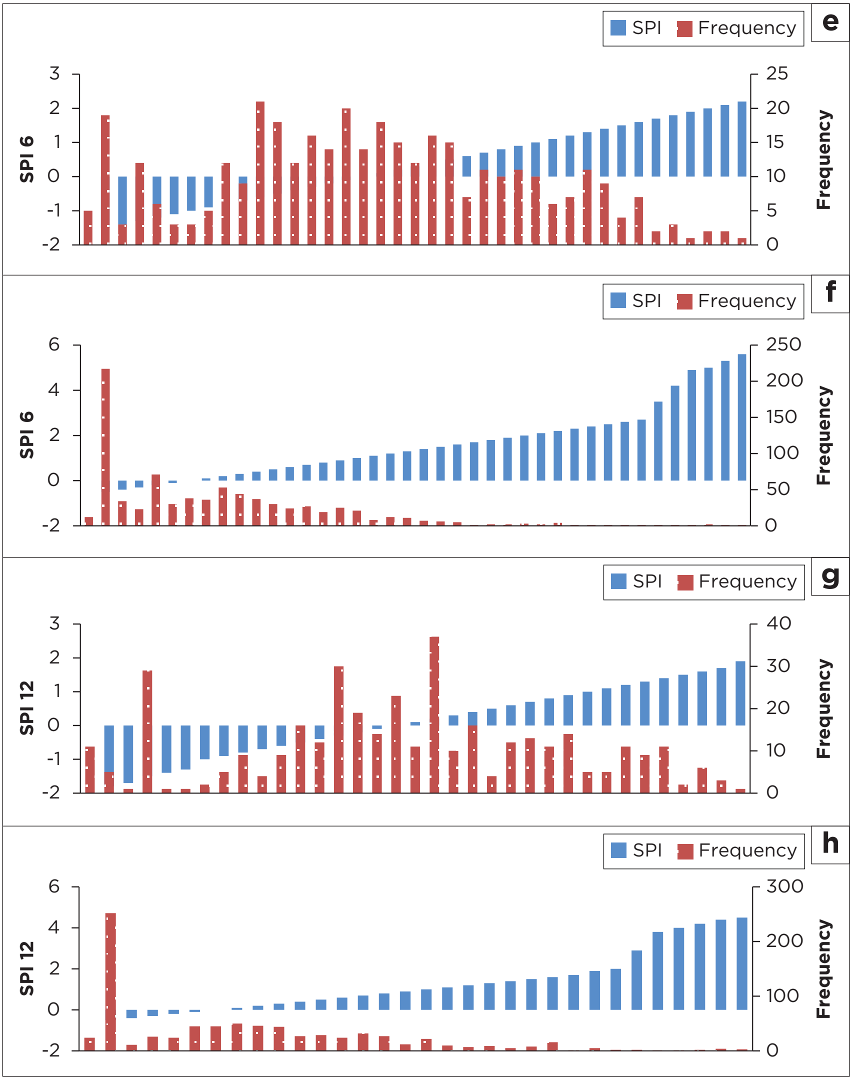
Generally, the modelled (AFDM) SPI values for timescales of 1 month, 3, 6 and 12 months for Katima Mulilo town indicate 'normal to intense drought' levels. The SPI values indicate alternating floods and drought patterns with a strong increase in drought trends and intensity from 1950 to 2018 (Figure 6.8). The ground-observed (NMS) computed SPIs (for 1-, 3-, 6- and



Source: Authors' own model results produced using data generated by the AFDM tool (PCA 2018b, 2018c) and the ground-observed data from the NMS (2018a, 2018b).
SPI, standardised precipitation index.

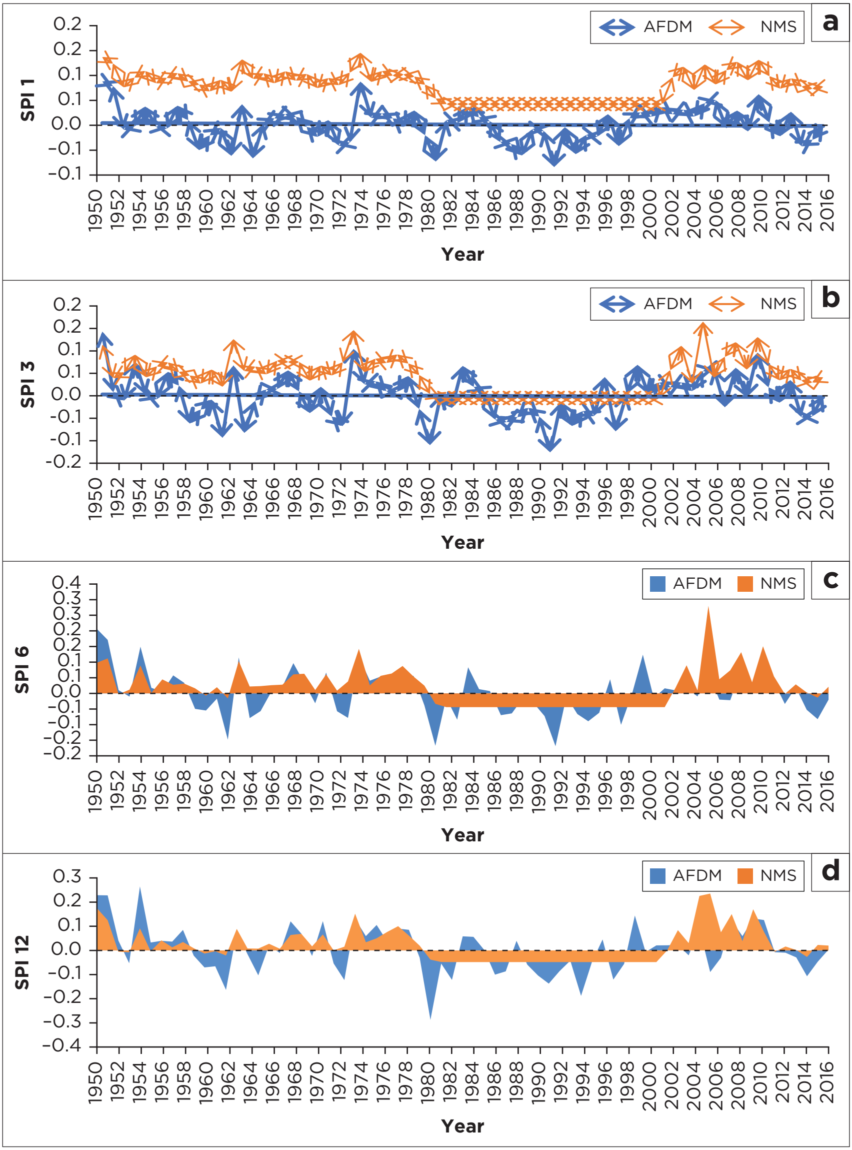
FIGURE 6.6: Comparison between (a, c, e & g) Katima Mulilo and (b, d, f & h) Ondangwa drought intensity and frequency at SPI 1, SPI 3, SPI 6 and SPI 12 timescales for ground-observed data (Namibia Meteorological Services).

Figure 6.6 continues on the next page→



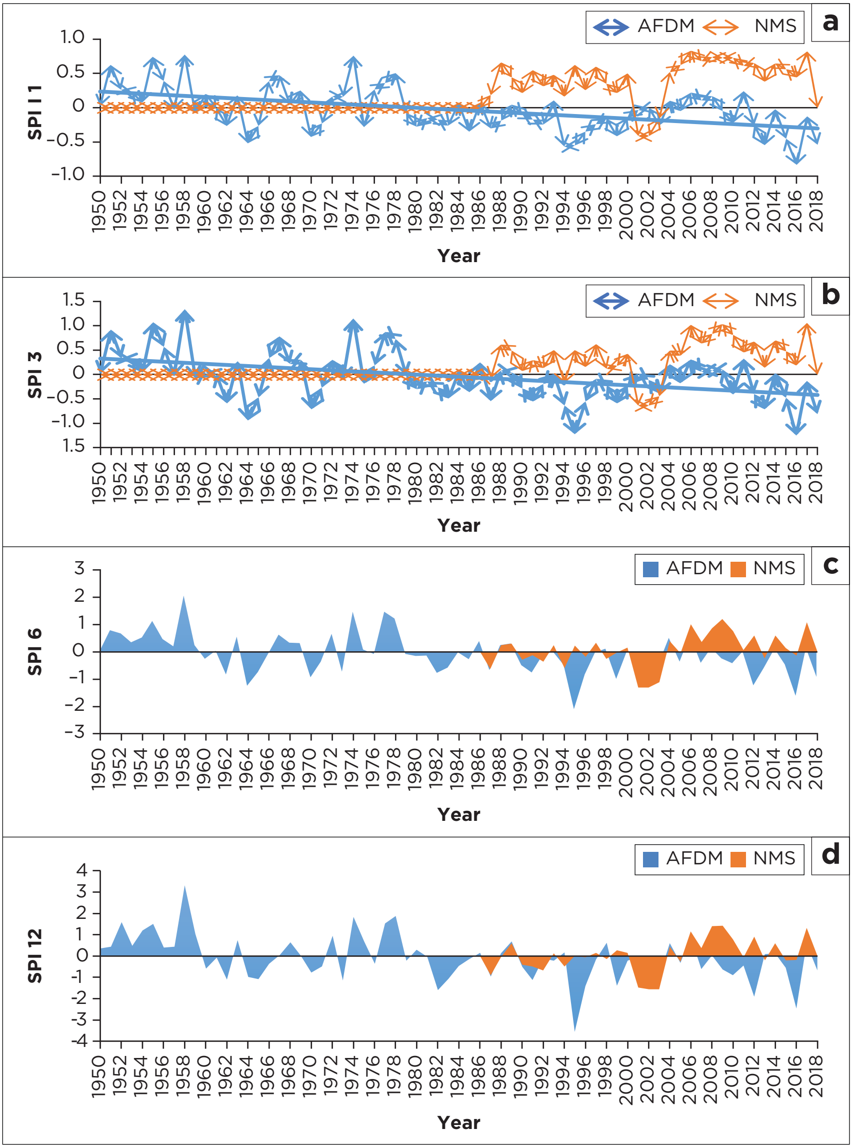
Source: Authors' own model results produced using data generated by the AFDM tool (PCA 2018b, 2018c) and the ground-observed data from the NMS (2018a, 2018b).
SPI, standardised precipitation index.

FIGURE 6.6 (Continues...): Comparison between (a, c, e & g) Katima Mulilo and (b, d, f & h) Ondangwa drought intensity and frequency at SPI 1, SPI 3, SPI 6 and SPI 12 timescales for ground-observed data (Namibia Meteorological Services).



Source: Authors' own model results produced using data generated by the AFDM tool (PCA 2018b, 2018c) and compared with the ground-observed data from the NMS (2018a, 2018b).
AFDM, African Flood and Drought Monitor; NMS, Namibia Meteorological Services.

FIGURE 6.7: Comparison of the modelled Standardised Precipitation Index (AFDM) and ground-observed (NMS) time series of the Standardised Precipitation Index at 1-, 3-, 6- and 12-month timescales for Ondangwa from 1950 to 2018.



Source: Authors' own model results, produced using data generated by the AFDM tool (PCA 2018b, 2018c) compared with the ground-observed data from the NMS (2018a, 2018b).
AFDM, African Flood and Drought Monitor; NMS, Namibia Meteorological Services.

FIGURE 6.8: Comparison of modelled Standardised Precipitation Index (AFDM) and the ground-observed (NMS) time series of Standardised Precipitation Index at 1-, 3-, 6- and 12-month timescales for Katima Mulilo from 1987 to 2018.

TABLE 6.4: Summary of statistical significance test performed at 95% confidence interval for African Flood and Drought Monitor and Namibia Meteorological Services datasets (1987–2018) for Katima Mulilo and (1950–2018) for Ondangwa.

Station name	Index	Dataset	Mean	S.D.	*N*	S.E.	df	S.E. of diff	*t*
Katima Mulilo	SPI 1	AFDM	−0.18	0.33	32.00	0.06	61.00	0.08	−7.66
	SPI 1	NMS	0.44	0.31	31.00	0.06			
	SPI 3	AFDM	−0.27	0.51	32.00	0.09	61.00	0.12	−5.30
	SPI 3	NMS	0.36	0.43	31.00	0.08			
	SPI 6	AFDM	−0.36	0.71	32.00	0.12	61.00	0.17	−2.47
	SPI 6	NMS	0.06	0.62	31.00	0.11			
	SPI 12	AFDM	−0.49	1.05	32.00	0.19	61.00	0.23	−2.28
	SPI 12	NMS	0.03	0.78	31.00	0.14			
Ondangwa	SPI 1	AFDM	0.02	0.36	68.00	0.00	134.00	0.10	−8.09
	SPI 1	NMS	0.80	0.30	68.00	0.10			
	SPI 3	AFDM	0.02	0.54	68.00	0.00	134.00	0.06	−7.89
	SPI 3	NMS	0.45	0.44	68.00	0.06			
	SPI 6	AFDM	0.01	0.74	68.00	0.00	134.00	0.02	−7.73
	SPI 6	NMS	0.19	0.62	68.00	0.02			
	SPI 12	AFDM	0.04	1.00	68.00	0.00	133.00	0.02	−6.64
	SPI 12	NMS	0.20	0.70	67.00	0.02			

Source: Authors' own model results produced using data generated by the AFDM tool (PCA 2018b, 2018c) and the ground-observed data from the NMS (2018a, 2018b).
AFDM, African Flood and Drought Monitor; df, degrees of freedom; NMS, Namibia Meteorological Services; S.D., standard deviation; S.E., standard error; SPI, standardised precipitation index; *t*, the ratio of the departure of the estimated value of a parameter from its hypothesised value to its standard error.

12-month) results for Katima Mulilo revealed above 'normal to severe wet' conditions (Figure 6.8) with a strongly increasing trend towards positive SPI values (floods) from 1987 to 2018. For Ondangwa town (Figure 6.7), observed SPI values revealed no drought conditions in any of the timescales (SPI–1, –3, –6, and –12) and the modelled SPI values revealed alternating drought- and flood-intensity levels.

At a shorter timescale (SPI-1), the model (AFDM) reported normal to dry conditions with intensity values between –0.5 and –0.8 in 1994 and 2016, respectively. The ground-observed SPI-1 reported above normal (+0.5) to wet climatic conditions from 1988 to 2016 with the exception of 2000 to 2003 where prolonged drought was observed with an approximate duration of 37 months (Figure 6.8a). The observed negative SPI value (–0.4) aligned well with the drought that happened within the country during the same period, followed by a major flood event in 2004. The AFDM drought results of SPI3 timescales (Figure 6.8b) suggest that the Katima Mulilo station was moderately hit by drought (–1.2) in 1995 and 2016 whilst ground-observed SPI-3 reported frequent normal to moderate wet conditions between 2006 and 2017 (Kooper 2018).

The modelled SPI-6 output indicates that Katima Mulilo town experienced extreme (–2) drought to normal conditions in 1995 and 2002 (–0.3), respectively, opposing the ground- observed SPI that reported the normal rainfall status in 1995 (+0.2) (Figure 6.8c). The ground-observed SPI values indicate moderate dryness (–1.31) in 2002, followed by floods after five years, although the modelled SPI-6 suggests a drought condition in 2009. The town experienced a devastating flood in 2009 with the SPI intensity level of (+1.2). This observation coincides well with the reported floods which occurred in the Zambezi-Kwando-Linyanti basin in 2009 (Inanbao 2009).

The modelled SPI-12 scales (Figure 6.7d) suggest that the town had experienced frequent and severe drought conditions from 1995 to 2018, whilst the ground observations suggest wet conditions to floods. This basin is frequently flooded because of the influence of the major river (Zambezi River) and rainfall from nearby countries such as the Congo.

Studies have revealed that SPI timescales of 1, 3 and 6 are good indicators for monitoring drought condition and SPI-6, SPI-12, SPI-24 and above are good for hydrology monitoring (Xia et al. 2018). For example, the sudden decrease in SPI levels in SPI-1 to SPI-3 (for NMS data sets) clearly indicates the onset of drought situations. At SPI-6 and SPI-12, the drought level increased to almost intense. Therefore, early drought onset are well captured at SP1-1 and SPI-3.

African Flood and Drought Monitor-modelled data performance test

The accuracy of detecting occurrence, frequency and severity of drought between models (AFDM) and ground-observed datasets differs. *T*-test statistics were performed to check the reliability of the AFDM data and the results are presented in Table 6.4.

Most researchers found that drought detection by satellite/modelled data, computed SPIs at shorter timescales than 1, 3, 6 as explained in Xia et al. (2018) produces accurate results. Studies of drought identifications, using modelled and observed data, for example, in India using SPI, SPEI and PSDI showed a strong positive correlation between the two data sets, indicating good performance levels (Shrivastava et al. 2018). In this study, the AFDM-modelled SPIs produced slightly different results. All of the SPI timescales (SPI-1, SPI-3, SPI-6 and SPI-12) at a 95% confidence interval (Tcrt.05 = 1.96) showed no statistical significance (Ts<Tcrt) as shown in Table 6.4.

Concluding remarks

The SPI has proven to be the easiest, best and suitable for most climatic conditions worldwide. Its easy calculations with multiple scales (1-, 3-, 6-, and 12-month SPI), data gaps and the minimum duration of as low as 30 years, are amongst the strengths that make SPI most commonly used with multiple applications in water resources and agriculture (McKee et al. 1993). Despite the fact that it does not account for other meteorological parameters, such as temperature, moisture and evaporation, the WMO made SPI the standard of use for assessing meteorological drought frequency, duration and intensity worldwide since 2009 (Svoboda & Fuchs 2016). Since there are very few variables (soil moisture) for measuring drought directly (Svoboda & Fuchs 2016), it is suggested by Adnan et al. (2017) that the use of SPI methods should be backed up by other methods to show drought variability over regions clearly. It has also proven that SPI alone can monitor drought in the short and long term (Xia et al. 2018), detect the early onset of drought up to 20 days in advance (Shrivastava et al. 2018), investigate short-scale seasonal forecasting (Sheffield et al. 2014), and classify drought occurrence and severity (Mallebrera, Abril & García-Galiano 2010).

Acknowledgements

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Chapter 7

Water demand and effects of climate change in the middle Kafue River basin

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Abstract

The ability to assess the catchment potential to satisfy water demands is vital for the management of the water resources of the country. The current water allocation system, which falls

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under the *Water Resources Management Act No. 21 of 2011,* needed to encourage the optimal use of water as it contributes to the management, development, conservation, protection and preservation of the water resources in the country. The Kafue basin, as a whole, experiences conflict regarding water permits, because of the high water demand from agriculture, hydropower generation and industry. The Water Evaluation and Planning (WEAP) Model was used to provide an effective means of ensuring the water resources were managed in an integrated and sustainable manner. Three different output scenarios were used in the WEAP model which projected the intensity of climate change on the Kafue basin. The scenarios included two climate scenarios namely MRCP 8.5 and MRCP 4.5 and one reference scenario which depicted the actual ideal conditions. The simulation showed that the Kafue basin is highly affected by the effects of climate change which in turn results in decreased rainfall, leading to a decrease in the Kafue River flow, increased temperatures and evaporation. The results showed that these effects were likely to affect the hydropower production from Itezhi-Tezhi and the Kafue Gorge within the basin and lower the agricultural production if the water resources were not managed effectively. Hence the model would be used to effectively manage the water resources in the Kafue basin as a decision-support tool.

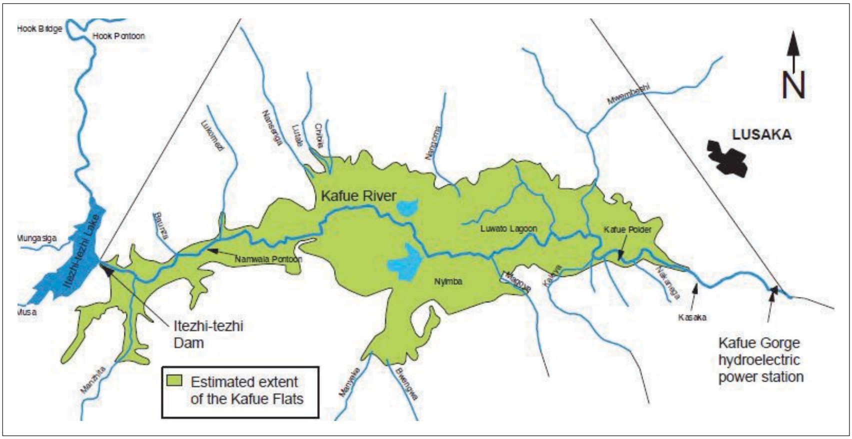
Keywords: Water evaluation and planning model; Water demand; Climate scenarios; Water allocation; River flow.

Introduction

The Middle Kafue down to the end of the Kafue Gorge lies at elevations of 1300 m to 1000 m above sea level. The point at which the Middle Kafue begins, flows 450 km through the Kafue flats over an estimated area of 450 km. The Kafue flats which cover the southern, central and Lusaka provinces of Zambia are comprised of swamps, open lagoon and its mostly flooded areas. The middle Kafue River is mainly characterised by the Kafue flats and this area provides an avenue for agricultural activities, such as aquaculture, commercial farming, subsistence farming, livestock farming and also the production of power which are of great importance to the national economy and to the regional economy of Southern Africa. The demand for water in the Middle Kafue has resulted in competing needs amongst the domestic, agricultural, hydropower and the environment calls. Hence optimisation of water allocation for various uses is key in addressing the conflict issues amongst users. The Middle Kafue is also characterised by streams that flow into the Kafue River and it is from these same streams that other users of the water draw. Figure 7.1 shows the extent of the area study; however, the study is mainly focused on the middle Kafue basin that stretches from the Iteshi Teshi dam to the lower Kafue Gorge hydropower station as shown in Figure 7.2.

Source: Chomba and Nkhata (2016).

FIGURE 7.1: Kafue watershed showing the extent of study area.



Source: World Wide Fund for Nature (2017).
FIGURE 7.2: Middle Kafue basin.

The Middle Kafue is also characterised by streams that flow into the Kafue River and it is from these same streams that other users draw water (see Figure 7.2).

To ensure the effective management of the water resources, there is a need to plan and ensure the sustainable and rational utilisation, management and development of water resources, based on community and public needs and priorities, within the framework of national economic developmental policies (Government of the Republic of Zambia 2011). In line with this mandate, Catchment Planning and Water Allocation Planning and Improvement are two of the key factors in setting sustainable environmental thresholds in developing water allocation plans. The prioritisation of water allocation varies from place to place (Bangash et al. 2012), and hence appropriate models are needed for optimal allocation efficiency.

The ability to assess the catchment potential to satisfy water demands is crucial in order to plan for future water use and make informed decisions (Lenton & Muller 2012). The current water allocation system needs to encourage the optimal use of water so that improvements in allocation practices could increase the value of water resources to communities; hence, modelling tools could provide an effective means of ensuring the water resource being managed in an integrated and sustainable manner. Competing demands could be met whilst achieving positive economic and environmental outcomes with the aid of modelling tools to analyse the impact of alternative water allocation policy scenarios. One of the important purposes of water management is to match or balance the demands for water with its availability, through a suitable water allocation arrangement (DFID 2003).

The allocation of water resources amongst the ever increasing number of different users has been a challenge and cannot be effectively achieved without the use of the appropriate technology to cope with the demand.

The objectives of this study included:

1. assessing the effective multi-sectoral water allocation plan in the Kafue basin, considering the impact of climate change
2. determining the environmental water requirements in the Kafue basin
3. assessing the availability of water in the Kafue basin
4. simulation of the water- allocation plan using a WEAP System Model tool.

The focus of the project is on the application of the WEAP model in assessing water demands and the effect of climate change in the Kafue basin. The water allocation tool is in fact a decision-support mechanism which could be implemented in the other catchments in order to balance needs when allocating water. The area of focus was limited to the middle Kafue basin and not the whole Kafue catchment area.

Climate change – Zambian perspective

According to Irish Aid (2016), Zambia is a 752 618 km^3 landlocked country located in Southern Africa:

> The average annual temperature in Zambia has increased by 1.3 °C degrees from 1960 to 2006 and is projected to increase by 1.2 to 3.4 °C degrees by the 2060s with more rapid warming in the southern and western regions. (p. 3)

The impact of climate change has resulted in challenges to the different aspects of the management of the water resources in the country; the decrease in annual precipitation will continue to affect surface-water allocations because of the high dependency on rain-fed agricultural practices and various activities including hydropower generation. The increase in population, in industrial activities and in irrigation activities will exceed the present demand for water resources, hence negatively impacting the economy of the country. The uneven distribution of surface waters at present causes other regions to experience water shortages, especially in the southern region. Part of this region was the focus of this study and from the findings, the region has faced a decline in precipitation leading to low flow volumes and a reduction in underground water, therefore affecting the availability of water for agriculture, the impact on hydropower generation and other human activities. However, the increase in heavy rainfall and flooding has not spared other parts of Zambia from sanitation problems, including pollution from industries that get carried by flooding to areas of residency, thereby posing health hazards.

The effect of climate change on agriculture and hydropower generation

Agriculture

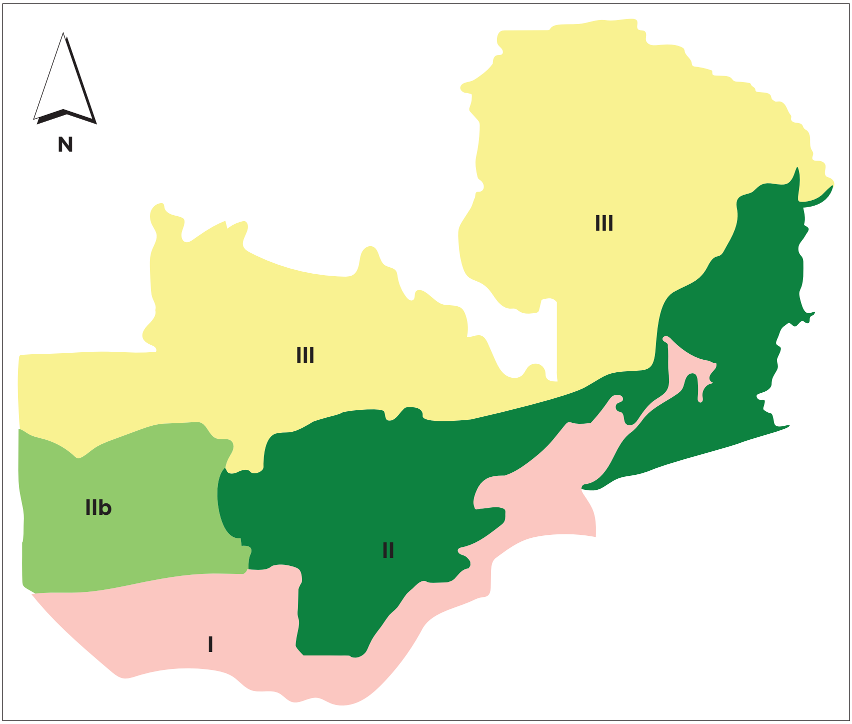
Agriculture has been found to be one of the most important livelihood strategies in the Kafue basin which consists of both commercial and small-scale farming. Small-scale farmers have estates of between 0.1 ha and 4.99 ha, whereas medium-scale farmers hold land between 5 ha and 20 ha. Agriculture employs a large portion of Zambia's labour force (Fink & Masiye 2015) and occupies 32% of its land, with small-scale farming accounting for 70% of farms. The majority of smallholder farmers produce one harvest annually and find it difficult to reach sufficient production for both household consumption and market sales. Most of the small-scale farmers rely on rain-fed maize as the main staple crop and this contributes to the vulnerability of small-scale farmers (Nash et al. 2016). The decrease in average rainfall and the increase in temperature have affected agriculture practices in Zambia. In the year 2001 there had been excessive rain, whilst the dry spells during the 2001 and 2002 growing season led to a major shortfall in maize production, resulting in a decrease of 42%, compared with the average annual production (Haggblade 2007).

Agriculture is one of the most important sectors of the economy highly dependent on climate. Significant efforts have been made towards understanding the impact of climate change on agricultural systems, since the first Intergovernmental Panel on Climate Change (IPCC) Assessment Report was published in 1990. The resulting advances in the understanding of the impact of climate have come from the collection of valuable data, the development of models, and the observation of the changes in climate and its impact. The impact of climate change includes changes in crop and livestock productivity, which in turn may lead to changes in the most profitable production systems at a given location (Antle & Stoorvogel 2008).

Zambia has abundant surface-water resources; however, communities living in arid parts of the country's agro-ecological Region I (Figure 7.3) experience severe water shortages during summer. The population increases in urban centres have also put pressure on groundwater through mismanagement.

☐ Hydropower

Hydropower is a major source of energy in almost all world regions; it's a source of social and economic development, ensures electricity security and is the pillar of renewable electricity production. Most of the water in Zambia is used for hydropower generation which is a non-consumptive use and the rest of the water for agriculture, domestic water and industry amongst other



Source: FEWS NET (2014).
Note: The demarcated areas represent Zambia's agro-ecological regions. Region I is the southern part, stretching to the east along the Zambezi and Luangwa valleys. It receives annual rainfall of less than 800 mm. Region IIa is the central, southern and eastern plateaus, considered to have the best agricultural potential in the country. It receives annual rainfall of 800 mm to 1000 mm. Region IIb is characterised as semi-arid plains due to differences in soils. The main features of the region include the Zambezi River and surrounding plains, providing fishing opportunities and wetlands suitable for rice production. The annual rainfall is also 800 mm to 1000 mm. Region III consists of plateaus punctuated by hills and mountains. The soils are moderately fertile, and it receives annual rainfall of more than 1000 mm.

FIGURE 7.3: Zambia agro-ecological regions.

purposes (Mweemba et al. 2010). But hydropower and its environmental impact are vulnerable to climate change. Hydropower projects involve the construction of dams so as to impound water to create enough head to run the turbines. These water development projects create complex ecological and environmental effects, hence the design and characteristics of each hydropower plant play a vital role in determining its vulnerability. The comparative resilience of such individual reservoirs in the face of climate change effects is vital in determining approach strategies (Bunyasi 2012). Since run-of-river hydropower plants (also called river power plants) use the natural water flow of a river or a diversion canal, any change in the hydrologic regime because of climate change will have immediate repercussions on the hydropower production. The gradual changes in various climate attributes in the form of temperature, precipitation, et cetera and possible changes in the frequency and intensity of extreme weather events progressively affect operation over time.

Hydropower plays a significant role in African regions and this is likely to expand in future. However, changing climate can affect hydropower by generating changes in river flow that are related to precipitation and temperature in any given catchment area. Also, the climate change may increase the likelihood of extreme flood events or droughts that increase costs and risks for hydropower projects. Sedimentation is another probable problem that could be created by climate change, resulting in blockages caused by fallen logs, turbine abrasions and also reduced efficiency from decreased storage capacity of the reservoirs.

In Zambia, the hydro-electric power generation has been negatively affected by the droughts and floods and, drought being more prominent, has led to economic reduction in the power potential. The influence of rainfall fluctuation on runoff, reservoir storage capacity and hydropower potential in the Zambezi River basin has adversely affected the region.

Hydropower generation and commercial agriculture rely on an adequate quantity of water resources, whilst environmental flows meant for ecosystem functions depend on the timing of the quantity, and it is this dynamic relationship between the quantity and the timing of water resources on the Kafue flats that has resulted in conflicts amongst water users in the Kafue basin. Hence the *Water Resources Management Act of 2011* places domestic water use as first priority, followed by water for conservation and lastly for hydropower generation, but because of the importance of hydropower for mining activities and commercial farming, hydropower has the highest priority in the basin (Chomba & Nkhata 2016).

Methods/study approach

Data collection

This study used quantitative and qualitative data. For qualitative data, survey forms were used to assess the multi-sectoral uses of water in the basin, including the water demand. The exercise involved identifying the various major tributaries of Kafue. A drone was flown over the area to ascertain exactly where the irrigation of crops was intensively practised and then images of the same were developed. The approach was to identify areas which were greener than the others, so this gave an indication that such areas where being irrigated. Visiting the actual places clarified whether such areas where being irrigated by the use of borehole water or are rain fed. In the case of quantitative data, it involved recording the actual quantities of water used in the basin.

Catchment water allocation

Water Evaluation and Planning is a modelling tool for water planning and allocation that can be applied on multiple scales, from community to catchment to basin. Water Evaluation and Planning models are adequate to evaluate and propose the best management strategies towards maximisation of benefits for a given number of users under given objective functions in the catchment (Juizo & Lidén 2010). The WEAP System model enables the evaluation of planning and management issues associated with water resources development. As a decision-support tool WEAP proved to be effective for water allocation, supply and demand analysis to evaluate the water management scenario (Mugatsia 2010).

Water evaluation and planning modelling

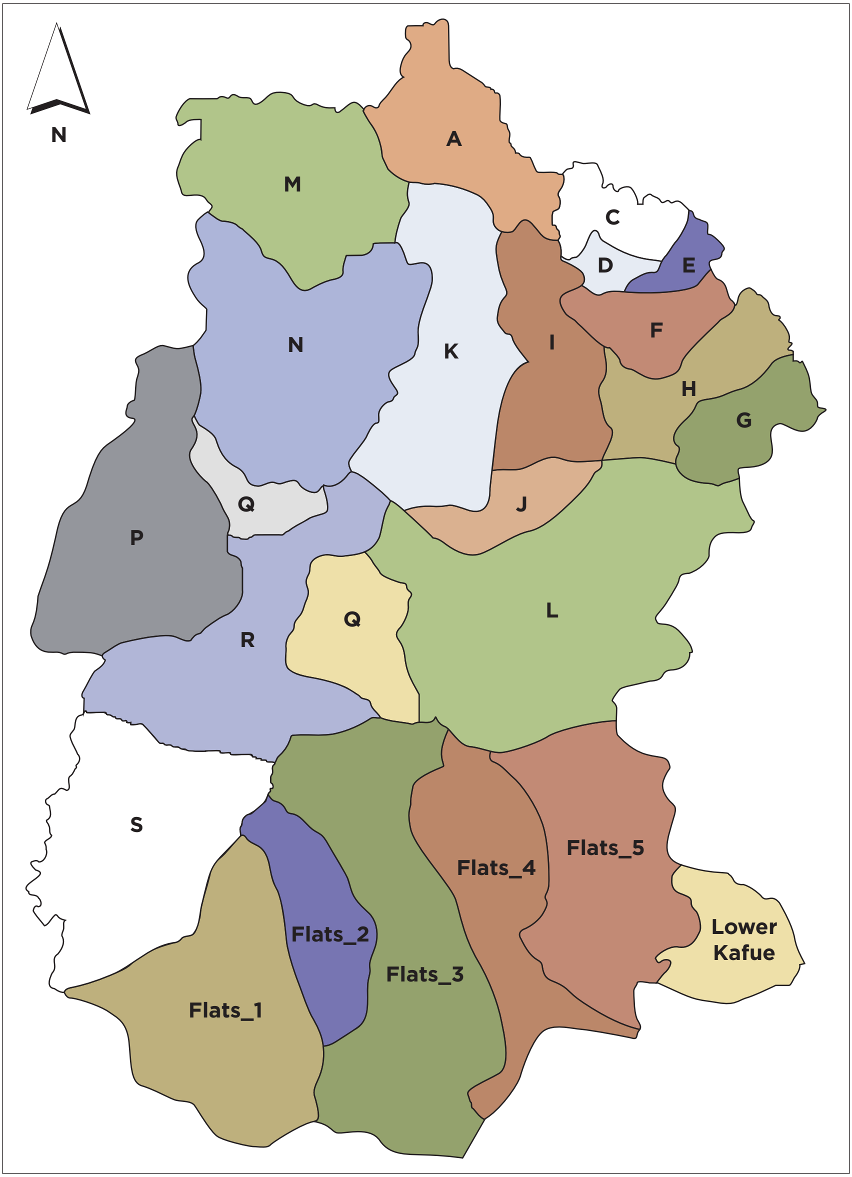
The Kafue basin was divided into 28 sub-basins, in order to effectively simulate the runoff within the whole Kafue catchment. These sub-basins act as collection points for runoff received from the precipitation, which meant that most of the tributaries within the basin were covered in the simulation so that the calibration of the model was effectively carried out, because of the flow gauges located within these sub-basins. The 28 sub-basins of the Kafue catchment are shown in Figure 7.4. The model was tested by comparison of time series of simulated and observed river flow at only 16 out of 103 gauging stations within the Kafue basin (Figure 7.5). The 16 were chosen because they are stationed along the Kafue River.

Data analysis

Simulation of the natural flows

The model was developed using historical streamflow data that were gathered from the Water Resources Management Authority (WARMA) and also climate (evaporation, rainfall and temperature) data for the period 1957–2012. The process also included collecting data for the Kafue basin components, such as sources of surface water supply, water use (i.e. agricultural and industrial). The GIS spatial data that were collected, included the Kafue basin map to link demand points with the exact location. After putting the above data into the model, simulation of natural hydrological processes was done to enable assessment of the availability of water within the Kafue basin, and the simulation of anthropogenic activities (including anthropogenic climate change activities) was also superimposed on the natural system to ascertain the influence on the available water resources and their allocation. To simulate the model, the Kafue River was divided into reaches (Figure 7.6).

The reach boundaries determine points in the Kafue basin between abstractions or return flows into the system or where there is any hydraulic structure in the form of a dam or gauging station. Then the model performed a mass balance of flow down the Kafue basin from the north to the south of the river system, making provisions for abstractions and inflows. In this way, the WEAP model configured the system to simulate a baseline (recent) year, for which the water availability and demand were determined before simulating alternative climate change scenarios.



Note: The various letters, 'flats' divisions and 'Lower Kafue' indicate the ideal sub-basins as determined by the model.

FIGURE 7.4: Map showing 28 sub-basins that were configured within the Kafue catchment.

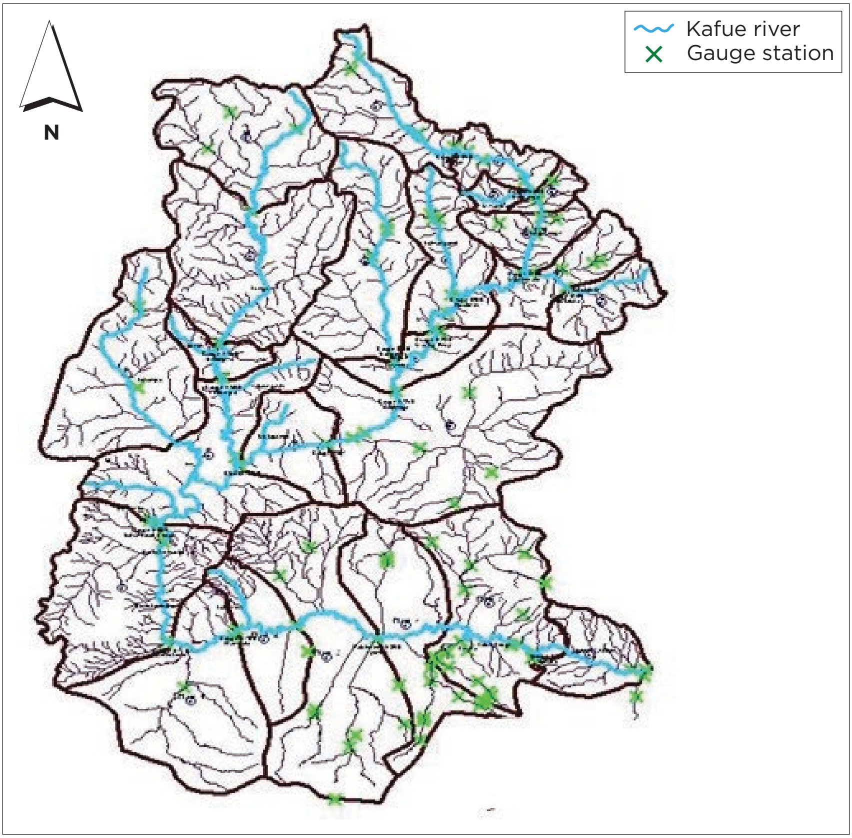


FIGURE 7.5: Map showing gauging stations within Kafue basin.

☐ Climate projections in water evaluation and planning

Both the historical and future climate data which were used in this study to assess the impact of climate change came from the GCM ECHAM which is downscaled to a 0.44° (approximately 50 km) resolution by the Swedish Meteorological and Hydrological Institute (SMHI) from the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative. The CORDEX program aims at developing a framework that allows

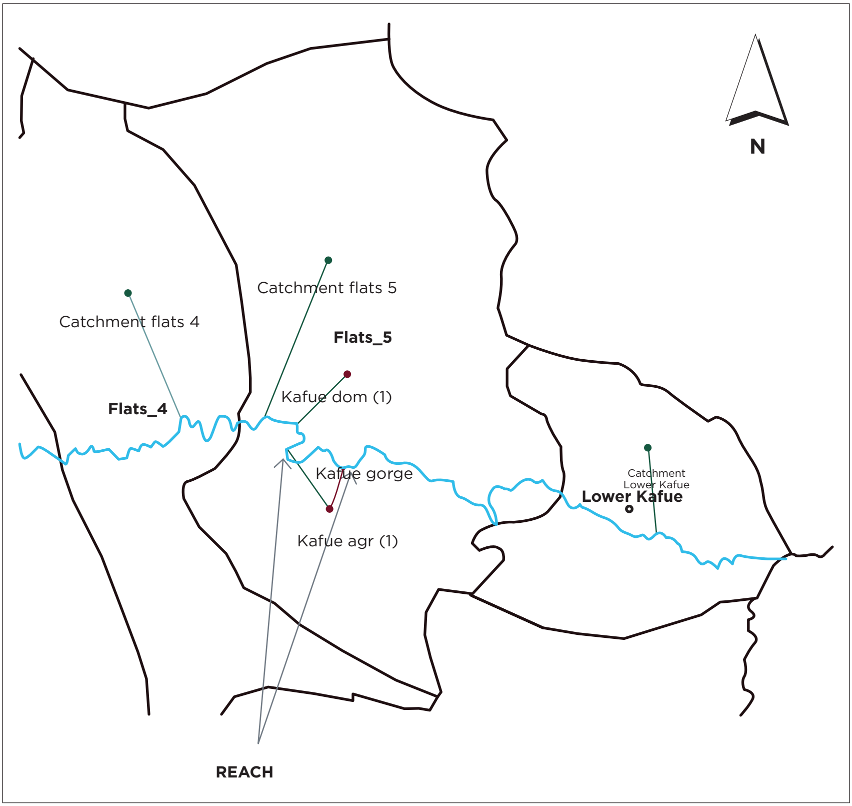


FIGURE 7.6: The 'reaches' within the Kafue River.

the use of downscaled global climate projections in assessing regional climate downscaling techniques and is funded by the World Climate Research Programme (Ozturk et al. 2012). CORDEX applies emission scenarios based on RCPs. These RCPs are four trajectories of the concentration of GHG adopted by IPCC for its fifth assessment report in 2014 and describe an emission trajectory and concentration by the year 2100 (Wayne 2013). These pathways are a set of four and were created based on radiative forcing degrees of 8.5, 6, 4.5 and 2.6 W/m^2 corresponding to RCP8.5, RCP6, RCP4.5 and RCP2.6, respectively, by the end of 2100. For the purposes of this study, the scenarios created were for the time interval of 1900 to 2100. Also in the WEAP model, only the two scenarios (RCP4.5 and RCP8.5) were taken into account together with one reference scenario.

Scenarios

RCP4.5: It is a stabilisation scenario, meaning the radiative forcing level stabilises at 4.5 W/m^2 before the year 2100, supposing an undertaking of emission mitigation by employing a range of strategies for reducing GHG emission mitigation policies.

RCP 8.5: It refers to the baseline scenario and is representing the highest RCP scenario, regarding GHG emissions that does not include specific climate- mitigating policies, though it corresponds to the rising radiative forcing pathway leading to 8.5 W/m^2.

Reference scenario refers to the current account scenario in which business as usual is implied and was generated, using Current Accounts (baseline) information for the period (1900 to 2100).

The WEAP model ascertains the runoff pattern in the Kafue basin.

Results and discussion

Water evaluation and planning model and water availability in the Kafue basin

From the gauging stations that are located within the Kafue basin, only 16 were validated and used in calibration of the model. Measurements of the flow discharge were also conducted at some of the stations where historical data were missing to ascertain the consistency of readings. Some of the average readings were as recorded in Table 7.1, including discharge measurements.

TABLE 7.1: Discharge readings.

Gauge no.	River/station	Discharge (m^3/s)
4710	Kafue Itezhi-Tezhi	698.280
4669	Kafue/Hook Bridge	832.833
4450	Kafue/Lubungu,	511.936
4560	Lunga/Chifumpa	196.730
4620	Lufupa/Kasempa	6.822
4302	Luswishi/Lwendo	42.514
4340	Lushishi/Kangondi	60.175
4821	Munyeke/Mapanza	3.014
4760	Kafue/Nanwala Pontoon	569.492
Misc.	Munyeke/ Monze-Niko Road	3.511
Misc.	Bwengwa/ Monze-Niko Road	2.994
Misc.	Nakasangwe/ Monze-Niko Road	1.354
4890	Kafue/Nyimba	390.750
4915	Magoye/Chimbumbu,	1.807
4949	Kaleya/G.N.R	0.195
4977	Kafue/Chiawa Bridge	155.687
4977	Kafue/Kasaka	445.801

The assessment included data from hydro-meteorological stations, evaporation rates including inflow and return-flow rates into the Kafue basin river system. From the total of 65 stations, monitored by WARMA, only 22 are Telemetric Stations in the Kafue basin which transmit recorded data to the point where it could be monitored and analysed. The average flows into the middle Kafue basin, approximately 270 km from the Kafue Gorge, lower amounts to 301 m^3/s and this is the inflow into the Itezhi-Tezhi dam operated by ZESCO Power Company. The return flow in the middle Kafue basin amounts to about 27 million m^3 annually. These return flows were estimated from urban, industrial, mining and agriculture water use, and evaporation in the middle Kafue basin amounts to between 1605 mm and 2166 mm, compared to the national average at 2061 mm. Average outflows into the Kafue Gorge dam were estimated at an average value of 289 m^3/s.

Water evaluation and planning modelling

The WEAP model was simulated by putting the inflow into the Kafue basin. Figure 7.7 shows the layout of the modelled Kafue basin together with its main tributaries.

The model was then made to run under natural flow conditions to depict the simulated flows by putting in the collected data

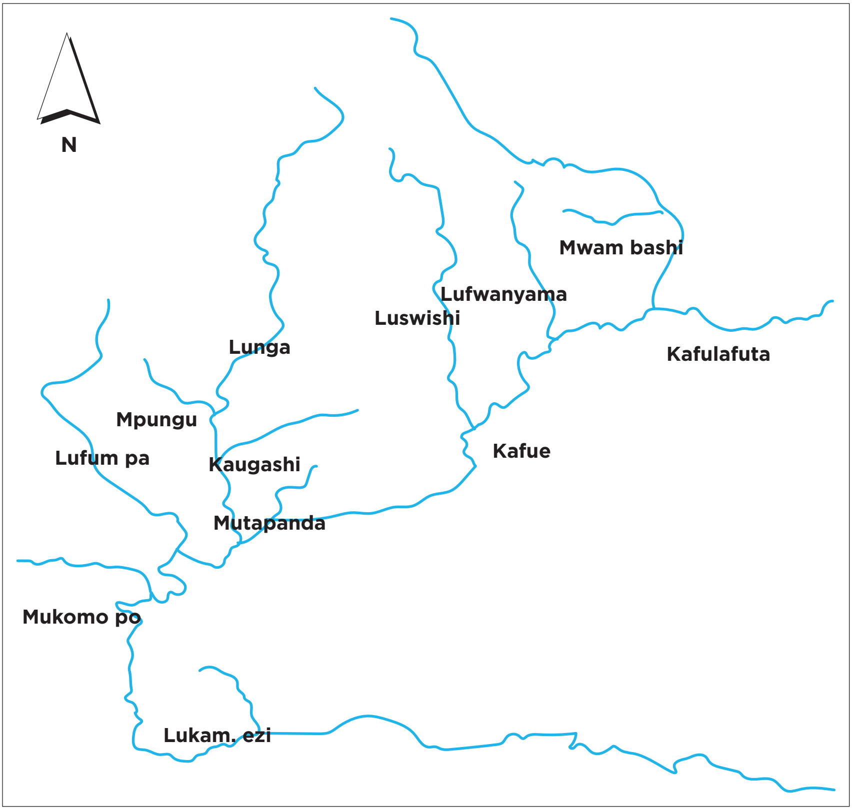


FIGURE 7.7: Kafue River inflow map.

from CORDEX, including mean precipitation values and mean temperature values. Empirically, model evaluation based on linear regressions are analysed by placing observed values in the Y-axis and predicted values in the X-axis (Piñeiro et al. 2008), because the opposite leads to inaccurate and incorrect estimates of the slope and Y-intercept, thereby creating false results in testing for correlation. Figure 7.8 shows the output of the sum of the yearly precipitation from CORDEX versus the observed flows.

Multi-sectoral water use

Agriculture water which has a high priority for the purposes of social and economic development accounts for over 96.9% of the consumptive users in the Kafue basin. Hydropower which is non-consumptive accounts for 1.17% of the water users in the catchment and water utility firms accounts for 1.93% as shown in Table 7.2.

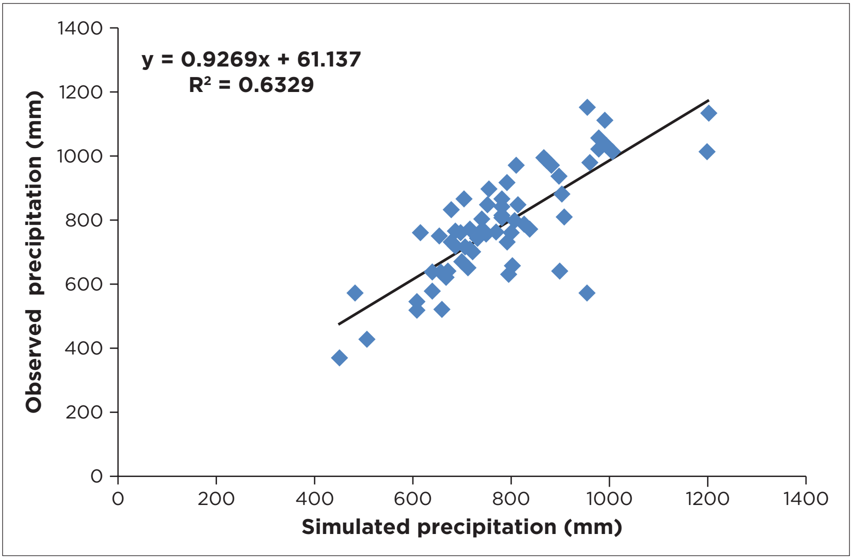


FIGURE 7.8: Sum of yearly precipitation between simulated and observed (1950–2011).

TABLE 7.2: Multi-sectoral water use.

Category	m^3/day
Irrigation	2 819 401
Hydropower	41 040 000
Water supply	175 500
Livestock/community use	126 000
Total	**44 286 901**

Apart from the major water users in the Kafue basin, some also included industrial and recreational users and, from the hydropower sector, the major hydropower generators include those installed at Itezhi-Tezhi and Kafue Gorge dam from which water allocation to hydropower generation stands at 301 m^3/s. Under the agricultural sector, most of the waters are used for commercial sugarcane production. Under the municipal water users, the Lusaka Water and Sewerage Company abstracts waters to supply to the community.

Environmental flows describe a water regime within a river in maintaining the ecosystem and their benefits where various water uses compete and flows are regulated. From the previous studies, the only portion where environmental flows have been allocated, is the downstream of Itezhi-Tezhi dam amounting to 25 m^3/s which is the flow through the middle Kafue basin.

Rainfall patterns over the Kafue catchment are derived mainly from a low-pressure system caused by the convergence of the trade winds known as the ITCZ. Annual rainfall varies from 1300 mm in the north to 800 mm in the south. The temperatures are generally warm with variations because of the difference in altitude with mean monthly temperatures ranging from 14 °C to 27 °C in June and July, respectively whilst the mean maximum and minimum temperature range from 16 °C to 34 °C in October and 7 °C to 24 °C in July, respectively.

Climate model analysis

Three out of the eight climate models were used in this study by considering the lowest, medium and worst conditions. The eight climate models from Coordinated Regional Climate Downscaling Experiment for Africa — (CORDEX-Africa) which were analysed, included RCMs, Climate Limited-area Modelling-Community (CLMcom) and Rossby Centre regional atmospheric model (RCA4); driven by four GCMs: the National Centre for Meteorological Research climate model developed by Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique CNRM-CERFACS-CNRM-CM5; Irish Center for High End Computing, European Commission Earth System model (ICHEC-EC-Earth); Met Office Hadley Centre (Hadley Centre Global Environment Model version 2) coupled Earth System model (MOHC-HadGEM2-ES); and the Max Planck Institute for Meteorology Earth System Low Resolution Model (MPI-M-MPI-ESM-LR).

Both precipitation and temperature data from CORDEX-Africa was obtained from SMHI. The data included RCPs 4.5 and 8.5 (RCP4.5 and RCP8.5) and Table 7.3 is a short format for the combination of GCMs and RCMs used in the study.

TABLE 7.3: Short format used for the combination of General Circulation Models and Regional Climate Models.

GCM	RCM	Abbreviation used in this study
MPI-M-MPI-ESM-LR	RCA4	LR_RCA4
MOHC-HadGEM2-ES	RCA4	ES_RCA4
CNRM-CERFACS-CNRM-CM5	CLMcom	CM5_CLMcom
ICHEC-EC-Earth	CLMcom	Earth_CLMcom
MOHC-HadGEM2-ES	CLMcom	ES_CLMcom
CNRM-CERFACS-CNRM-CM5	RCA4	CM5_RCA4
ICHEC-EC-Earth	RCA4	Earth_RCA4
MOHC-HadGEM2-EL	CLMcom	EL_CLMcom

CNRM-CERFACS-CNRM-CM5, National Centre for Meteorological Research climate model developed by Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique; GCM, General Circulation Model; ICHEC-EC-Earth, Irish Center for High End Computing, European Commission Earth System model; MOHC-HadGEM2-ES, Met Office Hadley Centre (Hadley Centre Global Environment Model version 2) coupled Earth System model; MPI-M-MPI-ESM-LR, Max Planck Institute for Meteorology Earth System Low Resolution Model; RCM, Regional Climate Model.

TABLE 7.4: CNRM-RCA4, EC-EARTH-CLMcom and ES-CLMcom statistical analysis.

Statistic	CNRM-RCA4	EC-EARTH-CLMcom	ES-CLMcom
Number of observations	150	150	150
Minimum	21.838	21.593	21.690
Maximum	24.795	25.696	25.535
Frequency of minimum	1	1	1
Frequency of maximum	1	1	1
1st Quartile	22.563	22.538	22.568
Median	23.165	23.393	23.459
3rd Quartile	23.960	24.057	24.372
Mean	23.266	23.283	23.476
Variance (*n*)	0.688	0.802	0.989
Variance (*n*-1)	0.693	0.808	0.996
Standard deviation (*n*)	0.830	0.896	0.995
Standard deviation (*n*-1)	0.832	0.899	0.998
Lower bound on mean (95%)	23.131	23.138	23.313
Upper bound on mean (95%)	23.400	23.428	23.638

CNRM-RCA4, Centre National de Recherches Météorologiques Rossby Centre regional atmospheric model; EC-EARTH-CLMcom, European Commission Earth System Climate Limited-area Modelling-Community; ES-CLMcom, Earth System Climate Limited-area Modelling-Community.

The temperature data from the eight models were statistically analysed and only three which showed both extremes and medium conditions were used, based on the assumption that to manage the water resources effectively through the use of model tools, extreme conditions had to be applied. The following statistical values (Table 7.4) were obtained from the three climate models that were used in the study.

Discussion

Water evaluation and planning model

The data sets which were developed from GIS software were imported into the WEAP model. These datasets included both vector (shape files and feature classes) and raster (Grids) files for gauge stations and hydrological basins, respectively. The inflows and outflows into the middle Kafue basin were modelled to indicate the flows into the basin and the outflows of the middle Kafue basin, respectively. The inflow was observed from the first sub-basin of the middle Kafue basin, that is Catchment Flat 1, and the outflow was observed at the outlet that is the lower Kafue catchment of the middle Kafue basin, thus the WEAP model could simulate flows in and out of the middle Kafue basin.

From the inflows and outflows above, the percentage change in the flow was calculated as shown below:

$$\text{Percentage change} = \frac{(\text{Inflows} - \text{Outflows})}{\text{Inflows}} * 100 \qquad \text{[Eqn 7.1]}$$

The percentage change inflows was found to be 24.6%. The percentage inflow was attributed to evaporation and demand points entered in the model. This shows that the model was suitable to simulate flows, as well as in river-flow simulations.

Climate model analysis

Representative Concentration Pathway's projections were used to simulate the inflow at the Itezhi-Tezhi dam and these included the chosen three of eight climate models under two different projections, that is RCP 8.5 and RCP 4.5. The simulated climate model in WEAP, considering the RCP 4.5 relative to the reference period, shows a decline in flows under RCP 4.5 between the period 1980 and 2010 and between the period 2046 and 2076. The same applied to RCP 8.5 relative to the baseline between the period 1980 and 2010 and between the period 2046 and 2076. Then considering the 95% confidence interval in the rainfall data, a margin of error was found to be 5.97 approximately 6 as shown in Table 7.5.

The percentage change in flow under RCP – 8.5 and RCP – 4.5 in the period 1980–2010 showed the following results (Table 7.6).

From the results RCP – 8.5 projections between the period 1980 and 2010 showed an increase in the percentage change of flow from the baseline, attributed to climate variability under

TABLE 7.5: 95% confidence of interval consideration for precipitation (mm).

Sample size	Average	Standard deviation	Margin of error	Max	Min
1760	100.85	127.9	6.0	490	0

TABLE 7.6: Percentage change (1980–2010).

Period	1980–2010
Reference	242
MRCP 4_5	233
MRCP 8_5	208.5
%CHANGE 4.5	3.7
%CHANGE 8.5	13.8

TABLE 7.7: Percentage change (2046–2076).

Period	2046–2076
Reference	253
MRCP 4_5	232.9
MRCP 8_5	192.3
%CHANGE 4.5	7.9
%CHANGE 8.5	24

these conditions. The percentage change was calculated to be higher than the period 1980 to 2010 as shown in Table 7.7.

From the calculations, RCP 8.5 projection resulted in a higher percentage change than that of RCP 4.5 as expected because RCP 8.5 represents the highest concentration pathway scenario that does not include specific climate mitigating policies.

Flows relative to the baseline flow (calibration) under RCP 4.5 projection between the periods 1980 to 2010 and the relative flow under RCP 4.5 between the period 2046 to 2076 showed higher effects on the flow as compared to the period 1980 to 2010. The same was concluded under RCP 8.5 between the periods 1980 to 2010 and 2046 to 2076, showing an increase in relativety for the later period as shown in Table 7.8.

TABLE 7.8: Stream flow relative to reference period between the periods 2046 and 2076.

Scenario	Sum	Minimum	Maximum	Mean	Median	S.D.	RMS
Calibration	0	0	0	0	0	0	0
MRCP4_5	-7530	-598.7	497.2	-20.2	-10	159.9	161
MRCP8_5	-22593.1	-929	639.7	-60.7	-5.6	299.1	304.8

S.D., standard deviation; RMS, root mean square.

TABLE 7.9: Temperature (°C) from the period 1980 to 2010.

Scenario	Sum	Minimum	Maximum	Mean	Median	S.D.	RMS
Calibration	0	0	0	0	0	0	0
MRCP4_5	-7530	-598.7	497.2	-20.2	-10	159.9	161
MRCP8_5	-22593.1	-929	639.7	-60.7	-5.6	299.1	304.8

S.D., standard deviation; RMS, root mean square.

TABLE 7.10: Temperature (°C) from the period 2046 to 2076.

Scenario	Minimum	Maximum	Mean	Median	S.D.	RMS	%change
Calibration	15.7	23	19.6	20.1	2.1	19.7	0
MRCP4_5	22	23	22.6	22.6	0.3	22.6	15.31
MRCP8_5	22	23.1	22.6	22.6	0.3	22.6	15.31

S.D., standard deviation; RMS, root mean square.

The model was subjected to run under RCP 4.5 and RCP 8.5 climate model for the period between 1980 and 2010 and this showed insignificant differences in the maximum temperatures (Table 7.9).

For the period 2046 to 2076, the results showed a slight increase in temperature in the maximum values for both RCP 4.5 and RCP 8.5 as shown in Table 7.10.

Conclusion

The WEAP model was simulated including two climate scenarios, that is RCP 8.5 and MRCP 4.5. The simulation with WEAP used mass balance principles in allocating the water resources in the Kafue basin, and also showed that climate change has an effect on the available water in the Kafue basin. All RCPs under different models resulted in the reduced flows along the Kafue basin and this knowledge is vital to optimising the allocated water in the basin. For the period 1980 to 2010, both RCPs showed slight differences in climate change; this was attributed to climate variability whilst the differences between 2046 and 2076 were attributed to climate change because of higher GHG emissions.

The use of WEAP would provide an effective means of ensuring the water resources along the Kafue basin are managed in an integrated and sustainable manner by considering different sectors that benefit from the water resources.

The model developed, is a tool that needs to be fed with information each time a client applies to abstract water from the middle Kafue basin and the basin at large in order to effectively manage the water resources. The existing users, including the new users, would need to be completely mapped, so as to characterise areas in the Kafue basin that might be stressed, so it would be easy to monitor and engage stakeholders in an integrated approach towards the effective management of the water resources.

The application of the WEAP model could be operationalised and improved further, so below are a number of recommendations that have been made:

1. The results will be shared amongst catchment offices to be used as a tool for the effective management of the water resources.
2. This tool should be used in informing decision makers about the impact of climate change and mitigation and also inform the water allocation process.
3. The current water allocation system needed to encourage the optimal use of water resources, whilst improvements in allocation practices could increase the value of water resources to communities, hence this modelling tool would provide an

effective means of ensuring the water resource is being managed in an integrated and sustainable manner.

4. By reducing poverty and mitigating environmental factors through integrated water management, this tool aids in analysing the impact of alternative water allocation policy scenarios.
5. Simulation-based water allocation models, with their mass-balancing principles to allocate resources in a river system, is efficient interactive tools, so the use of WEAP in river basin simulations should be encouraged.
6. The planning and allocation of water in the Kafue basin could be improved by this tool, as well as in other catchments.
7. There is a need for such knowledge to be disseminated in order to fully appreciate its applicability. It is recommended that training should be provided in WEAP modelling and data analysis in institutions that have the mandate in water resources management, including learning institutions.

Collecting climate-related data, monitoring the impact of climate change and moving from the development of adaptation plans to their implementation by the institutions mandated in water resources management, is the best approach in order to fully manage the water resources.

Chapter 8

The impact of surface-water demand for irrigation on water availability in Chongwe catchment

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Abstract

This study aimed to determine water demand for irrigation in the Chongwe catchment and its impact on water availability in the catchment. The water demand for irrigation was assessed by determining an irrigated area for the entire catchment from water users' information, as well as relevant institutions, compiling crop factor values from literature, multiplying values of crop factors with ET to have crop requirements, computing runoff depth from rainfall; then monthly precipitation values were subtracted from the crop water requirements to obtain the water demand for irrigation. The correlation between water demand and water availability was also determined, as well as correlation between the irrigation areas and water availability to determine the impact of the two demands on water-resource availability.

The study showed that the demand for irrigation has been increasing since 1963. Water demand for irrigation almost causes the flows of the Chongwe River at Chongwe Bridge to cease completely from mid-September to October every year. After October, the situation improves as some runoff is generated from rainfall. Nevertheless, the runoff generated in October is not adequate to sustain the river owing to the high demand for irrigation.

Analysis of the impact of demand on water availability gave positive correlation values, except at Kapiriomba station which gave negative correlation values. That means water demand has been causing a decrease in long-term flows at Kapiriomba station, unlike other stations. The increase in flows at other stations may be attributed to the construction of hydraulic structures such as dams.

Keywords: Chongwe catchment; Surface-water demand; Penman–Monteith equation; Water availability assessments.

Introduction

Background

In Zambia, the population has been increasing at a rate of 3.2% reaching 14.54 million people (CSO 2010). This has caused a lot of human activities that have been accompanied by the depletion of water resources in many areas of Zambia including the Chongwe catchment.

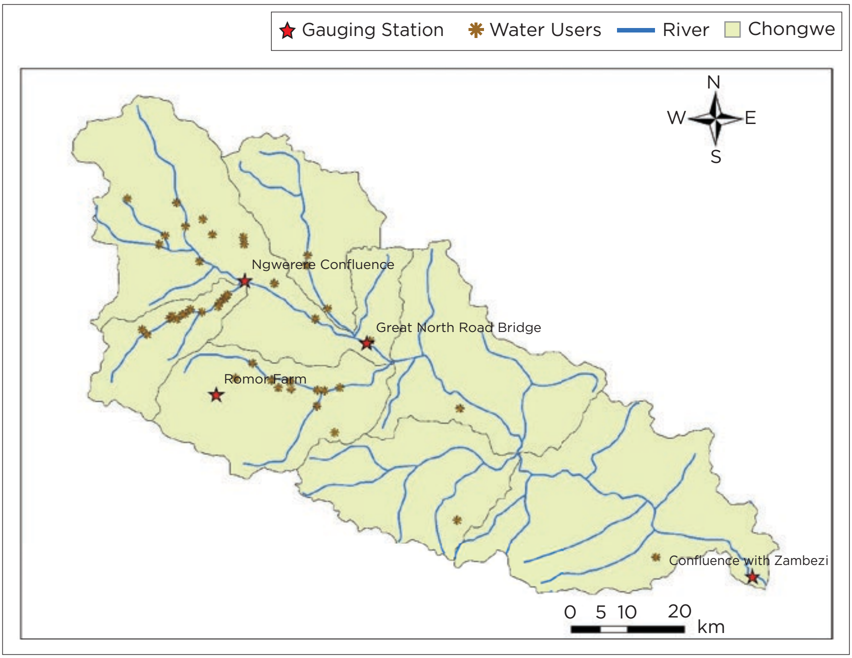
Population growth has, therefore, been characterised by an increase in agricultural activities such as irrigation (WARMA 2015). In the recent years, according to the Department of Water Affairs annual and quarterly reports, Chongwe River has been drying up every dry season (DWA 2014). Some work has been done by various institutions and researchers in the assessment of water resources in the Chongwe catchment but very little work has been done to assess the water demand. Studies done in 2000 by Mondoka and Kampata found that conflicts in Chalimbana, a Chongwe sub-catchment persist because of upstream lump-sum abstractions (Mondoka & Kampata 2000), and WARMA (2016a) concluded that such conflicts are linked to water stress in the catchment as the agriculture irrigation activities in the Chongwe catchment are the main consumer of water.

Although the effects of water depletion are seen, the extent of the water demand is still unknown. Therefore, in this research, water demand for irrigation was determined, as well as its impact on water resources availability.

The hypothesis for the study, therefore, was that there is an increase in water demand in the catchment causing a significant reduction in water availability. The study was significant as it involved evaluating water demand and determining its impact on water availability. In addition, the study will help determine suitable ways of managing water resources and the water allocation model for the catchment. It will also help determine environmental flow requirements. Furthermore, the research will help identify measures which may enhance the management and development of water resources in the catchment.

Figure 8.1 shows the map of Chongwe that was covered in the study. The size of the area considered was 5150 km^2 (GIZ 2015).

The aim of this study was to evaluate the water demand and determine its impact on water availability, and to explore the water resources and suitable storage designs that need to be constructed in the catchment. In addition, suitable ways of managing water resources and a water allocation model for the catchment are investigated. The study may further



Source: GIZ (2015).

FIGURE 8.1: Map of Chongwe catchment.

contribute to identifying some illegal water-use activities and understanding the possible causes of water depletion in the catchment. It may also clarify our understanding of environmental flow requirements. The research may provide measures that will upgrade the management and development of water resources.

Methods/study approach

Data collection

Flow data

WARMA collects water-level data from five stations in the Chongwe catchment. The authority also conducts periodic flow measurements and establishes the rating equations that are used to convert stage data to flow data. The flow data were plotted and the trend was analysed to see whether there was an increase in mean, minimum, median and maximum flows at each station over the years. However, it was observed that some data flows exhibit gaps. Gaps were filled by finding the relationship between the total mean flows for the respective years that had no missing information.

Climate data

The climate data, collected and used in this analysis, were from Lusaka International airport. The parameters that were used in the analysis for the determination of water availability, as well as water demands, include rainfall, radiation, humidity, temperature and wind speed. It was assumed that rainfall is equally distributed in the catchment. Rainfall was used in a rapid determination of water availability by determining runoff, whereas parameters such as radiation, humidity, temperature and wind speed were used to determine Reference Evapotranspiration using the FAO (Food and Agriculture Organization) Penman–Monteith equation.

Irrigated areas data

Irrigated areas data were collected from water users, as well as water rights information from WARMA. Commercial water users apply for water permits to WARMA as demanded by law. Therefore, their information helped to assess the water demand for irrigation. The data collected were used to assess water availability and determine irrigation water demand, as well as assessment of the impact of the irrigation water demand on the availability. A satellite imagery, Landsat 8 for 2017 was also downloaded and classified to observe irrigated areas for the year 2017 (Figure 8.2).

Data analysis

Rainfall data were also used during analysis since gauged stage data were already affected by irrigation and had inconsistent readings. The following climate data types were analysed, such as rainfall, radiation, humidity, temperature, wind speed and water use data, such as daily abstractions.

Water availability assessments

Water availability assessment was done by compiling all the daily flows over a period of time and analysing the trend lines. The daily flows were then converted to annual volumes and compared to annual demand. Because of the variations in flow, the trend line was used to determine whether the flow was increasing or decreasing.

Irrigation water demand analysis

According to Sharma (2008), the essence of irrigation is to replace water that the soil loses through ET. Therefore, to determine irrigated water demand, seven steps were followed:

1. Determining evaporation using the Penman–Monteith equation for the catchment.

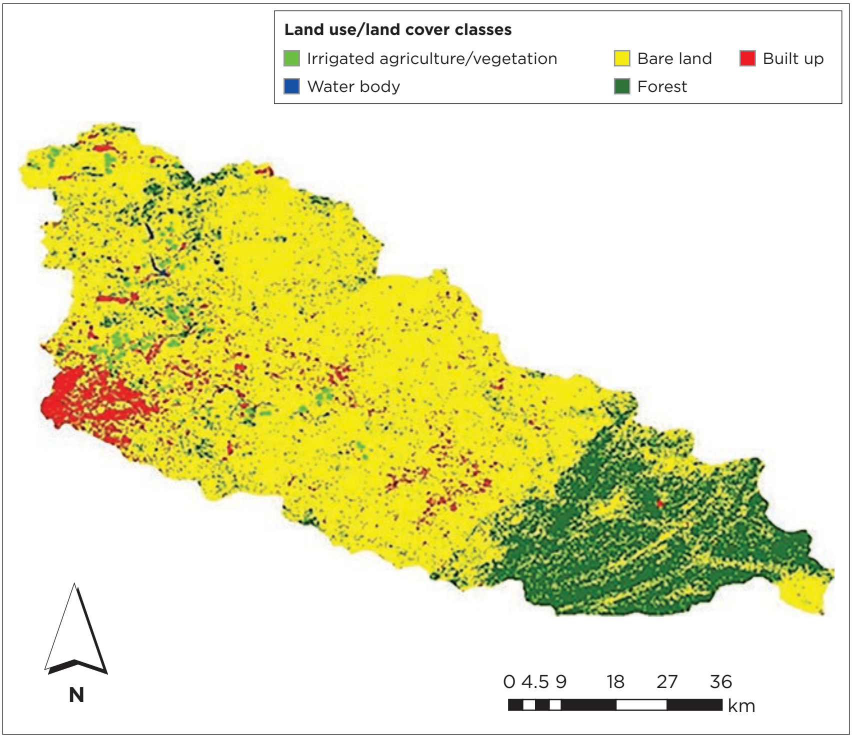


FIGURE 8.2: Land cover/land use map of Chongwe River catchment 2017.

2. Determining irrigation areas for the entire catchment from water users' information, as well as the relevant institutions.
3. Compiling crop-factors values from literature. Values of crop factors were obtained from the FAO guidelines.
4. Multiplying values of crop factors, ET to obtain crop requirements.
5. Computing annual and monthly rainfall values for the catchment using climate data.
6. Subtracting values for crop requirements from rainfall data.
7. Then monthly precipitation values were subtracted from the crop water requirements to show the deficit. The deficit

is what crops need, and is referred to as irrigation water demand.

The results of irrigation water demand were used to assess the trend of demand for other years and the impact on water resources. The results on water demand were also analysed further to compute the overall monthly water demand.

The duration of the growing period of field crops was assessed by averaging the growing periods of different crops provided by FAO (1986) in Table 8.1. The overall mean was 148 days which is almost 5 months.

☐ Determination of crop water requirement

The FAO Penman–Monteith formula was used to determine crop water requirement.

The Penman–Monteith form of the combination equation is:

$$\lambda ET = \frac{\Delta(R_n - G) + p_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad \text{[Eqn 8.1]}$$

where R_n is the net radiation, G is the soil heat flux, $(e_s - e_a)$ represents the vapour pressure deficit in the air, p_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapour pressure–temperature relationship, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances.

Then the crop water requirement (ETc) was calculated by multiplying the value of Penman ET and the crop factors. ETc was calculated as:

ETc = Crop factors (Kc) × Penman evapotranspiration (ET) [Eqn 8.2]

The annual irrigation water demand was computed using the overall average number of days during the growing period of crops as recommended by FAO (1986) in Table 8.1.

TABLE 8.1: Indicative average growing periods in days of different crops and averages.

S/N	Crop	Min	Max	Average	Crop	Min	Max	Average
1	Alfalfa	100	365	232.5	Lentil	150	170	160
2	Banana	300	365	332.5	Lettuce	75	140	107.5
3	Barley/ Oats/Wheat	120	150	135	Maize sweet	80	110	95
4	Bean green	75	90	82.5	Maize grain	125	180	152.5
5	Bean dry	95	110	102.5	Melon	120	160	140
6	Cabbage	120	140	130	Millet	105	140	122.5
7	Carrot	100	150	125	Onion green	70	95	82.5
8	Citrus	240	365	302.5	Onion dry	150	210	180
9	Cotton	180	195	187.5	Peanut/ Groundnut	130	140	135
10	Cucumber	105	130	117.5	Pea	90	100	95
11	Eggplant	130	140	135	Pepper	120	210	165
12	Flax	150	220	185	Potato	105	145	125
13	Grain/small	150	165	157.5	Radish	35	45	40
14	Rice	90	150	120	Sugarbeet	160	230	195
15	Sorghum	120	130	125	Sugarcane	270	365	317.5
16	Soybean	135	150	142.5	Sunflower	125	130	127.5
17	Spinach	60	100	80	Tobacco	130	160	145
18	Squash	95	120	107.5	Tomato	135	180	157.5
	Overall mean is 148 days							

Source: Food and Agriculture Organization (1986).

Analysis of demand on water resources availability

The water demand was plotted against water availability to determine the correlation in the trend of increase in demand and flow. Furthermore, the demand was analysed and monthly demands were computed and compared to monthly flows.

During analysis, it was observed that it was difficult to determine the impact of demand on water resources, using gauged flow data from the points located downstream water users. That means some of the gauged flows had already been tampered with by water users, and thus could not fully represent the total runoff received in that sub-catchment. Therefore, rainfall data were used during an assessment of the impact of demand on water availability.

Rainfall data were converted to runoff, using 0.1 runoff coefficient, as recommended by FAO (2010). However, at this stage of analysis, rainfall data were simply multiplied by 0.1 to obtain runoff. This was to avoid errors that could have been gotten from gauged data in which some water users could have abstracted water, causing low flow across the gauging station. The water level gauges may not capture all the data because the readings are only taken three times a day which is not enough to capture human-induced flow fluctuation.

The runoff from rainfall was added to the base flow of each station. The base flow was determined using the MEWD/JICA 1995 base flow-runoff index (MEWD/JICA 1995).

Therefore, water demand for irrigation was compared to the runoff, computed from rainfall combined with base flow to see the long term trend. The data were analysed also on a monthly basis using overall monthly means.

☐ Correlation analysis

The Pearson's coefficient of correlation was used to ascertain the long-term impact of demand on water resources in terms of flows and availability in the Chongwe catchment. It measures the linear association between two variables and if the data lie exactly along a straight line with positive slope, then $r = 1$ (Hensel 2002). The correlation coefficient values were computed and used in analysing the impact of the water demand for irrigation on flows of Chongwe River. Similar computations were done to assess the correlation between irrigated field sizes and flows. This was done to see if soil erosion or sedimentation from irrigated fields could possibly have affected the quality of water in the catchment.

Results

Catchment land use

The catchment land use was classified as shown in Figure 8.2 using the imagery of 2017 to have an overview of the location of irrigated areas. It was observed that human irrigation activities are common in the upper and middle parts of Chongwe catchment. No noticeable irrigation activities were found in the lower Chongwe catchment; only large irrigated fields could be observed unlike the small fields of small-scale farmers.

The overall average growing period of field crops was calculated to be 148 days, which is approximately 5 months.

Water demand

Table 8.2 shows the graph of Reference Evapotranspiration that was computed using the FAO Penman ETo method. October had the highest ETo value of 8.7 mm/day and September had 7.9 mm/day.

Figure 8.3 shows the monthly crop water requirements were calculated from monthly ETos and factors of different crops. The irrigation water demand was calculated by subtracting rainfall from crop water requirements. Both irrigation water demand and crop water requirements were plotted in the graph below.

The monthly ETos and crop factors of different crops were used to calculate the monthly crop requirements for January to June (Table 8.3), and July to December (Table 8.4).

Figure 8.4 shows the trend in water demand for Chongwe catchment.

Figure 8.4 shows an increase in water demand. The 'sharp' increase in demand observed for 2014 is linked to the period

TABLE 8.2: Results from the FAO Penman calculator.

Month	T_{mean} (°C)	RH_{mean} (%)	U (m/s)	R_n (W/m²)	ET (mm/day)
January	22.5	82.0	1.00	220.50	5.5
February	22.3	87.2	0.90	215.20	5.2
March	21.8	85.1	1.40	222.50	5.3
April	20.1	82.5	1.80	201.30	5.0
May	18.4	73.8	1.70	212.30	5.0
June	16.2	67.4	1.70	204.50	4.8
July	16.7	60.3	1.80	202.80	5.0
August	18.7	50.7	2.20	233.30	6.3
September	22.8	40.8	2.20	257.50	7.9
October	25.6	40.4	2.00	273.00	8.7
November	24.8	57.5	1.50	241.81	7.0
December	23.3	76.9	1.00	222.50	5.7

FAO, Food and Agriculture Organization; ET; evapotranspiration; RH_{mean}, mean relative humidity; R_n, net radiation; T_{mean}, mean temperature; U, wind speed.

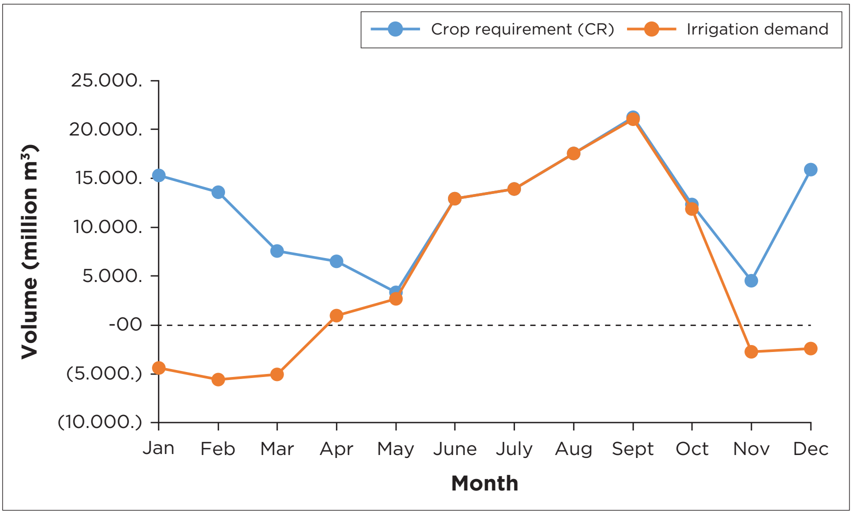


FIGURE 8.3: Monthly crop-water requirements and irrigation demand were calculated from monthly ETos and crop factors of different crops.

TABLE 8.3: The monthly crop water requirements were calculated from monthly ETos and mean crop factor of different crops (January–June).

Parameter	January	February	March	April	May	June
Evapotranspiration (ETo [mm/day])	5.5	5.2	5.3	4.7	5	4.8
Evapotranspiration (ETo [mm/month])	170.5	150.8	164.3	141	155	144
Crop factor (Kc)	1.00	1.00	0.51	0.51	0.24	1.00
Penman demand (m^3/month)	15 339 197	13 566 867	7 565 977	6 493 017	3 335 265	12 955 099
Effective rainfall depth on irrigated fields (mm/month)	219.85	213.55	141.00	61.95	7.30	-
Crop requirement (m^3/month)	15 339 197	13 566 867	7 565 977	6 493 017	3 335 265	12 955 099
Irrigation demand (m^3/month)	4 372 041	5 579 527	5 075 754	938 725	2 680 764	12 955 099
Effective rainfall on irrigated fields (m^3)	19 711 238	19 146 395	12 641 731	5 554 292	654 501	-

Irrigated area is 8966 ha and the maximum daily irrigation demand is 702 468 m^3/day.

TABLE 8.4: The monthly crop water requirements were calculated from monthly ETos and mean crop factors of different crops (July–December).

Parameter	July	August	September	October	November	December
Evapotranspiration (ETo [mm/day])	5	6.3	7.9	8.7	7	5.7
Evapotranspiration (ETo [mm/month])	155	195.3	237	269.7	210	176.7
Crop factor (Kc)	1.00	1.00	1.00	0.51	0.24	1.00
Penman demand (m^3/month)	13 944 724	17 570 352	21 248 867	12 332 143	4 518 746	15 896 986
Effective rainfall depth on irrigated fields (mm/month)	-	-	1.95	5.05	81.05	204.10
Crop requirement (m^3/month)	13 944 724	17 570 352	21 248 867	12 332 143	4 518 746	15 896 986
Irrigation demand (m^3/month)	13 944 724	17 570 352	21 074 034	11 879 372	2 748 007	2 402 144
Effective rainfall on irrigated fields (m^3)	-	-	174 832	452 771	7 266 754	18 299 130

Irrigated area is 8966 ha and the maximum daily irrigation demand is 702 468 m^3/day.

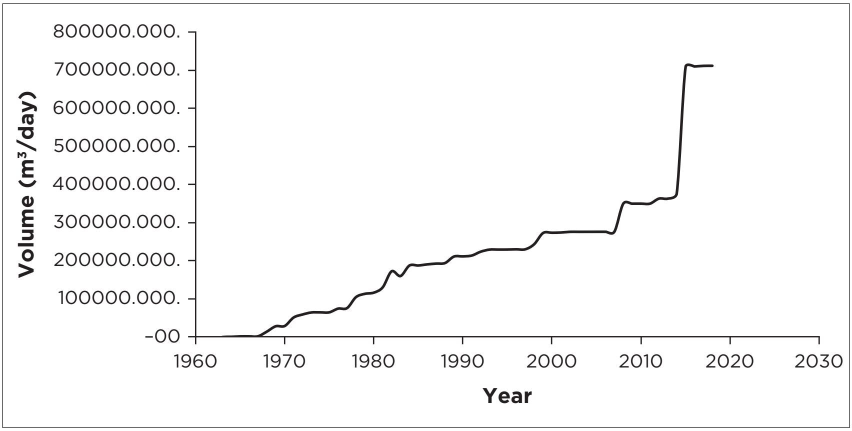


FIGURE 8.4: The trend of water demand for irrigation in Chongwe catchment.

when WARMA was converting water rights to water permits with a view to revoking all the dormant water rights. Water permit holders should have irrigated more during that period to protect their water rights, creating a sharp increase in water demand.

Water demand versus water resources availability (annual flows)

Figure 8.5 shows the annual flow of Chalimbana River and annual demand plotted against time from 1955 to 2018.

The correlation of the Chalimbana River annual flow with annual irrigation demand gave a Pearson correlation coefficient of 0.33 and p-value 0.02 at 95% confidence interval.

Results from the analysis of water used for irrigation and unused water at Chongwe River at Great East Road Bridge are summarised in Table 8.5.

Table 8.5 shows the analysis of flow patterns versus water demands of Chongwe River at the Great East Road Bridge.

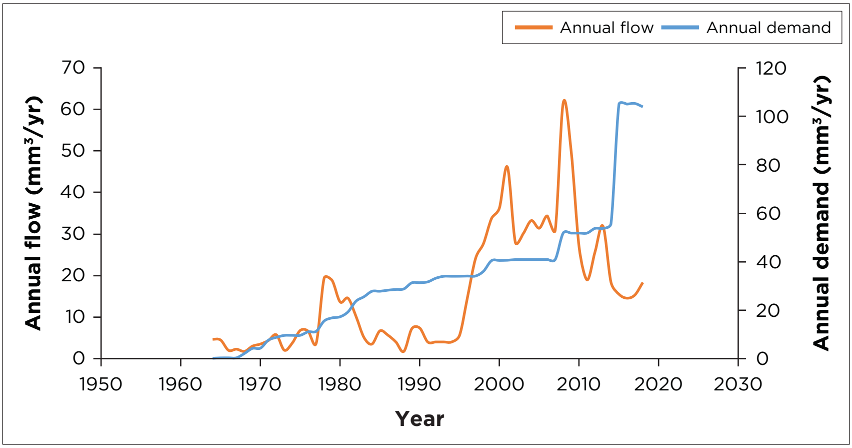


FIGURE 8.5: The annual flow of Chalimbana River and annual irrigation demand plotted against time.

Figure 8.6 shows the mean, maximum, minimum and median flows of Chongwe River at Great East Road Bridge from 1969 to 2018.

Figure 8.7 shows the annual flow of Chongwe River at Great East Road Bridge and annual demand plotted against time from 1970 to 2018.

The analysis of the Chongwe River at Great East Road Bridge shows a steady increase in the annual flow and water demand from 1960 to date. The analysis also gave a positive significant correlation value of 0.0484, which indicated an increase in both the minimum flow and demand of water.

However, the analysis of the *p*-value gave a value of 0.741 which was above the acceptable standards and this, therefore, indicated that the correlation was insignificant.

Further analysis of the correlation between rainfall and mean flow of the Chongwe River at Great East Road Bridge was done. The analysis gave a correlation value of 0.23 and a *p*-value of 0.11.

TABLE 8.5: Analysis of water used for irrigation and water not used in the catchment.

S/N	Parameter	January	February	March	April	May	June	July	August	September	October	November	December	Total
1	Potential evapotranspiration (mm/day)	5.5	5.2	5.3	4.7	5	4.8	5	6.3	7.9	8.7	7	5.7	71.1
2	Crop evapotranspiration (mm/day)	5.51	5.21	5.31	4.70	5.01	4.80	5.01	6.31	7.91	8.71	7.01	5.71	71.17
4	Rainfall depth (mm/day)	7.33	7.12	4.70	2.07	0.24	0.00	0.00	0.00	0.07	0.17	2.70	6.80	31.19
5	Irrigation requirement (mm/day)	0.00	0.00	0.61	2.64	4.76	4.80	5.01	6.31	7.84	8.54	4.31	0.00	44.81
6	Penman demand (million m^3/day)	0.49	0.47	0.48	0.42	0.45	0.43	0.45	0.57	0.71	0.78	0.63	0.51	6.38
7	Runoff (Rainfall volume plus base flow) (million m^3/day)	1.39	1.35	0.91	0.44	0.10	0.06	0.06	0.06	0.07	0.09	0.55	1.29	6.39
8	Irrigation demand (million m^3/day)	0.00	0.00	0.05	0.24	0.43	0.43	0.45	0.57	0.70	0.77	0.39	0.00	4.02
9	Flow (million m^3/day)	1.39	1.35	0.86	0.20	0.10	0.00	0.00	0.00	0.00	0.00	0.16	1.29	5.36
10	Water lost quickly (million m^3/day)	1.39	1.35	0.86	0.20	0.10	0.00	0.00	0.00	0.00	0.00	0.16	1.29	5.36

Percentage of water used for irrigation is 42.8% and 57.2% is not used. Irrigated area (ha) is 8966 ha and mean crop factor of 1.001 was used and base flow of 0.06 million m^3/day.

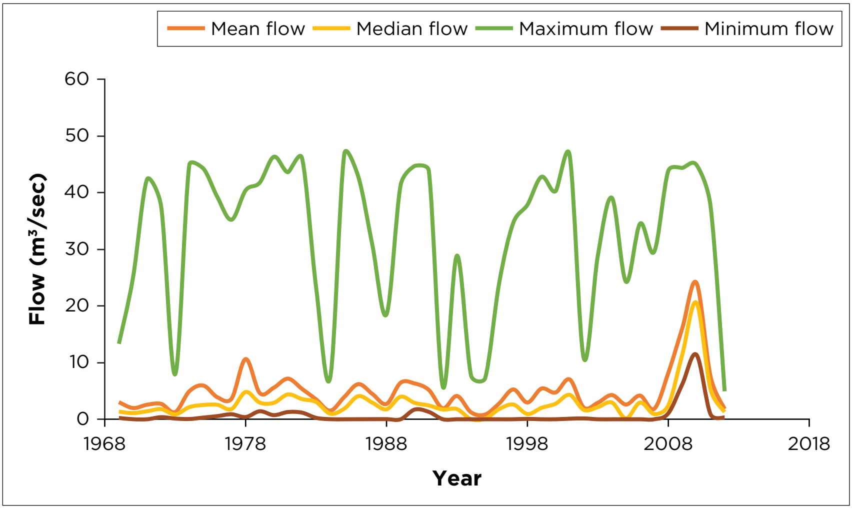


FIGURE 8.6: Flow patterns of Chongwe River at Great East Road Bridge.

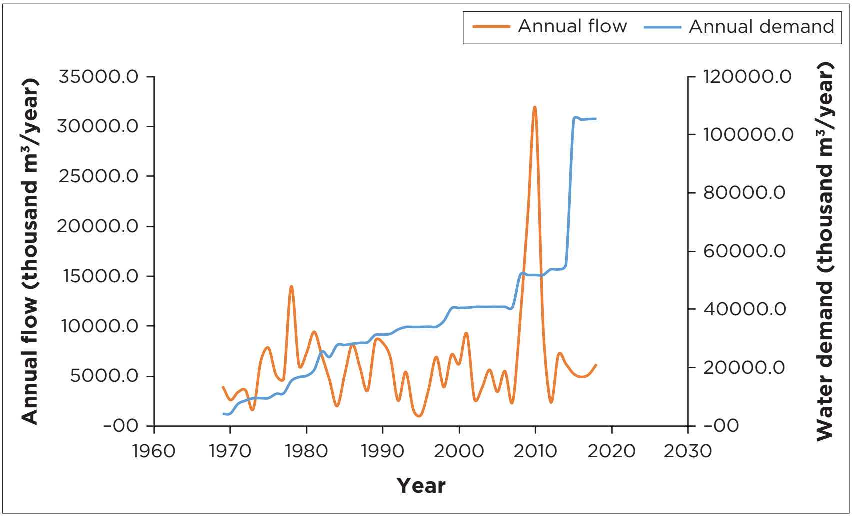


FIGURE 8.7: Flows of Chongwe River at Great East Road Bridge and annual demand plotted against time.

This, therefore, connotes that the increase in rainfall has caused an insignificant increase in mean flow.

Water demand and irrigated areas versus long-term flows

Table 8.6 shows the relationship results between water demand for irrigation and long-term flows, as well as irrigated field sizes against long-term flows.

Analysis of daily water demand versus daily flows

Results of the runoff analysis for Chalimbana River at Romar Farm are summarised in Table 8.7 and the flow patterns when water storage activities by farmers are put into consideration are depicted in Figure 8.8.

TABLE 8.6: Results of the impact of water demand and irrigation practices on water availability.

Station name	Measurement	Water demand versus flow			Irrigated area versus flow		
		Pearson correlation value	*p*	Remark	Pearson correlation value	*p*	Remark
Chalimbana River at Romar Farm	Mean	0.683	<0.05	Significant	0.615	<0.05	Significant
	Maximum	0.539	<0.05	Significant	0.652	<0.05	Significant
	Minimum	0.686	<0.05	Significant	0.626	<0.05	Significant
Chongwe River at Great East Road Bridge	Mean	0.3018	0.049	Significant	0.2165	0.153	Insignificant
	Maximum	0.099	0.528	Insignificant	0.053	0.731	Insignificant
	Minimum	0.3138	0.040	Insignificant	0.266	0.077	Insignificant

Note: Analysis of water demand and irrigated areas vs long-term flows at 0.95% confidence interval, $p < 0.05$ significant.

TABLE 8.7: Runoff analysis of Chongwe River at Chalimbana River at Romar Farm.

Month	Monthly rainfall mean (mm)	Runoff depth (mm)	Flow (m^3/month)	Flow (m^3/day)	Total flow (m^3/day)
January	219.85	21.99	2 594 230	83 685	85 197
February	213.55	21.36	2 519 890	86 893	88 405
March	141	14.10	1 663 800	53 671	55 183
April	61.95	6.20	731 010	24 367	25 879
May	7.3	0.73	86 140	2779	4291
June	0	0.00	–	–	1512
July	0	0.00	–	–	1512
August	0	0.00	–	–	1512
September	1.95	0.20	23 010	767	2279
October	5.05	0.51	59 590	1922	3434
November	81.05	8.11	956 390	31 880	33 392
December	204.1	20.41	2 408 380	77 690	79 202

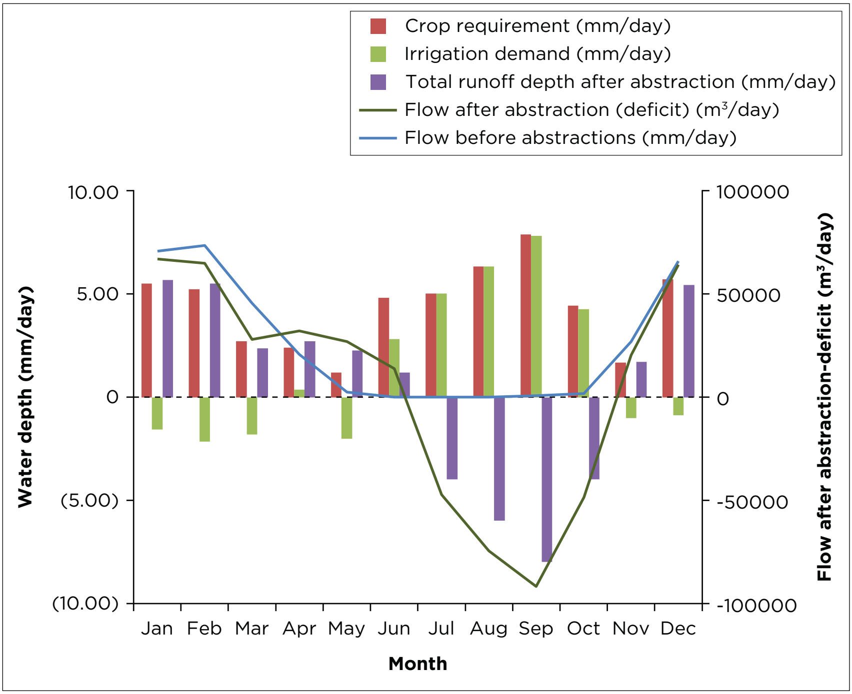


FIGURE 8.8: Flows and irrigation-demand pattern of Chalimbana River at Romar Farm.

TABLE 8.8: Runoff analysis of Chongwe River at Great East Road Bridge.

Month	Monthly rainfall mean (mm)	Run off depth (mm)	Flow (m^3/month)	Flow (m^3/day)	Total flow (m^3/day)
January	219.85	21.99	39 858 805	1 285 768	1 286 740
February	213.55	21.36	38 716 615	1 335 056	1 336 028
March	141	14.10	25 563 300	824 623	825 595
April	61.95	6.19	11 231 535	374 385	375 357
May	7.3	0.73	1 323 490	42 693	43 665
June	0	0	–	–	972
July	0	0	–	–	972
August	0	0	–	–	972
September	1.95	0.19	353 535	11 785	12 757
October	5.05	0.505	915 565	29 534	30 506
November	81.05	8.105	14 694 365	489 812	490 784
December	204.1	20.41	37 003 330	1 193 656	1 194 628

The FAO runoff coefficient is 0.1 and the catchment area is 118 km^2. Base-flow estimate is 1512 m^3/day from field measurement as flows near the end of the dry season were assumed to be base flow.

The results observed when catchment rainfall runoff and base flow were compared to irrigation demand for a better representation of reality. It was observed that water demand for irrigation causes no flow on the Chalimbana River from mid-June to November every year. After October, some runoff is generated from rainfall; however, the runoff is not enough to make the whole river flow because of high demand.

The FAO runoff coefficient is 0.1, catchment area was 1813 km^2, base-flow estimate was 972 m^3/day from the field-flow measurements and discharge near the end of the dry season was assumed to be base flow.

An analysis of flow and demand of Chongwe River at the Chongwe bridge is presented in Figure 8.9 and the analysis for the catchment is summarised in Figure 8.10.

When catchment rainfall runoff and base flow were compared to irrigation demand, it was observed that water demand for

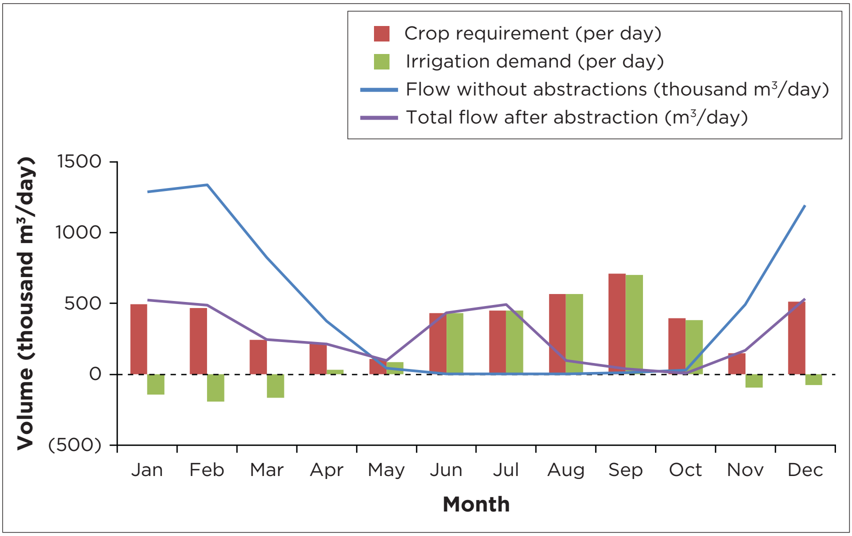


FIGURE 8.9: Flows and irrigation-demand pattern of Chongwe River at Chongwe Bridge.

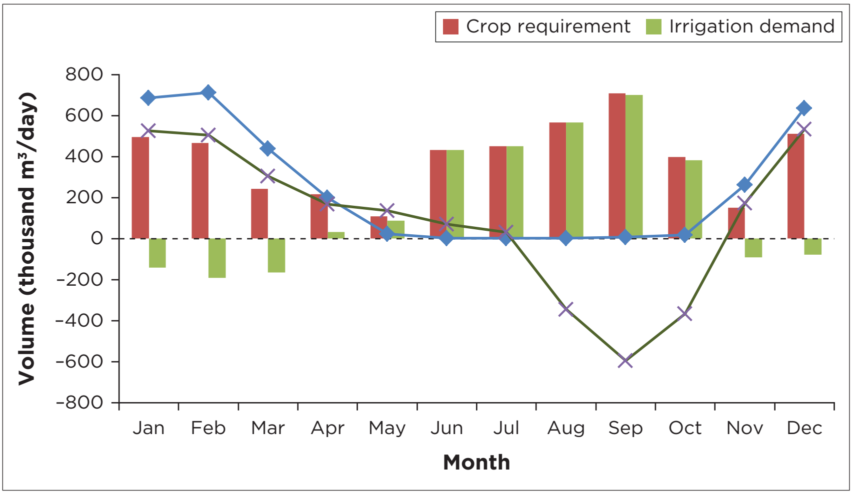


FIGURE 8.10: Flow and irrigation-demand pattern of Chongwe catchment outlet.

irrigation almost ceases the flow on the Chongwe River at Chongwe Bridge (Great East Road Bridge) from mid-September to October every year. This is the reason that during the same period there is a water crisis in Chongwe Township as the water level at Lusaka Water and Sewerage Company's abstraction point becomes too low to be pumped, thereby the company reduces its water supply to the public.

The overall results for the entire catchment showed that between July to October every year, the catchment will be having critical water shortages in several parts. However, after October, the situation should improve as some runoff generates. Nevertheless, the runoff in October will not be sufficient to sustain the river because of the high demand for irrigation.

Conclusion

The study observed that the demand for irrigation has been increasing since 1963. However, there has been a general increase in the flows. The average potential ET for September, the last month of irrigation, was computed to be 7.8 mm which is the maximum for all the months under irrigation (May to September) and Penman demand had increased from 492 m^3/day to 702 468 m^3/day. Analysis of the impact of demand on water availability gave positive correlation values. The increase inflows at the stations may be attributed to the construction of hydraulic structures such as dams, thereby increasing groundwater recharge, as well as surface water.

On the other hand, the analysis of daily flows versus demand revealed that during the irrigation period, daily water demand is generally higher than daily water availability. The high water demand is experienced during the irrigation season thus causing the river to dry up. Generally, the Chongwe River will be almost drying up between September and October because of the water demand for irrigation upstream, whereas the Chalimbana River will be drying up from mid-June and October.

Analysis of the impact of the increase irrigated area gave a positive correlation with water resources availability. As the irrigated area is increasing, mean flows of Chongwe are also increasing. This is attributed to changes in soil texture causing less groundwater recharged from rainfall, quick runoff from rainfall and its release out of the catchment. However, there was no observed dropdown in the minimum flow. This lack of dropdown in minimum flow was attributed to the following:

1. Release of effluent into the catchment by Lusaka Water and Sewerage and many other households. The amount of effluent needs to be determined by other researchers as there are many unknown points of effluent release into various streams of the catchment.
2. Few daily intervals of recording water-level data (three times a day only), thereby not recording certain important readings.
3. Construction of hydraulic infrastructures which may have increase groundwater recharge.
4. There is a good aquifer for groundwater and its source has a high piezometric level to which groundwater rises under hydrostatic pressure. Therefore, despite abstractions, water is being replaced from its source because of the hydrostatic pressure.

More research is needed in the following areas in order to have a better understanding of the impact of water demand on water availability in Chongwe catchment, as well as other catchments:

1. Rainfall runoff models development.
2. Research on possibilities of developing suitable hydraulic infrastructures to preserve water for use in time of peak water demand, so as to meet the water needs for irrigation. This can be done by first mapping areas that are good and suitable for dams, for example, putting into consideration the site's geology, hydrology, soil and other relevant factors.
3. Release of effluent into the catchment by the water and sewerage company and many other households. The research should involve mapping all the points of effluent discharge, as well as determination of the amount of effluent.
4. Capturing of real-time flow data for the catchment.

Chapter 9

Assessment of groundwater availability in a semi-arid river basin

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Abstract

Namibia continues to experience frequent droughts which affect the livelihood of most citizens, especially communal farmers.

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This is compounded by a growing population, the effects of climate variability and people's lifestyle, which call for research on the varying viable sources of water including underground water at locations that are most affected by the phenomena of climate change. This study focused on the assessment of recharge and storativity of groundwater with a specific look at the abstraction potential within the Kuiseb River basin in Namibia. The study used the quantitative convenient non-probability sampling method. Therefore, secondary data (the input parameters) such as borehole production volume and water level were sourced from Namibia Water Corporation (Ltd), also known as NAMWATER, whilst rainfall data were sourced from the NMS, as the two organisations granted access. Recharge and storativity were calculated using a programmed Saturated Volume Fluctuation (SVF) method, the November 2001 version for Namibia. The results further showed that about 37.3% of the rainfall recharges the aquifers with storativity of 0.0978. As a result of the geology of the aquifers in the upper Kuiseb formed in hard rocks, this creates a water table which is discontinuous with very low potential for abstraction.

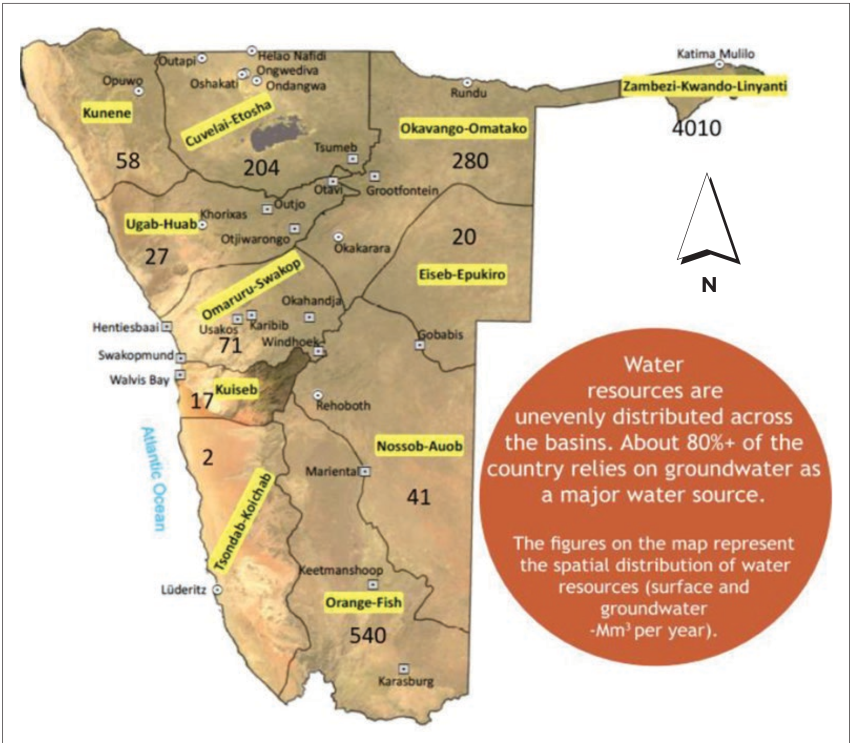
Keywords: Recharge; Storativity; Abstraction potential; Ground water; Saturated Volume Fluctuation.

Introduction

The scarce water resources in arid and semi-arid areas in the world are under increasing pressure because of a growing population, economic activities (manufacturing, mining and agriculture) and problems regarding surface-water quality are driving an increase in water requirements. As such, alternative sources of water are of importance in order to ensure that the water supply meets the demand, and groundwater may be an option (Bethune 1996).

In many regions of the world, groundwater resources are overexploited, threatened by pollution and managed in unsustainable ways. Thus, effective and sustainable water management is essential, which leads to investigations of the hydrological system in order to identify the natural state and the impact of environmental changes.

Utilisation of water and land resources in Namibia is managed at the lowest management level, known as the basin level. Therefore, Namibia is divided into 11 water management basins according to the common drainage flows of major water sources such as rivers, groundwater systems (aquifers), water supply canals and pipelines (Huntley 1985). The Kuiseb basin is located across parts of the Erongo and Khomas Regions. The basin is characterised by upper, middle and lower zones. Figure 9.1 shows the different river basins and the Kuiseb basin included as the main subject of this study.



Source: National Planning Commission (2010).

FIGURE 9.1: Namibia's water management basins and the study area.

The Kuiseb River basin

According to Huntley (1985), the Kuiseb basin covers an area of approximately 22 000 km², but most of the area receives very low rainfall of less than 50 mm per year on average, and such low rainfall produces very little to no runoff at all. Soils within the basin are not well developed and many are very shallow and derived from the bedrock on which they lie (BGR 1998). The combination of these factors makes the soil in the basin unsuitable for crop or agricultural production. According to Henschel, Seely and Zeidler (2000), the rainfall in this small area is responsible for determining the amount of water that flows down the river, the rate at which the river flows, the extent to which the water will flow and reach the basin, determining whether the aquifers in the lower catchments reaches will be recharged or not (Henschel et al. 2000).

Because of the lack of rainfall within the basin, the river does not flow for longer periods but rather for a short time when good rainfall of over 300 mm per year in the upper catchment is recorded. The flow of the Kuiseb River and the recharge of its underground waters depend entirely on the variable rains in the less arid eastern reaches of the basin (Mendelsohn & Obeid 2001).

The aquifers in the upper Kuiseb are made up of hard rock so the water is stored in the cracks, fractures and spaces of these rocks (Schneider 2004). The water table is said to be discontinuous which affects the potential of these hard rocks within the aquifers and limits its ability to hold water (Jacobson & Seely 1995). In the lower Kuiseb, the riverbed consists of unconsolidated grains of sand and gravel, so the water is stored between the particles and in the process forms an alluvial aquifer with a continuous water table.

Because of the nature of the terrain and climate variability, the rate at which the Kuiseb River flows and recharges its underground waters is entirely dependent on the timing and intensity of rains, especially in the less arid eastern reaches of the basin (Mendelsohn & Obeid 2001). Also, the soils throughout the basin are not well developed and most of them are very shallow and derived from the bedrock on which they lie. This, combined with little to very low rainfall, makes them unsuitable for crop production.

Also, it should be noted that groundwater is stored in an underground porous and permeable rock called an aquifer that enables the water to infiltrate and allows movement within the rock (Blom & Bouwer 1985). Thus we conducted this study to determine if the groundwater in the basin has the potential to be effectively recharged and stored in aquifers in the basin; and if there would be sufficient volumes of water released from the groundwater sources when needed in the basin. Therefore, the recharge and storativity of groundwater in the Kuiseb River basin were evaluated. The potential for the abstraction of water from the groundwater aquifers in the basin was assessed and a correlative analysis of the rock types, deposit and sediments with the physio-chemical quality of the groundwater was performed.

Recharge rates, abstractions and overexploitation of groundwater in the Kuiseb

According to Bate and Walker (1993), recharge is a hydrologic process of the movement of water downwards from surface water to groundwater. It is the primary method through which water enters an aquifer. Storativity can be described as the volume of water released from storage per unit surface area of the aquifer, per unit decline in hydraulic head. Recharge to the alluvial aquifers is facilitated by the vertical infiltration of runoff down the Kuiseb River and from through-flow within the alluvial aquifers, mainly during ephemeral flash floods (Barnard, Bethune & Kolberg 1998; Jacobson et al. 1995). The most important factor concerning recharge is the duration of the flood but not the intensity of the recharge. Because of high evaporation rates in Namibia, rainfall in the desert areas does not contribute significantly to groundwater recharge (NAMWATER 2001).

Depending on the intensity and location of rainfall in the catchment area, flash floods occur in the main streams and, as such, the amount of water and the duration change. According to Crerar, Fry and Slater (1988), every several decades a flash flood in the Kuiseb reaches the Atlantic Ocean, the last time in the 1962–1963 rain season, though flash floods since then, have not gone past the Rooibank. Most of the flash floods occurred in the eastern half of the catchment area and can recharge the groundwater below the dry bed of the lower Kuiseb (Kuells & Heidbuechel 2006).

At some places along the river basin bed, very small amounts of water from the flash floods reach the aquifer in the dunes area via the palaeochannels of the Kuiseb. This area was mapped as part of hydrogeological studies based on data from an aerial geophysical survey (Sengpiel & Siemon 1997). Correlation of borehole data with the maps of apparent resistivity prepared from the electromagnetic data show that palaeochannels of the Kuiseb cut through the Tsondab sandstone into the basement. In the lower Kuiseb dune area, according to findings of transmission loss, measurements by Kuells and Heidbuechel (2006), low water tables appear in the upper part and very high water tables in the lower part of the area and, as such, the assumption that a high water table reduces transmission losses even in arid regions can be supported by this finding.

A 14C in Kuiseb delta indicates that most of the groundwater is recent (Kuells & Heidbuechel 2006). BGR (1998) underlined that the groundwater table measurements in some parts of the palaeochannels and near the present Kuiseb River had to be viewed as a momentary picture of a continual natural drainage of the aquifer which, owing to its low permeability, may be assumed to occur very slowly. Kuells and Heidbuechel (2006) found that 14C ages indicates that groundwater in some palaeochannels was recharged about 4000 years ago by infiltration of river water. Kuells and Heidbuechel (2006) further stated that the places where the palaeochannels intersect the Kuiseb River are potential areas for infiltration, especially in the area west of Swartbank and there are springs at numerous places along the coast and at the lagoon at Sandwich Harbour.

Elango and Kannan (2007) studied the relationships between rainfall recharge and groundwater-level fluctuation with regard to the lower Palar River basin in Tamil Nadu, India, where they prepared hydrographs and isohyetal maps for carrying out an analysis of groundwater level.

Methods/study approach

Study area

The Kuiseb, an ephemeral river with a length of 560 km, drains a catchment of approximately 14 700 km^2 in west-central Namibia (Kuells & Heidbuechel 2006). Only the upper 9000 km^2 of this area is considered to be producing significant runoff, whilst the remaining part of the catchment area forms an arid to hyper-arid desert plain yielding runoff only in exceptionally wet years (Jacobson & Seely 1995). The Kuiseb River is bound to a clearly well-defined river bed until it reaches the lowlands in the delta area and hydraulically, the Kuiseb is the most monitored river of western Namibia, fitted with 8 rainfall and 14 flow gauging stations, distributed within the catchment. Records observed at Gobabeb over the years indicate that the river flows to a maximum of 105 days per year. In the early 1980s, the river did not flow at all for more than 4 years (Shanyengana 1997). Figure 9.2 shows the boreholes within the Kuiseb River basin.

Manning and Pallet (2004) report that the Kuiseb River basin is divided into three sub-basins. The upper Kuiseb River reaches from the Khomas Highlands through the escarpment in a generally well-incised river bed in the south-west direction over 220 km as far as Hudaob. The middle Kuiseb River, between Hudaob and Natab, flows for 40 km in the West North-West direction within a narrow, canyon-like river bed (Manning & Pallet 2004). From Natab downstreams, the lower Kuiseb River changes in a general north-west direction and flows for over 75 km within a

Source: Ministry of Mines and Energy (2018).

FIGURE 9.2: Boreholes within the Kuiseb basin.

broad, sandy river bed towards the delta region west of Rooibank, inland of Walvis Bay and the river rarely reaches the Atlantic Ocean (Huntley 1985).

Data collection and analysis

Secondary data (the input parameters) such as borehole production volume and water level were sourced from Namibia Water Corporation (Ltd), also known as NAMWATER, whilst rainfall data were sourced from the NMS.

The estimation of both storativity and groundwater recharge was done by using a programmed SVF method, the November 2001 version for Namibia.

The values of storativity, which were estimated from previous aquifer tests, as well as from the balance between the water flowing into the aquifer and the water flowing out in a given section of an aquifer, calculated from a cross-sectional area, topographical gradient and permeability of an aquifer, enabled the authors to estimate recharge using the balance between rainfall and the volume of the water, abstracted from the aquifer by simulating changes in the groundwater level over a given period of time.

The recharge was calculated using the SVF method, the November 2001 version for Namibia. The SVF method utilises the following formula:

$$I - O + Re - Q = S\frac{\Delta V}{\Delta T} \qquad \text{[Eqn 9.1]}$$

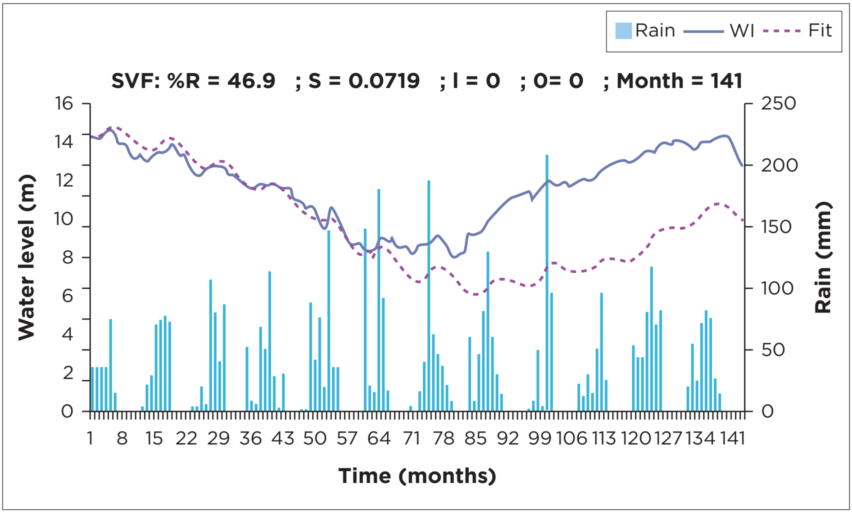
where S is the storativity, ΔV is the change in saturated aquifer volume, I is the lateral inflow, O is the lateral outflow, Re is the recharge, Q is the net discharge and Δt is the change in time.

Results

Recharge and storativity

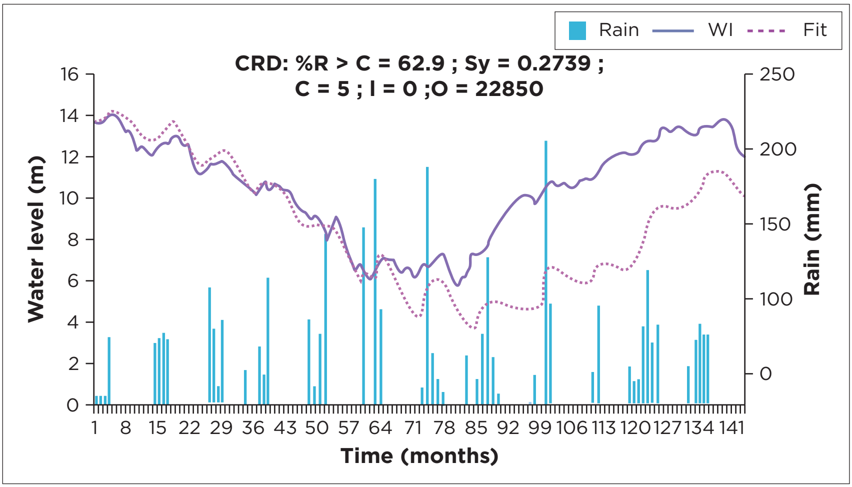
It has been observed that recharge to the aquifers of Kuiseb basin occurs mainly through the vertical infiltration of runoff down the dry Kuiseb River and from through-flow within the alluvial aquifers, mainly when there are ephemeral flash floods. During such a period, the flood duration plays a major role in recharging the groundwater, as opposed to their intensity. Because of the high evaporation rates in Namibia, rain in the desert areas does very little to contribute significantly to the recharge of the groundwater. Recharge percentages, storativity and the specific yield of the Kuiseb basin are shown in Figure 9.3 to Figure 9.6.

The figures show a mean percentage recharge of 46.9% and 27.6%, and storativity of 0.0719 and 0.0637 for the combined



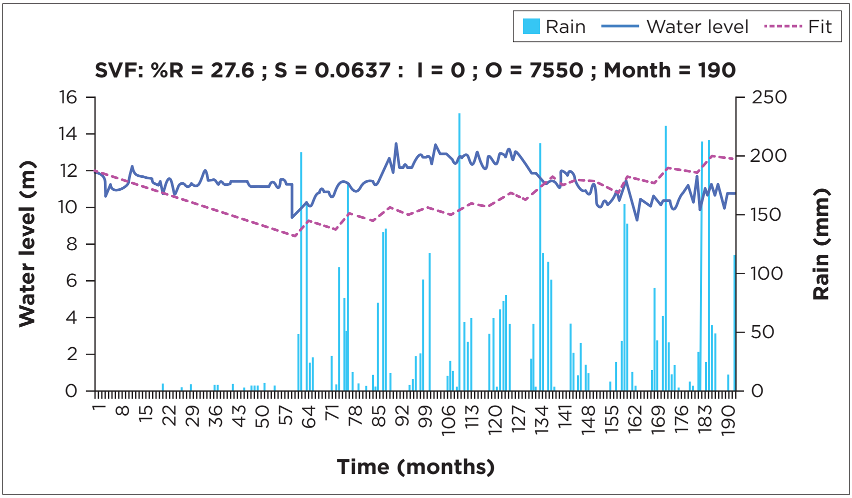
Source: Authors' own model results produced using secondary data provided by the Namibia Water Corporation (Ltd) (NAMWATER 2018b) and the NMS (2018).
I, inflow; O, outflow; %R, percentage recharge; S, storativity; SVF, Saturated Volume Fluctuation.

FIGURE 9.3: Recharge percentages and storativity of Swartbank-Rooibank A compartment.



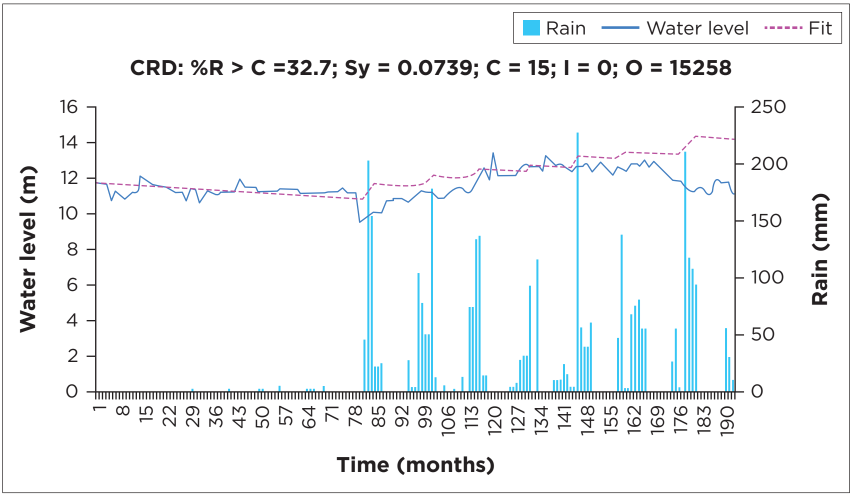
Source: Authors' own model results produced using secondary data provided by the Namibia Water Corporation (Ltd) (NAMWATER 2018b) and the NMS (2018).
C, cut off; CRD, cumulative rainfall departure; I, inflow; O, outflow; %R, percentage recharge; Sy, specific yield.

FIGURE 9.4: Recharge percentages and specific yield of Swartbank-Rooibank A compartment.



Source: Authors' own model results produced using secondary data provided by the Namibia Water Corporation (Ltd) (NAMWATER 2018b) and the NMS (2018).
I, inflow; O, outflow; %R, percentage recharge; S, storativity; SVF, Saturated Volume Fluctuation.

FIGURE 9.5: Recharge percentages and storativity of Dorop South and Rooibank B.



Source: Authors' own model results produced using secondary data provided by the Namibia Water Corporation (Ltd) (NAMWATER 2018b) and the NMS (2018).
C, cut off; CRD, cumulative rainfall departure; I, inflow; O, outflow; %R, percentage recharge; Sy, specific yield.

FIGURE 9.6: Recharge percentages and specific yield of Dorop South and Rooibank B.

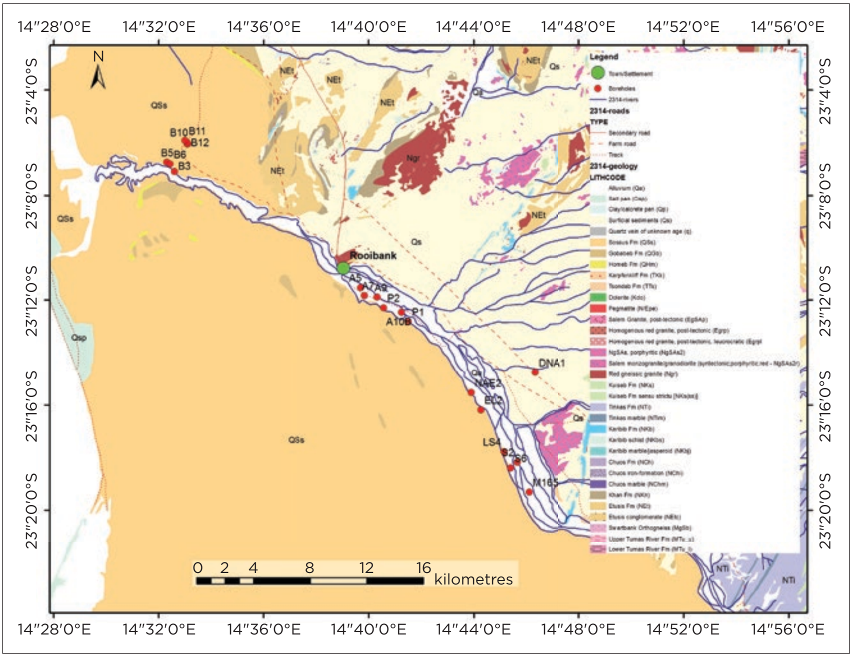
Swartbank-Rooibank A and Dorop South–Rooibank B, respectively. The result implies that there is about 46.9% and 27.6%, which averages to about 37.3% of the rainfall recharge for the Kuiseb aquifers. However, it is important to note that, depending on the intensity and location of rainfall in the catchment area, the amount of water and the duration of the flow determine recharge (De Vries & Simmers 2002). Literature indicates that every several decades a flash flood in the Kuiseb basin reaches the Atlantic Ocean, and the last time that happened, was during the 1962–1963 rain season. Flash floods since then have gone no further than Rooibank, except to Dorop in 1996/1997 (Jacobson & Seely 1995).

The flow of the Kuiseb River and the recharge of its aquifer depend entirely on the variable rainfall in the less arid eastern reaches of the basin. Rainfall does very little to help recharge aquifers as the rain is mainly responsible for most of the runoff. Muinjo (1998) reported that rainfall in and around the basin determines the volume of water that flows down the river, the frequency at which the river flows, the farthest distance the water reaches and whether the aquifers in the lower Kuiseb will be recharged by runoff or not. It is, however, important to note that there are some limitations to calculating the percentage recharge and storativity, using this method, because the balance between inflow and outflow is not known, resulting in a lot of assumptions that one has to make. In addition, storativity and specific storage are not well established because it requires further calculations of the pumping rate, an exercise not covered in this study.

Abstraction potential

Geology of the Kuiseb

The geology of the Kuiseb is depicted in Figure 9.7. The Kuiseb portrays the gravel plains of the Namib, underlain by massive granite and covered by thin soils in the north, from the dune fields

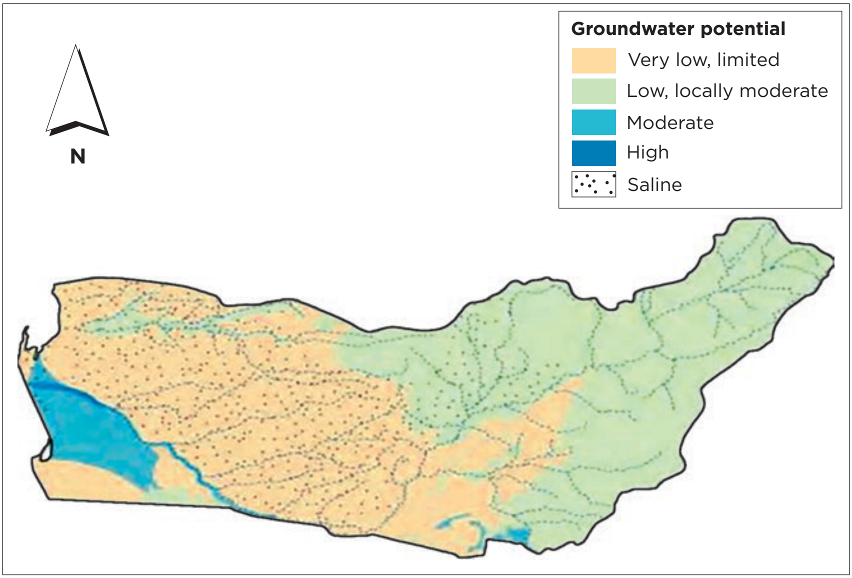


Source: Ministry of Mines and Energy (2018).

FIGURE 9.7: Geology of the Kuiseb basin.

of the Namib Sand Sea in the south (Kuells & Heidbuechel 2006). According to Kuells and Heidbuechel (2006), the following are the main aquifer types found in the basin: alluvium (Swartbank), palaeochannels, sandstone, Kuiseb River sediments, palaeo channels sediments and Tsondab sandstone.

According to BGR (1998), it is not the age of the rock that influence runoff but rather the type of rock, and it is these rocks that determine its capacity to store groundwater or not, and how accessible that water is. Rainwater that infiltrates into the ground passes through the cracks in the rock and between the soil particles. The alluvial aquifers (Figure 9.8) in the lower Kuiseb are extensive in such a way that they run eastwards from Swartbank



Source: Directorate of Water Affairs (2009).

FIGURE 9.8: Alluvial aquifers in the lower reaches of the Kuiseb that are relatively high-yielding.

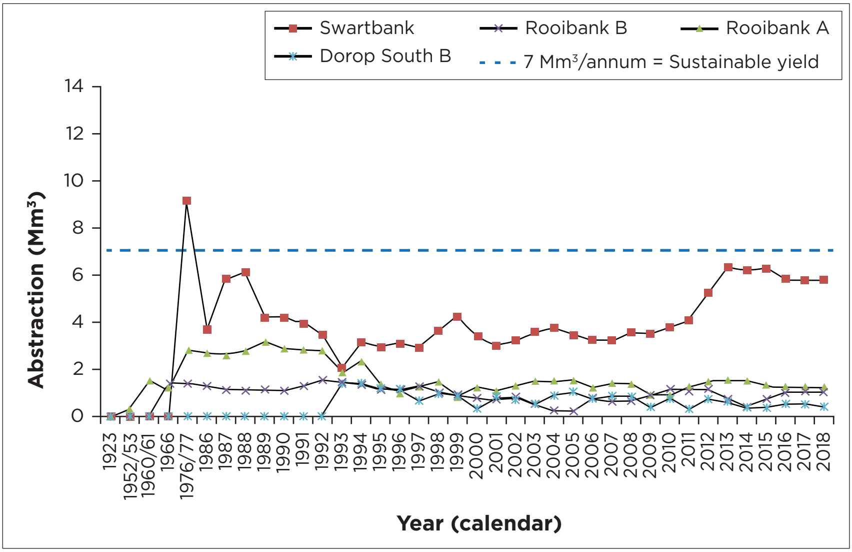
to the Kuiseb delta, and they are compartmentalised into four aquifers (BGR 1998). The Swartbank and Rooibank A aquifers form one continuous aquifer which is separated from Rooibank B and Dorop South aquifers by a hard rock barrier (Huntley 1985). It is thought that they are all interconnected, but the route and rates of percolation are not well understood. There is a series of palaeochannels running through the underlying Tsondab sandstone south of the river along which groundwater flows towards Sandwich Harbour.

A report by BGR (1998) further indicated that the aquifers in the upper Kuiseb are formed in hard rock, with the water being stored in the cracks, fractures and spaces within the rock. The water table is discontinuous and in general the potential of these hard rock aquifers is limited. However, Huntley (1985) reported that the riverbed in the lower Kuiseb consists of unconsolidated grains of sand and gravel so the water could be stored between the particles, forming an alluvial aquifer with a continuous water table. These alluvial aquifers in the lower reaches are extensive, relatively high-yielding and they have been exploited for over five decades (Huntley 1985).

□ Historic groundwater abstraction

Namibia Water Corporation (Ltd) is operating the abstraction areas, namely, Rooibank A and B, Dorop South and Swartbank for the water supply of most parts of the Erongo region. According to information provided by NAMWATER (2018a), 58 of the production wells are located in the lower Kuiseb abstraction areas. The historic groundwater abstraction in the lower Kuiseb aquifers is illustrated in Figure 9.8 (data provided by NAMWATER 2018b). Since 1923, groundwater has been abstracted from the Rooibank A area, followed by Rooibank B area in 1966. To supply additional water to Rössing Uranium Mine (and before the Omdel aquifer was developed), the Swartbank well field was established and abstraction started in 1977. Just after the development of the Swartbank aquifer in 1977, abstraction peaked at about 13 Mm^3/a. Meanwhile, the sustainable yield of 7 Mm^3/annum as derived from the 2001 model application by C. Wessels (NAMWATER 2001) , is currently applied as the basis of recommending abstraction strategies for the lower Kuiseb aquifers and this is represented by the dashed blue line in Figure 9.9.

Abstraction figures for the Swartbank well field officially date back to 1986, whereas those for the Rooibank (A & B) and Dorop well fields date back to 1993 when the schemes were taken over by the Department of Water Affairs from the Municipality of Walvis Bay. According to NAMWATER (2018a) information, a

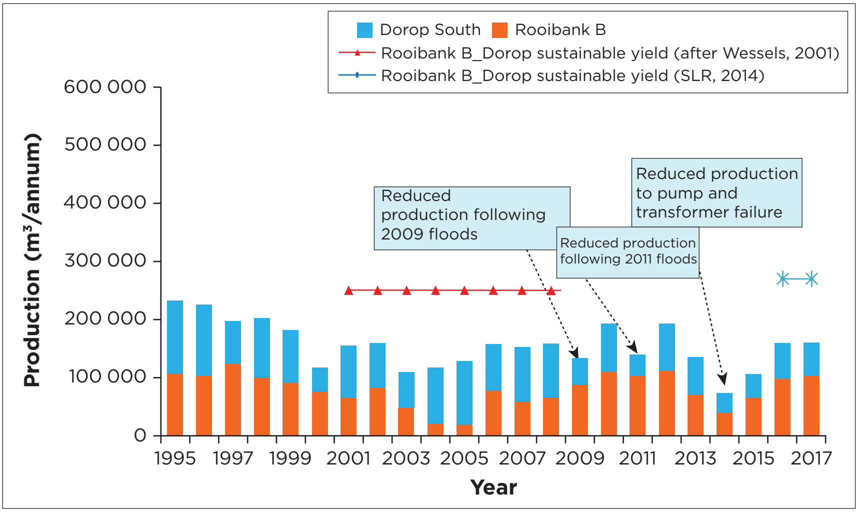


Source: NAMWATER (2018a) and Wessels (2001).

FIGURE 9.9: Historical perspective of groundwater abstraction in the lower Kuiseb.

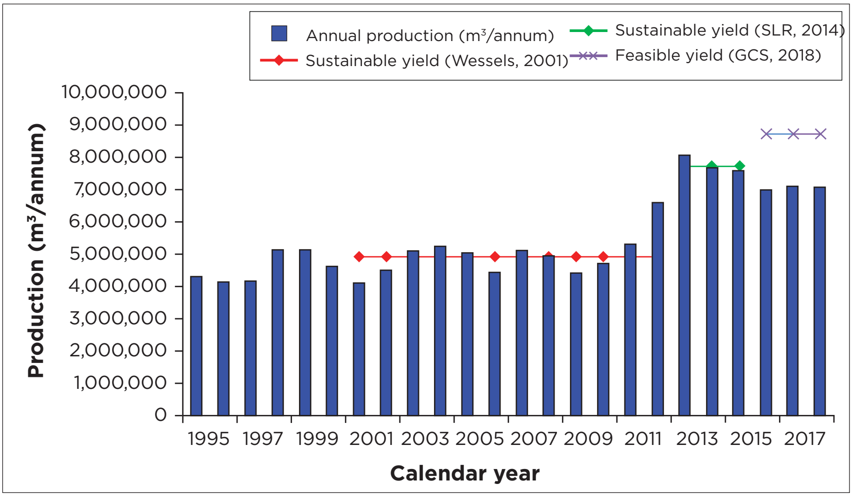
total of 60 production boreholes in the lower Kuiseb aquifers are currently being operated: 32 in Swartbank, 9 in Rooibank A, 11 at Rooibank B and 8 at Dorop South.

In Figure 9.10 and Figure 9.11, annual production volumes are illustrated respectively for the Rooibank A–Dorop South and Swartbank-Rooibank A compartment. A recent available numerical groundwater-flow model assessment, as reported by NAMWATER (2018a), indicates that the total sustainable yield of the active Kuiseb is 4.9 Mm^3/a which, if added to an additional 2.5 Mm^3/a of the Kuiseb delta (Rooibank B and Dorop South), will account for the total sustainable yield of the Kuiseb to 7.4 Mm^3/a (Table 9.1). If the environmental demand of about 0.8 Mm^3/year is included into the equation, it can be concluded that the sustainable yield for the active Kuiseb between Swartbank and the Delta is in the order of 7 Mm^3/year. With regard to the currently recommended sustainable abstraction, the Swartbank compartment is overutilised.



Source: NAMWATER (2018a).

FIGURE 9.10: Annual production for Rooibank B and Dorop.



Source: NAMWATER (2018a).

FIGURE 9.11: Annual production for Swartbank and Rooibank A.

TABLE 9.1: Sustainable yields calculated for Kuiseb aquifers.

Aquifer compartment	Flow components	Volume (Mm^3/annum)
Swartbank-Rooibank A compartment	Through flow	+0.30
	Recharge from runoff	+5.90
	Sub-total gain	+6.20
	Minus through flow loss (to dune area)	−1.30
	A: Sustainable yield Swartbank-Rooibank A	+4.90
Delta aquifer (Dorop South & Rooibank B)	Recharge from runoff	+2.75
	Minus through flow loss (to sea)	−0.25
	B: Sustainable yield Delta aquifers	+2.50
Kuiseb aquifer (A+B)	Sustainable yield	7.40

Source: NAMWATER (2001).

■ Conclusion

The recharge and storativity results showed a mean percentage recharge of 46.9% and 27.6% for the combined Swartbank-Rooibank A and Dorop South–Rooibank B, respectively. This implies that on average about 37.3% of the rainfall recharges into the Kuiseb aquifers. It is, however, important to note that depending on the intensity and location of rainfall in the catchment area, the amount of water and the duration of the flow determine the recharge. These findings are similar to Kuells and Heidbuechel (2006) who reported that the flow of the Kuiseb River and the recharge of its underground waters depended entirely on the variable rains in the less arid eastern reaches of the basin. Rainfall within the basin does very little to help recharge the aquifers but runoff along the basin determines the volume of water that flows down the river, the frequency at which the river flows, the furthest distance to which the water reaches and whether the aquifers in the lower reaches will be recharged or not (Kuells & Heidbuechel 2006).

The groundwater potential is a result of the geology of the aquifers in the upper Kuiseb, formed in hard rocks, and the water stored in the cracks, fractures and spaces within the rock. Together these create a discontinuous water table and, as such, the potential of these hard rock aquifers is limited with a very low potential for abstraction. The growing future demand, therefore, requires that authorities invest in an additional water supply by either optimising groundwater as an immediate remedy or, in the longer run, by exploring options such as surface-water dams or desalination plants. This finding proves to be in line with a report by Kuells and Heidbuechel (2006), who indicated that the currently available natural water resources of the Kuiseb and Omdel scheme cannot accommodate the growing population, as well as the mining demand in the Erongo region, unless this is increased to a maximum of 15.9 Mm^3/annum by developing other natural resources within both catchments. The construction of another additional desalination plant could be the most viable solution to meet the water demand, especially for future uranium mines.

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Conclusion

Postscript

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In Chapter 1, we found (using the Tanzanian studies) that most studies address the water and climate aspects separately. The model development, verification, simulations, projections, et cetera. do not necessarily lead to a water–climate output that can inform the implementation of the existing water policies/strategic plans. Moreover, only 30% of the studies could be linked to local adaptation and mitigation strategies, mostly in areas such as sustainable water-resource planning, basin management and water conservation.

Modelling the impact of regional climate change scenarios on the availability of water resources in a semi-arid river basin (ch. 2), the possible impact of climate change was projected to occur by mid-century as follows: rainfall decreases by 14%, a decrease in surface runoff by 11%, a 15% decrease in water yield, as well as a decrease in PET by 11%. The rainfall, surface runoff, water yield

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and PET are also referred to as water- balance components. Regional climate models are widely used in regional assessment of climate change impact. However, the reliability of the individual models needs to be assessed before using their output for impact assessment (Luhunga et al. 2016).

It is not always possible to determine the reliability of models without sufficient baseline and/or field data. The SADC is challenged by a lack of scientific data to inform policy and implementation. Thus, we evaluated the effectiveness of the AFDM in providing reliable information for precipitation extremes research, decision making and utilisation by local farmers; and suggesting procedures for making the tool user-friendly to all stakeholders (i.e. researchers, farmers and water managers). We found in Chapter 3, that the AFDM tool can generate historical data of more than 50 years. The study also found that the data generated, using the AFDM, were not always in agreement with ground-based observations of precipitation. This showed that the tool does not report one form of precipitation (e.g. rainfall) but combines all forms, that is rainfall, fog, snow and other potentially precipitable water in the atmosphere.

We investigated suitable tools (ch. 4 and ch. 5) to be used for short- and long-term projections of precipitation and other climate-related extremes in the region. The EPEs, Prcptot, CDD, CWD, R10, R20, Rx1 and Rx5 were assessed for selected towns. All indices of precipitation extremes showed a decreasing trend in the seasonal total rainfall and CWD, whereas there was an increasing trend in CDD. Moreover, we observed a decreasing trend in 1-day maximum rainfall, 5-day maximum rainfall, the intensity of the daily rainfall over 25 mm during the winter and 50 mm during summer, which together may indicate a future decrease in the magnitude and intensity of precipitation events.

Reduced precipitation and water flows could exacerbate drought and scarcity, thereby diminishing agricultural productivity, endangering public health, impacting migration and settlement patterns, and placing considerable strain on people's livelihood and social well-being. Similarly, increased rain events and water flows could produce destructive floods jeopardising human lives, destroying crops and habitats, forcing human relocation and damaging the social fabric of communities. The two precipitation-related challenges confirmed the need to develop water–climate tools suitable to the region.

Therefore, we develop mixed strategy game models needed for generating baseline data on the water–air interactions (ch. 5). We found dominantly 'year-oriented' trends for humidity and temperature data but 'station-oriented' for wind- speed data. The leaf- wetness profiles also follow more of a station-oriented pattern.

Observation of year-orientation and station-orientation patterns from the data simulations for some of the meteorological factors suggests the need for large data from more stations for further investigation towards identifying generalised patterns in the whole region.

We proceeded to assess drought occurrence, frequency, intensity and classification; and the effectiveness of AFDM data generator using SPI approach in Chapter 6. We verified the tools (AFDM and SPI) against ground-observed data. Reliability assessment of the modelled SPIs was performed at 95% (Tcrt = 1.96) confidence interval for SPI (1, 3, 6 and 12) for the two towns and this shows decreased significance differences (ts < tcr) for all timescales, thus suggesting reliable results.

water–climate information can inform planning in the agriculture and water management sectors. However, an understanding of the water demand and climatic effects is crucial to ensure water security in the SADC. We assessed the effective multi-sectoral water allocation plan in the Kafue basin considering the impact of climate change (ch. 7). Simulation of the water allocation plan was done using a WEAP model.

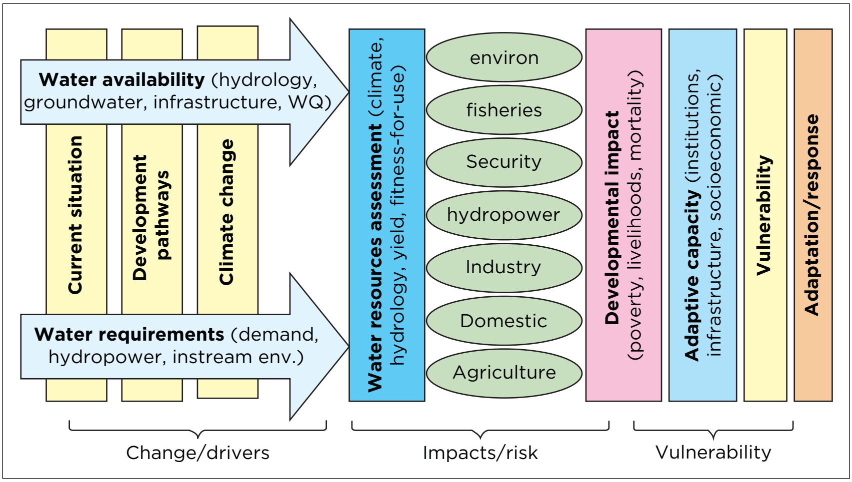
The WEAP model was simulated including two climate scenarios that are RCP 8.5 and MRCP 4.5. The simulation using mass balance principles in allocating the water resources in the

Kafue basin also showed that climate change has an effect on the available water in the Kafue basin. All RCPs under different models resulted in reduced flows along the Kafue basin, and this knowledge is vital for optimising water allocation in the basin. For the period 1980 to 2010, both RCPs showed slight differences in climate change and this was attributed to climate variability, whilst the differences between 2046 and 2076 were attributed to climate change because of higher GHG emissions.

We determined water demand for irrigation in the Chongwe catchment and its impact on water availability in the catchment in Chapter 8. The study observed that the water demand for irrigation has been increasing since 1963. However, there has been a general increase in the flows. The average PET for September, the last month of irrigation was computed to be 7.8 mm which is the maximum for all the months under irrigation (May to September) and Penman demand had increased from 492 m^3/day to 702 468 m^3/day. Analysis of the impact of demand on water availability gave positive correlation values. The increased inflows at the stations may be attributed to the construction of hydraulic structures such as dams.

Noting the fact that arid countries including Botswana and Namibia do not have consistent surface water, rely on groundwater for a sustainable supply. Therefore, we assessed groundwater availability in River Basins in Chapter 9 focusing on the assessment of recharge, storativity and abstraction potential within the Kuiseb River basin in Namibia. The results further showed that about 37.3% of the rainfall recharges the aquifers with a storativity of 0.0978. As a result of the geology of the aquifers in the upper Kuiseb, formed in hard rock, this creates a discontinuous water table with very low potential for abstraction.

Thus, a conceptual framework for assessing the impact of climate change on the water resources, similar to the one proposed by Pegasys (2009) and depicted in Figure 10.1 is herein proposed.



Source: Pegasys (2009).

FIGURE 10.1: Conceptual framework for managing the impact of climate on water resources.

Implementation of the framework will ensure effective water-resources management and climate -change adaptation in Southern Africa. It will ensure a transdisciplinary approach to selection, development and adaptation of water–climate management tools in the region where the researchers, water managers and users all contribute to the development, clarification and contextualisation of the water–climate challenges, the co-production of knowledge, and the production and implementation of solutions.

Therefore, taking the SADC forward, the combined effort of water and climate researchers, water managers, environmental managers, the private sector and local communities can help to improve on the climate, water insecurity and limited socio-economic development of the region.

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Preface

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The SADC region is characterised by a high level of interconnectedness between sovereign states because of the shared nature of surface water flows. Significantly, there are more transboundary river systems in the region than there are individual sovereign states in the SADC region. This is recognised in the SADC Water Protocol, the foundation document ratified when the SADCC became the SADC. This book contextualises that shared water resource management within a bigger context of climate resilience and hydrological security. It represents new thinking about the universal problem of how to create issue-linkage and spill-over as drivers of regional integration where the source of all national socioeconomic wellbeing is water over which no single country has a monopoly. It opens the discussion to include the management of groundwater in the context of ephemeral river basins where surface flows are sporadic and precipitation events increasingly unpredictable. It also embraces the African Flood and Drought Monitor (AFDM) tool developed by UNESCO. It provides a valuable resource for researchers, policy makers and investors as they make decisions about an uncertain future in a world where water is an economic enabler. It shows that lessons learned in Africa can be applied elsewhere in the world, for knowledge about a fundamental natural resource knows no political or ideological boundaries.

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Issues of water security and climate adaptation must be addressed in a world of changing climate. Water is a basic human need, yet its unavailability hinders human survival and nation development. This book assembles studies which shine light on this issue in SADC countries and offers insights on the knowledge gaps and solutions.

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