DEVELOPING INTEGRATED CLIMATE CHANGE ADAPTATION STRATEGIES USING THE WATER-ENERGY-FOOD NEXUS APPROACH: A CASE STUDY OF THE BUFFALO RIVER CATCHMENT, SOUTH AFRICA

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Bioresources Engineering, School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, South Africa. The research was financially supported by:

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The contents of this work have not been submitted in any form to another university, and except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

[redacted]

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Signed: Dr A Senzanje

Date: 02 April 2023

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Signed: Prof. T. Mabhaudhi

Date: 02 April 2023

DECLARATION OF PLAGIARISM

I, Nosipho Dlamini, declare that:

1. The research reported in this thesis, except where otherwise stated, is my original research.
2. This thesis or any part of it has not been submitted for any degree or examination at any other university.
3. This thesis does not contain any other persons' data, pictures, graphs or other information unless specifically acknowledged as being sourced from those persons.
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Nosipho Dlamini

DECLARATION OF PUBLICATIONS

The following manuscripts were submitted to journals

1. Assessing Climate Change Impacts on Surface Water Availability using the WEAP Model: A Case Study of the Buffalo River Catchment, South Africa (under review)
   Dlamini, N, Senzanje A, Mabhaudhi, T
   Journal: Journal of Hydrology: Regional Studies

The following manuscript is under preparation and set for submission to a journal

1. The Water-Energy-Food Nexus as a Tool to Develop Climate Change Adaptation Strategies: A Case Study of the Buffalo River Catchment, South Africa
2. Modelling the Water Supply-Demand Relationship in the Buffalo River Catchment, South Africa, Under Climate Change

The following chapter is under preparation for submission as a book chapter

1. Understanding the Nexus between Water, Energy and Food in the Context of Climate Change: A River Basin Perspective (under review)
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The following paper was presented at national and international conferences

1. Kenya Society of Environmental, Biological and Agricultural Engineers (KeSEBAE) Virtual Annual Conference on *Engineering for Transformation*, 25 November 2021
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In all the above papers and manuscripts, the conceptualization of the idea was done by N Dlamini (student), and A Senzanje and T Mabhaudhi (supervisors). N Dlamini conducted the research and the write up while the supervisors corrected and proof-read the manuscripts.

In the book chapter, the conceptualization of the idea was done by N Dlamini (student), C Taguta and TL Dirwai (co-authors) and A Senzanje and T Mabhaudhi (supervisors). N Dlamini, C Taguta and TL Dirwai conducted the research and the write up while supervisors corrected and proof-read the chapter.

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Nosipho Dlamini

ABSTRACT

South Africa's climate has high spatial and temporal variability. Literature on historical rainfall patterns shows substantial declines in rainfall across the country, except in south-western South Africa, which displays increasing trends. Under the Representative Concentration Pathways (RCPs) 4.5 and 8.5 scenarios, statistically downscaled rainfall projections show different patterns across South Africa throughout the 21st century. Literature indicates that this uncertainty will majorly impact South Africa's surface water availability as its main input variable is rainfall; hence, all possible outcomes need to be planned for. Planning should include the energy and food production sectors as they primarily depend on the water sector. The Buffalo River catchment, situated in the northern parts of KwaZulu-Natal, South Africa, is a high rainfall receiving area, with a mean annual precipitation of 802 mm. Despite its abundant rainfall, the catchment has had its fair share of droughts, significantly impacting livelihoods and socio-economic activities. Recent reports indicate that the Buffalo River catchment's surface water storage facilities are insufficient to meet the population's demands by 2050. A detailed water resources assessment is required to confirm and quantify the possible alterations that climate change could cause to the catchment's hydrology before any actions can be taken, especially regarding increasing the water storage capacity of the catchment.

As such, this study aims to investigate and assess the impacts of climate change on the Buffalo River catchment's surface water availability and reliability of water resources in meeting projected water demands, with a specific focus on agricultural and energy generation water demands. Furthermore, the study aims to develop integrated water resources adaptation strategies to increase water, energy and food security within the catchment.

Due to its transdisciplinary nature, the Water-Energy-Food (WEF) nexus methodology was used as an analytical tool to carry out the research's objectives. The study was based on the null hypotheses of climate change not varying surface water availability and reliability, and that the optimized CC water management strategies will not yield any improvements in merging potential gaps between water supply and demands.

Study findings indicate that the Buffalo River catchment is anticipated to receive increases in precipitation magnitude and fluctuations throughout the 21st century. However, the increases in surface water availability that result from the anticipated rainfall increases are insufficient and unreliable to meet the rise in demands for water within the catchment, more so the irrigation demands. Through investigating the catchment's already-existing proposed climate change policy interventions for water resources management, the study found that they were centred around boosting domestic water provisions whilst only meeting <3% of projected demands by the energy and agricultural sector. As such, by optimizing these policy plans using the WEF nexus' Climate, Land-Use and Water Strategies (CLEWS) framework's analytical tools, integrated climate change adaptation strategies were formulated, which were modelled to significantly improve the water storage capacity of the catchment, as well as water allocations and distribution among water users.

The study concluded that the Buffalo River catchment's surface water availability is expected to increase under climate change, however, current water storage capacity is not reliable to meet water demands throughout the 21st century. Lastly, the study also concluded that the catchment does possess immense potential for improved surface water availability to merge the gap between its water supplies and demands. Thus, the null hypotheses stipulated in this research are rejected. For discussions, policymaking and general research related to these improvements in water resources management in the Buffalo River catchment, the climate change adaptation strategies established in this research are recommended. Also, based on model evaluation statistics, the WEF nexus was successful in examining the interrelations among WEF resources, and is recommended for future studies to examine long-term integrated demand-supply strategies for WEF sectors.

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DEDICATIONS

This research is dedicated to:

1. Bongiwe Dlamini (*mother*), Thembinkosi Dlamini (*uncle*), and Vusumuzi Dlamini (*grandfather*).

2. My late grandmother, **Antonia Dlamini**.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
AEZ	Agro-Ecological Zoning
BAU	Business-As-Usual
BR	Buffalo River
BS	Baseline Scenario
CC	Climate Change
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station dataset
CLEWS	Climate, Land-use, Energy Alternatives System
CMA	Catchment Management Agency
CMIP5/6	Coupled Model Intercomparison Project – Phase 5/6
CV	Coefficient of Variation
CVT	Conceptual Visualization Tools
d	Index of Agreement
Dcov	Demand Coverage Index
ET_A	Actual Evapotranspiration
ET_R	Reference Evaporation
FAO	Food and Agriculture Organization of the United Nations
gAEZ	Global Agro-Ecological Zoning assessment
GCM	General Circulation Model
IPCC	Intergovernmental Panel on Climate Change

IWR	Irrigation Water Requirements
K_C	Crop Coefficient
LEAP	Long-range Energy Alternatives Planning
MAP	Mean Annual Precipitation
NEX-GDDP	NASA Earth Exchange Global Daily Downscaled Climate Projections
nRMSE	Normalised Root Mean Square Error
PBIAS	Percent Bias
$P_{eff\,(\%)}$	Effective Precipitation
PS	Policy Scenario
PS-Opt	Optimised Policy Scenario
Q	Streamflow
QAT	Quantitative Analytical Tools
R	Surface Runoff
R^2	Coefficient of Determination
RCP	Representative Concentration Pathway
RE	Reliability Index
SWA	Surface Water Availability
W_A	Water Abstractions
WEF	Water-Energy-Food
WEAP	Water Evaluation and Planning
WTP	Water Treatment Plant

1 INTRODUCTION

1.1 Climate Change and Water Resources

The effects of Climate Change (CC) are primarily felt on water resources (Nhamo *et al.*, 2018) through changing rainfall seasonality and erratic weather trends in the form of droughts and floods. Research is therefore required to promote the establishment of methodologies, tools, and case studies that assist in water planning and management from the perspective of adapting to long-term CC (DEA, 2013; Zubaidi *et al*., 2020). With 98% of surface water already allocated to different water users across South Africa (Nel *et al.*, 2017), it is important to understand how climate-induced changes in Surface Water Availability (SWA) and the reliability of water supplies to meet demands will restrict or encourage different growth pathways in various regions of South Africa, more so in matters pertaining to agricultural production and energy generation - this is at the heart of the Water-Energy-Food (WEF) nexus (Nhamo *et al.*, 2018).

1.2 The Water-Energy-Food Nexus

The management of water, energy, and food resources is conceptually integrated by the WEF nexus (Mpandeli *et al.*, 2018). Although the management of surface water resources and adaptation to CC using the WEF nexus approach can be carried out at all spatial scales (Mabhaudhi *et al.*, 2018), it is encouraged to implement the WEF Nexus at the catchment level to broaden its knowledge pool in South Africa. (Mabhaudhi *et al.*, 2018). Additionally, this scale is the most vulnerable to CC effects as they occur on a micro-level (DEA, 2013; Dibaba *et al*., 2020). Variations in water availability affect communities' health and socioeconomic status through implications on agriculture and power supply (Singh *et al.*, 2018).

Agricultural incomes and markets, both at commercial- and small-scale are severely affected by climate change induced disturbances in water productivity which in turn exacerbate poverty in catchment communities (Kumar *et al*., 2019). Such disruptions also transcend to the energy sector. Power plant cooling is an important process in the coal and nuclear energy production stages. A decrease in the available water supply reduces the quantity of energy that can be generated from coal and nuclear (Wassung, 2010; Thopil and Pouris, 2015). The development of climate change adaptation strategies using the interdisciplinary methodology of the WEF nexus is therefore essential for sustaining farmers' production and profitability, for the general well-being of communities within the catchment area (Kumar *et al*., 2019), as well as for discovering ways of executing water-independent energy generation approaches to bridge potential gaps created by lack of water supply to the energy sector (Mabhaudhi *et al*., 2018).

1.3 Problem Statement

The Buffalo River (BR) catchment, also known as the Buffelsrivier or uMzinyathi, is a tributary of the uThukela River, located in the northern parts of KwaZulu-Natal, South Africa. The BR system provides water to the Majuba power station via its Zaaihoek Water Transfer Scheme and is a major source for irrigation consumers (uMgeni, 2020). This region faces significant problems adapting to the multiple effects of CC, notably in water management. According to uMgeni (2020), the water distribution system in the KwaZulu-Natal's BR catchment, which is a high rainfall region receiving, on average, 802 mm/annum, has not been able to meet demand in recent years, and the droughts of 2015/2016 aggravated the situation. uMgeni (2020) further declared that the yield of the Ntshingwayo Dam, the BR catchment's largest water source, will not be sufficient to supply the 2035 water demands. Conversely, Dlamini and Mostert (2019) highlighted that the BR catchment has surplus water, which can be allocated; however, current allocation plans need to be revised. In this regard, emerging cross-sectoral approaches, such as the WEF nexus, could be useful for executing a detailed water resources analysis to quantify and confirm whether the water yield and existing CC development plans of the Buffalo River catchment's water system will support the existing and future water demands. This information will benefit policymakers when framing policies, tools, and guidelines for the sustainable management of resources.

1.4 Research Question

How can existing CC water management plans be optimized to boost the reliability of the Buffalo River catchment's water supply system in meeting energy generation and agricultural production water demands under CC conditions?

1.5 Aim and Specific Objectives

This research aims to develop adaptation strategies which respond to CC, using existing WEF nexus tools for water supply management in the BR catchment. The specific objectives are to:

(a) Assess CC impacts on SWA in the BR catchment.

(b) Investigate and analyse the reliability of the BR catchment's water resources system in supplying irrigated agriculture and energy generation water demands under CC.

(c) Apply the WEF nexus as a natural resource management tool to optimize existing CC development plans in merging potential gaps between water demands by irrigation and energy generation, and available surface water.

1.6 Specific Hypotheses

The specific null hypotheses for the specific objectives are as follows:

(a) CC will not affect SWA in the BR catchment.

(b) There will be no water reliability changes over time in the BR catchment.

(c) The optimized CC water management strategies will not alter the relationship between available water supply and water demands of the catchment under climate change.

1.7 Thesis Outline and Objectives Flow Chart

(a) Chapter 2 reviews general CC impacts on water resources in South Africa and the WEF nexus.

(b) Chapter 3 investigates and assesses CC impacts on SWA in the BR catchment.

(c) Chapter 4, the projections of irrigation and energy generation water requirements are integrated into the analysis of CC impacts on SWA in the BR catchment, including an analysis of the water systems' reliability in providing the catchment's water demands under CC.

(d) Chapter 5 investigates and assesses changes brought upon by the governments' proposed CC adaptation strategies to the catchment's water system. Such strategies are further developed to improve the overall water system's demand site coverage and reliability.

(e) Lastly, Chapter 6 provides the conclusions and recommendations. The thesis objective flow is shown in Figure 1.1.

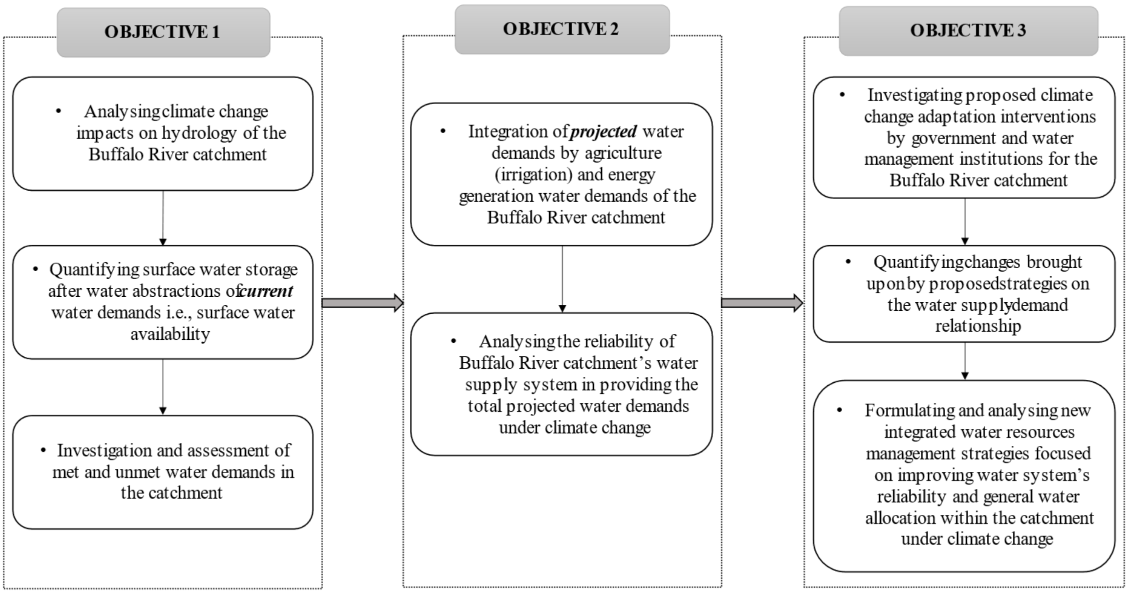

Figure 1.1 Thesis objectives map

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2 LITERATURE REVIEW

2.1 Background

South Africa is a contributor to, and experiences the consequences of, global Climate Change (CC) (Herrfahrdt-Pähle, 2010). With a Mean Annual Precipitation (MAP) of 464 mm (GoZa, 2015; Makou, 2017), South Africa is classified as a water-stressed region, and through evaporation losses and projected increased fluctuations in rainfall, the overall surface water available in South Africa is expected to decrease (Mpandeli *et al.*, 2018).

CC impacts on Surface Water Availability (SWA) vary for each catchment in South Africa (Knight, 2016). This is apparent from the various projections of mean annual runoff (MAR) through South African catchments. By 2050: (a) Warburton (2012) projected MAR to decrease by up to 35% for Upper Breede catchment in Cape Town, (b) for the uThukela catchment in KwaZulu-Natal, CC scenarios projected a 16% to 38% increase in MAR (Graham *et al.*, 2011), and (c) in the Upper Crocodile River catchment in Johannesburg, MAR is projected to decrease by 39% (Leketa and Abiye, 2019). SWA variations affect the ecological environment and the socioeconomic system of catchment communities (Herrfahrdt-Pähle, 2010).

Power generation uses a significant amount of water obtained from catchment Water Transfer Schemes (WTS); Eskom's water supply for 11 coal-fired base load power station comes from: (a) Komati WTS in the Komati River catchment, (b) Mokolo Crocodile Water Augmentation Project, (c) Usutu and Usutu-Vaal Government WTS, and (d) Zaaihoek WTS in the Buffalo River (BR) catchment (Eskom, 2018). By 2030, Eskom's water consumption per annum is expected to be 270 billion litres (Buthelezi, 2012). Irrigation produces 90% of South Africa's high-value crops. However, it consumes 62.6% of the total water available (Donnenfeld *et al.*, 2018; vanNiekerk *et al.*, 2018). Given the pressures imposed by CC on SWA and the fact that water supply has already been completely or over-allocated in many of South Africa's catchments (vanNiekerk *et al.*, 2018), CC adaptation strategies, therefore, require cross-sectoral approaches to promote efficient use of resources and sustainable development of the water, energy, and food sectors (Mpandeli *et al.*, 2018).

The Water-Energy-Food (WEF) nexus is a methodology that considers the "interactions, synergies, harmonisation and trade-offs among water, energy, and food" when managing water, energy, and food resources (Mpandeli *et al.*, 2018). This transdisciplinary management of resources makes the WEF nexus ideal for formulating CC adaptation strategies (Mpandeli *et* *al.*, 2018). The conceptual approach to the WEF nexus depends on the researcher or policymaker's perspective and can be examined in numerous spatial and temporal scales (Garcia and You, 2016).

Catchment Management Agencies (CMAs) regulate allocations for water use, and these bodies are responsible for formulating catchment management strategies. These strategies are based on an overview of the water availability and allocation plans in the catchment area (Herrfahrdt-Pähle, 2010). Prior to the advent of the WEF nexus concept, a sectoral approach was used when formulating policies, which resulted in policy conceptualization being viewed remotely. This sector-specific approach to policymaking is problematic and unsustainable due to South Africa's scarce water supply, minimal potential for arable land, and heavy reliance on fossil fuel-based energy generation (Mabhaudhi *et al.*, 2018).

The BR catchment, whose main river is the largest tributary of the uThukela River, is expected to face water supply allocation challenges (uMgeni, 2020). The Buffalo region's surface water infrastructure, which supplies water for recreation, irrigation, municipal and industrial use, receives water from the BR's main stem and tributaries via impoundments and abstractions (uMgeni, 2020). With the projected population increases and climate changes, the BR catchment's main district municipalities, the Amajuba and uMzinyathi are anticipated not to meet water demands by the year 2050 (DCGTA, 2015; LGCCP, 2018; uMgeni, 2020). Hence, assessing long-term yields for the entire BR catchment's resource infrastructure under various CC projections will be valuable for integrated water supply management and planning (uMgeni, 2020).

2.2 The Changing Climate of South Africa

As South Africa is located in the subtropics, its climate is mainly affected by atmospheric circulation in the tropics, subtropics and temperate latitudes (Phakula, 2016). Sea-surface temperatures and variations in topography are also responsible for the high spatial and temporal variations in climate conditions across the South African landscape (Phakula, 2016), especially the Mean Annual Precipitation (MAP). As a result, few statistically significant trends in MAP have been observed historically (DEA, 2013b).

2.2.1 Rainfall and temperature variability trends

In historical studies on rainfall trends over South Africa, Kruger (2006) and Nel (2009) deduced that even though the overall change in annual rainfall of South Africa is largely statistically insignificant, some parts of South Africa show significant changes in MAP. MAP has decreased significantly in the following areas: (a) northern Limpopo, (b) southern Mpumalanga, (c) north-eastern Free State, (d) western KwaZulu-Natal (KZN), and (e) south-eastern Eastern Cape. The following areas have had substantial increases in MAP: (a) the northern region of North West, and (b) parts of the Western Cape, Northern Cape, and Eastern Cape. These conclusions agree with a review by DEA (2017), as seen in Figure 2.1.

The DEA (2013b) and MacKeller *et al.* (2014) discovered, on their analyses of temperature variations in the period 1960 to 2010, that. with the exception of the central interior, where minimum temperatures drastically declined, South Africa's maximum (max) and minimum (min) temperatures both show significant increases, as seen in Figure 2.2. Kruger and Sekele (2013) found that the frequency of high temperatures increased while the frequency of the low temperatures decreased significantly in the western, north-eastern and extreme eastern parts of South Africa during the period 1962 to 2009; this agrees with an analysis done by DEA (2013b) for the period 1960 to 2010.

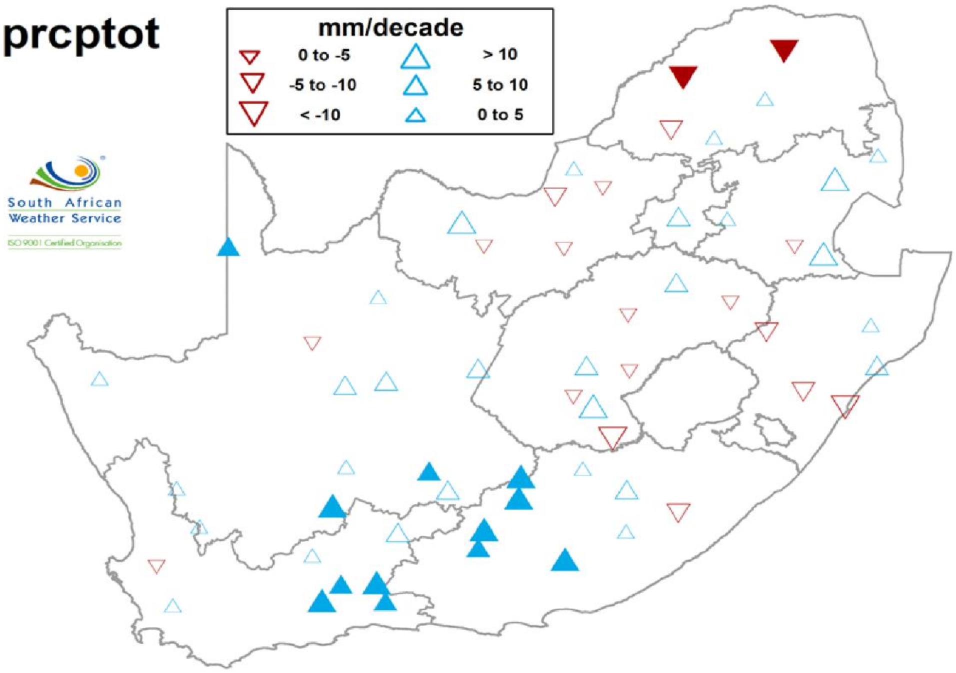

Figure 2.1 Trends in MAP per decade (mm/decade) for individual stations for the period 1921-2015. Shaded symbols indicate significant trends at the 5% level (DEA, 2017)

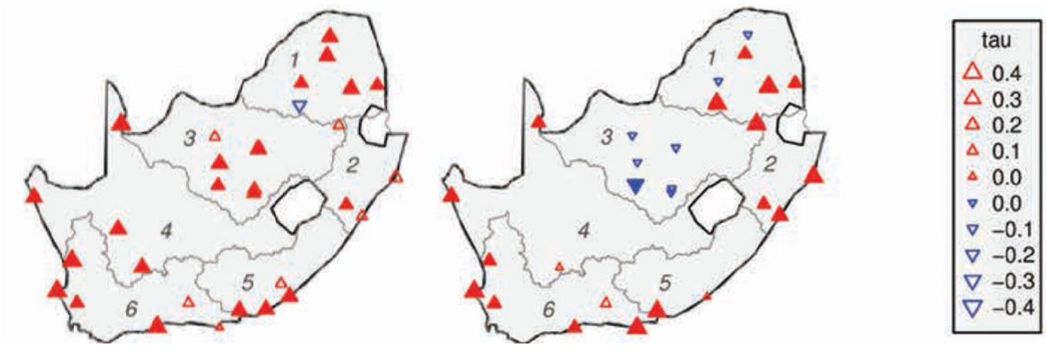

Figure 2.2 Annual mean daily maximum (left) and minimum (right) temperature in °C for period 1960-2010. The value of 'tau' represents the direction and relative strength of the trend. Shaded symbols denote trends that are significant at the 5% level (Welsch *et al.*, 2014)

2.2.2 Rainfall and temperature projections

The DEA (2013b) derived rainfall and temperature projections using statistical downscaling (SD) and dynamical downscaling (DD) techniques of different coupled General Circulation Models' (GCM) outputs for periods between 1961 to 2100. The projections were based on the Special Report on Emissions Scenarios (SRES) B1 and A2 and Representative Concentration Pathway (RCP) scenarios RCP 4.5 and RCP 8.5.

SD is the most common approach used to improve the resolution of precipitation for hydrological applications (Gutmann *et al.*, 2011). Under both RCP 4.5 and RCP 8.5 scenarios, SD projections displayed significant drying along the winter regions (south-Western Cape) for the near- and mid-futures. However, for the far-future, RCP 8.5 displays further drying in the winter regions, while the RCP 4.5 shows significant increases in rainfall, predicted to extend to the Cape south coast (DEA, 2013b).

Near-future RCP 4.5 projections' rainfall patterns are not well established for the eastern and central South Africa as ensembles displayed both wetter and drier conditions, yet for the RCP 8.5 scenario, significant rainfall increases are exhibited. For the mid- and far-futures, further increases in precipitation are shown by the RCP 4.5 scenario, and in contrast, RCP 8.5 displays drying over the central and eastern interior South Africa (DEA, 2013b). Therefore, adaptation researchers and policymakers need to consider these different predictions of rainfall during the decision-making process (vanNiekerk *et al.*, 2019).

2.3 Climate Change Impacts on Surface Water Availability

The effects of Climate Change (CC) are amplified by the hydrological cycle (Haji, 2011; Kusangaya *et al.*, 2013). Since rainfall is the key element that feeds most dams in South Africa, significant rainfall changes will consequently affect runoff response and ultimately, the quantity and quality of water supply (Botai *et al.*, 2018). It is important to note that the degree to which these CC consequences are felt on runoff in a catchment is also highly dependent on its physio-geographical characteristics (Warburton, 2012).

CC is expected to increase runoff along the eastern shore and in South Africa's central region as a result of anticipated increases in precipitation. However, in the Western Cape, declining runoff is projected due to decreased rainfall and drying (DEA, 2013a). Rainfall in the Breede River catchment, the largest river in the Western Cape and a vital resource for many economic activities there, is anticipated to decline by 2080, resulting in MAR that will be less than the ecological water requirements (Steynor *et al.*, 2009).

The Eastern Cape, southern Mpumalanga, and KZN are among the regions with the highest probabilities of severe runoff-related occurrences (DEA, 2013a). In KZN, streamflow projections in the Umgeni River catchment depicted an increase of up to 2.6 and even 5.3-fold by 2065 and 2100, respectively, and high risks of extreme peak streamflow are expected in the Nagle, Lions and Mpendle catchments (Summerton and Schulze, 2009). Similarly, based on ten regionally downscaled future climate projections, Graham *et al.* (2011) projected a substantial 16% to 38% increase in the Thukela River runoff by 2100. However, Graham *et al.* (2011) further stressed the likelihood of runoff decreases in the Thukela River; one of the downscaled projections showed a decrease in runoff in the mid- and distant-future. Emphasis was therefore made to include different perspectives in runoff in water security management. Other catchments show neutral to reduced risk in runoff (DEA, 2013a).

2.3.1 Impacts of climate change on the agricultural production sector

The agricultural sector is the first sector to encounter water supply reductions in South Africa during declining MAP. It does not demand the same high assurance of supply and, thus production rates from irrigated areas are affected. As South Africa is on the brink of internally produced self-sufficiency, reduced irrigation allocations will derail these efforts, sparking increased food insecurity (DEA, 2013c).

The overall Irrigation Water Requirements (IWR) in South Africa represent 62.6% of the total water use (Donnenfeld *et al.*, 2018). During the period 2002 to 2013, the area under irrigation has increased from approximately 0.77 million ha to 1.3 million ha (Baleta and Pegram, 2014), producing about 30% of the country's crops, hence making it essential for optimal production of agricultural products (DEA, 2013c). Less than 800 mm/yr in the eastern and southern areas and more than 1600 mm/yr in the north-western regions constitute the mean annual net IWR over South Africa (Schulze and Taylor, 2016). Intermediate (mid-future) projections show a 10% decrease of IWR in the central and eastern regions of South Africa due to increased rainfall outweighing increased demands triggered by higher temperatures and increased evaporation. In the drier western half and northern quarter of the country, IWR is expected to increase by 10% as depicted by Figure 2.3. However, in the distant future, 90% of South Africa's irrigation demands are projected to increase by 10-20%, and parts of the south-western Cape by even greater than 20%, also seen in Figure 2.3 (Schulze and Kunz, 2010).

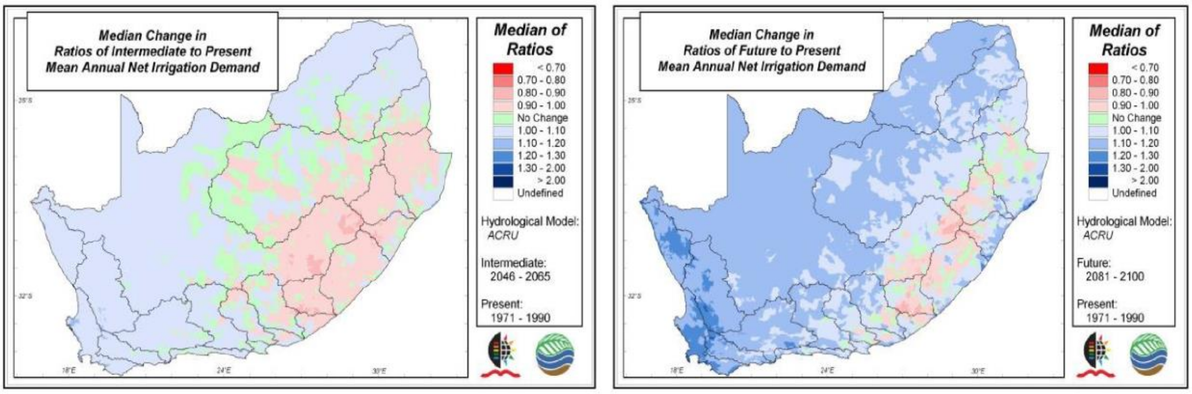

Figure 2.3 Median changes in ratios of intermediate (left) and future (right) to present net IWR, computed with the ACRU model from output of multiple GCMs (Schulze and Kunz, 2010)

The KZN province's agricultural development is extremely sensitive to CC (Shezi and Ngcoya, 2016). The effects of CC are projected to exacerbate food security in the coastal and northern parts of KZN through increased temperatures and rainfall (Zwane and Montmasson-Clair, 2016). The coastal KZN eThekwini municipal areas will suffer from crop impairment due to increased temperatures. Low crop yields are expected as the anticipated rainstorms and floods will cause leaching of nutrients and water-logged soils (Shezi and Ngcoya, 2016). The same is to be expected for the Amajuba and uMzinyathi municipalities, located in northern KZN's BR catchment where increased temperatures, drought, and increased frequency and severity of storm flood events will also be the cause of crop impairment (DCGTA, 2015; LGCCP, 2018).

Socio-economic instability in such catchment communities will therefore be exacerbated by this through increased food insecurity, and consequently worsened poverty conditions, especially in communities that rely heavily on rain-fed agriculture (Ofoegbu *et al.*, 2017).

Current CC policy action plans mostly focus on improving agricultural productivity through the expansion of areas under irrigation. Not much focus was given to the fact that this expansion requires more land, water and energy resources (Mabhaudhi *et al.*, 2018). For the BR catchment, it has been established that there is currently no water available for further irrigation development unless dams are constructed in the BR and in its tributaries. This would require a detailed water resources analysis to be performed for the whole system as the first step (DRDALR, 2016). As a result, trade-offs with the energy and water sectors may be debated and taken into account when creating policies. Priorities related to food security shouldn't take precedence over these factors since doing so would render any such programs unsustainable. By addressing food security and minimizing trade-offs with water and energy resources, the WEF nexus might offer a framework for sustainability in this context (Mpandeli *et al.*, 2018).

2.3.2 The future for energy generation water demands

Coal makes up 67% of South Africa's primary energy source, with crude oil contributing 20%. The remaining 13% is composed of nuclear, natural gas, and renewable energy sources (such as hydropower and biomass). 91% of South Africa's electricity is generated from coal, and the majority of it is done so by Eskom's coal-fired power facilities (Goga and Pegram, 2014). These coal-fired plants substantially impact water as they use a significant amount of it, especially the cooling process, as seen in Table 2.1. Eskom consumes an estimated 334 Gigalitres of water annually (GL.yr-1) for power production, which is equivalent to 2% of South Africa's water supply (Sparks *et al.*, 2014).

Table 2.1 Water usage in energy production by using thermal electric cycles (Sparks *et al.*, 2014)

Fuel	**Energy Production Stage**	**Water Use (litres/MWh)**	**Sources**
Coal	Pre-generation, mining & washing	183-226	(Martin and Fischer, 2012)
	Generation, cooling	1 420	(ESKOM, 2013b)
	Generation, dry cooling	100	(ESKOM, 2013b)
	Generation, indirect dry cooling	80	(Martin and Fischer, 2012)
	Generation, cooling	1380	(Martin and Fischer, 2012)
Nuclear	Generation, cooling	192 539	(ESKOM, 2013a)

Ten baseload plants, three return-to-service (RTS), and two newly constructed power stations comprise the fleet of coal power plants in South Africa. According to Thopil and Pouris (2015), the RTS power plants use the most water, and by 2020, their water consumption factor was predicted to reach 3 litres/kWh. The total energy-water requirement was projected to to drop by 12 to 15% if the RTS fleet retired by 2020 (~40 $GL.yr^{-1}$), as shown in Figure 2.4. If not, the water requirement was projected to roughly increase to 370 $GL.yr^{-1}$ by 2035 and beyond (Thopil and Pouris, 2015), which will weigh even more heavily on the water resources (Wassung, 2010). Currently, of the three water-consuming RTS power plants, the Komati has been retired (ESKOM, 2022). However, Eskom opted to postpone the retirement of the two remaining RTS power stations, Camden and Grootvlei, until 2030 (ESKOM, 2020), thus still posing a threat to water resources.

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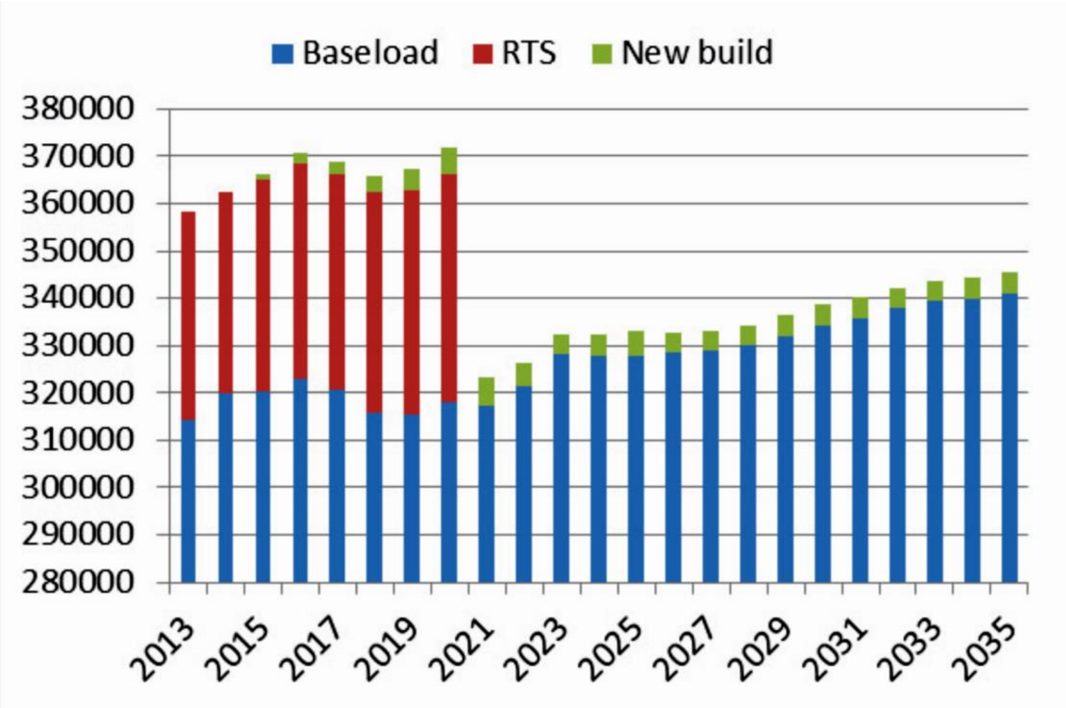

Figure 2.4 Combined water consumption (Megalitres per annum) of the baseload, RTS and new build power plants (*y-axis = Water consumption, *x-axis = year) (Thopil and Pouris, 2015)

The likelihood of energy generation requiring more water supply poses potential conflicts with the water and food sectors (Mpandeli *et al.*, 2018), especially since Eskom receives its water supply through catchment water schemes that provide water to other users (Eskom, 2018). The Zaaihoek Water Transfer Scheme, which forms part of the BR catchment in northern KZN, transfers 12% of its water to the Majuba power station for cooling purposes. The rest gets supplied to Water Treatment Plants (WTPs) and irrigation within the BR catchment (uMgeni, 2020). The Zaaihoek dam has been deemed unsuitable for further water allocations (Dlamini and Mostert, 2019) , thus any increases in water demands for energy will cause consequential impacts on other water demands, triggering the destabilization of the catchment's health and socio-economic state. (Singh *et al.*, 2018). Therefore, further energy generation water demands must be addressed in conjunction with the food and water demands. Management strategies for energy security should take into account trade-offs with the food and water sectors as well as the pressures of CC on these resources (Mpandeli *et al.*, 2018).

This further demonstrates the necessity of implementing the WEF nexus approach in economic growth and planning for CC adaptation (Mpandeli *et al.*, 2018). This can be accomplished by supporting the expansion and development of green technologies, including trade-offs between hydropower plants and irrigation, or by prioritizing the use of agricultural land for food crops as opposed to crops for biofuels in policymaking (Mabhaudhi *et al.*, 2018).

2.4 Managing Water, Energy and Food Resource Security under Climate Change

To strengthen water security in South Africa, building dams to increase water supply has been a methodology implemented since 1920 (Swatuk, 2010). High rainfall regions, especially those in KZN, still rely on this method. For the BR catchment, uMgeni (2020) and DRDALR (2016) encourage the building of dams and WTPs as a solution for future water needs due to the substantial amount of runoff not being captured and utilized. Desalination, wastewater reuse, and boosting water availability through water transfers—within river basins and to neighbouring basins—are other approaches. These transfers are essential for regions like Limpopo, the Eastern Cape, and Gauteng (Masindi and Dunker, 2016).

There are well-known technologies that can increase irrigation efficiency. Policies that advocate for industry to fully cover the costs of providing water access must be put in place at the industrial level. Decision-makers may now concentrate on water-saving solutions and explore water in places where water restrictions are less severe (Muller *et al.*, 2009).

Eskom has implemented several measures to help reduce energy demands and coal-produced energy consumption, such as building integrated photovoltaics (PV), energy efficient lighting, and solar water heating (Ziuku and Meyer, 2012). There are currently 138 212 small-scale integrated PV energy generation installations in South Africa (Bhungwandin *et al.*, 2019), more than 47 million Compact Fluorescent Light energy-efficient light bulbs installed nationally since 2006 (ESKOM, 2017a), and more than 156 000 solar water heaters installed since 2008 (ESKOM, 2017b). This reduces energy demands and reduces high carbon emissions, hence mitigating CC (Ziuku and Meyer, 2012).

In terms of Water Demand Management (WDM), which is ‘conserving water by controlling use, influencing demand and promoting efficient use’, the South African government has legislation and policies which promote such initiatives (Mutamba, 2014). These include legislations such as the White Paper on National Water Policy of 1997, the National Water Services Act and the National Water Act of 1998, as well as frameworks such as the National Water Conservation and Demand Management Strategy (Mutamba, 2014).

Besides restrictions set by these legislations and policies, another WDM strategy executed in South Africa is the improvement of the distribution system through measures such as pressure reduction, fixing leaks and the installation of flow regulators in impoverished households (Kotze, 2018). Additionally, tariffs have been introduced in South Africa, as well as water use efficiency awareness programs that entail comprehensive messaging and teaching through a variety of media platforms and interventions (Kotze, 2018).

Even with the efforts mentioned above for water, energy and food security improvement, water scarcity is still a reality in South Africa (duPlessis, 2017; Youssfi *et al.*, 2020). Though WDM has appealing perks and South Africa seems to have accepted the idea in theory, its application has not been successful. The percentage of Non-Revenue Water (NRW), a gauge of water use effectiveness, shows this clearly. NRW between 5% and 15% is generally regarded as acceptable. The national average NRW in South Africa, in contrast, is about 35%. (Mutamba, 2014). For addressing long-term climate changes, hands-on interventions involving planned policy and investment decisions to increase the adaptability of target agricultural and energy systems are still crucial (Mpandeli *et al.*, 2018).

2.5 South African Government's Approach to Climate Change Adaptation

There are robust water planning measures by the South African government that consider climate uncertainty due to historical climate variability, as shown in Figure 2.5. Nevertheless, planning for a range of climate futures that could encompass future changes in climate variability needs to be considered (DEA, 2013a).

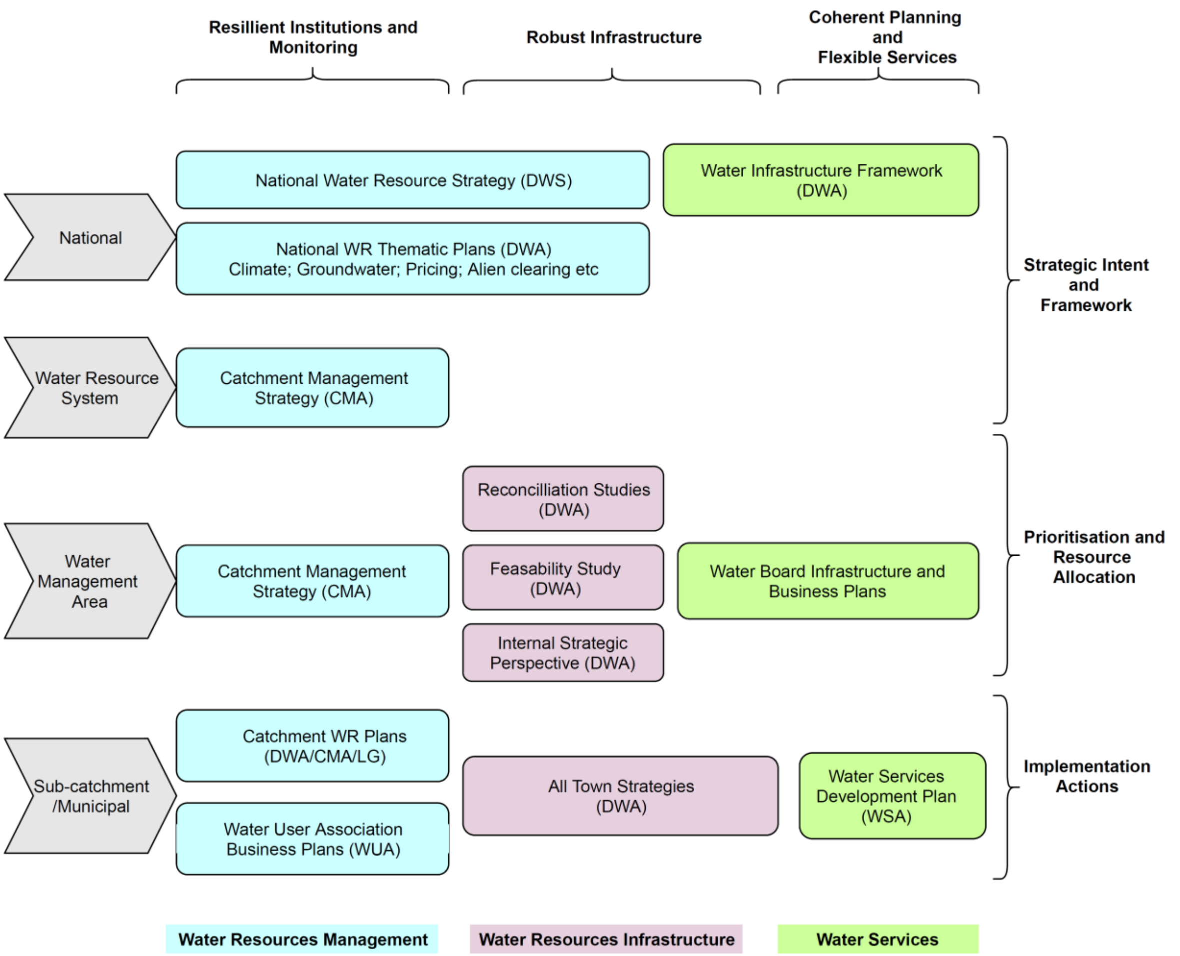

Figure 2.5 Climate adaptation interventions with reference to the water planning framework (DEA, 2013a).

At the catchment and sub-catchment level, the Catchment Management Agency (CMA) formulate catchment management strategies to build adaptive institutions for responding to local challenges, resources, and capacity. To develop these dynamic institutions and improve long-term catchment management strategies that incorporate CC, protocols are required (DEA, 2013a).

It is important to note that the development of CMAs is very delayed. Only two of the 19 proposed CMAs, the Usutu CMA and the Breede Gouritz CMA, have already been established and are broadening their areas of jurisdiction (Munnik, 2020). A wide range of political reasons are part and parcel of the delayed establishment of CMA, including objections to water resources being administered along hydrological catchments. As a result, local and district municipalities are primarily in charge of managing water resources and services. This raises a broader and deeper issue regarding trade-offs between a biophysical framework for managing water resources in accordance with hydrological (catchment) boundaries and a political framework for managing hydrologically segmented water resources (Munnik, 2020).

The Department of Planning, Monitoring and Evaluation (DPME (2019) proposed a slight departure from past water planning approaches and a focus on the long-term planning horizon beyond 2030. In terms of water governance, the Integrated Water Resources Management (IWRM) was initially embraced as the silver bullet of sustainable development because of its integrated analysis of sectors and resources. However, as the concept of IWRM is centred around water security, on its own, it is insufficient (Simpson and Jewitt, 2019). The WEF nexus could then, from this, form an integral part of the IWRM through the interrelationships between, and not limited to, water and agriculture, energy and CC (DPME, 2019). Many gaps in knowledge remain, which must be addressed to develop the WEF nexus adoption, including the potential impacts of CC on water availability, energy generation and food production in South Africa during the 21st century (Mabhaudhi *et al.*, 2018).

2.6 The Water-Energy-Food Nexus

The basis of the WEF nexus strategy is an attempt to manage different uses of natural resources, including energy, water, land, soil, and socioeconomic factors in an integrative manner. Given the inherent linkages between food, energy, and water that might lead to trade-offs (Mabhaudhi *et al.*, 2018), the WEF nexus approach deviates from the water-centric nature of the IWRM by approaching resource management in a more holistic and poly-centric philosophy. This all-encompassing strategy for resource management is likely to be advantageous for underdeveloped countries like South Africa, where there are considerable trade-offs between the water, energy, and food sector (Senzanje *et al.*, 2019).

Achieving sustainable outcomes using the WEF nexus relies on numerous factors, such as ensuring that the nexus is applied in an integrated approach, using inclusive and multi-scale nexus tools and good quality and quantity temporal and spatial data. However, the interaction among key decision-makers and experts is of utmost importance (Senzanje *et al.*, 2019). This interactive segment of the WEF nexus breeds the development of new trends which have to be implemented and reassessed, thus creating feedback that either reinforces existing trends or curbs them, depending on whether they are sustainable or not (Mohtar and Daher, 2016). These trends are normally based on the scenarios developed from the nexus assessment phase but can also be based on non-quantitative information (Flammini *et al.*, 2014).

2.6.1 Components of the nexus assessment

The WEF Nexus may be evaluated using a variety of methods, including analytical tools, conceptual frameworks, and discourse. Quantitative and/or qualitative methodologies are often used as analytical tools to comprehend how the WEF resources interact with one another (Nhamo *et al*., 2020). The nexus method serves as a conceptual framework that makes the WEF connections' aim of fostering consistency in policies and advancing sustainability more understandable (Albrecht *et al*., 2018). The conceptual method may be used to carry out WEF nexus analyses that are qualitative, such as through expert opinion or multi-stakeholder dialogue. However, if they rely on a quantitative assessment, they are often strengthened. Understanding society priorities and competing environmental, economic, and social objectives is made easier by doing so (Flammini *et al.*, 2014). The nexus concept can be used as a discourse to contextualize problems and encourage cross-sector cooperation and dialogue (Albrecht *et al.*, 2018).

In South Africa, numerous models can be applied to carry out a WEF nexus assessment, as displayed in Table 2.2 (Mabhaudhi *et al.*, 2018). Analytical models that deal specifically with WEF resources management and CC are the Climate, Land-Use, Energy and Water Strategies (CLEWS) and the ANEMI model. While the ANEMI model carries out an interconnected evaluation of the physical, ecological, and hydrological processes (Davies and Simonovic, 2010; Mabhaudhi *et al.*, 2018), the CLEWS involves integrating detailed land, energy and water models under various climate scenarios, hence enabling flexibility of analytical model selection for each WEF component (Mabhaudhi *et al.*, 2018).

Table 2.2 Tools and models applicable in South Africa for WEF nexus assessments (adopted from Mabhaudhi *et al.*, 2018; Nhamo *et al.*, 2020)

Nexus Tools	**Modelling Framework**	**Scale**	**System Breadth**	**Analytical Capability**	**Flexibility**	**Applicability to WEF nexus in South Africa**
Integrated Analytical Model	Calculating composite indices of defined WEF nexus indicators	All scales	WEF nexus components, socio-economy, environment	Indices provide an overview of the level of interactions, inter-relationships and inter-connectedness among water, energy and food sectors	Only considers indicators related to the security of water, energy and food resources	Yes
WEF Nexus Tool 2.0	Input-output	National	WEF nexus components	Scenario-based for given food self-sufficiency level calculates nexus resource flows and interactions, and greenhouse gas (GHG) emissions	Focused on food as an entry point and Qatar country	Yes
MuSIASEM	Input-output nested hierarchical view of the economy	Aggregated to national or sub-national level	WEF nexus components, land, economy, human capital and ecosystems	Accounting of flows and funds and their ratios as Indicators. GHG emissions and land-use	Adaptable to various contexts	Yes; it has already been applied to South Africa
Climate, Land-Use, Energy and Water Strategies (CLEWS)	Integrates detailed models from different tools (including WEAP, LEAP and AEZ)	National	Climate, Land, Energy and Water	Depend on the tools used for the CLEW assessment	Depend on the tools used for the CLEW assessment	Yes; if the model can be changed to evaluate the intersectoral influences of the WEF nexus components
ANEMI	Integrated assessment model	All scales	Climate, carbon cycle economy, population, land use, hydrological cycle, water demand and quality	Reveals the interconnections and feedback of each element	System dynamic simulation	Yes
Sankey diagram	Graphically represents the complex conversion pathways, flows and interdependencies between variables	All scales	WEF nexus components	Based on the data input	Adaptable to various contexts	Yes

2.7 The Climate, Land-Use, Energy and Water Strategies (CLEWS) Framework

According to Howells *et al*. (2013), CLEWS is a conceptual framework that combines the evaluation of land, energy, and water resource systems in order to understand how they are connected, where pressure points are prevalent, and how to reduce trade-offs while maximizing synergies. This is accomplished by using components of existing assessment methods for each of the three resources (Howells *et al.*, 2013), as per Figure 2.6, the most common ones being:

(a) "*Water Evaluation and Planning (WEAP) model simulates natural hydrological processes for assessing water availability and anthropogenic activities superimposed on the natural system*" (Arranz and McCartney, 2007).

(b) "*Long-range Energy Alternatives Planning System (LEAP) which is a software tool widely used for energy policy analysis and CC mitigation assessment, using scenarios of energy system evolution*" (Heaps, 2012).

(c) "*Agro-ecological Zoning (AEZ) defines zones based on combinations of soil, landform and climatic characteristics and uses this information to carry through assessment of land suitability and potential productivity*" (FAO, 1996).

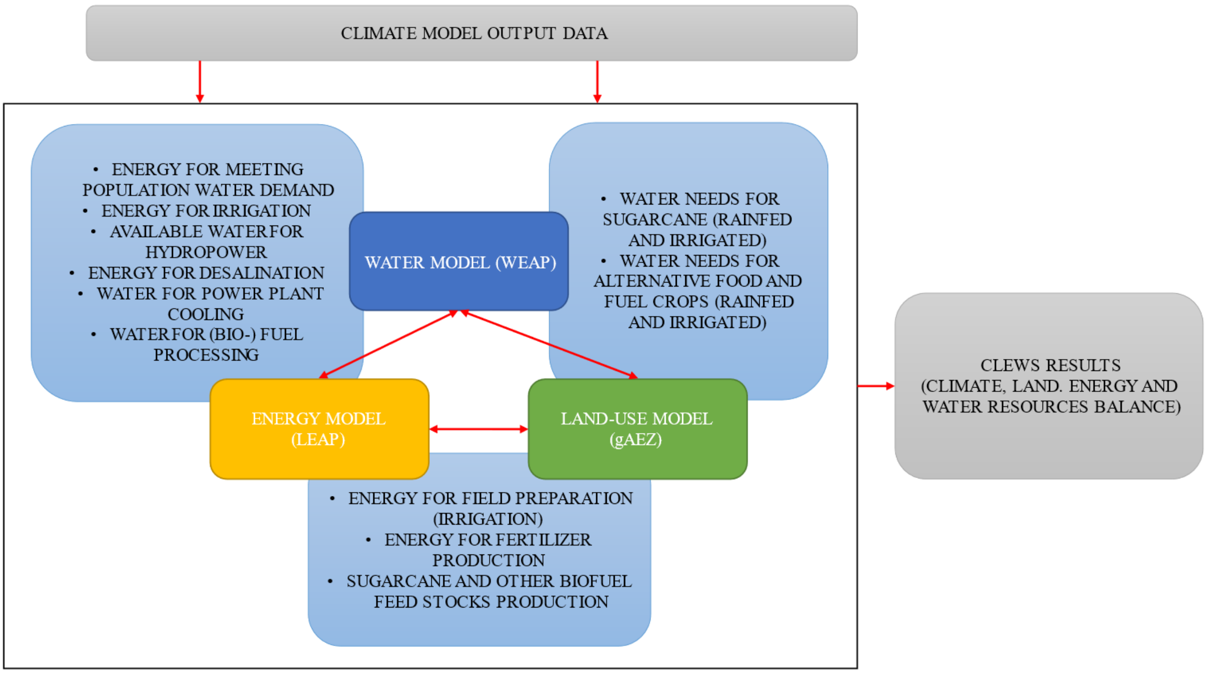

Figure 2.6 The CLEWS framework (Welsch *et al.*, 2014)

Studies have been conducted using each of the models separately, and to name a few implemented in Africa: Haji (2011) investigated the SWA of the upper Vaal River catchment using the WEAP model, and Seo (2014) used AEZ methods in evaluating the impacts of CC on micro-farming in sub-Saharan Africa. From these studies, the performance of the models are deemed satisfactory (Haji, 2011; Seo, 2014). However, they are sector-specific and communicate to one aspect of the water, energy and food nexus more than the other. Resource assessments need to display an understanding of all synergies, interlinkages and trade-offs among WEF sectors (Mabhaudhi *et al.*, 2018), which the CLEWS approach provides

The goal of the CLEWS approach is identifying the points where the resource systems interact and developing appropriate data exchanges between the modules, which are: (a) water requirements in the land-use and energy systems; (b) energy demands for water supply and land-use; and (c) land requirements for infrastructure for energy and water. A process is then introduced whereby data for these interlinkages are exchanged between modules. The output from one module forms the input for the other two modules, which are then solved sequentially and iteratively until a convergent solution is found (Howells *et al.*, 2013). This can be achieved either by: (a) accounting frameworks, (b) a fully integrated model that simulates land, energy and water systems and their relationships with climate in a single model, (c) running sectoral water, energy and land-use models in parallel and transferring inputs from one model to the next manually, or (d) by soft-linking water, land and energy models and using an iterative process to derive consistent scenarios across sectors (Howells *et al.*, 2013; Nexus, 2018).

The CLEWS framework applies to different geographical scales, from global to regional, national, and urban. It was successfully executed at the national level in Mauritius, focusing on the development of green energy. Likewise, case studies were conducted for Kenya and Bolivia (Mabhaudhi *et al.*, 2018). In South Africa, it has been applied in the City of Cape Town to investigate the energy implications of expanding the current water supply to meet future water demand (Ahjum *et al.*, 2015). Generally, a CLEWS approach is likely to be very useful for regions intending to adopt decentralized policies with potential ramifications in multiple resource systems. Anticipated climate-induced rainfall changes which conflict water management priorities indicate the importance of a CLEWS assessment (Welsch *et al.*, 2014; Hussain, 2016). The CLEWS fully integrated model is open source and freely available (Gardumi *et al.*, 2018)

2.8 Discussion and Conclusions

The studies presented in the literature review indicate that South Africa is susceptible to CC impacts. Historical trends display high spatial and temporal variations in rainfall and temperature across South Africa, which are expected to worsen under RCP 4.5 and 8.5

projections. Most in-depth and detailed case studies investigating climate trends and their impact on water resources and availability have been carried out on national and municipal scales. Moreover, most available information on catchments is brief and generalized. Thus, detailed hydrological modelling at catchment and sub-catchment scales is required to add to the CC body of knowledge in South Africa. This will also be beneficial for catchments, like the BR, to track system water losses and inform water management policies for decision-making purposes.

Studies also presented a clear projection of increased water usage by agricultural and energy production through irrigation and the cooling process of energy generation. This poses a significant threat to water supplies, particularly in regions like the BR catchment, that provide water to food and energy activities. South Africa's socioeconomic status is also threatened by CC, notably in catchment communities whose livelihoods are highly dependent on rainfed agriculture and overly allocated water resources. The BR catchment is currently facing such challenges, thus there is a need for the BR catchment and other catchments experiencing similar water supply issues to analyse CC impacts on SWA and the implications on food production and energy generation.

The IWRM approach, which is predominantly used in South Africa for river basin water resources assessments and management, is water-centric and focuses on water demand management instead of securing water, energy, and food resources. These three sectors must be treated as equals to maintain the balance among water, energy, and food resources. Thus, approaches that seek an understanding of the linkages, dependencies, and trade-offs associated with water, energy, and food sectors should be considered. The proposed resource management approach minimises conflicts among water users and promotes effective water use.

Numerous measures have been implemented to curb CC from further exacerbating water, energy, and food security. The South African government has even developed strategic CC and water planning institutions at national, catchment and sub-catchment scales. However, there still exists a pronounced lack of coordination and integration among water, energy and food resources, as well as climate security management. This also confirms the importance of investigating and implementing a fully integrated approach to resource management. The approach will potentially allow better comprehension of the dynamic inter-relationship among water, energy and food, and external influences such as CC.

Establishing a balance among different users of natural resources has proven to be fundamental in effective and efficient water resources management and planning; this is the advantage that the WEF nexus has over IWRM. The integrated, holistic approach of the WEF nexus deems it suitable in executing an assessment on CC impacts on water availability and formulating strategies for long-term water provision to food and energy activities. The information generated from these assessments can be used to develop management strategies, policies and guidelines related to WEF resource management.

The Climate, Land-use, Energy and Water Strategies (CLEWS) model stands out as the most suitable WEF nexus conceptual framework to be implemented in South Africa. This is noted in its successful application for the City of Cape Town. CLEWS performs CC and WEF resources assessments by integrating quantitative analytical models for each of the three resources, such as the Water Evaluation and Planning (WEAP) model, Long-range Energy Alternatives Planning (LEAP) model and Agro-ecological Zones (AEZ) model. The CLEWS approach has not been implemented in the BR catchment, and neither has its analytical models (WEAP, LEAP and AEZ). With the BR catchment in need of water resources management strategies under CC impacts, the CLEWS approach can then be used to interactively assess the state of the Buffalo regions' WEF resources, thus formulating the desired multi-sector evaluations and strategies for integrated water resource management.

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3 ASSESSING CLIMATE CHANGE IMPACTS ON SURFACE WATER AVAILABILITY USING THE WEAP MODEL: A CASE STUDY OF THE BUFFALO RIVER CATCHMENT, SOUTH AFRICA

Abstract

Study region: The Buffalo River catchment in KwaZulu-Natal receives a Mean Annual Precipitation (MAP) of 802 mm, with an area-weighted mean annual runoff (MAR) of 90 mm. The MAR to MAP ratio is 11%, slightly above the national average of 9%, which presents a challenge given the catchment's rising water demands and drought conditions.

Study focus: Assessing Surface Water Availability (SWA) variations under different Climate Change (CC) scenarios in the Buffalo River catchment from 2020–2100. A Water-Energy-Food (WEF) nexus quantitative analytical tool, the Water Evaluation and Planning (WEAP) model, is utilized to simulate and project SWA (net surface water storage from surface runoff, after accounting for evapotranspiration and water abstractions) variations using the catchment's physical and hydrological data, and projected climate data from an ensemble of GCMs under RCP4.5 and RCP8.5 scenarios from CMIP5.

New hydrological insights for the region: The linear scaling bias-correction method improved streamflow simulations. Increased SWA is anticipated under CC, accompanied by increases in evapotranspiration, surface runoff volumes at catchment outlets. Moreover, even with the projected increases in SWA, increased unmet demands are also projected. Such findings present an opportunity for the WEF nexus approach to be utilized for identifying synergies and trade-offs between surface water infrastructure development and water demand management, thus improving sustainable water use under CC.

Keywords: hydrological modelling; water balance; Water-Energy-Food nexus; sustainability

3.1 Introduction

Climate Change (CC) might perpetuate increased water demands and water scarcity caused by population growth and economic development through changes in rainfall magnitude and variability (DEA, 2012; Erler *et al.*, 2019; Exposito *et al.*, 2020). The gap that exists in many regions globally between water demand and supply capacity increases competition among various users (Exposito *et al.*, 2020). Investigating CC impacts on water availability is thus crucial, especially in matters pertaining to the sustainable development of CC adaptation and resilience strategies (Erler *et al.*, 2019).

The Water-Energy-Food (WEF) nexus is a methodology that offers an in-depth comprehension and methodical analysis of the connections between the environment and human activities to achieve more integrated management and utilization of natural resources across sectors and scales (McNamara *et al.*, 2018). Building on the Integrated Water Resources Management (IWRM) approach, which is water-centric, the goal of the WEF nexus is to approach resource management holistically (Mabhaudhi *et al.*, 2018).

WEF nexus assessments can be carried out using Conceptual Visualisation Tools (CVT) or Quantitative Analytical Tools (QAT), all of which constitute modelling tools. Frequently, modelling tools employ monthly time series data for parameters (e.g. climate, water and crop yields, agricultural areas and energy generation) to simulate determined target values based on various inputs (McNamara *et al.*, 2018). The simple manner in which models represent and simulate processes serves their advantage (Parra *et al.*, 2018). They can be used to assess a system's sensitive components and simulate future scenarios for decision support in planning (McNamara *et al.*, 2018). For water and basin management, the use of water balance models has recently increased, especially in CC impact studies and for the simulation of different environmental processes (Parra *et al.*, 2018).

The Stockholm Environment Institute (SEI) established the Water Evaluation and Planning (WEAP) system model as a comprehensive method for assessing both natural and artificial hydrological components of water demand and supply (Sieber, 2015). The WEAP model is classified as an IWRM tool due to its water-centric nature (Tena *et al.*, 2019). However, since WEAP is designed to interact with other models, it is used as a WEF nexus QAT by integrating food- and energy-centric models. This gave rise to the Climate, Land-use, Energy and Water strategies (CLEWS) WEF nexus modelling framework (Howells *et al.*, 2013), used internationally and within Africa.

To introduce integrated land and water management, the Government of Rwanda, for example, is in the process of developing plans for four selected demonstration catchments using the WEAP modelling framework (Droogers *et al.*, 2017). The island of Mauritius also utilized the WEAP model for modelling river systems in 60 catchments to assess the implications of local, municipal and agricultural water requirements on national water supply schemes (Welsch *et al.*, 2014).

Several water availability and management studies were performed in South Africa using the WEAP model. For example, Levite *et al.* (2003) evaluated the usefulness of WEAP in assessing water demand management scenarios in the Steelpoort sub-catchment of the Olifants River through the analyses of simulated catchments' met and unmet demands. Arranz and McCartney (2007) used WEAP to assess the impacts of likely future water use on the water resources of the Olifants catchment. Haji (2011) investigated the effects of future CC on meeting the water demands of different consumers in the Upper Vaal River Basin using the WEAP model. These studies concluded that WEAP was useful for water resources assessment in South African catchments and for a holistic view of an entire river basin.

The Buffalo River (BR) catchment is a sub-catchment of the Thukela Water Management Area, whose water source is in the Drakensberg region. The BR catchment is characterised as a relatively high runoff internal sub-catchment (Dlamini and Schulze, 2006) that supplies water to numerous sectors, including irrigation, power generation, domestic, mining and bulk industries (StatsSA, 2010). There have been severe droughts in past years, especially during 2015-2016, which consequently affected the livelihoods and socio-economic activities of local and surrounding communities, as well as the capability of the catchment to meet its water demands (uMgeni, 2020). Thus, an integrated Surface Water Availability (SWA) assessments is essential in such cases for the effective and responsible management of water resources (Tena *et al.*, 2019). It allows for tracking water losses within systems and serves as a base for future research in determining whether a water system will provide growing future water demands (uMgeni, 2020).

To our knowledge, a detailed water resources analysis has not been undertaken for the BR catchment (uMgeni, 2020). Therefore, the objective of this study was to assess the impacts of CC on SWA in the BR catchment. It is difficult to predict and quantify the exact available surface water and water balance. Hence, a scenario analysis was chosen as the most appropriate approach to meet the objective using the WEAP modelling tool. The study was also premised on the null hypothesis of climate change not altering surface water availability throughout the 21st century.

The results generated from this study are intended to inform researchers and policymakers on the current and future state of SWA within the BR catchment. In promoting the WEF nexus philosophy, the results should be analysed in conjunction with outputs from food and energy models when developing appropriate adaptation strategies focused on minimizing risks associated with potential CC impacts on water resources in the BR catchment.

3.2 Materials and Methods

3.2.1 Study site description

The BR catchment, seen in Figure 3.1, covers an estimated area of 9 803 km^2, and has minimum latitude and maximum longitude values of 28°42'59" S and 30°38'30" E, respectively (uMgeni, 2020). The catchment is situated in a warm and humid region that receives most of its annual rainfall during summer. The BR is the main northern tributary of the uThukela River. It flows approximately 339 km south-easterly from the eastern escarpment (Newcastle area) through the Amajuba and uMzinyathi District Municipalities, then confluences with the uThukela River in the Msinga Local Municipality (Dlamini and Mostert, 2019; uMgeni, 2020).

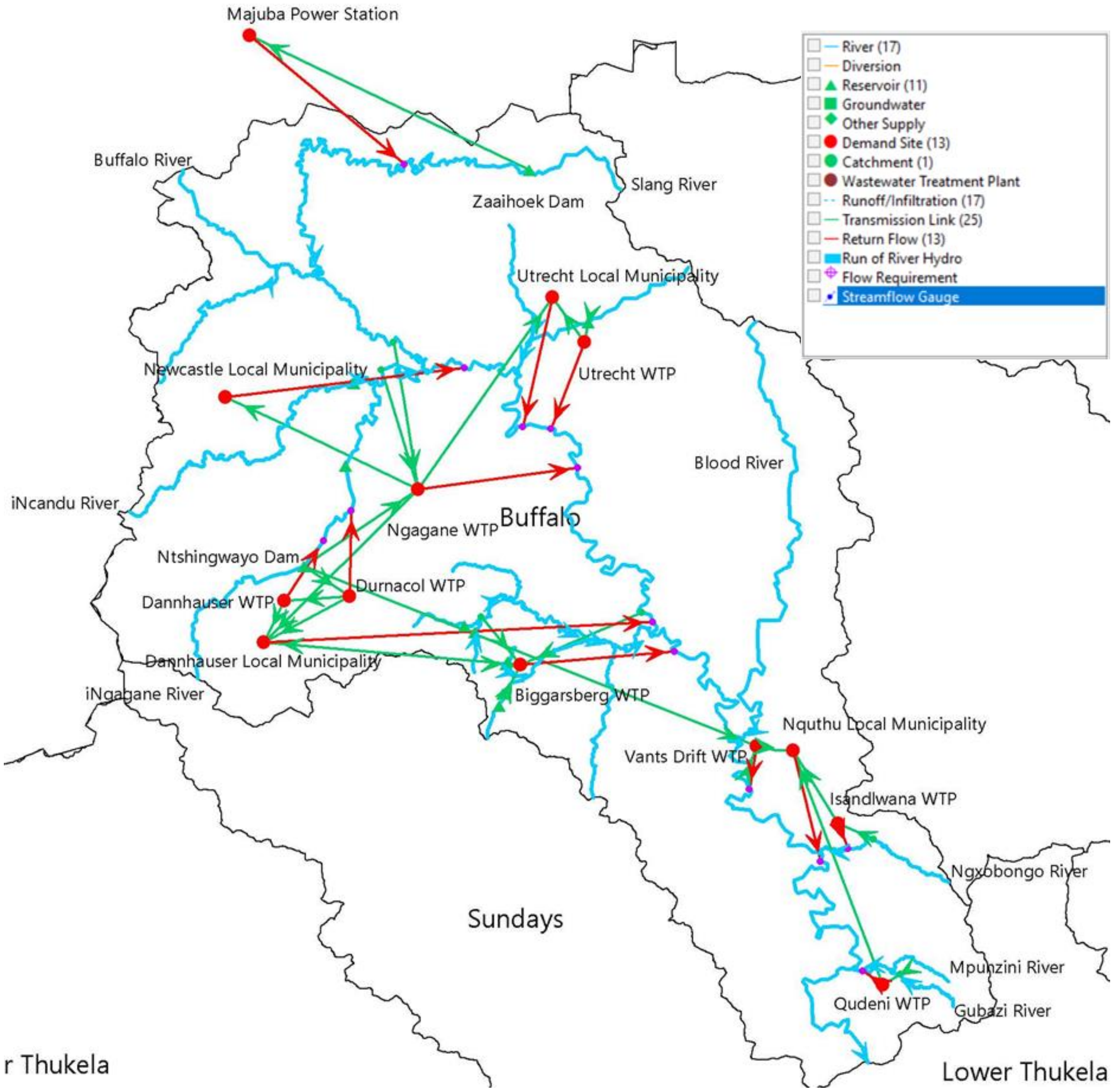


Figure 3.1 General layout of the Buffalo River catchment, KwaZulu-Natal, South Africa.

The predominant land cover in the BR catchment is grassland (58%), followed by cultivated land (22%), as seen in Figure 3.2 (uMgeni, 2020). Grassland is mostly utilized for the grazing of livestock (INR, 2019). Commercial-scale production of maize, soybean and wheat dominates the upper catchment region, with irrigated production mainly taking place in the fertile region of the western Newcastle Local Municipality (StatsSA, 2017; LGCCP, 2018). Commercial and subsistence farming under rainfed conditions is more prominent in the BR catchment's middle and lower southern regions (StatsSA, 2017).

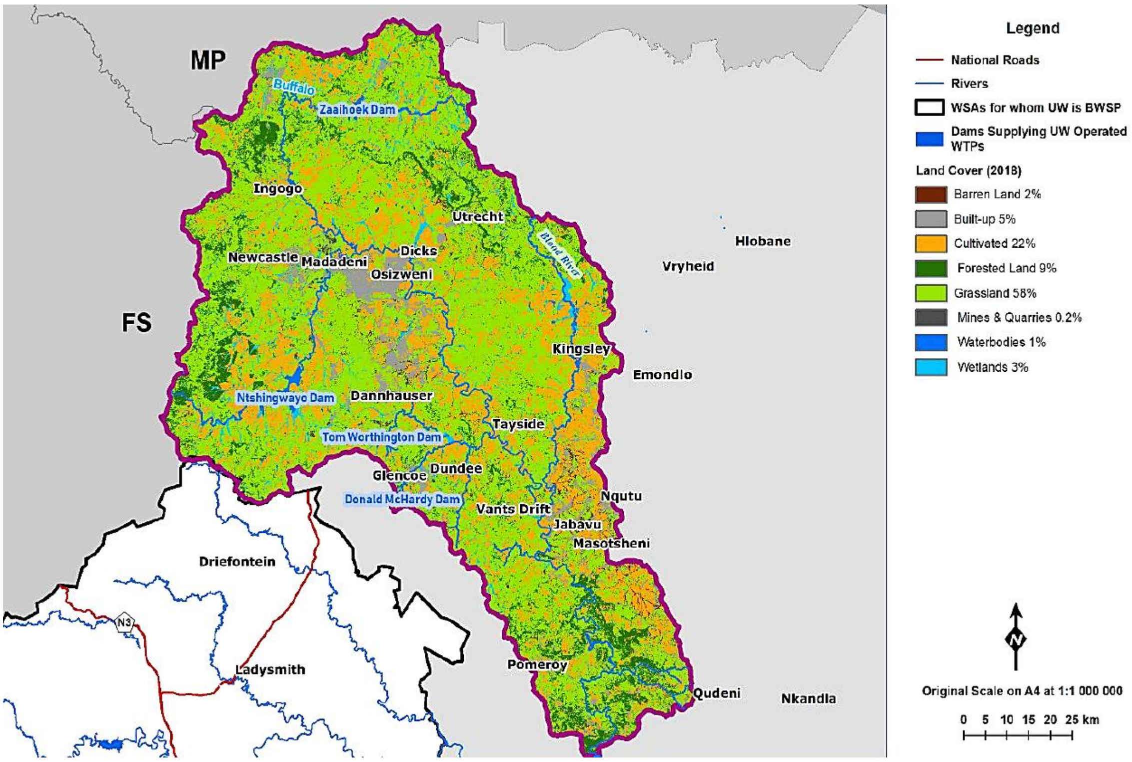


Figure 3.2 Land-use in the Buffalo River catchment (uMgeni, 2020)

Hydrological characteristics

The hydrological characteristics of the BR catchment are summarized in Table 3.1. The upper tertiary catchment V31, where the Slang, iNcandu and iNgagane rivers are located, generates the largest mean annual runoff of 119 mm/annum (DWS, 2015; uMgeni, 2020). This can be mostly attributed to the higher rainfall and steeper gradient of the Drakensberg Mountains regions (uMgeni, 2020). However, mean annual runoff reduces as the BR traverses to the middle (V32) and lower (V33) regions, decreasing to 73 and 64 mm/annum, respectively (DWS, 2015; uMgeni, 2020).

Table 3.1 Buffalo River catchment hydrological characteristics (DWS, 2015)

Tertiary Catchment	Area (km^2)	Annual Average		
		Evaporation (mm)	Rainfall (mm)	Natural Runoff (mm)
V31	3 948	1 435	851	119.0
V32	4 018	1 491	778	72.5
V33	1 837	1 477	747	64.2
Average	**9 803**	**1 465.8**	**801.6**	**89.7**

Surface water infrastructure

The total supply capacity of the BR catchment's existing surface water infrastructure is approximately 405 Mm^3/annum, providing a hydrological yield of 136.9 Mm^3/annum (unspecified assurance level) (uMgeni, 2020). The Ntshingwayo Dam contributes significantly to the water supply, with a full supply capacity of 211 Mm^3 and yield of 59 Mm^3/annum, as well as the Zaaihoek Dam, with a full supply capacity of 185 Mm^3 and yield of 54 Mm^3/annum (uMgeni, 2020). The Buffalo system also includes eight Water Treatment Plants (WTPs) which, as listed in Table 3.2, extract water from supply sources and distribute it to their designated supply areas. Other WTPs within the BR system, such as the Charlestown WTP, are primarily supplied by groundwater sources, and distribute approximately 440 kl/day to their respective water demand sites (uMgeni, 2020). Due to the lack of data availability related to the location and distribution of these groundwater resources, the aforementioned water treatment plants were not included in this study.

Table 3.2 Water treatment plants within the Buffalo River catchment (uMgeni, 2020)

WTP	Design Capacity (Ml/day)	Primary Water Supply Source(s)	Total Supply Requirement (Ml/day)	Primary Municipal Supply Areas
Ngagane	150	Ntshingwayo Dam, Ngagane River downstream, Buffalo River	173.5	Newcastle Local Municipality, Dannhauser Local Municipality
Biggarsberg	16	Dams in Ngobiya River, Dams in Sterkstroom River, Dams in Mpate River, Buffalo River	17.6	Dannhauser Local Municipality
Vant's Drift	14	Buffalo River Ntshingwayo Dam (supplementary)	12	Nquthu Local Municipality
Dannhauser	2	Durnacol WTP	1.8	Dannhauser Local Municipality
Durnacol	5	Ntshingwayo Dam	3.5	Dannhauser WTP Dannhauser Local Municipality
Utrecht	4	Dorps Dam	2	Utrecht Local Municipality
Qudeni	0.38	Gubazi River	0.38	Nquthu Local Municipality
Isandlwana	0.35	Ngxobongo River	0.35	Nquthu Local Municipality

3.2.2 WEAP model description

The WEAP model is an "*innovative, integrated modelling software that offers a detailed, dynamic and user-friendly framework for establishing water balances, scenario generation, planning and policy analysis*" (Ayele, 2016; Tena *et al.*, 2019). The model was designed for integrated water resources planning and can be used for municipal and agricultural sectors, a single catchment, or a complex transboundary drainage basin network (Tena *et al.*, 2019). (Ayele, 2016). The WEAP model simulates a variety of naturally occurring and engineered components of the aforementioned systems, including precipitation, streamflow, dams, groundwater release, and water demand and supply (Agarwal *et al.*, 2018).

WEAP model water balance computation

The WEAP model was used to simulate the water balance components in Equation (3.1) (Sieber, 2015) using climate, physical and hydrological inputs from the BR catchment. Actual evapotranspiration (ET_A) included evaporation losses from vegetation and open water bodies. Streamflow comprised of surface runoff only, i.e., no groundwater contributions. Hence, the impact of groundwater recharge on reservoir storage was assumed negligible. However, it is important to note that there are five hydrogeological units comprising one primary- and four secondary-type aquifers within the BR catchment. They exhibit moderate potential to provide mean yields of 0.9 to 2.7 litres per second (l/s) via boreholes that are 30 to 60 m deep (uMgeni, 2020). Thus, various water supply schemes within the BR catchment rely solely on groundwater supply from boreholes.

$$P + E_X = ET_A + Q + W_A \pm \Delta S \tag{3.1}$$

where P = precipitation (Mm^3/annum)

E_X = external flows (Mm^3/annum)

ET_A = actual evapotranspiration (Mm^3/annum)

Q = streamflow @Buffalo River outlet (Mm^3/annum)

W_A = abstractions (Mm^3/annum)

ΔS = change in reservoir storage (Mm^3/annum)

There are five methods which WEAP can be used for water resources simulation: *"(a) the Rainfall-Runoff and (b) Irrigation Demands Only versions of the Simplified Coefficient Approach, (c) the Soil Moisture Method, (d) the MABIA Method, and (c) the Plant Growth*

Model" (Sieber, 2015). The Rainfall-Runoff Simplified Coefficient Method was chosen due to the availability of data required by this approach. For the Rainfall-Runoff Simplified Coefficient Method, rainfall that is not used up by evapotranspiration is represented as runoff to a river or can be partitioned among runoff to a river and flow to groundwater via linkages between runoff and infiltration. It does not, however, track soil moisture changes (Sieber, 2015). The concept of water balance is based on mass conservation principles in a closed system (Sieber, 2015) and includes all water inflows and outflows in a catchment area (Tena *et al.*, 2019).

3.2.3 WEAP model scenario computation

A scenario is a plausible depiction of how the future may unfold based on a detailed and scientifically sound set of assumptions regarding key interconnections and driving factors (Arranz and McCartney, 2007). As it is impossible to forecast exactly how water demands and other variables affecting water supplies could change in the future, scenarios were employed in this study.

Initially, a Current Account of the BR catchment was created in the WEAP model. The Current Accounts, which serve as the foundation of all scenarios, provide a basic characterization of the water system as it currently stands by giving a snapshot of the system's actual water requirements, resources, and supply based on historical data (Sieber, 2015). The Representative Concentration Pathways (RCPs), which are scenarios developed for the climate modelling community as a basis for near- and long-term modelling experiments (Vuuren *et al.*, 2011), are named according to radiative forcing target levels for 2100, as per Table 3.3. This study used the following three scenarios to evaluate CC impacts on SWA in the BR catchment, which are further elaborated on later:

(a) The Baseline Scenario which reflects historical climate conditions and utilized for comparison purposes against RCP scenarios.
(b) The RCP4.5 Scenario which is a "*stabilization scenario that assumes climate policies are invoked to limit emissions and radiative forcing*" (Thompson *et al.*, 2011). By mid-century, carbon emission will be around 50% greater than the historical levels (Wayne, 2013).
(c) The RCP8.5 Scenario which is a high emission scenario based on no policy-driven mitigation (Vuuren *et al.*, 2011). "*Emissions continue to increase rapidly through the*

early and mid-parts of the century." Carbon dioxide concentration accelerates and reaches 1370 ppm by 2100 (Vuuren *et al.*, 2011).

Table 3.3 Overview of the representative concentration pathways (RCPs) (Vuuren *et al.*, 2011).

	Description
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W m^{-2} (~1370 ppm CO2 eq) by 2100
RCP 6	Stabilization without overshoot pathway to 6.0 W m^{-2} (~850 ppm CO2 eq) at stabilization after 2100
RCP 4.5	Stabilization without overshoot pathway to 4.5 W m^{-2} (~650 ppm CO2 eq) at stabilization after 2100
RCP 2.6	Peak in radiative forcing at ~3 W m^{-2} (~490 ppm CO2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W m^{-2} by 2100)

Buffalo river catchment schematic in WEAP

Using GIS-based vector data, a schematic of the BR catchment was created in the WEAP model (Figure 3.1). The vector layers included: (a) KwaZulu-Natal (KZN) secondary drainage regions, (b) KZN district municipalities, (c) river network of the Amajuba and uMzinyathi district municipalities, and (d) dams within the Amajuba and uMzinyathi district municipalities. All vector layers were obtained from DWS (2016), and their attribute data were further sorted using ESRI's ArcGIS software (Version 10.6.0.8321, released on 17 July 2018).

For the purpose of computing the rates and quantities of recharge and abstraction, thirteen demand nodes were created for the Buffalo River catchment water system's demand analysis. Every demand node corresponds to a particular group of water consumers: four represent the municipal demand (domestic and irrigation water demand), eight represent WTPs, and one represents the energy demands. As depicted, all water demand nodes depend on surface water resources only. The WEAP model was run at the monthly time step, with the hydrological year starting in October and ending in September.

Historical climate

The input climate data used in WEAP to simulate historical and current catchment conditions were obtained from the Climate Hazards Group InfraRed Precipitation with Station dataset (CHIRPS; Funk *et al.* (2015 The CHIRPS dataset "*builds on previous approaches to 'smart'* *interpolation and high-resolution techniques, where precipitation estimates are based on infrared Cold Cloud Duration (CCD) observations"* (Funk *et al.* (2015)). The algorithm uses satellite information to represent sparsely gauged locations and provides daily, pentadal, and monthly rainfall estimates from 1981 to the near present at a 0.05º spatial resolution.

Since the projections timeframe for this study spans from 01/01/2020 to 31/12/2099, data for a 30-year baseline period (WMO, 2021) was acquired for the entire boundary of the BR catchment from 01/01/1990 to 31/12/2019 using 0.05º pixels of the CHIRPS gridded data. To ensure that the CHIRPS dataset represented the catchment's climate conditions, it was bias-corrected using the linear scaling (LS) method, as demonstrated in Equation (3.2). The LS bias correction method was selected as it preserves the mean signal of the observed variable and yields very good hydrological performance when applied at a monthly time interval (Ghimire *et al.*, 2018). The scaling factor was derived using the catchment's observed MAP of 802 mm/annum obtained from uMgeni (2020), with the CHIRPS MAP of 722.03 mm/annum.

$$\boldsymbol{P_{corr} = P_{raw} \times CF} \text{ (Gudmundsson } \textit{et al.}\text{, 2012)} \qquad (3.2)$$

where P_{corr} = bias corrected precipitation (mm)

P_{raw} = raw precipitation data (mm)

CF = scaling factor = $\boldsymbol{MAP_{observed\ data} / MAP_{raw\ data}}$

The resulting historical annual precipitation values increased over time, with the lowest values of 645, 584, and 574 mm noted in the years 1992, 2003 and 2015, respectively. This coincides with the findings by Dube and Jury (2003) and Ndlovu and Demlie (2020), which highlighted the droughts experienced in the KZN province during these years. The year 1995 was modelled as an extreme wet year with an average annual rainfall value of 887 mm/annum, which aligns with Ndlovu and Demlie (2020) observation that northern KZN had extremely wet conditions in 1995. Ndlovu and Demlie (2020) also stated that there were more extreme dry conditions than wet ones during the historical period, which is mirrored in the outcomes of this study.

Future climate projections

The precipitation projections under both RCP4.5 and RCP8.5 scenarios were obtained from the NASA Earth Exchange Global Daily Downscaled Climate Projections dataset (NEX-GDDP; Thrasher *et al.* (2012)) via the Google Earth Engine. The NEX-GDDP dataset comprises of "*statistically downscaled climate scenarios for the entire globe at a spatial resolution of 0.25°*

(~25 by 25 km), derived from 21 Global Climate Model (GCM) runs conducted under Phase 5 of the Coupled Model Intercomparison Project (CMIP5). The NEX-GDDP dataset provides daily estimates of precipitation and temperature (maximum and minimum) for the historical period (1950-2005) and the future period (2006-2099) over the entire globe". (Thrasher *et al.*, 2012). From the ensemble of projections derived from 21 GCMs, the six selected GCMs used in this research are listed in Table 3.4.

Table 3.4 Description of the selected GCM models (Teng *et al*., 2021)

No	Model	Research Centre	Description
1	ACCESS1-0	CSIRO-BOM	Australian Community Climate and Earth System Simulator 1.0
2	MIROC-ESM-CHEM	MIROC	CCSR/NIES/FRCGC, MIROC, Japan Earth System Model with Chemistry
3	NorESM1-M	NCC	Norwegian Earth System Model 1 – medium resolution
4	CNRM-CM5	CSIRO-QCCCE	Centre National de Recherches Meteorologiques (CNRM) Earth System Model version 5, France
5	CCSM4	NCAR	NCAR Community Climate System Model version 4.0
6	MPI-ESM-LR	MPI-M	Max Planck Institute for Meteorology, Germany, Earth System Model with Chemistry

The selection was done by statistically comparing precipitation trends between each GCM's historical data and the corrected CHIRPS dataset from 01/01/1990 to 31/12/2005, using the coefficient of determination (R^2). R^2 represents the goodness of fit between the observed and simulated data. For R^2, a range of 0.5 to 1.0 represents a good agreement between observed and simulated values (Moriasi *et al*., 2007). The selected GCM models' precipitation outputs achieved the highest R^2 values, which ranged from 0.96 to 0.99, as observed in Figure A.1 in the Appendix, thus deeming them satisfactory. It is very important to note that careful consideration should be taken when using RCP data. One should be on the lookout for errors as they may occur, and bias-correction measures should be taken to minimise them (Eden *et al*., 2012; Maraun, 2013). For instance, a WRC-funded project (K5/2717//4, Kunz and Mabhaudhi (2022)), found a systematic error in the RCP4.5 scenario's data provided by CSIR, which produced inconsistent trends between the pre-2005 (historical) period and post-2005 (year in which projections were made) period.

In minimizing errors of the GCM outputs used in this study, the monthly historical rainfall data from 01/01/1990 to 31/12/2005 of the selected GCMs, including their RCP4.5 and RCP8.5 projection data from 01/01/2006 to 31/12/2019, were also bias-corrected using the LS method. The resulting trends are observed from Figure A.2 to Figure A.5 in the Appendix.. The scaling factor for each GCM model under each RCP scenario was factored into their respective projected precipitation data from 01/01/2020 to 31/12/2099.

Physical data

The BR catchment was delineated into four local municipalities, viz. (a) Newcastle, (b) Utrecht, (c) Dannhauser and (d) Nquthu. Physical data inputs included the population capacity and growth rate per local municipality, as given in Table 3.5. Regarding land use characteristics, statistics on historical irrigated agricultural land area per local municipality were taken into account (see Table 3.5) as they are the largest water consumers in the Buffalo system and highly influence the systems' annual water use rate.

Table 3.5 Physical data inputs per local municipality.

Local Municipality	**Population Capacity[1]**					**Population Growth Rate[2] (%)**	**Total Irrigated Area[3] (ha)**
	1996	2001	2007	2011	2016		
Newcastle	287 659	332 981	351 134*	363 236	389 117	7.1	5 576
Utrecht	23 915	32 277	33 576*	34 442	36 869	7.0	3 372
Dannhauser	102 779	99 216	102 408*	102 161	102 937	3.1	714
Nquthu	157 018*	160 595*	164 887	167 748*	171 325	0.81	1 787.5
Sources	(Mazibuko and Zungu, 2009; Kunene, 2019; Mahlaba, 2019; Ngubane and Zwane, 2019)					(Mazibuko and Zungu, 2009; Kunene, 2019; Mahlaba, 2019; Ngubane and Zwane, 2019)	(Mazibuko and Zungu, 2009; Kunene, 2019; Mahlaba, 2019; Ngubane and Zwane, 2019)

(= inter/extrapolated data)*

Hydrologic data

The hydrologic parameters used in this study were surface water abstractions (W_A) and reference evapotranspiration (ET_R). To quantify W_A for each local municipality within the BR catchment, annual water requirements for each WTP were used, together with domestic and irrigation water demands and water requirements for energy production. Water requirement data for each WTP and the Majuba power station was obtained from uMgeni (2020). The monthly free basic water policy of 6 m^3/household (Mahlaba, 2019) was used to compute domestic water use. From 2011 to 2016, the average number of people per household in the BR catchment's local municipalities was 5 (StatsSA, 2016); hence an annual value of 14.4 m^3/person, multiplied by the annual population, was utilized to quantify the total domestic water consumption. Maize, wheat, oats, soybeans, and ryegrass are the dominant irrigated crops across all local municipalities (DARD, 2015; StatsSA, 2017), with the irrigation water requirements per crop tabulated in Table 3.6. For this study, irrigation water requirements per crop type per hectare were assumed constant throughout the study period.

Table 3.6 Irrigation water requirements for each dominant crop grown in the Buffalo River catchment

Climate Classification	**Crop Type Irrigation Water Demand (mm/season)**				
	Maize (*Zea mays*)	**Wheat (*Triticum aestivum*)**	**Oats (*Avena sativa*)**	**Soybeans (*Glycine max*)**	**Ryegrass (*Lolium*)**
Humid, warm summers, summer rain	280	315	< 300	330	635
Source	**(Stevens *et al*., 2012)**	**(Stevens *et al*., 2012)**	**(DAFF, 2010)**	**(Stevens *et al*., 2012)**	**(Stevens *et al*., 2012)**

The ET_R was used to compute the maximum crop evapotranspiration (ET_C), as per Equation (3.3), for irrigated crops using crop coefficients (K_C). Due to ease of use and availability, and suitability in estimating South Africa's evapotranspiration (Jovanoic *et al*., 2015), ET_R data were obtained from the MODIS 16 Global Terrestrial Evapotranspiration Product (MOD16) via Google Earth Engine. The MOD16 global evapotranspiration data are available at a 1 km^2 resolution across the 109.03 million km^2 vegetated land area at 8-day, monthly and annual intervals (Jiang *et al.*, 2020).

$$ET_C = K_c \times ET_R \qquad (3.3)$$

where ET_C = maximum crop evapotranspiration (mm/month)

K_C = crop coefficient

ET_R = reference evapotranspiration (mm/month)

For the BR catchment, the 8-day ET_R data, which was the only dataset available in the Google Earth Engine, ranged from the period 01/01/2001 to 31/12/2014, as seen in Figure 3.3. The 8-day ET_R is the sum of ET_R during these 8-day periods in 0.1kg m^{-2}; thus, a conversion factor of 0.1 was applied to obtain ET_R values in mm per 8 days (Jiang *et al.*, 2020). The data was replicated to cover the period of 1990-2099, as per Figure A.6 (the Appendix), with an average value of 549.82 mm/annum. Monthly K_C values were obtained from Savva and Frenken (2002) and provided in Table 3.7. The largest K_C value was considered in months when more than one crop was planted.

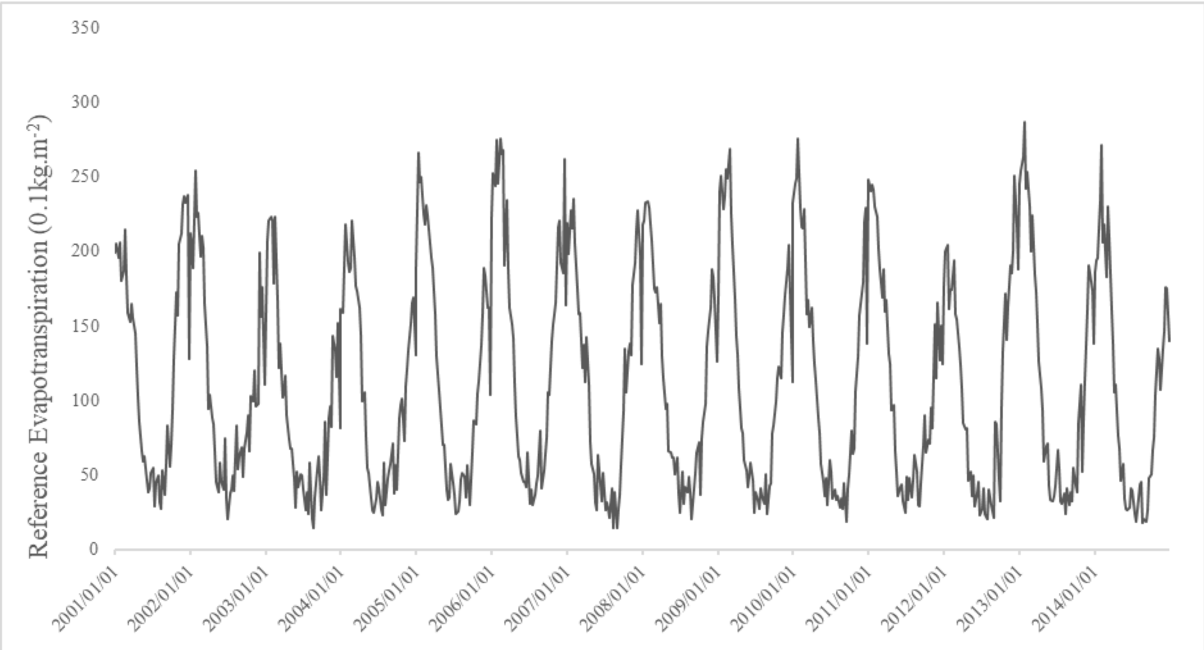


Figure 3.3 Terrestrial 8-day reference evapotranspiration data (0.1kg m^{-2}) for the Buffalo River catchment (Jiang *et al.*, 2020)

Table 3.7 *Kc* values for semi-arid regions (Savva and Frenken, 2002)

	Maize	Wheat	Oats	Soya Beans	Grass	K_C
January	**1.15**			**1.15**		**1.15**
February	**1.15**	**1.15**		**0.5**		**1.15**
March	**1.05**	**1.15**				**1.15**
April		**1.05**				**1.05**
May			**1.15**			**1.15**
June			**1.15**			**1.15**
July			**0.25**			**0.25**
August					**0.95**	**0.95**
September					**1.05**	**1.05**
October					**1.05**	**1.05**
November					**1.00**	**1.00**
December					**1.00**	**1.00**

In determining the actual evapotranspiration (ET_A), which is the amount of water consumed by evapotranspiration in the catchment, including water supplied by irrigation, the effective precipitation is initially determined. Effective precipitation percentage ($P_{eff\,(\%)}$) is the annual percentage of precipitation available for ET_A; the remainder contributes to R (Sieber, 2015). WEAP initially assumes a value of 100% for $P_{eff\,(\%)}$, i.e., all precipitation is available for ET_A. For this study, as part of calibrating and evaluating the WEAP model (see Chapter 3.2.4), $P_{eff\,(\%)}$ values were adjusted such that the historical streamflow closely matched the catchment's observed streamflow from 1990 to 2019. Using Equation (3.4), the average effective precipitation depth (P_{eff}) was computed by the WEAP model. Therefore, in determining the ET_A, the WEAP model selects the lowest value between the ET_C and the P_{eff} (ET_C cannot be greater than the amount of water available for evapotranspiration i.e., P_{eff}), as per Equation (3.5). The average ET_A was 496 mm/annum for the historical period, lower than that estimated by DWS (2015) of 802 mm/annum. This is consistent with the assumption that irrigated areas and crops remained unchanged during the study period.

$$P_{eff} = Monthly\ Precipitation \times (Area * 10^{-5}) \times P_{eff(\%)} \qquad (3.4)$$

where P_{eff} = effective precipitation depth (mm/annum)

$$ET_A = \min(ET_c, P_{eff}) \tag{3.5}$$

where ET_A = actual evapotranspiration (mm/month)

Reservoir storage data, such as storage capacity, reservoir elevation, net evaporation, and surface area, is also important in computing storage changes (ΔS). As there are many reservoirs within the BR catchment, it was impossible to simulate all reservoirs' operations; therefore, it was decided that only government-registered dams should be considered, and their operations were modelled. The above-mentioned data are tabulated in Tables A.1 and A.2 in the Appendix.

3.2.4 Model calibration, validation and data analyses

As previously mentioned, the model was calibrated to produce acceptable streamflow simulations by fine-tuning $P_{eff\ (\%)}$ from 1990-2019 (Sieber, 2015). The adopted annual variations of $P_{eff\ (\%)}$ for all bias-corrected GCM's precipitation are displayed in Figure 3.4. The $P_{eff\ (\%)}$ variations were replicated throughout the study period.

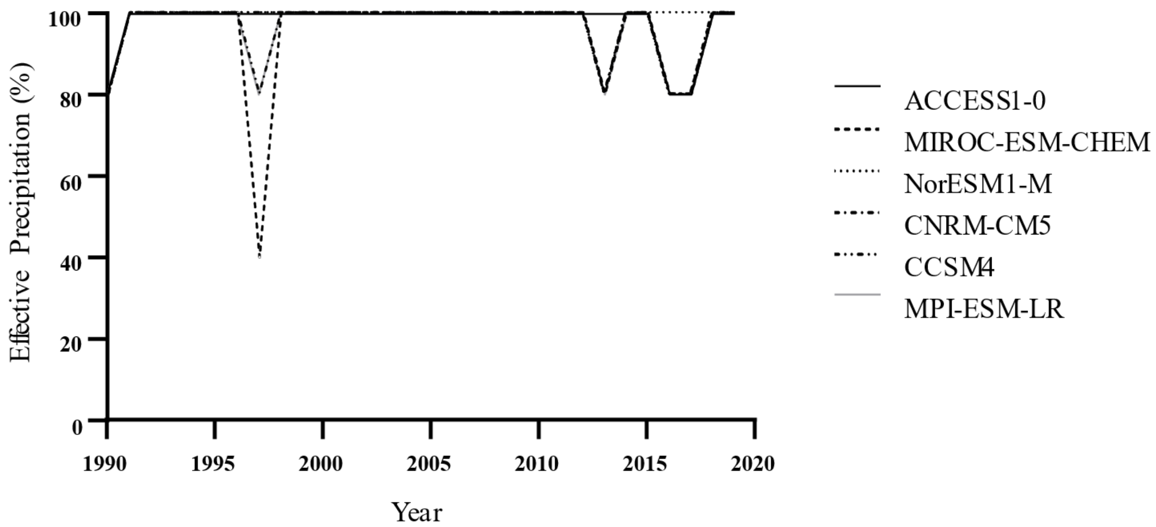


Figure 3.4 Effective precipitation percentages per annum for period 1990 to 2019.

During the calibration process, the model was evaluated by comparing the monthly CHIRPS- and GCM's average ensembles' simulated streamflow with the observed streamflow from 01/01/1990 to 31/12/2019, obtained from Station V3H010 (Buffels River @Tayside) at latitude 28°3'33.55" and longitude 30°22'24.13" (DWS, 2018). For the validation process, the observed streamflow data was obtained from Station V3H033 (Buffels River Return Flow @Schurvepoort) at latitude 27°36'9.65" and longitude 29°56'33.07" (DWS, 2018), and it was compared with the simulated streamflow data from 01/01/1994 to 31/12/2002. The study applied the following statistical criteria in the evaluation process: normalized root-mean-square error (*nRMSE*), Willmott's (1981) index of agreement (*d*), percent bias (*PBIAS*) and the R^2 to assess the model's performance. The selected criteria are defined by Equations (3.6) to (3.9), and the performance ranking is listed in Table 3.8.

$$nRMSE = \frac{\sqrt{\left(\frac{1}{m}\sum_{i=1}^{m}(O_i - P_i)^2\right)}}{O_{mean}} \tag{3.6}$$

where O_i =observed value

P_i = simulated value

O_{mean} = mean observed value

m = maximum number of data pairs

$$d = 1 - \left[\frac{\sum_{i=1}^{m}(O_i - P_i)^2}{\sum_{i=1}^{m}(|P_i - O_{mean}| + |O_i - O_{mean}|)^2}\right] \tag{3.7}$$

$$PBIAS = \left[\frac{\sum_{i=1}^{m}(O_i - P_i) * 100}{\sum_{i=1}^{m} O_i}\right] \tag{3.8}$$

$$R^2 = \left[\frac{\sum_{i=1}^{m}(O_i P_i) - \sum_{i=1}^{m}(O_i)\sum_{i=1}^{m}(P_i)}{\sqrt{[\sum_{i=1}^{m} O_i{}^2 - \sum_{i=1}^{m}(O_i)^2][\sum_{i=1}^{m} O_i{}^2 -]\sum_{i=1}^{m}(O_i)^2]}}\right]^2 \tag{3.9}$$

Table 3.8 Hydrological model assessment criteria (Moriasi *et al.*, 2007)

d	***PBIAS***	**Performance Rating**
0.8 < *d* ≤ 1	PBIAS ≤ ±10	Very Good (VG)
0.6 < *d* ≤ 0.8	±10 ≤ PBIAS ≤ ±15	Good (G)
0.3 < *d* ≤ 0.6	±15 ≤ PBIAS < ±25	Satisfactory (S)
***d* ≤ 0.2**	PBIAS ≥ ±25	Unsatisfactory (U)

The error index *nRMSE* shows the model's performance; however, it does not indicate the degree of over- and under-estimation. In order to identify incremental and proportional differences between observed and simulated means, *d* was used. It is important to note that *d* is very sensitive to extreme values because of the squared differences. (Moriasi *et al.*, 2007). *PBIAS*, which "*measures the average tendency of the simulated data to be larger or smaller than their observed counterparts*", was further utilized. *PBIAS* optimal value is zero percent, and low values indicate the model simulation is credible. Underestimation bias is shown by positive values, whilst overestimation bias is indicated by negative ones. If the measured and anticipated values are in perfect agreement, the *d* value is 1, and if they are not, it is zero (Moriasi *et al.*, 2007).

Descriptive statistics such as means, percent increases relative to the historical scenario, coefficients of variation, and box and whisker plots were employed to analyse the WEAP, LEAP and global Agro-Ecological Zones (gAEZ) models' output data. Tukey box and whisker plots can demonstrate dataset stability and general distribution. The variations of the minimum and maximum rainfall across the catchment are displayed by the whiskers of the box plots, with the median value shown by the line in the middle of the box plots, and outliers, which are individual points plotted beyond the whiskers of the box and whisker plots, are indicated by the dots above and/or below the boxplots.

3.3 Results and Discussion

3.3.1 Precipitation

From the box-and-whisker plots in Figure 3.5 and Figure 3.6, it is evident that the selected GCMs' bias-corrected historical precipitation data follow the general trend, observed by the median line on the plots, and spread, indicated by the whiskers, of the CHIRPS i.e., Baseline scenario, dataset for the RCP4.5 and RCP8.5 scenarios, except for the CNRM-CM5 model which over-simulated the dispersion and extreme rainfall events of the catchment. For the RCP4.5 scenario, as per Figure 3.5, the projected precipitation trends coincide with the DEA (2013b)'s statistically downscaled projections for eastern South Africa, where significant increases in BR catchment's rainfall magnitude and variability were projected in the far future. However, in the near- and mid-future, rainfall patterns are unclear and indicate a general mixed signal of wetter or drier conditions, depending on the GCM used. Under the RCP8.5 scenario, similar projections of average increases are found. However, the near-future scenario is the exception, as shown in Figure 3.6, where 4 out of 6 GCMs projected a decline in precipitation compared with the CHIRPS data.

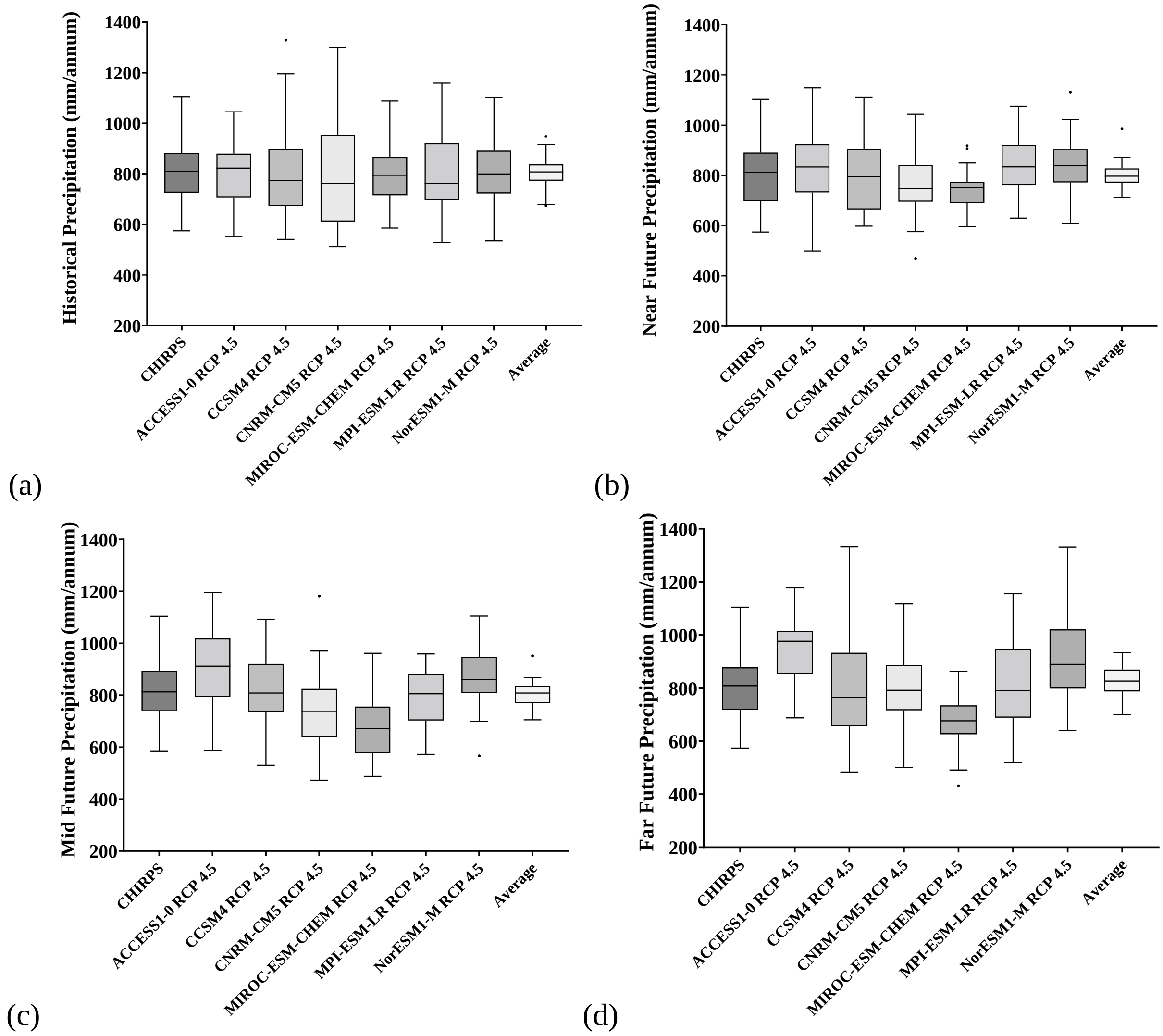


Figure 3.5 Comparison of bias-corrected GCM average annual precipitation (mm/annum) outputs during the historical (a), near future (b), mid-future (c) and far future (d) timeframes under the RCP4.5 scenario, with CHIRPS representing the historical remote sensed precipitation. In graphs (b) to (d), CHIRPS dataset is for comparison purposes only.

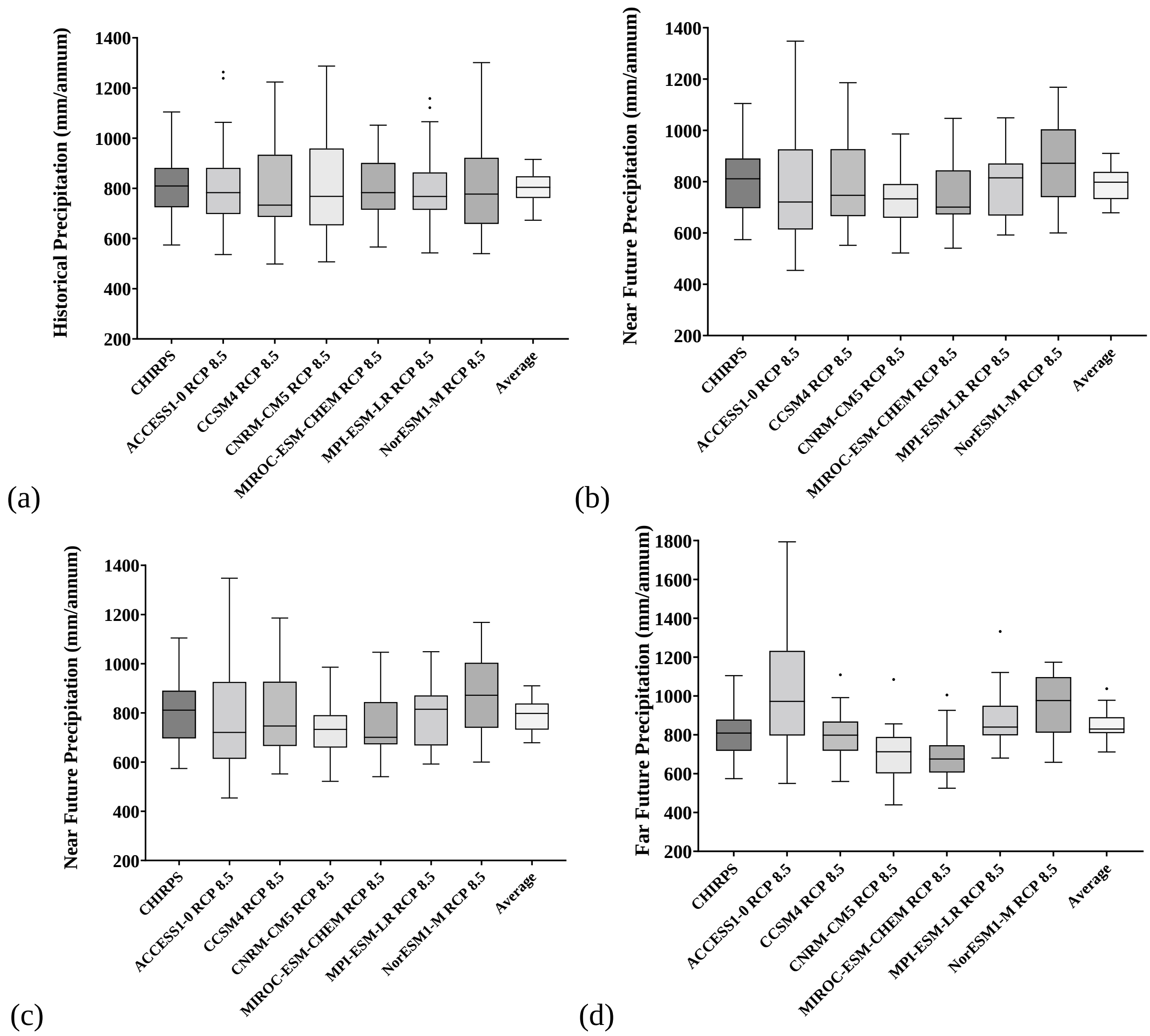


Figure 3.6 Comparison of bias-corrected GCM average annual precipitation (mm/annum) outputs during the historical (a), near future (b), mid-future (c) and far future (d) timeframes under the RCP8.5 scenario. In graphs (b) to (d), CHIRPS dataset is for comparison purposes only.

To investigate the overall projected changes in the BR catchment, the multi model ensemble mean approach was adopted (Tramblay *et al.*, 2018; Hadri *et al.*, 2022), whereby the projected changes of the 6 GCMs were averaged annually under both RCP4.5 and RCP8.5 scenarios. In the near- and mid-future periods, the average ensemble of the RCP4.5 scenario projected precipitation to increase, with MAP increasing by 0.06% and 0.32%, respectively. Decreases in variability are also modelled in the near- and mid-future timeframes for RCP4.5, shown by the coefficient of variation (CV) decreasing slightly from a historical value of 7.9%, to 6.5% and 6.7%, respectively. However, for the far-future timeframe, a slight increase in rainfall is projected as the percent increase of MAP is 3.4%. Increased variability is also noted by the CV value increasing to 7.1%.

The average ensemble of the RCP8.5 scenario projects a slight decrease in the amount of precipitation received by the catchment in the near future, with the MAP decreasing by -2%, thus resulting in an overall MAP value of 787 mm. The rainfall variations increased slightly during this timeframe as the CV increased from a historical value of 7.9% to 8.1%. Increases in precipitation magnitude and fluctuations in the mid- and far-future are more prominent than in the RCP4.5 scenario, with the percentage increase of MAP being 4.3% and 5.4%, respectively, and the CV value reaching 8.5% in both periods. From the box-and-whisker plot in Figure 3.7, a positive skewness resulted in the far future, signifying that the frequency of low rainfall occurrences (≤ 825 mm, lower than the average of 845 mm) is expected to increase. It is also important to take note of the widened lengths of the 75th and 90th quartile whiskers in the far-future, which reflect an anticipated increase in the magnitude of extreme wet events.

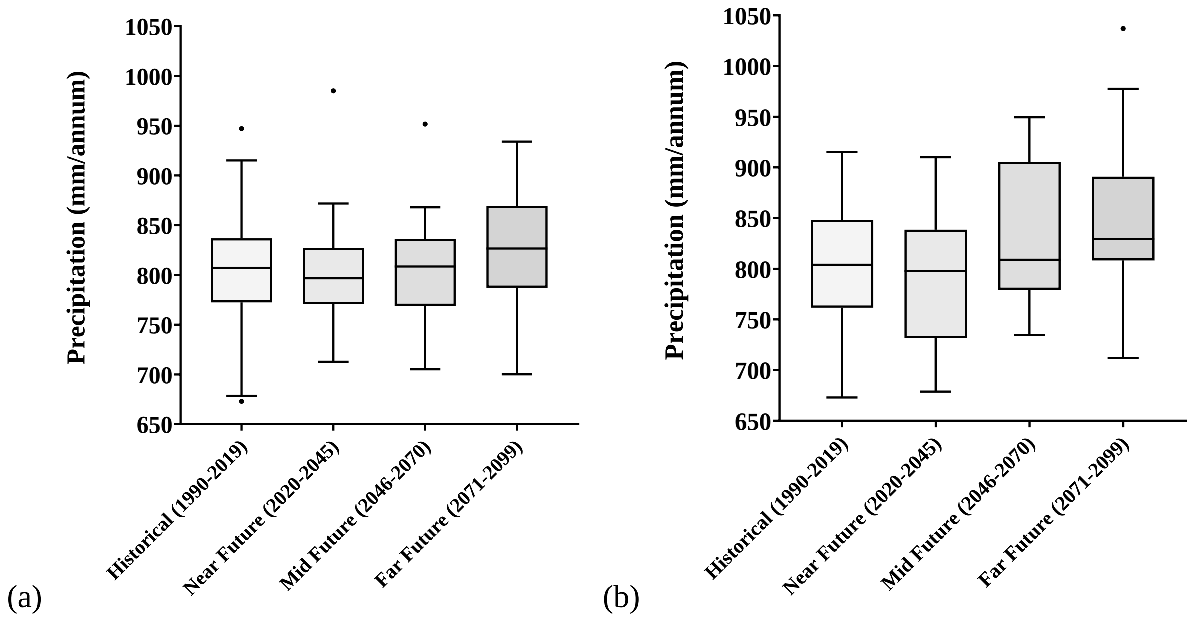


Figure 3.7 Distribution of average annual precipitation (mm/annum) for the average ensembles during the historical, near future, mid-future, and far future timeframes under the RCP4.5 scenario (a) and the RCP8.5 scenario (b).

3.3.2 Evapotranspiration

ET_A was the largest component of the water budget represented by the model. Figure 3.8 shows that low ET_A values are under-simulated for all GCM models compared to the CHIRPS dataset.

Overall, the average ensembles of ET_A projections under RCP4.5 and RCP8.5 scenarios maintained the average ET_A of 4500 Mm^3/annum. Slight declines in ET_A are only noted in the near future under the RCP8.5 scenario as the percentage decrease was -2%, this being a consequence of the projected decline in precipitation in the same timeframe.

There is a strong correlation between precipitation and ET_A patterns. For the RCP4.5 scenario, the ET_A's CV declined from a historical value of 10% to 7.5% and 7.9% in the near- and mid-future, respectively. However, the ET_A's CV increased to 9% in the far-future. The RCP8.5 scenario's CV increased in the near future from a historical value of 8.5% to 8.6%, and then it declined in the mid- and far-future to 8.1% and 8.4%, respectively; the decline is to be noted as a result of the increased frequency of low precipitation events.

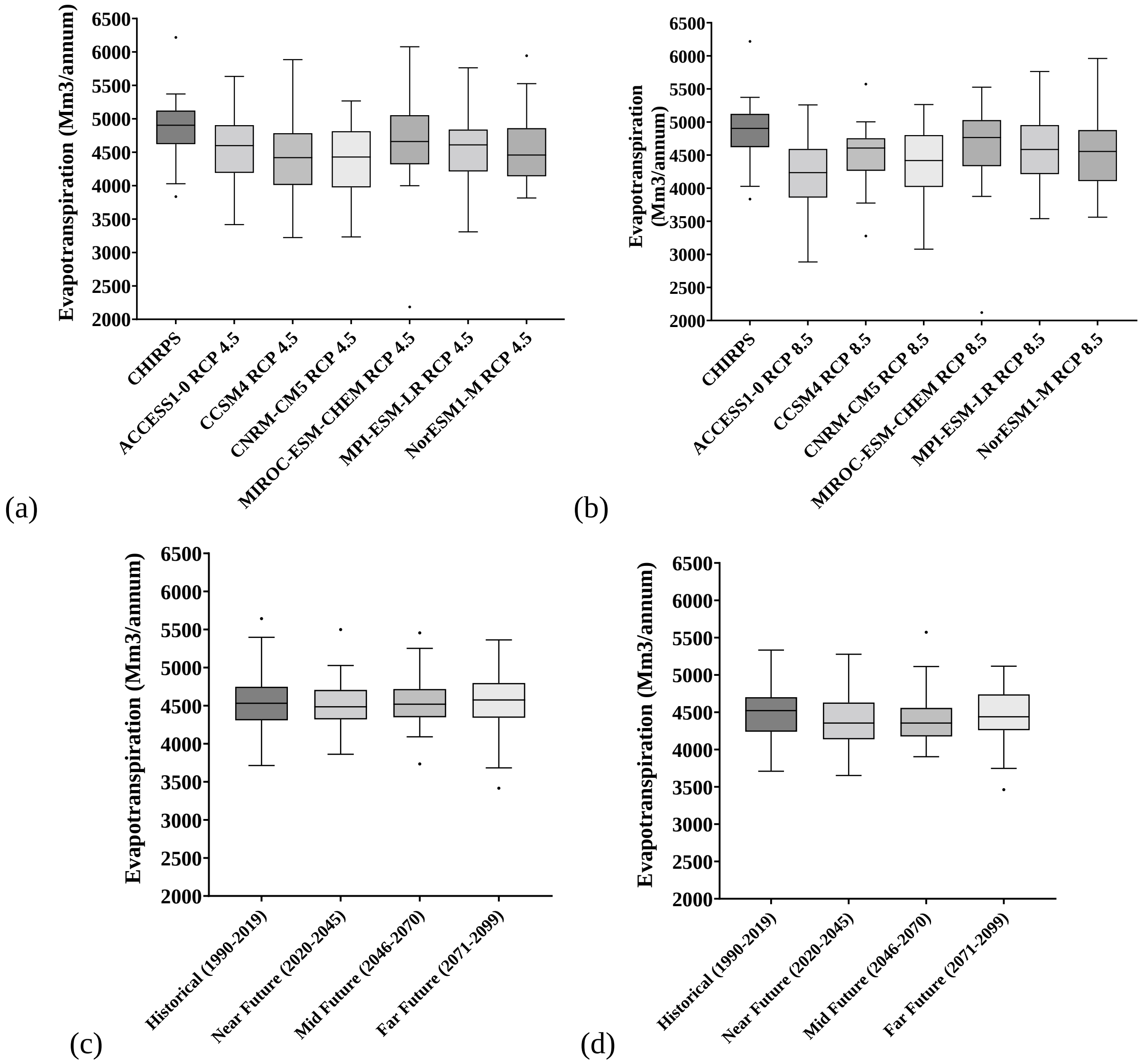
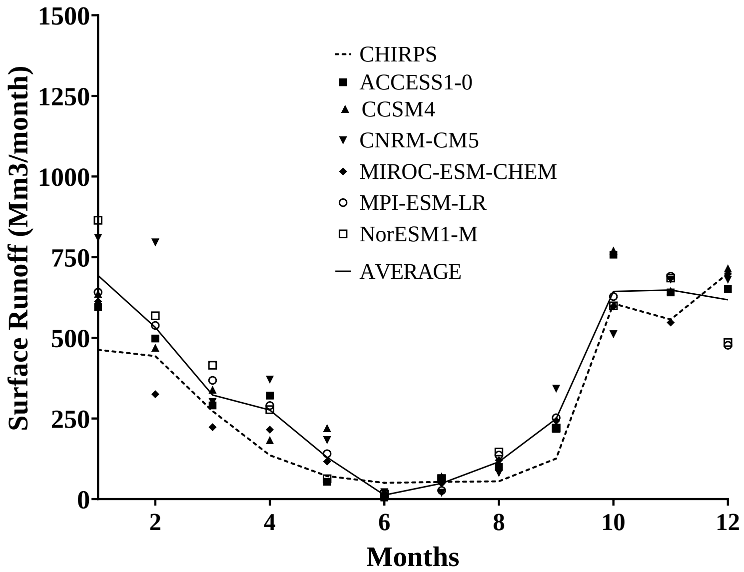


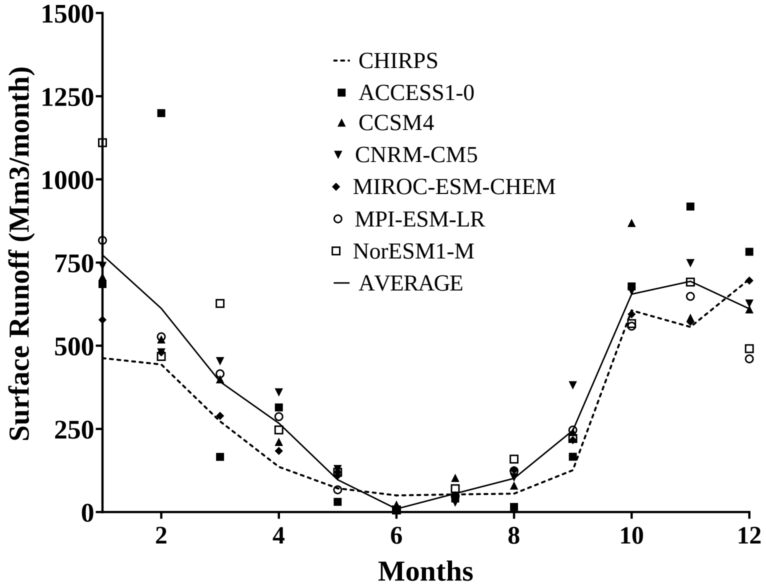
Figure 3.8 Comparison of simulated GCM average annual ET_A (Mm^3/annum) during the historical period under the RCP4.5 scenario (a) and RCP8.5 scenario (b), and distribution of simulated ET_A by average ensemble throughout the study period under the RCP4.5 scenario (c) and RCP8.5 scenario (d).

3.3.3 Surface runoff and streamflow

When compared to the surface runoff (*R*) simulated using the CHIRPS historical precipitation, Figure 3.9 shows over-simulated *R* values under both RCP4.5 and RCP8.5 scenarios. The over-simulation is, however, statistically insignificant; the one-way ANOVA performed on the CHIRPS, and all GCM output data produced a p-value of 0.98.



(a)



(b)

Figure 3.9 Comparison of the spread of average monthly simulated R (Mm^3/month) by CHIRPS data and all GCMs under the historical period for the RCP4.5 scenario (a) and RCP8.5 scenario (b).

For *R* projections, as seen in Figures 3.10 and 3.11, *R* remained unchanged throughout the study period under the RCP4.5 scenario with an average value of 3330 Mm^3/annum. However, significant increases are observed in the far-future as the mean average *R* increases to 3566 Mm^3/annum. The CV displays a decreasing trend as it dropped from a historical value of 19%, to 17% in the near future, and 15% in both the mid- and far future timeframes.

R projections under the RCP8.5 scenarios displayed decreased fluctuations in the near future; the CV dropped from a historical value of 19% to 16%; however, the mean remained unchanged as it was 3318 Mm^3/annum. For the mid- and far-future, notable increases in both magnitude and fluctuations are projected: the mean values increased by 0.6% and 8% to 3765 and 3815 Mm^3/annum, respectively, and the CV also increased to 21% and 17%, respectively.

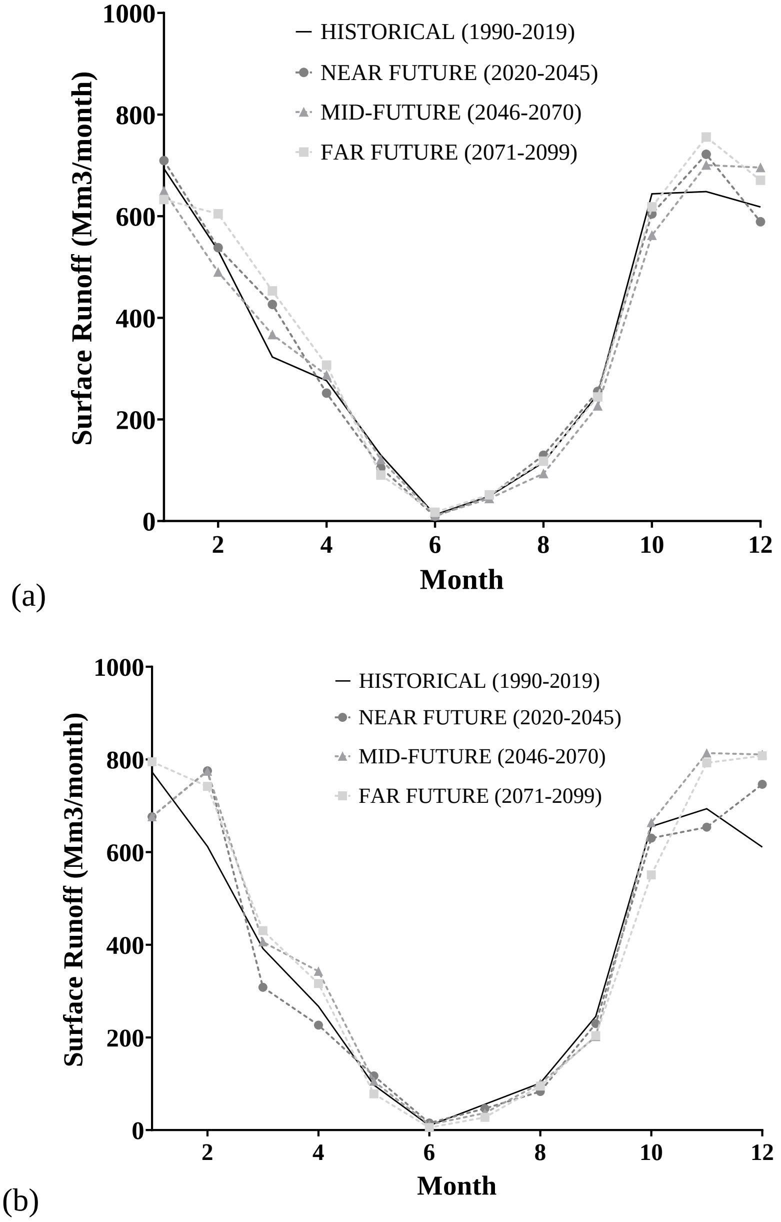


Figure 3.10 Comparison of the spread of monthly simulated R (Mm^3/month) by the average ensemble under the historical, near future, mid-future and far-future timeframes for the RCP4.5 scenario (a) and RCP8.5 scenario (b).

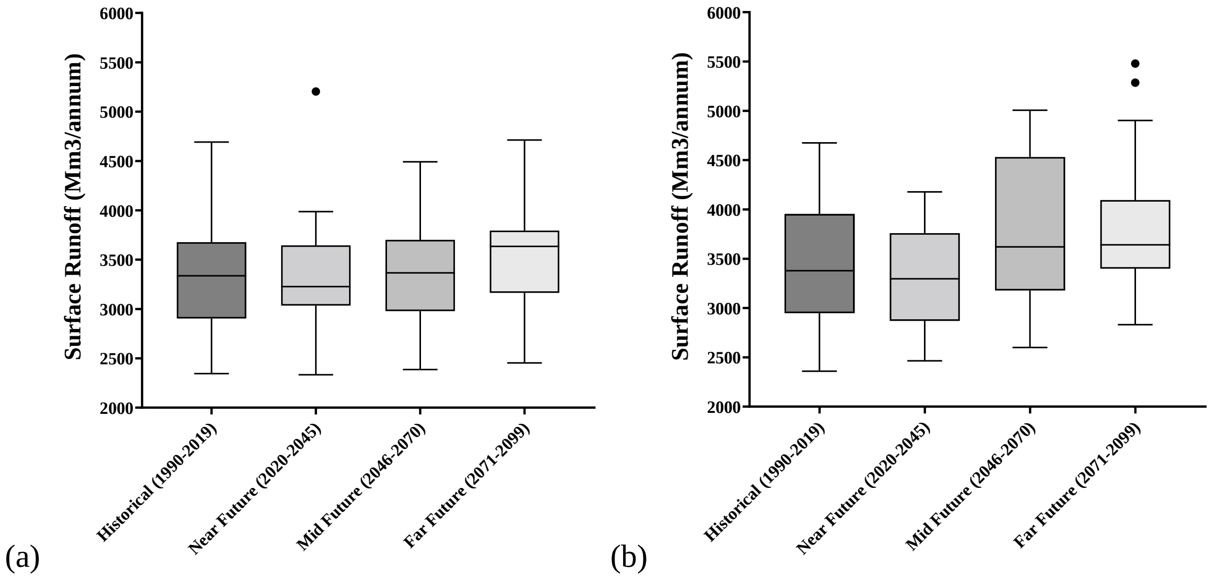


Figure 3.11 Distribution of simulated average annual R (Mm^3/annum) for the average ensemble during the historical, near future, mid-future, and far future timeframes under the RCP4.5 scenario (a) and the RCP8.5 scenario (b)

After computing surface water abstractions and return flows, incorporating changes due to population growth and taking reservoir storage into account, a streamflow graph was produced by the WEAP model of each river's nodes and reaches. In the water balance computation, the streamflow at the BR's outlet (*Q)* is considered. Projections for *Q* values under the RCP4.5 scenario display slight increases in the near- and mid-future, as the annual averages increase from a historical value of 3028 Mm^3/annum to 3034 and 3046 Mm^3/annum, respectively. As per the precipitation and *R* projection trends, *Q* also increased rapidly in the far-future, with the percentage increase shooting up from a mid-future value of 0.6% to 8% in the far future, and the annual average *Q* being 3267 Mm^3/annum.

The RCP8.5 scenario displays the highest *Q* averages under the mid- and far-future timeframes, as seen in Figure 3.12. A very slight decline by 2% in the annual average Q is projected in the near future, from a historical value of 3081 to 3024 Mm^3/annum. Moreover, increases by 13% and 14% are projected in the mid- and far-future timeframes, respectively. These increases in magnitude were accompanied by increased fluctuations as the CV increased from 17% in the near-future, to 22% and 18% in the mid- and far-future, respectively. The box-and-whisker plot for the far future timeframe also displays a positive skewness of 1.105, indicating anticipated increased events of high-value streamflow exiting the catchment. This is mainly attributed to high precipitation values, low magnitude, and variability in ET_A values during this period. These results are consistent with the research findings by Graham *et al.* (2011), DEA (2013a) and

Schütte *et al.* (2022), which projected that the RCP8.5 CC scenario would increase Q in KwaZulu-Natal.

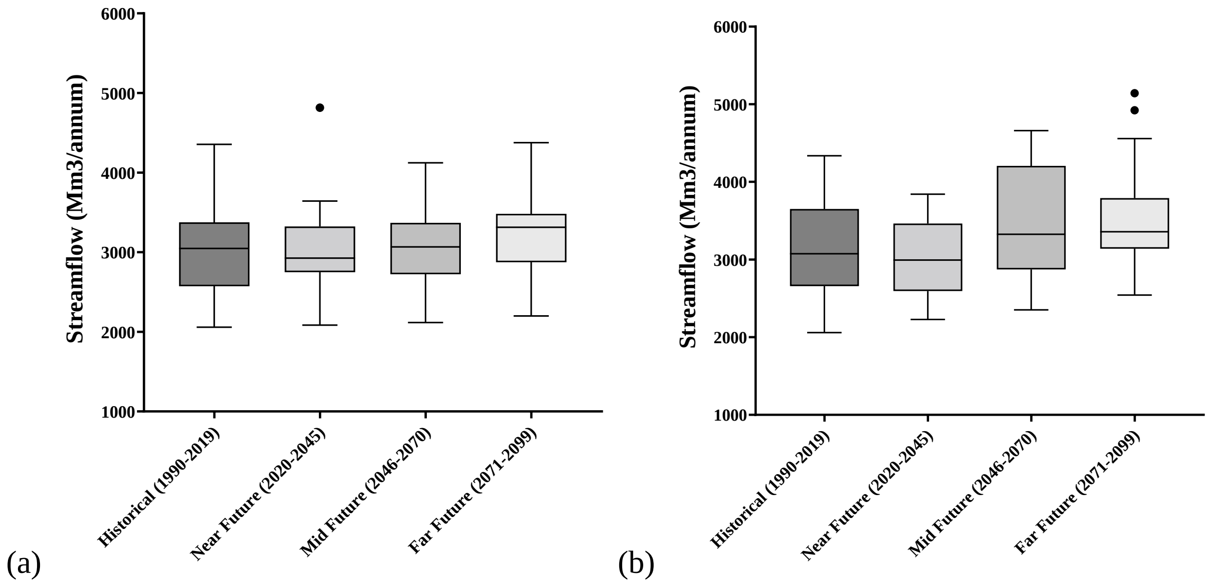


Figure 3.12 Distribution of simulated average annual Q (Mm^3/annum) for the average of the GCM ensemble during the historical, near future, mid-future, and far future timeframes under the RCP4.5 scenario (a) and the RCP8.5 scenario (b)

3.3.4 Water abstractions

In addition to ET_A and Q, water abstractions (W_A) were considered an outflow component of the water balance. The surface water demands from all the demand nodes are presented in Figure 3.13. These include energy production water use of the Majuba power station, and the water use per sector within each local municipality. The water use per sector is a function of the domestic water use within the respective local municipality, and the irrigation water requirements. The largest W_A were derived from the Ngagane Water Treatment Plant (WTP, mainly because it supplies numerous water demand sites, including the most densely populated and irrigated local municipality, Newcastle. Since only the population growth rate was addressed in this analysis, it is understood that the quantity of W_A will increase during the study period as domestic water demands increase. The average value of water demands throughout the study period is 157 Mm^3/annum, increasing from 151 Mm^3 in 1990 to 162 Mm^3 in 2099.

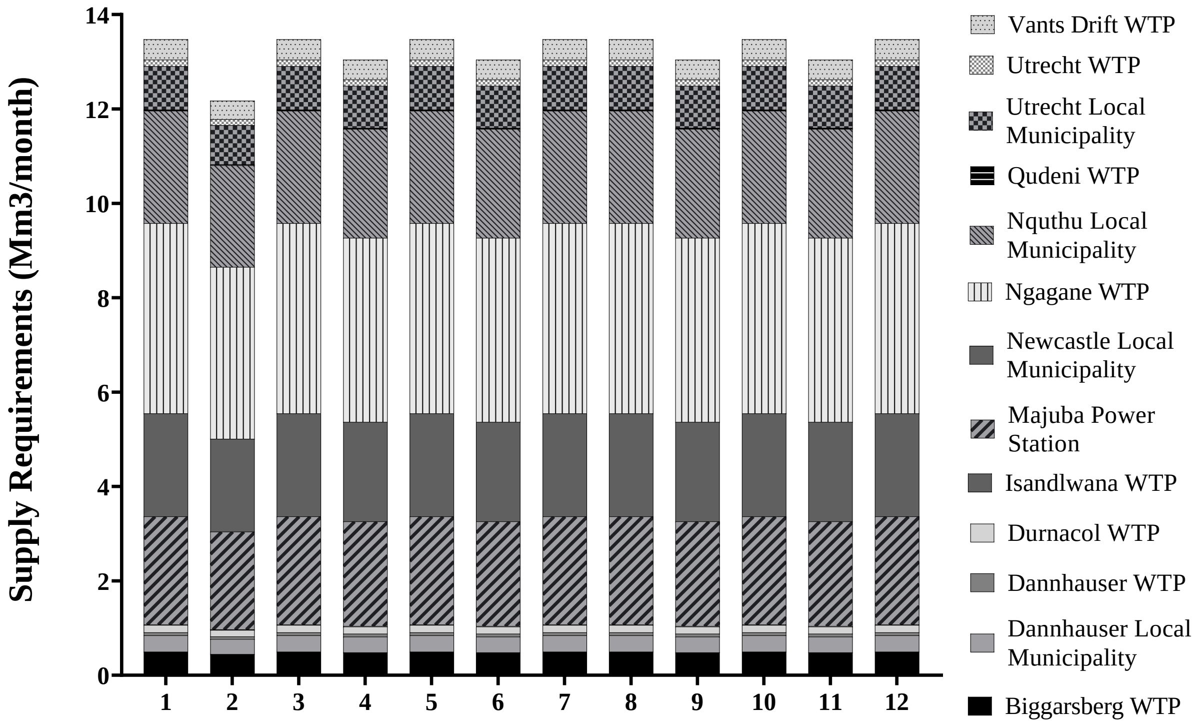


Figure 3.13 Total monthly supply requirements (Mm^3/month) throughout the projection period (01/01/2020-31/12/2099).

A correlation exists between precipitation and unmet water demands in the BR catchment. As shown in Figure 3.14, increases in unmet demands are anticipated under both climate scenarios, from a historical value of 40 Mm^3/annum to 47 Mm^3/annum in the far future. Additionally, the fluctuations of unmet demands also increased, especially under the RCP4.5 scenario, which yielded a CV of 9% in the far future timeframe. This is understood to be a result of the limitations imposed by the storage capacity of the BR catchment, which does not capture sufficient precipitation received throughout the 21st century to cater for the growing demand, and also confirms findings from the uMgeni (2020), which state that the BR catchment's water storage capacity is not sufficient to provide the increasing demands of the catchment.

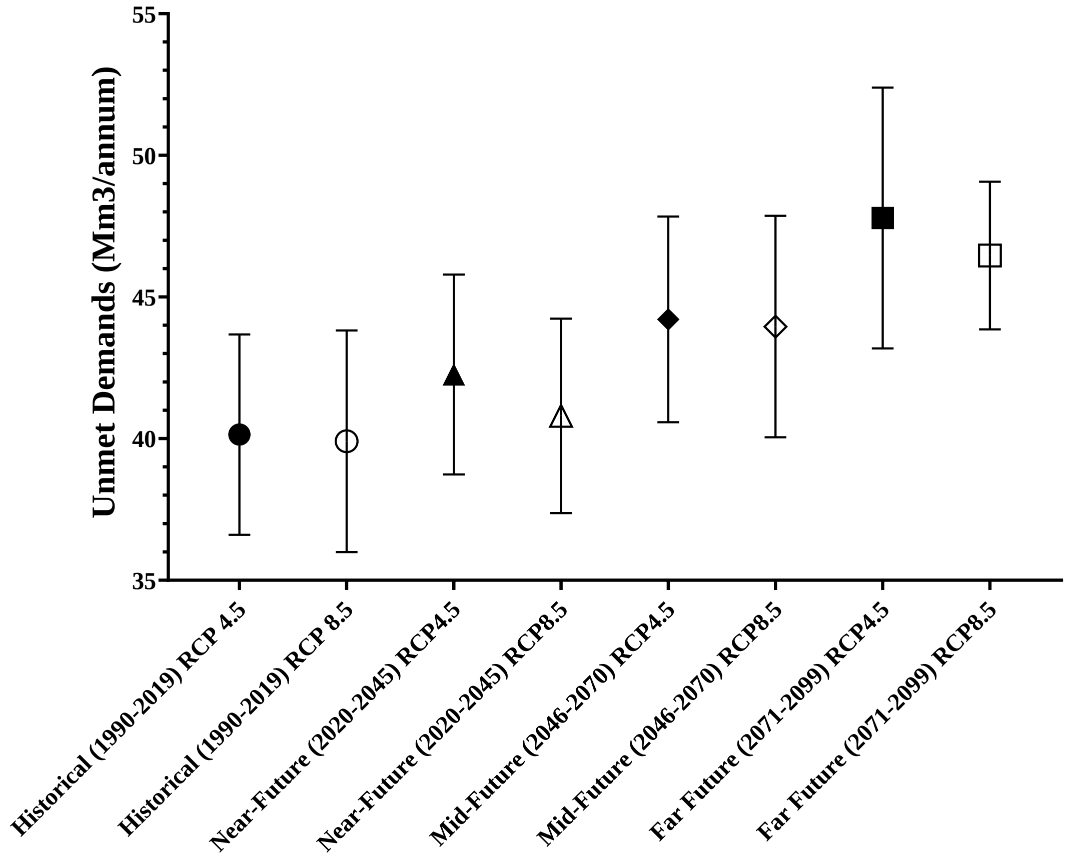


Figure 3.14 Total annual unmet demands throughout the study period for the average of the GCM ensemble under the RCP4.5 scenario and RCP8.5 scenario.

3.3.5 Changes in surface water store

The hydrological water balance components for the BR catchment developed from the WEAP model under the RCP4.5, and RCP8.5 scenarios are summarized in Tables 3.9 and 3.10, respectively. When compared to the historical surface water storage (S_N) simulated with the CHIRPS data which yielded a CV of 28.9%, both RCP4.5 and RCP8.5 historical average ensembles displayed slightly lower variations (see Figure 3.15), with the CV being 22%. This is attributed to the average ensembles' precipitation values, under both RCP scenarios, also consisting of lower fluctuations than the CHIRPs historical average (see Chapter 3.3.1)

Table 3.9 Estimated changes in mean annual surface water storage under RCP4.5 scenario.

Averages for RCP 4.5 Scenario (Mm^3)	Annual Averages			
	Historical (1990-2019)	Near Future Projections (2020-2045)	Mid-Future Projections (2046-2070)	Far Future Projections (2071-2099)
Precipitation	7 858.75	7 863.52	7 884.08	8 125.32
Evapotranspiration	-4 517.98	-4 516.40	-4 532.16	-4 547.71
Streamflow	-3 027.29	-3 033.73	-3 044.22	-3 265.11
Abstractions	-124.45	-125.59	-125.36	-126.05
Net Surface Water Store	3 009.83	3 173.63	3 211.22	3 322.11

Table 3.10 Estimated changes in mean annual surface water store under RCP8.5 scenario.

Averages for RCP 8.5 Scenario (Mm^3)	Annual Averages			
	Historical (1990-2019)	Near Future Projections (2020-2045)	Mid-Future Projections (2046-2070)	Far Future Projections (2070-2099)
Precipitation	7 865.63	7 707.33	8 207.30	8 286.30
Evapotranspiration	-4 472.81	-4 378.60	-4 378.46	-4 458.22
Streamflow	-3 079.95	-3 024.11	-3 466.73	-3 520.94
Abstractions	-124.02	-124.00	-125.21	-124.58
Net Surface Water Store	2 942.21	3 030.08	3 243.53	3 275.41

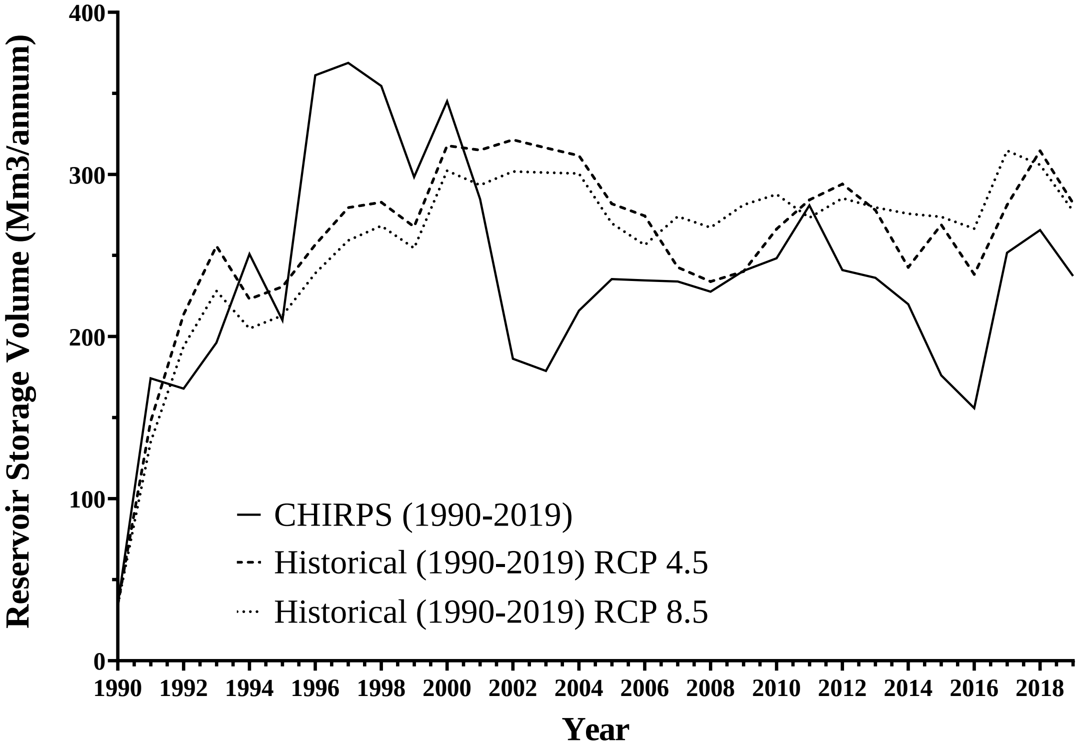


Figure 3.15 Difference between reservoir storage volume (Mm^3/annum) under each RCP scenario and the CHIRPS scenario.

From Figure 3.16, the annual projections of S_N indicate slight increases in magnitude and decreased variations, more so in the far future, whereby the average S_N is expected to increase by 8% under both climate scenarios relative to the historical average of 260 Mm^3/annum, and CV values declining to 7% and 8% under the RCP4.5 and RCP8.5 scenarios, respectively. This is expected as a result of the anticipated increased precipitation, especially under the RCP8.5 scenario. However, as also observed in Figure 3.16, these changes in water storage are similar to those of the historical timeframe and are minimal as compared to the precipitation increases expected towards the end of the 21st century. Such findings also reflect the inadequacies and limitations imposed by the water storage facilities of the catchment in capturing the increased precipitation, causing increased Q and unmet demands throughout the projection period.

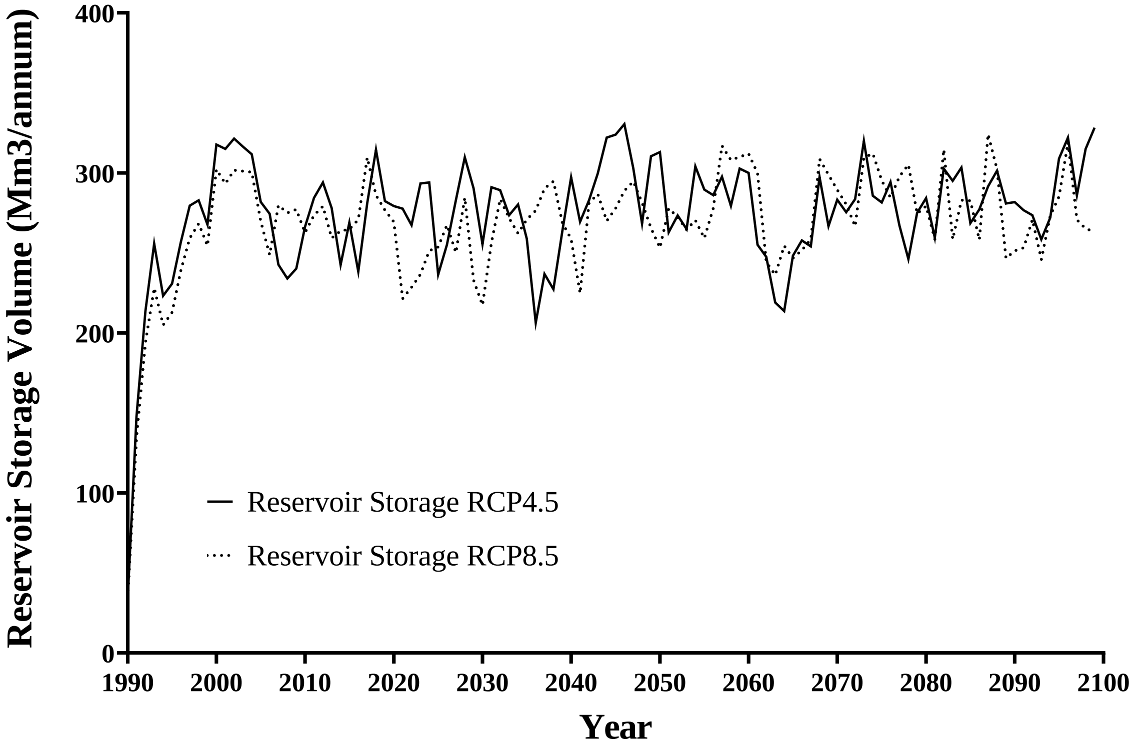


Figure 3.16 Distribution of simulated average annual reservoir storage (Mm^3/annum) for the average ensembles during the historical, near future, mid-future, and far future timeframes under the RCP4.5 and the RCP8.5 scenarios.

3.3.6 Model calibration and validation performance

The performance measures during the calibration and validation periods indicated a very good performance of the WEAP model in the BR catchment for streamflow simulation at a monthly scale. In the first instance of model calibration, the model's performance was satisfactory, as evidenced by the model performance statistics (see Table 3.11 below and Figures A.7 to A.9 in the Appendix). However, the model over-simulated streamflow under the CHIRPS dataset and under the average ensemble of the GCMs under the RCP4.5 and RCP8.5 scenarios, as seen in Figure 3.17. This is indicated by the *PBIAS* values ranging from -19.62 to -24.17. The over-simulation could be attributed to the use of 8-day ET_A data in the water balance computation, which had to be disaggregated evenly across 8 days to obtain daily ET_A values. However, the validation statistics all qualify as satisfactory. Under the RCP4.5 and RCP8.5 GCMs' average ensembles, the WEAP simulated streamflow displayed the least correlation when compared to the observed, with the R^2 values being 0.7614 and 0.805, respectively, as seen in Figures A.10 to A.12 in the Appendix, and the *nRMSE* values being 40.77 and 44.25, respectively.

Table 3.11 Statistical values of simulated streamflow by the CHIRPS dataset and RCP4.5 and RCP8.5 GCMs' average ensembles.

		CHIRPS	RCP4.5	RCP8.5
Calibration Statistics	***d***	**0.958 (VG)**	**0.860 (VG)**	**0.836 (VG)**
	nRMSE (%)	22.32	40.77	44.25
	PBIAS	-22.54 (S)	-19.62 (S)	-24.17 (S)
	R^2	0.902	0.7614	0.805
Validation Statistics	***d***	0.790 (G)	0.951 (VG)	0.832 (VG)
	nRMSE (%)	5.51	2.674	4.933
	PBIAS	18.43 (S)	8.940 (VG)	16.49 (G)
	R^2	0.905	0.988	0.987

After validating the performance of the model, the model's performance was deemed to be very good. An improvement in the streamflow simulation was observed, as seen in Figure 3.18, which yielded positive *PBIAS* values ranging from 8.94 to 18.43. In terms of correlation among the streamflow trends, the model produced streamflow values with improved correlation when compared to the observed as the *nRMSE* values decreased from a range of 22.32 to 44.25 during calibration, to a range of 2.674 to 5.51.

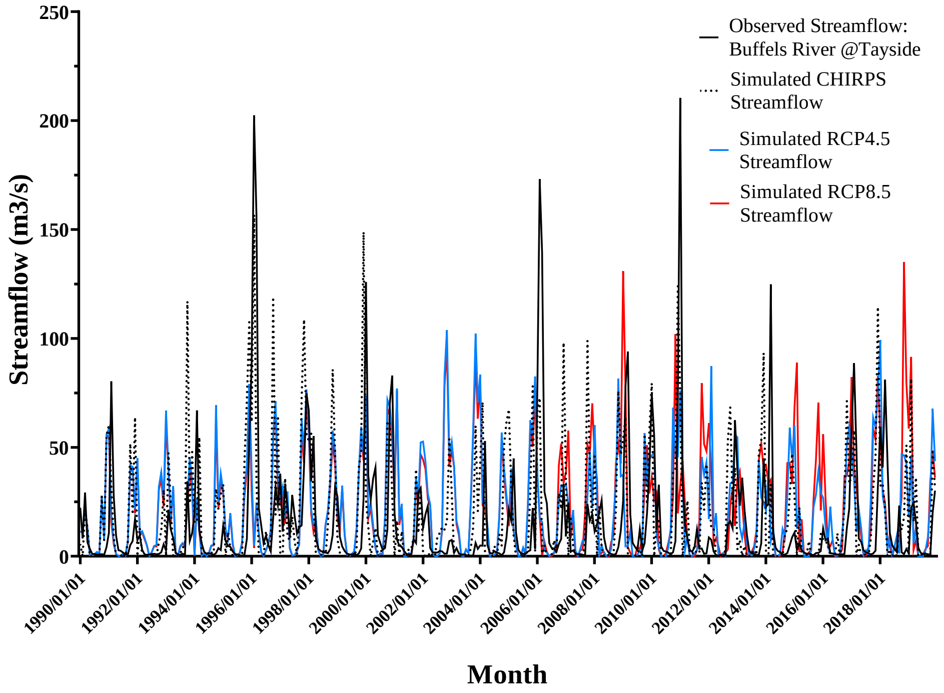


Figure 3.17 Monthly simulated versus observed streamflow of the Buffalo River for the calibration period (01/01/1990-31/12/2019).

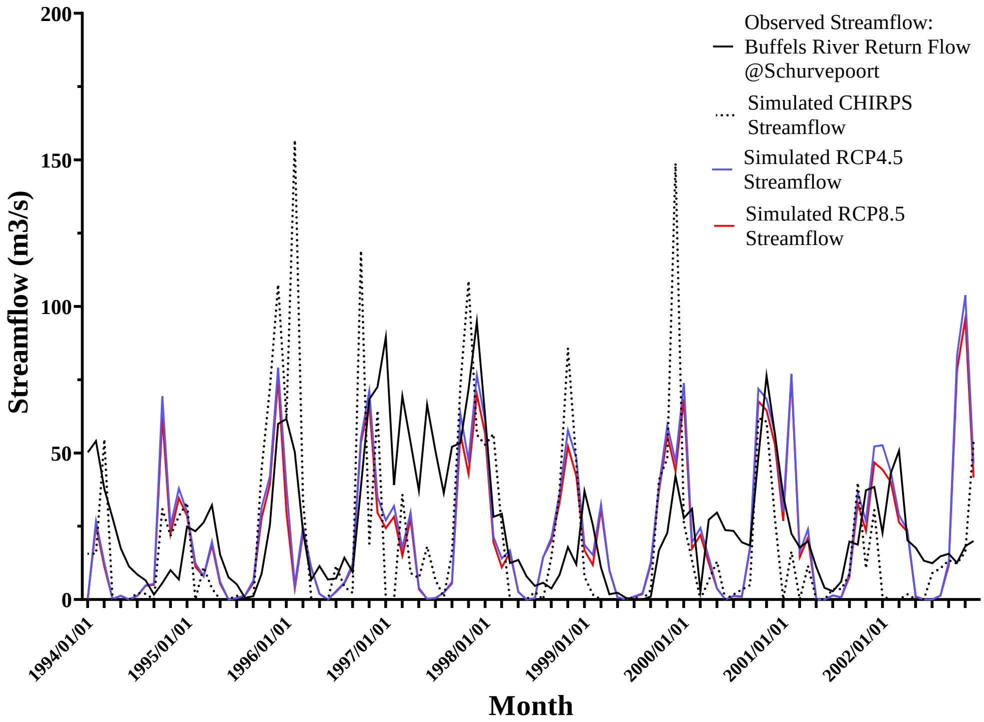


Figure 3.18 Monthly simulated versus observed streamflow of the Buffalo River catchment for the validation period (01/01/1994-31/12/2002).

3.4 Conclusions and Recommendations

The objective of this study was to assess the impacts of CC on SWA in the BR catchment. Various future scenarios were developed by acquiring the catchment's historical and climate model output data. These were integrated into the WEAP model, which evaluated the catchment's available surface water under all scenarios. It is concluded that mean annual precipitation is expected to increase under CC, consequently inducing increased ET_A and R. Increased magnitudes of droughts and floods are also anticipated under CC, and as such, larger variations in R and reservoir storage were modelled. Through recharge during periods of peak flood (extreme wet) events, CC is expected to increase SWA. As such, we reject the postulated null hypothesis of this study.

Even with the increased SWA, unmet demands are anticipated to increase in the catchment. The study's results also revealed that the bulk of the catchment's precipitation is converted to ET_A. R at the outlet of the catchment is projected to increase under CC; therefore, it is recommended that the catchment's surface water storage capacity be increased. Water storage capacity can be optimized through the expansion and construction of new water treatment facilities and using various water harvesting technologies such as multi-purpose reservoirs, micro dams, ponds, weirs, and check dams. Such projects do, however, need to take into consideration the maintenance of environmental flows needed to maintain river ecosystems, and as part of the WEF nexus ideology, trade-offs that may result from their implementation need to be addressed.

The WEAP model's accuracy depends on the amount of available information and the degree of detailedness. Thus, it is highly recommended that future works improve the accuracy of details used in simulating hydrological processes using the WEAP model. This involves the utilization of dynamically downscaled precipitation projections, groundwater quantification and computation, and the integration of a detailed assessment of changing water demands, especially those of agricultural production which are highly influenced by land-use and suitability changes. Nonetheless, the performance of the WEAP model was assessed statistically, and the statistics indicate a sufficient model fit from the analyses. This study's findings illustrate the WEF nexus' CLEW complex relationships, particularly the examined relationship between climate and water availability.

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4 MODELLING THE WATER SUPPLY-DEMAND RELATIONSHIP IN THE BUFFALO RIVER CATCHMENT, SOUTH AFRICA, UNDER CLIMATE CHANGE

Abstract

Background: The Buffalo River (BR) catchment, located in northern KwaZulu-Natal, South Africa, has encountered some issues regarding its water distribution plans to its water demand sites.

Problem Statement: While surface water is available, there are inequalities in water allocations among users, thus contributing to the catchment's water system's unreliability.

Objective: The study therefore investigated how climatic changes may affect the Buffalo River catchment's water supply system's reliability in meeting water demands throughout the 21st century.

Results: Study findings were derived by conducting a comparative analysis on the variations in water system's reliability in meeting existing and projected water requirements of the catchment under Climate Change (CC). The findings projected increases in the water system's reliability in meeting demands of the highly populated Dannhauser, and Newcastle local municipalities, especially demands from these municipalities domestic sector. However, for the sparsely populated and agricultural intensive Nquthu and Utrecht local municipalities, the Buffalo River catchment's water supply system was projected to be unreliable to provide their water demands. Such unreliability is anticipated to consequently put strain on agricultural production as more than 70% of irrigation water demands come from these respective municipalities.

Conclusions and Recommendations: CC is anticipated to vary the reliability of the water system in meeting mostly domestic water demands throughout the projection period. As such, considering the relatively wide range of probable impacts on water resources, and the large differences in the reliability of the water supplies to meet energy, agriculture and domestic water demands in the Buffalo River catchment, integrated water allocation and capacity augmentation plans are strongly recommended.

Keywords: Water supply system, KwaZulu-Natal, water-energy-food nexus, CLEWS

4.1 Introduction

The reliability of a water supply system is broadly described as the probability of meeting water system objectives (Lund, 2016), and it is crucial in ensuring access to water for people, agriculture and industry, and for releasing environmental flows in watercourses during dry seasons (Kiewiet, 2019; Sýs *et al.*, 2021). The pressure on freshwater resources due to climate change (CC), population growth and increasing diverse water-reliant activities largely reduces a water system's reliability. Such factors increase water demands and competition amongst water users (Arthington *et al.*, 2018). Integrated water system reliability assessments in the context of CC are therefore paramount for determining whether existing water distribution systems and plans are capable of meeting current and future domestic, industrial, agricultural, and ecological water demands (Staveley, 2020), as well as making informed water management decisions that prevent over-allocation of water (Kiewiet, 2019).

Meeting increased energy demand from agricultural production and domestic and industrial uses will require increased energy generation and capacity (Welsch *et al.*, 2014). Since the process of producing energy requires water, the likelihood of the energy sector requiring additional water in the future could cause disputes with the agricultural and water supply sectors (Mpandeli *et al.*, 2018). In this regard, identifying the availability of water under present and future CC scenarios is critical in assessing the reliability of water supply when the supply-demand cycle across sectors, such as energy and agriculture, is relevant. Such information is important for optimizing water allocations based on demand for available water resources at different time periods (Ahmadzadeh *et al.*, 2022), thus avoiding potential inequalities in water supply distribution and the consequential conflicts among water users (Yao *et al.*, 2019).

According to uMgeni (2020), the water distribution system in the KwaZulu-Natal's Buffalo River (BR) catchment, which is a high rainfall region receiving, on average, 802 mm/annum, has not been able to meet demand in recent years, and the droughts of 2015/2016 aggravated the situation. uMgeni (2020) further declared that the yield of the Ntshingwayo Dam, the Buffalo River catchment's largest water source, will not be sufficient to supply the 2035 water demands.

To the best of our knowledge, a detailed water resources analysis looking into water availability, demand coverage and reliability of the BR system under CC does not exist. With the above-mentioned water supply issues in the catchment, an analysis is indeed required to determine whether the system can meet current and future water demands for WEF resources securities (uMgeni, 2020), more so under CC. The objective of this study was to therefore determine the reliability of the BR catchment's water system in meeting the anticipated water requirements under CC conditions, and the study is based on the null hypothesis of reliability not changing with time. The study seeks to assist in informed decision-making regarding water resource management in the BR catchment, considering the influence of spatial variability of water resources and long-term CC.

4.2 Materials and Methods

4.2.1 Description of case study – Buffalo River catchment

The BR catchment, shown in Figure 4.1, is a sub-catchment of the Thukela Water Management Area, whose water source is in the Drakensberg region, northern KwaZulu-Natal, South Africa. The BR catchment covers an estimated 9 804 km^2 and it is located between latitude 28°42'59" S and longitude 30°38'30" E, in South Africa (uMgeni, 2020). It is the main northern tributary of the uThukela River. It flows approximately 339 km south-easterly, from the eastern escarpment (Newcastle area) and then confluences with the uThukela River (Dlamini and Mostert, 2019; uMgeni, 2020). The BR catchment is categorised as a high runoff internal sub-catchment, supplying water to numerous sectors, including irrigation, power generation, domestic, mining and bulk industries (uMgeni, 2020). There have been severe droughts in the past years, especially during 2015 and 2016, affecting livelihoods and socio-economic activities within the BR catchment and surrounding areas (uMgeni, 2020). Thus, the implications of possible CC outcomes on the BR catchment's capability to meet its water demands must be evaluated.

The BR catchment covers the following local municipalities: (a) Newcastle Local Municipality (LM), (b) Dannhauser LM, (c) Utrecht LM and (d) the Nquthu LM. As per Table 4.1, the catchment population is approximately 0.7 million, with an average population density of 79.83 per km^2. From the community census conducted in 2011 and 2016 by StatsSA (2016), the number of households in the BR catchment's local municipalities increased from 142 713 to 149 878, and the household size remained at five people per household. Table 4.2 provides a breakdown of household statistics per LM.

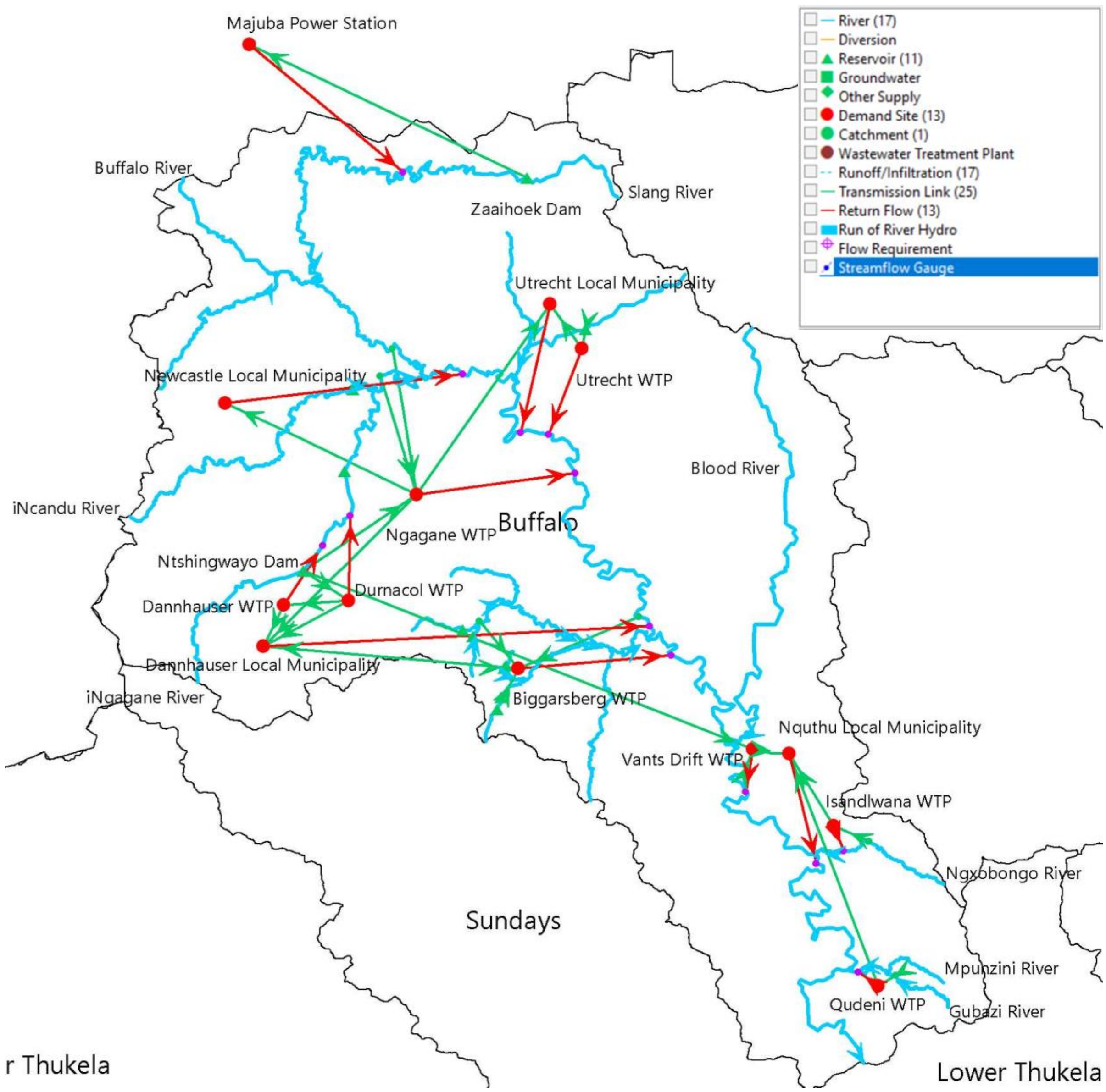


Figure 4.1 Schematic of the Buffalo River catchment with water demand sites and reservoirs.

Table 4.1 Physical and demographic characteristics of the Buffalo River catchment's local municipalities for the year 2016.

Local Municipality	**Area[1,2] (km^2)**	**Population Capacity[3]**	**Population Growth Rate[3] (%)**	**Population Density per km[1]**	**Source(s)**
Newcastle	1 689	389 117	1.56	215	1(Mahlaba, 2019),
Utrecht	3 539	36 869	1.55	18.3	3(StatsSA, 2016)
Dannhauser	1 518	102 937	0.52	67.5	
Nquthu	1 962	171 325	0.81	84	2(StatsSA, 2011), 3(StatsSA, 2016)
Total	**8 708**	**700 248**	**1.22**	**79.83**	

Table 4.2 Household statistics per local municipality (StatsSA, 2016)

Local Municipality	Household Numbers		Household Size	
	2011	2016	2011	2016
Nqutu	31 610	32 622	5.2	5.3
Newcastle	84 271	90 347	4.3	4.3
Utrecht	6 252	6 667	5.5	5.5
Dannhauser	20 580	20 242	5	5.2
Total	**142 713**	**149 878**	**5.0**	**5.1**

Hydrological characteristics and water supply system

With dry winters and wet summers, the BR catchment has a semi-arid climate. The region typically receives monthly minimum and maximum daily temperatures of about 11 °C and 25 °C, respectively; but, during the summer months (October to March), temperatures can reach as high as 39 °C. (Taruvinga, 2008). Although it is a relatively small catchment, its rainfall patterns in terms of magnitude, and temporal and spatial variations are diverse and characterized by its topography (uMgeni, 2020). The elevation and proximity to the coast have a significant impact on precipitation patterns. In the upper BR catchment, where the Newcastle and Utrecht local municipalities are located, the Mean Annual Precipitation (MAP) ranges from as low as 750 mm/annum to over 1 300 mm/annum, whereas in the interior part of the catchment, the MAP ranges from 780 - 980 mm/annum (Taruvinga, 2008; uMgeni, 2020). Information on the surface water infrastructure i.e., water supply system, of the catchment can be found in Section 3.2.1..

Agricultural land-use and production

The local municipalities within and supported by the BR catchment are predominantly rural and dominated by extensive commercial farmlands (Taruvinga, 2008; uMgeni, 2020). As per Figure A.13 in the Appendix, intensive irrigated commercial farmlands mainly occur in the upper fertile regions of the BR catchment, where the Newcastle and Dannhauser local municipalities are situated. The main commercial crops are maize, wheat, oats, ryegrass and soybeans (Lazarus, 2015). Full control irrigation increased from 3 710 hectares in 2007 to 18 155 hectares in 2017 (StatsSA, 2007; StatsSA, 2017). More than 60% of this irrigated area is used for maize production (StatsSA, 2017).

Overall, approximately 2% of the total area in the BR catchment is cultivated and under irrigation. While the Nqutu LM, located in the lower region of the BR catchment, has soil erosion and water shortages challenges, it has some arable tracts of land that have agricultural potential (Shabalala *et al.*, 2020). As shown in Figures A.14 and A.15 which are also in the Appendix, it produces high commercial crop yields of maize, oats, wheat, and ryegrass, and utilizes these fodder crops for its extensive livestock and poultry production (Shabalala *et al.*, 2020).

Electricity demands and production

The population of the BR catchment is supplied with electricity via connections to the grid of South Africa's state-owned electricity utility Eskom, or non-grid energy, including gas, paraffin, wood, coal, animal dung, solar and generators (StatsSA, 2016). Figure A.16 in the Appendix illustrates the distribution of energy types for cooking and heating across the catchment. A majority of the energy comes from Eskom's electricity grid. Figures A.17 and A.18, also in the Appendix, narrow the sources of electricity down to local municipalities; it is evident that, because the catchment is predominantly rural, there is no significant difference between the number of households using non-grid energy, and the ones that depend on Eskom's grid. Newcastle LM is an exception since it is the economic hub of the BR catchment area (Mahlaba, 2019).

Apart from meeting household demands, over the past three decades, the BR catchment has provided water to the Majuba Power Station for energy generation through the Zaaihoek Water Transfer Scheme (ZWTS) (uMgeni, 2020). Completed in 2001, Majuba is the latest of Eskom's six power plants, and the second-largest power plant with an installed capacity of 4110 Megawatt (MW) (ESKOM, 2022b). Water to the Majuba Power Station is pumped from the Zaaihoek Dam, situated in the upper regions of the BR catchment, to the Uitkyk Reservoir (uMgeni, 2020). The pump station has a maximum capacity of 3 m^3/s, but generally delivers about 0.34 m^3/s (uMgeni, 2020).

4.2.2 CLEWS modelling framework and tools

The CLEWS modelling framework focuses on the analysis of interactions among climate, land, energy, and water systems, supported by quantitative studies of the interactions and use of resources; thus, it is interdisciplinary (Ramos *et al.*, 2020). The Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGE), MARKAL (an acronym for MARKet ALlocation), and Long-range Energy Alternatives Planning (LEAP) models are typical CLEWS analytical tools used for energy system analysis. LEAP is an integrated, scenario-based modelling tool (Nieves *et al.*, 2019), well-fitting to this study's intended methodology of utilizing scenarios. Additionally, LEAP enables the tracking of energy consumption, production, and resource extraction in all sectors of the economy (Nieves *et al.*, 2019). The Water Evaluation and Planning (WEAP) model is normally used for water system planning in CLEWS (Miralles-Wilhelm, 2016). Thus, it was used in this study. WEAP's advantage is that it is a scalable resource planning tool that allows the comparison of water supplies and demands and provides capabilities for projecting demands (Shannak *et al.*, 2018). The selected land-use methodology for this study is the Agroecological Zones (AEZ), commonly used in CLEWS for analysing changing agricultural yields and crop production potential (Welsch *et al.*, 2014). The selected models are further described and elaborated on later.

4.2.3 Current practice approach

In setting up for the CLEWS approach analysis, the Current Practice Approach (CPA), as shown in Figure 4.2, was established as the initial step. In the CPA, the WEAP model was used to calculate the effects of rainfall variability on streamflow and net surface water storage without explicitly considering the interlinkages between land-use and energy systems.

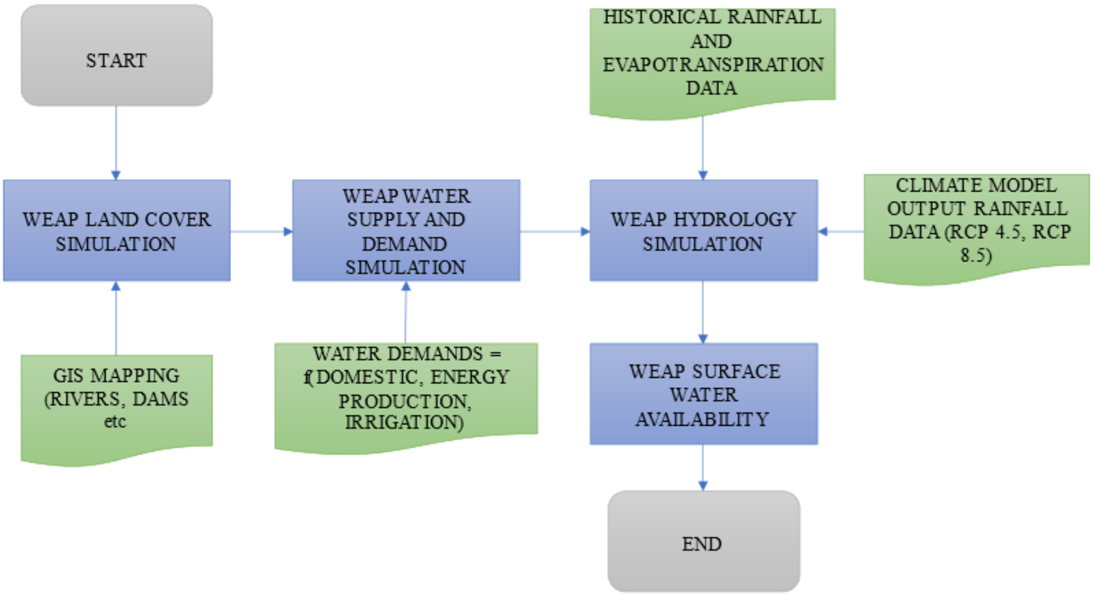


Figure 4.2 Flow chart of Current Practice approach.

The WEAP model is an "*innovative, integrated modelling software that offers a detailed, dynamic and user-friendly framework for establishing water balances, scenario generation, planning and policy analysis"* (Sieber, 2015). Developed by the Stockholm Environment Institute (SEI) for integrated water resources planning, WEAP simulates a wide range of natural and engineered components, from precipitation to streamflow, reservoirs, groundwater discharge, and water demand and supply (Agarwal *et al.*, 2018).

The vector layers used to create the schematic of the Buffalo River catchment, as per Figure 4.1, included: (a) KwaZulu-Natal (KZN) secondary drainage regions, (b) KZN district municipalities, (c) river networks, and (d) dams within the BR catchment. All vector layers were obtained from DWS (2016), and their attribute data were further sorted using ESRI's ArcGIS software (Version 10.6.0.8321, released on 17 July 2018). Demand nodes of the Buffalo system's water demand sites, including local municipalities and WTP, were created in the WEAP model, with their respective operational water recharge and abstraction rates.

Climate data inputs

According to WMO (2021), the 1991 to 2020 baseline period provides the most recent baseline for climate information and services to climate-sensitive sectors and recommended the timeframe to be adopted as a standard reference period for the comparison of variations in temperature and precipitation projections. Thus, the water system of the BR catchment was set up based on historical climatic and demand data from 01/01/1990 to 31/12/2019 The historical precipitation data were obtained from the Climate Hazards Group InfraRed Precipitation with Station dataset (CHIRPS) (Funk *et al.* (2015)). The CHIRPS dataset "*builds on previous approaches to 'smart' interpolation and high-resolution techniques, where precipitation estimates are based on infrared Cold Cloud Duration (CCD) observations"* (Funk *et al.* (2015)). Additional information related to the CHIRPS dataset and the bias-correction methods used to ensure that the data reflects the BR catchment's climate conditions can be found in Section 3.2.3.

For analysing and comparing the best- and worst-case scenarios of CC, two scenarios were considered:

(a) The Representative Concentration Pathway (RCP) 4.5 Scenario, i.e., best-case scenario, is a "*stabilization scenario that assumes climate policies are invoked to achieve the goal of limiting emissions and radiative forcing*" (Thompson *et al.*, 2011). Under this scenario, carbon emissions peak mid-century at around 50% higher than the historical levels (Wayne, 2013).

(b) The RCP8.5 Scenario, i.e., the worst-case scenario, is a high emission baseline scenario, including no policy-driven mitigation. "*Emissions continue to increase rapidly through the early and mid-century*" (Vuuren *et al.*, 2011).

External climate models were not developed as part of this assessment. Instead, the precipitation projections under both RCP4.5 and RCP8.5 scenarios were obtained from the NASA Earth Exchange Global Daily Downscaled Climate Projections dataset (NEX-GDDP) Thrasher *et al.* (2012) via the Google Earth Engine. The NEX-GDDP dataset comprises of "*statistically downscaled climate scenarios for the entire globe at a spatial resolution of 0.25° (~25 by 25 km), derived from 21 Global Climate Model (GCM) runs conducted under Phase 5 of the Coupled Model Intercomparison Project (CMIP5). The NEX-GDDP dataset provides daily estimates of precipitation and temperature (maximum and minimum) for the historical period (1950-2005) and the future period (2006-2099) over the entire globe*". (Thrasher *et al.*, 2012).

The NEX-GDDP dataset provides daily estimates of precipitation and temperature (maximum and minimum) for the historical period (1950-2005) and the future period (2006-2099) over the entire globe (Thrasher *et al.*, 2012). From the ensemble of projections derived from 21 Global Circulation Models (GCMs), the following 6 models were selected; ACCESS1-0, MIROC-ESM-CHEM, NorESM1-M, CNRM-CM5, CCSM4 and MPI-ESM-LR. The selection process was done by statistically comparing precipitation trends between each GCM's historical data and the corrected CHIRPS dataset from 01/01/1990 to 31/12/2005, using the coefficient of determination (R^2). The selected GCM models' precipitation outputs achieved the highest R^2 values, which ranged from 0.96 to 0.99. Additional information on the selection process and data processing can be obtained from Section 3.2.3.

Evapotranspiration computation

The reference evapotranspiration (ET_R) was used to compute the maximum crop evapotranspiration (ET_C) for irrigated crops using crop coefficients (K_C). ET_C assumes optimal water supply for evapotranspiration, and it is used in the computation of actual evapotranspiration (ET_A), which is calculated based on the amount of water available for evapotranspiration, as detailed in Section 3.2.3.

Domestic water demand inputs

In the CPA, projected irrigation water demands and the Majuba power station's energy generation water requirements followed historical annual growth rates. The domestic water demands per household were assumed to be 6 m^3/capita/month (Mahlaba, 2019). As the annual average number of people per household in each local municipality is 5 (StatsSA, 2016), the value of the annual water demands per person of 14.4 m^3 was multiplied by the annual population to quantify the total annual domestic water consumption of the catchment. The population growth rate was entered explicitly per the local municipality's historical statistics.

Water storage capacity inputs

In computing the total catchment's surface water storage capacity, all dams and water treatment plants were modelled individually (refer to Tables A.1 and A.2 in the Appendix), including inflows from rivers and outflows from evaporation, water abstractions, and surface runoff. The summative value of their net water store was computed as the total amount of BR catchment's available surface water. The projection analyses were split into three timelines: (a) the near future, which ran from 01/01/2020 to 31/12/2045, (b) mid-future from 01/01/2046 to 31/12/2070 and (c) far-future, which spans from 01/01/2071 to 31/12/2099.

4.2.4 CLEWS approach

The scenarios assessed in the CPA were reassessed using the CLEWs approach, considering interlinkages inspired by the integrated CLEWS approach, as shown in Figure A.19 in the Appendix. This approach draws on individual, well-tested and specialised resource models. While the structure of the WEAP model and timeframes were kept the same as in the CPA, the following interlinkages to water, energy and agricultural systems using LEAP and gAEZ, observed in Figure 4.3, were considered and further explained in this sub-section:

(a) The irrigation water requirements to produce the projected agroecological attainable yield of the catchment's irrigated commercial crops were derived from the gAEZ land-use assessment.

(b) Energy demands for irrigation and household use were derived using the LEAP model.

(c) Water demands for producing LEAP energy demands were modelled in the WEAP model.

The model interactions incorporating these interlinkages are further elaborated on in the study.

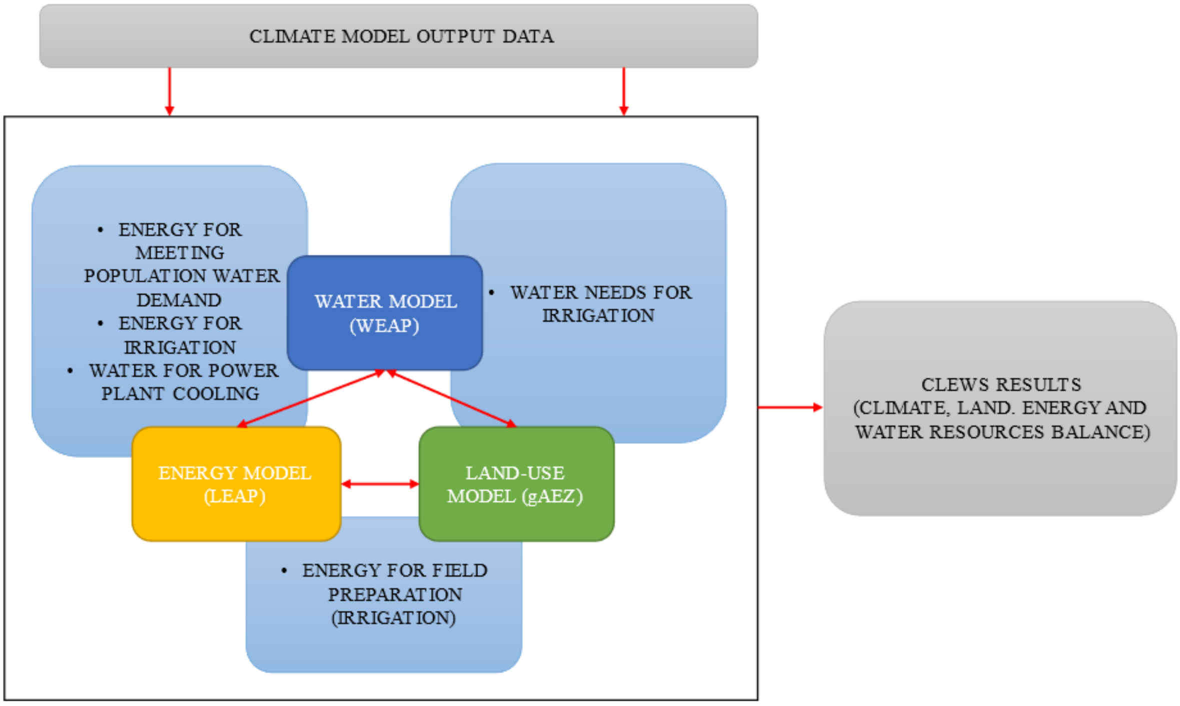


Figure 4.3 Model interactions derived from the CLEWS approach.

Land-use modelling

The modelling of the land-use system was not set up as an integral part of this assessment. Instead, results from a global Agro-Ecological Zones (gAEZ) assessment made by the Food and Agricultural Organisation (FAO) and the International Institute of Applied Systems Analysis (IIASA) using the Agroecological Zones and production planning model were used (Fischer *et al.*, 2021).

The gAEZ relies on well-established land evaluation principles to assess natural resources for finding suitable agricultural land utilization options (Fischer *et al.*, 2021). As there is no component of actual availability, reliability, and quality of irrigation water supply in the gAEZ assessment, it was therefore recommended that its results be used in assessing water availability and reliability for potential irrigated crop production systems, especially in view of CC assessments and irrigation planning (FAO and IIASA, 2022)

The results of global Agro-Ecological Zoning (gAEZ)'s crop suitability and land productivity evaluation are stored as separate databases, each organized in terms of 5 arc-minute (about 9 x 9 km at the equator) grid cells (Fischer *et al.*, 2021). Separate files are generated, holding results by crop, input level, type of water supply and climate scenario/time period. Each of these crop databases contains sub-grid distribution information regarding suitable extents, potential production, water deficit and fallow factors, with all information kept by suitability classes (Fischer *et al*., 2021).

Land-use modelling: suitability classification

From the gAEZ's land and water resources maps, the BR catchment is labelled an exclusion/unprotected tropic, a highland area with a sub-humid climate, thus given AEZ (by the aggregate 33-class system) and Exclusion (EXC) class codes of 5 and 1, respectively. As only irrigated commercial farmlands are considered in this study, a land cover (LC) class code of 9 was assigned.

The suitability class for the BR catchment was determined per crop type using the assessment's suitability class maps. As 5 arc-minute grid cells can be made up of multiple soil types and terrain slope classes, the assessment assigns an estimate to each of these components, to capture the heterogeneity of each grid cell, which produces a distribution of results falling into different suitability classes per crop type. Table 4.3 describes each suitability class.

Table 4.3 Suitability class description (Fischer *et al*., 2021)

Acronym	Suitability Description	Farm Economics
VS	Very suitable land (80-100% of maximum attainable yield)	Prime land offering best conditions for economic crop production
S	Suitable land (60-80%)	Good land for economic crop production
MS	Moderately suitable land (40-60%)	Moderate land with substantial climate and/or soil/terrain constraints requiring high product prices for profitability
mS	Marginally suitable land (20-40%)	Commercial production not viable. Land could be used for subsistence production when no other land is available
vmS	Very marginally suitable (<20%)	Economic production not feasible
NS	Not suitable	Production not possible

Maize, wheat, oats, soybeans, and ryegrass are the most dominant irrigated crops in the BR catchment, and as such, they were included in this research. Each LM was assigned the suitability class with the most area coverage using these crops' suitability maps. An example is shown in Figure 4.4 which displays the historical spatial variation of the wheat suitability class. It is important to note that the gAEZ assessment was carried out in 2010. Hence historical spatial and temporal variations in agro-ecological zones were recorded from 1981-2010, and projections were made from 2011 to 2100, using the CRUT32 model.

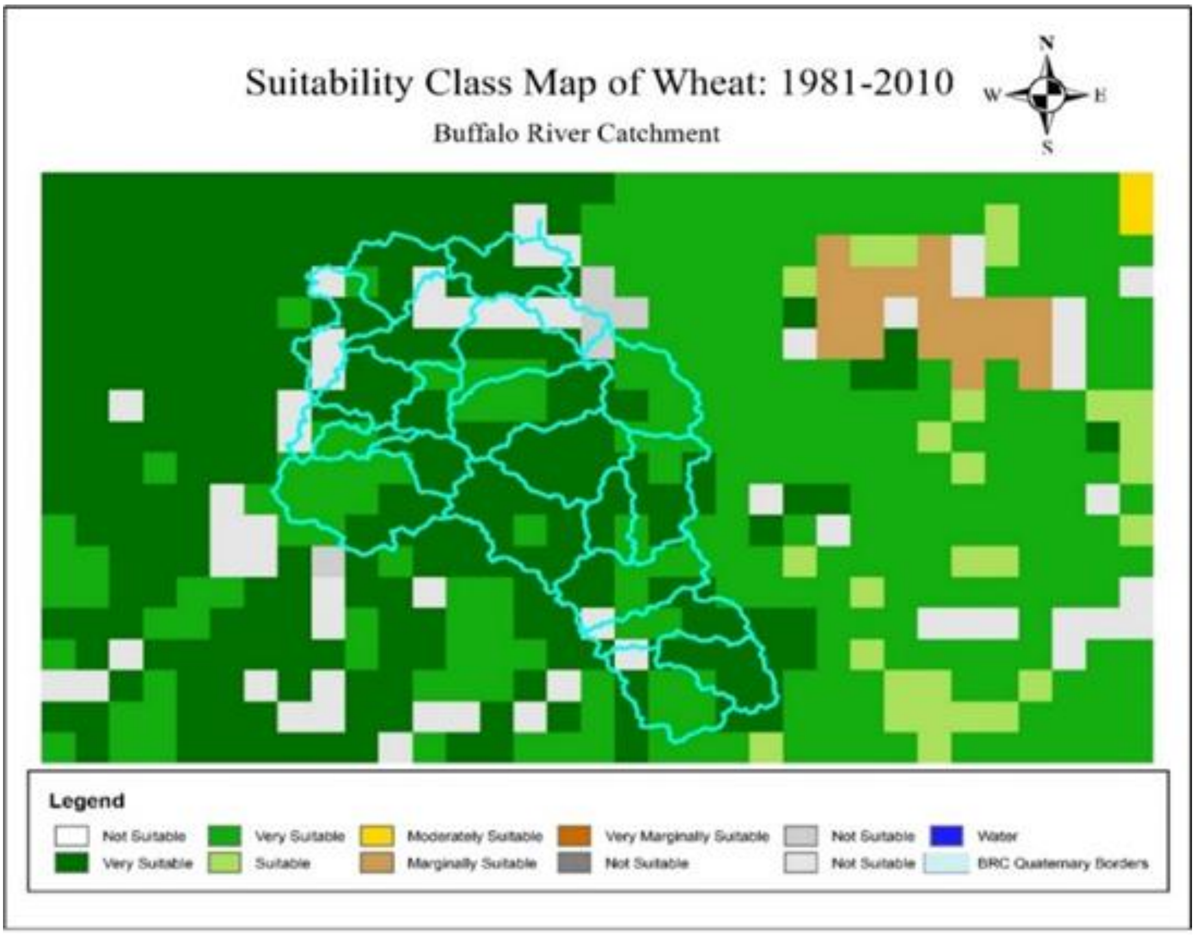


Figure 4.4 Average historical suitability class of wheat from the year 1981-2010 in the Buffalo River catchment.

The MIROC-ESM-CHEM, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and the NorESM1-M models were utilized in the gAEZ for these projections under all RCPs. For this study, only data from RCP 4.5 and RCP 8.5 scenarios were considered. The MIROC-ESM-CHEM and NorESM1-M climate models were selected based on comparisons done in the CPA analysis of recorded historical climate data and the model's projected data from 2006 to 2019. After observing the individual model suitability class outputs for all crop types, both models projected similar changes in suitability classes under each RCP scenario throughout the study period, with examples for wheat shown in Figures A.20 to A.21 in the Appendix. As such, the average ensemble of their outputs was utilized in this research. Table 4.4 lists the overall dominant suitability classes, inclusive of the historical and projected suitability classes.

Table 4.4 Suitability class for wheat

	1981-2010	2011-2040		2041-2070		2071-2100	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Newcastle	S	S	S	S	S	S	S
Utrecht	S	S	S	S	S	VS	S
Dannhauser	VS	VS	VS	VS	VS	VS	S
Nqutu	S	S	S	S	S	VS	S

Land-use modelling: agro-attainable yields and projected irrigation water requirements

Crop summary tables are used to determine the agro-ecological attainable yield upon assigning the suitability classes. The crop summary tables provided by the gAEZ contain standardized information for each crop by administrative units (country or country/province for a few major countries) and by broad hydro-regions. The comprehensive tables summarize by suitability class the:

(a) suitable extents,
(b) attainable yields for each crop,
(c) various constraint factors (due to the thermal regime, moisture deficits, agro-climatic constraints due to pest, disease, and workability limitations and due to soil/terrain limitations), and
(d) aggregate simulated water deficits (rain-fed conditions) respectively net irrigation requirements (irrigated conditions).

Using South Africa’s standardized crop information in the country crop summary tables, the agro-ecological attainable yield per LM in the BR catchment for irrigated wheat is summarized in Table 4.5. Such was also done for maize, oats, soybean, and ryegrass. The corresponding net Irrigation Water Requirements (IWR) for all crops were obtained from the crop summary tables. Table 4.6 displays the historical and projected IWR of wheat in each LM. It is crucial to note that, for irrigated crops, the gAEZ assessment only considered sprinkler irrigation.

Table 4.5 Agro-ecological attainable yield of wheat in kg/ha.

Local Municipality	1981-2010	2011-2040		2041-2070		2071-2100	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Newcastle	6783	6668	6777	6257	6187	6206	5547
Utrecht	6783	6668	6777	6257	6187	8199	5547
Dannhauser	8206	8326	8403	8184	8239	8199	5547
Nqutu	6783	6668	6777	6257	6187	8199	5547

Table 4.6 Net irrigation requirements of wheat in mm/season.

Local Municipality	1981-2010	2011-2040		2041-2070		2071-2100	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Newcastle	410	463	463	529	530	572	563
Utrecht	410	463	463	529	530	572	563
Dannhauser	515	534	534	601	610	637	653
Nqutu	515	534	534	601	610	637	653

Agricultural production and land statistics used in gAEZ assessment were at a national scale, and do not reflect the spatial heterogeneity of agricultural production systems at finer resolutions (Fischer *et al*., 2021. In this case, Fischer *et al.* (2021) suggested downscaling outputs when aggregating national production statistics to individual spatial units. For the gAEZ yield projections to be more consistent with those of historical observations, they were bias-corrected using the linear scaling (LS) method since it preserves the mean of the observed variable (Ghimire *et al*., 2018). In the LS method, correction factors (CF) are derived by dividing each crop type's historical observed crop yield, tabulated in Table 4.7, by the simulated crop yield. The resultant CFs were multiplied by the projected crop yield values, as per Equation (4.1). Table 4.8 displays the adjusted projections of wheat throughout the study period. The same bias correction methodology was also applied to the gAEZ IWR.

Table 4.7 Historical crop yields (kg/ha) (StatsSA, 2017)

Local Municipality	Maize	Wheat	Oats	Soyabeans	Ryegrass	Maize for Silage
Dannhauser	9098.48	0.00	0.00	0.00	0.00	3887.91
Utrecht	6843.39	1831.64	1814.36	3495.70	0.00	7991.07
Newcastle	8138.32	2948.51	1814.36	3132.60	77.54	5443.08
Nqutu	7796.49	4827.49	2335.87	2856.52	2950.45	49928.81
Total	31876.69	9607.65	5964.59	9484.82	3027.99	67250.88

$$CY_{corr} = CY_{raw} \times CF \tag{4.1}$$

where CY_{corr} = bias corrected crop yield (mm)

CY_{raw} = raw crop yield data (mm)

CF = correction factor = $\boldsymbol{CY_{observed\ data}} / \boldsymbol{CY_{raw\ data}}$

Table 4.8 Adjusted projected attainable yield of wheat (kg/ha).

Local Municipality	1981-2010	2011-2040		2041-2070		2071-2100	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Newcastle	2948.51	2949	2949	2767	2692	2744	2413
Utrecht	1831.64	1832	1832	1719	1672	2252	1499
Dannhauser	0	0	0	0	0	0	0
Nqutu	4827.49	4827	4827	4530	4407	5936	3951

Land-use modelling: projected irrigated areas

The water use efficiency parameter was utilised to compute the projected changes in irrigated field sizes (ha). Water use efficiency (WUE) is the ratio of crop yield to applied water (Bos and Nugteren, 1974). Per LM, each crop type's historical WUE was calculated using Equation (4.2) and kept constant throughout the study period. The volume of irrigated water applied per hectare for the near, mid-, and far future timelines was calculated using the projected attainable yield.

$$WUE = \frac{CY}{WA} \tag{4.2}$$

where WUE = Water use efficiency (kg/m^3)

CY = Crop yield (kg/ha), and

WA = Volume of irrigated water applied (m^3/ha)

Using the projected volume of irrigated water applied per hectare values, the projected irrigated areas were then calculated using Equation (4.3) (Smajstrla, 1993). Table 4.9 consists of the projected irrigated areas for wheat in the different local municipalities, and the same output was presented for all crops investigated in the study, with the total projected irrigated areas per local municipality under the RCP4.5 and RCP8.5 scenarios presented in Figures 4.5 and 4.6, respectively.

$$A_{new} = \frac{WA}{10IWR} \times A_{hist} \tag{4.3}$$

where A_{new} = Projected irrigated area (ha), and

A_{hist} = Historical irrigated area (ha)

IWR = Irrigation water requirements (mm/m^3)

Table 4.9 Irrigated areas of wheat in ha.

Local Municipality	**1981-2010**	**2011-2040**		**2041-2070**		**2071-2100**	
		RCP 4.5	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**
Newcastle	1 275	1 275	1 275	1 020	1 031	1 052	938
Utrecht	525	525	525	420	425	517	386
Dannhauser	0	0	0	0	0	0	0
Nqutu	812	812	812	649	657	800	597

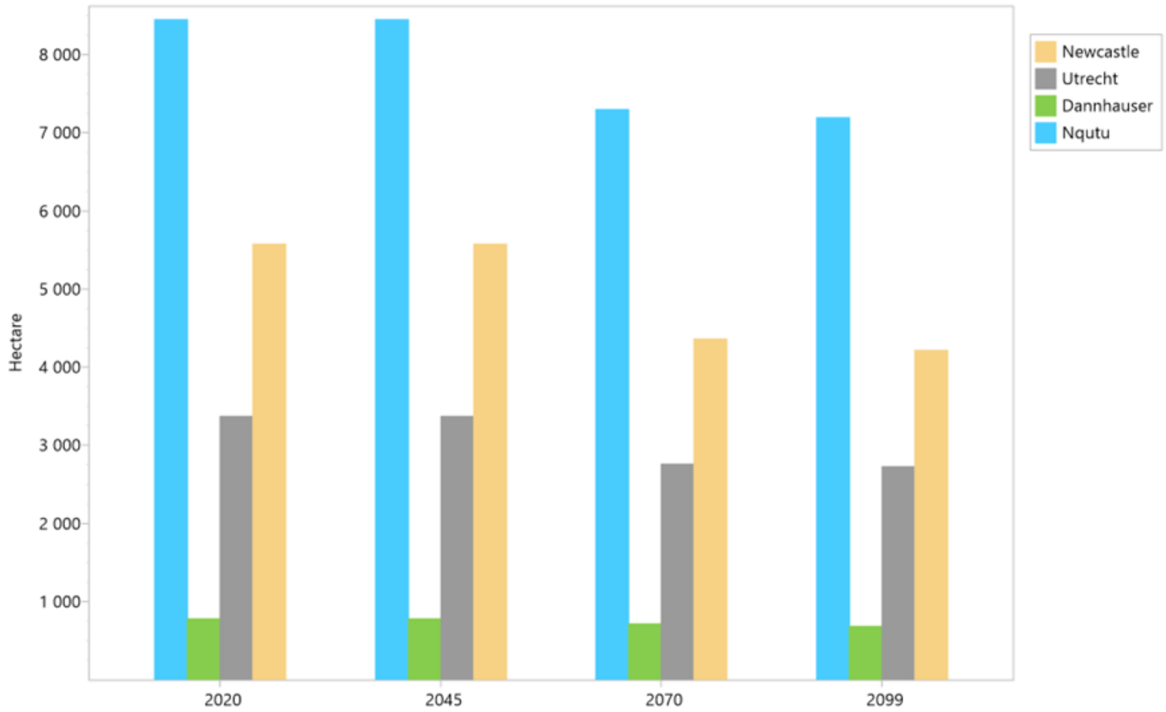


Figure 4.5 Total projected irrigated area per local municipality under the RCP4.5 scenario.

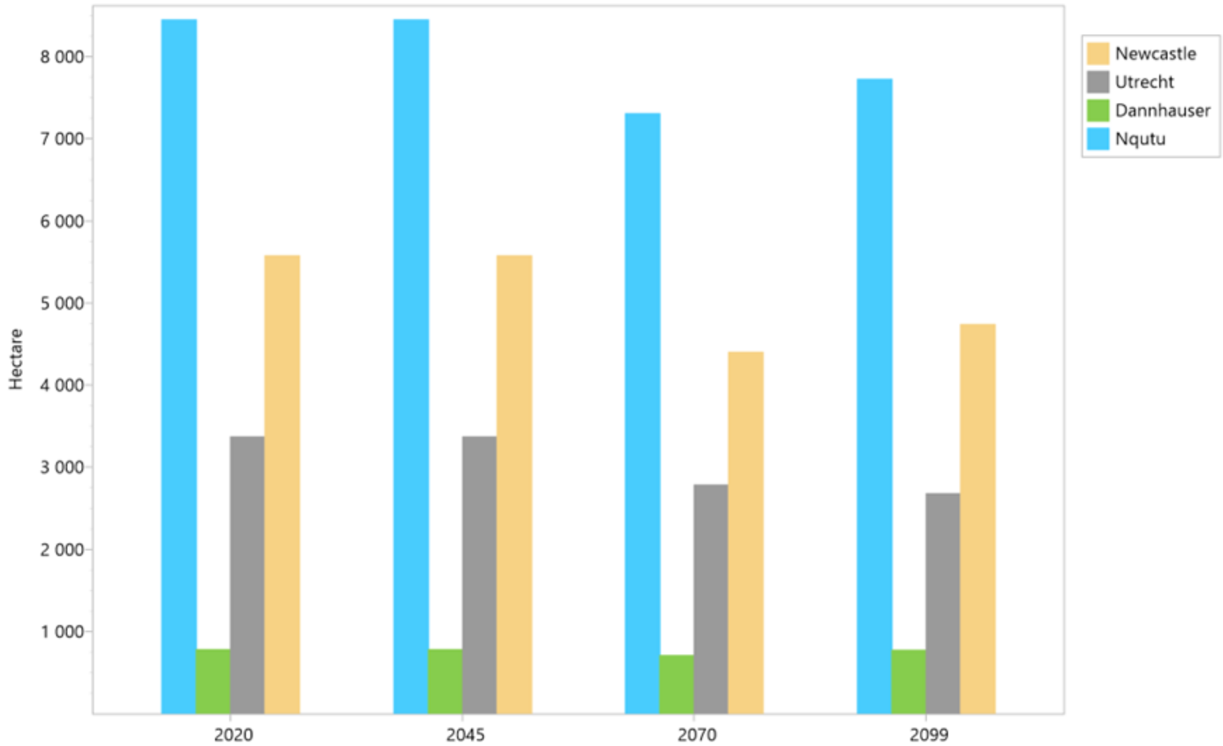


Figure 4.6 Total projected irrigated area per local municipality under the RCP8.5 scenario.

Energy modelling

The energy system was assessed with the Long-range Energy Alternatives Planning (LEAP) tool. Developed by the Stockholm Environment Institute (SEI), LEAP is a widely used scenario-based energy-environment modelling tool for analysing energy systems, including power dispatch and capacity expansion. It considers various economic sectors, technologies, costs and emission profiles (Welsch *et al.*, 2014). The LEAP tool was set up to reflect the energy demand. Energy demand or supply in the LEAP model is calculated by summing up each type of activity's energy consumption and supply (Heaps, 2012). Equation (4.4) defines the demand analysis of the total energy consumption (Rivera-Gonzalez et al., 2019). In this study, the household and irrigation energy demands were modelled.

$$EC_i = \sum AL_i(t) \times TE_i(t) \quad (4.4)$$

where EC = total energy consumption for a specific sector (i)

AL = activity level in percentage (%) of the social or economic activity sector (i) for which energy us consumed in time (t)

TE = annual total final consumption of energy in GWh of the sector (i), in the time (t) in years.

Energy modelling: household electricity consumption

The household electricity consumption in the BR catchment was modelled using each LM's household statistics. From Figure A.22 to A.25 in the Appendix the growth in household numbers per LM during the historical period is depicted. As also evident in these figures, households were divided into urban and rural areas. Urban households were assumed to be fully electrified, and the rural households were further split into electrified and non-electrified. For this study's household energy consumption, electricity is only considered; thus, non-electrified rural households were not considered.

According to Anon (2016), low-income households earn below R86 000 per annum (pa), while the middle-income group earns between R86 001 pa to R1 480 000 pa, and the high-income group receives above R1 480 001 pa. Thus, from the distribution of household incomes in 2016 for each LM, shown in Figure A.26 in the Appendix, the BR catchment is predominantly low-income: 89% of Newcastle LM's households fall under the low-income bracket, as well as 99%, 77% and 96% of Utrecht, Nquthu and Dannhauser LM households, respectively.

As such, regarding the results of a recent study conducted by Dinkwanyane *et al.* (2021), seen in Table A.3 in the Appendix, the total electricity consumed by appliances and energy services in the BR catchment is approximately 6 432 kWh pa per household in 2015. The National Energy Efficiency Strategy (NEES) set a target for the residential sector of 10% improvement in energy efficiency by 2015 relative to a baseline projected from 2000 (DoE, 2015). For the purpose of this study, in quantifying the changes in energy efficiency of household appliances and energy services, the NEES approach will be adopted by assuming a 10% improvement after every 15 years.

In Figure A.27 in the Appendix, apart from the accounted "other" additional energy services, we observe that refrigeration contributes largely to electricity consumption within the BR catchment, with a mean average consumption of 134.53 million kWh pa (approx. 30% of the overall energy demand). With larger volumes of electrified households and urbanised areas and sporadic population growth rate, the Newcastle LM households utilize a significant amount of electricity annually, as seen in Figures A.28 in the Appendix and Figure 4.7 below. Contrarily, the stagnant population and household numbers' growth rates and the lack of urbanization in the Dannhauser and Utrecht LMs are the main reasons behind their low values in household electricity usage.

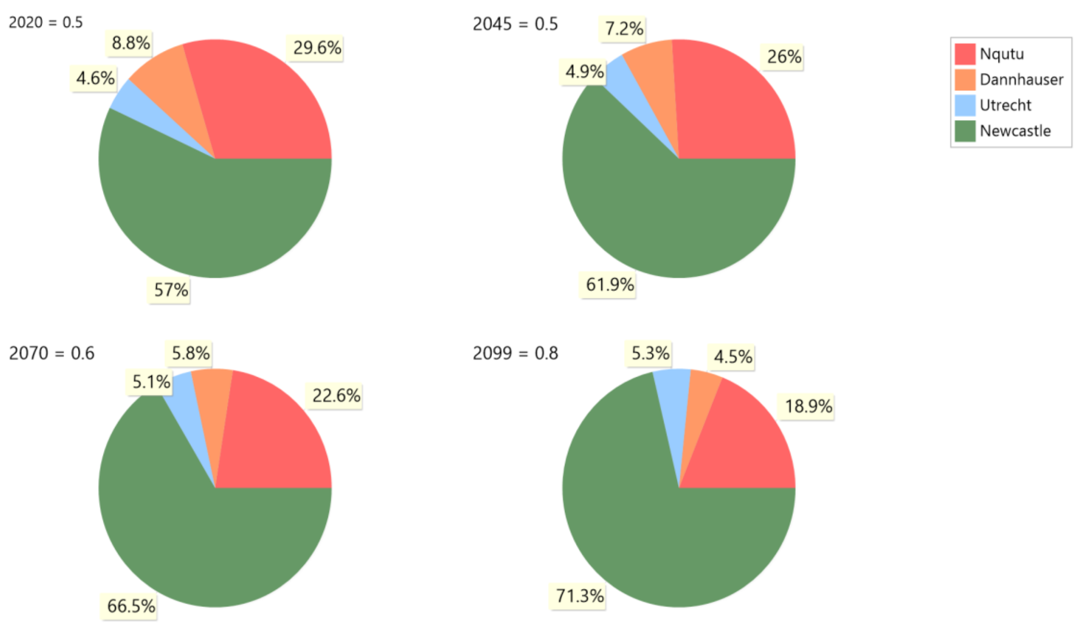


Figure 4.7 LEAP household energy demands under each local municipality in the Buffalo River catchment (MWh/annum).

Energy modelling: irrigation energy consumption

For irrigation energy consumption, as per the gAEZ assessment, only sprinkler irrigation was considered. The power requirements per crop type per hectare were calculated using Equation (4.5) (Montero *et al*., 2013; Dirwai *et al*., 2021).

$$P = \frac{C_e}{En_c} \tag{4.5}$$

where P = power requirements for water application (kWh/year/ha),

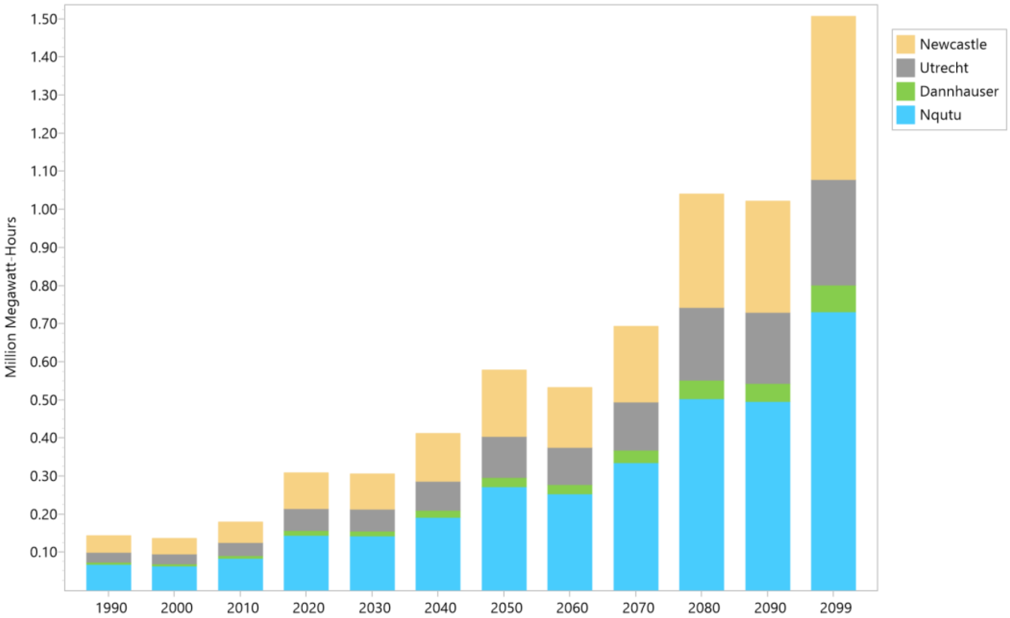
C_e = annual energy cost to operate centre pivots (R/year/ha), and

En_c = energy rates (R/kWh).

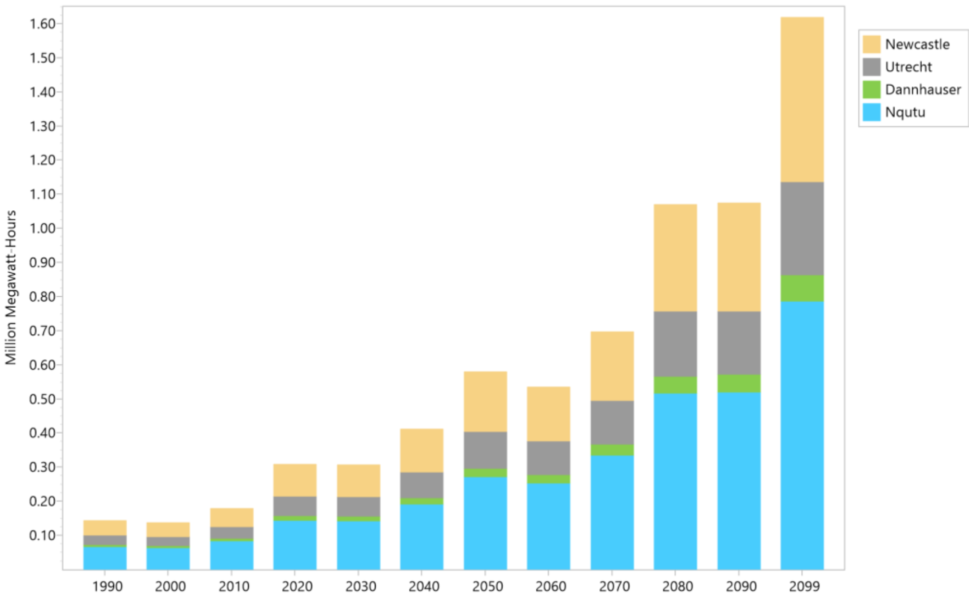
In computing the historical En_c values displayed in Figure A.29 in the Appendix, the average Eskom rates for rural/farming users in Rands per kilowatt-Hour (R/kWh) were obtained from Eskom's annual reports (ESKOM, 2022a).

According to Venter *et al.* (2017), approximately 80.3% of registered irrigation systems in South Africa are pressurized types, which include centre pivots, sprinklers, drip and micro-sprinkler systems, and commercial farmers tend to be more favourable towards centre pivots (Kom *et al.*, 2020). As commercial farmlands are considered in this study, it was assumed that all irrigation in the catchment is carried out using centre pivots. For the annual energy cost to operate centre pivots (C_e), the values are the sum of fixed and variable electricity costs. Fixed electricity costs are constant and can only be changed by the electricity supplier, Eskom (Venter *et al.*, 2017). As such, their rates are per energy rates (En_c) rates. The variable electricity costs are a product of irrigation hours, kilowatt (kW) requirements and electricity tariff. From a study conducted by Venter *et al.* (2017), which compared the total electricity costs of operating a small (30.1 ha) and large (47.7 ha) centre pivot under the Landrate and Ruraflex electricity tariffs at different system delivery capacities, it was found that Ruraflex is more profitable than Landrate irrespective of the centre pivot size and irrigation system delivery capacities. Thus, results under the Ruraflex electricity tariff were used in this study and are tabulated in Table A.4 in the Appendix. For 2018, the C_e value of the large centre pivot with a system delivery capacity of 8 mm/day was deployed in this study since it was the most profitable system.

As Eskom introduced the Ruraflex electricity tariff in 2003, its tariffs growth rates since then were utilized in interpolating the variable electricity costs based on the 2018 value also tabulated in Table A.4. The Ruraflex tariffs were obtained from ESKOM (2022a). From 1990 to 2003, it was assumed that the variable electricity costs' growth rates were the En_c rates. Figure A.30 in the Appendix displays the growth trends of C_e under the historical timeframe and these trends were duplicated throughout the study period. The LEAP model thus simulated, using power requirements for water application per hectare (kWh/ha/annum) and the irrigated areas per crop type under different timeframes, the energy required for irrigation application. Figure A.31 also in the Appendix shows the catchment's total historical energy demand values for irrigated maize, wheat, oats, soybean, ryegrass, and maize for silage, and Figure 4.8 shows the total irrigation energy demands per local municipalities under RCP4.5 and RCP8.5 scenarios.



(a)



(b)

Figure 4.8 LEAP irrigation energy demands (MWh/annum) per local municipality in the Buffalo River catchment under the (a) RCP4.5 and (b) RCP8.5 scenario for period 01/01/1990 – 31/12/2099.

4.2.5 Model interactions

The projected expansion of irrigated areas per crop type, as well as their respective irrigation water demands were obtained from the gAEZ assessment. The gAEZ assessment based its projections on a range of GCMs output data under each RCP scenario. As such, to maintain consistency, the GCMs selected for projecting changes in precipitation under each RCP scenario were also selected in the gAEZ.

After quantifying irrigation water demands and changes in irrigated areas using the gAEZ assessment (see "land-use modelling" in Section 4.2.4), the annual energy demands (MWh/annum) for household and irrigation electricity consumption were calculated utilizing the LEAP model using the procedure also described in Section 4.2.4, respectively. The projected changes in irrigated areas and water demands, as well as the total energy demands quantified using the LEAP model, were manually transferred into the WEAP model.

Since the LEAP model cannot simulate the water requirements for energy generation per kWh, a value of 1100 litre/MWh, which is the average water use of the Majuba power station (ESKOM, 2022a), was computed as the annual water use rate for energy generation. As a result, the WEAP model simulated the total water supply requirements, considering the variations in household, irrigation, and energy generation requirements in the historical and projected timeframes.

4.3 Results and Discussion

4.3.1 Evapotranspiration and surface runoff

Under both climate scenario projections, for CPA and CLEWS, actual evapotranspiration (ET_A) projections are coherent with historical averages, even in the far future where the percent increases, relative to the historical value, are 0.6% and -0.3% respectively, as seen in Figure 4.9. However, the surface runoff at the BR's outlet (Q) projected by the CPA and CLEWS approaches, display significant differences throughout the 21st century. CLEWS projected Q values which are on average 8.5% lower than those projected by the CPA approach under both climate scenarios, thus flagging increased water usage and/or storage within the water supply system. Nonetheless, average Q volumes are still anticipated to increase under CLEWS from a historical value of 3080 Mm^3/annum to 3523 Mm^3/annum under RCP8.5 in the far future. This projected increase in Q is reflective of the expected increases in rainfall throughout the study period (see Section 3.3.1. for projected precipitation trends).

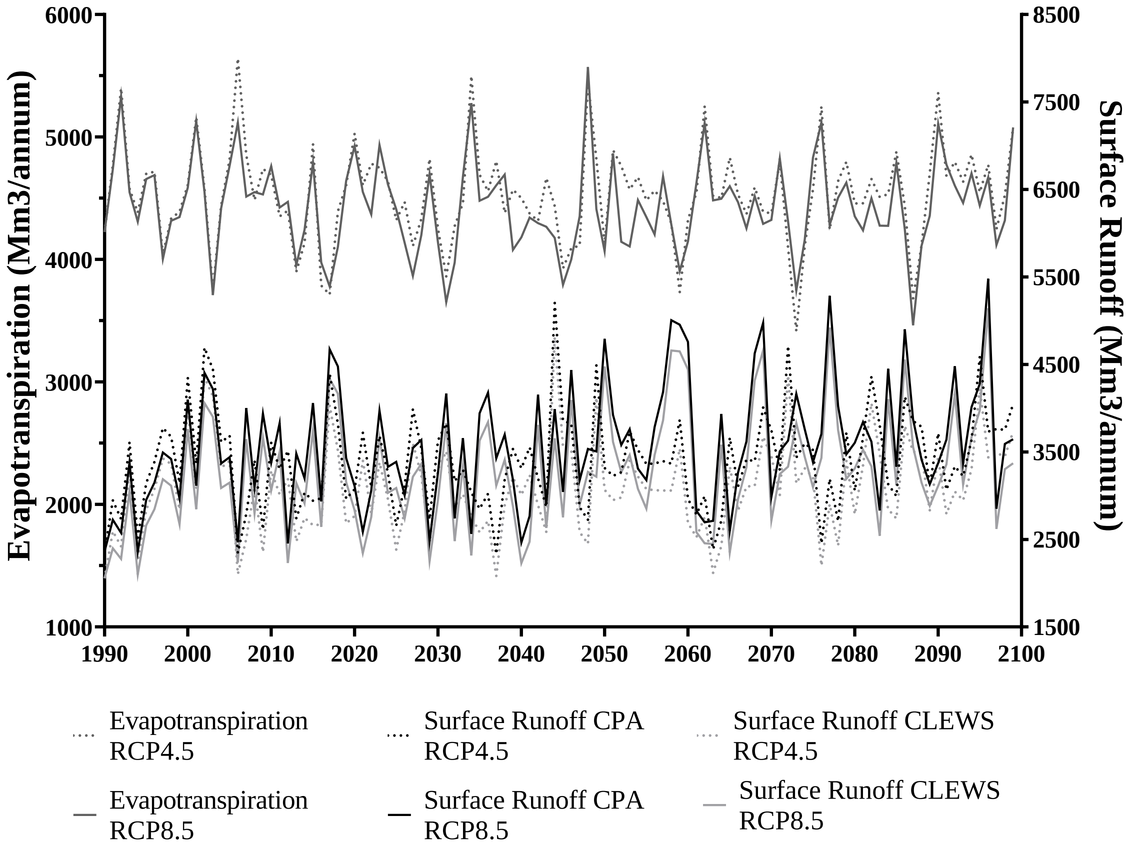


Figure 4.9 Evapotranspiration (Mm^3/annum) and surface runoff (Mm^3/annum) projections from 01/01/1990 to 31/12/2099 in the Buffalo River catchment using the CPA and CLEWS approach.

4.3.2 Water requirements

Irrigation water requirements

When compared to Irrigation Water Requirements (IWR) projected using the CPA approach, which assumed IWR to remain constant, the summative IWR projected using the CLEWS approach are lower by -17% and -19% in the mid- and far future under RCP4.5, while RCP8.5's IWR are lower by -16% and -12% for the above-mentioned periods, respectively. This is attributed to the anticipated decreases in suitable hectares (ha) for crop maize and soyabean production projected by the gAEZ assessment. Even with the expected increases in IWR/ha for maize from a historical value of 280 mm to 346 mm in the RCP4.5's far future timeframe, the decline in areas suitable for maize crop production from 11 087 ha to 9 538 ha decreased the total IWR. Similarly, for soyabean crop production, IWR are expected to increase from a historical value of 330 mm to 864 mm under RCP8.5's far future period, however, the land (hectares) suitable for its crop production is anticipated to decrease from 3 074 ha to 1 361 ha, respectively.

Domestic and energy generation water requirements

The total domestic water demands for both CLEWS and CPA increased in the near, mid-, and far future by 30%, 59% and 89%, respectively. This is due to the increasing population of the BR catchment, more so the Newcastle LM, which on average, makes up 60% of the total population, and solely projected to require, on average, 25 Mm^3/annum. From the results visualized in Figure 4.10, increases in CLEWS energy demands are anticipated under climate change.

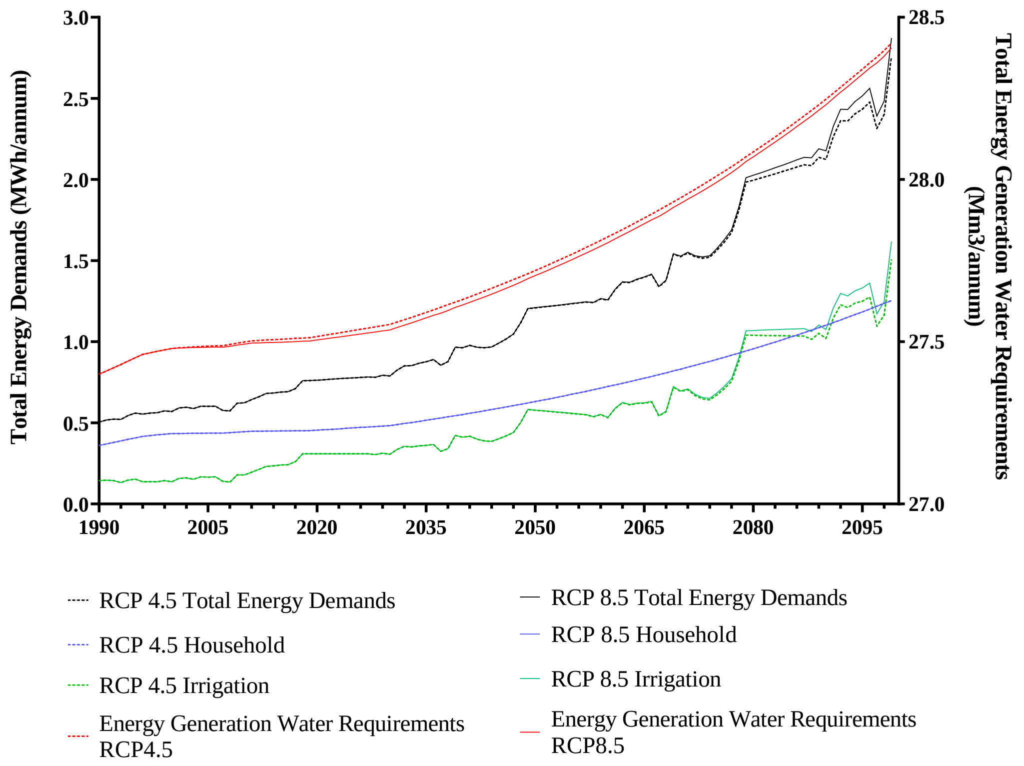


Figure 4.10 Total energy demands (MWh/annum) in the Buffalo River catchment throughout the study period (01/01/1990-31/12/2099) under the RCP4.5 and RCP8.5 scenarios.

The Newcastle LM's contributed the most to the expected increases in household energy requirements (0.36 million MWh/annum in 1990 to 1.25 million MWh/annum in 2099) also due to its large and fast-growing population. Irrigation energy demands increased to 2 million MWh in 2099 under both climate scenarios, mainly due to Nquthu LMs agricultural production (see Figure 4.10), and fluctuations are shown to significantly impact total energy demand variations. To support this observation, the R^2 values of the household and irrigation energy demands, when compared to the total energy demands, are 0.993 and 0.987, respectively, with the R^2 plots displayed in Figure A.32 in the Appendix.

The CPA method only considered the Majuba power station's water demands for energy generation. As such, the Zaaihoek Water Transfer Scheme's transfer of 3 m^3/second to the Majuba power station, equating to 27 Mm^3/annum of the catchment's water supply, was dedicated to power generation. In the CLEWS approach, when adding this demand with water required to generate household and irrigation energy, water requirements for total energy generation increase to a maximum of 28.5 Mm^3/annum at the end of the 21st century. Such minimal water demands from the energy sector are anticipated as energy generation in South Africa only consumes approximately 5% (inclusive of coal mining) of the total water supply (Reddick *et al.*, 2018).

Total water supply requirements

A significant gap is observed between the projected CPA and CLEWS RCP4.5 and RCP8.5 total water supply requirements, as seen in Figure 4.11. IWR are noted to be the reason behind this; after the CLEWS' incorporation of changes in attainable yield and their respective reduced overall IWR, a consequential reduction of total water supply requirements results. This is also in line with the national statistics of water use by sectors, which indicate that agriculture and irrigation are largely responsible for, and influence the trends of, water resource consumption in South Africa (Thopil and Pouris, 2015).

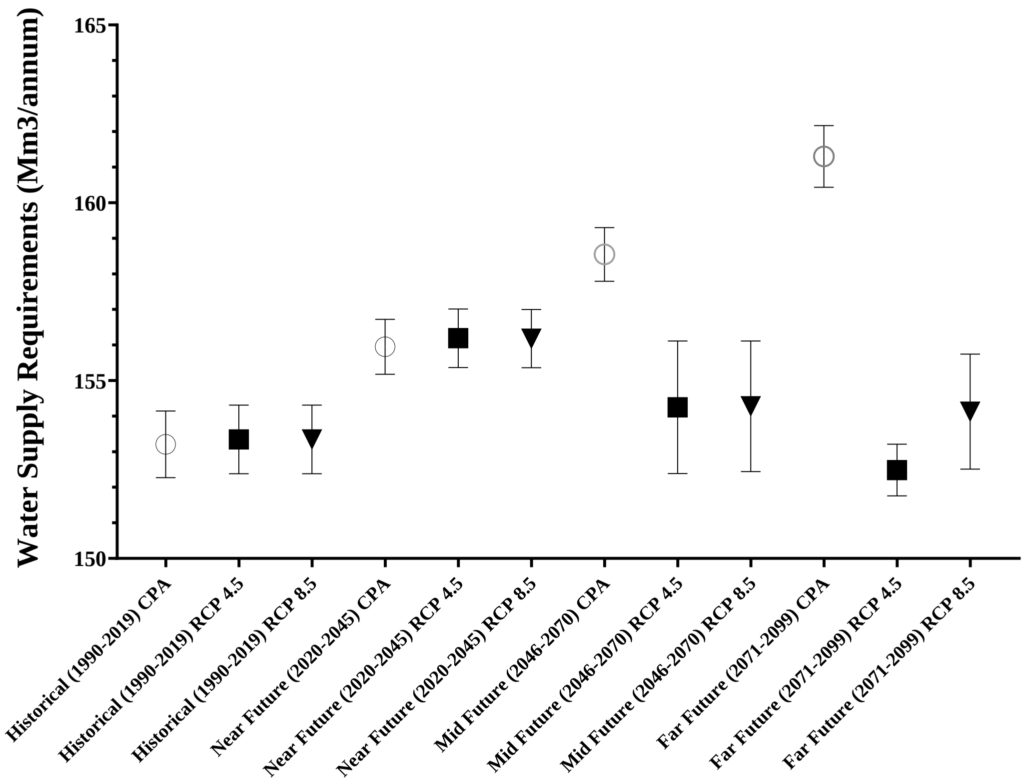


Figure 4.11 Total water supply requirements in the Buffalo River catchment under all scenarios from period 01/01/1990 – 31/12/2099.

4.3.3 Reservoir storage changes and unmet demands

The net reservoir storage (S_N) projected under CLEWS are similar to those modelled using the CPA approach, as per Figure 4.12. Such results are expected as no changes were made in the CLEWS approach to reservoir operational rules. Moreover, despite considerable expected precipitation increases in the far future (see Section 3.3.1), projected S_N values under both climatic scenarios show minor increases, surprisingly, even in the far future. This is primarily due to storage capacity restrictions, increased surface runoff, and for CLEWS, this highlights potential of increased water extractions from the water system. It is also important to note from Figure 4.32 that the historical S_N modelled under RCP4.5 and RCP8.5 are slightly over-estimated. This is attributed to the over-simulation of streamflow produced through the use of historical NASA-NEX GDDP dataset (see Section 3.3.6.).

Even though the projected S_N values are similar in both CPA and CLEWS approaches, deviations in the projected unmet demands are noted in the mid- and far-future timeframes, with the average differences being -9% and -16% respectively. The lower unmet demands simulated using CLEWS corresponds to its lower projected Q values, thus also highlighting increased water extractions from the catchment's supply system. Furthermore, CLEWS lower unmet demands also reflect the expected declines in total IWR, which decrease total water requirements to be met.

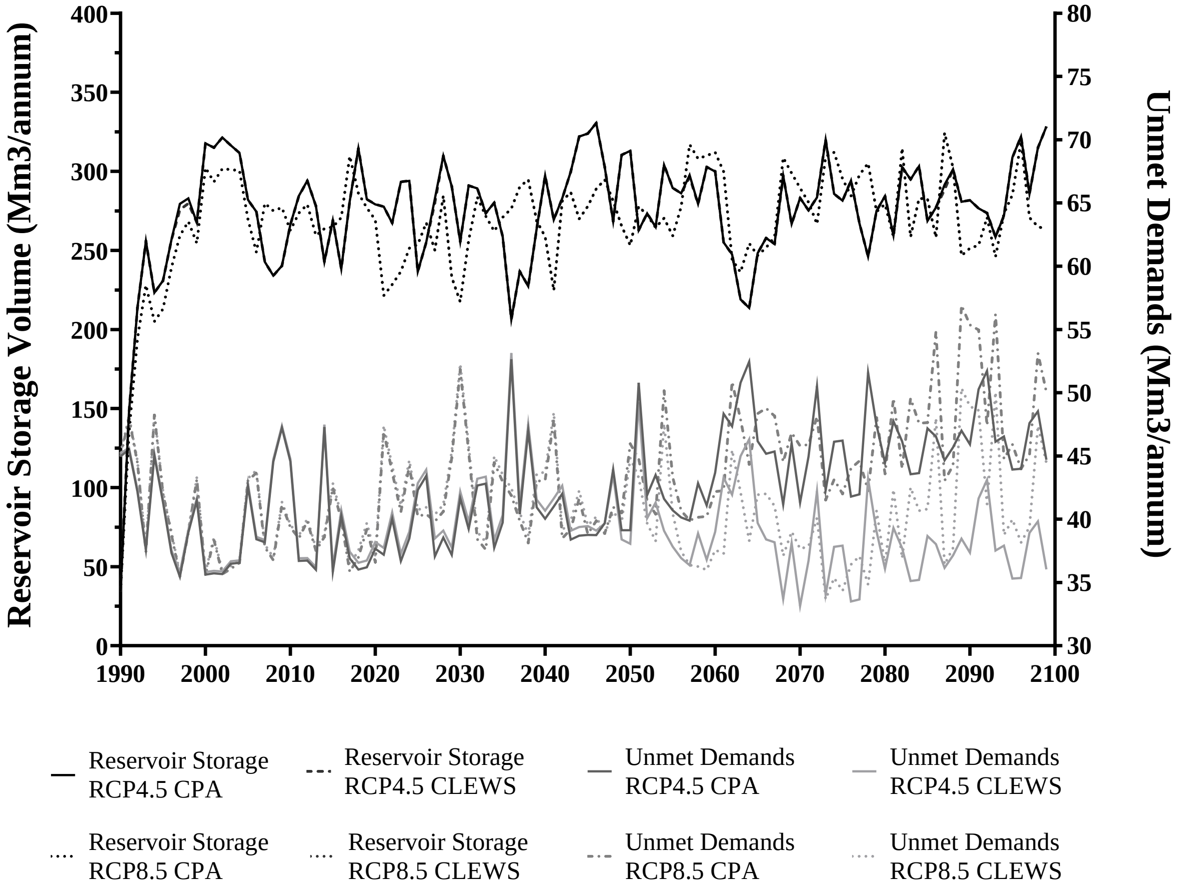


Figure 4.12 Simulated annual reservoir storage (Mm/annum) and unmet demands (Mm/annum) in the Buffalo River catchment using the CPA and CLEWS approach for period 01/01/1990 to 31/12/2099.

4.3.4 Demand site coverage

The demand coverage (*Dcov(%)*), which is the percentage of demands met per demand site, was analysed for local municipalities as they are primary demand sites i.e., water is ultimately transmitted to them for domestic, energy and agricultural purposes. From Figure 4.13, the annual *Dcov(%)* for each local municipality are different, this being a result of the water allocation plans of the Buffalo system. The Newcastle and Dannhauser LMs demands are highly prioritized when it comes to water distribution in the Buffalo system, with simulated mean historical *Dcov(%)* values being 96% and 99%, respectively. However, the Utrecht and Nquthu

LMs' historical maximum *Dcov(%)* being 7% and 11%, respectively, indicates an incredibly low prioritisation of these LMs water demands

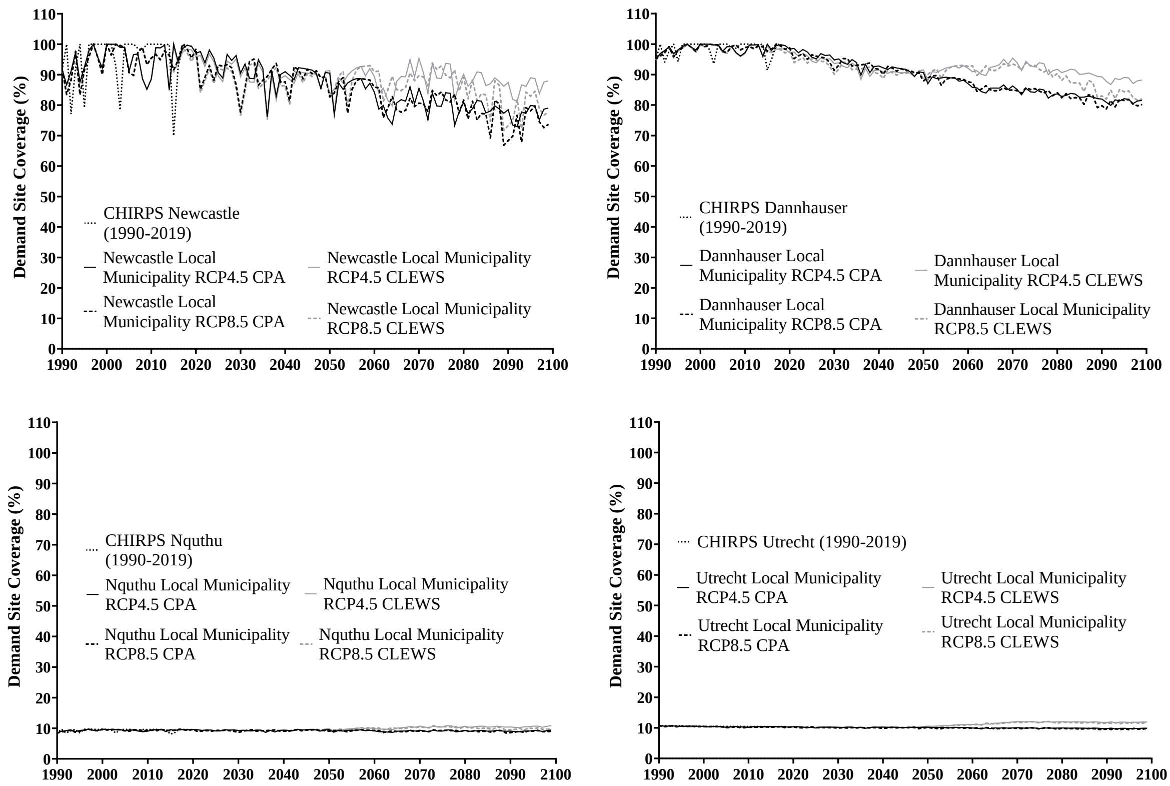


Figure 4.13 Annual demand site coverage (%) of the Buffalo River catchment's local municipalities under the RCP4.5 and RCP8.5 climate scenarios, established using the CPA and CLEWS approaches.

When the *Dcov(%)* values projected by the CPA and CLEWS approaches are contrasted, the CLEWS *Dcov(%)* is significantly higher in high-priority demand sites, particularly in the Newcastle local municipality; in the mid- and far-future timeframes, CLEWS *Dcov(%)* for Newcastle is higher by 5% and 10%, respectively. As such, this provides the reason behind the lower *Q* and unmet demands projected using the CLEWS approach. The Buffalo River catchment's water system's functionality and allocation plans are centred around meeting water demands in high-priority demand sites, thus enabling these sites to maintain a *Dcov(%)* above 70%, even under worsened CC conditions. This benefits the domestic and energy sectors as a minimum of 76% of their water requirements emanate from high-priority demand areas, thus yielding a maximum of 30% of their water demands not being met under CC.

However, for the agricultural sector, more than 65% of its water demands stem from low-priority regions. As a result of the low prioritization of Nquthu and Utrecht local municipalities, it is expected that an average of 90% of irrigation water demands in these regions will not be met, this equating to approximately 60% and 65% of the catchment's total IWR not being met under the RCP4.5 and RCP8.5 scenarios, respectively.

Differences in projected water demand coverage for RCP4.5 and RCP8.5 scenarios

To check for significant differences in the CLEWS *Dcov(%)* under the RCP4.5 and RCP8.5 scenarios, as the primary demand sites, the local municipalities' *Dcov(%)* outputs were analysed with the statistical Welch test for parametric t-tests and the Mann-Whitney test for non-parametric t-tests (Mauser *et al.*, 2015), after checking for the assumption of normality using the Shapiro-Wilks test (Gyamfi *et al.*, 2016). The t-tests were carried out fixing the significance level(α) at 5%, so that the null assumption (the means do not differ) is rejected where this is true, and the results are tabulated in Tables 4.10 and 4.11.

From the statistical comparison of *Dcov(%)* results obtained under the RCP4.5 and RCP8.5 CC scenarios, as seen in Table 4.11, in the near future timeframe, the differences in the mean *Dcov(%)* values (RCP4.5 mean value – RCP8.5 mean value) per local municipality range from -0.02 to -0.84. This highlights that under the RCP8.5 scenario, the water demands that can be covered in each local municipality are expected to be lower than those anticipated under the RCP4.5 scenario.

In the mid-future, all local municipalities' *Dcov(%)* values obtained under the RCP4.5 and RCP8.5 scenarios did not display any significant difference. This is to be expected as, for the RCP4.5, precipitation values in the mid-future reflected similar averages when compared to the historical timeframe, with the RCP8.5 scenario projecting slight yet insignificant increases.

However, in the far future, 3 out of 4 local municipalities' *Dcov(%)* values obtained under the RCP4.5 and RCP8.5 are significantly different. This is also to be expected as, under the RCP4.5 and RCP8.5 scenarios, precipitation under this timeframe displayed significantly larger differences in both magnitude and variations. The differences in means for both RCP scenarios' *Dcov(%)* values mirror this as they range from -0.21 to -3.91, indicating that lower *Dcov(%)* are expected under this CC scenario.

Table 4.10 Normality test results of local municipalities' demand coverage results

	Local Municipality	Newcastle	Dannhauser	Utrecht	Nquthu
Near Future (2020-2045)	**RCP4.5**	**No**	**Yes**	**No**	**No**
	RCP8.5	**Yes**	**No**	**Yes**	**No**
Mid-Future (2046-2070)	**RCP4.5**	**No**	**No**	**Yes**	**Yes**
	RCP8.5	**Yes**	**No**	**Yes**	**Yes**
Far Future (2071-2099)	**RCP4.5**	**Yes**	**No**	**Yes**	**No**
	RCP8.5	**Yes**	**No**	**Yes**	**Yes**

Table 4.11 Inferential statistics comparing the significant differences in demand site coverage results per local municipality in the Buffalo River catchment, obtained under the RCP4.5 and RCP8.5 scenarios.

	Local Municipality	P-value	Significant difference?	Differences in means (RCP4.5 - RCP8.5)
Near Future (2020-2045)	**Newcastle**	**0.1355**	**No**	**-0.84**
	Dannhauser	**0.0488**	**Yes**	**-0.28**
	Utrecht	**0.0374**	**Yes**	**-0.285**
	Nquthu	**0.1361**	**No**	**-0.015**
Mid-future (2046-2070)	**Newcastle**	**0.74**	**No**	**-0.03**
	Dannhauser	**0.9419**	**No**	**0.18**
	Utrecht	**0.3303**	**No**	**-0.1224**
	Nquthu	**0.6786**	**No**	**-0.0248**
Far Future (2071-2099)	**Newcastle**	**0.0048**	**Yes**	**-3.908**
	Dannhauser	**0.1453**	**No**	**-0.43**
	Utrecht	**0.0171**	**Yes**	**-0.2862**
	Nquthu	**<0.0001**	**Yes**	**-0.21**

4.3.5 Reliability of water system

The WEAP model projected the reliability of the Buffalo River catchment system in providing its water demands per demand site, as observed in Figure 4.14. From Equation (4.6), reliability (*RE(%)*) is calculated as the percentage of timesteps in which the demand site was fully satisfied i.e., 100% *Dcov(%)*.

$$RE(\%) = \left(T - T_D/_T\right) \times 100 \qquad \text{(Sieber, 2015)} \qquad (4.6)$$

where *RE(%)* = reliability of demand site (%)

T = total number of years of respective timeframe

T_D = total number of years where demand site *Dcov(%)* ≠ 100%

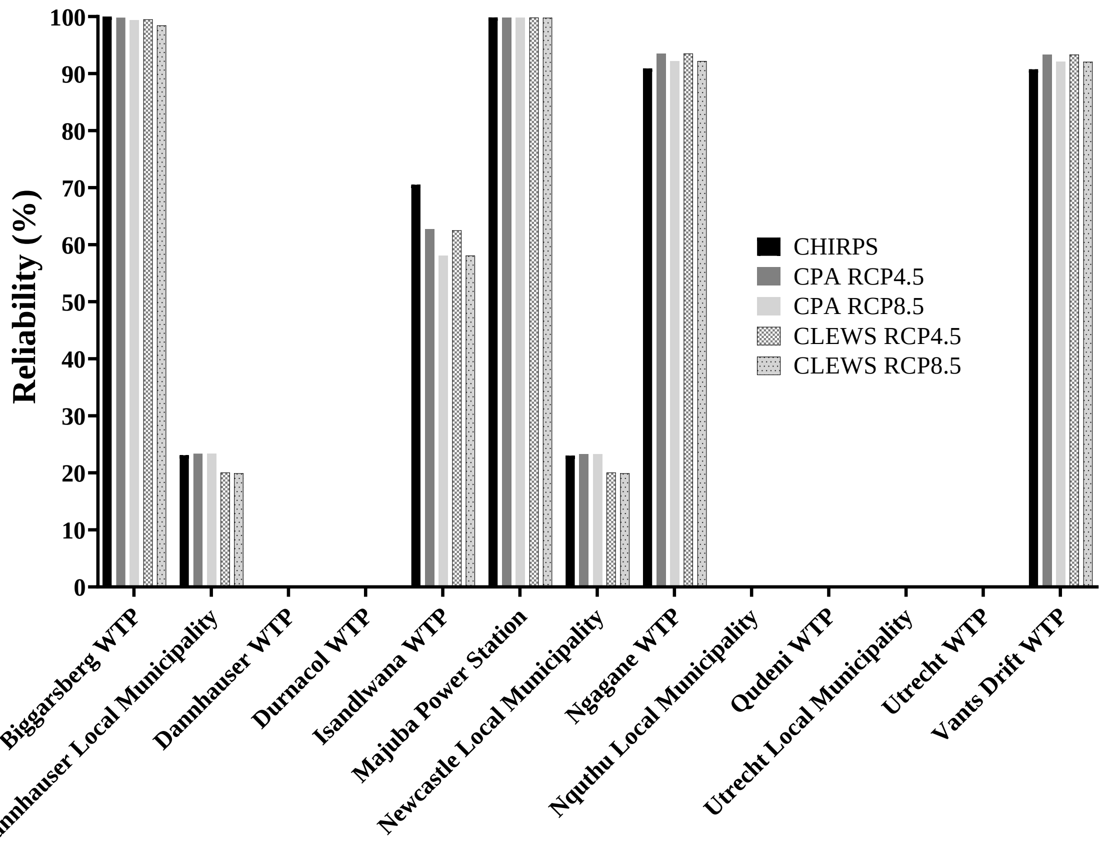


Figure 4.14 Water system supply reliability (%) throughout the study period (01/01/1990-31/12/2099) in the Buffalo River catchment.

Demand sites which yielded high *RE(%)* of over 50% include the Majuba power station, Biggarsberg WTP, Isandlwana WTP, Ngagane WTP and the Vant's Drift WTP. The Majuba power station is the only demand source extracting water from the Zaaihoek Water Transfer scheme via the Zaaihoek Dam, which is located in the upper regions of the Buffalo River catchment. As such, this provides reason for the high *RE(%)*. The Biggarsberg, Isandlwana, Ngagane and Vant's Drift WTPs' first supply preferences are primary demand sites, and as such their demands for transmission are met first, hence their high *RE(%)* values. To elaborate, the Qudeni WTP is a secondary supply preference for the Nquthu local municipality, whereas the Vant's Drift WTP is the primary supply preference, which is why Qudeni's *RE(%)* value is 0% while Vant's Drift is roughly 93%.

When comparing the primary demand sites *RE(%)* values, the Newcastle and Dannhauser local municipalities *RE(%)* are approximately 23% for CPA and 20% for CLEWS under CC conditions, as seen in Figure 4.14. This is owing to them being high-priority sites, also having multiple supply points which increases the stability of their *RE(%)*. CLEWS projected *RE(%)* to be 3% lower than CPA, which corresponds with the slight increases in *Dcov(%)* for the Nquthu and Utrecht sites towards the end of the 21st century that proved to be insignificant; the Nquthu and Utrecht local municipalities *RE(%)* values are 0% i.e., their annual water demands are projected to not be fully supplied throughout the projection period i.e., *Dcov(%)* ≠ 100%.

4.4 Conclusions and Recommendations

Assessments of climate change impacts on water resources is vital for sustainable water policy framing. This should be done in an integrative approach, looking closely at the nexus of water, energy, and food resources since they are intrinsically linked. As such, the objective of this study was to determine the reliability of the BR catchment's water supply system in providing the anticipated water demands under CC, with a specific focus on domestic, irrigation and energy generation water requirements within the catchment's local municipalities.

The study findings suggest that increased rainfall magnitude and variation are to be anticipated towards the end of the 21st century, accompanied with increases in evapotranspiration and surface runoff. On the contrary, CC is also anticipated to decrease land suitable for agricultural production, thus propelling the summative values of irrigation water demands to decline. Such declines in the agricultural sector are a significant cause of concern for food security and the socioeconomic standing of the catchment communities, and they are expected to have a significant influence on the catchment's total water supply requirement, despite increased demands from domestic and energy generation water requirements. However, decreases in irrigation water demand are likely to benefit the domestic sector, as increases in their water allocations are projected as a result of CC.

In conclusion, we reject the null hypothesis as the overall reliability of the catchment's water supply system in providing water demands was projected to fluctuate under CC throughout the study period. The Newcastle and Dannhauser local municipalities' water demands are highly prioritized, resulting in a high reliability, or consistency, of all their demands being met. The Utrecht and Nquthu local municipalities were identified as low-priority demand sites, and the Buffalo system was found unreliable in providing their water demands. This is particularly concerning as both Nquthu and Utrecht, provide a vast amount of agricultural produce for both crop and livestock purposes, and also possess potential for further agricultural expansion. Plans in reallocating water to these demand sites are encouraged to strengthen the system's reliability in meeting their needs. This can be executed by redirecting some water transmission links from the high priority demand sites to Utrecht and Nquthu, re-establishing the operational rules of WTPs, especially the Utrecht WTP, and increasing water storage targeted at providing water to the low priority area.

The performance of both the WEAP and LEAP models is determined by the amount of data provided and its level of detail. Hence, improving the quality and details of the data utilized in the simulation procedures of the models is strongly suggested for future study. Recommendations include the use of dynamically downscaled precipitation projections, which are of a higher resolution than statistically downscaled data, as well as the use of the newly established CMIP6 GCM climate output data. However, based on the WEAP model performance assessment data, the bias-correction approach used to derive precipitation estimates from the used statistically downscaled data delivered adequate precipitation values that reflected the catchment's hydrology, as highlighted in the model performance evaluation.

Studies focused on detailed quantitative data collection on groundwater availability and consumption, energy usage in the catchment for household and irrigation purposes, as well as energy consumption investigations per activity within the BR catchment, are recommended to improve the quality of research focused on the Buffalo River catchment, and for decision-making purposes. To boost the catchment’s water supply system’s reliability, studies focusing on expanding the catchment’s water supply infrastructure and altering water transmission and diversions during periods of system failure are also recommended. The CLEWS framework illustrated the complex WEF nexus’ relationships in the BR catchment; thus, it is encouraged for studies that examine CC impacts on WEF resources.

4.5 References

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5 THE WATER-ENERGY-FOOD NEXUS AS A TOOL TO DEVELOP CLIMATE CHANGE ADAPTATION STRATEGIES: A CASE STUDY OF THE BUFFALO RIVER CATCHMENT, SOUTH AFRICA

Abstract

Background: It is essential to manage water resources in the context of long-term Climate Change (CC), taking into consideration the nexus among water-energy-food (WEF) sectors. Furthermore, policies developed to co-balance water allocation must be evaluated, as they often pose new problems towards their implementation.

Problem Statement: Due to the Buffalo River catchment's water resources system's lack of infrastructure development and unreliable main water supplies, CC is predicted to increase the water supply deficits by exacerbating water distribution inequalities.

Objective: To assess and optimize existing CC policy plans on the Buffalo River catchments water system, with a specific focus on increasing the water system's reliability in meeting projected domestic, agricultural, and energy water demands under CC conditions.

Results: Existing water policy plans are anticipated to increase domestic water provision by >70% under CC; however, due to a <3% increase in irrigation and energy generation water demand coverage, a significant contrast in reliability was predicted between densely populated areas and regions with extensive agricultural activities. After optimizing the policy action plans, the newly developed CC adaptation strategies are anticipated to avoid this contrast by increasing water provision for all sectors by >20% under CC, thereby improving the overall water system's reliability.

Conclusion & Recommendations: When compared with existing CC integrated development plans, the optimized CC adaptation strategies developed in this study do possess more potential in merging the gap between the catchment's water supplies and water demands from the energy and agricultural sectors. The developed CC adaptation strategies are anticipated to significantly improve the reliability of the water system in meeting these sectors water requirements throughout the 21st century, even under worsened CC conditions. Furthermore, based on the outcomes of the water supply performance indices, the optimized policy actions are suggested for future research, dialogue, and discussions related to water resource management in the Buffalo River basin.

Keywords: Scenario development, River basin management, Water allocation, Reliability index, CLEWS framework, WEF nexus

5.1 Introduction

Extreme weather events brought on by Climate Change (CC), such as droughts and floods, have emerged as the biggest threats to southern Africa's rapidly growing and developing economy. Risk and uncertainty are expected to increase if temperatures continue to rise and rainfall patterns change considerably, particularly in regions with limited ability for adaptation (Mpandeli *et al*., 2018).

Currently, CC is increasing water stress and exacerbating hydrologic variability in South Africa (Nhemachena *et al*., 2020). The KwaZulu-Natal province, unlike the rest of the South African regions, is likely to be at risk from more extreme flooding events due to an anticipated increase in intensity and frequency of rainfall (Graham *et al*., 2011; Zwane, 2019). Moreover, through the hydrologic variability induced by CC, water availability may be limited (Tabari, 2020), and the degree of limitation is dependent on increased water consumption perpetuated by population growth (UNESCO, 2015), and human interventions through land and water management (Ashraf *et al*., 2019).). To improve the management of water resources, it is crucial to take into account the interactions between anthropogenic drivers of water availability and climate change (Ashraf *et al*., 2019).

To strengthen water security, hydraulic infrastructures, like reservoirs and canals, may be a viable solution. However, they require an efficient operation and sustainable allocation strategies to accommodate the demand from various users (Wicaksono and Kang, 2019). Sustainable water allocation strategies recognize safe drinking water for basic domestic needs, achieving food and energy security, supporting sustenance agriculture, and meeting the minimum ecosystem needs (Agarwal *et al*., 2018). Therefore, a transdisciplinary and transformative resource management approach, like the Water-Energy-Food (WEF) nexus (Mabhaudhi *et al*., 2019), which seeks an understanding of the linkages, dependencies, synergies, and trade-offs associated with WEF sectors in resource management, is ideal for the optimization of water allocation (Hui *et al*., 2021)

The WEF nexus approach facilitates addressing the multifaceted and dynamic interactions between the food, energy, and water systems (Nhamo *et al*., 2019). It has become a strategy that offers chances for cross-sectoral collaboration and policy harmonisation to resolve complex issues in a sustainable approach (Nhamo *et al*., 2019). The WEF Nexus' nature is three-dimensional as it is used either as a conceptual framework, for discourse and as an analytical tool (Keskinen *et al*., 2016). For discourse, the WEF nexus concept can be used to contextualize problems and improve cross-sectoral interactions, and as a conceptual tool, the WEF nexus approach provides a framework for understanding the complex interrelationships, synergies, and trade-offs among water, energy, and food. (Albrecht *et al*., 2018). As an analytical tool, the WEF nexus employs a systematic application of quantitative and qualitative methodologies to comprehend the relationships across WEF resources (Nhamo *et al*., 2020a).

Due to its holistic approach in resource management (Wicaksono and Kang, 2019), the WEF nexus approach can be utilized towards informing CC strategies for sustainable development and resource security (Nhamo *et al*., 2020b). From a water perspective, the WEF nexus shifts from the current "silo" approach of resource management (Naidoo *et al*., 2021) and attempts to involve the energy and agricultural sectors in the analysis of the water issues so to raise awareness of the interdependencies of energy, food and water security (Shannak *et al*., 2018). Regions within South Africa could benefit from this holistic approach as they experience significant trade-offs among WEF sectors (Senzanje *et al*., 2019).

From a South African river basin perspective, the Buffalo River (BR) catchment, which forms part of the uThukela Water Management Area in KwaZulu-Natal, lacks infrastructure development, and consists of unreliable main water supplies, including the BR, Ngagane River and Ntshingwayo Dam (Ngubane and Zwane, 2019). As a result, this high rainfall receiving area in the KwaZulu-Natal province experiences water supply shortages, has underutilized agricultural potential, and relies heavily on rainfed agricultural produce (LGCCP, 2018; Kunene, 2019; Ngubane and Zwane, 2019; Shabalala *et al*., 2020). The above-mentioned issues were exacerbated during the 2015 and 2016 drought period, which severely affected the livelihood, and the ability to provide water to its numerous activities, including irrigation, power generation, domestic, mining and bulk industries (uMgeni, 2020). According to the uMgeni (2020) report, as a result of population growth, the current water supply schemes within the BR catchment are anticipated not to cater for their water demands by 2050.

Though the conceptual linkages between WEF sectors may be described, the actual feedback loops are complicated, frequently undetectable, and influenced by outside variables (Wicaksono and Kang, 2019). Several strategies may be used in South Africa to investigate and assess the WEF nexus., such as the: (a) WEF Nexus Tool 2.0, (b) MuSAISEM, (c) Climate, Land-Use, Energy and Water Strategies (CLEWS), and (d) ANEMI (Mabhaudhi *et al*., 2018). Analytical approaches that deal specifically with WEF resources management and CC are the CLEWS and the ANEMI model. While the ANEMI model is a single model that carries out an interconnected evaluation of the physical, ecological and hydrological processes (Davies and Simonovic, 2010; Mabhaudhi *et al*., 2018), CLEWS is a conceptual framework which involves integrating analytical land, energy and water models under various climate scenarios, hence enabling flexibility of analytical model selection for each WEF component (Welsch *et al*., 2014; Mabhaudhi *et al*., 2018; Ramos *et al*., 2020).

Concurring to uMgeni (2020), the water distribution system in the BR catchment has not been able to meet demands in recent years, and Dlamini and Mostert (2019) further stated that water allocation plans should be revised to mitigate water distribution inequities in the future. We therefore applied the CLEWS framework to investigate the impacts of CC and proposed policy interventions on the Buffalo River catchment's water system's reliability in supporting its future demands. This research was based on the null hypothesis which states that optimized CC water management strategies will not alter the relationship between available water supply and water demands of the catchment under climate change. The study also uses water supply performance indices to scrutinize the integrity of the water supply system and formulate recommended CC adaptation strategies based off the results.

5.2 Material and Methods

5.2.1 Description of the study site

The Buffalo River catchment is a sub-catchment of the Thukela Water Management Area in KwaZulu-Natal, South Africa, located at 28°42'59" S, 30°38'30" E (uMgeni, 2020). The catchment covers an area of approximately 9 803 km^2, in the warm, humid and high elevation Drakensberg Mountain region. It receives the bulk of its yearly rainfall during the summer months, averaging 802 mm per annum (uMgeni, 2020). The Buffalo River (BR) flows approximately 339 km south-easterly from the eastern escarpment (Newcastle area) through the Amajuba and uMzinyathi District Municipalities, then confluences with uThukela River in the Msinga Local Municipality (Dlamini and Mostert, 2019; uMgeni, 2020). The catchment is primarily rural, has a population of approximately 0.7 million, and covers the following municipalities: (a) Newcastle Local Municipality (LM), (b) Dannhauser LM, (c) Utrecht LM, and (d) Nquthu LM (uMgeni, 2020).

5.2.2 CLEWS framework

The focus of the CLEWS conceptual framework is the analysis of interactions between the systems of climate, land, energy, and water, supported by quantitative studies of interactions and use of resources. Therefore, it is interdisciplinary in nature (Ramos *et al*., 2020). It includes the use of publicly available tools such as the Long-range Energy Alternatives Planning (LEAP) model, Water Evaluation and Planning (WEAP) model, and Agro-Ecological Zoning (AEZ) model, and connects their inputs and outputs, followed by the analysis of the results at an integrated WEF layer (Byers, 2015). The description of the models and their interaction can be found in Section 4.2.4 and Section 4.2.5.

Figure 5.1 illustrates the study's overall use of the CLEWS approach, which is partitioned into two phases: data collection and nexus modelling, and scenario analysis. The data collection and nexus modelling phases highlight the complex linkages among the water, energy, food, and CC sectors. The models established in this step are utilized in the following phase to create a scenario-based analysis, whereby two climate scenarios and existing policy scenarios are combined.

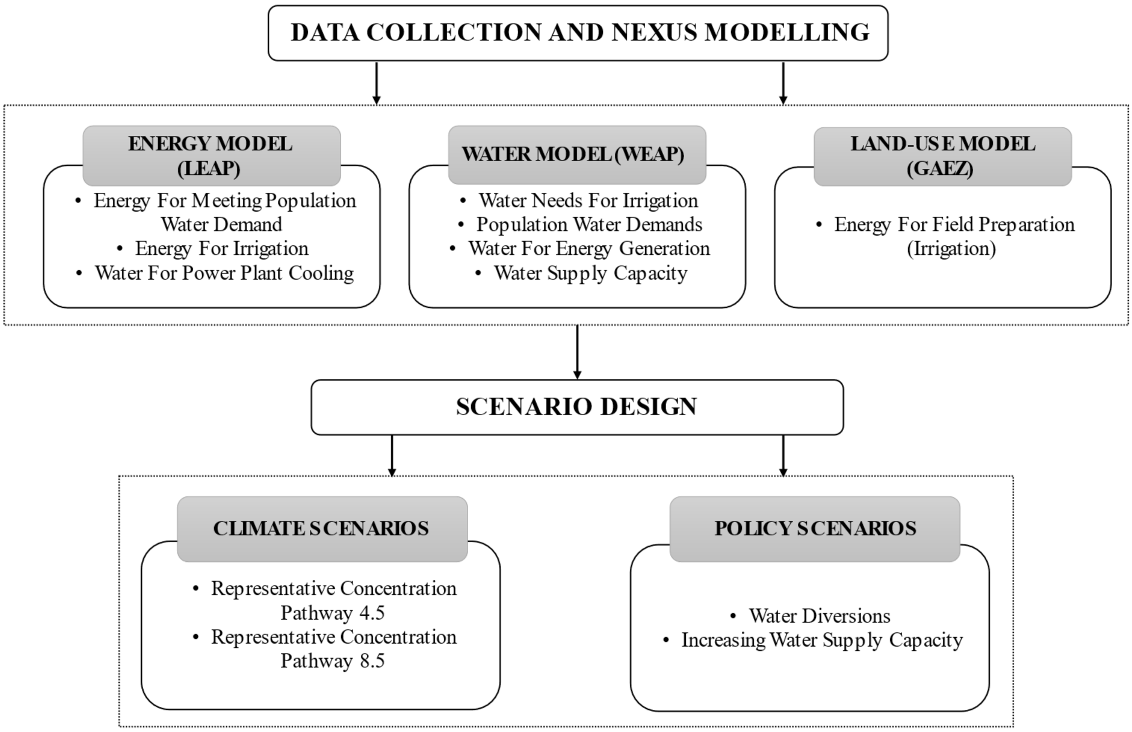


Figure 5.1 Methodology of the study.

5.2.3 Climate change adaptation assessment

In response to CC, adaptation minimizes climatic risks and vulnerability, mostly through modifying existing system. Multiple adaptation strategies exist and are utilized to assist in managing expected CC consequences, but their implementation is dependent on the governance and decision-making processes' capability and efficacy (Portner *et al*., 2022). As such, this study presents a policy-oriented framework for analysing various CC adaptation strategies for the 2100 horizon year.

Climate scenarios

Projections of the effects of CC on water resources made using models can vary greatly. If this is the case, managers of water resources and decision-makers cannot place their trust on only one individual future scenario (Kundzewicz *et al*., 2018). In order to overcome this uncertainty, the "*precautionary principle*" and "*adaptive management*" are two potential alternate courses of action that can be taken. The former is an adaptation of the min-max principle, which advocates for choosing the course of action that minimizes the worst possible consequence. The latter is supported by the notion that adaptive planning should be centred on ensembles and multi-model probabilistic techniques given the wide range of outcomes in various climate impact scenarios (Kundzewicz *et al*., 2018).

As such, for this study, in analysing CC scenarios, the precautionary principle was utilized, whereby the best- and worst-case CC scenarios were analysed using the CLEWS approach. Information on the CC scenarios' input data for CLEWS and their respective sources can be found in Section 4.2.4.

Policy scenarios

Different governmental agencies develop various policies and development plans (Nasrollahi *et al*., 2021). For the BR catchment, water management recommendations made by uMgeni Water, a South African state-owned water resources management organisation, as well as those stated in the BR catchment's local municipalities' development plans, are centred around increasing the catchment's total water supply capacity, as presented in Table 5.1. It is important to note that uMgeni Water does not currently operate infrastructure in the BR catchment, however their recommendations are based on projections of population water demands from 2020 to 2050 (uMgeni, 2020).

Table 5.1 Water supply strategies for the Buffalo River catchment.

	Water Supply Strategies	Source(s)
Short- to Medium-Term Strategies (2020-2050)	Upgrade Ngagane WTP to deliver an extra 30Ml/day OR Replace pipelines to recieve full allocation for Ngagane WTP of 113.5 Ml/day	(uMgeni, 2020; uThukelaWater(Pty)Ltd, 2021)
	Newcastle to receive 33 Ml/day, therefore new WTP required as Biggarsberg delivers 16 Ml/day OR Increase supply of Tayside by 11 Ml/day from Ntshingwayo Dam	
	Decommission Dannhauser (not efficient)	
Long-Term Strategies (>2050)	Construction of Ncandu Dam with storage capacity = 19.15 million m^3 and yield = 5.04 million m^3	(Ngubane and Zwane, 2019; uMgeni, 2020; uThukelaWater(Pty)Ltd, 2021)
	Investigation of possible dam/s on Buffalo or Blood River to benefit Vant's Drift WTP	(Kunene, 2019; uMgeni, 2020)
	Investigation of possible dam on Ngogo River to assist and ease demand on the Ntshingwayo Dam	(uMgeni, 2020; uThukelaWater(Pty)Ltd, 2021)
	Upgrade the Ngagane WTP to deliver 220 Ml/day instead of 130 Ml/day by 2050	

To eliminate the potential of distorting aspects of the policies, the short-, medium- and long-term strategies were integrated into one policy strategy (PS). In the PS scenario, strategies related to the implementation of new dams and WTP with no recommended design specifications were rendered incomplete, thus omitted. A Business-As-Usual (BAU) scenario was also created for comparison purposes. In the BAU scenario, changes to the existing surface water infrastructure were not made, so that the ability of the current surface water infrastructure to meet water demands could be assessed. Ultimately, a combination of two CC scenarios and two policy scenarios, as seen in Figure 5.2, are assessed using adaptation performance indices which will be defined later.

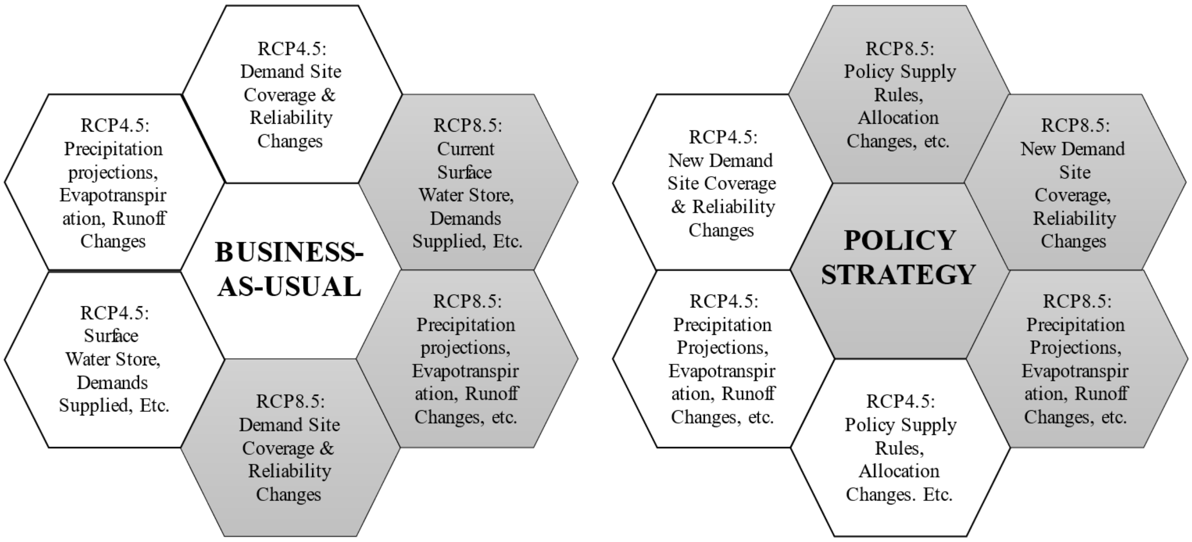


Figure 5.2 Climate change adaptation framework showing Business-As-Usual (left) and Policy Strategy (right) scenarios

5.2.4 Adaptation performance indices

In assessing the BR catchment's water supply system's performance and analysing the system differences under each climate and policy scenario, two performance indices were utilized. These are Demand Site Coverage (*Dcov*) and the Reliability Index (*RE*) performance indicators. The *Dcov* is the percent of each demand site's water requirement that are met, from 0% (no water delivered) to 100% (delivery of full requirement). The *RE* is defined as the probability that the water resources system can provide sufficient water supply to meet demands during the entire simulation period (Hashimoto *et al*., 1982; Sieber, 2015; Al-Juaidi and Al-Shotairy, 2020). In essence, it is the percent of time when demands were fully satisfied (Sieber, 2015).

5.3 Results and Discussion

5.3.1 Climatic and hydrological changes

Actual evapotranspiration and surface runoff

Projected annual ET_A values are presented in Table 5.2, which show a slightly increasing trend with time under RCP4.5. This is coupled to the increase in rainfall over time (see Section 3.3.1) which equates to more water being available for ET_A to occur. Exceptions to this are the projected periods where rainfall decreases and limits water availability. Case in point, the RCP8.5's ET_A declined by -2%, -1% and -0.3% in the near-, mid- and far-future, respectively, which is consistent with the expected decrease in rainfall in the near-future, and the gradual increase thereafter.

Also from Table 5.2, following the increase in precipitation under both RCP scenarios , increased volumes of water exiting the catchment via *R* are expected, especially in the RCP8.5 far future, with 16% and 14.5% increases projected under the BAU and PS scenarios, respectively. These outcomes are consistent with the increased water supply capacity under the PS scenario, which allows for more volumes of precipitation to be captured.

Table 5.2 Projected actual evapotranspiration and surface runoff (Mm^3/annum) under each climate and policy scenario for the historical (1990-2019), near future (2020-2045), mid-future (2046-2070) and far future (2071-2099) periods.

Timeframe	Actual Evapotranspiration		Surface Runoff @ Buffalo River Outlet			
	RCP4.5	RCP8.5	RCP4.5		RCP8.5	
	BAU and PS		BAU	PS	BAU	PS
Historical	**4519.5**	**4472.8**	**3026.1**	**3026.2**	**3080.4**	**3026.4**
Near future	**4518.1**	**4378.6**	**3032.8**	**3032.3**	**3024.3**	**3024.1**
Mid-future	**4533.4**	**4429.5**	**3044.6**	**3044.8**	**3468.3**	**3466.7**
Far future	**4549**	**4458.2**	**3265.7**	**3206.1**	**3523**	**3465.3**

Surface water storage

In Figure 5.3, variations of the annual net surface water storage after W_A i.e., Surface Water Availability (SWA), are shown. Increases are estimated throughout the study period, however, when comparing RCP4.5 and RCP8.5 results for both policy scenarios, the modelled RCP4.5 SWA is lower by -6% and -2% in the near- and far future timeframes, respectively. This is expected as the estimated variation of precipitation and volumes of *R* are significantly lower under RCP4.5 relative to RCP8.5. The PS scenario projected lower SWA in comparison to the BAU, with the differences in values being -3%, -7% and -5% in the near-, mid- and far-future timeframes, respectively. This is an unexpected outcome since PS, as previously mentioned, projected lower quantities of water leaving the catchment as *R*. However, this could be due to increased water extractions from the catchment's water supply system under the PS water allocation plans.

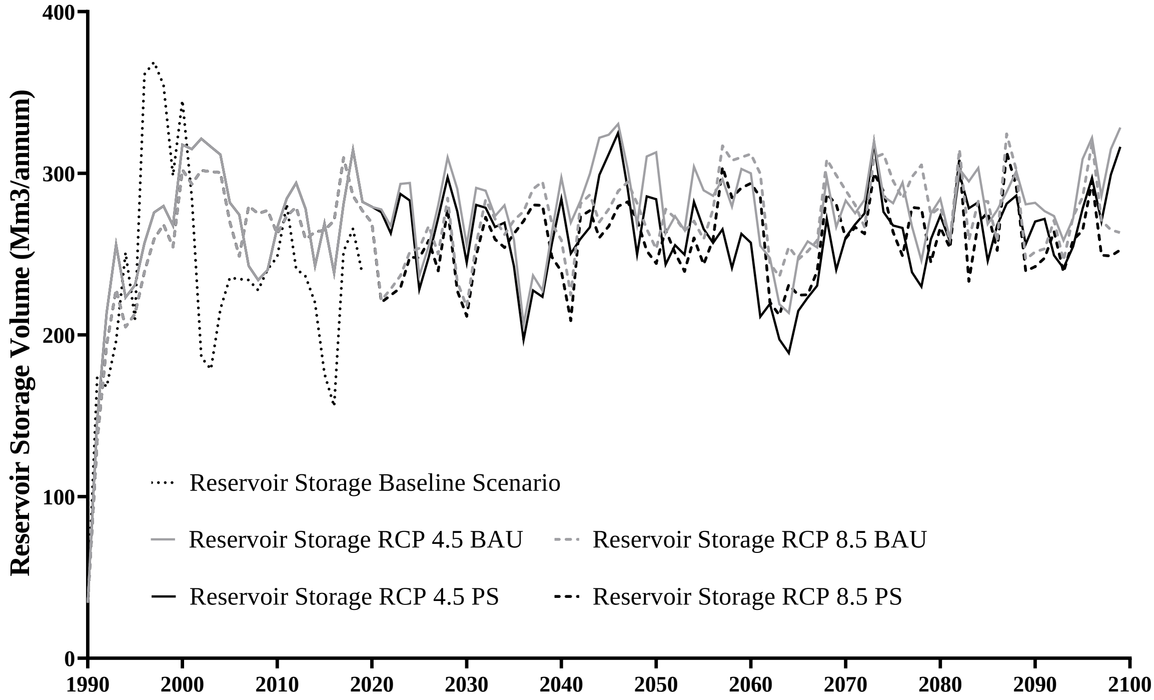
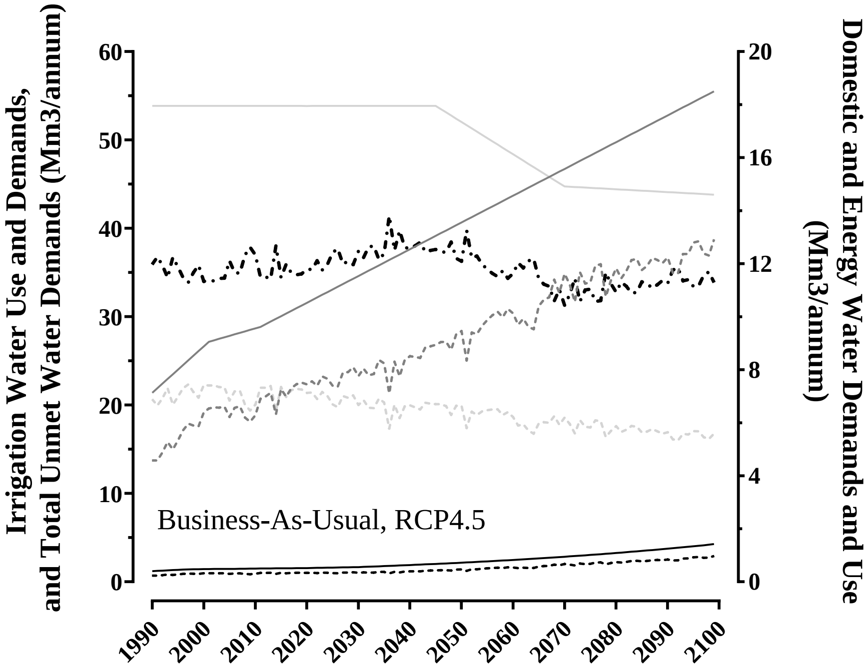


Figure 5.3 Reservoir storage volume (Mm^3/annum) under each climate change and policy scenario

Projected water provisions

The impacts of the four scenarios on total water demands, unmet water demands, and water use (supply delivered) by household, irrigation and energy are shown in Figure 5.4. For BAU, declines in Irrigation Water Requirements (IWR) by -17.8% and -14.8% are projected under the RCP4.5 and RCP8.5 scenarios, respectively. These findings coincide with the results retrieved from the gAEZ assessment, which indicated a drop in suitability for maize and soyabean cropping under the RCP8.5 scenario, thus consequently reducing the amount of water required for irrigation (see Section 4.2.2). For the domestic sector, 90% and 79% of water demands are met under the RCP4.5 and RCP8.5 scenarios, respectively. With the population growth rate being equal under both climate scenarios, the significantly higher percentage of met domestic demands under RCP4.5 reduced *R* and SWA modelled under this scenario.

Under the RCP4.5 scenario, the PS scenario improved irrigation provisions by 1.2%, and under the RCP8.5 scenario, by 3%. For the domestic sector, the quantity of water allocated to it is expected to increase by 0.5% under the PS RCP4.5 scenario, and 3% under the PS RCP8.5 scenario. Also, for this case, the previously calculated SWA declines under the PS can be credited to the expected increase in water provision for the domestic sector.


Irrigation Water Use and Demands,
and Total Unmet Water Demands (Mm3/annum)
Domestic and Energy Water Demands and Use
(Mm3/annum)
Business-As-Usual, RCP4.5
60
50
40
30
20
10
0
20
16
12
8
4
0
1990
2000
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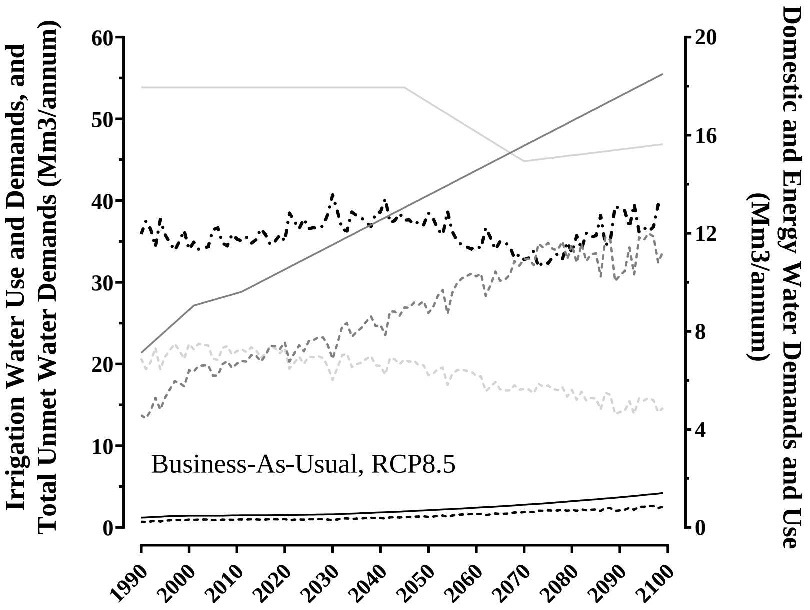
(a)


Irrigation Water Use and Demands, and
Total Unmet Water Demands (Mm3/annum)
Domestic and Energy Water Demands and Use
(Mm3/annum)
Business-As-Usual, RCP8.5
60
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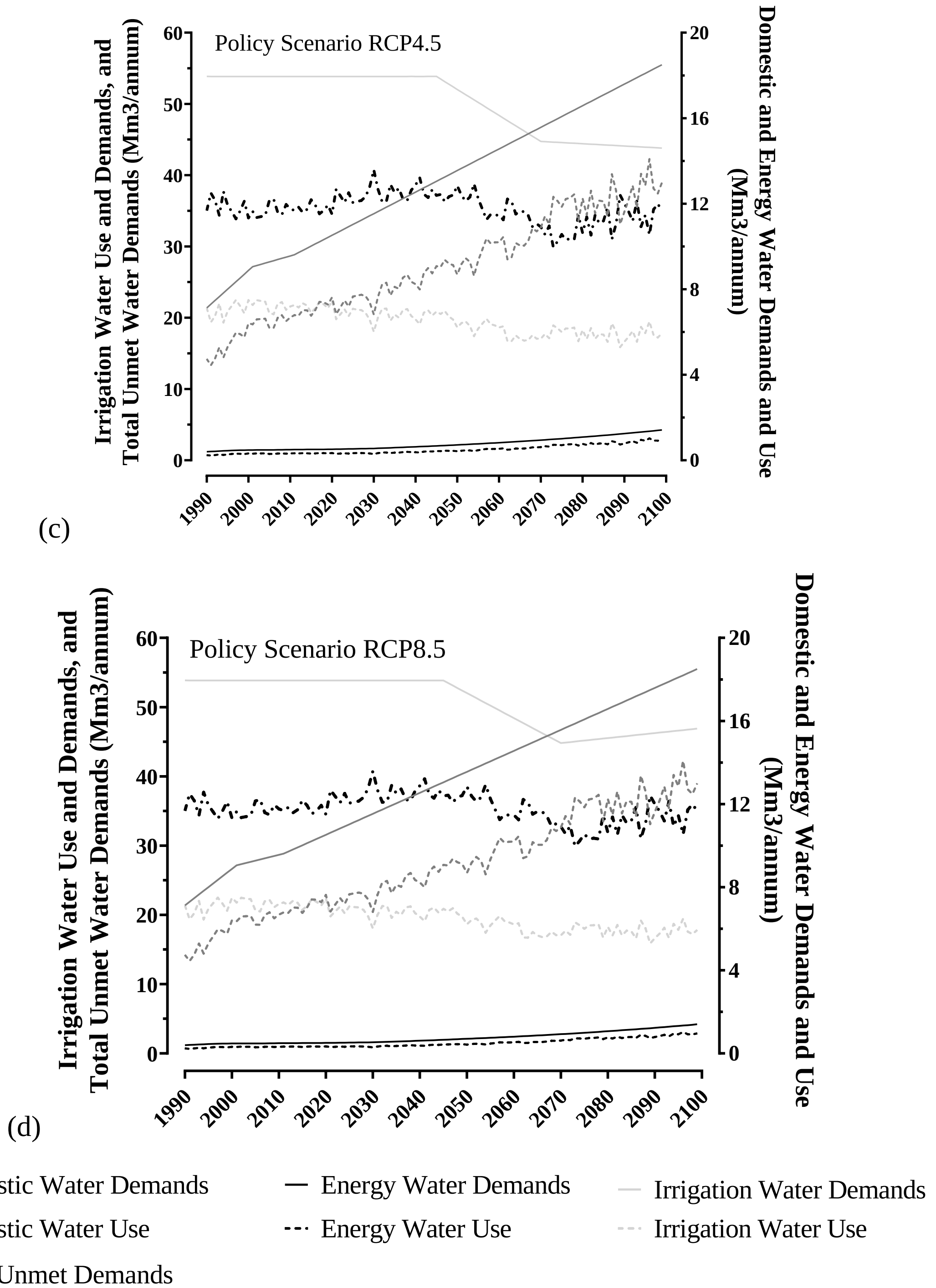


Figure 5.4 Total unmet water demands, irrigation water demands and use, and domestic and energy water use and demand for period 01/01/1990 to 31/12/2099.

An assessment of significant differences in the BAU and PS scenarios was carried out to investigate if the water provision changes made by PS are substantial. The projected total unmet demands were analysed using the statistical parametric Welch test and F-test, and the Mann-Whitney non-parametric t-test, after testing for normality using the Shapiro-Wilks test (Royston, 1995; Sheskin, 2003). The t-tests were carried out fixing the significance level (α) at

0.05, so that the null hypothesis (no significant difference) is rejected where α is greater than or equal to 0.05, and results are tabulated in Table 5.3. Under RCP4.5, both parametric tests indicated no significant difference between the two policy scenarios' unmet demands. However, a conflict of results was produced under RCP8.5, whereby the Welch test results indicated no significant difference, while the F-test results suggested that there is a significant difference. As such, the modelled water supply delivered under both policy scenarios in RCP8.5 for the domestic, energy and irrigation sectors were further tested for significance. The results, listed in Table 5.3, indicate no significant difference. Henceforth, it is safe to say that the changes imposed by the PS scenario are statistically insignificant. This is due to the water strategies' emphasis being on increasing water storage capacity, with minimal focus on water allocation changes among demand sites.

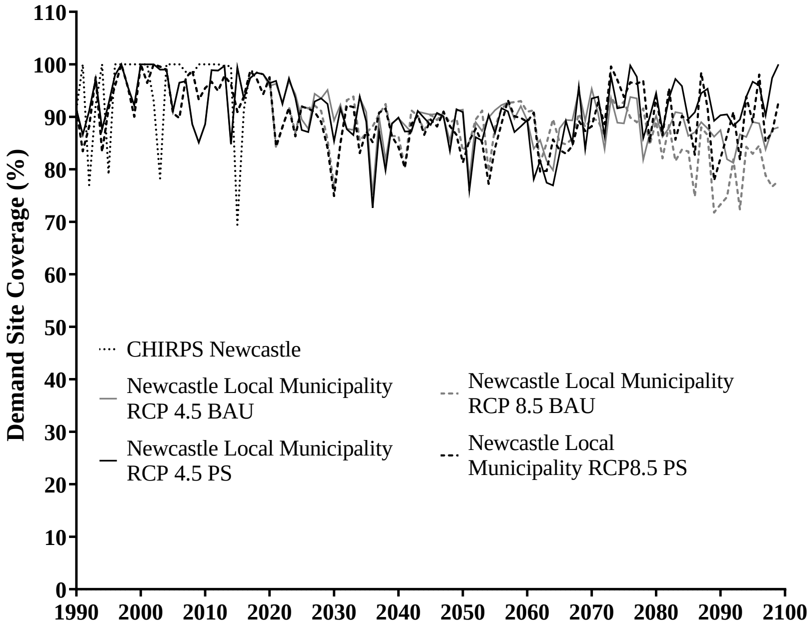
Table 5.3 Significant difference tests of the Business-As-Usual scenario (BAU) and Policy Scenario (PS)

			RCP4.5	**RCP8.5**			
			Total Unmet Demands	**Total Unmet Demands**	**Domestic**	**Energy**	**Irrigation**
Normality Test	**Shapiro**	**BAU**	**0.30**	**0.55**	**0.0008**	**<0.0001**	**<0.0001**
		PS	**0.18**	**0.18**	**0.0061**		**0.0007**
Parametric t-test	**Welch**		**0.97**	**0.01**	**-**	**-**	**-**
	F-test		**0.25**	**0.27**	**-**	**-**	**-**
Non-parametric t-test	**Mann-Whitney**		**-**	**-**	**0.48**	**0.82**	**0.13**

5.3.2 Demand site coverage evaluation

When analysing the *Dcov* of local municipalities within the BR catchment, and as per Figure 5.5, it is evident that the Dannhauser and Newcastle local municipalities are high-priority areas when it comes to water distributions, as their *Dcov* values are greater than 60% throughout the study period, however the Nquthu and Utrecht local municipalities are shown to be low priority areas, with their *Dcov* values falling under 20%. CC is most likely to have a negative impact on the high-priority areas' *Dcov*, as declines are projected under both RCPs. Conversely, the low-priority regions are to expect increases by 10%, 11% and 12% in the near, mid- and far-future, respectively.

PS strategies, when compared to the BAU results, are anticipated to slightly improve the *Dcov* for the high-priority demand sites (Newcastle and Dannhauser local municipalities), especially Dannhauser, whereby 5%, 7% and 8% increases in *Dcov* are noted in the near-, mid- and far future timeframes, respectively. *Dcov* improvements by 27% are also expected, as a result of PS, in the Utrecht local municipality, this being attributed to the modelled increases in extractions of the Utrecht WTP from the Dorps Dam in the near- and mid-future strategies. However, the PS scenario proved to be unfavourable on the Nquthu local municipality as an average difference of -1% is calculated when comparing the PS scenario *Dcov* projections with those of the BAU scenario.



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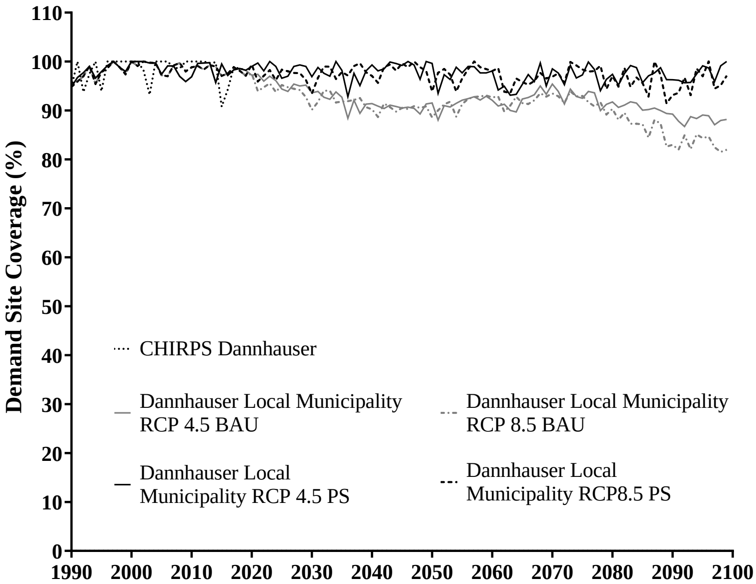

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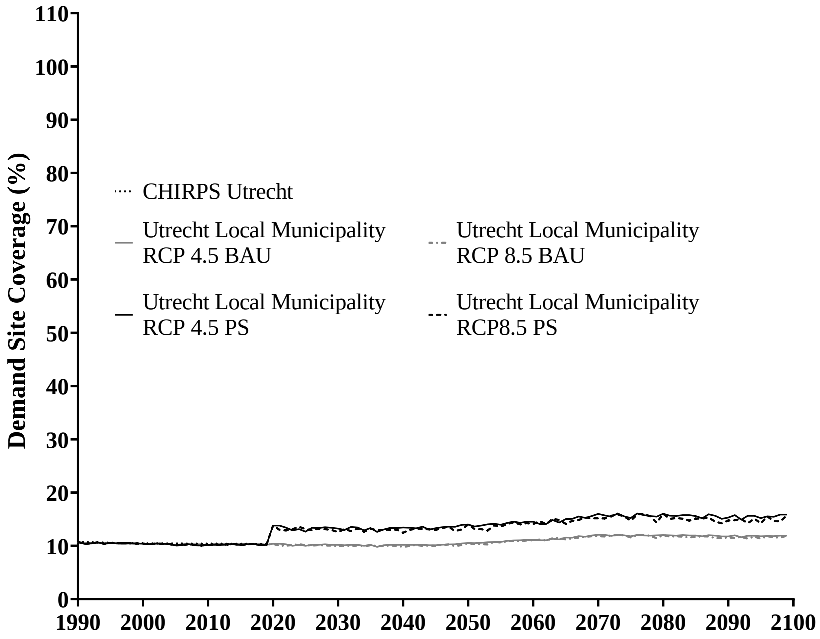

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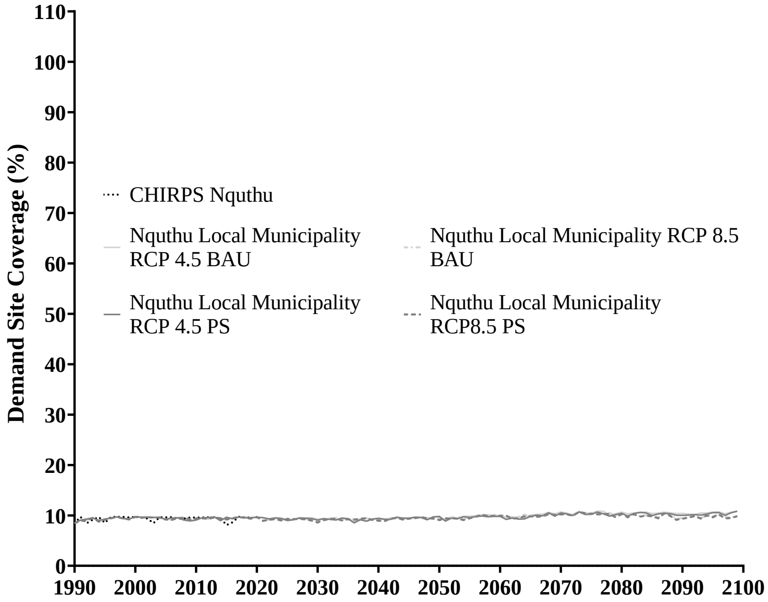


(d)

Figure 5.5 Demand site coverage (%) annual variations for the (a) Newcastle, (b) Dannhauser, (c) Utrecht and (d) Nquthu local municipalities, from 1990 to 2100.

5.3.3 Reliability evaluation

The *RE* of water system is defined as the percent of time demand is fully satisfied (Hashimoto *et al*., 1982; Sieber, 2015; Al-Juaidi and Al-Shotairy, 2020). When observing the *RE* of the BR system in providing water demands to its respective demand sites, as per Figure 5.6, *RE* is projected to be lower under the RCP8.5 scenario relative to the RCP4.5 scenario. This is a result of the radiative forcing under the RCP8.5 scenario increasing the variability of precipitation and surface water storage.

The strategies of the PS scenario proved to be beneficial for the Dannhauser local municipality by increasing its *RE* value by 73%. This is understood to be a result of the increased extractions of the Biggarsberg WTP from Tayside, which supplies the Dannhauser local municipality directly. The Newcastle local municipality's *RE* doubled, from an average of 20% in the PS, to 40% in the PS-Opt. This is ascribable to the proposed Ncandu Dam, which increases the supply delivered to Newcastle in the far-future.

The Nquthu and Utrecht local municipalities' *RE* remains as 0%. This unreliability is expected as the projected *Dcov* values for these low-priority regions is under 20%, leaving approximately 80% of the demands unsatisfied annually. The Nquthu local municipality is the highest producer of agricultural produce and requires approximately 29% of the total IWR. The -64% difference in IWR and the supplied water for irrigation is largely due to this very low allocation of water to the municipality.

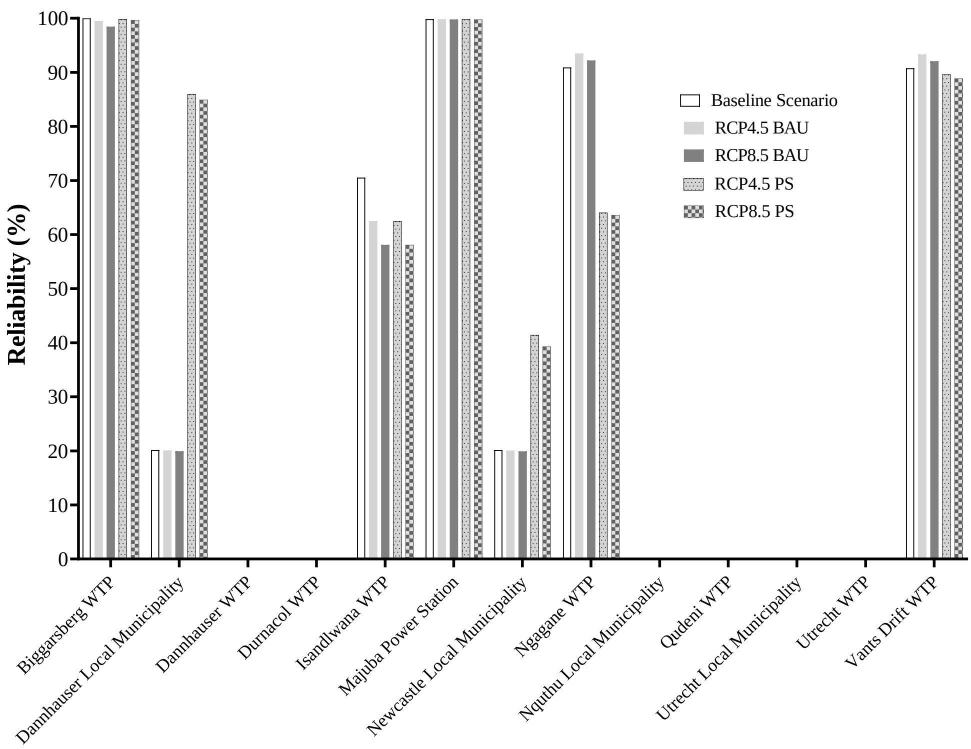


Figure 5.6 The reliability of the Buffalo system from 01/01/1990 to 31/12/2099 under the Business-As-Usual scenario (BAU) and Policy Scenario (PS)

5.3.4 Optimized water management strategies results

In the optimization of PS, as summarized in Table 5.4, the focus was mainly on adapting to climatic changes expected under RCP8.5, as well as increasing supply in low-priority regions, which as previously established, are the Nquthu and Utrecht local municipalities. For strategies involving increasing W_A from reservoirs, an assumed 50% of streamflow remained in the system for consumption losses (CL), which includes 30% for environmental flow release (Hughes and Mallory, 2008), and 20% for uncertainty losses (Hughes and Mantel, 2010).

For the short- to medium-term strategies in the PS scenario, which cover the near- and mid-future periods of this study, the following changes are made:

(a) W_A from the Utrecht WTP to the Utrecht local municipality were increased by 2 Ml/day, thus enabling the Utrecht WTP to supply its full capacity of 4 Ml/day.

(b) The Dannhauser local municipality is currently allocated 40 Mm^3 more than its maximum water requirements per annum projected in 2099. Therefore, as a strategy to increase water allocated to the Utrecht local municipality, the 33 Ml/day water supply from the Ngagane WTP to Dannhauser was decommissioned, and an additional 20 Ml/day was redirected from the Ngagane WTP to the Utrecht local municipality.

(c) To accommodate the 35 Ml/day water inflow losses to Dannhauser local municipality resulting from decommissioning Dannhauser WTP and cutting off the supply from Ngagane WTP, the Durnacol WTP's operational capacity was expanded from 3.5Ml/day to 5.5 Ml/day, as well as the Biggarsberg WTP's operational capacity, from 16 Ml/day to 30 Ml/day.

For long-term PS strategies, which in this study fall under the far-future timeframe, an additional increase of 10 Ml/day from the Ngagane WTP to Utrecht local municipality was modelled, with the intention of meeting the Utrecht local municipality's projected maximum annual demand of 11 Mm^3. Lastly, a reservoir at the Ngxobongo River with a storage capacity of 27 million m^3 was integrated into the BR catchment's modelled water supply system. As the existing water supply capacity is anticipated not to meet the Nquthu local municipality's supply requirements, which range from 25 to 30 Mm^3/annum, the purpose of the proposed Ngxobongo Dam is to supply the Nquthu local municipality's water deficits. The dam location was chosen based on the river's proximity to the Nquthu local municipality, in addition to modelling the resulting changes in flow imposed by the dam. As per Figure 5.7, the proposed Ngxobongo

Dam reduces the flow rate by -17% on average, however, this is acceptable as sufficient water is still released for *CL*. The Blood River could also serve as an ideal site for this proposed dam.

Table 5.4 Optimized water management strategies for adapting to climate change .

	Water Supply Strategies
Short- to Medium-Term Strategies (2020-2050)	Upgrade Ngagane WTP to deliver an extra 30Ml/day
	Increase water abstractions from Dorps Dam to Utrecht WTP from 2 Ml/day to 4 Ml/day
	Increase water allocations from Utrecht WTP to Utrecht local municipality from 2 Ml/day to 4 Ml/day
	Newcastle to receive 33 Ml/day
	Increase Biggarsberg operational capacity to 29.6 Ml/day from 16 Ml/day, and water abstractions from Buffalo River to 25 Ml/day from 13 Ml/day
	Decommission Dannhauser, and *increase operational capacity of Durnacol from 3.5 Ml/day to 5.5 Ml/day*
	Increase allocation from Ngagane WTP to Utrecht local municipality to 20 Ml/day (by 2045)
	Decommission supply from Ngagane WTP to Dannhauser local municipality
Long-Term Strategies (>2050)	Construction of Ncandu Dam with storage capacity = 19.15 million m^3 and yield = 5.04 million m^3
	Construction of Ngxobongo Dam with storage capacity = 27 million m^3 and yield = 19.50 million m^3
	Increase allocation from Ngagane WTP to Utrecht local municipality by an additional 10 Ml/day, making total water allocations 30 Ml/day
	Upgrade the Ngagane WTP to deliver 220 Ml/day instead of 130 Ml/day by 2050

**Individual strategies which are not in italics are not modified*

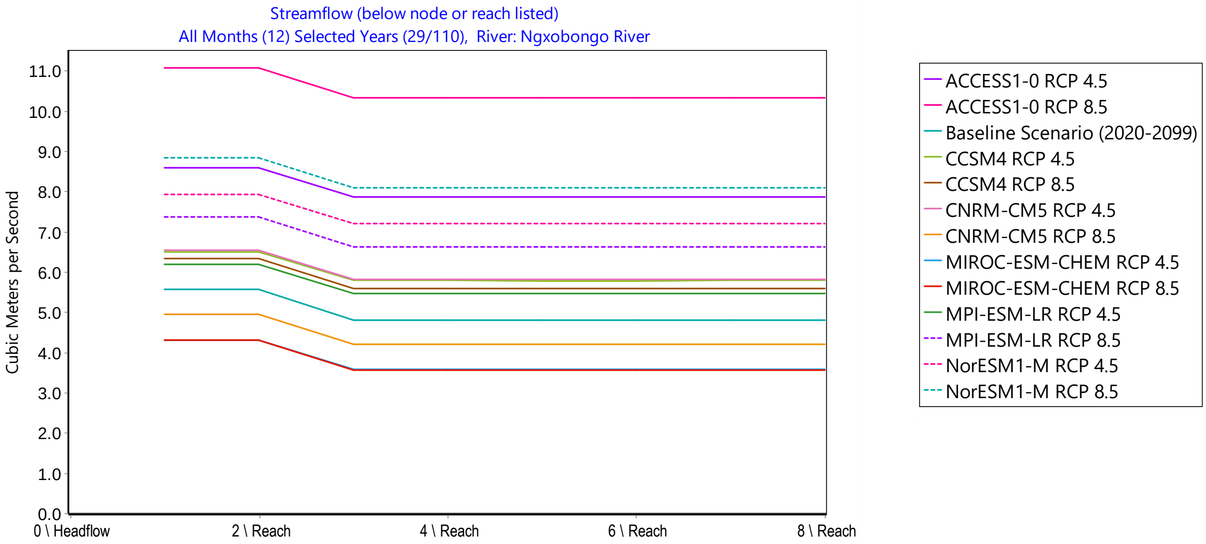


Figure 5.7 Streamflow profile (m^3/second) changes of the Ngxobongo River under the Optimized Policy Scenario (PS-Opt) for far future timeframe (2071-2099).

Hydrological changes

The simulated and projected changes of ET_A under the optimized policy scenario (PS-Opt) reflected the same results as those of the PS scenario, as per Table 5.5. However, the modelled PS-Opt *R* were lower than that of the BAU and PS scenario under both RCP scenarios. This is a result of increasing reservoir and water treatment facility operational capacity, which further produced a commensurate increase in the volume of surface water available in the BR catchment. The anticipated annual increases in reservoir storage quantities are shown in Figure 5.8 as evidence of this.

Table 5.5 Projected surface runoff (Mm^3/annum) under the Business-As-Usual scenario (BAU), Policy Scenario (PS) and Optimized Policy Scenario (PS-Opt) for the historical (1990-2019), near future (2020-2045), mid-future (2046-2070) and far future (2071-2099) periods.

Timeframe	Surface Runoff @ Buffalo River Outlet					
	RCP4.5			RCP8.5		
	BAU	PS	PS-Opt	BAU	PS	PS-Opt
Historical	3026.1	3026.2	3026.2	3080.4	3080.4	3080.4
Near future	3032.8	3032.3	3027.3	3024.3	3024.1	3019.2
Mid-future	3044.6	3044.8	3020.1	3468.3	3466.7	3442.2
Far future	3265.7	3206.1	3182.6	3523	3465.3	3441.6

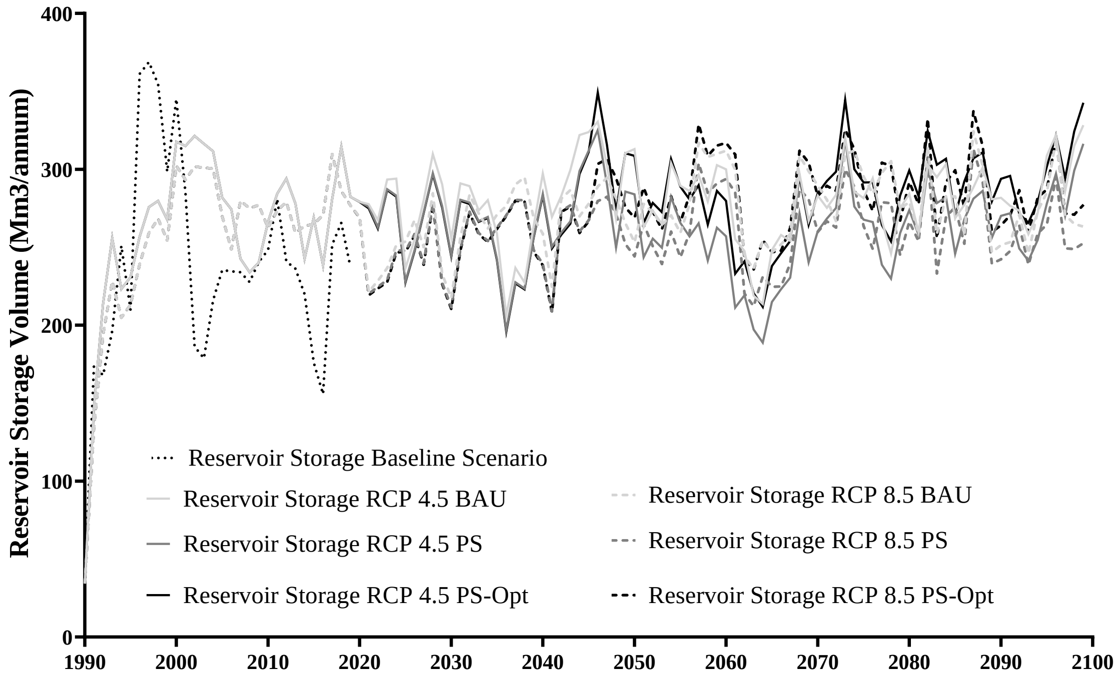
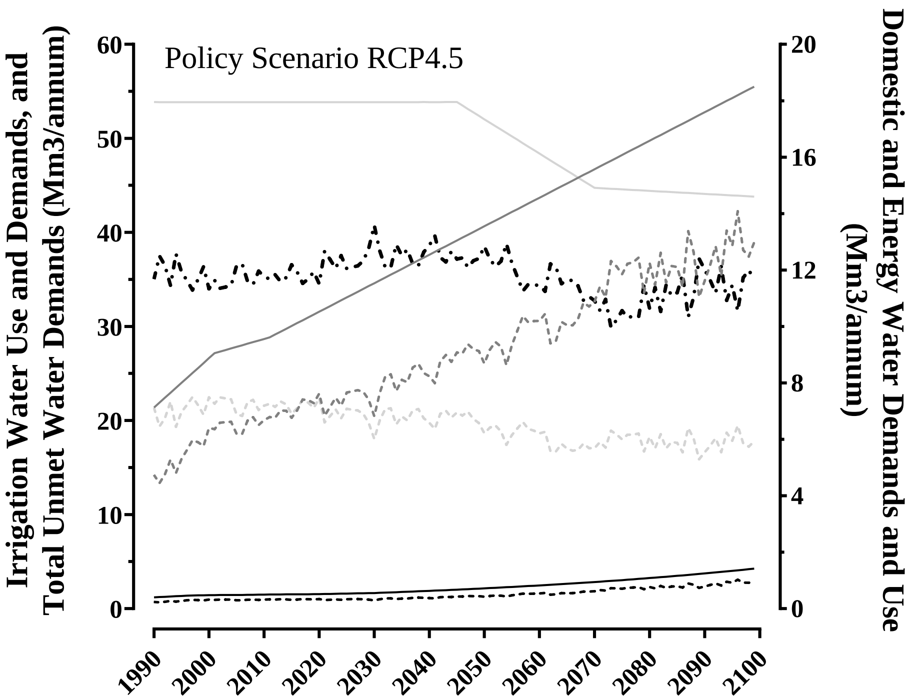


Figure 5.8 Reservoir storage volume (Mm^3/annum) under the Business-As-Usual scenario (BAU), Policy Scenario (PS) and Optimized Policy Scenario (PS-Opt)

Water provisions

The total unmet supply requirements are expected to differ significantly between the PS and PS-Opt scenarios, particularly in the far future. This is attributable to the proposed Ngxobongo Dam, which is anticipated to boost water supply delivered in low-priority regions in the mid- and far-future. In Figure 5.9, we observe that the average water supply delivered in the far future period for domestic, energy generation and irrigation are modelled to increase by 20%, 27% and 70%, respectively. As a consequence, a significant drop in the total unmet water demands is anticipated to take place, from 35 Mm^3/annum in the near-future, to 5 Mm^3/annum in the mid- and far-future periods. The statistical results in Table 5.6 further emphasize that the PS-Opt has a significant impact in meeting the catchment's water needs. In terms of agricultural production changes, maize production is expected to benefit the most from the PS-Opt scenario even under worsened CC conditions, as shown in Figure 5.10. Towards the end of the 21st century, 95% of the 3149 hectares suitable for irrigated maize cropping is expected to be under full irrigation.


Policy Scenario RCP4.5
Irrigation Water Use and Demands, and Total Unmet Water Demands (Mm3/annum)
Domestic and Energy Water Demands and Use (Mm3/annum)
0
10
20
30
40
50
60
0
4
8
12
16
20
1990
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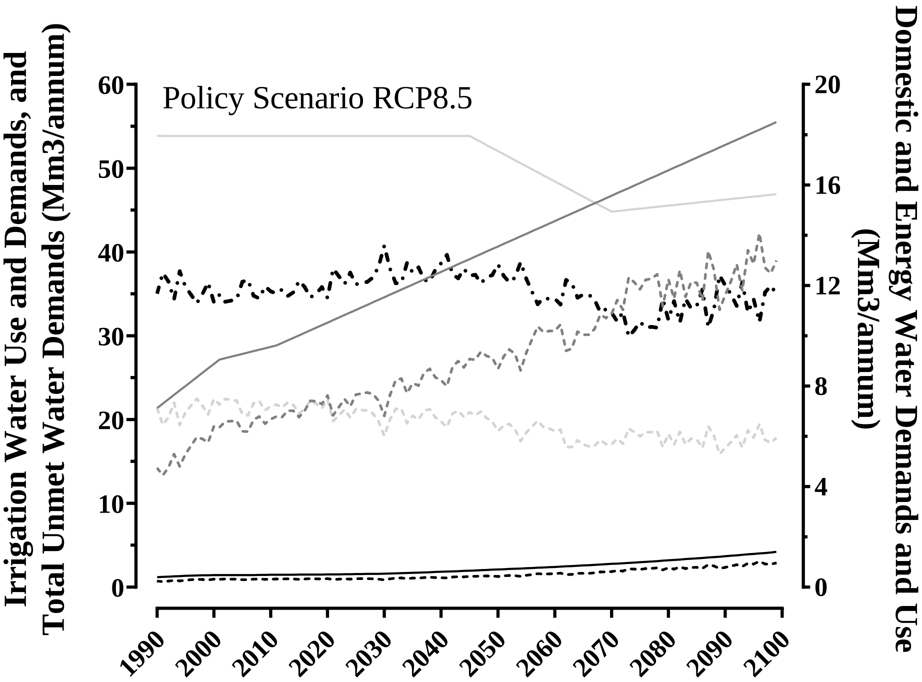
(a)


Policy Scenario RCP8.5
Irrigation Water Use and Demands, and Total Unmet Water Demands (Mm3/annum)
Domestic and Energy Water Demands and Use (Mm3/annum)
0
10
20
30
40
50
60
0
4
8
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1990
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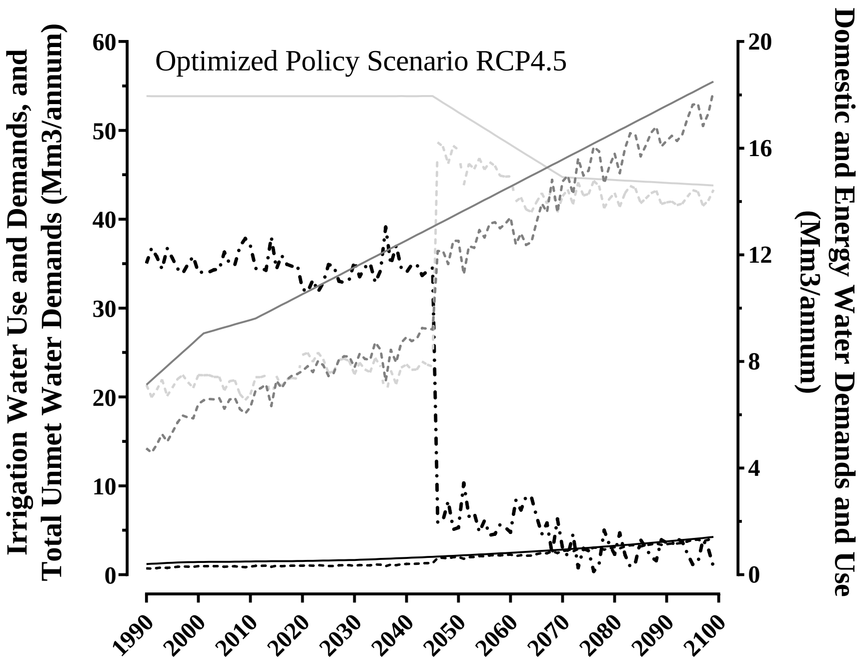

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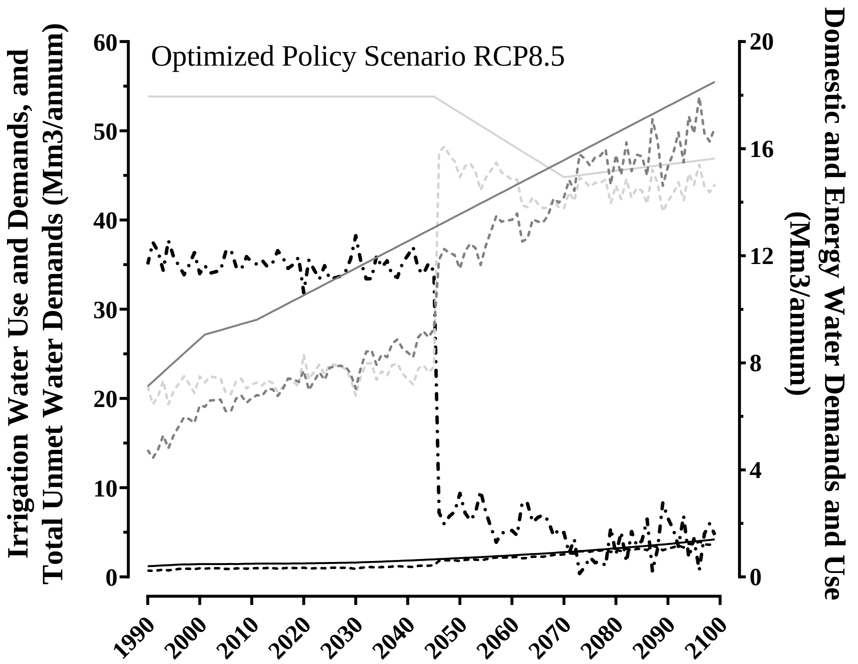


(d)

Domestic Water Demands
Energy Water Demands
Irrigation Water Demands
Domestic Water Use
Energy Water Use
Irrigation Water Use
Total Unmet Demands

Figure 5.9 Total unmet water demands, and irrigation, domestic and energy water use and demands for period 1990-2099 under (a) PS: RCP4.5, (b) PS: RCP8.5, (c) PS-Opt: RCP4.5 and (d) PS-Opt: RCP8.5.

Table 5.6 Significant difference tests of the Business-As-Usual scenario (BAU) and Optimized Policy Scenario (PS-Opt)

			RCP4.5	**RCP8.5**
			Total Unmet Demands	**Total Unmet Demands**
Normality Test	**Shapiro**	**BAU**	**0.30**	**0.55**
		PS	**<0.0001**	**<0.0001**
Parametric t-test	**Welch**		**-**	**-**
	F-test		**-**	**-**
Non-parametric t-test	**Mann-Whitney**		**<0.0001**	**<0.0001**

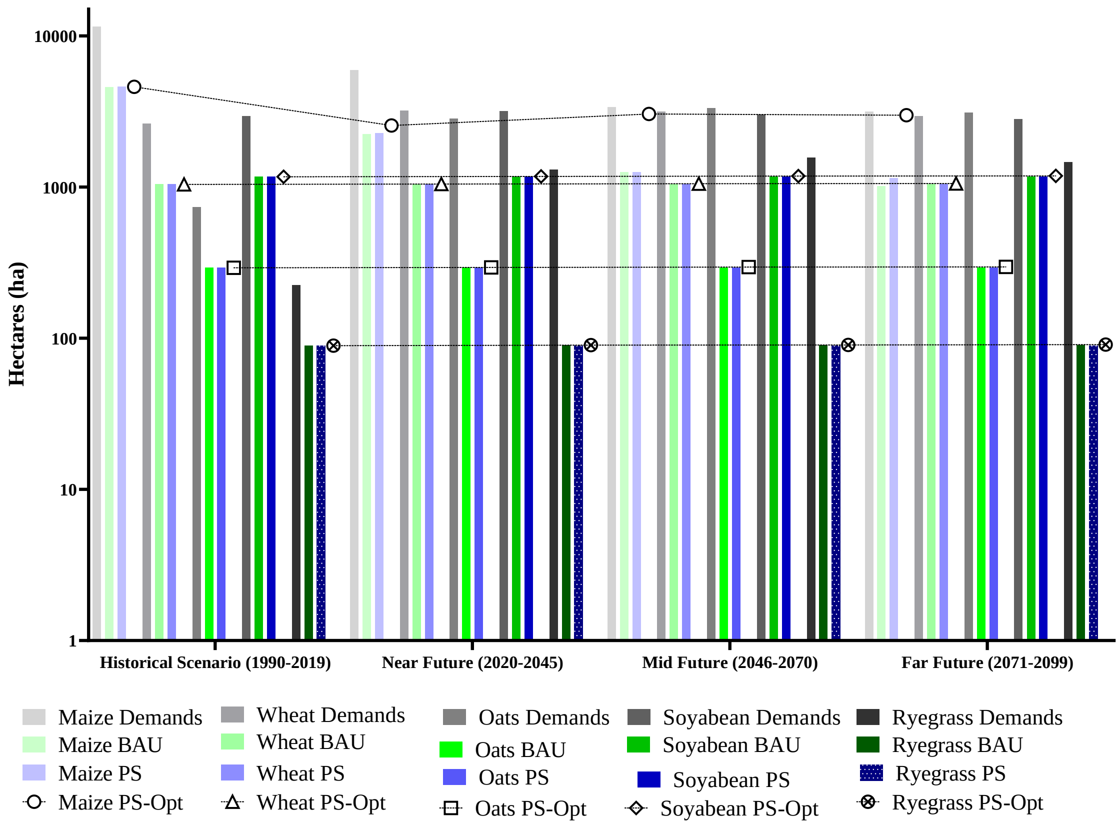
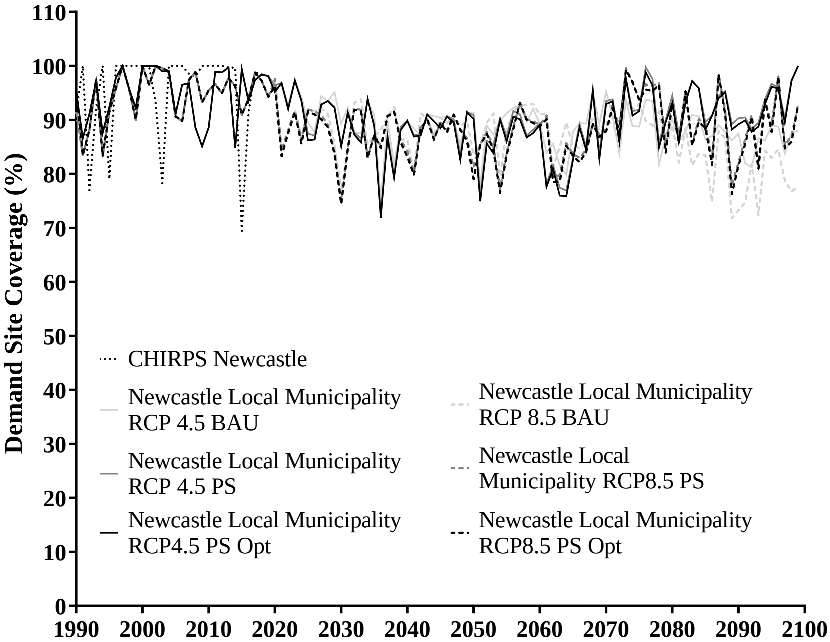


Figure 5.10 Changes in irrigated hectares under the RCP8.5 scenario for the Business-As-Usual scenario (BAU), Policy Scenario (PS) and Optimized Policy Scenario (PS-Opt).

5.3.5 Demand site coverage changes

As shown in Figure 5.11, for PS-Opt, the Newcastle local municipality's *Dcov* slightly decreased by -7.8% and -9.4% during the near- and mid-future, respectively. This is mainly due to the increased water allocations of the Ngagane WTP to Utrecht local municipality, which in turn decreased supply to Newcastle. Nonetheless, the minimum *Dcov* value of 70% is comparatively higher than the historical averages of low-priority regions, and this trade-off significantly improves the demands met in Utrecht local municipality. The *Dcov* of Utrecht local municipality markedly improved under PS-Opt, from 14% under both RCPs in the PS scenario, to 37%, 72% and 90% in the near-, mid- and far-future respectively. Similarly, the proposed Ngxobongo dam significantly improved the *Dcov* of Nquthu, increasing it from an average of 10% to 100% in the mid- and far-future timeframes, respectively.



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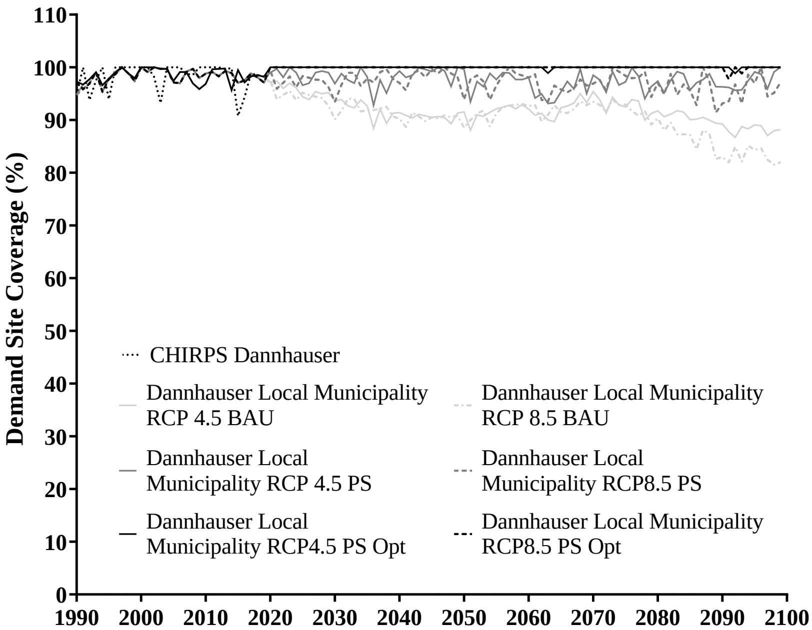

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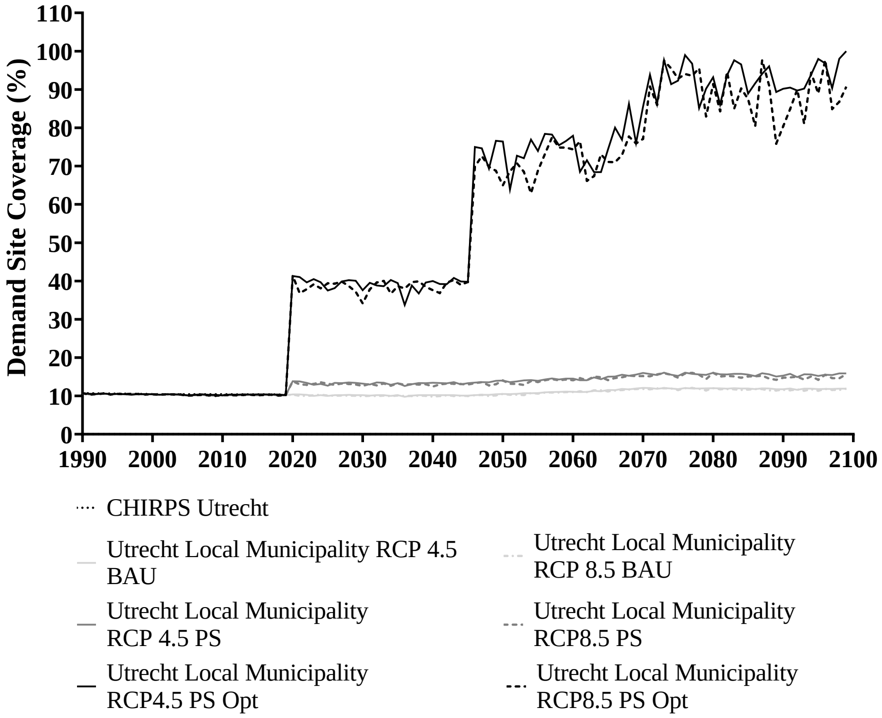

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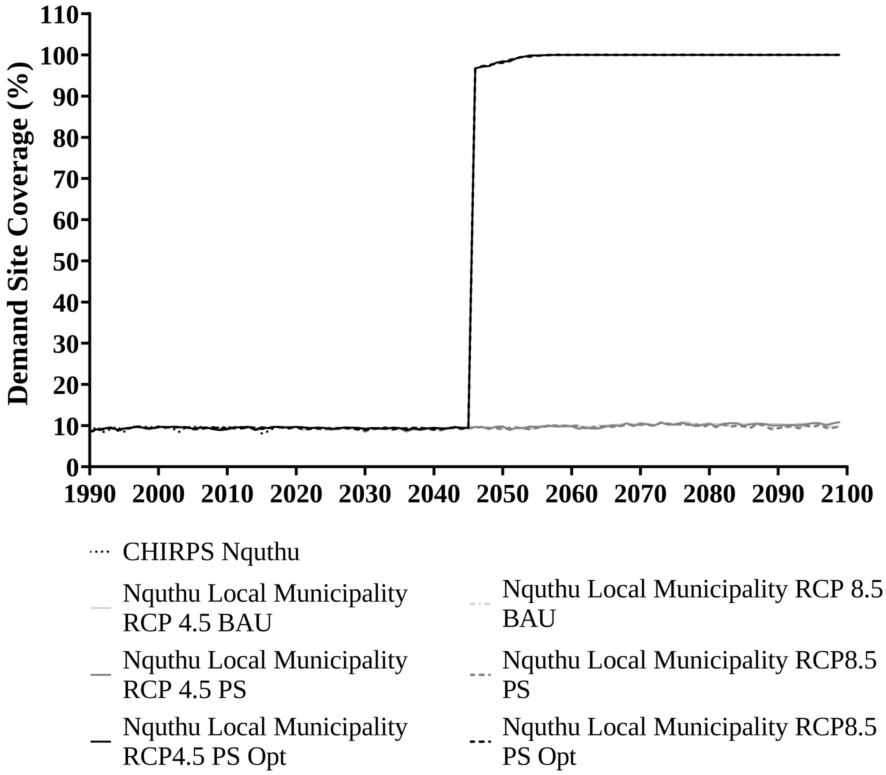

(d)

Figure 5.11 Demand site coverage (%) annual variations for the (a) Newcastle, (b) Dannhauser, (c) Utrecht and (d) Nquthu local municipalities, from 1990 to 2100 under the Business-As-Usual scenario (BAU), Policy Scenario (PS) and Optimized Policy Scenario (PS-Opt)

5.3.6 Reliability changes from PS-Opt

In the Biggarsberg, Durnacol, Ngagane and the Vant's Drift WTPs, the *RE* declined under PS-Opt. This is inevitable considering the additional water required from these individual sources. However, for the Qudeni and Utrecht WTPs, *RE* is 0%. Such suggests that their sources, the Gubazi River and the Dorpspruit (Dorps) Dam respectively, cannot supply 100% of their yearly water requirements. As WTPs are transmission units, this is permissible since other transmission units that provide water to the same demand site can compensate for water delivery deficits. With reference to the demand sites, as per Figure 5.12, all local municipalities' *RE* increased under the PS-Opt, with the Dannhauser local municipality anticipated to have the highest *RE* of 93%. Despite the decreased *Dcov*, the Newcastle local municipality's *RE* still remains at 40%. The water allocation and capacity changes under PS-Opt in Utrecht and Nquthu local municipalities' resulted in significant *RE* improvements, which increased from 0% under the BAU and PS, to 20% and 42%, respectively.

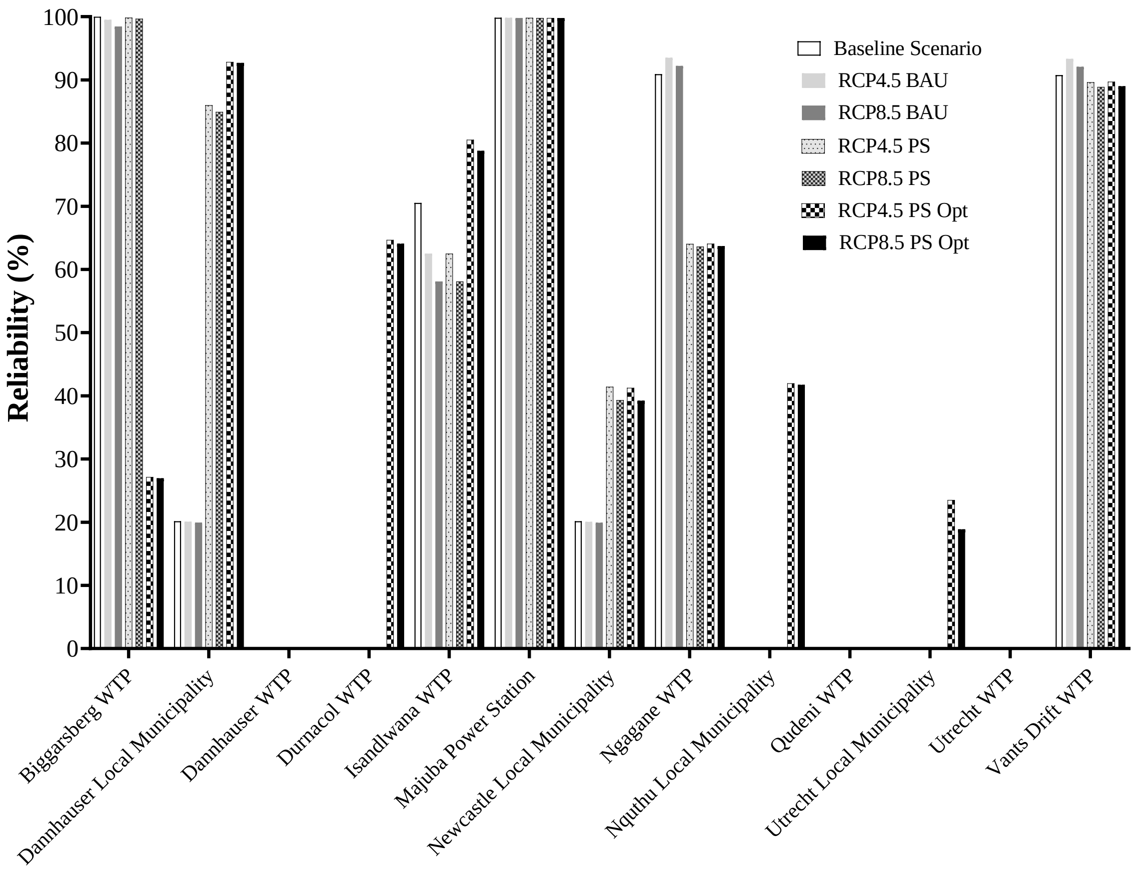

Figure 5.12 The reliability of the Buffalo system from 01/01/1990 to 31/12/2099 under the Business-As-Usual scenario (BAU), Policy Scenario (PS) and Optimized Policy Scenario (PS-Opt).

5.4 Conclusions and Recommendations

Strategies for adapting to CC ought to be premised on a comprehensive understanding of the dynamic interactions and processes that occur within water resource systems, taking into consideration the system's socioeconomic and environmental aspects in addition to its hydrological characteristics. As part of this study's efforts to assess CC impacts and existing policy interventions on the BR catchment's water system's performance, with the intent of designing improved adaptation strategies, the WEF nexus' CLEWS modelling framework assisted in the quantitative exploration of interactions between water, energy, and food systems, as well as CC. The WEAP, LEAP, and gAEZ analytical models successfully provided some insight into what could transpire once the water resources development plans are fully implemented under CC conditions throughout the duration of the 21st century.

In conclusion, the proposed policy interventions do not adequately and equally provide and distribute water to the catchment's water users under climate change. The findings suggest that existing CC and water resources policy plans are centred around increasing the water supply capacity and meeting the projected domestic water requirements in high-priority water allocation sites. Therefore, even with the highly anticipated increases in the BR catchment's precipitation modelled by six GCMs, and increased SWA, the proposed policy actions are predicted to exacerbate the discrepancies in water distribution, making the water supply system's reliability in providing domestic, agricultural and energy water demands in low-priority regions very low.

Additionally, we reject the null hypothesis which states that optimized CC water management strategies will not alter the relationship between available water supply and water demands of the catchment under climate change. The optimized CC strategies not only increased SWA, but also improved equality in water distribution among sectors, this being noted by the increased *Dcov* and *RE* of the water system in providing water demands to all local municipalities. As such, it is recommended that policymakers adapt the specifications of optimized policy strategies which correspond to the goals of the proposed policy strategies without design specifications, and to also consider the re-allocation plans proposed by the optimized policy strategies developed in this research. The vast majority of optimized policy strategies necessitate the rehabilitation of transmission pipelines and the construction of reservoirs. Therefore, it is also proposed that detailed feasibility and technical studies be conducted to investigate the practicability of the optimized strategies.

In this CLEWS analysis, data was transferred manually from one model to the next, which increases error risks. Future research is therefore recommended to soft-link WEAP, LEAP, and AEZ models to minimize data transmission errors. The WEAP model's accuracy depends on the amount of available information and its degree of detailedness. As such, since the analysis of historical precipitation changes was made based on data and information gathered from gridded climatic data, the use of recorded hydrological data, preferably at quinary scale, is highly recommended. Furthermore, future studies should include other components of the water balance, such as groundwater and changes in soil moisture, as well as the inclusion of all dams within the catchment, for more accurate estimates of hydrological changes. Nevertheless, the outcomes from this study can still be used for comparison purposes as the calibration and validation statistics performed using the WEAP streamflow outputs indicate that the model sufficiently simulated the BR catchment's hydrology.

5.5 References

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6 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Due to their inherently low adaptative capacity and, more importantly, the lack of inclusion of climate change adaptation strategies in the development plans, developing regions are heavily impacted by climate change. Given the complexity, variability, and immediacy of climate change, sustainable adaptation solutions should not just concentrate on mitigating its impacts but also consider the larger societal context in which these changes will occur, and the consequential impact on the security of water, energy, and food. This thesis, therefore, explored the Water-Energy-Food (WEF) nexus approach in developing climate change adaptation strategies, as the WEF nexus methodology encourages the integration of WEF resource sustainability under climate change. The Buffalo River catchment, located in KwaZulu-Natal, South Africa, presented an excellent case study as recent reports indicated that the catchment's water supply facilities are unreliable and anticipated not to meet water demands by 2050.

6.1 Summary

It is projected that climate change will result in increased precipitation throughout the 21st century, amounting to more evapotranspiration and surface runoff. However, owing to the limitations imposed by the catchment's current surface water storage, the excess precipitation that could be used to alleviate the rising unmet demand within the catchment is not captured and stored; instead, it accumulates as surface runoff at the Buffalo River's outlet. Using the WEF nexus as a resource management tool, climate change adaptation strategies were developed, which proved to increase the capacity of the water supply system within the catchment, decrease unmet demands, and increase the Buffalo system's reliability in meeting the catchment's increasing water demands. The following sections provide concise conclusions of the study and key recommendations for future works on climate change adaptation and water resources management.

6.2 Conclusions

6.2.1 Climate change impacts on surface water availability

From a scenario-based analysis of climate change, the study concludes that climate change alters and increases the surface water availability within the catchment. This was proven to be a result of increased precipitation, which consequently increase the frequency with which reservoir storage volumes are replenished, thus correspondingly increasing surface water availability (see Chapter 3).

6.2.2 Reliability of water resources under climate change

Even with the anticipated increased surface water availability under climate change conditions, the total water system's operational capacity of 304 Ml/day was insufficient to provide the catchment's current water demands. From a water demand perspective, through a WEF nexus lens, study findings projected the total irrigation water requirements to decrease under climate change as a result of reduced land suitability for crop production, and energy generation water requirements to increase, predominantly due to the sporadic growth of the catchment's population. Nonetheless, the resultant water demands, which also accounted for domestic water requirements, increased throughout the projection period, with agricultural water use making up a vast majority of the demands. As such, from investigating the water supply-demand relationship under climate change, the study concluded that the current surface water storage capacity is inadequate in meeting the growing water demands of the catchment, more so demands from low-priority agriculture-intensive regions as more than 90% of their demands were not met throughout the study period (see Chapter 4)

6.2.3 Developing integrated climate change adaptation strategies

In developing climate change adaptation strategies, already-existing water resources development strategies were assessed, and the study found that they are heavily focused on allocating large quantities of water to densely populated regions to meet demands by the domestic sector, thus rendering them unsustainable as such sector-specific management of water resources could potentially cause conflict among other water users and reduce the security of energy and food. By optimizing these existing water policy plans through the use of the Climate, Land-use, Energy and Water Strategies (CLEWS) approach, which is a WEF nexus conceptual framework, the developed strategies not only improved the catchment's water supplies, but also increased the reliability of the water system in providing water to domestic, as well as energy and agricultural sectors within the catchment. Thus, the study concludes that the WEF nexus modelling tools successfully identified adaptation strategies that possess potential in merging the water supply-demand gap under climate change (see Chapter 5) .

6.3 Recommendations

The study sought to investigate the use of the WEF nexus in developing climate change adaptation strategies in the Buffalo River catchment. The investigation yielded the following recommendations for future studies:

(a) The study used statistically downscaled climate output precipitation data, which lacks spatial resolution compared to dynamically downscaled data. Therefore, it is encouraged that future studies on climate change use dynamically downscaled data, which is high-resolution and contains factors that affect rainfall distribution, such as local frontal systems, topographic channelling of flow, and the interaction of atmospheric dynamics with hydrometeor microphysics.

(b) This study also used six GCMs; thus, it is crucial to emphasize that they do not completely represent the entire CMIP5 ensemble of more than 70 GCMs. Future studies are encouraged to include additional GCMs from the most recent CMIP6 to analyse climate change projections.

(c) Manual data transmission from one model to the next was used in the CLEWS approach, which leaves a possibility for error. Future research is therefore recommended to soft-link WEAP, LEAP, and AEZ models to decrease errors and time taken to run scenarios.

(d) Due to the unavailability of data related to energy consumption within the households of the catchment, national statistics were utilized. Therefore, future studies are encouraged to conduct surveys on household energy consumption in the catchment for more accuracy in computing energy demands.

Nonetheless, based on the model evaluation statistics, the WEAP model, which is the primary model used to simulate the catchment's hydrology, achieved satisfactory results. Researchers investigating the Buffalo River catchment's WEF resources and policymakers and decision-makers are encouraged to consider the study's findings when evaluating the degree to which climate change may occur and disrupt the catchment’s functionality. The study also strongly endorses the WEF nexus approach for examining the effects of climate change on WEF resources since it effectively emphasizes the relationships and linkages among these resources.

A. APPENDIX

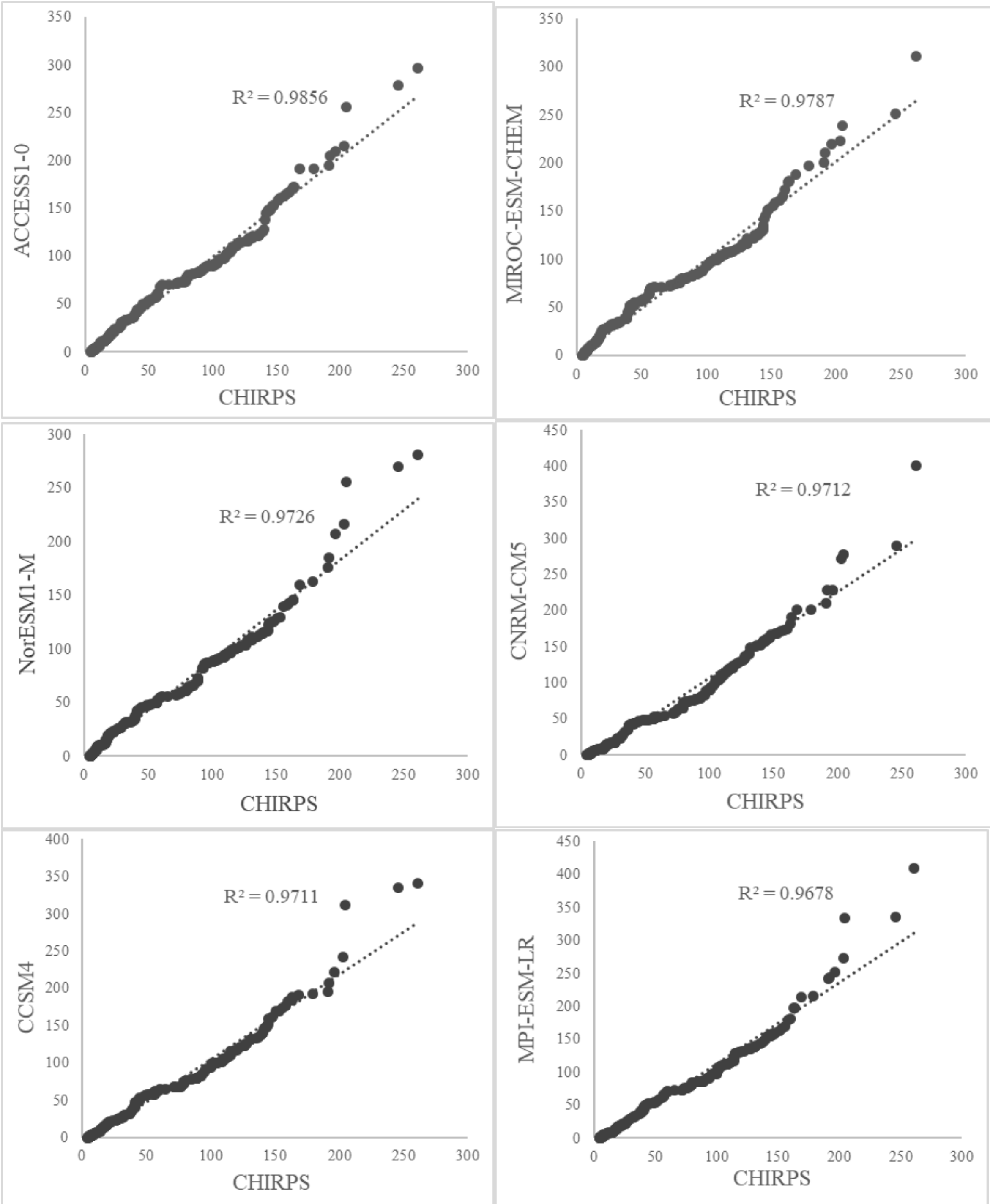


Figure A.1 Comparison of selected GCM's precipitation data and CHIRPS precipitation data for period 01/01/1990 to 31/12/2005.

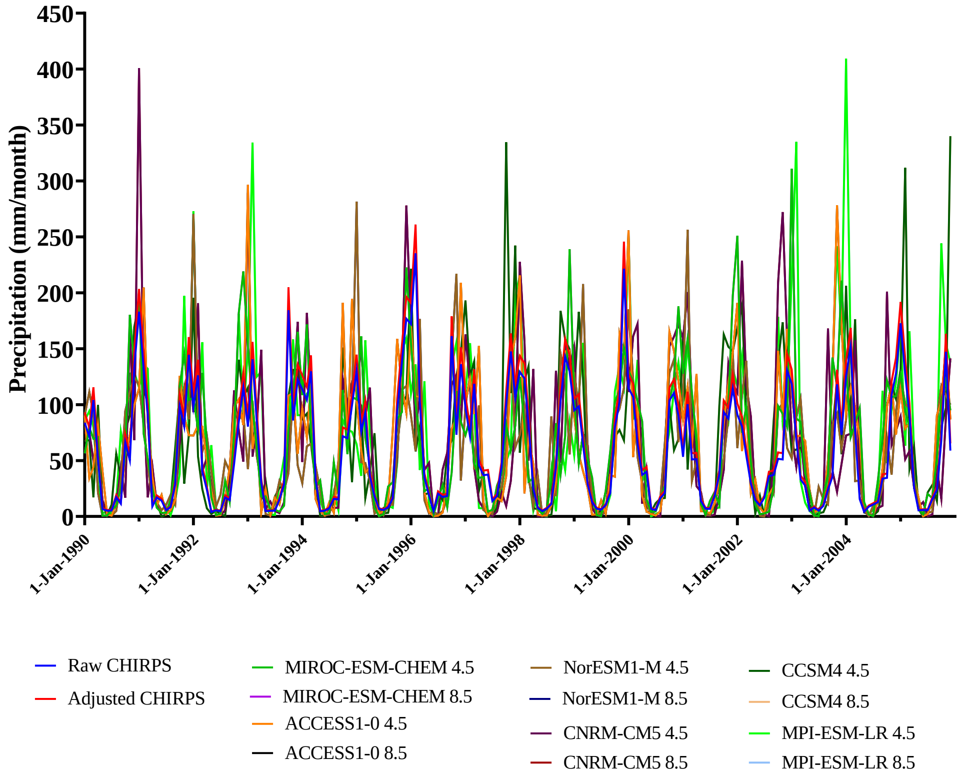


Figure A.2 CHIRPS precipitation data vs raw GCM precipitation projections under RCP4.5 and RCP8.5 for period 01/01/1990 to 31/12/2006.

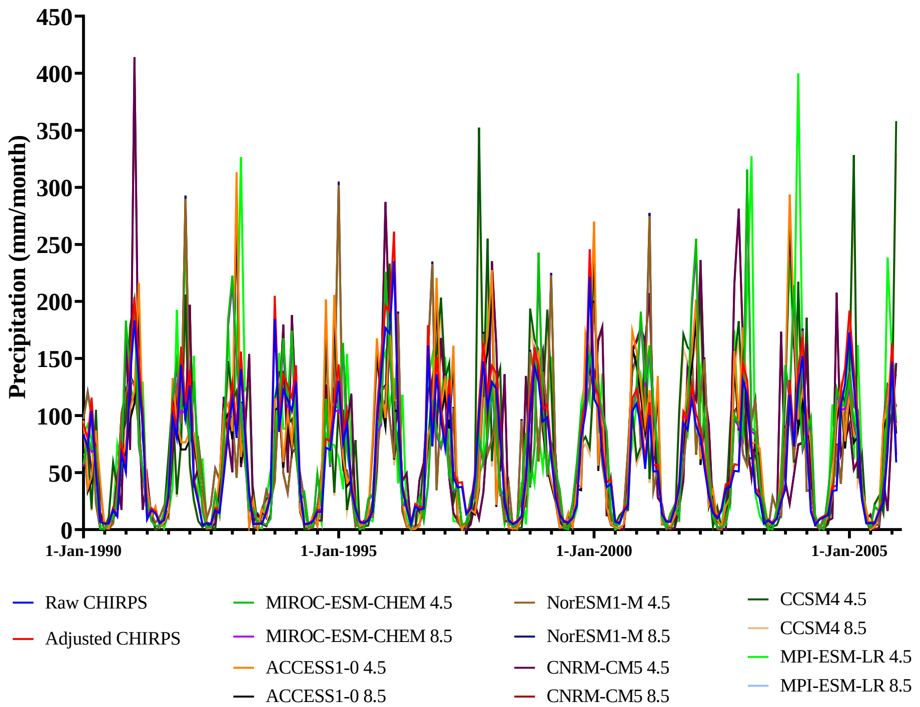


Figure A.3 CHIRPS precipitation data vs bias-corrected GCM precipitation projections under RCP4.5 and RCP8.5 for period 01/01/2006 to 31/12/2019.

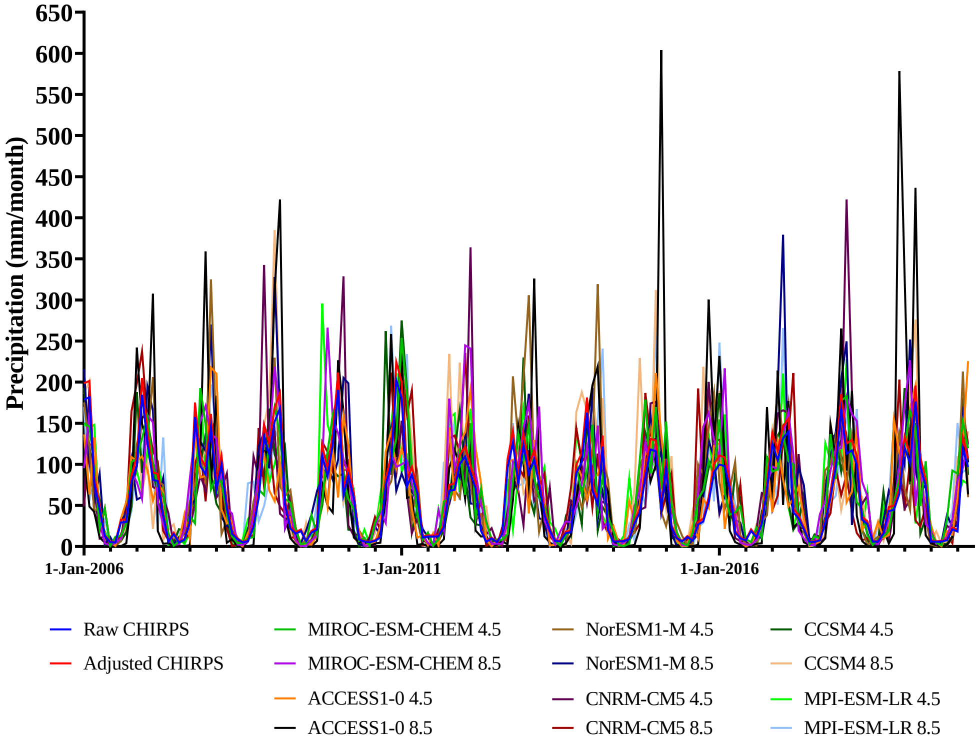


Figure A.4 CHIRPS precipitation data vs raw GCM precipitation projections under RCP4.5 and RCP8.5 for period 01/01/2006 to 31/12/2019.

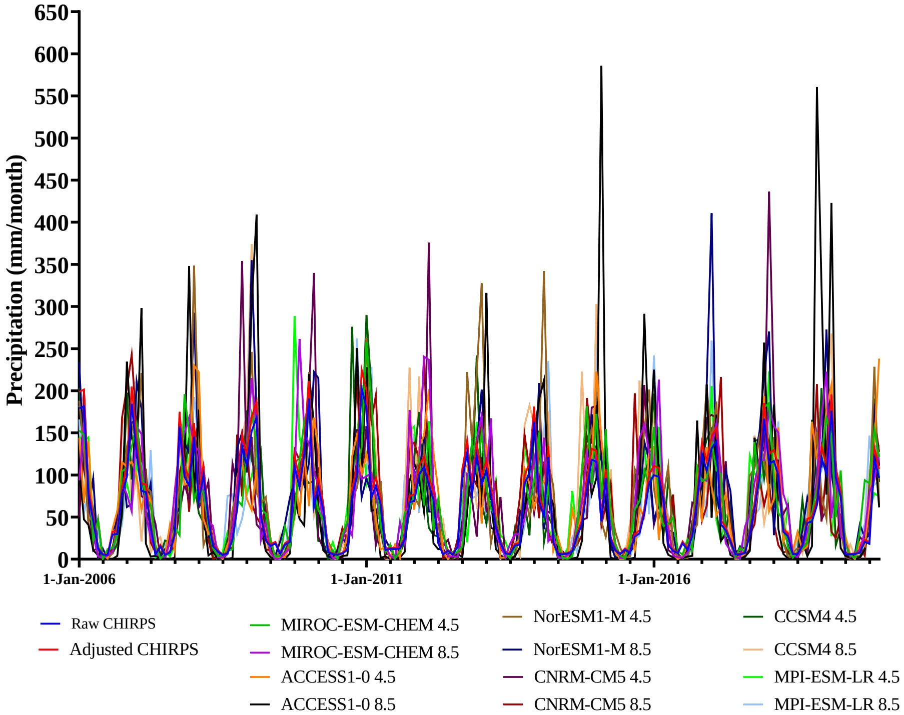


Figure A.5 CHIRPS precipitation data vs bias-corrected GCM precipitation projections under RCP4.5 and RCP8.5 for period 01/01/2006 to 31/12/2019.

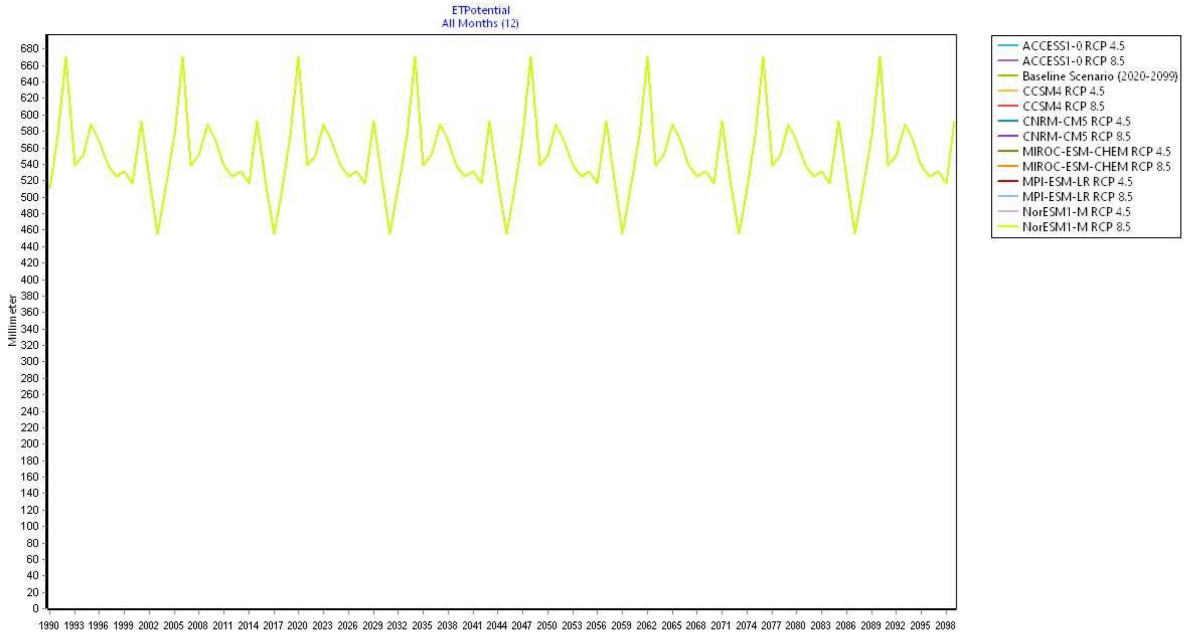


Figure A.6 Reference evapotranspiration in mm/annum for the period 1990-2099 (Jiang *et al.*, 2020)

Table A.1 Spatial data of dams within the Buffalo River catchment (DWS, 2018)

No of dam	Name of dam	Quaternary Drainage Area	Local Municipality	Completion date	River or Watercourse
V300/02	Zaaihoek Dam	V31A	Utecht	1988	Slang River
V303/36	Grootspruit Dam	V32G	Utrecht	9876	Grootspruit River
V302/47	Kwaggasdrift no.1 Dam (Dorps Dam)	V32D	Utrecht	1984	Buffalo River Tr.
V300/08	Amcor Dam	V31J	Newcastle	1959	Ncandu River
V300/04	Ntshingwayo Dam (Chelmsford Dam)	V31E	Newcastle	1982	Ngagane River
V301/33	Torrington Dam	V31E	Newcastle	-	Ngagane River
V302/31	Donald McHardy Dam	V32E	Glencoe	1970	Sterkstroom River
V300/12	Verdruk Dam	V32E	Dundee	1934	-
V302/32	Upper Mpati Dam	V32E	Dundee	1880	Mpate Stream
V302/33	Lower Mpati Dam	V32E	Dundee	2001	Mpate Stream
V300/11	Tom Worthington Dam	V32E	Dundee	1955	Ngobiya River
V302/52	Sandspruit-Wilderness Dam	V32E	Dundee	2003	Sandspruit River
V302/34	Preston Pan Dam	V32E	Dundee	1970	Sterkstroom River

Table A.2 Physical data for dams in the Buffalo River catchment.

No of dam	Name of dam	Wall Height (m)	Crest Length (m)	Storage Capacity (1000 m^3)	Surface area (ha)	Net Evaporation (mm)
V300/02	Zaaihoek Dam	43.5	527	185000	1244.6	1440
V303/36	Grootspruit Dam	12	0	500	15	-
V302/47	Kwaggasdrift No.1 (Dorps Dam)	10	500	1000	25	-
V300/08	Amcor Dam	10	590	480	28	-
V300/04	Ntshingwayo (Chelmsford Dam)	23	1549	211258	3610.1	1450
V301/33	Torrington Dam	6.7	0	128	7.4	-
V302/31	Donald McHardy Dam	12	354	2680	71	1500
V300/12	Verdruk Dam	11	86	1290	29	1500
V302/32	Upper Mpati Dam	18	293	264	5	1500
V302/33	Lower Mpati Dam	13	171	128	2	1500
V300/11	Tom Worthington Dam	14	144	1890	55	1500
V302/52	Sandspruit-Wilderness Dam	12.5	0	800	0	-
V302/34	Preston Pan Dam	6.3	230	268	13	1500
Source		**(DWS, 2018)**				**(uMgeni, 2020)**

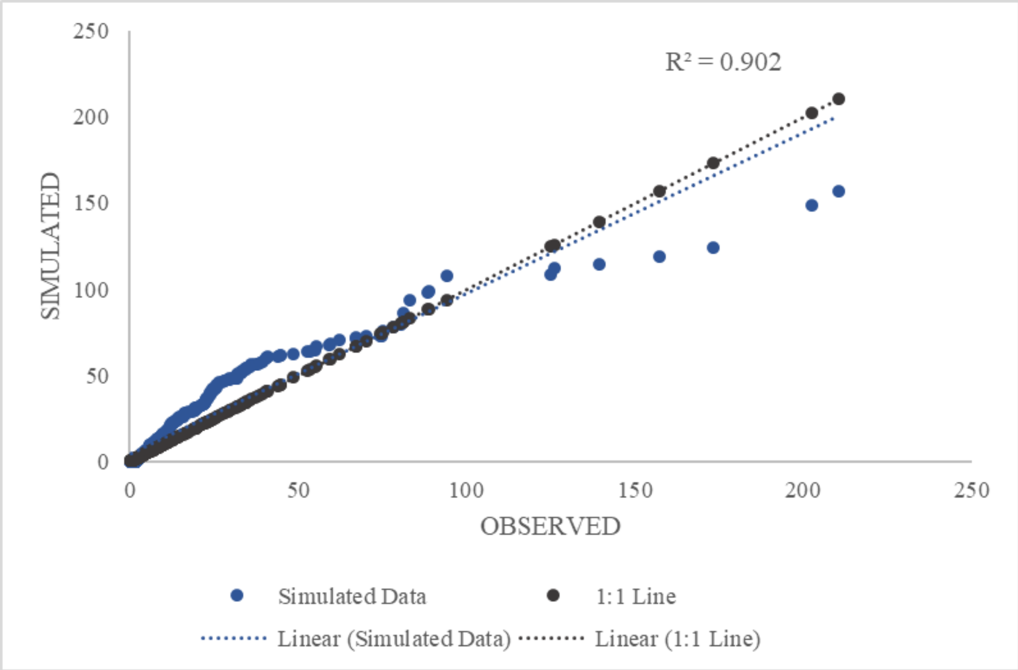


Figure A.7 Comparison of the CHIRPS simulated monthly streamflow values and the observed at the Buffels on Tayside (Station no.: V3H010) for the period 01/01/1990 to 31/12/2019.

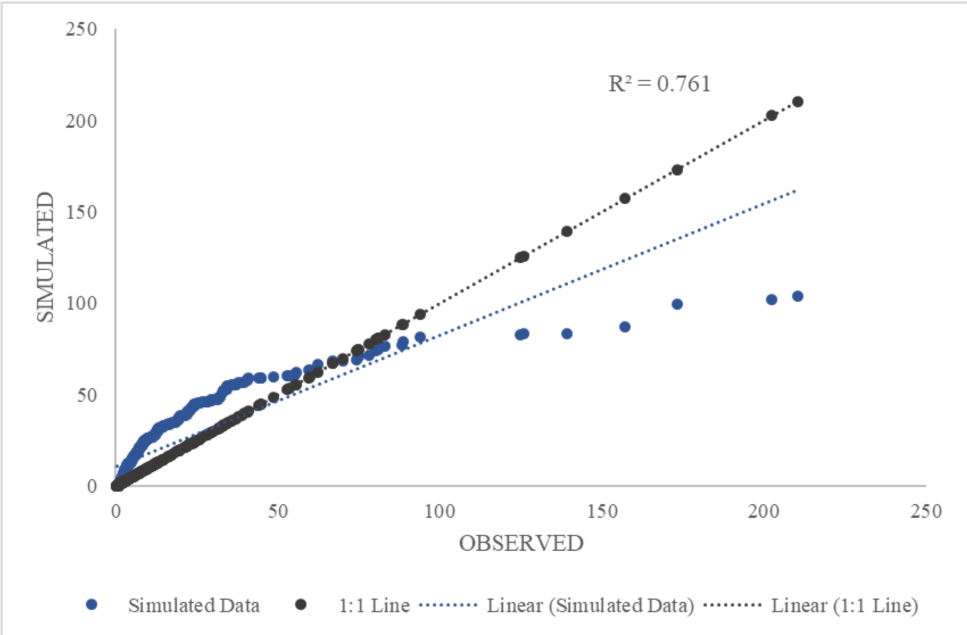


Figure A.8 Comparison of the RCP4.5 GCMs' average ensemble simulated monthly streamflow values and the observed at the Buffels on Tayside (Station no.: V3H010) for the period 01/01/1990 to 31/12/2019.

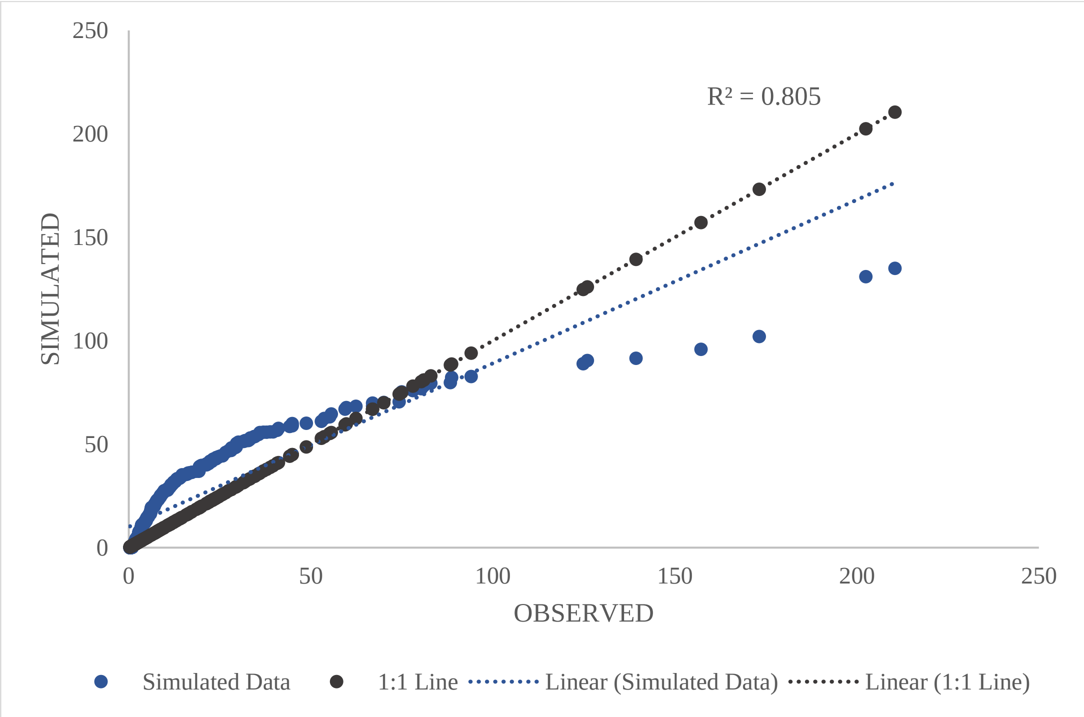


Figure A.9 Comparison of the RCP8.5 GCMs' average ensemble simulated monthly streamflow values and the observed at the Buffels on Tayside (Station no.: V3H010) for the period 01/01/1990 to 31/12/2019.

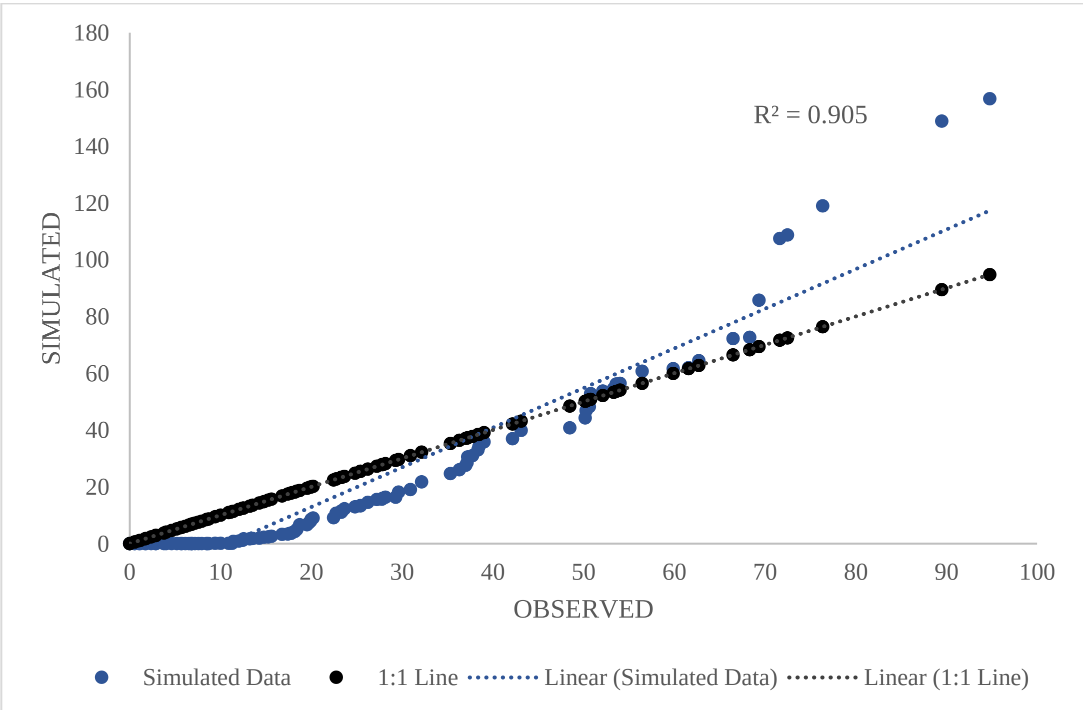


Figure A.10 Comparison of the CHIRPS simulated monthly streamflow values and the observed at Buffels River Return Flow @Schurvepoort for the period 01/01/1994 to 31/12/2002.

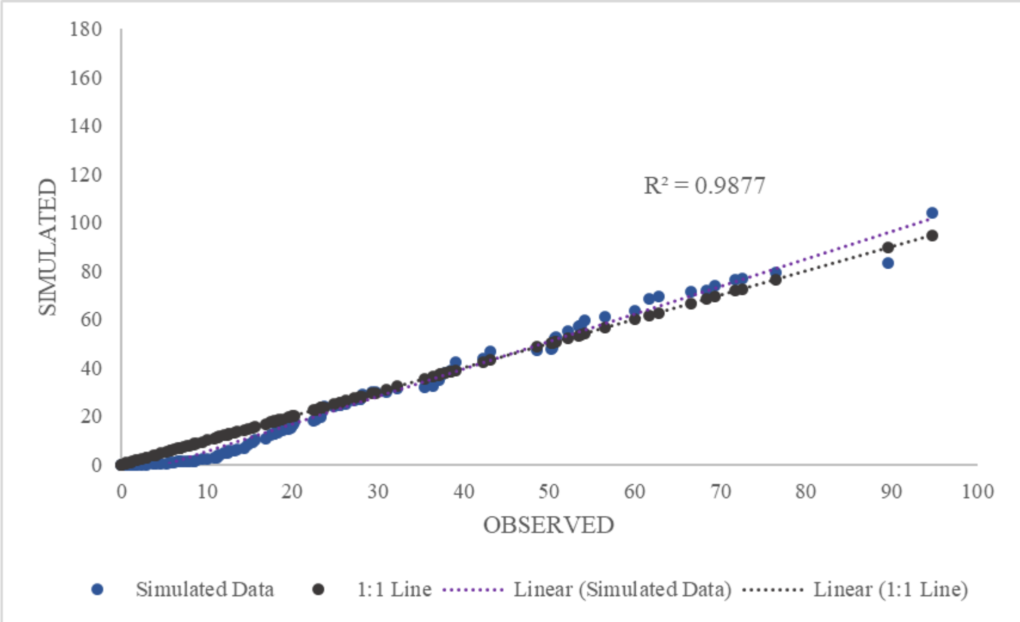


Figure A.11 Comparison of the RCP4.5 GCMs' average ensemble simulated monthly streamflow values and the observed at Buffels River Return Flow @Schurvepoort for the period 01/01/1994 to 31/12/2002.

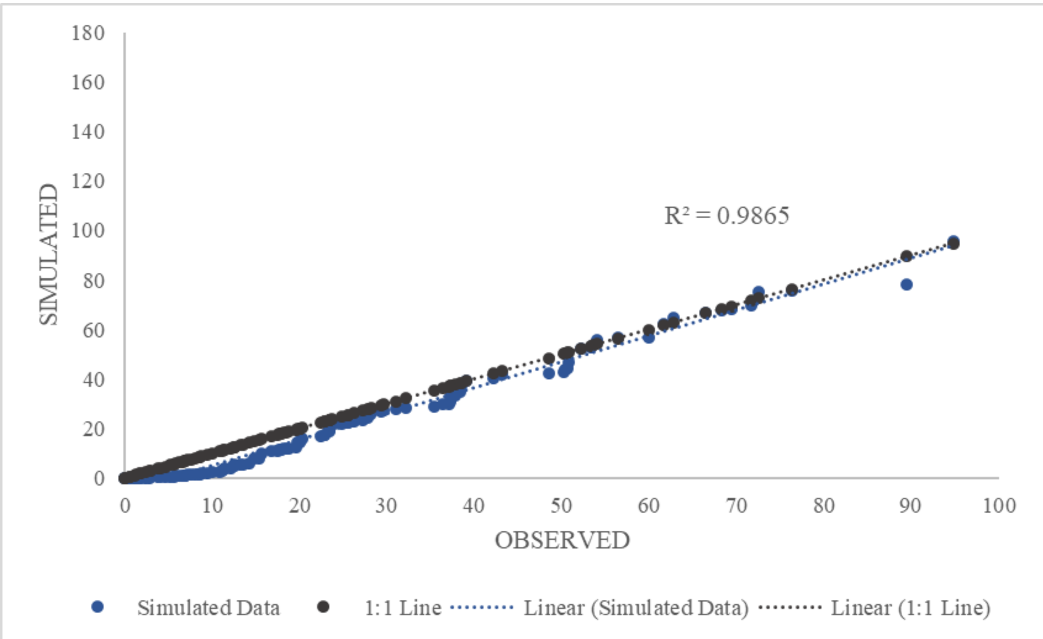


Figure A.12 Comparison of the RCP8.5 GCMs' average ensemble simulated monthly streamflow values and the observed at Buffels River Return Flow @Schurvepoort for the period 01/01/1994 to 31/12/2002.

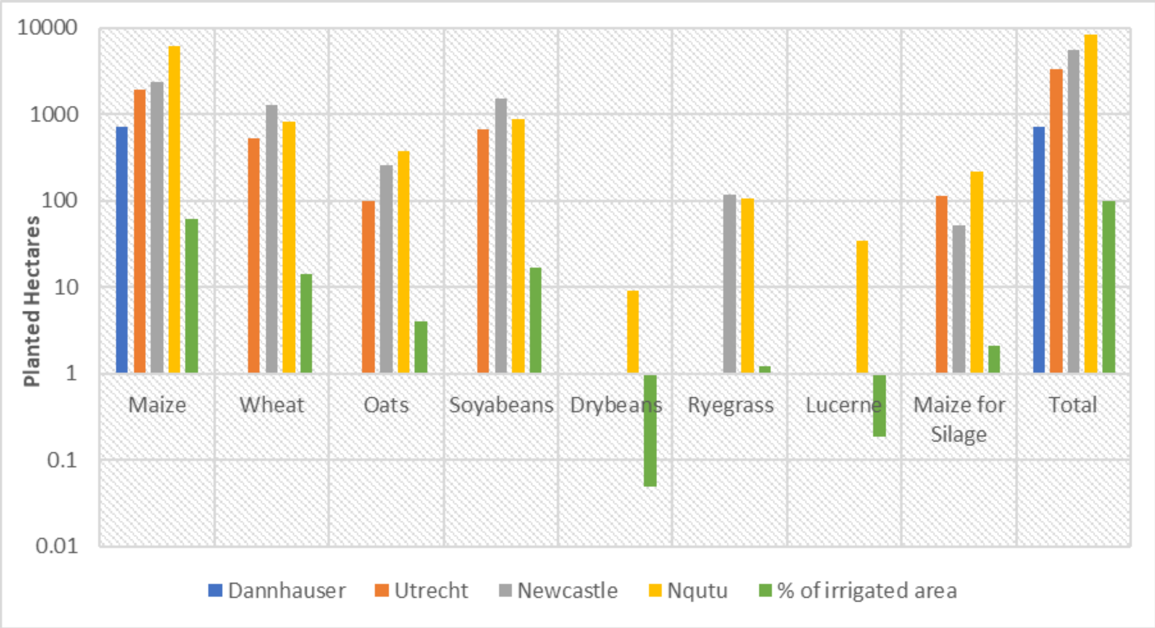


Figure A.13 Planted hectares (StatsSA, 2017)

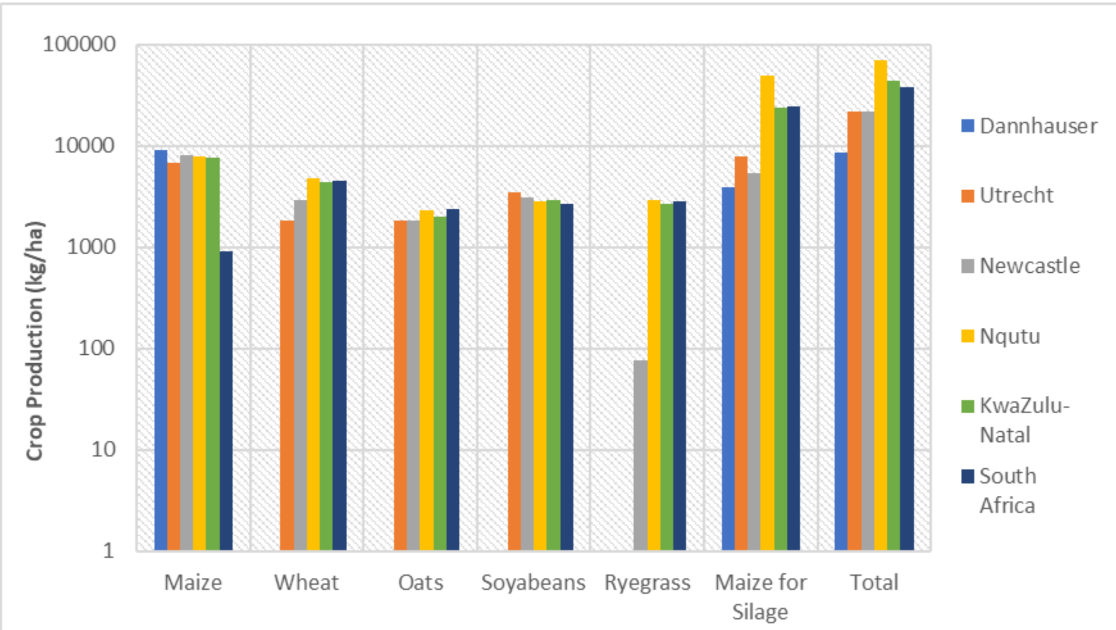


Figure A.14 Irrigated commercial crop production (kg/ha) (StatsSA, 2017)

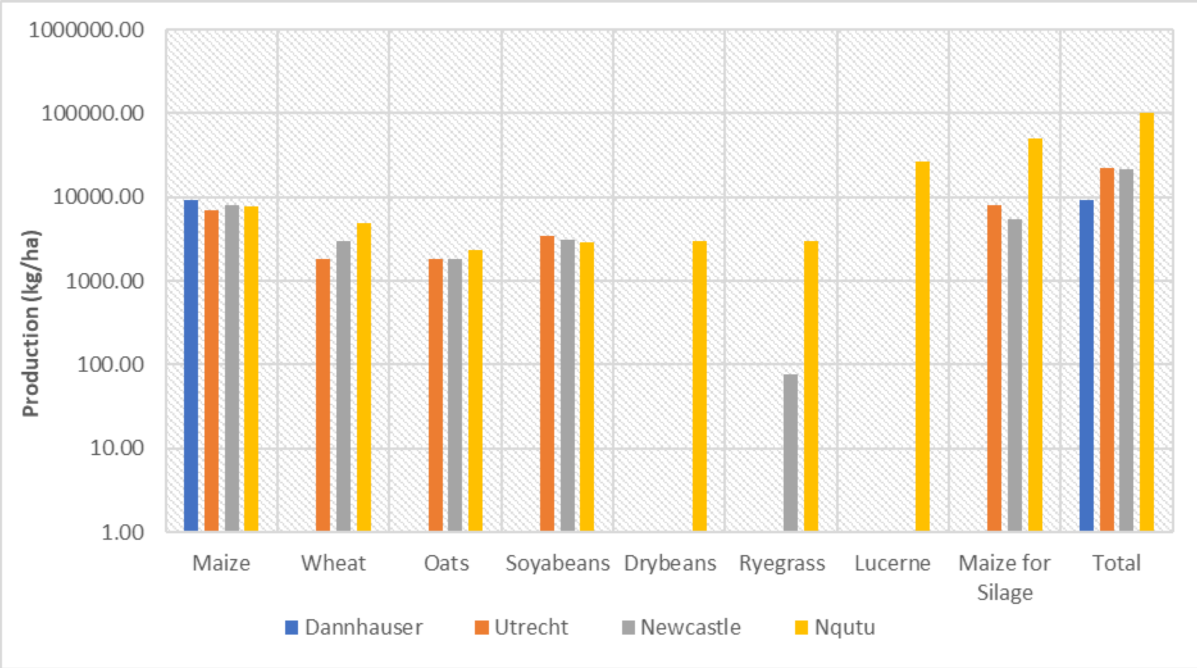


Figure A.15 Production in kg/ha (StatsSA, 2017)

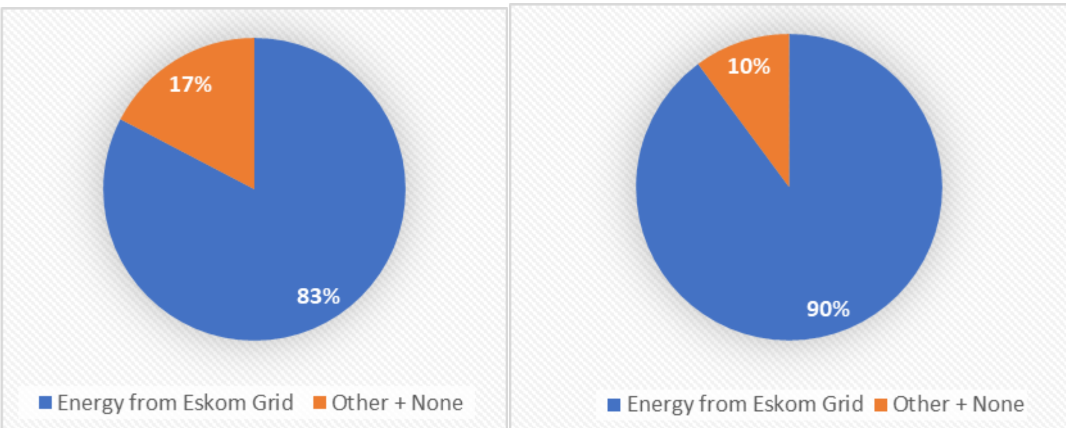


Figure A.16 Energy sources of the BR catchment's local municipalities for cooking (left) and heating (right) (StatsSA, 2016)

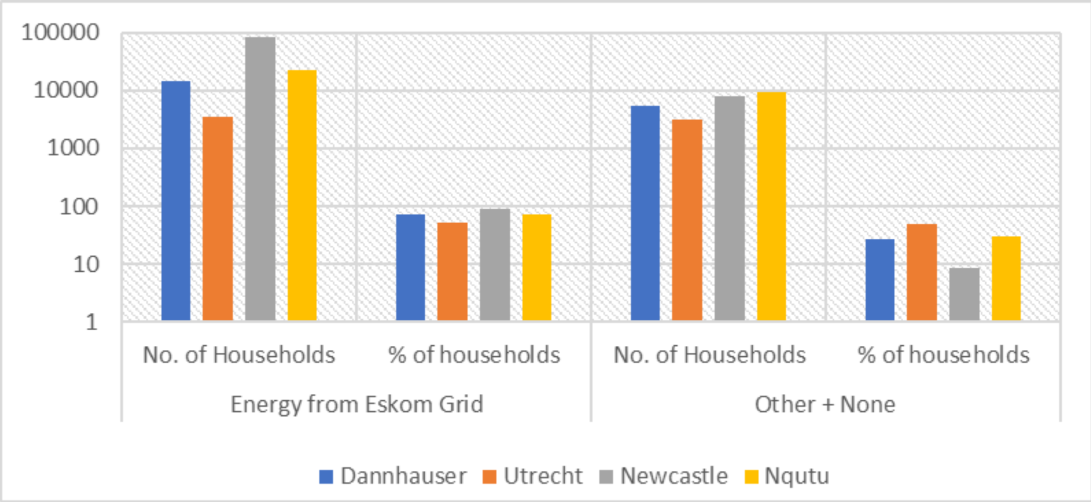


Figure A.17 Households by main source of energy for cooking (StatsSA, 2016)

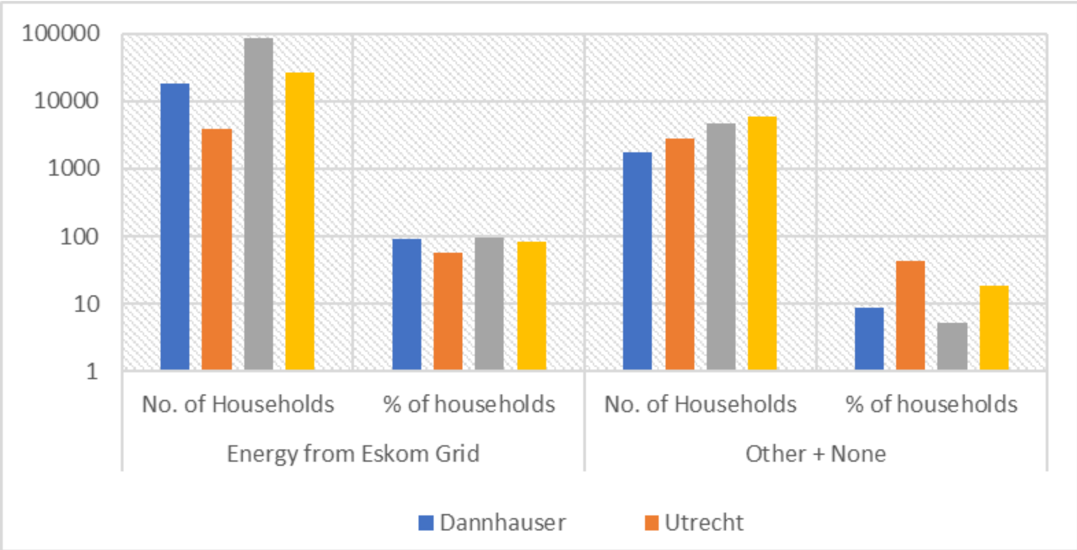


Figure A.18 Households by main source of energy for heating (StatsSA, 2016)

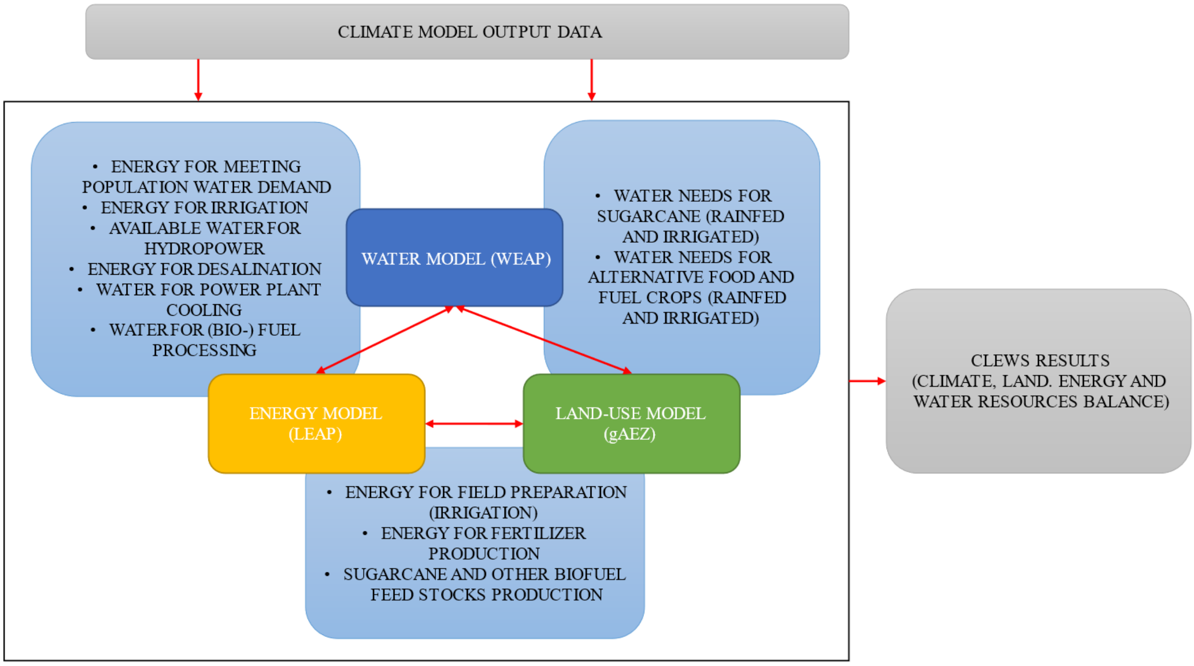
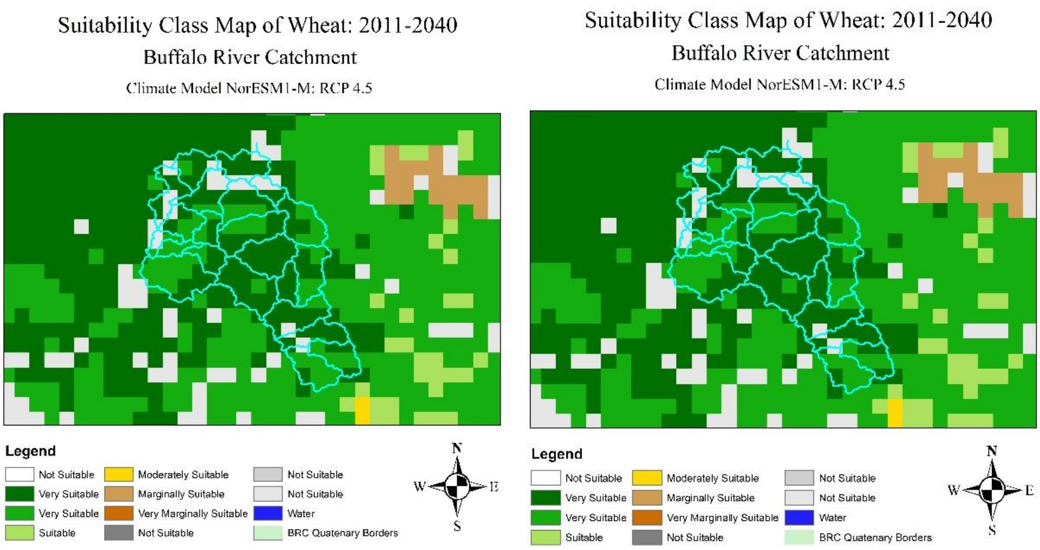


Figure A.19 Schematic of CLEWS approach (Welsch *et al.*, 2014)



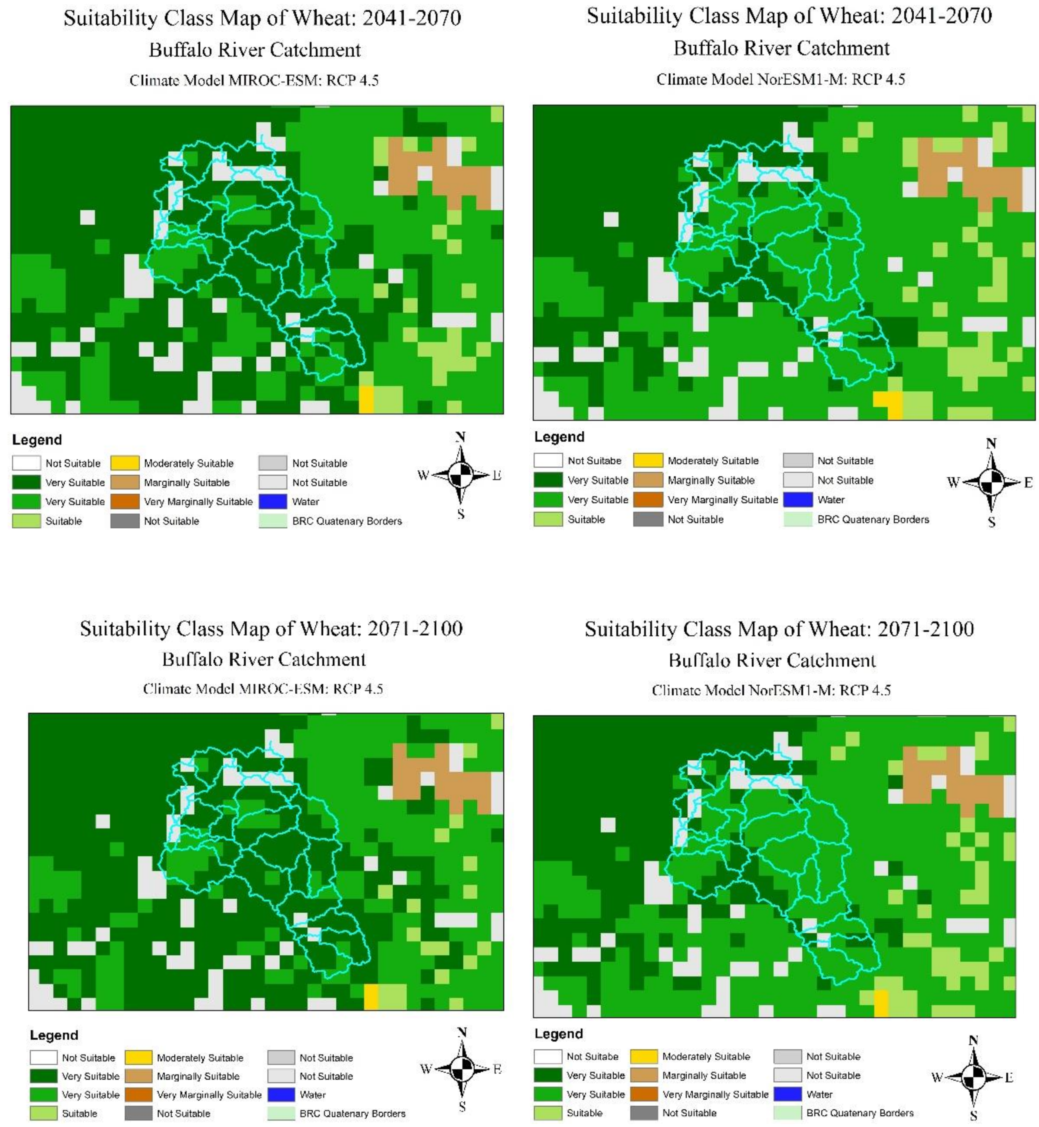
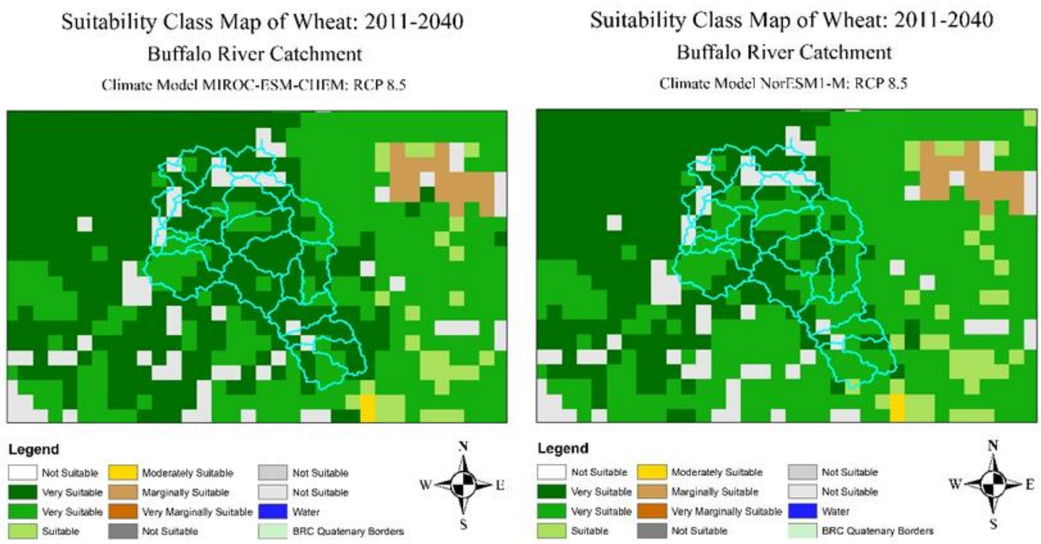


Figure A.20 Suitability class of wheat projected by MIROC-ESM-CHEM and NorESM1-M climate models in the Buffalo River catchment under the RCP 4.5 scenario.



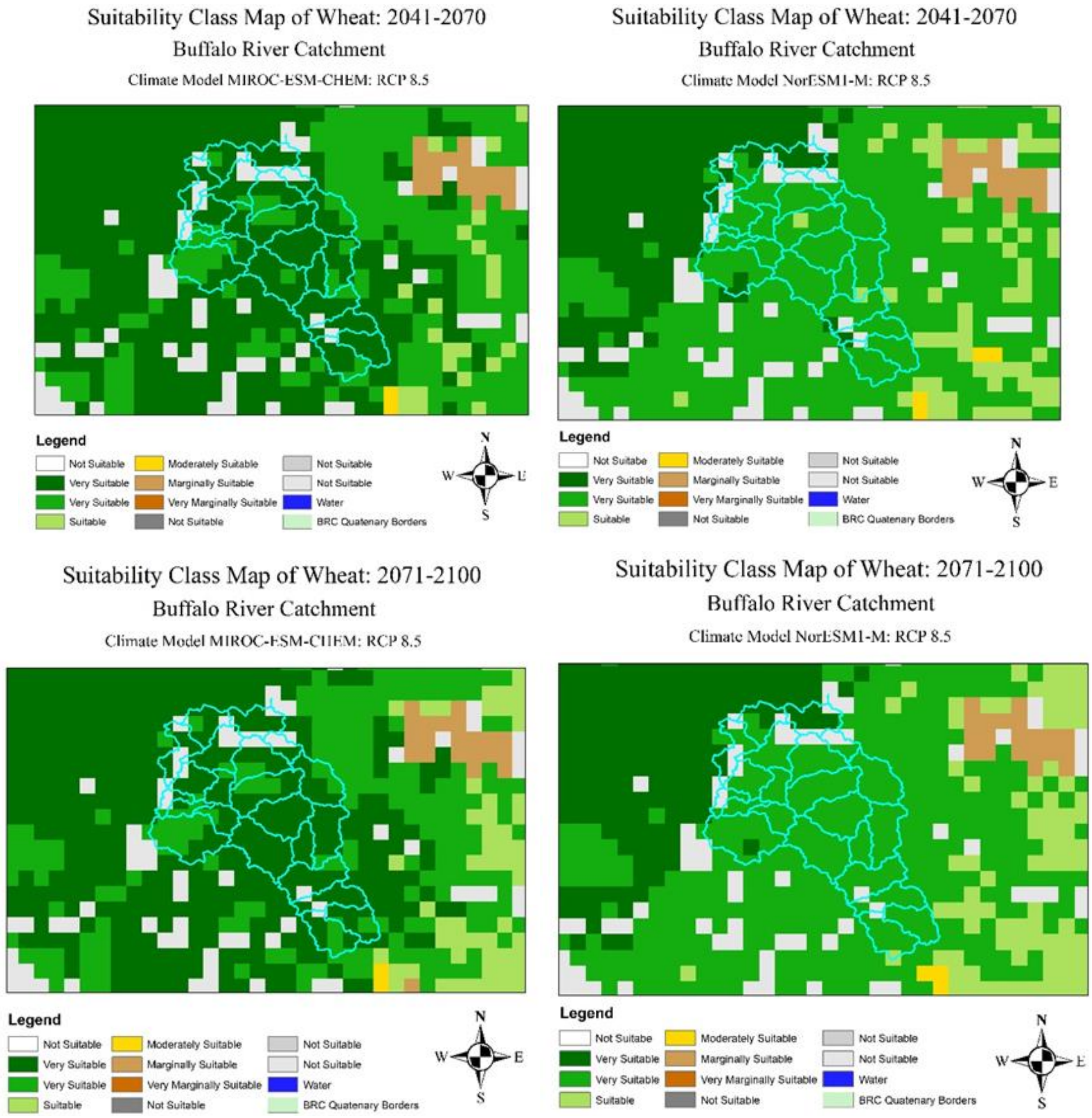


Figure A.21 Suitability class of wheat projected by MIROC-ESM-CHEM and NorESM1-M climate models in the Buffalo River catchment under the RCP 8.5 scenario.

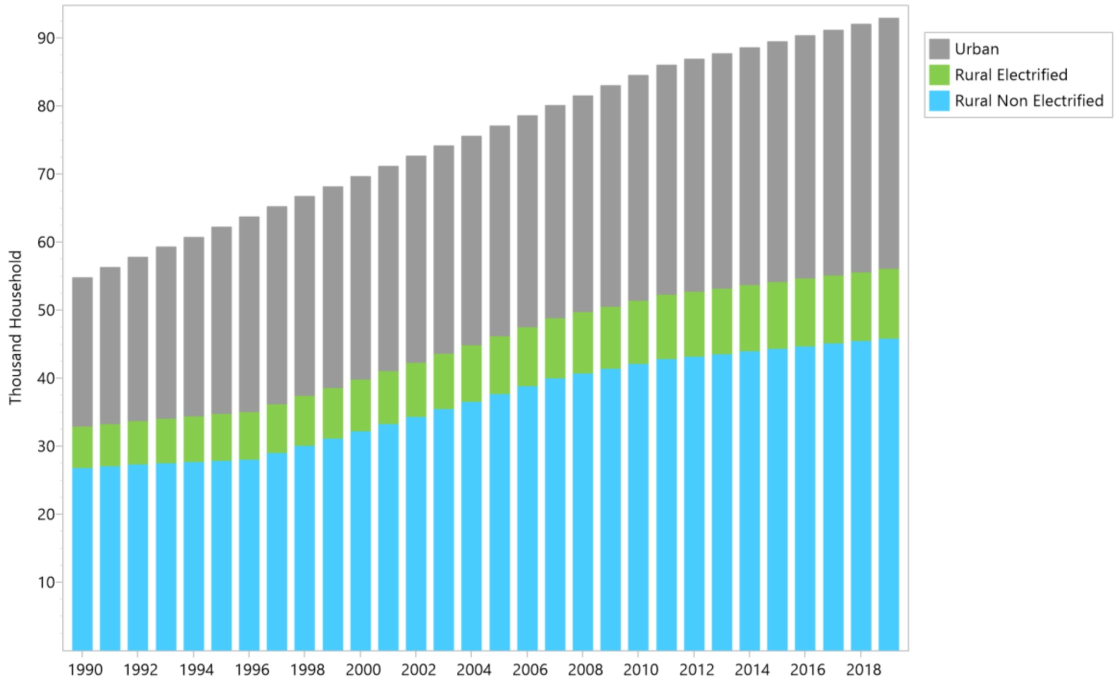


Figure A.22 Historical growth rate of households in Newcastle Local Municipality

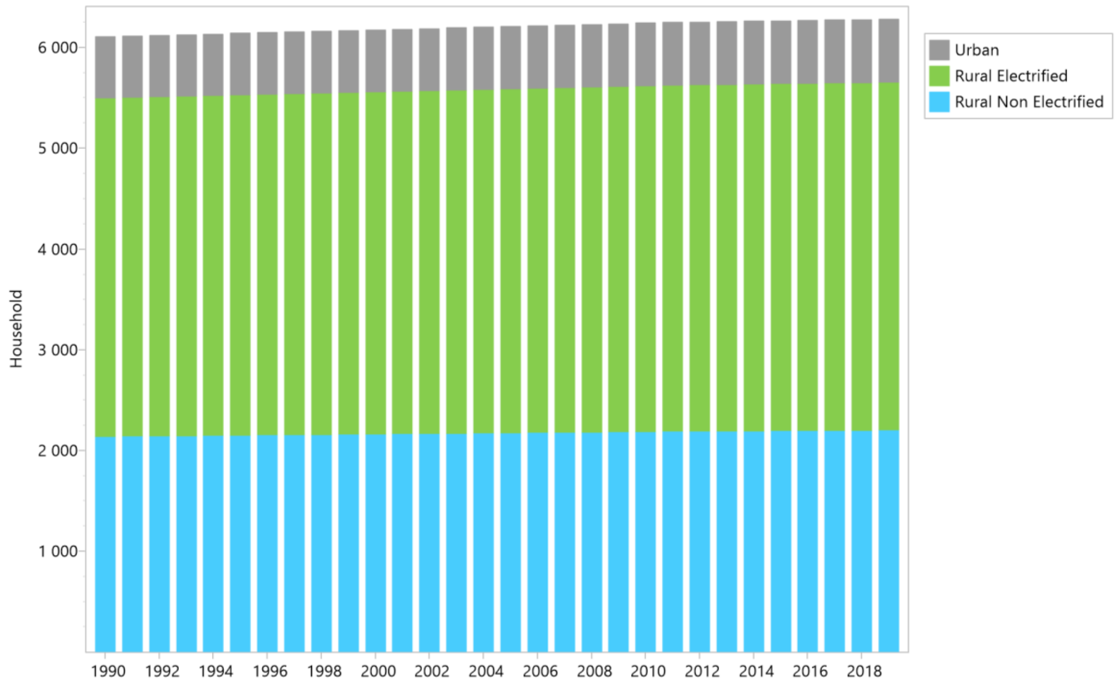


Figure A.23 Historical growth rate of households in Utrecht Local Municipality

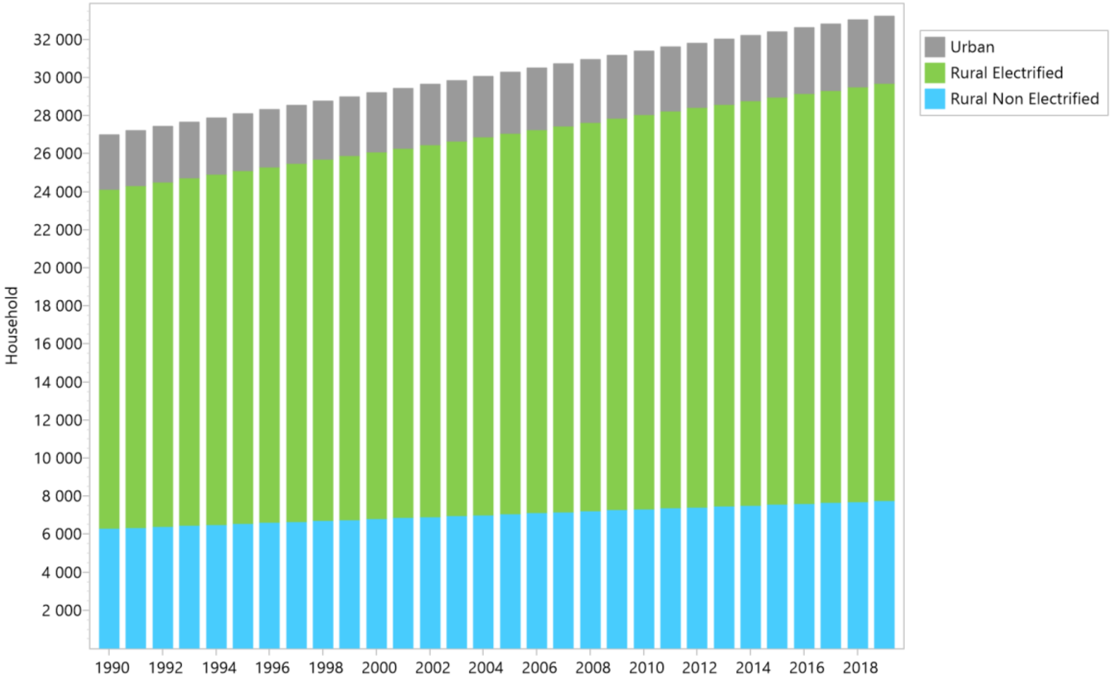


Figure A.24 Historical growth rate of households in Nquthu Local Municipality

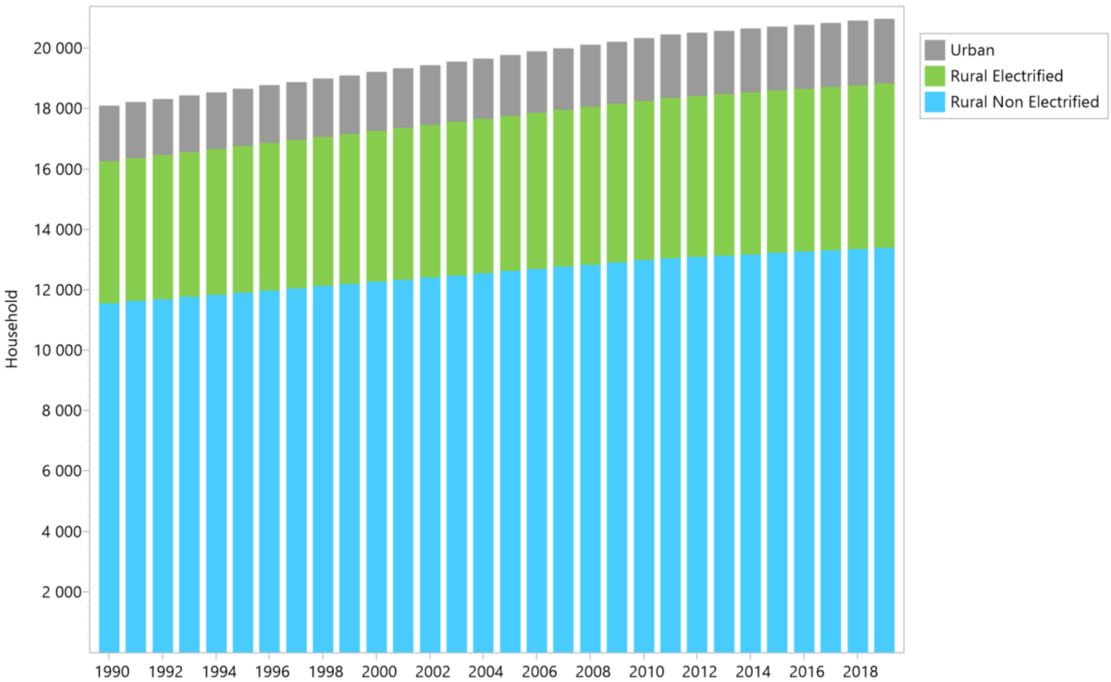


Figure A.25 Historical growth rate of households in Dannhauser Local Municipality

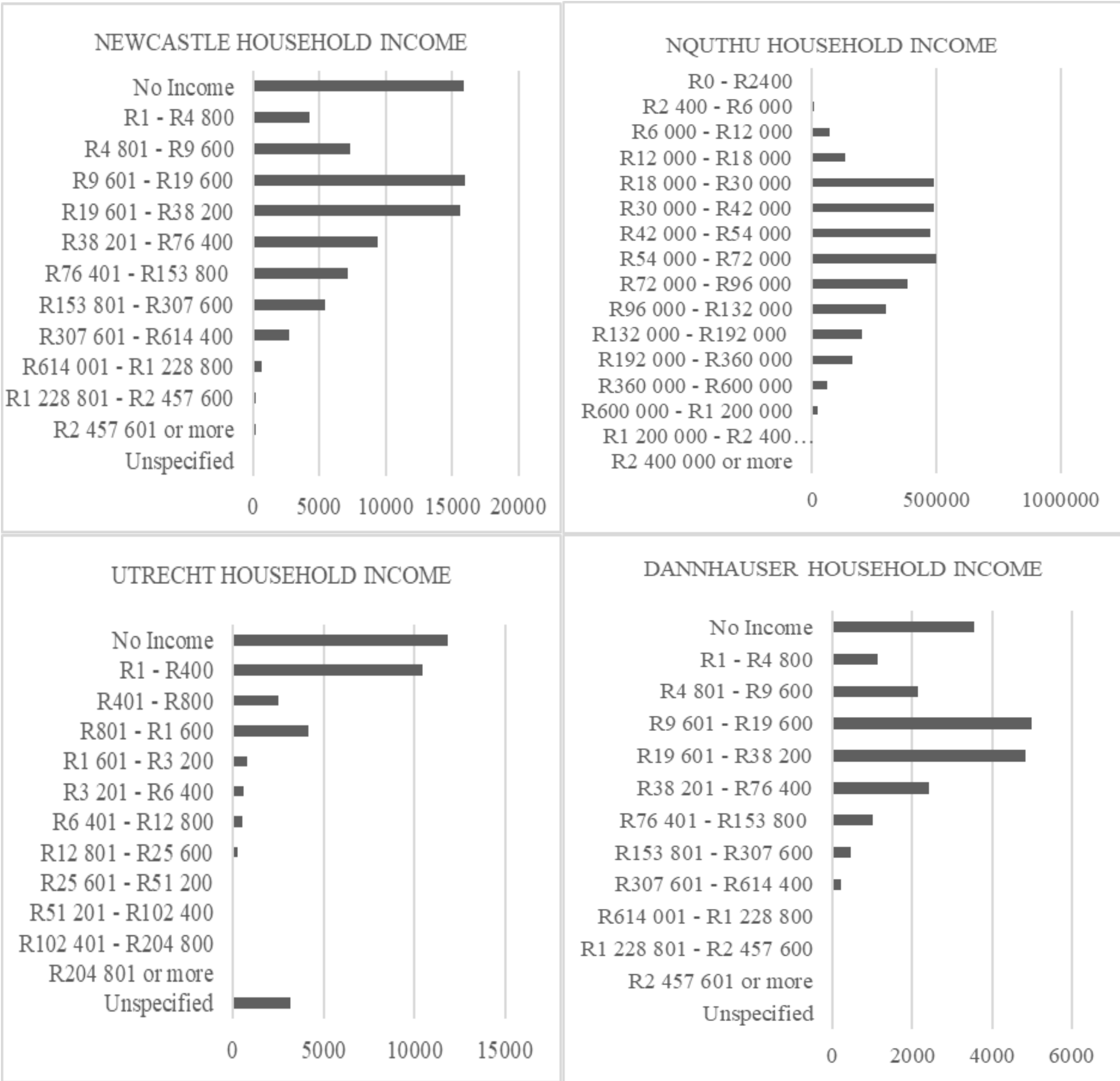


Figure A.26 Household incomes per annum of the LM's in the Buffalo River catchment.

Table A.3 Average energy consumption of electric appliance/energy service in kWh per income group for the year 2015 (Dinkwanyane *et al*., 2021).

Energy Service	**Appliance**	**Annual Average kWh per household**		
		Low Income	**Middle Income**	**High Income**
Lighting	Light Bulbs	229	287	438
Cooking	Oven	224	249	272
	Stove	226	208	308
	Microwave	45	54	59
	Kettle	192	210	225
	Other	14	37	28
Refrigeration	Fridge/Freezer 1	487	499	543
	Fridge/Freezer 2	397	439	453
	Deep Freezer 1	564	552	569
	Deep Freezer 2	437	437	437
Water Heating	Hot Water Geyser	0	2 804	3 923
	Hot Water Geyser + SWH/HP	0	0	1 348
	Hot Water – Kettle	97	77	62
Space Heating	Heater	44	191	167
Other	Dishwasher	606	363	389
	Washing Machine	179	192	237
	Tumble Drier	795	573	509
	Pool Pump	894	521	799
	Aircon	735	709	682
	Other	99	392	286
Total		**6 432**	**9 029**	**12 079**

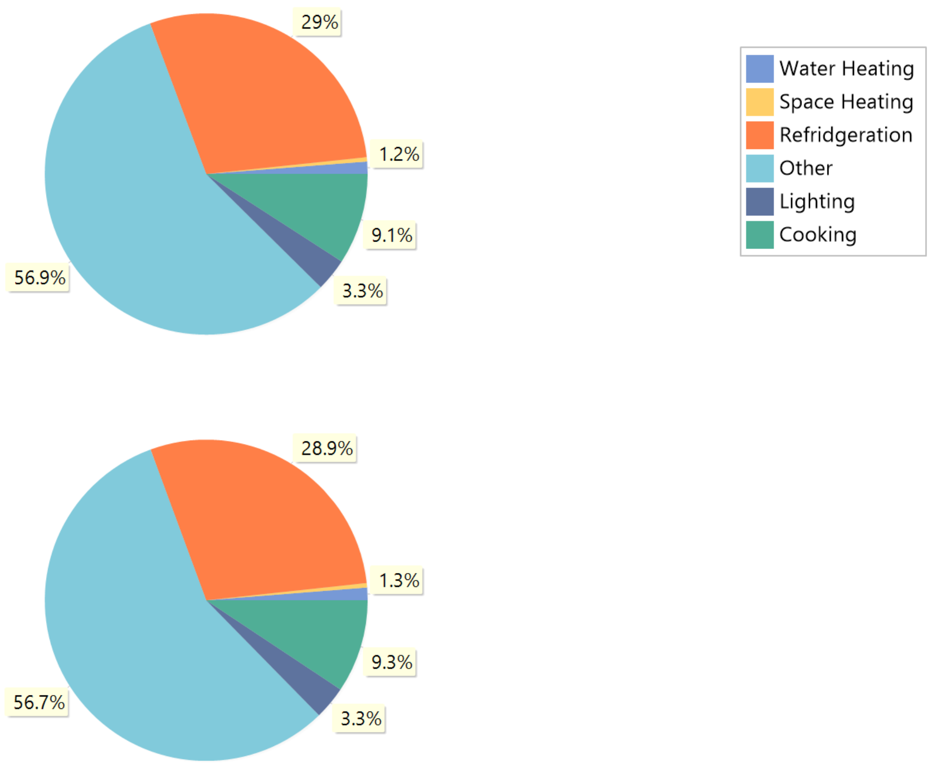


Figure A.27 Electricity consumption of household energy services in the Buffalo River catchment in 1990 (above) and 2019 (below).

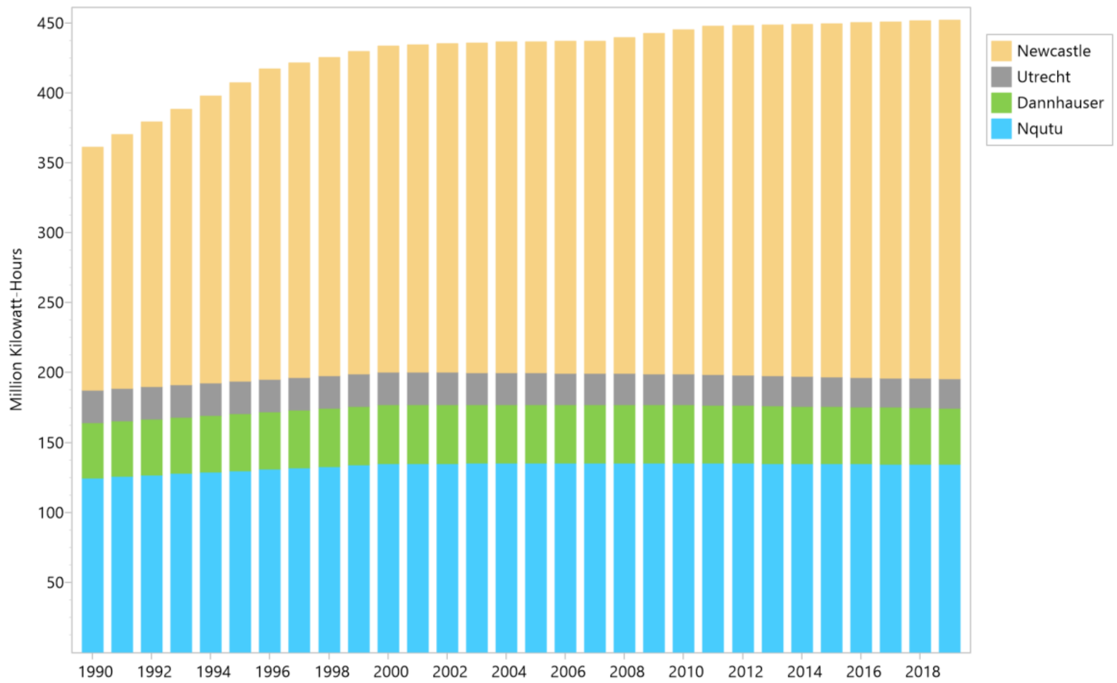


Figure A.28 Total household electricity consumption per local municipality.

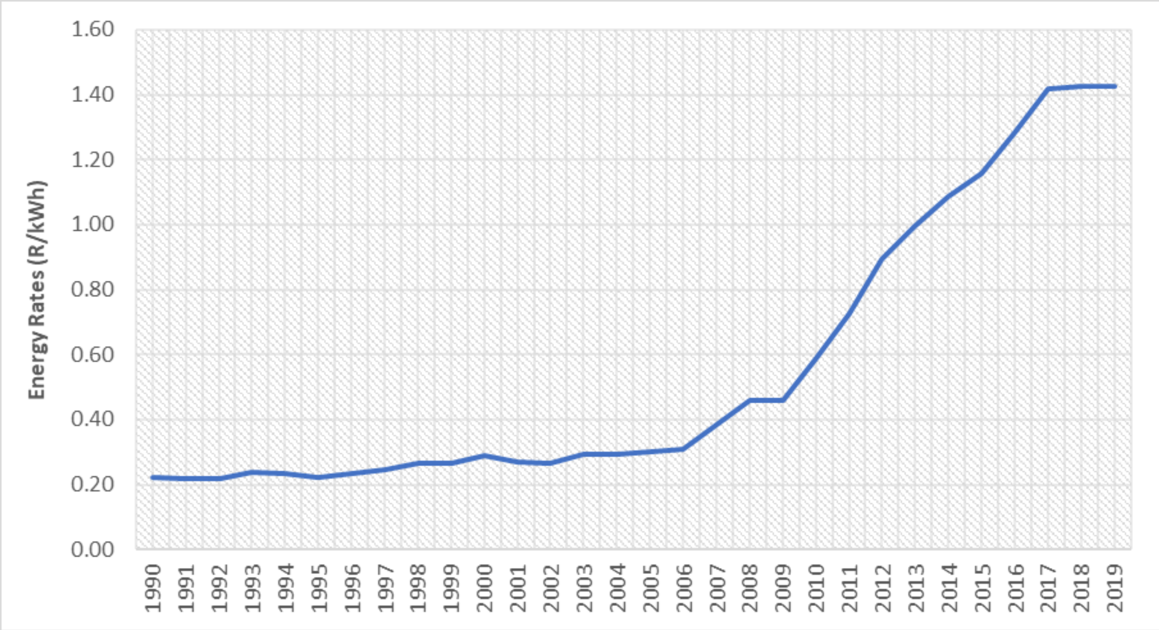


Figure A.29 Eskom energy rates (R/kWh) for rural and farming activities (ESKOM, 2022a).

Table A.4 Optimised investment and electricity costs using Ruraflex (Venter *et al*., 2017)

Centre Pivot Size (ha)	**Small (30.1)**				**Large (47.7)**			
Irrigation System Delivery Capacity (mm/day)	**8**	**10**	**12**	**14**	**8**	**10**	**12**	**14**
Pipe Investment (R)	**112 853**	**112 853**	**179 895**	**179 895**	**179 895**	**179 895**	**276 158**	**276 158**
Pivot Investment (R)	**638 483**	**669 000**	**723 186**	**739 654**	**815 452**	**835 239**	**842 405**	**930 818**
Pump Investment (R)	**14 368**	**21 655**	**20 661**	**20 661**	**20 661**	**22 216**	**22 216**	**22 216**
Total Investment Costs (R)	**765 704**	**803 508**	**923 742**	**940 210**	**1 016 008**	**1 037 350**	**1 140 779**	**1 229 192**
Total Variable Electricity Costs (R)	**541 411**	**549 204**	**508 959**	**494 362**	**849 125**	**865 063**	**832 717**	**883 347**
Total Fixed Electricity Costs (R)	**307 099**	**307 099**	**307 099**	**307 099**	**307 099**	**307 099**	**394 056**	**394 056**
Total Electricity Costs (R)	**848 510**	**856 303**	**816 058**	**801 461**	**1 156 224**	**1 172 162**	**1 226 773**	**1 277 403**
Total Electricity Costs (R/ha)	**28 190**	**28 449**	**27 112**	**26 627**	**24 240**	**24 574**	**25 719**	**26 780**

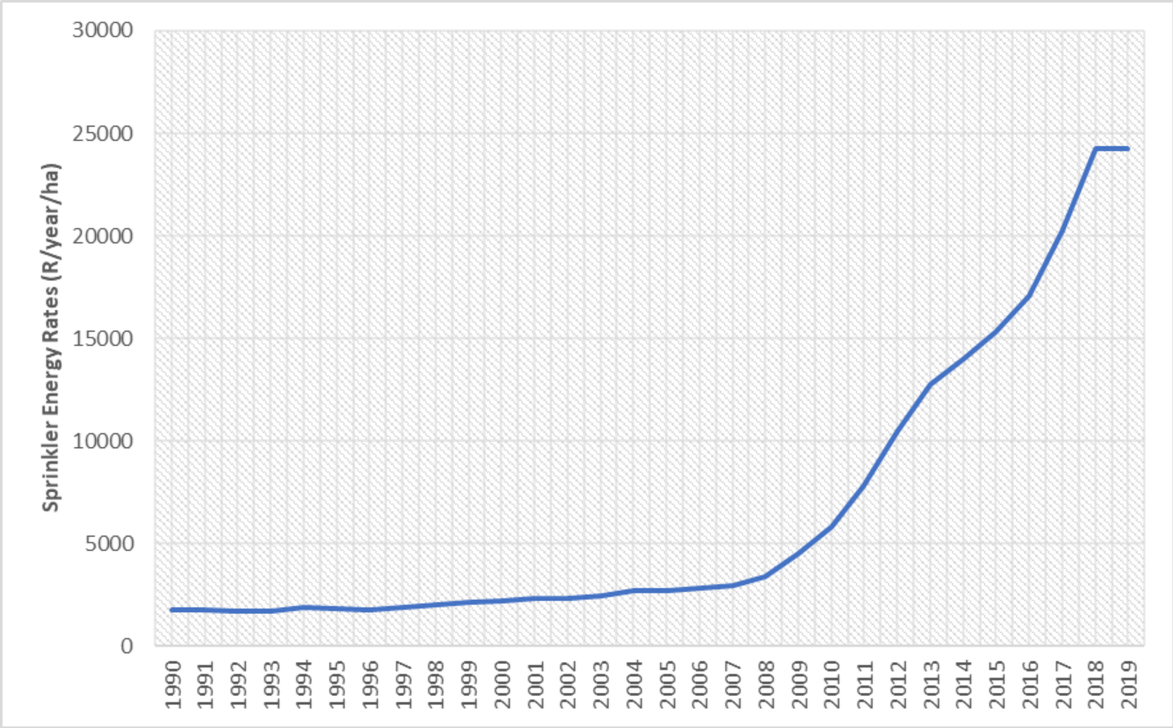


Figure A.30 Sprinkler energy rates (R/year/ha).

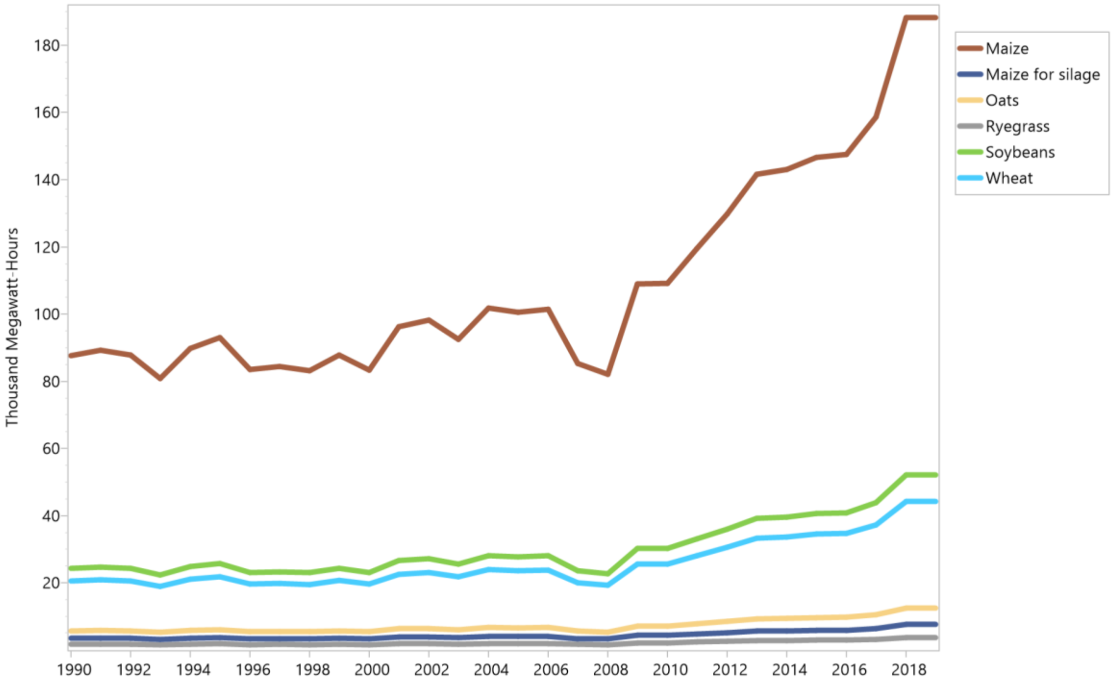
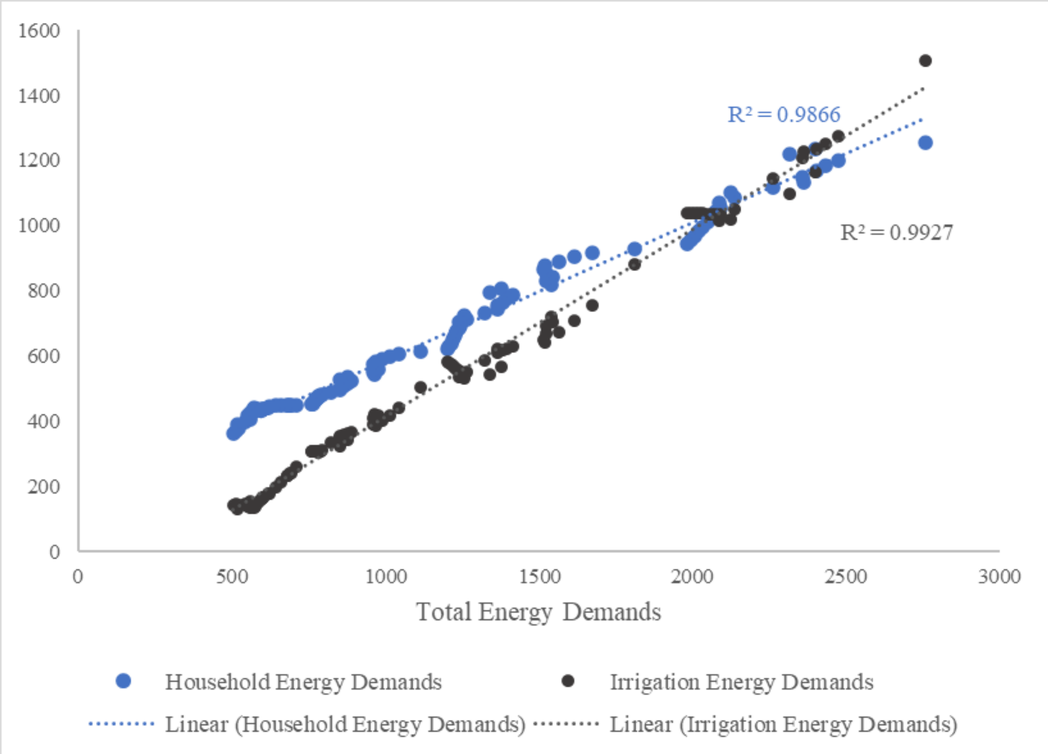
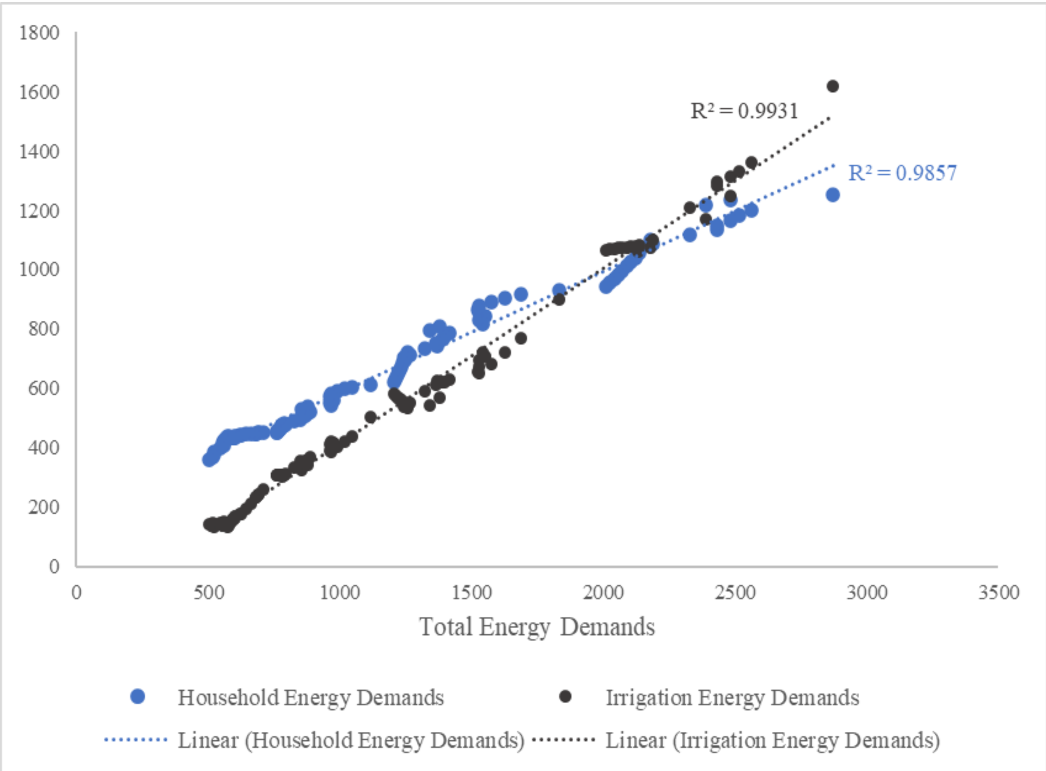


Figure A.31 Total irrigation energy demands (MWh/annum) under the historical timeframe.



(a)



(b)

Figure A.32 Comparison of irrigation energy demands, and the total energy demands throughout the projection period (01/01/2020 – 31/12/2099) under the (a) RCP4.5 scenario and (b) RCP 8.5 scenario.