Assessing the Sensitivity to Climate Change of the Berg River Vöelvlei Abstraction System, Western Cape Province, South Africa

By

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DECLARATION

I know the meaning of plagiarism and declare that all of the work in the dissertation, save for that which is properly acknowledged, is my own.

Signature:

Date: 14 March 2024.

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LIST OF ACRONYMS

BR	Berg River
BRVAS	Berg River Vöelvlei Abstraction Scheme
CO_2	Carbon Dioxide
CC	Climate Change
CCT	City of Cape Town
CSIR	Council for Scientific and Industrial Research
DEA	Department of Environmental Affairs
DWS	Department of Water and Sanitation
EWRs	Ecological Water Requirements
FDC	Flow Duration Curve
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IAP	Invasive Alien Vegetation
IPCC	Intergovernmental Panel on Climate Change
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
RCP	Representative Concentration Pathway
SST	Sea Surface Temperature
SWC	South-Western Cape
SD	Sustainable Development
SDGs	Sustainable Development Goals
TCTA	Trans-Caledon Tunnel Authority
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNFCCC	United Nations Framework Convention on Climate Change
VD	Vöelvlei Dam
WWF	World Wildlife Fund
WTW	Water Treatment Works
WWTW	Wastewater Treatment Works
WCWDM	Water Conservation and Water Demand Management
WMA	Water Management Area
WCWSS	Western Cape Water Supply System

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ABSTRACT

There is increasing evidence that climate change (CC) will negatively impact the water sector in many regions of the world, including South Africa, by reducing the availability of water resources in both dams and rivers, changing streamflow patterns, and disrupting aquatic biodiversity. The water resources of the southwest region of the Western Cape Province are particularly sensitive to anthropogenic CC, because the entire Western Cape Water Supply System (WCWSS) relies on rainfall-runoff to fill the main six renowned reservoirs, especially during the winter season. During the 2015-2018 drought event that occurred in the southwestern Cape (SWC) region around Cape Town, which ultimately lasted three consecutive years, these six reservors declined due to a shortage of rainfall that was exacerbated by anthropic factors associated with the growth of the urban population, as well as largely unabated demand amongst local water users. The records showed that rainfall in 2017 was the lowest since the 1880s, and subsequent analysis showed that human influence on climate had increased the likelihood of a drought of this magnitude in the SWC by a factor of three. Several options for augmenting supply in the WCWSS have been proposed, including the Berg River Vöelvlei Abstraction System (BRVAS), which will draw water from the Berg River (BR) in winter and pump it into the Vöelvlei dam (VD). However, there has been no analysis to date of the reliability of the BRVAS scheme under river flow conditions experienced in the recent 2015-2018 drought, or under projected climate change.

This study aims to assess the reliability of the BRVAS to climate change. The two research questions for this study were as follows: (1) Given that the previous BRVAS reliability calculations made use of abstraction simulations using the earlier dry period of 1968-1972, would simulations using a period that spans the more severe 2015-2018 drought have the potential to alter the calculated reliability of the scheme? (2) How will the water available for abstraction change in the future under CC scenarios, and what are the implications of these changes for the reliability of the BRVAS?"

An abstraction model was set up in Excel that used historical streamflow (G1H020-Daljosafat streamflow gauge) and projected river flow data as input. The observed, extending from 1965 to 2021 were retrieved from the Department of Water and Sanitation (DWS) website. The CC model-driven runoff data came from an existing study on the future of water resources in South Africa for three different periods, the recent past (or baseline) from 1961-1990, the near future from 2015-2044, and the distant future from 2070-2099.

For the observed period, analysis of the data using the G1H020 Daljosafat streamflow gauge historical data showed that the simulated abstraction amounts and estimates are reduced if one considers the recent drought of 2015-2018 that happened in the SWC region of South Africa. Similarly, for the near and far future, it was found that the water abstraction amounts available were reduced quite dramatically across a large majority of hydrological flows simulated using the six different climate change model outputs.

The minimum annual abstraction amount in 2015-2018/19 was found to be 33% lower than the earlier period, while the median annual abstraction amount was 75% different. Similarly, for projections, the frequency of flows below the 25th percentile (Q1) in all models ranged from -1% to -13% in the near future of 2015-2044, and from -1% to -39% in the distant future of 2070-2099, whereas the median annual abstraction differences for the near future ranged from 0% to -6% and 0% to -29% for the far future. The abstraction of 95% of the time (FDCs) exceeded during the observational record and the range across the models in differences between the far future and the recent past was noted to be from -50% to -83 percent.

CHAPTER 1: INTRODUCTION

1.1 Study Background

Climate change (CC) is regarded to be one of the key environmental issues facing the planet (UN, n.d). This is due to the increase in weather and climate extremes that have caused irreparable impacts on human and natural systems, making them unable to adapt to these environmental changes. The evidence has shown that CC affects water resources throughout the planet through extreme weather events, sea-level rise, ocean acidification, changes in sea surface temperature, changes in precipitation patterns, water temperature changes, glacier and snowmelt changes, impacts on agriculture, and increased water stress (IPCC, 2022). For example, adverse impacts from tropical cyclones associated with loss and damage have intensified due to sea-level rise, and the intensity of heavy precipitation. Adverse impacts in human and natural systems from slow-onset processes, disasters related to sea-level rise, ocean acidification, and regional reduction of rainfall have been attributed to human-induced CC (IPCC, 2022). The Global CC has a major impact on available water resources. This is because the impacts of CC affect both the quality and quantity of water worldwide, further reducing the availability of water resources in dams and rivers, as well as changing streamflow patterns (DWS, 2017). Mitigation and adaptation strategies are vital in addressing the impacts of CC on water resources. This involves the development of resilient infrastructure, practices of sustainable water management, and determinations to lower greenhouse gas (GHG) emissions to help mitigate the effects of CC in the future. Additionally, international cooperation is crucial to addressing water-related issues on a global scale level.

The impacts of CC are projected to affect water availability, and increase with each degree of global warming levels (GWL) (IPCC, 2022), particularly in most exposed and vulnerable regions. Individuals living in these exposed regions are expected to face high water-related risks. Water-related hazards and physical water availability risks are projected to continue to rise in the mid-long term of 2041-2100 in all evaluated regions with high risk at GWL (IPCC, 2022). By mid-century, the future water-related impacts of CC on different economic sectors are projected to reduce the gross domestic product (GDP), ranging from 0.49% (RCP8.5 and SSP3) of GDP to less than 0.1% (RCP8.5 and SSP5), with high projected losses likely in middle- and low-income countries (IPCC, 2022; WorldBank, 2016). CC is and has been projected to further lower water availability in several water-scarce regions, especially in the sub-tropics, due to continuously increased evaporation, increased drought frequency, and changes in rainfall patterns, and runoff. While droughts can be influenced by CC, it is important to note that not all droughts are directly caused by CC. For instance, from 1970-2019, 7% of all disaster events globally were recorded as drought-related, reflecting the significant impact of these events regardless of their specific causes (IPCC, 2022). CC, together with the increases in intensity and frequency of extremes, has decreased water and food security, hindering the efforts to meet sustainable development goals (SDGs).

CC poses significant problems in Southern Africa, by impacting the three pillars of sustainability associated with economic, social, and environmental aspects. The Southern African countries also participated in a global cooperation conference of the United Nations Framework Convention on Climate Change (UNFCCC), reaching an agreement to combat CC issues and adapt to their effects (UN, 2016) through adaptation and mitigation strategies by providing the framework for finance and capacity-building by means of which to support countries in need. This 21st Paris Agreement Conference was held in Paris in 2015, and aimed to strengthen the global response to the CC threat by keeping the rise of global temperatures this century to well below 2 degrees Celsius (°C) over pre-industrial levels, and pursuing an effort to potentially limit it further to 1.5°C (UN, 2016). The Southern African countries address CC through adaptation strategies, international cooperation as well and regional initiatives. Countries in this region are engaged in developing and implementing policies that foster sustainable development (SD), mitigate CC impacts, and build resilience. International partnerships and organisations offer support for CC adaptation and mitigation in Southern African countries. However, this region continues to deal with the complex problems posed by CC.

The future climate projections for Southern Africa show that at 1.5°C of GWL, the length and frequency of droughts are likely to intensify in Southern Africa (Trisos et al., 2022). Unprecedented severe droughts are also projected to arise at 2°C and above 3°C of GWL (IPCC, 2022). In addition, average annual precipitation is expected to reduce by approximately 10-20% in summer precipitation, particularly in the western areas (Trisos et al., 2022). The period of meteorological droughts is expected to double from two to four months. In Southern Africa, evidence has shown that there is growing water demand, especially for energy and agricultural production (Trisos et al., 2022). Future climate change and growing social demands over scarce water resources have been projected to increase trade-offs and water-energy-food competition. The probability of extreme climate conditions associated with the reduced rainfall that triggered the multi-year Cape Town drought have intensified due to human-induced CC (Otto et al., 2018). As a result of the impacts of CC over Southern Africa, there will be potential climate risks for water in the future. It is therefore notable that the impacts and causes of CC cannot be addressed by any one country alone; it remains a global issue that requires global solutions, which can only be achieved through the cooperation of all developing and developed countries in the world.

South Africa has been deemed a water-scarce country (Cole et al., 2018a; Scholes & Engelbrecht, 2021). This country has already encountered water scarcity challenges, and CC exacerbates this problem. Uneven rainfall patterns, increased evaporation rates, and prolonged droughts affect the availability of water, particularly in the Western Cape region. The adverse impacts of CC are often experienced more severely by poor individuals, who contributed the least to its causes (DWS, 2017). Most of these individuals are highly exposed and extremely vulnerable to the negative impacts of CC due to their high dependency on natural resources, including water, for their daily livelihoods. They have a limited capacity to cope with or adapt to climate variability and extreme events. As a country, South Africa has been engaged in different initiatives to address the CC challenges. This is because CC causes major challenges by affecting different aspects related to biodiversity, communities, the economy, as well as agriculture. This country also participated in the Paris Agreement, setting targets to lower GHG emissions. It has invested in projects associated with renewable energy and implemented policies to help encourage resilience and sustainability. However, there is still a need for continuous effort, especially when it comes to adaptation strategies, building community resilience, as well and sustainable practices, to help mitigate the impacts of CC on water resources in South Africa.

The South-Western Cape (SWC) region is in South Africa, specifically in Cape Town. This region has been facing water challenges, as well as severe drought events. It has experienced numerous years of below-average rainfall, which has led to the depletion of water reservoirs (Odoulami, Wolski & New, 2023; Ziervogel, 2019). The City of Cape Town implemented stringent water restrictions, water-saving measures, and public awareness campaigns to help cope with the drought crisis at the time. As a result of a drought event observed in the SWC, the water supply in the Western Cape of South Africa was reduced to a capacity of 20% in January 2018 (Kam et al., 2021), and agricultural yields declined by 25% in 2019. Kam et al.

(2021) evaluated the impact of climate change on the duration of droughts and found that anthropogenic greenhouse gas (GHG) emissions seemed to double the probability of the drought duration observed in 2015-2019 (Kam et al., 2021). Meanwhile, Otto et al. (2018) assessed the role of climate change on drought severity and concluded that climate change made the likelihood of such severe droughts three times larger.

CC has been projected to contribute to more variable and extreme weather patterns, possibly leading to more severe and frequent droughts. Modifications in rainfall patterns may impact water availability. The CC projections show that there will be a decline in rainfall in the SWC region of approximately 5% by 2060 (WCDEA&DP, 2023), due to the poleward shifts of the cold fronts related to the winter weather system. The primary impact of a decline in rainfall on water availability will be reduced surface water supply. For example, less rainfall will lead to lower inflows into dams/ reservoirs, which reduce their storage levels. This will diminish the available surface water supply for the city, agriculture and industries. Also, rivers and lakes will experience decreased water levels or even dry up during prolonged periods of low rainfall, further reducing available freshwater and resulting in a severe water crisis. A high mean annual temperature is expected to increase evaporation and decrease water balance (WCDEA&DP, 2014). Water resources in this region are projected to be further reduced in the near and far future, due to anthropogenic CC, amongst other non-climate-related factors (Hall, 2020). This is due to the decline in rainfall decreasing the total volume of runoff that flows and fills up water into these reservoirs, especially in the winter rainfall season (Hall, 2020). The impacts related to future climate projections for this region will increase, especially if the climate vulnerability is not eased within this area (WCDEA&DP, 2014).

The Western Cape Water Supply System (WCWSS) is renowned for being extremely sensitive to CC, because the entire system depends on rainfall-runoff to fill up the major six reservoirs (Hall, 2020). The Western Cape Province is highly susceptible to the effects of climate change due to its classification as a region that receives winter rainfall, unlike other South African provinces that receive rainfall during the summer season (WCDEA&DP, 2014). For example, there are higher irrigation needs in summer (if there is no rainfall in the growing season, then more of the rainfall captured in winter needs to be available for agriculture). This province is already vulnerable to fire, floods, and drought, posing a major challenge associated with service delivery to the Western Cape Government and municipalities. It is also vulnerable to sea-level rise, being a province with a significant amount of coastline.

The Cape Town drought can be considered a calamitous event taking place in South Africa from 2015-2018 (CCT, 2019). The Cape Town region encountered a severe water scarcity during this period, and there were worries that the city's water supply could run out, leading to a so-called "Day Zero" (Enqvist & Ziervogel, 2019; Odoulami, Wolski & New, 2021; Otto et al., 2018). The Cape Town drought provides an apt example of the type of impacts related to CC and variability. Scientists have indicated that CC could influence the intensity and frequency of extreme weather hazards associated with drought (Clarke et al., 2022). The Cape Town drought was, furthermore, exacerbated by high temperatures, below-average precipitation, and increased demand for water due to population growth (OECD, 2021). The impacts of CC on water can be noticeable in different ways, such as in changes in rainfall patterns, longer and more intense droughts, altered snowmelt patterns, as well as distribution of water resources (Clarke et al., 2022). These alterations may have significant effects on water availability, affecting ecosystems, human population, and agriculture. The total cost of the 2015-2019 drought impact was R14 billion for the agricultural sector alone, responding to CC-driven drought (WCDEA&DP, 2023). About 30,000 jobs were lost due to the severity of the drought (DWS, 2021), and a decline in the precipitation days in summer and autumn has been observed, particularly on the Southern Coast. Urgent action is needed to improve understanding and efficiently manage drought risk in order to help ease the devastating socioeconomic toll, especially for humans and both the ecosystems to which they contribute, as part of a globally interconnected set of environments (UNDRR, 2021). Adapting to and mitigating the impacts of CC is vital to building resilience, mostly in vulnerable societies.

Muller (2018) described deficiencies in water resources management and operations as one of the causes of the CT water crisis. The author criticised that the water planning models flagged a need to increase water supplies after 2015, but the officials chose to delay these measures, prioritising other expenditures (Muller, 2018). The author also claimed that the completion of the Berg River Dam was delayed by six years due to environmental opposition, which contributed to the water crisis during the drought, and that Cape Town officials overlooked the fact that farmers and gardeners were not using their full water allocations during wet years but increased their usage in dry years further straining water supplies. Also, the decision to delay infrastructure investments resulted in higher costs later on, with the author noting that a timely investment could have been much cheaper than dealing with the crisis (Muller, 2018).

The Berg River Vöelvlei Abstraction Scheme (BRVAS) is a planned augmentation scheme that involves infrastructure construction to withdraw/divert water from the Berg River (BR) to the Vöelvlei Dam (VD) during the winter season in order to help supply the SWC region with water resources (DWS, 2020). This proposed scheme forms part of efforts to secure additional water resources of 23 million m^3 per annum (CCT, 2018) to the WCWSS in order to sustain the growing demand/needs in the Western Cape Province, particularly during limited rainfall season/ drought periods. By abstracting water resources from the Berg River, it serves to boost the entire water supply and aid in mitigating the impact of water scarcity on agriculture, industries, and communities of this region. Therefore, the BRVAS project is a strong proposed solution intended to address the increasing demand and reduced supply within the WCWSS. This is because this scheme aims to transfer surplus winter flows from the Berg River to Voëlvlei Dam, increasing the dam's capacity to store water for use during the dry summer months. This helps improve the reliability of the water supply, especially in times of drought or low rainfall, as was experienced in the Western Cape during the 2015-2018 drought.

One of the major reservoirs in WCWSS is the VD, which is fed by diversion canals from the Klein Berg and the Twenty-Four Rivers catchments (SBM, n.d). An additional diversion from the BR into the VD to augment supply is planned through the BRVAS (CCT, 2018). The problem of this is that these diversions can only divert water during winter, and only within certain minimum and maximum capacities. If climate change alters the nature of future high-flow events in the Berg, this planned augmentation may not perform as expected. For instance, in terms of possible less frequent/shorter duration events, but with higher peak capacities, this may result in a net loss in terms of the total volume of water that can be diverted even if there is no change in the total volume of water in the river (likely monthly/ annual basis). If both monthly and annual runoff (MAR) is dropping and the flood events are getting shorter, then it could have a double impact on the yield from the VD off-channel reservoir, more than on the other major dams. Therefore, this study seeks to provide a sounder understanding of and insight into how CC may affect the efficiency of the planned new diversion into the VD.

The reliability of the original Berg River Voëlvlei Augmentation Scheme (BRVAS) was modelled using the Water Resources Yield Model (WRYM) for the Western Cape Water Supply System (WCWSS). Several steps were taken to determine the incremental yields based on several operating rules and pump capacities (DWS, 2012): A daily time-step diversion function was required to account for the streamflow variability over short durations (hours to days). This function aimed to better represent the behaviour of the diversion scheme by preventing the overestimation of diversion efficiency, which could occur if a monthly time-step were used. Since insufficient observed flow was available post-Berg River Dam implementation, a simulated daily time series was created to represent present-day conditions. The observed data from a gauging station (G1H013) was scaled down by 81.4% to account for the reduced flow caused by the Berg River Dam and Supplement Scheme (DWS, 2012). A spreadsheet model using hourly data from flow gauges (G1H004 and G1H020) simulated the operation of the Berg River Supplement Scheme. The resulting time series was used to disaggregate the monthly WRYM flows for the worst drought period (1 November 1968 to 30 April 1974). Diversion functions were determined for their abstraction scenarios such as a 6 m^3/s capacity pump station with dynamic adjustment to maintain the low-flow EWR while pumping the remainder of the flow; a 3 m^3/s capacity pump station with stepped pumping increments and a 1 m^3/s baseflow allowance; and a 4 m^3/s capacity pump station with similar stepped rules and a 1 m^3/s baseflow allowance (DWS, 2012). These methods ensured that diversion efficiency reflected the real-time variability of stream flows and the ecological water requirements.

In short, the authors of the original BRVAS study calculated abstraction amounts using a model similar to the one that this study utilised. The authors did a Monte-Carlo simulation randomly sampling from all the daily abstractions to estimate reliability. So, this study compares the simulated abstraction amounts in the same period they used (1968-1972) to the recent drought of 2015-2018, to see if the amounts that would be input into such a reliability analysis would be different if a more recent dry period had been used (and therefore, could have reduced the reliability if this was calculated).

1.2 Rationale

The calculated abstraction potential for the BRVAS by the Department of Water and Sanitation (2012) is based on the assumption that the characteristics of winter river flow have not changed in recent decades, and will not change in the future. Should the duration and volume of winter high-flow events have changed, or should they change in the future, this may alter the amount of water that can be abstracted, and hence the calculated reliability of the scheme, as well as the wider WCWSS.

1.3 Research Questions

The two questions for this study entail:

1) Given that the previous BRVAS reliability calculations made use of abstraction simulations using the earlier dry period of 1968-1972, would simulations using a period that spans the more severe 2015-2018 drought have the potential to alter the calculated reliability of the scheme?
2) How will the water available for abstraction evolve under future climate change scenarios, and what are the implications of these changes for the reliability of the BRVAS?

1.4 Aim

This study aims to assess the reliability of the BRVAS to climate change in the Western Cape Province, South Africa.

1.5 Objective

The objective of this study is to test the sensitivity of the Berg River Vöelvlei Abstraction Scheme (BRVAS) to changes in the characteristics of winter river flows in the Berg River, firstly, in the context of the 2015-2018 drought, and secondly to projected future changes in river flow in the Berg River.

1.6 Importance of the Study

The Western Cape Province experienced the most severe drought in recorded history between 2015 and 2018 (CCT, 2019), with extreme water restrictions extensively impacting water use by different sectors, inter alia domestic, agricultural, and industrial. This event demonstrates that climate change needs to be understood, addressed, and included in the district and local level master planning and functions (WCDEA&DP, 2014), associated with disaster development plans, spatial development frameworks, and integrated development plans of the Western Cape Province. Additionally, there is a need to up-scale and prioritise climate action in communities that are vulnerable to the adverse impacts of CC (WCDEA&DP, 2014).

For sustainable management of water resources, climate change needs to be extensively included in water resource planning so as to help during severe drought periods, and assist society to adapt to CC by building resilience, both now and in the future. The negative impact of climate change may alter the reliability of different components of the Western Cape Water

Supply System (WCWSS). To date, this has not been done for the BRVAS, where the aim herein is to provide such an assessment. The results of this study are of potential benefit to future WCWSS reconciliation studies.

1.7 Outline of Chapters

This dissertation is comprised of five chapters.

Chapter 1 presents the introduction relative to this study, with the key purpose of specifying a rational statement of why it may be important or necessary to conduct this research. An in-depth synopsis of the research question, aim, and objective is articulated. The importance of the study and chapter outline are discussed in this section.

Chapter 2 provides a literature review on the key themes associated with water security, namely: global water security, water security in South Africa, and water security in the South-Western Cape (SWC). It will also discuss adaptation options for water resources, off-stream storage systems, and case studies. The chapter will also discuss the WCWSS; the reconciliation and planning process; current and future water requirement projections of the WCWSS; the VD, and its proposed abstraction.

Chapter 3 focuses on the research methodology; study area; material and methods; data collection and analysis.

Chapter 4 will concentrate on the results and discussion.

Lastly, Chapter 5 will provide conclusions and recommendations for the study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter provides an in-depth description of several key areas of water security, focusing much on the main drivers of physical and economic scarcity. The potential for CC to increase water scarcity will also be explored. The chapter describes in detail water security in South Africa, paying much attention to drought as the main driver of periods of water insecurity. It further explores the water security in the SWC and draws attention to the 2015-2018 Cape Town drought as a driver of acute water insecurity. This includes adaptation options for water resources. The off-stream storage systems and case studies will be discussed, concentrating in the main on how previous work has assessed the size and reliability of an off-stream storage system. Lastly, a comprehensive description of the WCWSS; how the system operates; the reconciliation and planning process; and current and future water projections of the WCWSS, as well as the VD and its proposed abstraction options, will be considered.

2.2 Water Security

This section provides an in-depth description of global, South African, and SWC water security.

Water security refers to the availability of sufficient and safe water to support human health, livelihoods, ecosystems, and production with minimal risk to the environment, economy and human health.

2.2.1 Global Water Security

Water security has many definitions, but one such commonly used is the availability of sufficient and safe water to support production, ecosystems, human health, and livelihoods with minimal risk to the economy, humans, and environment (Grey & Sadoff, 2007). For centuries, water has been deemed the most vital natural resource suitable for consumption by both humans and biodiversity globally (Grey & Sadoff, 2007). It is also practically utilised as an input to almost all production, particularly in the transport, industry, energy, as well and agricultural sectors (Jiménez Cisneros, 2014). However, the freshwater systems associated with wetlands, streams, groundwater, reservoirs, and rivers are widely threatened by the anthropogenic CC (Vörösmarty et al., 2010), since humans drive CC through burning fossil fuels related to natural gas, oil, and coal into the atmosphere all around the world (Chen et al., 2021; Eyring et al., 2021; IPCC, 2022). As a result, these systems become more vulnerable, and are exposed to pollution, which disrupts the quantity and quality of water resources affecting human water supply, and extensively impacting aquatic biodiversity by threatening the movement of organisms, altering habitats, and changing flow regimes (Vörösmarty et al., 2010). It is vital to preserving vulnerable water systems that are at risk, and to mitigate the impacts of water-related hazards associated with droughts and floods, manage water resources in an equitable and integrated manner, and safeguard access to services and functions to help achieve water security worldwide (UNESCO, 2021). An integrated understanding of water, environmental flows, and the biosphere is needed in order to support sustainable agricultural and economic systems to help reduce CC, reduce pressure, and demands on freshwater resources, protect vulnerable people during extremes, and adapt to the inevitable (UNWater, 2018b).

Water insecurity is a growing global issue. The IPCC WGII report, the chapter on water stated that about two billion individuals globally lack access to safe drinking water (IPCC, 2022), whereas approximately 771 million do not have basic sanitation services, mainly in rural areas and Sub-Saharan Africa. This statistic is expected to increase due to the economic barriers that many countries experience. Often, the main setback is not physical water scarcity, where demand surpasses potential supply, but socio-economic scarcity. The aspects that influence socio-economic scarcity, include inadequate investment in water services infrastructure and water resources management, the inadequate political will to increase water infrastructure, lack of human capital and skills to manage water supply services, and exclusion of specific groups due to political affiliation, inability to pay, age, race, social status, and disability. All these aspects need to be taken into consideration in order to help attain water security across the globe.

2.2.1.1 Two Types of Water Scarcity

Water scarcity is a term utilised to define the link between water demand and its availability. The following are the two types of water scarcity, namely, physical, and socio-economic water scarcity. Physical scarcity refers to a condition where there is no adequate water to meet the needs of people; this occurs when the demand of the people exceeds the available water resources due to population growth, mainly when water resources are overexploited (WaterAid, 2012), whereas socio-economic scarcity is a condition where there is adequate water, but is unavailable due to shortage of investment in water infrastructure. This occurs when there is a lack of proper infrastructure management, skills, and political will to manage increasing demands for water, and insufficient access to this resource (WaterAid, 2012). In both circumstances, whether socioeconomic or physical scarcity, the condition in many countries is worsening (Liu et al., 2017), where water is available, but poor societies lack access to this resource. In Sub-Saharan Africa, South Asia, Oceania and Latin America, water insecurity can primarily imply both the factors of physical scarcity and socio-economic barriers, preventing equitable access to water resources (WaterAid, 2012). The quality and quantity of water supplies accessible to society are inadequate to meet basic human needs. In this regard, the United Nations (UN) estimated that global water use has been intensifying the world population growth rate twofold. The projections showed that two-thirds of the global population may face water scarcity by 2025 (Liu et al., 2017). According to the IPCC Working Group II (WGII), about four billion people around the globe encounter water scarcity at least once a month per year, which is driven by climatic and non-climatic factors (IPCC, 2022). Intensifications in physical water scarcity are projected, with estimations between 800 million to 3 billion people affected by 2°C global warming, and about 4 billion at 4°C of global warming (IPCC, 2022).

Water scarcity is a global problem (Shan, Singh & Haritash, 2020), where, for centuries, water use has been increasing at more than twice the rate of population growth (UN, 2014). As a result, there is an increase in water shortages in some regions, even though there is little or no global water scarcity. This is because there is adequate fresh water on earth for seven billion people, but it is unevenly distributed, and the excessive amount of it is unsustainably managed, wasted, and polluted (UN, 2014). About 1.2 billion people of the world's population live in areas of physical water scarcity (Shan, Singh & Haritash, 2020), and around 500 million people or more are approaching it, as shown in Figure 1. Over 1.6 billion people are exposed to economic water scarcity, even though water is available locally, however, countries lack the appropriate infrastructure to take on water from aquifers and rivers (Shan, Singh & Haritash, 2020). Approximately 700 million people in 43 countries across the world were reported to experience water stress of below 1700 m^3 of water per person (Shan, Singh & Haritash, 2020; UNDESA, 2015). One-fourth of the population of India, China and Sub-Saharan African countries are living in water-stressed environments, and the number is continuously growing. The Middle East is the most water-stressed region in the world, having an average of 1200 m^3 of available water resources in the region per person per year (Shan, Singh & Haritash, 2020). This measure of water scarcity does not refer to the amount of water available to each person, but is the water available to the country, expressed in a per capita manner. Much of this water would be used for activities such as agriculture, industry, with some being provided as potable water for household use. However, it is important to consider that water scarcity is not solely about the total amount of water available, but also about distribution, access, and sustainable management of water resources. During the Cape Town drought, for example, residents were limited to just 80 litres per person per day, highlighting the severity of the water scarcity situation in that context. Water availability per person per annum is declining continuously, and is expected to trigger a future water crisis (Shan, Singh & Haritash, 2020).

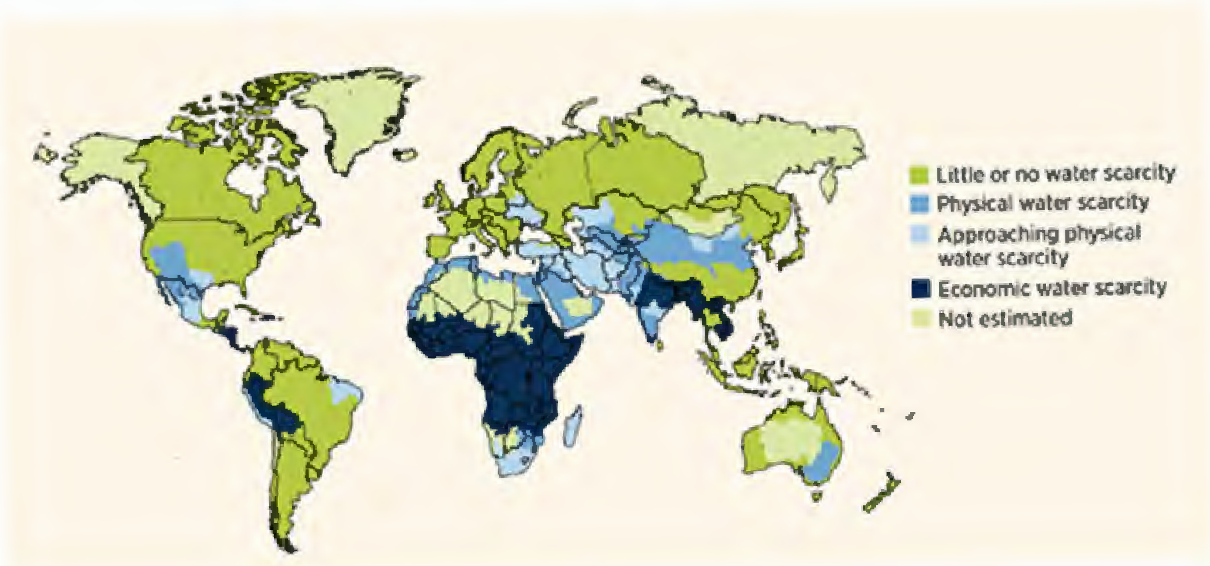


Figure 1: Global physical and economic water scarcity (WWAP, 2012).

If no action is taken now, there will be a water scarcity in some regions in which it is currently abundant, such as in East Asia and Central Africa. Water scarcity will significantly worsen in areas where there is already a shortage of water supply in the Sahel and the Middle East in Africa (WorldBank, 2016). There is a great potential that the growth rate of these regions might decline by 6% of the GDP by 2050, due to water-related impacts on health, income, and agriculture (WorldBank, 2016). Droughts are increasing water scarcity, and negatively impacting productivity and people's health in some regions (UNWater, 2018b).

2.2.1.2 Water Scarcity and Water Demand Projections

The United Nations has projected that an estimated of about 3.6 billion people reside in water-scarce areas and experience scarcity at least once a month, yearly (UNWater, 2018a). This number is expected to increase by 4.8 - 5.7 billion by 2050 (Burek et al., 2016). The IPCC AR6 WGII stated that between 1.5 - 2.5 billion people live in areas exposed to water scarcity across the world (IPCC, 2022). Economic factors related to food consumption and population growth patterns determine water scarcity. However, the climate is gradually shown to be a key component that drives scarcity globally. Water scarcity is frequently a seasonal event, and CC is estimated to intensify seasonal extremes. Consecutive years with dry conditions lead to a long-term reduction in groundwater tables, and directly affect water availability and soil moisture.

Water demand is estimated to change as a result of socioeconomic changes (IPCC, 2022). The global water demand for industrial, agricultural, and domestic uses is currently around 4,600 km^3 per year, and is estimated to increase by 20% to 30% by 2050, depending on the socio-economic scenario (IPCC, 2022). Changes in water availability and demand have been estimated in numerous studies, using socioeconomic scenarios and climate models (Gosling & Arnell, 2016; Koutroulis et al., 2019). The estimated changes in water availability result from differences in evapotranspiration (ET) and precipitation (P). Both ET and P are subject to a very high degree of uncertainty in the main processes associated with regional CC patterns and the influence of vegetation responses to increased carbon dioxide (CO_2) on the transpiration (IPCC, 2022).

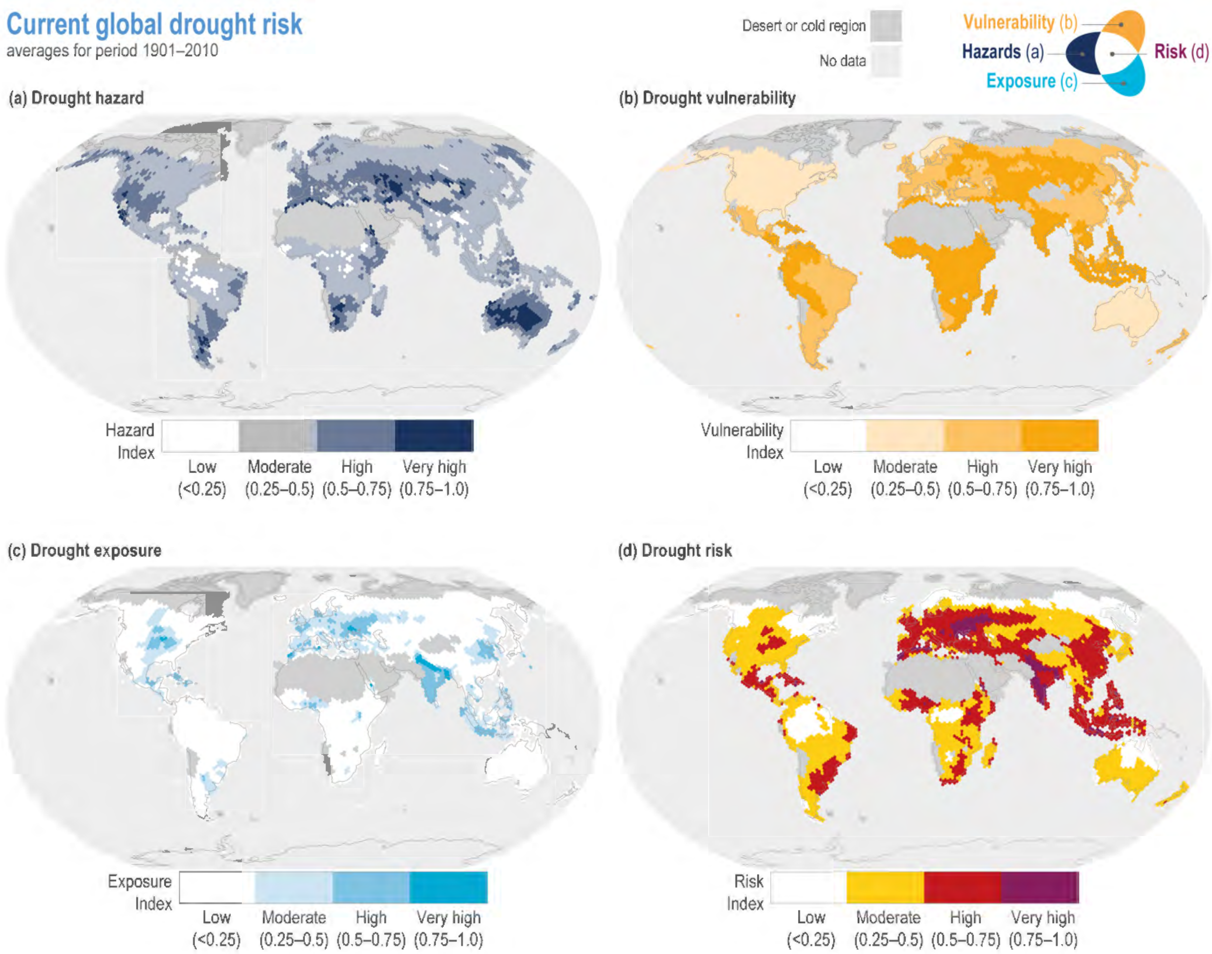


Figure 2: Recent global drought-related risk and its components (IPCC, 2022).

Figure 2 illustrates the recent global drought-related risk and its components (Carrão, Naumann & Barbosa, 2016), where: (a) represents drought hazard for the events from 1901 to 2010, based on the possibility of exceeding the median of global severe rainfall deficits using rainfall data retrieved from the Global Precipitation Climatology Centre (GPCC) (Carrão, Naumann & Barbosa, 2016); (b) shows drought vulnerability, which was derived from an arithmetic composite model combining infrastructural, social and economic factors (Carrão, Naumann & Barbosa, 2016); (c) signifies drought exposure, computed at the sub-national level with the non-compensatory data envelopment analysis (DEA) (Carrão, Naumann & Barbosa, 2016); and (d) demonstrates drought risk, based on the hazard, vulnerability, and exposure components (Carrão, Naumann & Barbosa, 2016).

The likelihood of drought is estimated to increase in most regions over the 21st century, even with resilient CC mitigation, and more severe without it (IPCC, 2022). Various forms of drought largely display similar patterns of the estimated change in several regions, but the frequency of agricultural drought is expected to rise over broader areas, as compared to meteorological drought. Clarity in describing drought is significant to informed decision-making. With the SSP2 and RCP6.0 scenarios, the global population exposed to the extreme exceptional terrestrial water storage drought is estimated to increase from three to eight percent over the 21st century (IPCC, 2022).

2.2.2 Water Security in South Africa

South Africa is ranked the 30th driest country out of 193 countries in the world (RSA, 2023). The country has high and low variable rainfall both inter-annual and intra-annual, shallow dam basins, erratic runoff, and a high degree of evaporation (Cole et al., 2018a). Water resources in South Africa are highly limited and unevenly distributed (see Fig. 3) (Cole et al., 2018a). About 60% of South Africa's River flow arises from 20% of the land area that requires large-scale inter-basin transfers. South Africa is a relatively water-scarce country, with a Falkenmark index[1] of 918 m^3/c/a (Cole et al., 2018a; Crookes, Hedden & Donnenfeld, 2018). The country experiences severe drought spells. The water supply sector in this country has been crucial for economic growth for the past three decades. As a result, surface water resources are

[1] Falkenmark indicator is one of the key indicators that is widely used to measure water stress (Nepomilueva, 2017). This indicator is based on the measure of water availability per capita per year within the country or region. "Falkenmark index measures the amount of renewable freshwater available per capita" (Falkenmark et al., 1989; IPCC, 2022).

approaching their full utilisation capacity. The population is about 60,6 million people (StatsSA., 2022), and the total annual renewable resources are 51,350 Mm^3/a (Cole et al., 2018b). Inequality, unemployment, and poverty are major problems in this country. Approximately 64% of the population is not capable of meeting their daily basic needs (Cole et al., 2018b), 37% is considered to be the unemployment rate and 0.65 is the Gini index for income inequality. Almost 45% of South Africa's population has access to water resources in their households, but this varies and it ranges from 0.07% to 100%, mainly at the ward level (Cole et al., 2018a). The national per capita water use in South Africa is 208 litres per person per day (l/c/d) but varies from 8 l/c/d to 2,414 l/c/d at the town level (Cole et al., 2018a). Social aspects associated with income and water access, as well as non-natural aspects associated with runoff or rainfall, have the highest influence, mainly on per capita water use in South Africa.

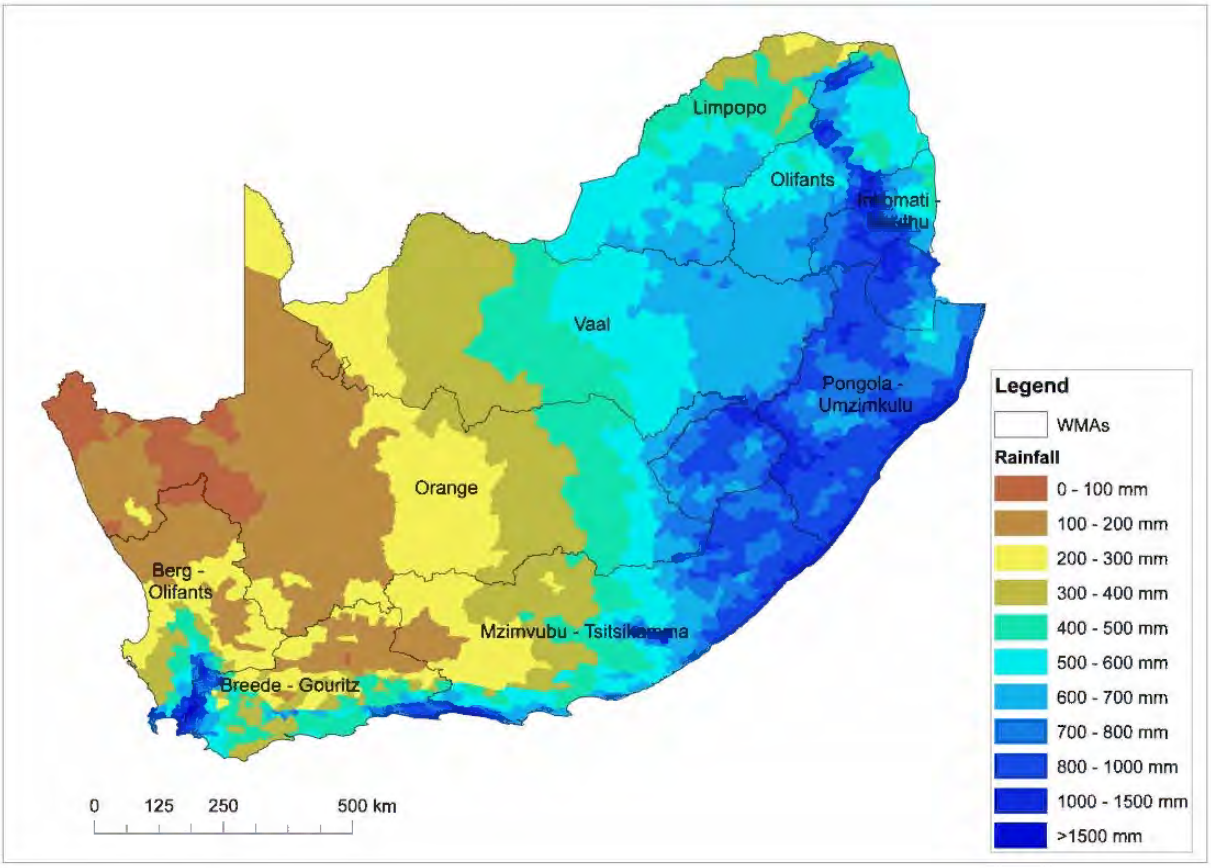


Figure 3: South Africa's annual precipitation within WMAs (Cole et al., 2018).

Large areas of the country (South Africa) have a semi-arid climate (defined as rainfall between 250 and 500 mm per year) (DWS, n.d-b; ESI-Africa, 2019). For example, about 20% of this country has a MAP of less than 200 mm, while 47% has a MAP of less than 400 mm. Only 9% of South Africa receives more than 800mm MAP each year (Lynch, 2004).

2.2.2.1 Why SDG 6 is Significant

Achieving other SDGS is highly contingent on first addressing the Sustainable Development Goal (SDG) 6 pertaining to clean water and sanitation. This is because water is considered a basic enabler of economic growth and other human development outcomes, such as health and food security (Cole et al., 2018b). It is fundamental for basic human rights, food security, health, and sanitation. Water demand remains greater than supply in South Africa (Blignaut & Van Heerden, 2009), where the demographic trends show that South Africa is expected to have a water deficit of around 1.7% by 2025 (Blignaut & Van Heerden, 2009). This refers to the overall water demand exceeding the available supply in South Africa. This could encompass both the availability of water resources and the functionality/ effectiveness of water supply systems. The volume of surplus water available for any use is declining very fast, this indicates that water is becoming a scarce resource, and the limiting factor to economic development. Also, the water supply of a suitable quality standard is expected to be South Africa's single biggest and most pressing development obstacle (Blignaut & Van Heerden, 2009). The surface waters are already committed for use, and the country has to import water from neighbouring countries. Additionally, groundwater resources are limited, and their quality must be maintained to ensure their sustainable use (Blignaut & Van Heerden, 2009).

Water security in South Africa is at risk because there is a growing demand for water resources to support economic development due to the rising population. Threats are also posed by land-use changes, CC, catchment degradation, and decreasing water quality. There is thus an urgent need for South Africa to start managing its limited water resources efficiently to ensure sustainable water security moving forward (Mutamba, 2019). It is significant to notice that the security of South Africa’s water resources is attained in its infrastructure, institutions, as well and regulatory frameworks, that direct the administration of the water delivery (Mutamba, 2019). Projections show that demand will exceed supply by 2025 (Mutamba, 2019). Due to this increasing demand, the country needs to govern its water resources more wisely and effectively.

South Africa primarily depends on surface water, which contributes 77% of its water supply (Mutamba, 2019), where groundwater accounts for 9% and returns flow of about 15 percent. A portion of South Africa's water resources is imported, mostly from the neighbouring country of Lesotho, to sustain the economy of Gauteng Province. Most sources of surface water have been allocated. Irrigated agriculture constitutes the largest water user in South Africa

(Mwendera & Atyosi, 2018), and accounts for as much as 60% of total demand. Domestic accounts for a total of 29% (24% is for urban use and 5% accounts for rural supply). In 2004, the national irrigation water usage sat at around 62%, whereas irrigation usage in 10 of the 19 Water Catchment Management Areas surpassed 70% (Mwendera & Atyosi, 2018). It is important to keep a portion of the surface runoff to support the Ecological Reserve within the river, ensuring the preservation of the natural environment along the watercourse.

2.2.2.2 Climate Projections in South Africa

The South African long-term adaptation scenarios (LTAS) report indicates that the impacts of CC in South Africa are expected to be felt largely through effects on water resources by reducing water availability, while impacts will be unequally distributed, where the eastern coastal zones of South Africa tend to be wetter (DEA, 2013b; IPCC, 2022). The interior, as well as the western areas, will probably experience more extreme and prolonged drought periods, with reduced stream flows (Mwendera & Atyosi, 2018). CC will likely result in weather events that are more variable and intense e.g., excessive volume of precipitation, resulting in flooding. Slight changes in precipitation can result in very large changes in water resources. Projections indicate that a reduction of 8% in precipitation results in a 36% decrease in groundwater recharge and a 30% decrease in surface runoff (Mwendera & Atyosi, 2018). In both wet and dry conditions, a high frequency of drought or flood extremes is projected (DEA, 2013a). Water will continue to be supplied to meet domestic urban and industrial demands (DEA, 2013a). Under high emission scenarios, the CC projections for South Africa until 2050 and beyond show highly significant warming of about 5 to 8°C across the South African interior by the end of this century (DEA, 2013b). Also, a risk of dry conditions to the south and west of the country, as well as a risk of wet conditions in the east (DEA, 2013b).

A major impact of CC is projected changes in runoff around the country. Under a wet future climate scenario, substantial increases in runoff would result in increased flooding, ecosystem disturbance, human health risks, as well and aesthetic impacts (DEA, 2013a). Dry future scenarios would result in reduced surface water availability, but would not prevent the risk of severe flood events. The national runoff projections range from a 20% decrease to a 60% increase, based on the unmitigated emissions pathway, which shows significant uncertainty in rainfall projections (DEA, 2013a). Around the country, this ranges from increases in rainfall along the eastern coastline and central interior to decreases in rainfall in the Western and

Northern Cape (DEA, 2013a). Zones displaying a high risk of extreme runoff involve Kwazulu-Natal, southern Mpumalanga, and the Eastern Cape. Other zones display neutral to reduced risk from runoff, except for the lower and central Orange River region. Areas of high risk from increased evaporation decreased runoff and decreased rainfall involve the southwest areas of the country, central western areas, and extreme northern areas (DEA, 2013a). It is significant to note that both high and low rainfall events greatly impact the water security of the country. Consequently, proper management is needed to help mitigate the impacts and effects of CC on the water security of South Africa.

2.2.2.3 Implications of Climate Change on Water in South Africa

In South Africa, CC influences the hydrological cycle. It alters the quality of the water (Zhu & Ringler, 2012) and increases evaporation, even if rainfall does not change, there might be less surface water, that is, soil water, river water, and groundwater. The influences of CC also increase the risks of water scarcity, and sometimes floods (Zhu & Ringler, 2012). The impacts of CC on the water in South Africa could worsen existing water-related problems, and create other new problems associated with changing rainfall seasonality, climate variability, and extreme weather events (DEA, 2013a; IPCC, 2022). This could affect a broad range of economic sectors, including livelihoods and impact the development of infrastructure in the future and water quality-related issues (DEA, 2013a). Projected impact due to changes in evaporation rates and rainfall, further influenced by climate drivers, namely, air temperature and wind speed, as well as geology, soils, topography, and land, cover most South African water catchments (DEA, 2013a). There is an urgent need to investigate the socio-economic implications of a variety of possible climate-water futures to inform key decisions in adaptation and development planning in South Africa to help build the climate resilience of vulnerable groups and communities (DEA, 2013a).

In South Africa, adaptation response strategies for water resources can usefully be identified at different levels of governance (DEA, 2013a). Consistency and coherence in adaptation planning are needed between the national, water management area (WMA), or system and sub-catchment/ municipal scales. Specific adaptation interventions vary for each level and area. For instance, water resources management requires capacitated organisations, flexible institutional rules, and effective monitoring to respond to and observe changing climate conditions. Water resources infrastructure relies on robust infrastructure with operational flexibility to operate under different future climate conditions. Water services need coherent planning with other municipal services, with flexibility in water infrastructure and services under different climate future conditions (DEA, 2013a). The development of strategic intent and enabling adaptation framework at the national scale would ensure a coherent national response. The key institution at a sub-national/system scale could usefully participate in allocating and prioritising resources to interventions that consider adaptation imperatives. At the sub-catchment/municipal scale, the design of local implementation actions must respond to local issues, capacity, and resources (DEA, 2013a).

2.2.3 Water Security in the South-Western Cape

The South-Western Cape (SWC) is situated in the Western Cape Province, and is heavily dependent on surface water. Cape Town is the largest water user within the SWC area. Out of the nine proposed new Water Management Areas (WMAs) by the national DWS, only two WMAs contribute to the WCWSS (Cole et al., 2018b; DWS, 2016), namely Berg-Olifants and Breede-Gouritz. The WCWSS supplies water resources to Cape Town and nearby areas in the Winelands and West Coast District Municipalities, drawing on water from both the Berg catchment and via water transfers from the Breede. The Breede-Gouritz catchment supplies about 59% of water resources to Cape Town, whereas the Berg-Olifant supplies only 41% (OECD, 2021). These catchments are widely used for irrigation purposes in neighbouring areas. The City of Cape Town (CCT) obtains 95% of its water resources from the six rainfed dams/systems, namely Theewaterskloof, Lower Steenbras, Upper Steenbras, Wemmershoek, Berg and Vöelvlei. These dams are also used for other SWC urban areas and agriculture.

During a year of non-drought, the CCT uses over 64% of the available drinking water in the WCWSS, while the agriculture sector uses around 29% of water for irrigation and small towns use only 7% (see Fig. 4) (CCT, 2018; OECD, 2021). The dams are owned by the DWS and CCT. The DWS allocates and controls all water from the big six dams on which residents of Cape Town depend. As the groundwater supply in this area is highly limited, surface water sources cover about 98.5% of the water in the WCWSS (Petschelt, 2013). A network of six big dams linked by pipelines and tunnels tries to reduce spillage (Petschelt, 2013). The WCWSS provides 905,017 Mm^3 of total storage capacity (Petschelt, 2013).

Figure 4: Water consumed by different types of users within the WCWSS during a year of non-drought (CCT, 2018).

2.2.3.1 The Berg WMA, Berg River Catchment and CCT

The Berg WMA is in the southwestern (SW) of the Western Cape Province. It is named after the 285 km long Berg River, though it is now part of the Olifants-Berg WMA "one of 9 new WMAs recognised in 2013" (Cole et al., 2018b). Precipitation ranges from >3000 mm/a in the southeast mountains to <300 mm/year in the west and northwest coastal plain (Cole et al., 2018b). The natural mean annual runoff (MAR) is about 1094 million cubic metres per year (Mm^3/a), 2.2% of the national total (Cole et al., 2018b). Recent mean annual runoff is about 784 Mm^3/a, and 65 Mm^3/a of groundwater resources are being used. The Falkenmark indicator for the Berg WMA is about 193 cubic metres per person (m^3/c/a) compared to 921 m^3/c/a for the South Africa (Cole et al., 2018b). This reveals that both areas are water scarce. The thresholds that Falkenmark uses for different levels of water scarcity were proposed as follows: if the annual renewable available freshwater falls below 1,700 m^3/cap/a, this simply means that the area is water-stressed[2] (Liu et al., 2017). If the annual freshwater available falls below 1,000

[2] The thresholds that Falkenmark uses for different levels of water scarcity are proposed to be 1,700 m^3/cap/a "below which social stress and a high level of competition for water emerges. If the water falls below 1,000 m^3/cap/a then the area experiences high water scarcity and below 500 m^3/cap/a is absolute scarcity". (Liu, J., Yang, H., Gosling, S.N., Kummu, M., Flörke, M., Pfister, S., Hanasaki, N., Wada, Y. et al. 2017. Water scarcity assessments in the past, present, and future. *Earth's future.* 5(6):545-559. DOI:10.1002/2016EF000518.

m^3/cap/a then this means that the region encounters water scarcity, and if the annual fresh water available falls below 500 m^3/cap/a, this means that the region is experiencing absolute scarcity (Liu et al., 2017). The above thresholds assist in understanding and categorising countries/ regions based on their availability of water per person, and by highlighting whether their water scarcity condition is severe or not.

The BR Catchment is considered a primary catchment that forms a part of the WCWSS, which supplies water to the urban population of Cape Town and the neighbouring irrigation farming and industrial areas from the number of interconnected reservoirs, including the 130 Mm^3 Berg River Dam (Clark et al., 2022). The MAR reaching the estuary had declined to 70% of natural MAR in 1993 and about 54% in 2010. In recent years, the quality of water in the catchment has also declined drastically, due to discharges from wastewater treatment works and agricultural return flows. The levels of nitrogen ($NO_3^- + NO_2^-$) and phosphate (PO_4^{3-}) in the BR have intensified by 1.5 and 2-fold since 1990 (Clark et al., 2022). Currently, the health of the Berg River Estuary is at severe risk (Turpie, Horn & Kloppers, 2021). During the recent 2015 to 2018 Cape Town drought, no freshwater from the catchment reached or even flowed to the estuary. Monitoring data collected by the Western Cape Government indicated that the upper reaches of the estuary became saltier than the ocean. Supplying adequate water to the estuary to restore it to a C-category would cost around R0.6 to R1.2 billion in water demand and supply measures (Turpie, Horn & Kloppers, 2021).

The CCT is situated in the Western Cape Province in South Africa. The topography in this area is characterised by flat plains well-known as the Cape Flats, as well as hills and mountains (Petschelt, 2013). The water storage capacity and rivers within the CCT are relatively small. Only 13% of the water supplied comes from sources within municipal boundaries (Petschelt, 2013). In this regard, most of the water supply is distributed from outside of the CCT catchment management area (CMA). The annual precipitation in the CCT is around 515 mm per annum, and its mean temperature is approximately 16.7°C (Petschelt, 2013). In the CMA of CCT, precipitation mainly occurs during the winter months. During summer, when the water demand is at its peak level, the lowest run-off is accessible (Petschelt, 2013). This variance requires a bulk water supply system in order to ensure that the water provision for CCT is normal in dry summers via stored water from the winter rainfall period.

2.2.3.2 Cape Town Drought 2015 - 2018

Cape Town experienced a severe drought event over three consecutive years from June 2015 to June 2018 (CCT, 2019; Otto et al., 2018; Wolski, 2018; Ziervogel, 2019). This event was driven by the southward shift in the westerlies, and decreased moisture influx into the SWC region (Odoulami, Wolski & New, 2021). The local sea surface temperature (SST) and sea ice anomalies are other factors that affect the SWC rainfall (Odoulami, Wolski & New, 2021; Otto et al., 2018). Its severity was increased by the rainfall deficit, which is the main driver behind the reduced surface water availability (Otto et al., 2018). The rainfall anomaly led to a severe water crisis in this region (Otto et al., 2018). This was also exacerbated by anthropic factors associated with the growth of the urban population, as well as competition amongst local water users, where every part of these has placed enormous strain on limited resources (OECD, 2021). During the drought period of June 2015 to June 2018, rainfall showed a long-term average of approximately 50-70% (Wolski, 2018). The records showed the lowest rainfall in 2017 since the 1880s (Wolski, 2018). This low level of precipitation anomaly resulted in lowering dam levels (see Fig. 5). The overall storage level in the six major reservoirs, which accounts for around 99% total storage system, declined from 100% in 2013 to 71% in 2014, 60% and 35% in the subsequent years "as measured at the start of each hydrological year, 1 November, also marking the start of the dry season" (Ziervogel, 2019). The 2015 - 2018 drought is a driver of acute water insecurity in the CCT.

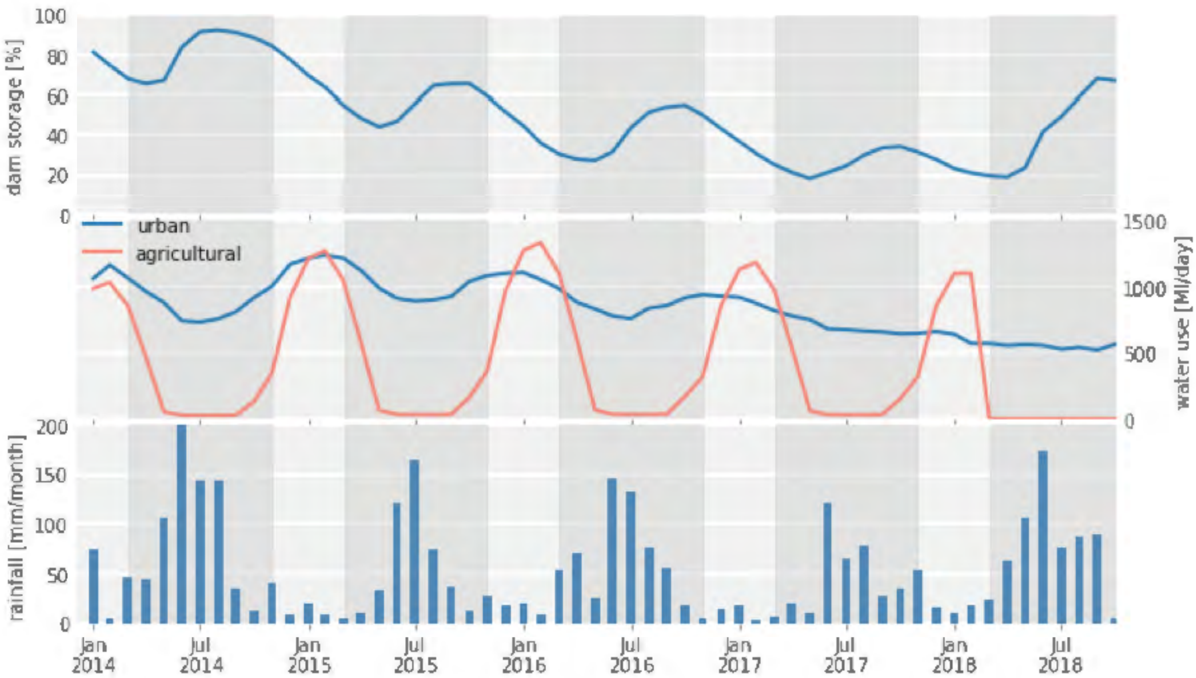


Figure 5: Dam storage levels, rainfall, agricultural and urban usage in the Western Cape from 2014 - 2018 (Ziervogel, 2019).

The Cape Town drought shows how a highly diverse African city and its people responded to prolonged and projected water scarcity (IPCC, 2022). After three consecutive years of low rainfall, Cape Town braced for a so-called "Day Zero" as the day on which the entire pipes could run dry and Cape Town residents would have to fetch their water from communal taps. A large section of the CCT would run out of water, when the water demand to meet basic needs outstrips supply (Otto et al., 2018; Ziervogel, 2019). The risk of "Day Zero" was projected to cascade to affect risks to economic output, security, and health (IPCC, 2022). The agricultural sector in the Western Cape Province lost a significant amount of money, approximating R5.9 billion (WWF, 2018). The 2018 restrictions that cut 60% of water usage for irrigation resulted in a loss of as many as 37,000 jobs in the province (Toale & Molfetas, 2019). An estimated 50,000 people have been pushed below the poverty line due to job losses, inflation rate and rising food prices since the water crisis began. The agricultural sector lost R14 billion (USD$1.17 billion) due to water shortages in February 2018 (Phakathi, 2018; Toale & Molfetas, 2019). The Western Cape needs to heavily invest in drought resilience, and implement water infrastructure projects to increase storage capacity and diversify water sources, such as desalination plants.

A media campaign was introduced to inform 3.7 million Cape Town residents about the severity of the drought, and to encourage water conservation (Otto et al., 2018). With the stringent demand management through high water tariffs, this movement played a crucial role in reducing water consumption from 540 to 280 litres per household, per day (Booysen, Visser & Burger, 2019). The drought event led the CCT municipality to consider a broad diversity of water supply options, namely groundwater, developing city-scale slow-onset disaster planning, and building an enhanced relationship with this most vital of resources. This event required cooperation between multiple spheres of government, and good management of stakeholders and political entities. A lack of coordination among political entities and organs can reduce response efficiency (IPCC, 2022). Despite investments in water security by private and public entities, one-quarter of Cape Town's population remains in persistent situations of water stress, emphasising the challenge and significance of inclusive solutions that address the persistent socio-economic stressors that affect vulnerability to water scarcity (Enqvist & Ziervogel, 2019). Some authors, especially Muller (2018), have suggested that the crisis was largely driven by a lack of planning and preparation by national, provincial and municipal authorities. He lists the following as important failures: failure to follow risk assessments during planning, delays in infrastructure projects, mismanagement of available resources, and short-sighted planning (Muller, 2018).

2.2.3.3 History of Water Supply in Cape Town

Up until 1921, Cape Town was fully supplied with water from Table Mountain (CCT, 2018). As the city grew, water demand exceeded supply, which led to the construction of the Steenbras Dam above Gordon's Bay. A 63-kilometre (km) pipeline was required to transfer the water to the city (CCT, 2018). Nowadays, water is transferred from some other catchment areas, including those from the Riviersondered, Palmiet, and Berg rivers through an integrated water supply system known as the Western Cape Water Supply System (WCWSS). This network consists of a complex system of dams and pipelines managed by either the National Department of Water and Sanitation (DWS) or the City of Cape Town (CCT).

As the city continues to grow, there is also a growing demand for water and additional water resources will be required. The Berg River Vöelvlei Abstraction Scheme (BRVAS) has been identified as the most appropriate next abstraction scheme. This scheme involves diverting surplus winter water from the BR for storage in the VD and has a projected water yield of about 23 million m^3 per annum (CCT, 2018). Other future water sources being considered include seawater desalination, water reclamation, groundwater from the Table Mountain Group Aquifer (TMGR), diversion of the Lourens River, and diversion of water from the Upper Wit and Molenaar Rivers.

2.3 Adaptation Options for Water Resources

Adaptation to CC has been deemed one of the most significant issues to be taken into consideration since this was included for the first time in the IPCC AR3 in 2001 (Jang et al., 2014). In early discussions, adaptation to CC was conducted in relatively vulnerable developing countries (Jang et al., 2014). However, lately, as the impacts of CC are not limited to developing countries, developed countries have also joined the global discussion. The CC triggered by GHG will continue (Jang et al., 2014). Therefore, to prepare for future changes and find efficient ways to respond to CC, it is important to execute adaptation and mitigation together at the same time.

The IPCC WGII AR6 Chapter 1 defined adaptation into two systems, namely human systems and natural systems, in response to the actual/expected climate stimuli and their effects (IPCC, 2022; Jang et al., 2014). In human systems, adaptation is referred to as the process of adjusting to current or expected climate conditions and their impacts to reduce harm and take advantage of beneficial opportunities. In natural systems, adaptation is defined as the process of adjusting to actual and expected climate effects with human intervention (IPCC, 2022). The main types of adaptation include anticipatory vs. reactive, autonomous vs. planned, and incremental vs. transformational adaptation (IPCC, 2022). Adaptation frequently has five general stages ranging from awareness, assessment, planning, and implementation, to monitoring and evaluation. The private sector, government and non-government actors have adopted a broad range of approaches to adaptation to address these five stages. Adaptation in natural systems involves autonomous adjustment, throughout evolutionary and ecological processes (IPCC, 2022). It also incorporates the usage of nature throughout the ecosystem-based adaptation (EbA). The role of species, ecosystems, and biodiversity in such adaptation options can range from restoration or rehabilitation of ecosystems, e.g., mangroves or wetlands, to a hybrid combination of grey and green infrastructure (IPCC, 2022).

Adaptation plays a crucial role in reducing risks and vulnerability in the CC (IPCC, 2022; Noble et al., 2015). This is why it is important, as it helps to manage climate risk. Implementing adaptation and mitigation actions together with SDGs aids in reducing trade-offs and exploiting synergies, making all three more efficient. From a risk perception perspective, limiting atmospheric GHG concentrations reduces climate-related hazards, whereas adaptation, as well as sustainable development, reduces exposure and vulnerability to hazards. Adaptation enables development, which is increasingly hampered by the risks and impacts of CC. Development enables adaptation using expanding resources and capacity to lower climate risks and vulnerability (IPCC, 2022). The main purposes of CC adaptation are to reduce the risk and vulnerability to CC, and to enhance well-being and capacity so as to anticipate and respond effectively to change and strengthen the resilience (IPCC, 2022).

The adaptation options for water resources involve a reduction of risk through a systems approach to water resources planning and management; adopting nexus lenses; climate-proofing water infrastructure; decision support tools for managing complex water systems; surface-groundwater management and rainwater harvesting; and water supply options, such as desalination, aquifer recharge, stormwater harvesting, and re-use. For further detailed descriptions of these options look at Table 1.

Table 1: Adaptation options for water resources (Author).

Adaptation Options	Description	Reference
Reducing risk through a systems approach to water resources planning and management	Integrated systems and a risk-based approach is required for the design and management of water resources. This will support the resilience of water systems to human pressures and climate change.	(IPCC, 2022)
	Integrated water resources management (IWRM) is required mainly for dryland areas.	(Stringer et al., 2021)
	Nature-based solutions (NbS) to maintain the integrity of ecosystems and biodiversity.	(Sowińska-Świerkosz & García, 2022)
	Institutional capacity for management of complex water supply systems under rising demand and CC strain to achieve water security.	(IPCC, 2022)
Adopting Nexus Lenses	Understanding the interlinkages between the water-energy-food (WEF) nexus is required to aid in characterising risks to water resource scarcity, identify co-benefits and clarify the diversity of multisectoral actors involved in and impacted by development decisions.	(Rasul & Sharma, 2016)
Climate proofing water infrastructure	The provision of urban water security relies on the functioning of complex bulk water infrastructure systems, comprising inter-basin transfers, dams, pump stations, pipelines, distribution networks, and water treatment plants. It is important to invest in the latest infrastructure to improve the reliability of the water supply. Additionally, it is significant to improve and maintain the existing infrastructure associated with water supply systems, reservoirs, and dams to help cope during extreme weather events.	(IPCC, 2022)
	Reducing leakages and enhancing efficiency through technology and water improvement is significant in building climate-resilient water conveyance systems.	(IPCC, 2022)
Decision support tools for managing complex water systems	To assess the impacts of CC on hydrology under different climate and development scenarios.	(Serrat-Capdevila, Valdes & Gupta, 2011)
	Collaboration between policymakers and scientists can help address the complexity of decision-making under uncertainty, coupled with community contributions in participatory scenario development. These are effective tools, mostly for more beneficial adaptive and resilience-building actions.	(Serrat-Capdevila, Valdes & Gupta, 2011)
Surface-groundwater management and rainwater harvesting	Important for IWRM, help to reduce vulnerabilities in water supply systems. Also, mitigate the water supply stress in responding to CC. IWRM strategies need to be developed and implemented to optimise the use of water resources available. It is significant to capture and store rainwater mainly for later usage to help mitigate water scarcity during drought periods.	(IPCC, 2022)
Water supply options such as desalination, aquifer recharge, stormwater harvesting, recycling and re-use	Desalination is required to increase water availability, meet peri-urban and urban water supply, and address water scarcity in large cities. Converting seawater into freshwater can increase freshwater sources, particularly in coastal areas. However, this is very costly because of high energy consumption. Wastewater treatment to reuse in landscaping, industrial and agricultural processes to help reduce the stress of available freshwater resources.	(Blersch & Du Plessis, 2017)
Demand reduction and efficiency	Water demand can be reduced through reductions in water loss from the system associated with pipe leakage and water conservation measures. Implement water-efficient irrigation related to drip irrigation to reduce water wastage in agriculture (climate-resilient agriculture). It is vital to switch to more efficient irrigation techniques related to drip irrigation/ improved agricultural methods that can help conserve water, particularly in farming. Implement water-saving techniques and practices in households, industry, and agriculture. Implementing policies that encourage sustainability and sustainable water management and support efficient water use is paramount. Establish and implement water management policies that account for the impacts of CC.	(IPCC, 2022; Zhao & Boll, 2022)
Restoration of ecosystem	Restoring and protecting wetlands, watersheds and forests can improve water filtration, availability, and retention.	(Shannon et al., 2019)
Community Engagement	Educate communities on practices of how to conserve water.	(Liu, Li-Yin, Brough & Wu, 2022)
Innovation and research	Invest in research to help understand better the impacts of CC on water resources. Support the establishment of innovative tools as well as approaches for better management of water resources.	(IPCC, 2022)
Early warning techniques	Develop and improve early warning techniques for severe weather events, droughts, and floods to help increase response and preparedness.	(Tang, Liu & Qiu, 2023)

2.4 Off-stream Storage Systems and Case Studies

Reservoirs and dams can play a crucial role in supplying a reliable source of water (Di Baldassarre et al., 2018). They are also important for a variety of human activities and needs. The number and total storage capacity of large reservoirs and dams have rapidly increased globally over the past 100 years (Di Baldassarre et al., 2018). More than half of the world's reservoirs are designed and managed to supply water for agricultural, domestic, and industrial purposes (Di Baldassarre et al., 2018). These reservoirs store water during excess periods to bridge periods of water deficit/increased demand (Di Baldassarre et al., 2018). Some reservoirs and dams offer different services associated with hydropower generation and flood control (Di Baldassarre et al., 2018).

In general, reservoirs are used around the world to provide irrigation water, flood management, fishing, boating and hydro-electricity services (Iradukunda & Bwambale, 2021). They provide multiple-use and recreational use benefits. This is because they regulate seasonal flows by providing reliable flows. For example, during drought events, the water level in rivers may decline, and water is discharged from the reservoir so that the downstream ecosystems can benefit (Iradukunda & Bwambale, 2021). That is why reservoirs are required worldwide with high hydrologic variability, where the volume or amount of water flowing into the rivers varies annually or seasonally (Iradukunda & Bwambale, 2021). High-capacity reservoirs are needed to store adequate water so as to assist during the dry-spells period.

The off-stream reservoirs can be considered powerful tools, used to help increase system reliability by improving raw water quality and meeting water demand (Jain et al., 2007), improving the yield and water quality reliability. The off-stream reservoirs have a major impact on increasing the reliability of surface water resources, supplying water to meet the total demand of the area, and mitigating water quality and quantity challenges worldwide (Jain et al., 2007; Zahraei, Eslamian & Saadati, 2016). Construction of off-stream reservoirs is on the rise to supply water demand mostly to support the agricultural, industrial, and municipal sectors (Zahraei, Eslamian & Saadati, 2016). For example, the operation of off-stream dams in Egypt helped control floods and the water supply by diverting water from the Nile River to the El Fayyum reservoir. The withdrawal of water from Peace River in Manasota to the off-stream reservoir together with the supply in the aquifer helped to improve the drinking water supply, mainly during drought conditions (Zahraei, Eslamian & Saadati, 2016). Off-stream reservoirs are not physically or hydrologically connected to a water course, and have fewer impacts on wetland, stream and riparian habitats. Off-stream conveyance methods incorporate aqueducts, pipes, and artificial methods. Still, depending on the diversion and use, a water right is required for these diversion types and storage. It is worthwhile taking into account the local landscape and hydrology when constructing an off-stream reservoir to ensure that it stays off-stream and does not connect to a watercourse.

The following are factors that could impact a water system, namely, minimum flows and levels, the use of aquifer storage and recovery (ASR), demand shifts, and raw water quality (Jain et al., 2007). This is because some models are modified so as to allow for the recharge of ASR wells and off-stream reservoirs only during certain months, based on raw water quality (Jain et al., 2007).

The off-stream storage system is constructed outside the main river channel, using constructing the impoundment in an up-land area (Morris, 2020; Morton, 1978). Clearwater is diverted into the off-stream reservoir by pumping, or by gravity, but the bulk of sediments-laden flow bypasses the storage (Morris, 2020). Off-stream reservoirs have been utilised mainly for daily regulation storage for run-of-river hydropower and water supply (Morris, 2020). Off-stream storage can be very effective in reducing sedimentation and storing enough water for supply during drought (see Table. 2). The development of off-stream facilities has been deemed a primary solution to the water management problem (Morton, 1978). To prevent the occurrence of an extreme and possibly disastrous water crisis in the future, sizable carry-over water storage facilities related to on-stream reservoirs will be required (Morton, 1978).

Table 2: Off-stream storage systems case studies (Author).

Off-stream Reservoirs example	Location	Description	Reference
Knellpoort reservoir	South Africa	It is an off-channel storage dam that helps to solve sedimentation issues. The canal and Tienfontein pumping station are equipped with a silt trap to ease siltation in the reservoir. The reservoir was constructed to abstract the supply to Bloemfontein through the Caledon-Bloemfontein pipeline.	(Morris, 2020)
Hybrid off-river augmented storage (HORAS) scheme	Malaysia	This project aimed to increase the yield and water resource storage of the State of Selangor and to mitigate flooding downstream of Bestari Java areas.	(Kusin et al., 2016)
Ncwabeni off-channel storage dam	South Africa	The Ncwabeni off-channel storage dam is intended to store water during the high-flow season to be used during the low-flow season.	(Ross & Ross, 2012)
Voëlvlei Dam	South Africa	It is an off-channel dam with a small catchment area of about 38 km^2. Klein Berg River and the 24 Rivers divert water during winter months through a canal.	(SBM, n.d)

2.5 The Western Cape Water Supply System (WCWSS)

This section focuses on a description of the Western Cape Water Supply System (WCWSS) and its operation; the reconciliation and planning process; current and future water requirements projections of the WCWSS; as well as the VD and its proposed operation. Much of the rest of the description of the WCWSS comes from these key documents (DWS, 2012; DWS, 2020; RSA, 2019; TCTA, 2021).

2.5.1 What it is and how it Operates

The WCWS is an integrated system of canals, tunnels, pump stations, pipelines, and dams from the Berg and the Breede catchment systems (DWS, 2020), as well as two small river catchments, the Steenbras and Palmiet. The system helps to improve the assurance of supply, maximise yield, and minimise spillage by optimising the use of water resources (DWS, 2020). It collectively grants an opportunity for water to be transferred amongst catchment systems and dams to service a variety of water demand centres. The WCWSS serves the City of Cape Town (CCT), nearby urban areas, and irrigators alongside the Berg, Eerste, and Sonderend Rivers (TCTA, 2021). This system contains infrastructure components that are owned and operated by both the CCT and the DWS (see Table 3).

The WCWSS supplies water to most communities in Stellenbosch, Wellington, Paarl, and Greater Cape Town, and also on the West Coast and the Swartland areas. Irrigators along the Eerste and Berg rivers and urban users in the Riviersonderend catchment, Breede Water Management Area (WMA), also receive water from this system. The main water user of this system is the urban sector around the CCT.

The primary storage dams of the system incorporate the Theewaterskloof and Voëlvlei dams, which are owned and operated by the DWS. The BR dam is owned by the Trans Caledon Tunnel Authority (TCTA), but operated by the DWS. The Wemmershoek, Upper, and Lower Steenbras dams are owned and operated by the CCT. The water storage in the system is assessed at the end of the wet season, no later than November 1st. This evaluation is done to determine whether water supplies should be restricted in the following year to ensure that enough water remains for basic needs.

Table 3: Big six storage dams of the WCWSS (DWS, 2020).

Name of the Storage Dams	Location	Water Sources	Owner	Completed	Storage Capacity (million m^3/a)
Theewaterskloof	Villiersdorp	Riviersondered River	DWS	1978	480.25
Vöelvlei	Gouda	Klein Berg, Leeu and Twenty-Four Rivers	DWS	1971	164.12
Berg River Dam	Franschhoek	Berg River	DWS	2009	130.00
Wemmershoek	Franschhoek	Wemmers River	CCT	1957	58.64
Lower Steenbras	Gordon's Bay	Steenbras River	CCT	1921	33.52
Upper Steenbras	Gordon's Bay	Steenbras River	CCT	1977	31.77

The Berg River Voëlvlei Abstraction Scheme (BRVAS) was identified as one of the best surface water interventions, suitable to meet/avert the severe water deficit in this area (RSA, 2019). The Environmental Impact Assessment (EIA) for the proposed BRVAS was conducted, and authorisation was granted in terms of the National Environmental Management Act (NEMA) (Act No. 107 of 1998), which superseded the Environmental Conservation Act (ECA) (Act No. 73 of 1989). Interested parties were invited to submit their written comments on the proposed project by 29 February 2020 (RSA, 2019).

2.5.2 The Reconciliation and Planning Process

The reconciliation strategy helps meet the growing water requirements that will need to be supplied by the WCWSS (DWAF, 2007). This strategy includes a review of future water requirement scenarios, as well as planning and implementing interventions, to help meet the water requirements in the next 25 years.

The water users of the WCWSS have implemented several reconciliation options, ranging from those identified in previous reconciliation strategy updates to those prompted by the drought, to help address the severe water shortages and improve their water security. The following are the four water abstraction options identified by several institutional stakeholders and devoted to implementing the short to medium-term water reconciliation options (DWS, 2020).

2.5.2.1 Invasive Alien Plants Removal

The IAP removal incorporates seven sub-catchments, covering a total of 54 300 hectares. This also includes the catchments of Wemmershoek, BR, and Theewaterskloof Dams. It has been estimated that the outcomes of this IAP will generate an additional 60 million m^3 of water over 30 years (DWS, 2020).

2.5.2.2 Groundwater Development by the CCT and Municipalities in the WCWSS

The development of groundwater was initially aimed at mitigating the most significant effects of CC, for example, the most recent drought that occurred in Cape Town from 2015 to 2018. However, this has become a part of the WCWSS climate resilience and adaptation programme, even though groundwater also depends mostly on weather and CC.

The major aquifers that are an appropriate fit for strategic water resources in the WCWSS are namely, the Cape Flats Aquifers, which have a capacity for a sustainable water yield of about 18 million m^3/a; the Atlantis Aquifer, which supplies and abstracts safe drinking water to the Atlantis town through managed aquifer recharge with the possibility of additional development; the Table Mountain Group Aquifer, which has an average recharge capacity of 1%-5% of MAP and was developed by CCT; and lastly, the Langebaan Road, Hopefield as well as Elandsfontein, which have the potential for additional development by Saldanha Bay Local Municipality (DWS, 2020).

2.5.2.3 Water Re-use and Desalination of Seawater Development

Currently, the CCT is implementing a 70 Ml/d water reclamation plant at Zandvliet Wastewater Treatment Works (WWTW) (DWS, 2020). The treated water will be pumped to the Faure Water Treatment Works (WTW), where it will be blended and further treated. Since wastewater in coastal towns does not have downstream demands and is mostly discharged to the sea, there is a robust argument to be made that wastewater reuse ought to be a component of the coastal towns' future source of water supply. The hydrological risk of using this resource is very low compared to surface water resources. Hydrological risk refers to the potential hazards and uncertainties associated with water resources, including the availability, quality, and sustainability of water sources. In the context of wastewater reuse, hydrological risk assessment considers factors such as the potential for contamination, impacts on ecosystems, and the effectiveness of treatment processes in mitigating any potential risks to human health and the environment. In the case of the water reclamation plant at Zandvliet WWTW in Cape Town, the hydrological risk of using reclaimed water for blending and further treatment at the Faure WTW is considered to be very low compared to relying solely on traditional surface water resources. This assessment takes into account the rigorous treatment processes and monitoring measures in place to ensure the safety and reliability of the reclaimed water supply for future use as a source of water supply.

The CCT constructed temporary desalination plants for emergency water supplies to help during the 2017/18 drought crisis. However, the CCT is considering a permanent desalination plant with a capacity between 50 Ml/d to 150 Ml/d (DWS, 2020). Diversifying the water resources for water supply through desalination as well as water reuse provides valuable protection during severe water restrictions.

2.5.2.4 Surface Water Resources Development

The development of surface water resources is one of the options being considered to augment the water supply. Currently, BRVAS Phase 1 is in the implementation phase. The Lower Berg River is under stress, and the scheme is urgently required to address the reliability of the water supply in the lower catchment. The deficit is estimated at 10.1 million m^3/a at a mixed assurance of supply (DWS, 2020). However, this will depend on whether all water users, including agriculture, agree to the uptake of the scheme. If there are no off-take agreements with some users, this will have a significant impact on the implementation of the project, and may influence whether and how the scheme is ultimately implemented.

The City of Cape Town (CCT) has embarked on enhancing its reliability of water supply, mainly by undertaking management interventions and the development of new water sources. It has commenced implementation of its committed New Water Programme (NWP). The City of Cape Town's NWP plays a vital role in the city's water reconciliation strategy by diversifying and expanding its water supply sources. The NWP focuses on interventions such as desalination, water reuse, and groundwater abstraction to increase the city's water supply and enhance reliability, particularly during periods of drought and water scarcity. By developing alternative water sources and implementing management interventions, the NWP directly contributes to achieving the reconciliation strategy's goal of balancing water supply and demand through the efficient and sustainable use of water resources. The interventions introduced in August 2019 involve invasive alien vegetation clearing, water conservation, and water demand management. The Table Mountain Group Aquifer (TMG) Phase 1 focuses on the well-fields of Steenbras Dam, Nuweberg, and Groenlandberg. The Cape Flats Aquifer will be developed in two phases, incorporating artificial recharge of the aquifer by injection of high-standard treated effluent and seawater barrier.

2.5.3 Current and Future Water Requirement Projections of the WCWSS

This section provides a detailed description of the current and future water requirements of the WCWSS.

2.5.3.1 Past and Current Water Requirements

The water requirements of the WCWSS have been revised to reflect the historical growth in water demand up to the current 2019/20 hydrological year. Actual water usage data has been obtained from municipalities up to June 2020, with estimations provided until October 2020, reflecting the impacts of the current drought in the WCWSS on the water requirement of the system and the extent of recovery in the water requirement post-drought period (DWS, 2020). In addition, the current unit water consumption projected for the future takes into account the bounce-back scenarios in the WCWSS.

The past and current water requirements of the Western Cape Water Supply System (WCWSS) refer to the historical and present water needs of the WCWSS. This includes an analysis of how much water has been required and utilised in the past and at present.

On the other hand, future water requirement projections are estimates of how much water will be needed in the future based on various factors such as population growth, urbanisation, industrial development, and climate change. These projections help in planning for future water demand and ensuring that the water supply system can meet the anticipated needs.

2.5.3.2 Future Water Requirement Projections

The future water requirement prediction for domestic and industrial sectors supplied by the WCWSS was undertaken based on the unit demand analysis, as well as population changes, that considered changes in economic activities and land use planning for several municipalities. A scenario-based approach was utilised to determine the future water requirement. The five future water requirement scenarios were developed in the updating of the annual status report based on the extended historical abstraction/consumption and population projections and the estimated recovery from the recent severe drought in the WCWSS.

The water balance assessment that was undertaken based on the available water supply scenario considers the reduction in yield due to Invasive Alien Plants (AIP) and prolonged hydrology to 2017 of 545 million m^3/a at 98% assurance of supply indicated the following future water requirements scenarios (DWS, 2020):

- Scenario 1 - The Median Growth Scenario is projected to exceed the integrated system yield by the 2021/22 hydrological year with a 98% assurance of supply. This depends on the recovery of the water requirements for the industrial and domestic sectors to the levels before the severe water restrictions implemented during the recent drought.
- Scenario 2 - Median growth with water conservation and water demand management (WCWDM) will provide additional water and increase the reliability of supply to the industrial and domestic sectors.
- Scenario 3 - High Growth Unconstrained Demand is the worst-case scenario, which would have been realised, were it not for the successful implementation of a comprehensive water conservation and demand management programme in the WCWSS. The additional water would have been needed from the 2018/19 hydrological year, or more restrictions would have been put in place to keep the dams of the WCWSS from declining.

The WCWSS will be in scarcity in the near future, because the available water supply cannot meet the growing water requirements from the system at the level of assurance of supply of 97% for domestic and industrial use, and 91% for the agricultural sector (DWS, 2020). At this point, the projected future impact of CC on the yield of the WCWSS is small. Still, it requires that the WCWSS identify and develop water abstraction options that reflect the need to be climate-resilient and adaptable to climate change so as to mitigate against substantial CC effects.

The 97% and 91% assurance levels relate to the certainty that the water supply will meet the demand for domestic and industrial sectors and the agriculture sector, respectively. In contrast, the 98% assurance level refers to the integrated system yield relative to the future water requirements forecast for Scenario 1 - Median Growth Scenario. The differences in these assurance levels reflect the varying degrees of certainty in meeting water demand for different sectors within the system.

Table 4: New/ planned water sources from abstraction options short and medium-term (Author).

New/ planned water sources				
Water Sources	Added Supply	Available Date	Total Additional Yield	Percentages/ Accounts
Once the implementation of the additional water yield from abstraction options (short and medium-term) is accomplished, this will provide 126.48 million m^3 per year during the hydrological year of 2028-2029.				
Non-surface water resources (groundwater).	WCWSS	2028-2029	45.68 million m^3/a	37.5%
Seawater desalination and water reuse from treated wastewater.	WCWSS	2028-2029	54.84 million m^3/a	43.5%
Berg River Vöelvlei Abstraction System (BRVAS). Supplies the domestic, agricultural, and industrial sectors.	WCWSS	2028-2029	23 million m^3/a	19%

All values from Table 4 were obtained from the DWS annual status report for 2020. The researcher transcribed the text and created a table. Note: these data appear to be partly erroneous, as the values for additional yield do not add up.

After the implementation of the additional yield from the abstraction options (short and medium-term), such as the removal of invasive alien plants, groundwater development by the City of Cape Town, desalination and water reuse development, and surface water resources development (BRVAS), it has been projected to offer a total yield of 126.48 million m^3/a during the 2028 - 2029 hydrological year (see Table 4) (DWS, 2020).

Figure 6 presents the implementation of the abstraction options to address the medium-term water requirements. According to the DWS (2020), the implementation of these abstraction options will not be sufficient to meet the future water requirements for Scenario 1, which focuses on medium growth. The identified options will effectively improve water supply issues in the WCWSS, and reduce the severity of water restrictions during periods of low rainfall. However, they will only meet future water requirements up to 2026, with the required assurance of water supply with the implementation of further Water Conservation and Water Demand Management (WCWDM) measures, which fall under Scenario 2. If the industrial and domestic water requirements increase by 99.5%, this will lower the quantities of available water and result in early water scarcity.

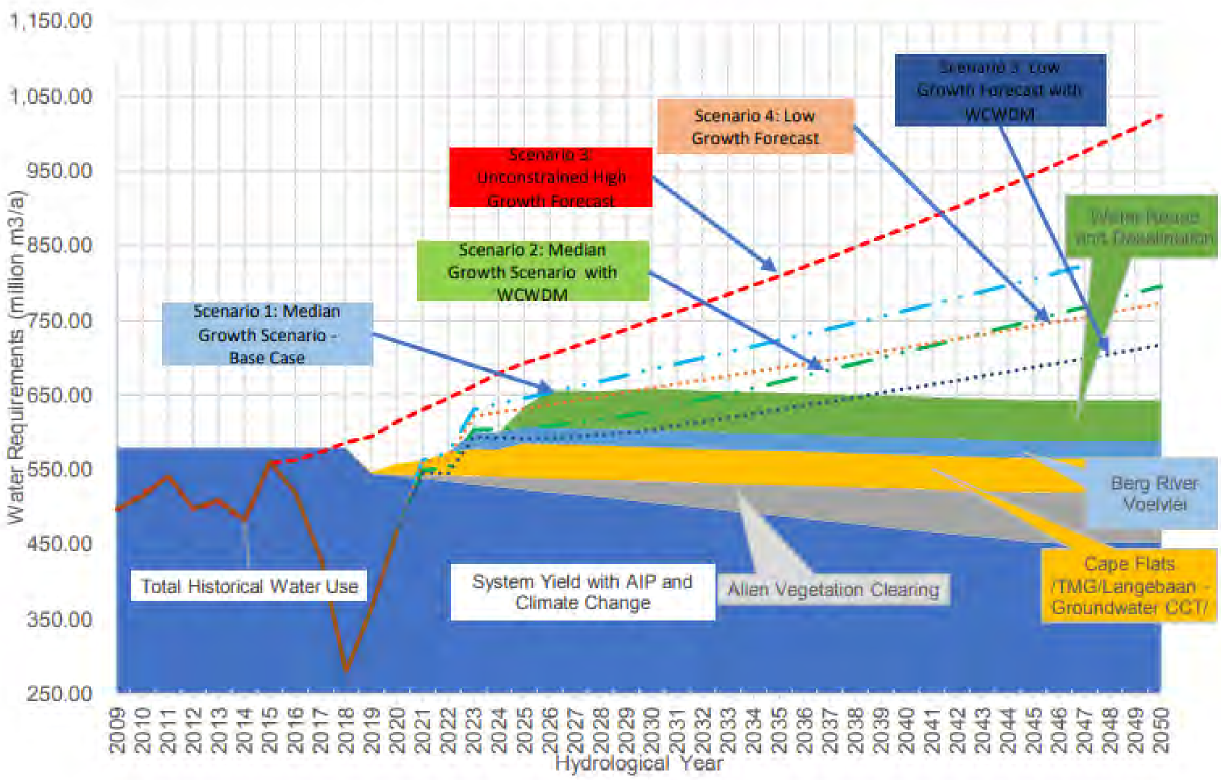


Figure 6: Water balance scenario of the committed abstraction options (DWS, 2020).

The main justification for this study is that the BRVAS does not incorporate a climate change factor built into it. It would appear to assume that the amount available will remain the same through 2050.

The non-conventional and conventional water reconciliation strategy options are the most viable options to meet the long-term future requirements for the WCWSS. For the conventional option, there is limited scope for additional development of surface water resources in the BR system. The surface water abstraction option will stem from transfer from neighbouring catchments, namely the Breede and Palmiet river systems. Consequently, in order to improve the diversification of the WCWSS water resources to address water resilience and lower severe risk and frequent water restrictions in the Western Cape, non-conventional water reconciliation options associated with seawater desalination, water reuse, and aquifer storage and recovery will be required.

2.5.4 The Vöelvlei Dam, and its Proposed Abstraction

The VD is in the Western Cape Province of South Africa (see Fig. 8). This dam was commissioned in 1952 (DWS, 2020), and its construction involved impounding the natural Vöelvlei Lake near Gouda. It is considered the first large water supply scheme located within the BR catchment area (DWS, 2012). Due to the very small size catchment of 40 km^2, the additional water was diverted from the neighbouring rivers such as the Klein Berg River. A small weir was constructed into a canal leading to the VD, which adds about 1.7 million m^3 of water daily (CGA, n.d). Currently, this dam is supplied by abstracted runoff from the 24 Rivers, Klein BR, and Leeu River catchments, through a system of canals (DWS, 2012). The VD supplies water to the Cape Town metropolitan areas, Swartland towns, and downstream users requiring irrigation water. The Voëlvlei Water Treatment Works (WTW) provide water to the CCT.

Figure 7: Representation of the existing VD outlet canal to the BR (DWS, 2012).

While other users obtain their water requirements from different nodes of the system, the West Coast District Municipality obtain the bulk of their water supply from the VD (DWS, 2012; DWS, 2020). In this regard, a larger Voëlvlei water yield, therefore, offers greater operational flexibility. This exceptional feature makes abstracting the WCWSS through the BRVAS scheme more valuable when compared to other options associated with surface water development.

Water quality in the BR poses a key challenge in terms of current and future water use opportunities, and any water abstraction from the river must be taken into consideration when it comes to the intended water use (DWS, 2012). As a result, water quality was analysed and an appropriate rule to guide the timing of winter abstractions has been considered. Currently, there are no red flags regarding water quality to prohibit the BRVAS implementation (DWS, 2012).

Figure 8: The Berg River Vöelvlei Abstraction Scheme location (DWS, 2012).

The BRVAS Phase One infrastructure incorporates a weir construction and intake works in the Breede River downstream of Sonquasdrift by Spes Bona. A 4 m^3/s pump station will help pump the surplus during winter flows, but this will only occur after or once the environmental water requirements in the downstream lower BR and estuary are met (DWS, 2012). Additionally, a 6.3 km long 1700 mm diameter pipeline will run from the pump station to the VD (DWS, 2020).

The feasibility study shows that a yield of 23 million m^3/a could be added to the WCWSS, with a 98% assurance of supply (DWS, 2020). The benefits of the BRVAS development will ensure that more additional water is available from VD through the proposed scheme. The additional water will be used to increase the supply assurance to the current users who receive their water from the VD. The proposed weir at the pump station intake will have a maximum height of 1 metre (m) over the riverbed, and will only cause minor effects on the water levels for a distance of 1 km upstream of the weir.

The Berg River Vöelvlei Abstraction Scheme (BRVAS) is an abstraction project planned by the DWS. This scheme involves the pumped abstraction of winter water from the beginning of April to September months each year, mainly from the BR, to help increase the yield in the existing off-channel VD (RSA, 2019). The abstraction of winter water can only occur immediately, once the downstream ecological water requirements (EWRs) of the river, as well as the estuary, have been fulfilled. The ecological Reserve with Category D, the river, has been accounted for in the operation and modelling of the scheme.

The Berg River Estuary Reserve requires a flow ranging between 0.6 m^3/s and 0.9 cubic metres per second (m^3/s) during the summer months (DWS, 2020; RSA, 2019). To help meet the required reserve inflow into the estuary, an extra flow ranging between 0.3 m^3/s and 0.6 m^3/s will need to be released from VD during the four months of summer (from December to March months of the year) (DWS, 2012). An assumption has already been made in the system modelling of the proposed scheme that an additional release of 0.5 m^3/s must be made from the VD for six months of summer (DWS, 2012).

A 4 m^3/s pump station with a stepped-pumping operating rule has been chosen (RSA, 2019). The choice of a 4 m^3/s pump was based on economic and water yield considerations (RSA, 2019). This pump size can deliver 23 million m^3 of water, compared to only 20 million m^3 that would be probable with a 6 m^3/s pump.

2.6 Summary

This chapter described in detail several key areas of water security, focusing on global, South African and SW Cape water security.

The main drivers of two types of water scarcity, namely physical and economic/socio-economic were explored in this chapter. The climate is shown to be a key component that gradually drives scarcity globally. In South Africa, water security is at risk due to an increase in population and a need for water resources to sustain economic growth. Additionally, threats are posed by CC, land-use changes, declining water quality, and catchment degradation. The severity of the 2015-2018 Cape Town drought in the SWC was intensified by a rainfall deficit that is the main driver behind the reduced surface availability. The rainfall anomaly led to a severe water crisis in this region. As a result, urgent action is needed for South Africa to start managing its limited water resources efficiently so as to ensure sustainable water security moving forward.

This chapter builds on the literature review associated with the adaptation options for water resources that were considered to provide solid evidence to the reader about the importance of adaptation options. The off-stream storage systems have been described along with relevant case studies that assessed the size and reliability of an off-stream storage system. Lastly, an in-depth description of the WCWSS and its operation, the reconciliation strategy, and its planning process was also provided. This includes the current and future water projections of the WCWSS, followed by the VD, and its proposed abstraction. To date, the sensitivity of the BRVAS to climate change has not been directly evaluated.

The chapter that follows describes the research methodology used in this study.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter focuses on the study's methodology, starting with a description of the study area, followed by a detailed description of the methodology, data collection, and analysis. An in-depth step-by-step description will be provided to lend more detail to the data collection and analysis.

3.2 The Study Area

The planned diversion site for the BRVAS is situated at Lorelei, just upstream of the gauging station G1H020 at Daljosafat along the BR catchment in the Western Cape Province in South Africa. The gauge G1H020 (latitude -33.70777° S and longitude 18.99111° E) is therefore the nearest to the area of the proposed abstraction point, where the abstraction will happen. The upstream catchment area at the gauging station is about 628 km^2 (DWS, 2011; DWS, n.d-a). This station was chosen because it is the only gauge station located near the proposed planned diversion site. Figure 9 demonstrates the location of the proposed BRVAS and the abstraction gauging site.

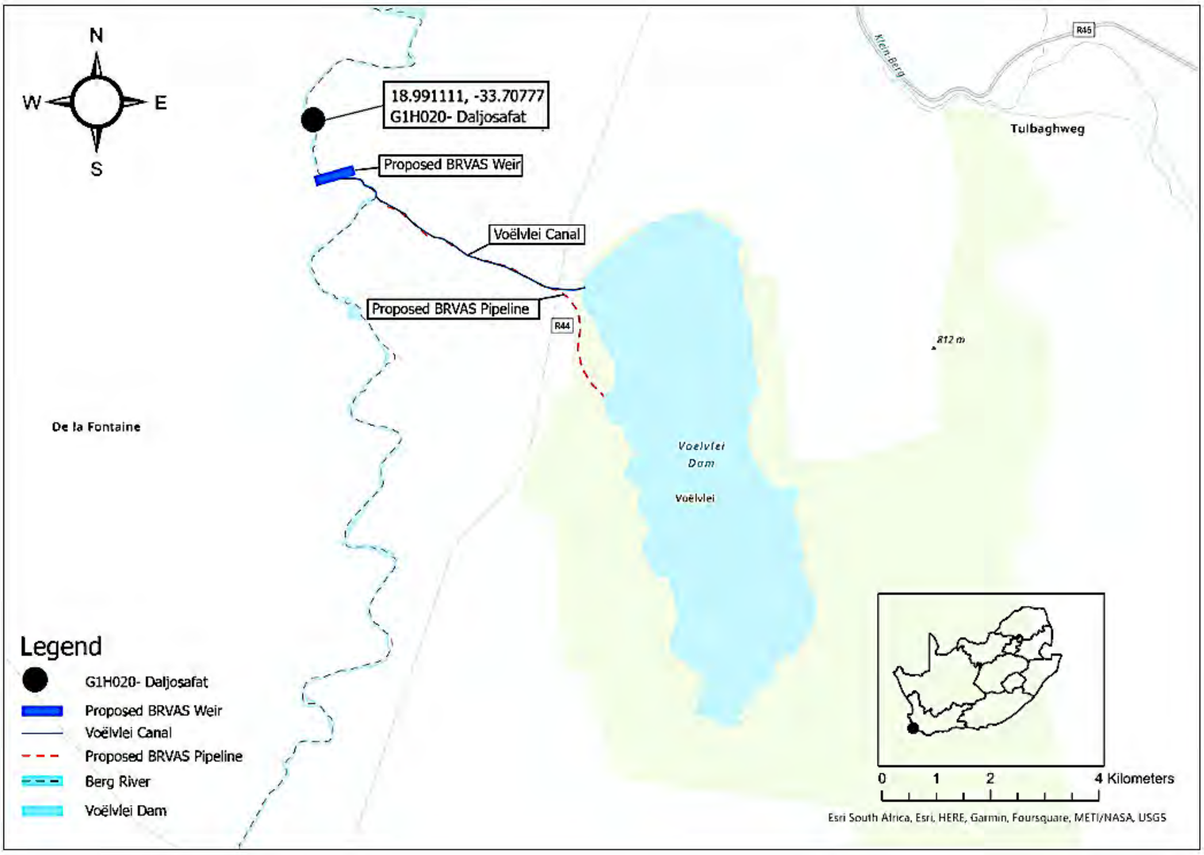


Figure 9: Proposed BRVAS and the abstraction site (Google Maps; Author).

The overall BR catchment is situated in the southwestern area of South Africa in the Western Cape Province, covering a total area of about 13000 km^2 (Umvoto, 2022). It sits between 23°45' latitude and 33°50' S and 18°15' longitude and 18°55' E (DWAF, 2009; WRC, 2006). This catchment system borders the Olifants or Doring Water Management Area (WMA) in the north, as well as the Breede-Gouritz WMA in the east. This system experiences a Mediterranean climate, and most of the rainfall takes place in the winter season. As much as 80% of the total annual rainfall has been estimated to start from the April-September months (DWAF, 2009), while there is enormous spatial variability in the mean annual precipitation and temperature within this area, due to differing topography in the low-lying coastal plain in the north-western section of the catchment and high mountain reaches in the eastern edge (Umvoto, 2022). The precipitation ranges from about 3000 mm/a south-east mountains to even less than 300 mm/a west as well as in the coastal plain (Cole et al., 2018b). The natural mean annual run-off (MAR) is approximately 1094 Mm^3/a (million cubic metres per year) 2.2% of the nation's total (Cole et al., 2018b), even though the present-day MAR is about 784 Mm^3/a, due to agricultural land use, small dams on private property for irrigation, and groundwater abstraction. The monthly evaporation varies from 40-50 mm in winter to 230-250 mm in summer (DWAF, 2009), due to the fact that the region is a semi-arid area.

3.3 Material and Methods

This section describes the methods, data collection and analysis.

3.3.1 Methods (Summary)

This study followed the following three steps to achieve its research, each of which is described in greater detail in subsequent sections of this chapter.

1) Describe the data used, and any processing of this data (e.g. bias correction of the projected river flows);
2) Describe the abstraction model – the operating rules and how these were coded in the abstraction model;
3) Analyse the outputs from the abstraction model – conversion into monthly and annual abstraction totals in terms of summary statistics and abstraction duration curves.

3.3.2 Data Collection

This section provides in-depth details about the data collection of this study.

3.3.2.1 Daily Observed Streamflow Data

The daily observed streamflow data from the 1967-2021 record length were retrieved from the DWS station gauge website.[3] This historical data is already available online, updated and reviewed, it gives daily mean flow. This observed data covers a period of 55 years.

3.3.2.2 Projected Future Daily Data

The projected future daily flow data were acquired from an existing study conducted on the future of water resources in South Africa for three different periods, the recent past from 1961-1990, the near future from 2015-2044, and the distant future from 2070-2099 (Schütte, Schulze & Clark, 2022). The daily simulated flow for these two periods, and for the "recent past", at the same gauge as the observed data, was extracted from the existing study. These data were then input into the Excel abstraction model described below. As a result, six models (see Table. 5) were produced in an Excel^{TM} spreadsheet. Daily data were captured in Excel and everything was recalculated automatically. We then began to examine whether the abstraction curve and the water abstraction amount in each year change in the future.

Table 5: Six climate change scenarios models with their full details (Schütte, Schulze & Clark, 2022).

The Six GCMs Models	
Model Acronym	**Full Name Modelling Centre**
ACCESS1-0	Australian Community Climate and Earth System Simulator
GFDL-CM3	Geophysical Fluid Dynamics Laboratory Coupled Model
MPI-ESM-LR	Max Planck Institute Coupled Earth System Model
NorESM1-M	Norwegian Earth System Model
CCSM4	Community Climate System Model

The emission scenarios used are the representative concentration pathways (RCP4.5 and RCP8.5) climate scenarios.

The downscaled CSIR climate data were used for input into the Agricultural Catchments Research Unit (ACRU) hydrological model, to simulate streamflow. The conformal-cubic

[3] See https://www.dws.gov.za/Hydrology/Verified/hymain.aspx

atmospheric model (CCAM) model's ability to realistically simulate present-day Southern African climate has been extensively demonstrated (Schütte, Schulze & Clark, 2022). An important feature of the downscaling done by the CSIR was that the model was forced with biased-corrected sea-surface temperatures (SSTs) and sea-ice fields from the GCMs (Katzfey et al., 2009). A simple monthly scale mean bias-correction procedure was also applied, using average monthly temperature and rainfall. The daily minimum and maximum temperatures were also bias-corrected using a similar procedure. The result was a set of high-resolution climate scenarios across all of South Africa at about 8 km grid resolution for both precipitation and temperature, including changes in extreme temperature and rainfall that were to derive risks for floods, drought, water security, and wildfires. These data are also now available in the CSIR Greenbook.[4]

A recent study on the part of the Water Research Commission (WRC K5/2833) undertook additional downscaling of the Greenbook climate scenarios and hydrological modelling using ACRU to determine potential climate change impacts on the hydrological yield of different hydro-climatic zones in South Africa (Schütte, Schulze & Clark, 2022). This study considered the resulting daily climate simulations for both RCP 4.5 and RCP 8.5, but was only able to undertake further analysis on the RCP 8.5 scenario. This additional analysis included additional downscaling and bias correction of daily rainfall and temperature projections at quinary catchment scale across the whole of South Africa, including Lesotho and Eswatini. The resulting daily climate scenarios were then combined with an updated ACRU database of natural and current-day land cover types to produce daily time series data for not only precipitation and temperature, but also potential (PET) and actual evapotranspiration (ET). These were then used to determine the likely impact on daily catchment runoff, accumulated streamflow, design streamflow events representing both high and low flow conditions, soil water drainage to groundwater, baseflow and hydrological yield under both natural and current land cover.

The simulated daily time series of cumulative streamflow (CELRUN) for the historic time period, near future and far future were extracted from the ACRU results for the quaternary catchment G10D3, that is, the catchment in which the Daljosafat stream gauge and proposed

[4] See https://greenbook.co.za

BRVAS is located. The units of streamflow in ACRU are mm/d, and in order to convert these to m^3/s the output time series were first normalised by dividing them by the average daily streamflow for the historic period, which could then be multiplied by the mean daily flow rate, derived from the observed streamflow record at the Daljosafat streamflow gauge. The hydrological model ran at 8km x 8km grid resolution for both precipitation and temperature.

3.3.2.3 Bias correction or Normalisation Process of the Projected River flows

The bias correction/normalisation process is known as a statistical procedure that is used to adjust data/models to help eliminate/reduce systematic errors or biases that may be present. Bias can develop from different sources associated with modelling assumptions, or measurement errors, and might lead to misleading or inaccurate results in the data analysis. The main aim of bias correction is to make data/models more reliable and accurate by mitigating and accounting for these biases, thereby enhancing the quality of information used mainly for research decision-making purposes.

The following is the description of how the process of bias correction/normalisation was achieved:

1) Calculate the ratio of the mean flow in the model to that observed over the period of 1965-1990 (the period that is common to observed data and models); and
2) Divide all model values by this ratio (for bias), for all periods (1961-1990; 2015-2044; 2070-2099).

This needs to be done because the operating rules are based on observed flow, and so biases in simulated flows will bias the climate change projection results, if not corrected.

Normalisation was done for each of the six models against its own 1965-1990 mean, then multiplied by the normalised value by the 1961-1990 mean. Thereafter, the biased corrected flow was calculated by multiplying the normalised average value by the observed average value of 10.093. All the calculated biased corrected datasets were then copied and pasted to the existing BRVAS Excel abstraction model spreadsheet to replace the observed data with the biased corrected flow data, and all calculations in a spreadsheet were automatically recalculated the daily flow threshold amounts, total abstraction and outflow, as well as year and month in which the abstraction happens. This procedure was adopted for the recent past of 1961-1990, near 2015-2044 and distant future of 2070-2099 time periods. The GCM is the Acc, Ccs, Gfd, Mpi and Nor, whereas the RCP is 085 (for RCP8.5).

In short, observed flow data already in m^3/s were captured in Excel. Averages of this data were calculated to be 10.093 m^3/s. Normalised data were also captured, and the average of 1.004 m^3/s was calculated. To get a normalised model daily flow, the normalised value was divided by the normalised average of 1.004 m^3/s. To calculate biased corrected flow, the normalised model daily flow value was multiplied by the observed average value of 10.093 m^3/s.

3.3.2.4 Accuracy of the Bias Correction Using Q-Q plots

The accuracy of the bias correction was assessed by producing Q-Q plots for bias-corrected flow versus observed flow for the common period, 1965-1990. The key reason why the Q-Q plots were in this study was to determine whether the simple bias correction resulted in a reasonable representation of low flows, but also the wider range of flows from low to high. Only the mean bias was adjusted, where the model biases might be different at low, median and high flows; in which case the normalisation by the mean bias might not result in a completely robust bias correction.

To generate the quantile-quantile (Q-Q) plots, the biased corrected daily flow data were for 23 years of record from 1967-1990, and compared to the Daljosafat streamflow gauge daily data for the same years of record (these are the common overlapping years). To compare the biased corrected flow against the observed flow, the biased corrected flow and observed flow datasets were sorted from the smallest to highest values, and plotted against each other (no formula/equation was used). The Q-Q plot entails assessing the linearity of points on the graph, identifying patterns, considering outliers, and looking for deviations from linearity. These observations offer insight into the appropriate fit between the observed flow data, as well as the expected distribution.

3.3.3 Excel Abstraction Model

This section describes how the abstraction model works.

3.3.3.1 Observed Streamflow data

An abstraction model for BRVAS was set up using Excel. The abstraction model takes daily observed flow as input and determines the abstraction amount on any single day, according to the operating rule. This model was used because it helps to estimate the amount of water that can be abstracted/ withdrawn from the water source, such as a river/ stream, for different purposes associated with industrial processes, municipal water supply and irrigation. That is why this basic model was created to estimate water abstraction.

The created sheets in this abstraction Excel served to input the necessary data of the observed flow and determine the water abstraction amount on any single day, based on the operating rule.

Excel formulas were used to calculate the total amount of water available for abstraction, based on the input daily observed streamflow data.

3.3.3.2 Operating Rules For Excel Abstraction Model

The operating rules are crucial to ensuring responsible and sustainable water use, such that the abstraction of water does not harm downstream users and aquatic ecosystems. The rules are proposed to balance the need for water abstraction to protect the ecosystems and water resources for the long term.

The operating rules for this Excel model were created to only abstract water in the winter season from June to October (five months) of a specific year, and when the flow reaches a certain volumetric threshold. Seasonal winter abstraction was chosen, because the SWC region gets its peak rainfall during the winter period. The abstraction of this winter rainfall for BRVAS is estimated to add a water yield of about 23 million m^3 per annum to the WCWSS in order to help during drought periods. Operating rules for understanding how the Excel abstraction model works are shown in Table 6.

Table 6: Two operating rules for understanding how the Excel abstraction model works (Author).

Operating rules for understanding how the EXCEL model works	
June to October rule.	Only abstract water in the winter months season from June to October (month 6-10).
Thresholds for daily abstraction rule.	If the flow are 2 m^3/s thresholds, only withdraw an amount of 1 m^3/s during the winter abstraction months of June to October (only in months 6,7,8,9 and 10) and leave 1 for ecological reserve. In other words, when the flow exceeds or reaches the 2 m^3/s threshold extract 1 m^3/s and leave the remaining flow for the surrounding ecosystem. The flow thresholds are particular discharge levels or flow rates in streams, rivers/ water bodies that trigger significant hydrological and ecological changes.
	If the flow are 3 m^3/s thresholds, only abstract 1 m^3/s and leave the rest 2 m^3/s for ecological reserve.
	If the flow are 4 m^3/s thresholds, only abstract 1 m^3/s and leave 3 m^3/s for the ecological reserve.
	If the flow are 5 m^3/s thresholds, then only abstract 1 m^3/s and leave 4 m^3/s for ecological reserve.

3.3.3.3 Coding of Data into Excel Abstraction Model

Coding of data into the Excel abstraction model involves structuring and organising the data to allow the model to perform simulations/calculations. Data was organised into rows and columns. Observed historical streamflow raw data (values) was entered into the designated cells. To ensure consistency, data was checked, and followed the correct units and format for accurate calculations. Excel functions and formulas were used to create equations that were used to calculate the preferred outputs based on the input streamflow data (e.g. formulas were used to calculate flow thresholds, abstraction totals, outflows, etc.). In order to verify the results, the model outputs were checked against the known values. Known values in this context refer to the historical streamflow data or any other reference data for which the model outputs are being compared. These are the values that are already known or have been previously calculated, and they are used to verify the accuracy of the model's outputs. This was achieved to ensure accuracy. Calculations were validated so as to ensure that they aligned with the expected outcomes. To produce a visual representation of the data, as well as outputs of the model, charts/ graphs were created to help understand the patterns/ trends within the data.

To achieve the coding of data into the Excel abstraction model, equations were used to calculate the daily flow amount and monthly and annual totals of both the streamflow data and the projected river flow. The IF statement function was used to achieve the daily analysis and the SUMIFS function was used to achieve the monthly and annual analysis.

Figures 11 and 12 shows the Excel screenshot presenting the actual amounts and formulas used. Table 7 shows the BRVAS Excel model flow steps. This table is an easy visual picture that explains how the model works, including some formulas used in the spreadsheet. It demonstrates in detail the steps used to calculate the daily flow amount, and monthly and annual totals.

Table 7: BRVAS Excel model flow steps (Author).

The BRVAS EXCEL Model	
Steps Used to Calculate Daily Abstraction Amount, Monthly and Annual Totals	**EXCEL Equation (s) for this Step**
Check if the month is June – October.	=ROUNDDOWN(((A5/10000)-FLOOR.MATH(A5/10000))*100,0) Where: A5 is the cell that contains the date YYYMMDD format in Column A to YYYY, MM equivalents in columns I and J, a row which can be checked in the month in J-O. This is done for each daily amount, where row 5 in the EXCEL sheet is the first day of the record.
Check if the flow is above a certain threshold, then abstract and calculate an IF function statement.	=IF($B5>C$2,C$4,0) Where: $B5 contains the observed flow value. C$2 is a cell that has the flow threshold number. C$4 comprises of abstraction amount number.
Calculate the total abstraction amount.	=IF(AND(J5>=$J$2,J5<=($J$3)),SUM(C5:F5),0) Where: J5 presents the months. $J$2 represent the winter abstraction month 6 (June). $J$3 denote the winter abstraction month 10 (October). C5:F5 signify the flow thresholds and abstraction amounts.
Calculate the total outflow	=B5-G5 Where: B5 is the inflow and G5 is a cell that encloses the total abstraction amounts.

The following is a description of how the daily amounts were calculated:

The IF statement function was used to achieve the daily amounts using this formula to calculate/ find the flow thresholds abstraction amounts =IF($B5>C$2,C$4,0). This formula evaluates a condition and returns one of the two values based on whether the condition is true or false where $B5 refers to a cell in column B and row 5 contains the observed flow value 0.72, C$2 refers to a cell in column C and row 2 have the flow value of 2 thresholds, C$4 refers to a cell in column C and row 4 have the abstraction amount of 1. This formula checks if the value in cell B5 is greater than the value in cell C2, where, if this condition is true, it returns the value from cell C4, and if the condition is false, it then returns 0.

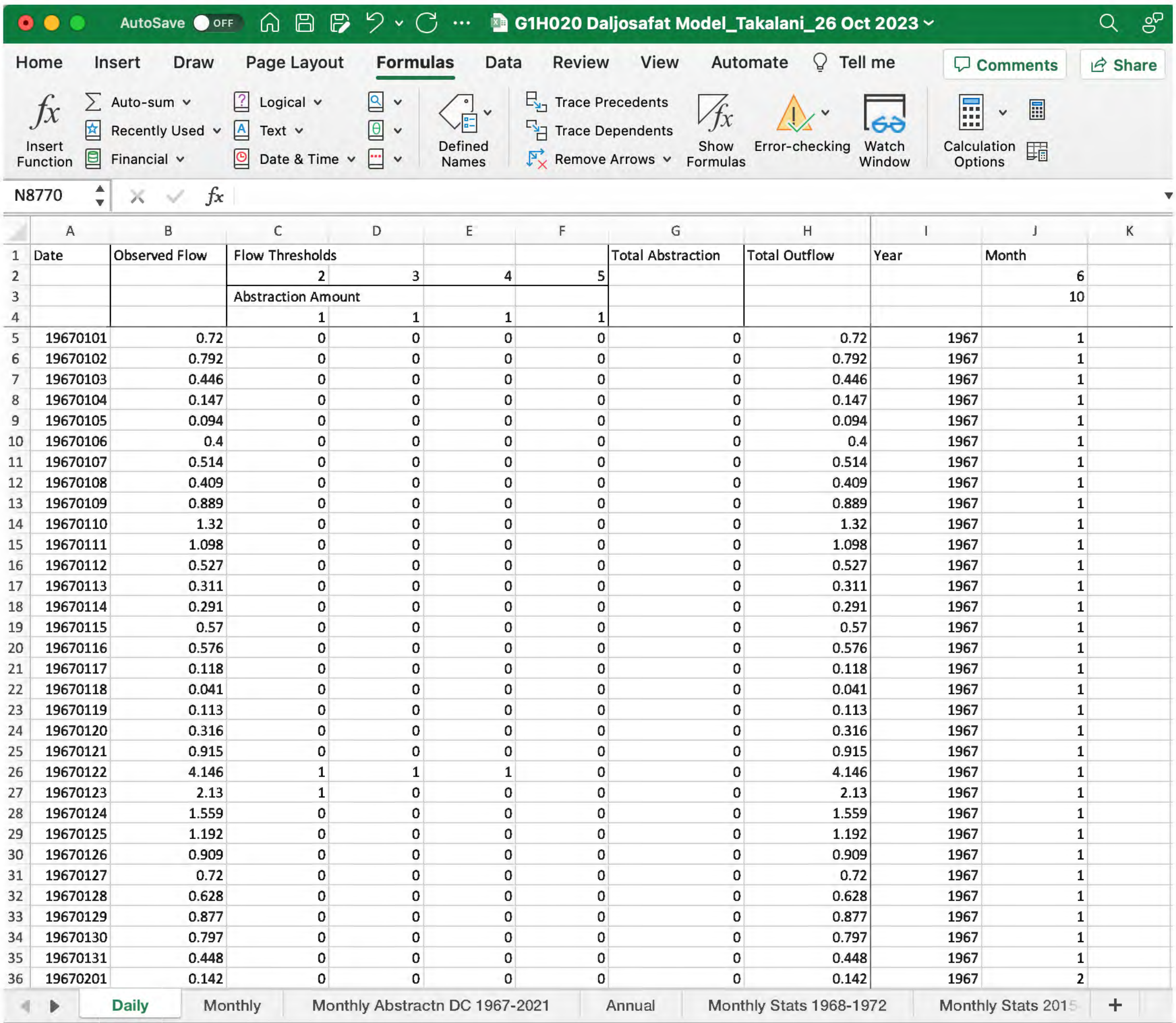
To check two conditions, the AND function formula was used to ascertain the daily total abstraction amount =IF(AND(J5>=$J$2,J5<=($J$3)),SUM(C5:F5),0). This formula was used to calculate the total abstraction amounts, where J5 signifies a cell in column J and row 5 contains the abstraction month, which is 1, $J$2 presents a cell in column J, and row 2 has winter abstraction month 6. $J$3 is a specific cell in column J and row 3 contains the winter abstraction month 10. C5:F5 presents a range of cells from column C to column F in row 5 having the calculated abstraction amounts of 0. This formula checks whether the value in cell J5 is greater than or equal to the value in cell 2, and also checks if the value in cell J5 is less than or equal to the value in cell J3. If the value in cell J5 is within the range defined by J2 and J3, it then calculates the sum of the values in cells C5 through F5 otherwise return 0.

To check the difference between the values in two cells, this formula was used to find the daily total outflow =B5-G5. This simply means that Excel subtracts the value in G5 (contains the total abstraction value of 0) from the value in cell B5 contains the observed flow of 0.72, where B5 is the cell in column B and row 5, and G5 refers to a cell in column G and row 5. This formula finds the difference between the values in the two cells.

To round down the value in cell A5 divided by 10000 to the nearest whole number in order to find the year we use this formula =ROUNDDOWN(A5/10000,0). Where A5 is a cell in column A and row 5 contains the date (19670101). 10000 is a fixed number. This formula gives the value in cell A5 by 10000 and then the ROUNDDOWN function was used to round down the value to the nearest whole number. 0 specifies that zero only decimal places are needed.

To calculate the abstraction month, we used the ROUNDDOWN function formula to calculate the percentage component of a value after removing its whole number part:
=ROUNDDOWN(((A5/10000)-FLOOR.MATH(A5/10000))*100,0). A5 is a cell in column A and row 5 contains the date (19670101). Whereas 10000 is a fixed number. Where A5/10000 divides the value in cell A5 by 10000, this actually converts a large number into a decimal between 0 and 1 depending on the value in A5, which is the date. The FLOOR.MATH(A5/10000) subtract the value from the original decimal to obtain the fractional part of the decimal. We then multiply the fractional part by 100 and convert it into a percentage. The ROUNDDOWN function is applied to round down the percentage to the nearest whole number with zero decimal places.

Daily amounts are then summed to monthly and annual totals, using the SUMIFS function.



	A	B	C	D	E	F	G	H	I	J	K
1	Date	Observed Flow	Flow Thresholds				Total Abstraction	Total Outflow	Year	Month	
2			2	3	4	5				6	
3			Abstraction Amount							10	
4			1	1	1	1					
5	19670101	0.72	0	0	0	0	0	0.72	1967	1	
6	19670102	0.792	0	0	0	0	0	0.792	1967	1	
7	19670103	0.446	0	0	0	0	0	0.446	1967	1	
8	19670104	0.147	0	0	0	0	0	0.147	1967	1	
9	19670105	0.094	0	0	0	0	0	0.094	1967	1	
10	19670106	0.4	0	0	0	0	0	0.4	1967	1	
11	19670107	0.514	0	0	0	0	0	0.514	1967	1	
12	19670108	0.409	0	0	0	0	0	0.409	1967	1	
13	19670109	0.889	0	0	0	0	0	0.889	1967	1	
14	19670110	1.32	0	0	0	0	0	1.32	1967	1	
15	19670111	1.098	0	0	0	0	0	1.098	1967	1	
16	19670112	0.527	0	0	0	0	0	0.527	1967	1	
17	19670113	0.311	0	0	0	0	0	0.311	1967	1	
18	19670114	0.291	0	0	0	0	0	0.291	1967	1	
19	19670115	0.57	0	0	0	0	0	0.57	1967	1	
20	19670116	0.576	0	0	0	0	0	0.576	1967	1	
21	19670117	0.118	0	0	0	0	0	0.118	1967	1	
22	19670118	0.041	0	0	0	0	0	0.041	1967	1	
23	19670119	0.113	0	0	0	0	0	0.113	1967	1	
24	19670120	0.316	0	0	0	0	0	0.316	1967	1	
25	19670121	0.915	0	0	0	0	0	0.915	1967	1	
26	19670122	4.146	1	1	1	0	0	4.146	1967	1	
27	19670123	2.13	1	0	0	0	0	2.13	1967	1	
28	19670124	1.559	0	0	0	0	0	1.559	1967	1	
29	19670125	1.192	0	0	0	0	0	1.192	1967	1	
30	19670126	0.909	0	0	0	0	0	0.909	1967	1	
31	19670127	0.72	0	0	0	0	0	0.72	1967	1	
32	19670128	0.628	0	0	0	0	0	0.628	1967	1	
33	19670129	0.877	0	0	0	0	0	0.877	1967	1	
34	19670130	0.797	0	0	0	0	0	0.797	1967	1	
35	19670131	0.448	0	0	0	0	0	0.448	1967	1	
36	19670201	0.142	0	0	0	0	0	0.142	1967	2	

Figure 10: Excel screenshot with the actual amounts of the observed streamflow gauge – Daljosafat (Author).

This screenshot shows the first few lines and sheets of the model in Excel, showing the actual amounts. Sheet 1 covers the daily observed stream flow – Daljosafat data, where: sheet 2 is the monthly flow; sheet 3 contains the monthly abstraction duration curve from 1967-2021; sheet 4 encompasses the annual data; sheet 5 has the monthly statistics data from 1968-1972; sheet 6 enclose the monthly statistics data from 2015-2019, etc.

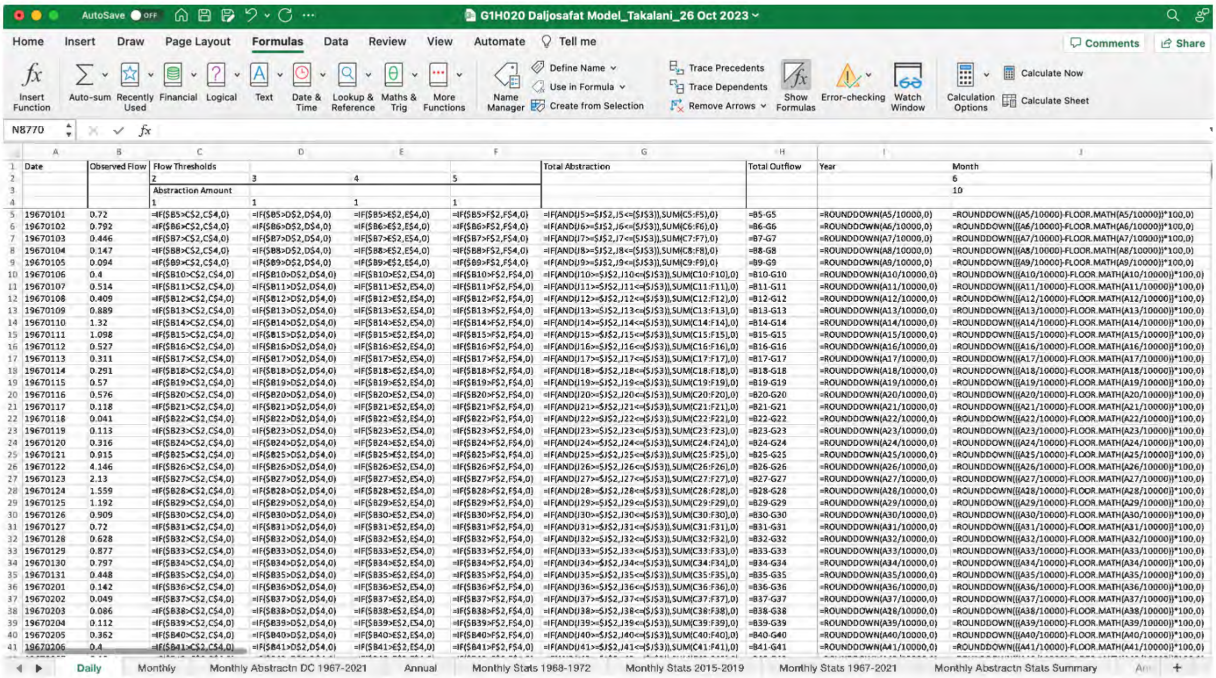


Figure 11: Excel screenshot showing the actual formulas of the observed streamflow gauge – Daljosafat (Author).

This figure also represents the first few lines of the model in Excel presenting the actual formulas with different sheets that calculated the monthly and annual abstraction etc.

The same procedure used to analyse the streamflow data was also exercised to analyse the projected river flow data of three different periods, the recent past from 1961-1990, the near future from 2015-2044, and the distant future 2070-2099. The main techniques used when analysing data include abstraction duration curves, abstraction statistics, etc.

3.3.4 Analysis of Outputs from the Abstraction Model

The outputs of the Excel abstraction model are the outcomes/ results produced by the formulas, calculations and analysis performed within this Excel spreadsheet. In this study, the outputs created from this model include the monthly and annual flows. To get the numeric results, the sum of the range of values was calculated through the SUM function. The average of a set of numbers was calculated by the AVERAGE function. Maximum and minimum values were identified by the MAX and MIN functions. Percentiles were computed by using PERCENTILE.INC function. This section provides information on the post-processing of daily abstractions to get monthly and annual flows (see Table. 8).

Table 8: Daily abstraction post-processing to get monthly and annual flows (Author).

Apply the formula to cells in different spreadsheet tabs to calculate the monthly total flow by summing up the daily values for each month.	
Calculate the monthly observed flow.	=SUMIFS(Daily!$B:$B,Daily!$I:$I,Monthly!$A2,Daily!$J:$J,Monthly!$B2) Where: $B:$B includes a range list of observed flow values in column B in the Daily sheet. $I:$I encloses the criteria range of year in column I from 1967-2021 in the Daily sheet. $A2 this cell has the year (1967) in the Monthly sheet. $J:$J column that comprises months in the Daily sheet. $B2 is a cell that has the month 1 (January) in the Monthly sheet.
Calculate the monthly total abstraction.	=SUMIFS(Daily!$G:$G,Daily!$I:$I,Monthly!$A2,Daily!$J:$J,Monthly!$B2) Where: $G:$G is the column that comprises the total abstraction amount in the Daily sheet.
Calculate the monthly total outflow.	=SUMIFS(Daily!$H:$H,Daily!$I:$I,Monthly!$A2,Daily!$J:$J,Monthly!$B2) Where: $H:$H a column that encompasses the total outflow in the Daily sheet.
Apply the formula to cells in different spreadsheet tabs to calculate the annual total flow by summing up the monthly values for each year.	
Calculate the annual observed flow.	=SUMIFS(Monthly!$C:$C, Monthly!$A:$A, Annual!$A2) Where: $C:$C column that refers to the observed flow value in the Monthly sheet. $A:$A column that specifies the year in the Month sheet from 1967-2021.
Calculate the annual total abstraction.	=SUMIFS(Monthly!$D:$D, Monthly!$A:$A, Annual!$A2) Where: $D:$D is a column that shows the total abstraction amounts values in the Monthly sheet.
Calculate the annual total outflow.	=SUMIFS(Monthly!$E:$E, Monthly!$A:$A, Annual!$A2) Where: $E:$E column that presents total outflow values in the Monthly sheet.

The following is the description of how the post-daily abstraction was processed to get monthly and annual flows:

The SUMIFS function was used to achieve the post-daily processing to get monthly flows using this formula =SUMIFS(Daily!$B:$B,Daily!$I:$I,Monthly!$A2,Daily!$J:$J,Monthly!$B2). This formula calculates/ finds the sum of numbers in the Daily sheet. It provides the sum of all values that meet the criteria. Where SUMIFS signifies an Excel function, it is normally used to sum numbers that meet multiple criteria. Daily!$B:$B refers to the range of numbers (observed flow values) required to be summed, which is column B in the Daily sheet. Daily!$I:$I is the first criterion range (the year 1967-2021), which is in column I in the Daily sheet. Monthly!$A2 specifies the first criterion in cell A2 (the year 1967) in the Monthly sheet, this formula sums the numbers/values from the Daily sheet, where the corresponding number in Daily column I (the year 1967-2021) matches the number in Monthly cell A2 (the year 1967). Daily!$J:$J is the second criterion range, which is Column J (months 1-12 of a specific year) in the Daily sheet. Monthly!$B2 relates to a second criterion, which is in cell B2 (month 1-12) in the Monthly sheet. This formula is summing numbers/values from the Daily sheet, where the corresponding number in Daily sheet column J (month 1-12) matches the number in the Monthly sheet cell B2 (Month 1).

The formula =SUMIFS(Daily!$G:$G,Daily!$I:$I,Monthly!$A2,Daily!$J:$J,Monthly!$B2) was used to sum values in column G in the Daily sheet but only for rows that meet two criteria. Criteria 1, the number in the corresponding row in column I (the year 1967-2021) in the Daily sheet must match the number in cell A2 (year 1967) in the Monthly sheet. Criteria 2, the number in the corresponding row column J (month 1-12) in the Daily sheet must match the number in cell B2 (month 1) in the Monthly sheet, where Daily!$G:$G is the range of numbers that are required to be summed up in column G (total abstraction) in the Daily sheet.

To sum value in column H in the Daily sheet. but only for the row that meets two criteria, the formula =SUMIFS(Daily!$H:$H,Daily!$I:$I,Monthly!$A2,Daily!$J:$J,Monthly!$B2) was used. Criteria 1, the number in the corresponding row in column I (the year 1967-2021) in the Daily sheet must match the number in cell A2 (year 1967) in the Monthly sheet. Criteria 2, the number in the corresponding row column J (month 1-12) in the Daily sheet must match the number in cell B2 (month 1) in the Monthly sheet. Where Daily!$H:$H signifies the range of numbers that needed to be summed in column H (total outflow) in the Daily sheet.

The SUMIFS statement function was used to attain the post-daily processing to obtain <u>annual flows</u> using this formula =SUMIFS(Monthly!$C:$C, Monthly!$A:$A, Annual!$A2). This is an Excel formula that is used to calculate the sum of numbers in the Monthly sheet grounded on a single criterion. Where SUMIFS refers to an Excel function that is utilised to sum numbers that meet certain criteria. Monthly!$C:$C signifies the range of numbers that are required to be summed up in column C (observed flow) in the Monthly sheet. Monthly!$A:$A relate to a criterion range in column A (year 1967-2021) in the Monthly sheet. Annual!$A2 specifies the criteria in cell A2 (year 1967) in the Annual sheet. This formula is summing numbers from the Monthly sheet, where the corresponding number in the Monthly column A (year 1967-2021) matches the number in cell A2 (year 1967) in the Annual sheet.

To sum the values in column D (total abstraction) of the Monthly sheet, but only for the rows where the value/number in the corresponding row in column A (the year 1967-2021) in the Monthly sheet matches the number in cell A2 (the year 1967) in the Annual sheet, this formula was used =SUMIFS(Monthly!$D:$D, Monthly!$A:$A, Annual!$A2), where Monthly!$D:$D refers to the range of numbers that are required to be summed up in Column D (total abstraction) of the Monthly sheet.

To sum the numbers in column E (total outflow) in the Monthly sheet, but only for the rows where the value/number in the corresponding row in Column A (the year 1967-2021) in the monthly sheet matches the numbers in cell A2 (the year 1967) in the Annual sheet, this formula was used =SUMIFS(Monthly!$E:$E, Monthly!$A:$A, Annual!$A2). Monthly!$E:$E denotes the range of numbers that needed to be summed in Column E (total outflow values) of the Monthly sheet.

3.3.5 Analysis Methods

The analysis methods used in this study include the monthly abstraction duration curves for simulated abstraction amounts, and flow duration curves for river flow; annual total abstraction; and annual and monthly abstraction statistics, such as average, maximum, minimum, median, 25th percentiles and 75th percentiles.

3.3.5.1 Flow Duration Curve and its calculation process

The main purpose of a flow duration curve (FDC) is to show the percentage of time/ duration that a particular flow rate is exceeded/equalled. Also, it offers insights into the frequency and duration of different flow conditions. The FDC has been deemed one of the key tools used in hydrology. This is because it describes the relationship between the magnitude and frequency of streamflow (Castellarin et al., 2004) over a given period (Leong & Yokoo, 2021). The FDC is applied to solve a lot of hydrological issues associated with hydropower generation, water quality assessment, water allocation and habitat suitability, water-use assessment, and river and/or reservoir sedimentation (Castellarin et al., 2004). It is also a graphical tool, used in water resources engineering and hydrology to characterise and analyse the behaviour of a stream or river, and give a thorough graphical view distribution of streamflow variability or river discharge at a specific site (Zhang, 2017). The y-axis of the FDC presents the corresponding flow values, whereas the x-axis exhibits the exceedance probability ranging from 0%-100 percent. By assessing the FDC, water resource professionals and hydrologists can make valuable assessments regarding the magnitude and frequency of both low and high flows. These flows are highly significant for flood risk assessments, water resources management, and hydraulic structure designs associated with bridges and dams.

The following is the process of how FDC was calculated:

Step 1) The monthly total abstraction amount (m^3/s) data for the period of 1967-2021 was sorted in Excel from the largest to the smallest value. The given discharge was arranged in descending order.

Step 2) A new column called Rank was created which is denoted by the letter (n), giving the rank from 1-275, which is the number of events for the record period. The total number of ranks is N=275. Assigned the discharge with a respective rank number from 1-275.

Step 3) Another new column called Frequency was created denoted by (F), to find the frequency from the total number of Rank. To obtain the frequency total number of Rank was divided by Rank value.

$F = N/n$……………………………………………………………………………………(1)

Where F refers to the frequency.

N is the total number of Rank values which is 275.

n is the rank value from 1-275.

Step 4) The probability of exceedance (P) column was created and denoted by (1/F)*100. This calculates the probability of exceedance (%).

$P = 1/F*100$………………………………………………………………………………(2)

Where P signifies the probability that a particular flow rate will be equalled/ exceeded (%) of time.

The representation of the FDC was then produced/plotted using the discharge values and the probability of exceedance values. Discharge (m^3/s) is on the y-axis and the x-axis denotes the percentage probability of exceedance (%). The percentage of probability exceedance counts amounts to 100.

3.3.5.2 Monthly and Annual Abstraction Statistics and its Calculation Process

The purpose of monthly and annual abstraction statistics is to track the amount of water being abstracted over specific periods from the abstraction point. Based on this study, the monthly/ annual total abstraction statistics use quantitative data, as well as information associated with the withdrawal or abstraction of water, and a bit of inflow and outflow from the abstraction point within a specified period e.g. months or 1 year. The monthly/annual abstraction statistics provide a comprehensive view into the amount that can be abstracted or taken from stream/river/reservoir monthly/annually in the winter abstraction months of June-October for different purposes, such as industry, public water supply, agriculture, and other uses. This can help to identify areas facing water scarcity, high water demand, and overexploitation. The monthly/annual abstraction data helps to assess the sustainability of water use, the effectiveness of water management strategies, and climate impact variability on water resources. The statistics provide a quantitative basis for understanding potential impacts on the environment, water availability, and usage patterns. The statistics help stakeholders and authorities to make informed decisions associated with water allocation, sustainable water management practices and conservation measures.

The monthly and annual total abstraction statistics calculated comprise the min, Q1 (first quartile), median, Q3 (third quartile), max, and average. Table 9 describes the statistical analysis of the monthly and annual abstraction of this study.

Table 9: Example of statistical analysis of the monthly and annual abstraction (Author).

Calculated Statistics	Description of the Formula Used.
AVERAGE	=AVERAGE(B2:B6) Where: B2:B6 refers to an array of cells in column B from cell B2-B6. AVERAGE calculates the average of an array of numbers.
MAX	=MAX(B2:B6) Where: MAX is an EXCEL function that is used to return the highest number in a set of numbers.
MIN	=MIN(B2:B6) Where: MIN is a function that is utilised to calculate the minimum or smallest number in the array from cell B2-B6.
MEDIAN	=MEDIAN(B2:B6) Where MEDIAN is a function that returns the median, which is known as the middle number of a set of values.
Q1	=PERCENTILE.INC(B2:B6, 0.25) Where: PERCENTILE.INC is a function that returns the K-th percentile of numbers in an array. 0.25 symbolises the 25^{th} percentile.
Q3	=PERCENTILE.INC(B2:B6, 0.75) Where 0.75 refers to the 75^{th} percentile.

The following are descriptions of formulas used to calculate the monthly abstraction statistics:

The Excel formula =AVERAGE(B2:B6) was used to find the average of the numbers/values (monthly abstraction statistics of winter abstraction months 6-10) in the array from cell B2-B6; where B2:B6 signifies the range of cells in column B (the min column), from cell B2-B6, giving a total average of 75. This formula takes over the numbers in cells B2 (46), B3 (73), B4 (114), B5 (106), and B6 (34) adds them together, and then divides the sum by the value of cells in the array. The AVERAGE function is an essential tool for reporting and data analysis.

The =MAX(B2:B6) formula calculates the maximum or largest value in the array from cells B2-B6, where MAX is a function that returns the largest number in a set of numbers. The total MAX calculated from cell B2-B6 is 114.

This Excel formula =MIN(B2:B6) is used to calculate the minimum/ smallest number in the array from cell B2-B6. Where MIN refers to a function that is used to return the lowest number in a set of values. The total MIN value calculated from cell B2-B6 is 34. The MIN function is considered a power tool for decision-making and data analysis in Excel.

The formula =MEDIAN(B2:B6) was used to find the median of the numbers in the array from cell B2-B6. MEDIAN signifies a function that returns the median, which is well-known as the middle number of a set of values. The calculated median from cell B2-B6 is 73. This function is valuable when dealing with data wherein the average (mean) might be influenced by extreme values, since the median is less sensitive to outliers. The median is used in data and statistics analysis to provide a robust/ strong measure of central tendency.

=PERCENTILE.INC(B2:B6, 0.25) formula was utilised to calculate the 25th percentile, which is acknowledged as the first quartile of the numbers in the array from cell B2-B6. PERCENTILE.INC represents the function that returns the k-th percentile numbers in an array. It sorts the numbers in the specific array in ascending order, and then calculates the number at the position that corresponds well to the 25th percentile, or 0.25 (25%). The calculated 25th percentile (Q1) from cell B2-B6 is 46.

This Excel formula =PERCENTILE.INC(B2:B6, 0.75) was used to determine the 75th percentile recognised as the third quartile of numbers in the array from cell B2-B6. Where 0.75 is the 75th percentile (Q3). The calculated 75th percentile (75%) from cell B2-B6 is 106.

The calculations for both the annual abstraction and for individual months of the year are similar. The different statistics used in this study summarise the spread of abstraction amounts in any given year or month. As the lowest 25%, or quarter value, the 25th percentile provides the lowest abstraction amount in any of one month/year, giving a sense of the amounts available during drought years, or the reliability abstraction amount for use in water resource modelling. The same analysis was done for monthly and annual values of the observed streamflow and projected river flow.

The following codes were used to calculate the monthly statistics for the 2015-2019 drought period (observed streamflow gauge - Daljosafat):

The MIN function, together with the IF statement as well as range operations was used to calculate monthly statistics for 2015-2019. =MIN(IF(Monthly!$B$578:$B$637=A2, Monthly!$D$578:$D$637)) code was used to find the minimum value in column D in the "Monthly" sheet, centred on a condition in Column B. Monthly!$B$578:$B$637 is the array in Column B (months 1-12) in the "Monthly" sheet from rows 578-637. Monthly!$D$578:$D$637 refers to the array in Column D (total abstraction) in the "Monthly" sheet from rows 578-637. A2 is a cell, and the formula helps to determine whether the numbers in the specific array in column B are equal to the numbers in cell A2. IF(Monthly!$B$578:$B$637=A2, Monthly!$D$578:$D$637) code indicate range operation, and is used to create a range of numbers from column D where the corresponding numbers in column B are equal to the number in cell A2. If the condition is TRUE, it takes in the numbers from Column D, or else, it includes a blank space. MIN(IF(….)) is used to calculate the minimum number from the range of numbers obtained centred on the condition order.

=PERCENTILE.INC(IF(Monthly!$B$578:$B$637=A2,Monthly!$D$578:$D$637),0.25) code was exercised to calculate the 25th percentile (Q1) of numbers in column D (total abstraction) in the "Monthly" sheet from rows 578-637. PERCENTILE.INC(…., 0.25) was used to find the 25th percentile of the range of numbers from Column D, or else, it includes a blank space.

This code =MEDIAN(IF(Monthly!$B$578:$B$637=A2,Monthly!$D$578:$D$637)) was utilised to find the median of numbers in Column D (total abstraction) in the "Monthly" sheet grounded on a condition order in Column B. MEDIAN(IF(….)) was utilised to determine the median of the range of numbers obtained grounded on the condition order.

=PERCENTILE.INC(IF(Monthly!$B$578:$B$637=A2,Monthly!$D$578:$D$637),0.75) code was exercised to find the 75th percentile (Q3) of numbers in column D (total abstraction) in the "Monthly" sheet from rows 578-637. PERCENTILE.INC(…., 0.75) was used to find the 75th percentile of the range of numbers from column D, or else, it includes a blank space.
=MAX(IF(Monthly!$B$578:$B$637=A2,Monthly!$D$578:$D$637)) code was utilised to calculate the maximum number in Column D (total abstraction), centred on a condition order

in Column B. MAX(IF(….)) calculates the maximum number from the range of numbers obtained centred on the condition order.

The same analysis was done for monthly and annual values of the observed streamflow and projected river flow.

3.4 Summary

This chapter described in detail the appropriate methodology that was exercised to achieve this study. The description of the study area was outlined, and the detailed methodology was clarified. Followed by the data collection process as well as the method used to analyse the data.

The chapter to follow explores the results and discussion of the study.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter concentrates on the results analysis and discussion of the findings. All the results in this chapter are produced by utilising the methods specified in Chapter 3. It starts with the results obtained from the analysis of streamflow gauging data using the BRVAS Excel abstraction model, focusing mainly on the total annual abstraction, and the monthly abstraction streamflow data. This is followed by the projected river flow analysis, first through evaluating the bias-correction method through quantile-quantile (Q-Q) plots of the biased corrected flow against the observed flow, and the total abstraction from Daljosafat streamflow gauge, subsequently by presenting results on changes in abstraction in the near and far future.

4.2 Abstractions Based on the Observed Streamflow Gauge Historical Data

This section presents results answering Research Question One (1): is the analysis of abstraction statistics or differences in simulated abstraction amounts based on the earlier drought period robust, given the more recent drought?

4.2.1 Annual Streamflow Abstraction Amounts

This section provides the annual abstraction results from the Daljosafat streamflow gauge, comparing the two five-year periods that had historically low flows (Figure 13; Table 10).

4.2.1.1 Annual Streamflow and Simulated Abstraction Data

The actual Daljosafat observed streamflow results present the underlying annual streamflow data between the two dry periods alongside the abstraction amounts (see Fig. 12). In the first dry period, there are three years with particularly low flows, 1969, 1971 and 1972, with the latter having the lowest flows and abstraction amounts. The graph also displays an extremely low flow record in the critical recent drought year of 2017, for the WCWSS as shown in Figure 12 and presented in red. Based on the annual streamflow results, it can be observed that there is a significant difference between the two periods as the lowest annual observed flow/streamflow between the two periods of 1968-1972 and 2015-2019 was noticed in 2017 compared to 1972 previous drought. This could be the main driving force that limits the amount of water that can be abstracted during the winter abstraction period of June to October in the BRVAS in the Western Cape Province of South Africa.

In terms of the simulated abstraction results, the average annual abstraction over the recent drought period is 31% lower than the earlier one (see Table. 10). The difference is even larger when examining the minimum annual abstraction values of 439 m^3/s (past drought) and 143 m^3/s (recent drought) at 67% difference. The 25th percentile across all annual abstraction statistics difference was found to lower by seven percent. All five years in the recent period are below the long-term average, while in the earlier one, only two of the five years are below average.

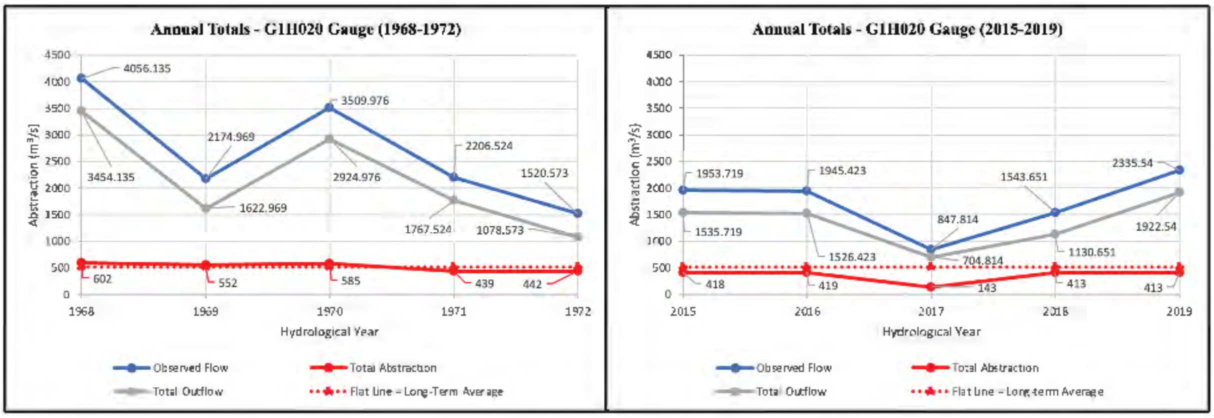


Figure 12: Simulated annual time series hydrograph shows the total abstraction amount (m^3/s) from 1968-1972 past drought and from 2015-2021 recent drought winter months of June-October at the streamflow gauging station G1H020 - Daljosafat along the BR Catchment. The blue colour time series graph indicates the observed flow, the grey colour displays the total outflow, the red colour without a dashed dot exhibits the total abstraction and the red dashed dot presents a flat line = the long-term average from 1967-2021 for each variable (Author).

Table 10: Statistics of the annual abstraction amounts (m^3/s) (%) between 1965-1972, 2015-2019 and 1967-2021 (Author).

Statistics of Annual Abstraction Summary (Daljosafat Stream Flow Gauge)				
Excel Function	Past Drought (1968-1972) 5 Years	Recent Drought (2015-2019) 5 Years	Full Record (1967-2021) 55 Years	2015-2019 as a Percentage of 1968-1972
1967-2021				
Average	524	361	518	69
Max	602	419	612	70
Min	439	143	143	33
Median	552	413	511	75
25th Percentile	442	413	463	93
75th Percentile	585	418	583	71

4.2.2 Monthly Abstraction Based on Historical Data

This section provides results of the monthly abstraction streamflow gauge historical data. The section will answer the question as to whether using the 2015-2018 drought is the worst-case scenario for the simulated abstraction amounts. Only 95% of the time exceeded during the observational record will be compared for the two dry periods. The three curves shown in this figure present different periods from the full record of 1967-2021, the 1968-1972, and the 2015-2019 flow duration curve. These three different curves plotted against each other in this way (see Fig. 12) make it easier to compare one abstraction duration curve, and see the difference for that specific period against the most recent drought period.

4.2.2.1 Monthly Abstraction Duration Curves

The findings from Figure 13 depict that the early dry period and full records seem to have the same abstractions amounts. It seems that the monthly abstractions are the same, and at times larger for high and moderate flows, while the low flows are indeed noticeably lower. Consequently, low flows are suitable for the worst case at the time of the study. The recent drought period has abstraction at different probabilities that are even lower, confirming that the recent period presents a better option for worst-case planning. In this regard, the lowest monthly abstraction amount for the recent drought of 2015-2019 was found to be about 15 m^3/s with a probability of 95% exceeded during the observational record, while the past drought 1968-1972 monthly abstraction value reached approximately 39 m^3/s at 95% probability of time exceeded during the observational record (see Table. 11). For the abstraction exceeded 95% of the time, the difference across all periods of months of the year (FDCs) is -58 percent.

The lowest flows in the red curve were found to be smaller than on the grey curve. This means that there is a year NOT in 2015-2019 or 1968-1972 where abstraction in one or couple of months is lower than the lowest. The 1973 year in month 6 (June) was noticed to be the period during which where these lowest flows occurred.

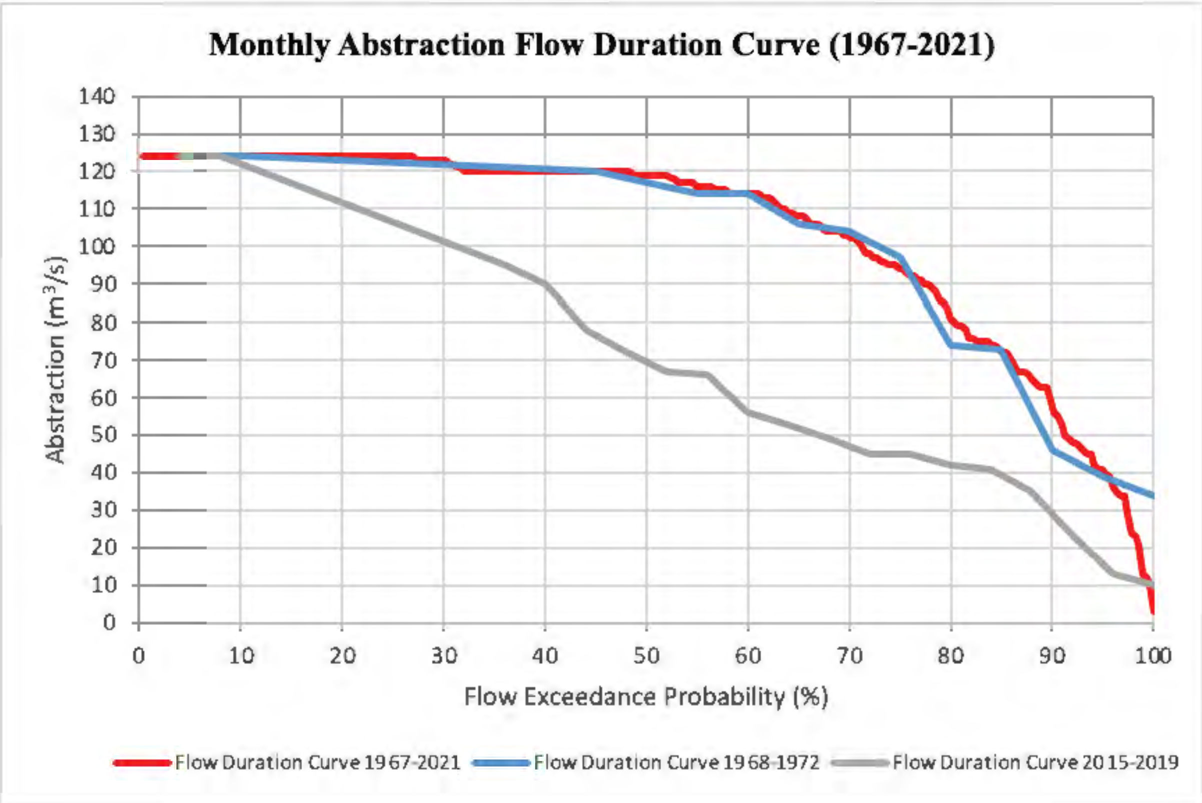


Figure 13: Simulated monthly abstraction duration curves (m^3/s) from Daljosafat streamflow gauge from 1967-2021. The three flow duration curves are included in one plot/graph. The red colour curve represents the full duration record, the blue colour curve signifies the past drought of 1968-1972 and the grey curve colour denotes the recent drought of 2015-2019 (Author).

Table 11: Abstraction amounts at different percentiles/probabilities (m^3/s) (%) (Author).

Percentile	Past Drought	Recent Drought	Full Record	Abstraction Difference (m^3/s)	% Difference
0	124	124	124	0	0
5	124	124	124	0	0
10	124	124	124	0	0
25	124	124	124	0	0
50	117	68	119	-49	-21
75	97	44	95	-53	-41
90	46	28	59	-18	-35
95	39	15	41	-24	-58
100	34	10	3	-34	-71

4.2.2.2 Monthly Abstraction Statistics

Results from Figure 14 demonstrate that min and Q1 abstractions for the recent dry period are much more extremely affected than in the earlier period. In the recent dry period, the minimum flows are consistently lower than the earlier period, although only in June, they are quite similar. There are other minima in the longer record (all years) that were found lower than the recent dry period. These are isolated months in random years, where one year of 1973 in month 6 (June) contributes to most of these minima.

The monthly abstraction statistics min, Q1, median, Q3 and max findings of the recent drought that happened in Cape Town in the SWC region show the lowest total average abstraction of 72 m^3/s in the recent drought of 2015-2019 when considering the monthly statistics of the past drought of 1968-1972 (see Table. 12). The minima of the monthly abstraction differences were found to be -36 m^3/s. The 25th percentile of monthly abstraction statistics difference is -72 percent. Monthly abstraction statistics differences across all drought periods were found to be -64% (average) and -71% (min).

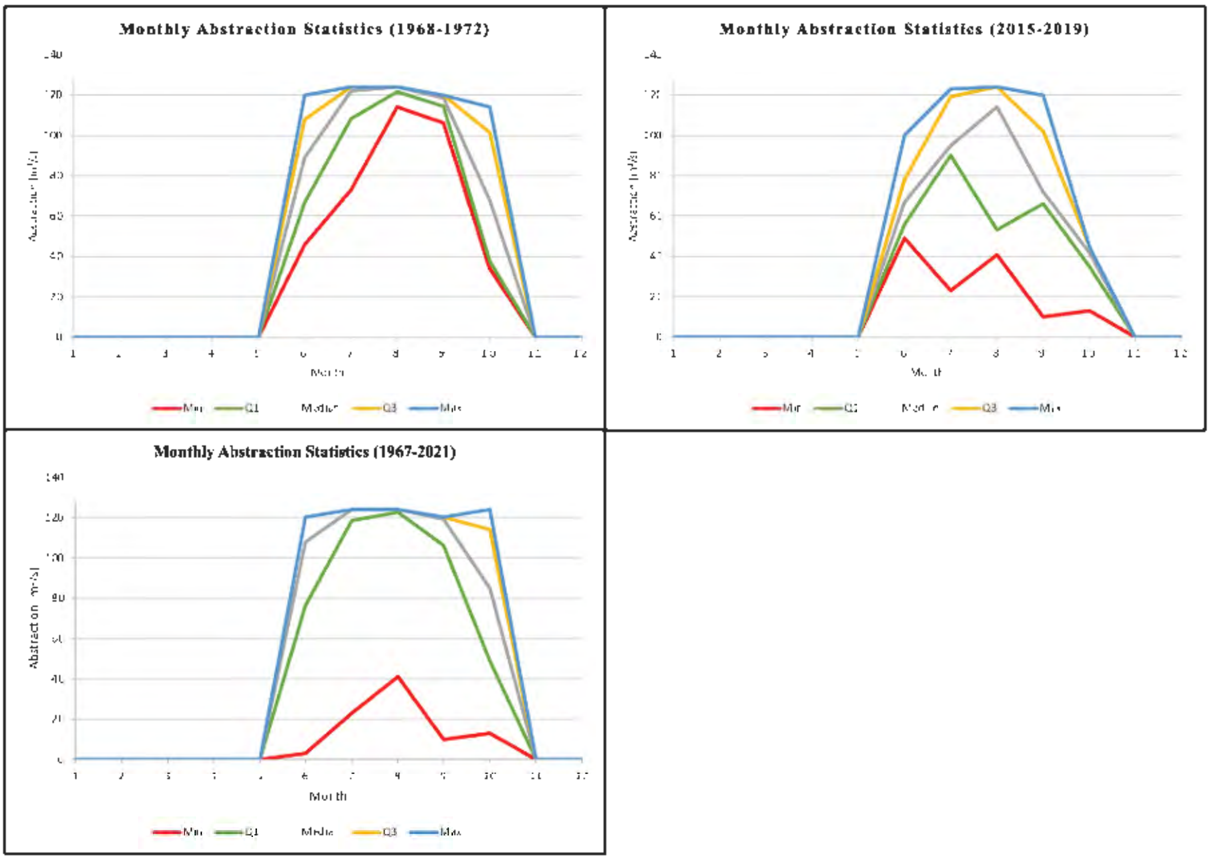


Figure 14: Simulated monthly abstraction statistics (m^3/s) of the Daljosafat streamflow gauge of the past drought of 1968-1972, the recent drought of 2015-2019 and the full record of 1967-2021. For ease of plotting, each month of a year is renumbered from 1 to month 12 (Author).

Table 12: Statistics of monthly abstraction (m^3/s) across the two dry periods and the full period of record, as well as the differences between these periods (Author).

Statistics of Monthly Abstraction Summary (Daljosafat Stream Flow Gauge)						
Excel Function	**Min**	**Q1**	**Median**	**Q3**	**Max**	**Total Average**
Past Drought (1968-1972) 5 Years						
Average	75	90	104	115	120	101
Max	114	122	124	124	124	123
Min	34	38	68	101	114	71
Median	73	108	119	120	120	108
25th Percentile	46	67	89	108	120	86
75th Percentile	106	114	122	124	124	118
Recent Drought (2015-2019) 5 Years						
Average	27	60	78	94	102	72
Max	49	90	114	124	124	100
Min	10	35	42	45	45	35
Median	23	56	72	102	120	75
25th Percentile	13	53	67	78	100	62
75th Percentile	41	66	95	119	123	89
Full Period (1967-2021) 55 Years						
Average	18	95	112	120	122	93
Max	41	123	124	124	124	107
Min	3	49	85	114	120	74
Median	13	106	119	120	124	96
25th Percentile	10	77	108	120	120	87
75th Percentile	23	119	124	124	124	103
Statistics of Monthly Abstraction Differences (2015-2019 Minus 1968-1972)						
Average	-48	-30	-26	-21	-18	-29
Max	-65	-32	-10	0	0	-23
Min	-24	-3	-26	-56	-69	-36
Median	-50	-52	-47	-18	0	-33
25th Percentile	-33	-14	-22	-30	-20	-24
75th Percentile	-65	-48	-27	-5	-1	-29

The rows in this table display the statistics of monthly water abstraction amounts (m^3/s) (%) from the Daljosafat stream flow gauge. It includes the average, maximum, median, 25th and 75th percentile values for the past drought period of 1968-1972, the recent drought period of 2015-2019, and the entire period of 1967-2021. Additionally, it presents the statistics of monthly abstraction differences between the recent and past drought periods. The columns also show the summary of monthly abstraction statistics (minimum, 1st quartile, median, 3rd quartile, maximum, and total average) for all these periods.

4.2.3 Answering Research Question One (1)

To interpret what these annual abstraction results suggest for the previous BRVAS reliability calculations that made use of abstraction simulations using the earlier dry period of 1968-1972, the results of this study indicate that, if more recent data were used, the reliable abstraction estimates would likely be lower than in the original feasibility study. The monthly abstraction results show that the earlier period data was perhaps compromised, where more recent drought was much more severe, and resulted in much lower abstraction amounts.

4.3 Projected River Flows and Abstractions

This section presents the results of the projected river flows, answering Research Question Number Two (2): how will the water available for abstraction change in the future, under climate change conditions?

4.3.1 Evaluation of Bias Correction Using QQ Plots

This section provides the results of the Q-Q plots of biased corrected flow against the observed flow, and uncorrected flow against the observed flow of the five winter abstraction months from the June to October period – focusing only on the lower flows, so as to assess any biases in the range of flows for which the abstraction happens.

4.3.1.1 Q-Q Plots of the Biased Corrected Flow Against the Observed Flow

This section evaluates whether the bias correction results in the bias-corrected model data having the distribution to the observed. It would be beneficial were the sorted values in the Q-Q plot to fit close to a 1:1 line. However, what we see is that for all the models, the normalisation results in an underestimation of the larger flows. It also results in an overestimation of the lower flows, where the blue dots are below the 1:1 line (see Fig. 15).

Therefore, while we have removed the mean bias, this has not resulted in an unbiased dataset across the entire distribution.

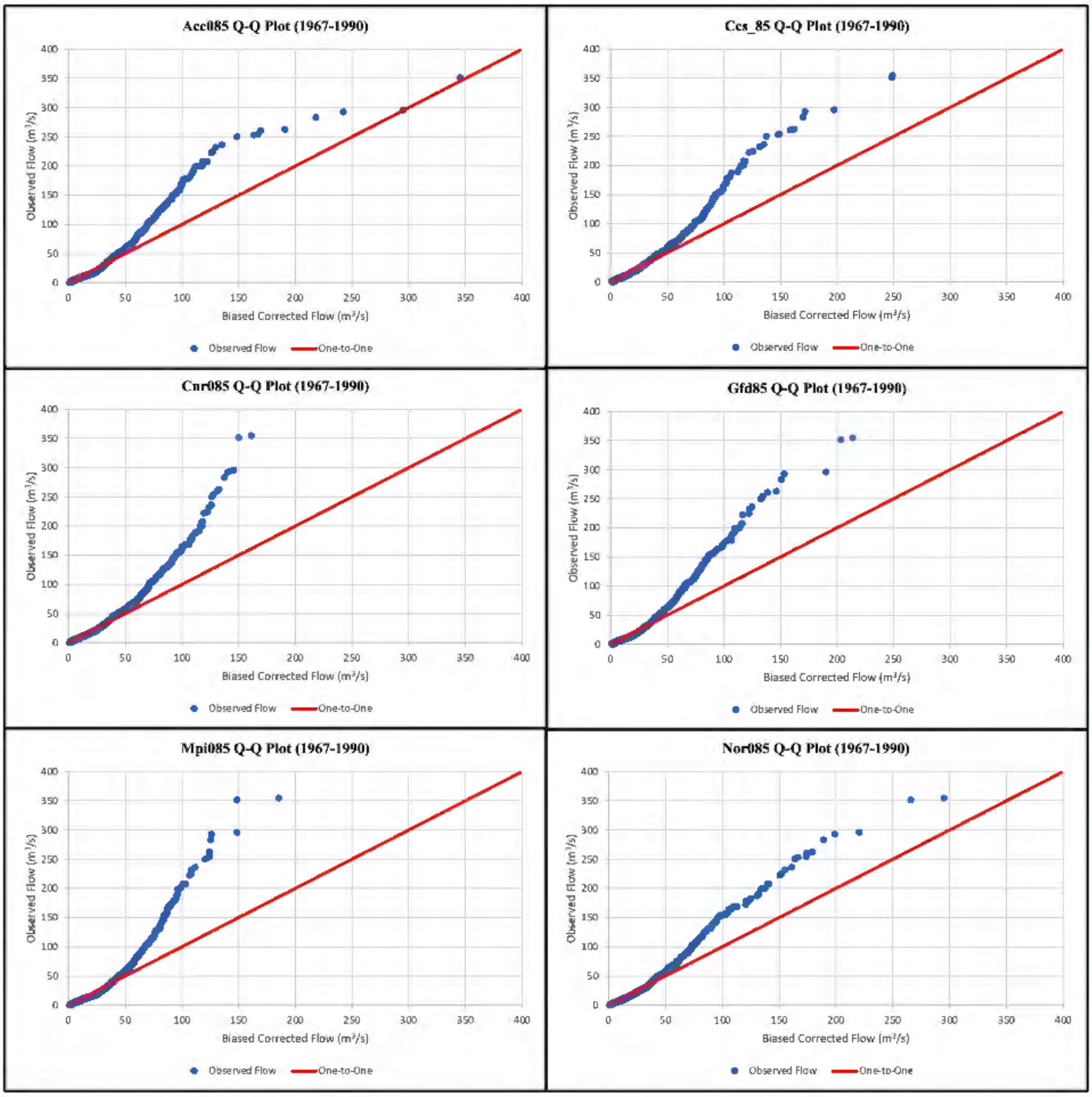


Figure 15: Simulated quantile-quantile (Q-Q) plot of biased corrected flow against the observed flow of six climate change scenarios (m^3/s) from the 1967-1990 period (Author).

4.3.1.2 Q-Q Plots of the Biased Corrected Flow Against Total Abstraction

Figure 16 shows the simulated findings of the Q-Q plot that focuses on the daily abstraction period of June-October, and demonstrates the bias correction. It shows the lower flows for which the abstraction happens between 0 and 10 m^3/s. This simulated plot helps understand whether there are problems with the flow thresholds for abstraction (2-5 m^3/s). For higher flow values – above 5-6 m^3/s, the biases are not of significance, because the limit to abstraction is 4 m^3/s. The rest of the analysis using these data is potentially useful. Although the results may not be fairly compared to the observed flow results, the relative changes between periods within the model reveal a great deal about how simulated abstraction amounts might change in the future, despite acknowledged biases.

As shown in Fig 16, the flow simulated using observed data often has values close to zero, whereas the bias-corrected climate model-driven flow does not have such low flows (min flows are in the range of 0.7-0.9 m^3/s). Therefore, the bias-corrected data will still result in some biases in abstraction because the threshold for abstraction to start is 1 m^3/s, close to where this mismatch occurs. This underestimation could lead to an inaccurate assessment of water availability during critical periods, particularly in drought conditions or during dry seasons. However, because differences between the same model-driven results are compared in each time period, some of this mismatch is avoided.

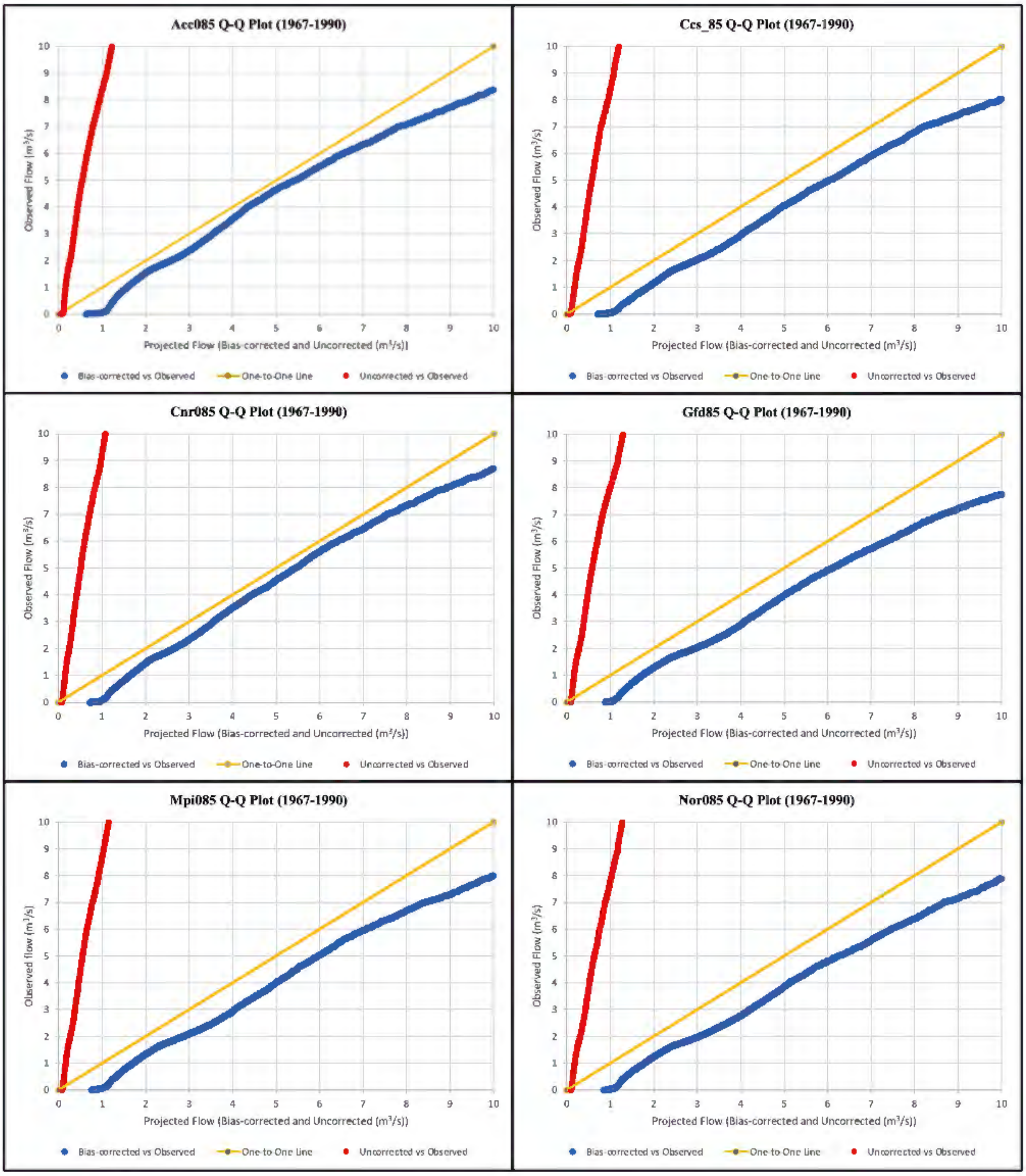


Figure 16: Simulated quantile-quantile (Q-Q) plot of lower flows of six climate change scenarios (m^3/s) from the 1967-1990 period (Author).

4.3.2 Abstraction Amounts Under Projected Climate Change

This section presents the results of the annual abstraction of the six climate change scenarios.

4.3.2.1 Total Annual Abstraction

The overall results depict that the distant future has the lowest abstraction amounts, followed by the near future and the recent past (see Fig.17). The mean abstraction amount over a 30-

year period gets lower for all models as one goes from recent (338 m^3/s) to near (331 m^3/s) to far (121 m^3/s) (see Table.13).

The frequency of years is worse than the lowest abstraction in the recent past. In all models, frequency is higher in the far future between 3 to 10 times in the 30-year period (see Fig.17). The frequency of years in all models is lower in the near future between 2 to 5 times in the 30-year period as compared to the far future.

The frequency of flows below the 25th percentile (Q1) in all models ranges from -1% to -13% in the near future of 2015-2044 and -1% to -39% in the distant future of 2070-2099. The result displayed that the near future has a low percentage of flows, as compared to a high percentage of the distant future. This verified that there will be a higher frequency of flows in the distant future than in the near future.

The average annual abstraction statistics difference for all the six climate change scenarios (Acc085, Css_85, Cnr085, Gfd085, Mpi085 and Nor085) ranges from 6 m^3/s to -58 m^3/s in the near future and from 6 m^3/s to -190 m^3/s in the far future (see Table.13).

The findings revealed that the multi-model average abstraction is only slightly reduced in the near future, but is much more significantly reduced in the distant future. For example, the outcomes for statistical annual abstraction difference for the near future show that in one model, there will be an increase in the near future, which is the second model (Css_85), because it displayed a +6 value. The average overall results depict that 5 of the 6 models show a decrease in the amount of water that can be abstracted, whilst min shows only two of the six models displayed a decrease in the water amount that can be abstracted. The max values show a decrease in the annual yield abstractions in all of the six climate change scenarios (Acc085, Css_85, Cnr085, Gfd085, Mpi085 and Nor085). For the median, 5 of the 6 models present a decrease in the water amount that could be abstracted, whereas the 25th and 75th percentiles show a decrease in annual abstraction in the near future.

In answering the question as to whether all models show the same direction of change in the near future, it can be predicted that there will be a slight change related to the reduction of the annual water abstraction amounts that could be abstracted in the near future.

To answer the question as to whether a clearer picture may emerge in the far future, a clearer picture emerges in the distant future of 2070-2099. When looking at the statistical difference results it is possible to predict that indeed there will be a significant reduction regarding the annual water yield amounts that can be abstracted annually in all of the six climate change scenarios under climate change conditions. All the Excel functions (the averages, maximum, minimum, median, 25th percentile and 75th percentile) show low-significance abstraction amounts in all models in the distant future.

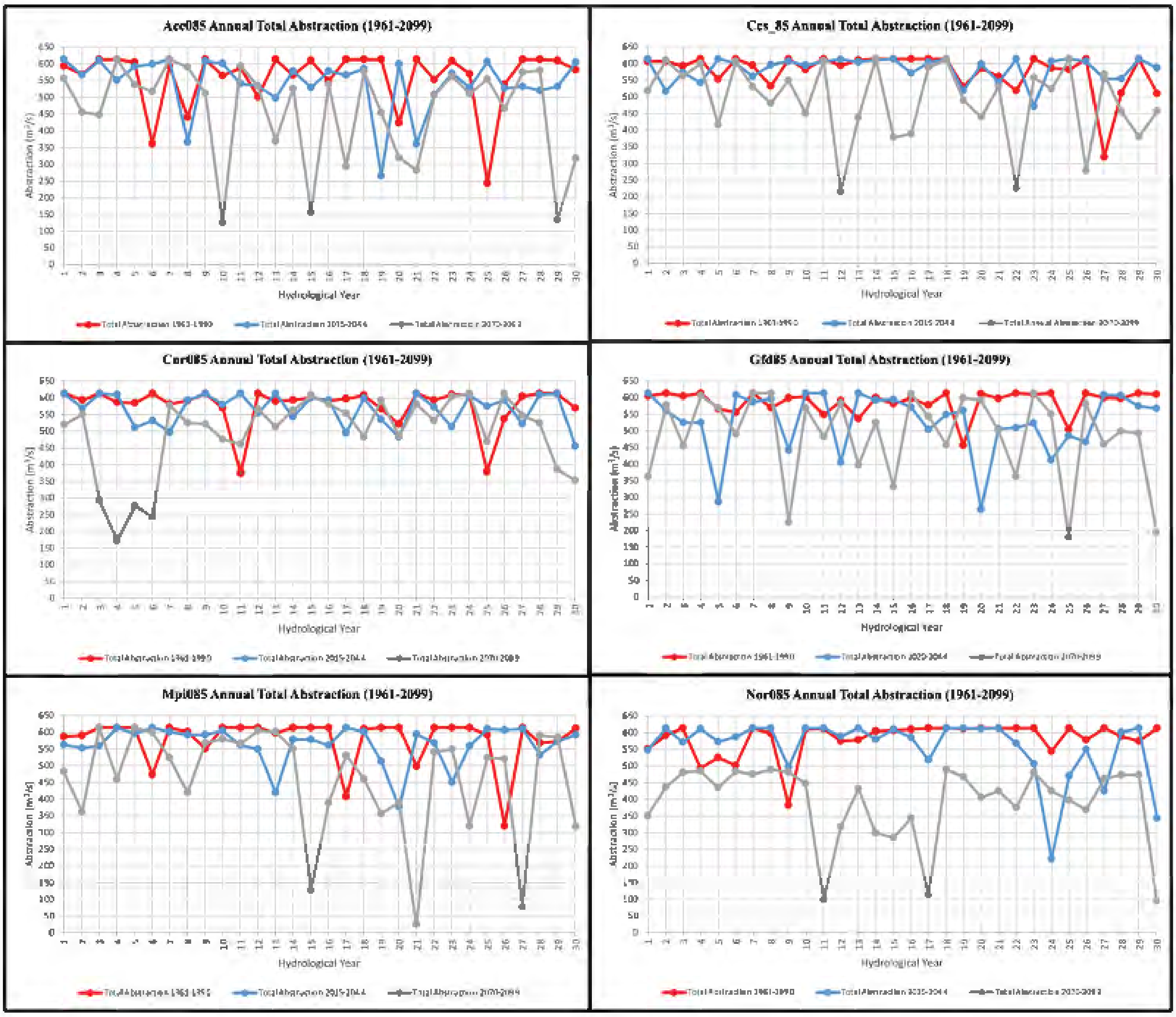


Figure 17: Simulated total annual abstraction of the six climate change scenarios (m^3/s) from 1961-1990, 2015-2044, 2070-2099. The three different time series plots with straight lines and points are included in one plot. For ease of plotting, each 30-year period is renumbered from 1 to year 30 (Author).

Table 13: Statistics of total annual abstraction summary (m^3/s) of the six climate-hydrological models (Author).

Statistics of Total Annual Abstraction Summary (Six Climate Change Scenarios)							
Excel Function	Acc085	Ccs_85	Cnr085	Gfd085	Mpi085	Nor085	Multi-Model
Recent Past (1961-1990)							
Average	559	577	576	587	579	582	577
Max	612	612	612	612	612	612	611
Min	243	320	377	455	320	381	349
Median	593	600	594	599	612	607	601
25th Percentile	555	566	583	579	588	576	575
75th Percentile	612	612	611	612	612	612	611
Near Future (2015-2044)							
Average	542	583	567	529	564	556	[illegible]
Max	612	612	612	612	612	612	611
Min	264	471	455	264	377	222	[illegible]
Median	566	601	587	561	578	587	[illegible]
25th Percentile	528	563	533	505	558	547	[illegible]
75th Percentile	598	610	609	595	601	612	604
Distant Future (2070-2099)							
Average	460	583	493	487	461	392	[illegible]
Max	612	612	612	612	612	488	591
Min	125	471	172	179	24	95	[illegible]
Median	513	601	525	513	523	433	[illegible]
25th Percentile	388	563	471	454	389	354	[illegible]
75th Percentile	561	610	574	583	576	475	[illegible]
Statistics of Total Annual Abstraction Difference (2015-2044 Minus 1961-1990)							
Average	-17 (-3%)	6 (1%)	-11 (-2%)	-58 (-10%)	-15 (-3%)	-26 (-4%)	-20
Max	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0
Min	21 (9%)	151 (47%)	78 (-21%)	-191 (-42%)	57 (18%)	-159 (-42%)	7
Median	-27 (-5%)	1 (0%)	-7 (-1%)	-38 (-6%)	-34 (-6%)	-20 (-3%)	-21
25th Percentile	-27 (-5%)	-3 (-1%)	-50 (-9%)	-74 (-13%)	-30 (-5%)	-29 (-5%)	-36
75th Percentile	-14 (-2%)	-2 (0%)	-2 (0%)	-17 (-3%)	-11 (-2%)	0 (0%)	[illegible]
Statistics of Total Abstraction Annual Difference (2070-2099 Minus 1961-1990)							
Average	-99 (-18%)	6 (1%)	-85 (-15%)	-100 (-17%)	-118 (-20%)	-190 (-33%)	[illegible]
Max	0 (-0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	-124 (-20%)	-21
Min	-118 (-49%)	151 (47%)	-205 (-54%)	-276 (-61%)	-296 (-93%)	-286 (-75%)	[illegible]
Median	-80 (-13%)	1 (0%)	-69 (-12%)	-86 (-14%)	-89 (-15%)	-174 (-29%)	[illegible]
25th Percentile	-167 (-30%)	-3 (-1%)	-112 (-19%)	-125 (-22%)	-199 (-34%)	-222 (-39%)	[illegible]
75th Percentile	-51 (-8%)	-2 (0%)	-37 (-6%)	-29 (-5%)	-36 (-6%)	-137 (-22%)	[illegible]

4.3.3 Monthly Abstraction Duration Curve of Six Climate Change Scenarios

For the monthly FDCs, three different periods were produced into one plot to develop the three different curves, namely: the recent past, and near and distant future (see Fig. 18). The monthly FDC takes all the data of water abstraction of the river flow and turns it into a graph that gives the probability of the flow being exceeded during the observational record. It tells what the flow is, or if the water abstraction of 95% or 100% of the time exceeded during the observational record, where, with the given abstraction statistics we can then start to compare the FDC and the different periods and future as well as the present climate condition. For conciseness, the results will only focus on the second-highest probability of 95 percent. It will also concentrate on the lowest abstraction amounts.

4.3.3.1 Monthly Flow Duration Curve

The future period results display abstractions amount at nearly all probabilities that are lower than the recent past period, indicating a robust climate change-driven reduction in water abstraction yields in the future (see Fig. 18). The near future FDCs do not show such a strong signal, with overlap between with the recent past FDCs in half of the models (Acc085, Ccs_85, and Mpi085). The distant future period shows a much more consistent reduction in abstraction yields across the full FDC, compared to the recent past.

For the abstraction exceeded 95% of the time, the range across the models in differences between the far future and the recent past, between -50% and -83% (see Table. 14). The lowest abstraction amount differences across all six climate scenarios ranged from 0 m^3/s to -76 m^3/s. The outcomes of this study indicate that the water available for abstraction will change in the future under climate change conditions, as shown in Table 14.

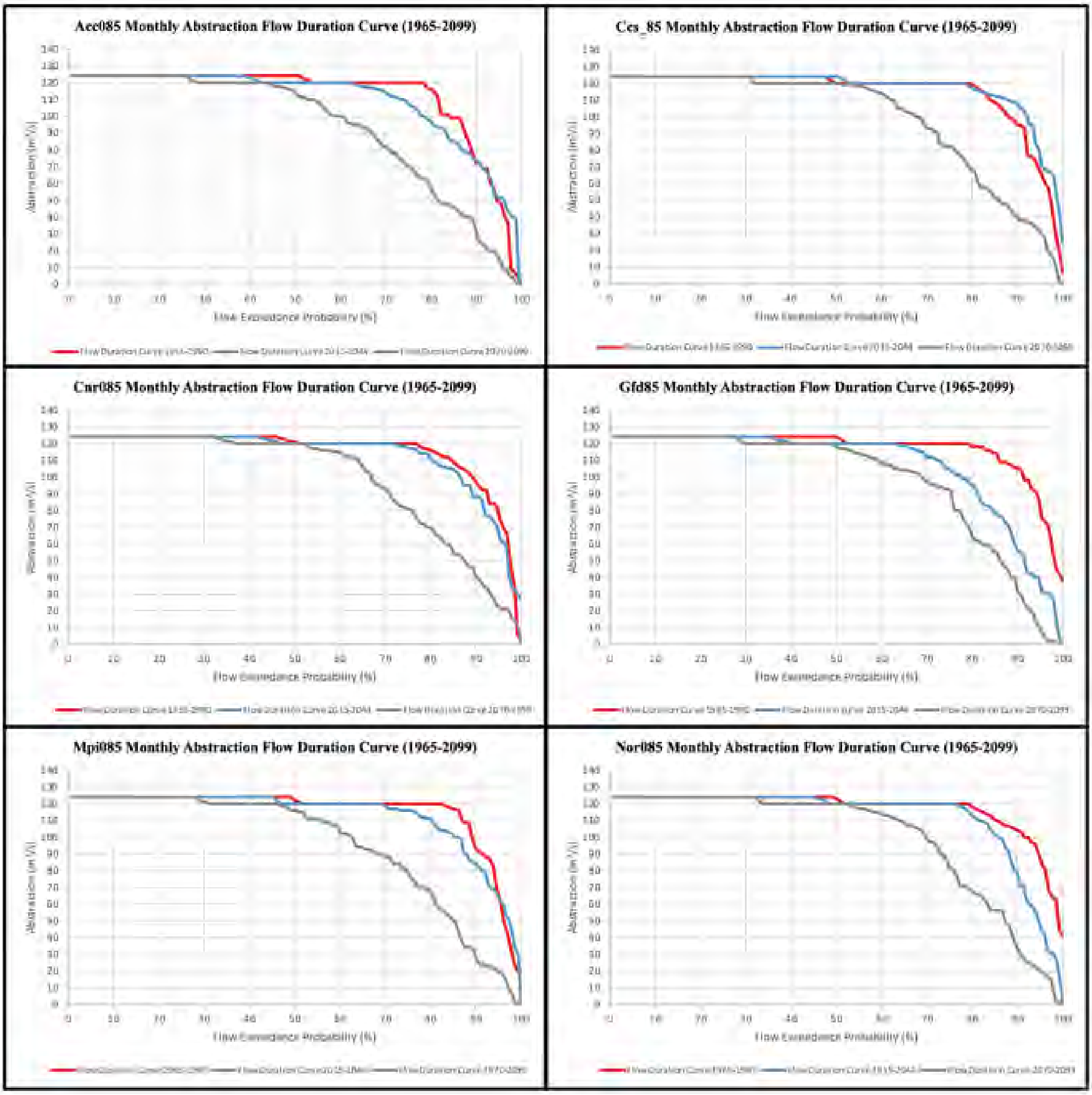


Figure 18: Simulated monthly abstraction flow duration curve of all the six climate scenarios models (m^3/s) (%) from past, near and distant future from 1965-2099. Three flow duration curves are included in one plot/graph. The red colour curve presents the recent past from 1965-1990, the blue colour curve shows the near future from 2015-2044 and the grey curve colour displays the distant future from 2070-2099 (Author).

Table 14: Abstraction amounts (m^3/s) (%) at different percentiles/probabilities (Author).

Percentile	Model 1 (Acc085)		Model 2 (Ccs_85)		Model 3 (Cnr085)		Model 4 (Gfd85)		Model 5 (Mpi085)		Model 6 (Nor085)	
	Abstraction Difference (m^3/s)	% Difference	Abstraction Difference (m^3/s)	% Difference	Abstraction Difference (m^3/s)	% Difference	Abstraction Difference (m^3/s)	% Difference	Abstraction Difference (m^3/s)	% Difference	Abstraction Difference (m^3/s)	% Difference
100	0	0	-7	-100	-4	-100	-38	-100	-20	-100	-41	-100
95	-36	-70	-37	-50	-59	-68	-76	-83	-49	-68	-70	-74
90	-41	-51	-55	-52	-56	-52	-74	-63	-61	-59	-70	-61
75	-50	-31	-38	-24	-39	-24	-27	-17	-42	-26	-38	-24
50	-10	-4	0	0	-1	0	-6	-2	-6	-2	-2	-1

4.3.3.2 Monthly Abstraction Statistics

Most models show large reductions in minimum flows during the start of winter, suggesting that supply augmentation might not help in refilling the Voëlvlei Dam earlier in the winter, when dam levels might be lowest.

The findings show that min and Q1 flow for all six climate change scenarios are much more extremely affected, across all months in the abstraction period (see Fig. 19). The min flows of the Mpi085 model are enormously affected when compared to the min values of other models. In the more distant period, the minimum flows are consistently lower than in the near future and the recent past, although the minimum flows for the Mpi085 in the June to October months are quite similar. The lowest monthly abstractions occurred in the near and the distant future compared to the recent past period of 1965-1990. The distant future even showed very low-significant abstraction amounts for the min and Q1 compared to other periods, the recent past as well as the near future. The overall min abstraction for all climate change scenarios in all winter abstraction seasons of June-October ranges from 0 m^3/s to 124 m^3/s (see Table. 15).

From all the six climate change scenarios, the distant future min presents a low water abstraction amount, compared to the recent past and near future models. Also, month 6 seems to have low min, Q1, median, Q3 and max monthly abstraction statistics amounts in most of the six climate scenarios Acc085, Ccs_85, Cnr085, Gfd85, Mpi085 and Nor085. In this study, the lowest water yield abstraction was found to be 0 m^3/s, whereas the highest was 124 m^3/s

for winter abstraction month across all the years. In all the distant future periods of 2070-2099 monthly abstraction statistics, five of six models depict the lowest minimum value of 0 m^3/s in the first (Month 6) winter abstraction month. Followed by the near future, of which four of the six models show the lowest minimum abstraction amount; and only one of the six recent past models display the lowest minimum abstraction amount as shown in Table 15.

That is why it is recommended that since the abstraction amount is/ will be significantly reduced, a reasonable budget needs to be allocated to also start implementing additional water supply options, particularly in the SW Cape, such as desalination, such that water supply failure risk during drought is reduced. While the BRVAS is a relatively small component of the total WCWSS, similar effects will likely be felt in other parts of the system that are dependent on surface water supply.

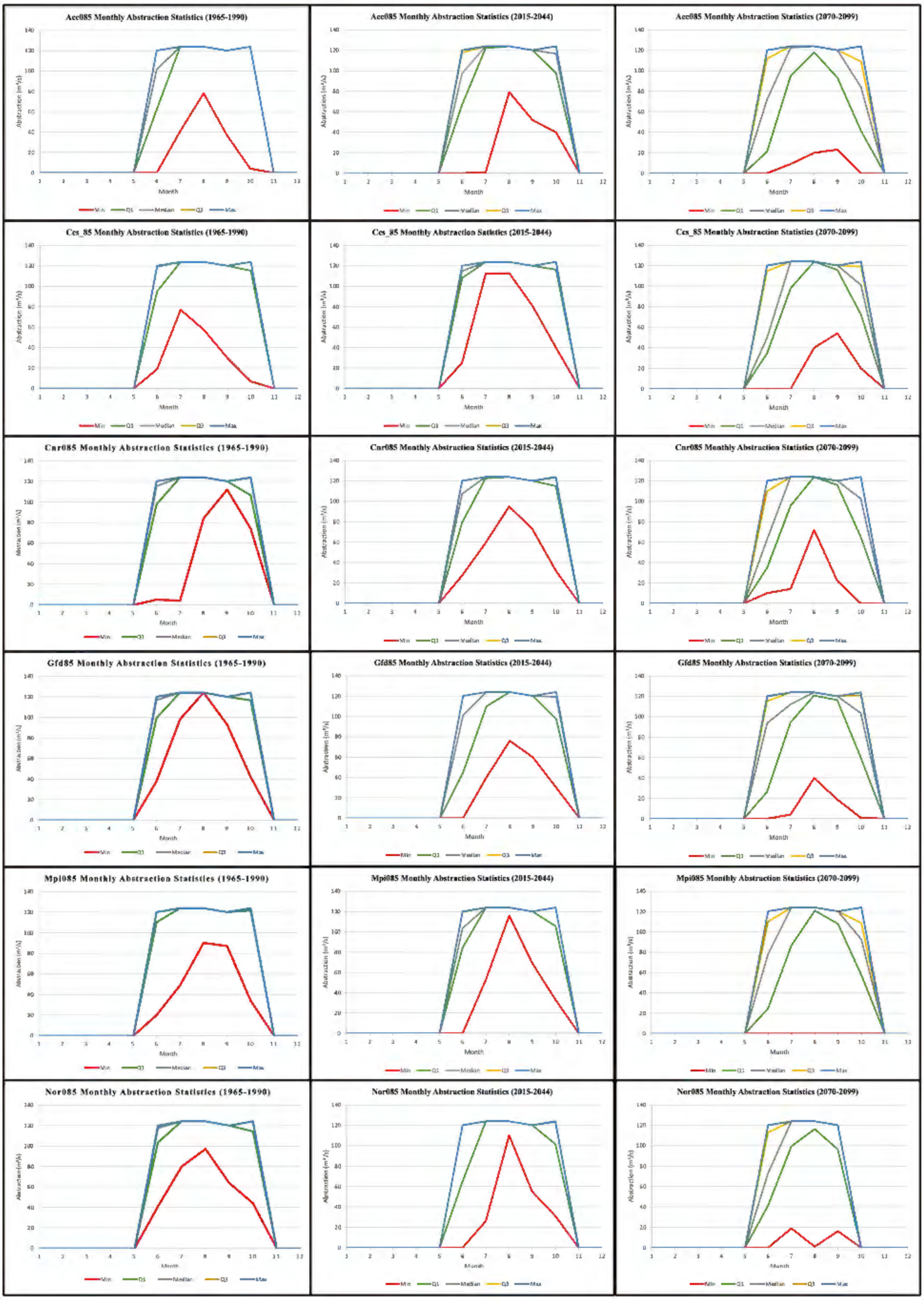


Figure 19: Simulated monthly abstraction statistics (m^3/s) of the six different climate change scenarios from 1965-1990 recent past, 2015-2044 near future and 2070-2099 distant future. For ease of plotting, each month of a year is renumbered from 1 to month 12 (Author).

Table 15: Statistics of the monthly abstraction (m³/s) (%) for the six climate change scenarios (Author).

Acc085 Monthly Abstraction Statistics (1965-1990)					
Month	Min	Q1	Median	Q3	Max
(Recent Past)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	52	107	120	120
7	41	116	124	124	124
8	78	128	124	124	128
9	34	120	130	120	128
10	1	124	124	124	124
11	0	0	0	0	0
12	0	0	0	0	0

Acc085 Monthly Abstraction Statistics (2015-2044)					
Month	Min	Q1	Median	Q3	Max
(Near Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	67	96	118	120
7	3	122	124	124	124
8	76	124	124	130	128
9	57	120	125	122	128
10	40	58	117	124	124
11	0	0	0	0	0
12	0	0	0	0	0

Acc085 Monthly Abstraction Statistics (2070-2099)					
Month	Min	Q1	Median	Q3	Max
(Distant Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	21	77	112	120
7	8	55	125	124	124
8	20	118	126	130	128
9	24	53	120	120	120
10	0	41	84	109	124
11	0	0	0	0	0
12	0	0	0	0	0

Can_85 Monthly Abstraction Statistics (1965-1990)					
Month	Min	Q1	Median	Q3	Max
(Recent Past)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	19	95	114	120	120
7	77	124	124	124	124
8	57	128	126	124	128
9	38	120	130	120	120
10	7	125	124	124	124
11	0	0	0	0	0
12	0	0	0	0	0

Can_85 Monthly Abstraction Statistics (2015-2044)					
Month	Min	Q1	Median	Q3	Max
(Near Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	27	100	115	120	120
7	112	124	124	124	124
8	132	124	124	130	128
9	81	120	130	120	128
10	40	120	124	124	124
11	0	0	0	0	0
12	0	0	0	0	0

Can_85 Monthly Abstraction Statistics (2070-2099)					
Month	Min	Q1	Median	Q3	Max
(Distant Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	25	50	115	120
7	0	58	124	124	124
8	48	124	124	130	128
9	54	116	130	120	120
10	20	72	101	119	124
11	0	0	0	0	0
12	0	0	0	0	0

Cnr085 Monthly Abstraction Statistics (1965-1990)					
Month	Min	Q1	Median	Q3	Max
(Recent Past)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	3	90	116	120	120
7	4	124	124	124	124
8	84	128	124	124	128
9	112	120	130	120	128
10	74	107	124	124	124
11	0	0	0	0	0
12	0	0	0	0	0

Cnr085 Monthly Abstraction Statistics (2015-2044)					
Month	Min	Q1	Median	Q3	Max
(Near Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	27	79	105	120	120
7	52	123	124	124	124
8	93	124	124	130	128
9	73	120	130	120	128
10	80	125	122	124	124
11	0	0	0	0	0
12	0	0	0	0	0

Cnr085 Monthly Abstraction Statistics (2070-2099)					
Month	Min	Q1	Median	Q3	Max
(Distant Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	10	15	63	110	120
7	14	56	124	124	124
8	22	124	124	130	128
9	22	116	130	120	120
10	0	65	108	124	124
11	0	0	0	0	0
12	0	0	0	0	0

GDM5 Monthly Abstraction Statistics (1965-1990)					
Month	Min	Q1	Median	Q3	Max
(Recent Past)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	38	100	117	120	120
7	88	116	124	124	124
8	124	128	124	130	128
9	93	120	130	120	128
10	42	117	124	124	124
11	0	0	0	0	0
12	0	0	0	0	0

GDM5 Monthly Abstraction Statistics (2015-2044)					
Month	Min	Q1	Median	Q3	Max
(Near Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	45	101	120	120
7	40	110	124	124	124
8	79	124	124	130	128
9	62	120	130	120	128
10	30	58	119	124	124
11	0	0	0	0	0
12	0	0	0	0	0

GDM5 Monthly Abstraction Statistics (2070-2099)					
Month	Min	Q1	Median	Q3	Max
(Distant Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	27	94	115	120
7	4	55	133	124	124
8	48	121	124	130	128
9	15	116	130	120	120
10	3	60	106	121	124
11	0	0	0	0	0
12	0	0	0	0	0

Mpi085 Monthly Abstraction Statistics (1965-1990)					
Month	Min	Q1	Median	Q3	Max
(Recent Past)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	28	110	120	120	120
7	48	116	124	124	124
8	90	128	128	124	128
9	87	120	130	120	128
10	30	122	124	124	124
11	0	0	0	0	0
12	0	0	0	0	0

Mpi085 Monthly Abstraction Statistics (2015-2044)					
Month	Min	Q1	Median	Q3	Max
(Near Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	84	106	119	120
7	59	124	124	124	124
8	119	124	124	130	128
9	62	120	130	120	128
10	33	100	124	124	128
11	0	0	0	0	0
12	0	0	0	0	0

Mpi085 Monthly Abstraction Statistics (2070-2099)					
Month	Min	Q1	Median	Q3	Max
(Distant Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	25	78	110	120
7	0	87	134	124	124
8	6	121	124	130	128
9	0	108	130	120	120
10	0	58	95	109	124
11	0	0	0	0	0
12	0	0	0	0	0

Nor085 Monthly Abstraction Statistics (1965-1990)					
Month	Min	Q1	Median	Q3	Max
(Recent Past)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	41	106	118	120	128
7	60	116	124	124	124
8	97	128	124	124	128
9	64	120	130	120	128
10	44	118	124	124	124
11	0	0	0	0	0
12	0	0	0	0	0

Nor085 Monthly Abstraction Statistics (2015-2044)					
Month	Min	Q1	Median	Q3	Max
(Near Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	45	120	120	120
7	35	124	124	124	124
8	131	124	124	130	128
9	53	120	130	120	128
10	21	102	123	124	124
11	0	0	0	0	0
12	0	0	0	0	0

Nor085 Monthly Abstraction Statistics (2070-2099)					
Month	Min	Q1	Median	Q3	Max
(Distant Future)					
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	41	75	110	120
7	19	100	124	124	124
8	3	158	124	130	128
9	16	57	129	120	120
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0

4.4 Summary

This chapter provides an in-depth presentation of the results analysis of this study. Two main analyses were undertaken. First, the abstraction was simulated using the observed flow from the Daljosafat streamflow gauge data, to assess whether the use of more recent data that includes the 2015-2017 SW Cape drought might affect the abstraction statistics of the offtake estimates in the original BRVAS feasibility study. This was followed by an analysis of how the projected river flows for the future, under the RCP8.5 emissions scenario, might affect the simulated abstraction amounts in the scheme.

The annual results for simulated abstraction using historical gauge data have shown that the abstraction estimates of the most recent drought 2015-2018 are significantly lower as compared to 1968-1972, with the previous worst drought on record for the SWC area. The biggest relative reductions were in the winter abstraction seasons of August and October, where the monthly results are consistent with the annual results. The recent drought period has a more severe impact on the abstraction potential. For the observed streamflow findings, the simulated annual abstraction results showed an average annual abstraction over the recent drought period of 31% more than the earlier one. All five years in the recent period were found to be below the long-term average, whereas, in the earlier one, only two of the five years were noticed to be below average. The results for the abstraction difference of 95% of time exceeded during the observational record across all periods of months of the year (FDCs) was found to be -58 percent, whereas the 25th percentile of monthly abstraction statistics difference was noticed to be -72 percent. In the recent dry period, the minimum flows were found consistently lower than in the earlier period, although only in June were these quite similar.

In terms of the projected future changes in river flows and resultant abstractions, this research has shown that there are differences between the near and distant future scenarios, because the climate change signal becomes larger in the far future, but is less strong in the near future. For the projected river flow, the results revealed that the frequency of flows below the 25th percentile (Q1) in all annual abstraction statistics models ranged from -1% to -13% in the near future of 2015-2044 and -1% to -39% in the distant future of 2070-2099. Whereas the abstraction of 95% of the time (FDCs) exceeded during the observational record and the range across the models in differences between the far future and the recent past was found to be -50% to -83 percent. The overall min abstraction statistics for all climate change scenarios in all winter abstraction seasons/months of June-October ranged from 0 m^3/s to 124 m^3/s. Most models show big reductions in minimum flows during the start of winter, suggesting that supply augmentation might now help in refilling the Voëlvlei Dam earlier in the Winter, when dam levels may be lowest.

This study finds that the water availability for abstraction will likely be significantly impacted and changed in the future under CC conditions, because the water abstraction amounts available have been reduced quite severely across most hydrological flows simulated using the six different CC model outputs.

The findings of this study confirm that the BRVAS is indeed sensitive to CC, with potential impacts on water availability. The CC projections indicate that the SWC region will likely experience changes in water abstraction amounts in the future, which will exacerbate the existing water management challenges in the BRVAS. There is a need for adaptive and proactive management strategies to ensure the long-term sustainability of water resources in the face of CC.

The chapter that follows explores the conclusion and recommendations for this study.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter summarises and discusses the results in Chapter 4 and makes recommendations based on the results/findings.

5.2 Summary of Key Findings

This section provides the summary of key findings centred on Chapter 4, answering the two research questions, such as, is the analysis of the simulated abstraction amounts of the BRVAS robust considering the most recent drought, and how the water available for abstraction changes in the future, under climate change conditions. This served to test the sensitivity of the BRVAS to changes in the characteristics of winter river flows in the Berg River. The most interesting part about this study was that this has not been done for the BRVAS, and the aim here was to attempt to determine how CC might alter the abstraction statistics of one of the components of the WCWSS.

5.2.1 Observed Streamflow Historical Data Findings Summary

1) In general, the annual streamflow gauge findings for BRVAS showed low flows in the three previous drought periods in the years 1969, 1971 and 1972. Extremely low flows and abstraction amounts were found in 2017 of the recent drought year for the SWC. Based on the annual streamflow finding, it can be noted that, if more recent data were used, the simulated abstraction estimates for the BRVAS would likely be lower than the original feasibility study.
2) With the monthly FDC results, the more recent drought period has abstraction amounts at different probabilities that are much lower, where validating that the recent drought period showed a better option for worst-case planning. Additionally, it was noticed that the past drought period data seemed to possibly be compromised, because the more recent drought was found to be more severe and resulted in much lower monthly abstraction yield amounts.
3) The monthly abstraction statistics results for min and Q1 revealed that yield abstractions for the recent drought period were much more extremely affected when compared to the past drought period. The minimum flows was found to be consistently

lower in the more recent dry period than in the past period, although in winter abstraction season of August and October were quite similar.

5.2.2 Projected River Flows Findings Summary

1) The evaluation of whether the bias correction (Q-Q plots) resulting in the biased corrected model data having the distribution to the observed findings confirmed that we would anticipate that sorted values in the Q-Q plot would fit close to a 1:1 line, but in all the models we notice that the normalisation findings in an underestimation of the larger flows. Also, it results in an overestimation of the lower flows, where the blue dots are below the 1:1 line. Therefore, the results have proven that when we removed the mean bias, this did not result in an unbiased dataset throughout the entire distribution.
2) The overall results for the annual abstraction of the six climate change scenarios indicated that the distant future of 2070-2099 has the lowest abstraction amounts, followed by the near future and the recent past. These results prove that the amount of water that can be abstracted in the BRVAS to add into the WCWSS will change in the future under future climate change. These findings show that there will be a change associated with the reduction of the annual water abstraction amounts that may be abstracted in the near future.
3) For the monthly abstraction FDC of the six climate change scenarios, the results gave a good picture that the future period water abstraction amount at nearly all probabilities that are lower than the recent past period. This indicates a robust climate change reduction in water abstraction yield in the future. It was found that the near future FDCs do not present such a strong signal, with overlap between the recent past FDCs in half of the models (Acc085, Ccs_85, and Mpi085). The outcomes of this study revealed that the water available for abstraction will change in the future, under climate change conditions within the BRVAS.
4) The results for monthly abstraction statistics gave evidence that min and Q1 flow for all six climate change scenarios are extremely affected, across all winter abstraction months period. The min flows of the Mpi085 scenario are enormously affected when compared with the min values of other climate change scenarios. In the more distant period, the minimum flows are seen to be consistently lower than in the near future and the recent past, although the minimum flows for the Mpi085 in the June to October abstraction season/months are quite similar. Given these results, it can be said that water

available for abstraction in winter months will change in future, under future climate change conditions, which proved that the BRVAS will/is sensitive to changes in the characteristics of winter river flows in the Berg River.

5.3 Aim of Study

This study aimed to assess the reliability of the BRVAS to climate change in the Western Cape Province, South Africa. This aim was fulfilled by the following objective:

1) **Test the sensitivity of the Berg River Vöelvlei Abstraction Scheme (BRVAS) to changes in the characteristics of winter river flows in the Berg River, firstly, in the context of the 2015-2018 drought, and secondly to projected future changes in river flow in the Berg River.**

This objective was fulfilled by setting up the Excel abstraction model to analyse the historical streamflow (G1H020 - Daljosafat streamflow gauge) and the projected river flow data. The observed flow data for Daljosafat from the 1967-2021 record length were downloaded from the DWS hydrological information system website. The CC model-driven runoff data came from an existing study on the future of water resources in South Africa for three different periods, namely: the recent past from 1961-1990; the near future from 2015-2044; and the distant future from 2070-2099.

5.4 Research Questions

The two research questions for this study were as follows:

1) **Given that the previous BRVAS reliability calculations made use of abstraction simulations using the earlier dry period of 1968-1972, would simulations using a period that spans the more severe 2015-2018 drought have the potential to alter the calculated reliability of the scheme?**

Based on the findings, for the observed period, analysis of the data using the G1H020 Daljosafat streamflow gauge historical data showed that the simulated abstraction amounts and estimates are reduced if considering the recent drought of 2015-2018, that happened in the SWC region of South Africa.

2) **How will the water available for abstraction change in the future, under climate change scenarios, and what are the implications of these changes for the reliability of the BRVAS?**

It was found in this study that in future, the water abstraction amounts available reduced quite dramatically across most hydrological flows simulated using the six different climate-hydrological model outputs.

5.5 Limitations

This section presents information regarding the limitations of the observed streamflows and the projected river flows.

5.5.1 Observed Streamflow Limitations

1) Many gaps were present (missing values), zeros were found in the streamflow-gauged data, and more negative values occurred, such as -999. In order to ensure the representativeness and reliability of available data, consistent and complete time series as well as the robustness of the sensitivity analysis, we had to delete all the gaps, zeros and negative values in the streamflow gauged data so as to make it easier to accurately analyse hydrological behaviour of the system. This is because negative values in the streamflow gauged data may sometimes indicate unusual conditions associated with measurement errors or reverse flows, where these anomalies can lead to uncertainties when analysing extreme events related to floods or droughts.
2) Only one observed streamflow gauge, namely the Daljosafat, were considered for the analysis of data, where it was possible to consider another streamflow gauge to compare the changes in the winter abstraction yield amount. Comparing the two or multiple observed streamflows helped to interpret and validate the behaviour of watersheds and predict streamflow under different conditions. Two streamflow gauge data offers redundancy, ensuring data quality and allowing for a more broad comprehensive analysis of temporal and spatial variations in streamflow, which is paramount for hydrological studies. This also provides a more wide-ranging picture of water availability, which is crucial for making informed decisions in water management.
3) Daily flow rather than hourly or shorter flow was used, which is how the abstraction would operate. This could mean that the results are slightly inaccurate to the sub-daily flow regime changes in ways that are different to the daily flow regime.

4) The observed flow contains multiple anthropogenic signals that may affect low flows in Winter: this includes new large dams (the Berg River Dam), as well as changes in on-farm water use. Therefore, the flows during the recent drought period, may not only be due to direct climate change, but also water trends.
5) For the observed streamflow, this study did not examine how the structure of individual high-flow events changed, but instead, examined summary results, rather than actual underlying flows during abstraction events.

5.5.2 Projected River Flows Limitations

1) The bias correction was not perfect; producing low flows was overestimated by bias-corrected ACRU data, while high flows were underestimated. Quantile-quantile-based bias correction would maybe help improve this.
2) The projections are based on only six climate change models; while the research that produced the flows showed that these model results are representative of the wider set of CMIP5 simulations, they could potentially be missing some of the more extreme scenarios.
3) For projected river flows, this study did not examine how the structure of individual high-flow events changed. It only examined summary results, rather than what the actual underlying flows during abstraction events looked like.

5.6 Recommendations

The following recommendations are made:

1) Since climate projections are already used in the WCWSS reconciliation strategy, the results of this study suggest the need for improvements in CC assessments.
2) The near future and the historical results suggest that estimates of how much water could be provided by BRVAS may already be underestimated, especially during drought periods. Medium-term forecasts of supply need to be updated in the WCWSS reconciliation work.
3) Since the average abstraction is only slightly reduced in the near future, but more significantly reduced in the distant future, a reasonable budget needs to be allocated to also start implementing water supply options, particularly in the SW Cape, such as desalination, such that water supply failure risk during drought is reduced. While the BRVAS is a relatively small component of the total WCWSS, similar effects will likely be felt in other parts of the system that are dependent on surface water supply.

4) Water demand management proves paramount, mainly for ensuring the sustainable use of water resources, protecting ecosystems, promoting long-term economic and social stability and adapting to climate change. It entails a combination of efficient use of water, conservation practices, and the adoption of technologies that contribute to the responsible management of this vital resource. As a result, given that most surface water resources are already exploited in WCWSS and that these are likely to be reduced in future, demand management becomes even more important. The following is the list of what has already been proposed for demand reduction in the WCWSS reconciliation:
    a) surface water schemes;
    b) desalination of seawater;
    c) re-use of water; and
    d) Table Mountain Group Aquifer scheme.
5) Given that the outcomes of the distant future of 2070-2099 show the reductions in water abstraction, these adaptation strategies/options/responses help to mitigate/reduce the CC impacts on the BRVAS. Additionally, increasing other water storage will help during the drought events in the Western Cape Province of South Africa. The already proposed augmentation options are associated with the increase of groundwater storage management, implementation of other surface water resources, Table Mountain group aquifers, rainwater harvesting, water reuse and the implementation of seawater desalination. As the WCWSS is more sensitive to the negative impacts of CC, these may help the SWC region to be water-secured over short, medium, and long-term periods. These are some of the fundamental implications to consider for this study.

5.7 Further Studies

The following are further studies that can build upon this existing study, and explore new avenues for managing and understanding the system:

1) Since the WCWSS is all about integrated water resources management (IWRM), it examines the effectiveness and feasibility of implementing the principles of IWRM in the BRVAS, investigate the social, environmental and economic benefits of adopting an integrated approach to water management, and investigate practical strategies for its implementation. It is therefore significant to bring more climate change information into the management of the WCWSS.

2) Long-term climate projections and the use of more climate models reveal a need to conduct further studies that serve to refine climate projections for the region focusing on higher resolution and localised climate models. This would improve the accuracy of future climate scenarios and their implications for the BRVAS.
3) Ecological assessment assesses the ecological impacts of CC on BRVAS. Investigate the responses of key habitats, ecosystems and species to changing water availability, water quality and flow patterns. Explore the potential for ecological conservation and restoration measures in the CC context.
4) Further studies should assess whether a larger abstraction system would be feasible and what the impacts of a larger system might be on both downstream users and downstream ecology. There is a need to explore the downstream impacts of the scheme under climate change in terms of potentially less downstream outflow.

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<u>The following is the appendix of abstractions based on the observed G1H020-Daljosafat streamflow gauge historical data:</u>

Appendix: A

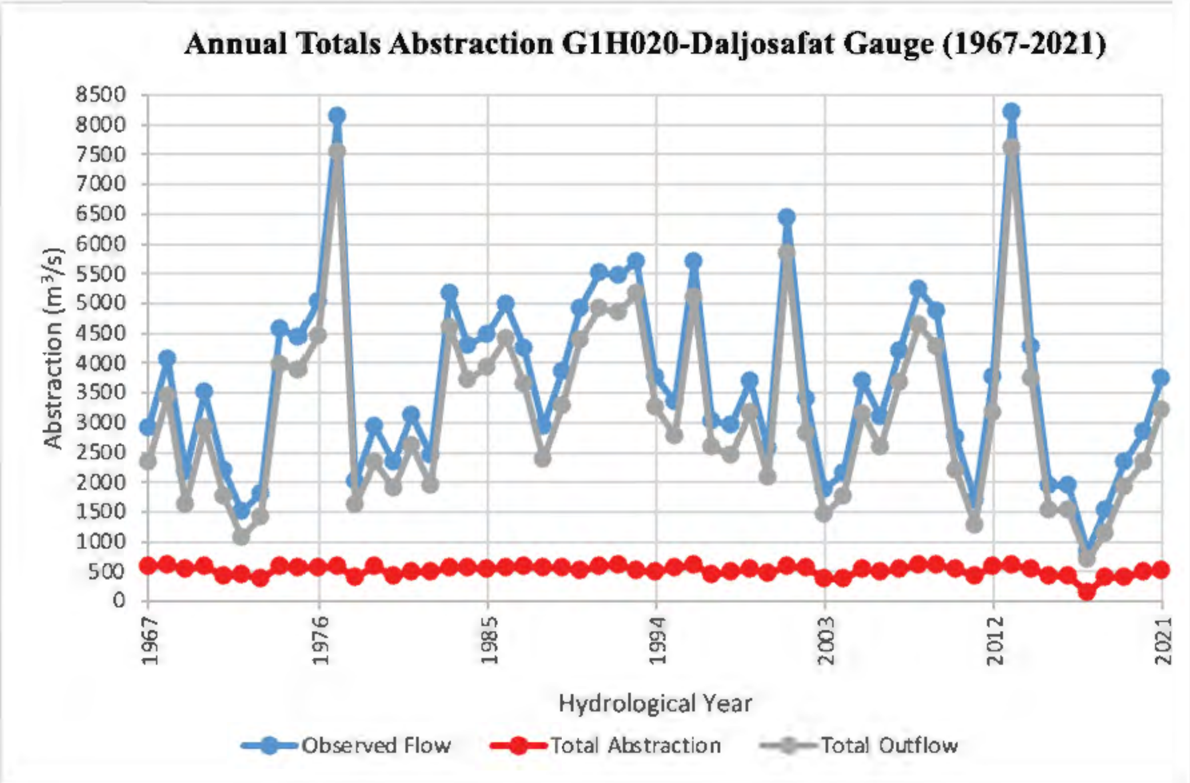

Figure 20: Total annual abstraction (m^3/s) of the G1H020 gauge from 1967-2021 (Author).

Appendix: B

Table 16: Statistics of the monthly abstraction (m^3/s) for Daljosafat streamflow gauge from 1968-1972, 2015-2019 and a full record of 1967-2021 (Author).

Statistics of Monthly Abstraction (Daljosafat Streamflow Gauge)						Statistics of Monthly Abstraction (Daljosafat Streamflow Gauge)						Statistics of Monthly Abstraction (Daljosafat Streamflow Gauge)					
Month	Min	Q1	Median	Q3	Max	Month	Min	Q1	Median	Q3	Max	Month	Min	Q1	Median	Q3	Max
1968-1972 (Past Drought-5 Years)						2015-2019 (Recent Drought-5 Years)						1967-2021 (Full Period-55 Years)					
1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
2	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	0	0
3	0	0	0	0	0	3	0	0	0	0	0	3	0	0	0	0	0
4	0	0	0	0	0	4	0	0	0	0	0	4	0	0	0	0	0
5	0	0	0	0	0	5	0	0	0	0	0	5	0	0	0	0	0
6	46	67	89	108	120	6	49	56	67	78	100	6	3	77	108	120	120
7	73	108	122	124	124	7	23	90	95	119	123	7	23	119	124	124	124
8	114	122	124	124	124	8	41	53	114	124	124	8	41	123	124	124	124
9	106	114	119	120	120	9	10	66	72	102	120	9	10	106	119	120	120
10	34	38	68	101	114	10	13	35	42	45	45	10	13	49	85	114	124
11	0	0	0	0	0	11	0	0	0	0	0	11	0	0	0	0	0
12	0	0	0	0	0	12	0	0	0	0	0	12	0	0	0	0	0

<u>The following is the appendix of the projected river flows and abstractions:</u>

Appendix: C

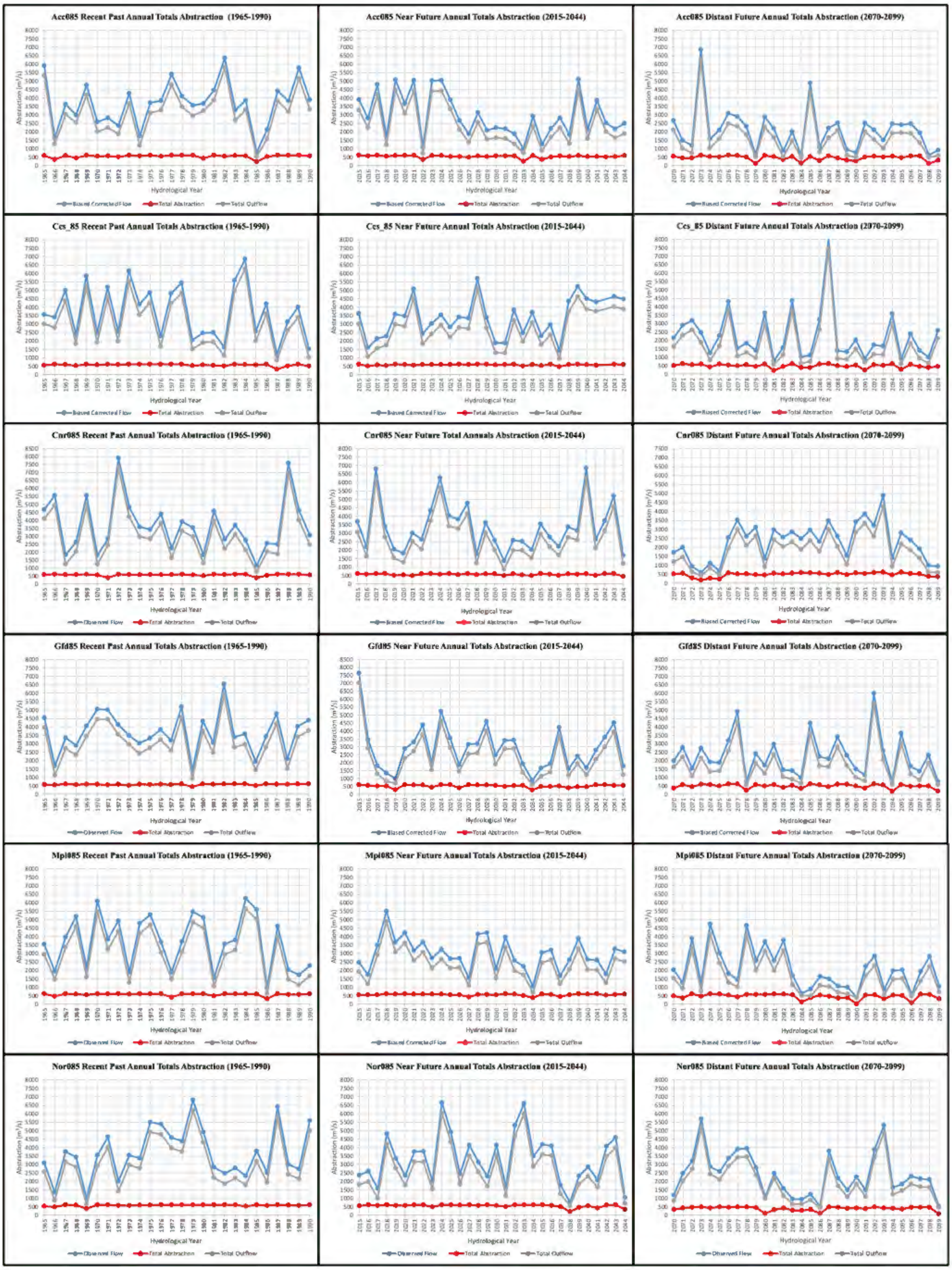

Figure 21: Total Annual Abstraction (m^3/s) of the six climate change scenarios from 1965-1990 recent past, 2015-2044 near future and 2070-2099 distant future (Author).

Appendix: D

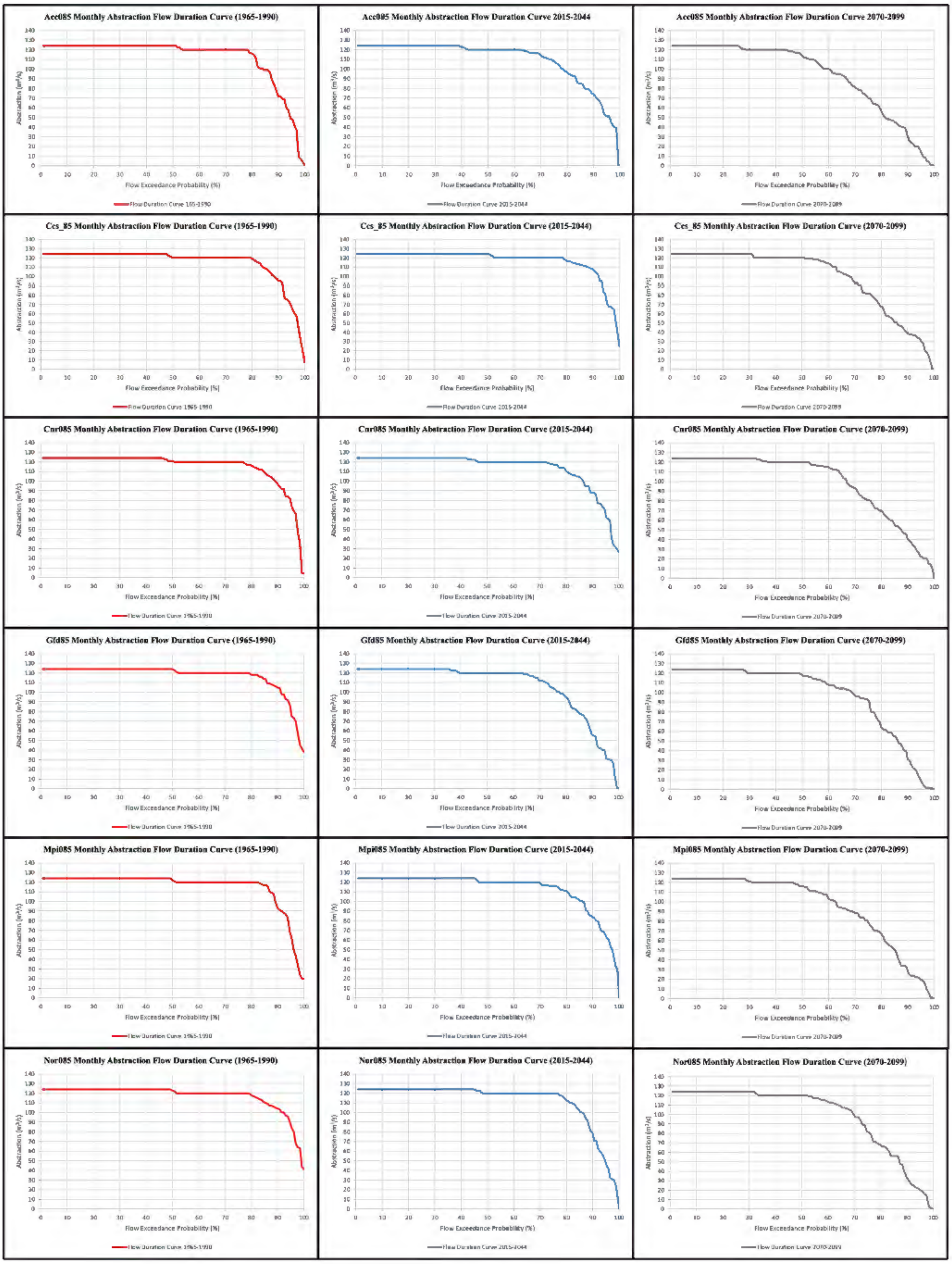

Figure 22: Monthly abstraction flow duration curve (m^3/s) (%) from 1965-1990 recent past, 2015-2044 near future and 2070-2099 distant future (Author).

Appendix: E

Table 17: Flow duration curve abstraction amounts (m^3/s) (%) at different percentiles in all six climate change scenarios (Author).

Percentile	Model 1 (Acc085)				
	Recent Past	Near Future	Distant Future	Abstraction Difference	Statistics Difference (%)
100	0	0	0	0	0
95	49	52	13	-36	-70
90	72	74	31	-41	-51
75	120	107	70	-50	-31
50	124	120	114	-10	-4
Percentile	**Model 2 (Ccs_85)**				
	Recent Past	Near Future	Distant Future	Abstraction Difference	Statistics Difference (%)
100	7	25	0	-7	-100
95	70	71	33	-37	-50
90	95	108	40	-55	-52
75	120	120	82	-38	-24
50	120	124	120	0	0
Percentile	**Model 3 (Cnr085)**				
	Recent Past	Near Future	Distant Future	Abstraction Difference	Statistics Difference (%)
100	4	27	0	-4	-100
95	82	71	23	-59	-68
90	97	88	41	-56	-52
75	120	118	81	-39	-24
50	121	120	120	-1	0
Percentile	**Model 4 (Gfd85)**				
	Recent Past	Near Future	Distant Future	Abstraction Difference	Statistics Difference (%)
100	38	0	0	-38	-100
95	87	40	11	-76	-83
90	105	56	31	-74	-63
75	120	104	93	-27	-17
50	124	120	118	-6	-2
Percentile	**Model 5 (Mpi085)**				
	Recent Past	Near Future	Distant Future	Abstraction Difference	Statistics Difference (%)
100	20	0	0	-20	-100
95	68	66	19	-49	-68
90	93	84	32	-61	-59
75	120	116	78	-42	-26
50	122	120	116	-6	-2
Percentile	**Model 6 (Nor085)**				
	Recent Past	Near Future	Distant Future	Abstraction Difference	Statistics Difference (%)
100	41	0	0	-41	-100
95	90	50	20	-70	-74
90	104	79	34	-70	-61
75	120	120	82	-38	-24
50	123	120	120	-3	-1

Appendix: F

Table 18: Monthly abstraction statistics (m^3/s) (%) for the six climate change scenarios (Author).

Statistics of Monthly Abstraction Summary (Six Climate Change Scenarios)															
Excel Function	Min	Q1	Median	Q3	Max	Min	Q1	Median	Q3	Max	Min	Q1	Median	Q3	Max
	Acc085 (1965-1990)					Acc085 (2015-2044)					Acc085 (2070-2099)				
Average	32	111	119	122	122	34	106	116	122	122	10	74	105	118	122
Max	78	124	124	124	124	79	124	124	124	124	23	113	124	124	124
Min	0	62	102	120	120	0	67	98	118	120	0	21	72	109	120
Median	37	124	124	124	124	40	120	120	124	124	9	93	120	120	124
25th Percentile	4	120	120	120	120	1	98	117	120	120	0	41	84	112	120
75th Percentile	41	124	124	124	124	52	122	124	124	124	20	95	123	124	124
	Css_85 (1965-1990)					Css_85 (2015-2044)					Css_85 (2070-2099)				
Average	38	116	122	122	122	74	118	121	122	122	23	89	104	120	122
Max	77	124	124	124	124	113	124	124	124	124	54	124	124	124	124
Min	7	95	119	120	120	25	108	115	120	120	0	35	50	115	120
Median	30	120	124	124	124	81	120	124	124	124	20	98	120	120	124
25th Percentile	19	115	120	120	120	40	116	120	120	120	0	72	101	119	120
75th Percentile	57	124	124	124	124	112	124	124	124	124	40	116	124	124	124
	Cnr085 (1965-1990)					Cnr085 (2015-2044)					Cnr085 (2070-2099)				
Average	56	115	122	122	122	57	112	120	122	122	24	87	107	120	122
Max	112	124	124	124	124	95	124	124	124	124	72	124	124	124	124
Min	4	98	116	120	120	27	79	108	120	120	0	35	63	110	120
Median	74	120	124	124	124	59	120	123	124	124	14	96	120	124	124
25th Percentile	5	107	120	120	120	32	115	120	120	120	10	65	103	120	120
75th Percentile	84	124	124	124	124	73	123	124	124	124	22	116	124	124	124
	Gfd85 (1965-1990)					Gfd85 (2015-2044)					Gfd85 (2070-2099)				
Average	79	117	122	122	122	41	99	118	122	122	13	84	111	121	122
Max	124	124	124	124	124	76	124	124	124	124	40	121	124	124	124
Min	38	100	117	120	120	0	85	101	120	120	0	27	94	115	120
Median	93	120	124	124	124	40	110	120	124	124	4	95	112	121	124
25th Percentile	42	117	120	120	120	30	98	119	120	120	1	60	104	120	120
75th Percentile	98	124	124	124	124	60	120	124	124	124	19	116	120	124	124
	Mpi085 (1965-1990)					Mpi085 (2015-2044)					Mpi085 (2070-2099)				
Average	56	120	122	122	122	54	112	119	122	122	0	80	108	117	122
Max	90	124	124	124	124	116	124	124	124	124	0	121	124	124	124
Min	20	110	120	120	120	0	84	104	119	120	0	25	78	109	120
Median	49	122	124	124	124	53	120	124	124	124	0	87	120	120	124
25th Percentile	34	120	120	120	120	33	106	120	120	120	0	58	93	110	120
75th Percentile	87	124	124	124	124	69	124	124	124	124	0	108	124	124	124
	No085 (1965-1990)					Nor085 (2015-2044)					Nor085 (2070-2099)				
Average	65	117	122	122	122	44	107	122	122	122	7	71	88	96	98
Max	97	124	124	124	124	110	124	124	124	124	19	116	124	124	124
Min	41	104	118	120	120	0	65	120	120	120	0	0	0	0	0
Median	64	120	124	124	124	31	120	123	124	124	1	97	120	120	120
25th Percentile	44	114	120	120	120	26	102	120	120	120	0	41	73	113	120
75th Percentile	80	124	124	124	124	55	124	124	124	124	16	100	124	124	120