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by Thusego Setswammung

Assessing the vulnerability of Gaborone Dam to climate change up to the year 2090 for the purpose of water security in the Greater Gaborone

By

Student: Thusego Sebastian Setswammung, STSTHU001

Supervisor: Piotr Wolski (PhD)

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PLAGIARISM DECLARATION

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

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Date: 9 June 2025

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Over the years, the song *“Don’t Give Up”* by Peter Gabriel featuring Kate Bush has been the background music through many long and tiresome days and nights. I found the lyrics to be most potent and fitting for a student trying to get some work done and contribute significantly to the academic world, and indeed to the general society. I dedicate this dissertation to my sister Pearl.

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LIST OF ACRONYMS

AR	Assessment Report
AR6	Sixth Assessment Report
ASL	Above Sea Level
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station *Data*
CRU	Climatic Research Unit
CORDEX	The Coordinated Regional Downscaling Experiment
CMIP6	Coupled Model Intercomparison Project Phase 6
DMS	Department of Meteorological Services
DWA	Department of Water Affairs
ERA5	European Centre for Medium-Range Weather Forecasts (ECMWF) *atmospheric* Reanalysis *generation* Five (5)
GCMs	General Circulation Models
GCOS	Global Climate Observing System
GDC	Gaborone Dam Catchment
GG	Greater Gaborone
GGWSS	Greater Gaborone Water Supply System
GHGs	Greenhouse gases
GMST	Global Mean Surface Temperature
GPCC	Global Precipitation Climatology Centre
HBV	Hydrologiska Byråns Vattenbalansavdelning (hydrological model)
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
MME	Multi-Model Ensemble
MCM/Mm^3	Million Cubic Meters
NDP	National Development Plan
NSC/NSWC	North-South (Water) Carrier
PE	Potential Evaporation
PET	Potential Evapotranspiration
RCMs	Regional Climate Models
RCP	Representative Concentration Pathways
SADC	Southern African Development Community
SDGs	Sustainable Development Goals
SPEI	The Standardised Precipitation-Evapotranspiration Index
SSKA	Sir Seretse Khama Airport
SSP	Shared Socioeconomic Pathways
Tx/TX	Maximum Temperature
Tn/TN	Minimum Temperature
WCRP	World Climate Research Program
WMO	World Meteorological Organization
WUC	Water Utilities Corporation

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ABSTRACT

Water forms part of critical infrastructure, and this dissertation covers the impacts of projected climate change on water resources. The primary focus is on climate change's effect on the water balance of the Gaborone Dam. Gaborone Dam forms part of the city of Gaborone's (*and surroundings - Greater Gaborone*) water supply. The motivation for this study is that Botswana is a landlocked country with present water challenges (scarcity) and hence in need of good water governance, especially for its capital city—Gaborone. Given the projected climate and increase in population, especially in the city, water resources are likely to be even more vulnerable than it is presently. The Gaborone Dam has reached critical states (low volumes) a few times in the past 20 years, and chances of drier conditions remain for the future. Since water is paramount for sustainable development and its insecurity jeopardises the country's sustainable ambitions and could potentially exacerbate societal inequalities, the water security of the country and especially the city has to be assessed as is done in this study. The study used multi-model ensembles of CMIP6 and CORDEX Africa with a focus on SSP2-4.5/SSP5-8.5 and RCP4.5/RCP8.5 future socio-economic development and scenarios of greenhouse gas emissions, respectively, to assess future rainfall and temperature of the study area—the Gaborone Dam. With historical observed rainfall and temperature values used as a baseline (1991 to 2020), the Gaborone Dam and its catchment's future rainfall and temperature were assessed for near (2031 to 2060) and far (2061 to 2090) future periods. Subsequently, the water balance of the Gaborone Dam was calculated, and a range of possible future water supply deficits were determined. Finally, these results were evaluated in the context of the literature and policies relevant to Gaborone's water security now and in the future. The results indicate that future climate projections encompass a broad range of conditions, suggesting that both increases and decreases in rainfall, and consequently water resources, are possible. Overall, however, there is a higher chance of a decline in available water resources. Is the current policy framework compatible with this? The answer seems to be a 'No' in that the primary policy managing water does not seem to address climate change specifically, nor the population growth rate of Greater Gaborone.

1 CHAPTER 1: INTRODUCTION AND STUDY BACKGROUND

1.1 Introduction

Botswana is a semi-arid country which experiences droughts from time to time, which affect water resources (Batisani and Yarnal, 2010; Byakatonda et al., 2018b). The Gaborone Dam is an important water source for Greater Gaborone, which is the city of Gaborone and its surroundings. When considering that in the future, most people will be living in cities and Botswana is no exception, water resources and water supply systems form part of what is called Critical Infrastructure (CI), i.e. infrastructure that is vital for livelihoods and the country's sustainable development aspirations. The way the city grows spatially over time will have a huge bearing on its water as a critical resource. One of the main threats to Botswana's water resources is that the summers are characterised by evaporation rates that are more than three times higher than rainfall consequent to high solar radiation in the summer months (Byakatonda et al., 2018b; Meinhardt et al., 2018). Further, there is strong evidence that since the early 1980s, the yearly evapotranspiration on land has grown globally, and anthropogenic forcing has a significant role in this (Douville and Jiang, 2021). This means that under anthropogenic climate change, the country's water resources are very vulnerable to evaporative water loss. It can be concluded that generally the hotter it becomes, the drier it becomes in the country (Byakatonda et al., 2018b), hence rendering the country's water resources very vulnerable to extreme weather events owing to climate change. To safeguard Gaborone's future, it is paramount that studies be carried out that evaluate water stress levels and inform appropriate water governance.

1.2 Study Justification

Urban water scarcity is especially problematic, as potentially many more people are affected as opposed to rural areas. It is therefore important that there be water security studies in Botswana dealing with urban water security now and into the future, and with consideration for climate change. Specific to the future water situation for the capital city of Gaborone, only a few studies addressed that problem (Mphoeng, 2021; Farrington, 2015; and Moalafhi et al., 2012). Furthermore, there is a need for area-specific research for Global South cities, considering individual cities. This study intends to build knowledge specific to the city of Gaborone. The results of this study contribute to a knowledge base informing policymaking and future water security planning.

1.3 Problem Statement

In the age of the Anthropocene, Africa's well-documented developmental challenges make the member states especially vulnerable to climate change. The Anthropocene refers to the geological epoch, under consideration, to mark the great influence human activities have on the natural environment or the Earth system, especially since the Industrial Revolution (Zalasiewicz et al., 2010; Steffen et al., 2011). Anthropogenic climate change refers to the change in climate owing to the effects of human activities. Literature also shows that in the future, most people will be living in cities (for example, Cohen, 2006), and Botswana is no exception. An increase in the city population means increased pressure on city resources such as potable water. Water insecurity is a threat to most developmental endeavours. Botswana relies on both surface and groundwater for raw water. However, current usage and climate render its water resources vulnerable and projected future climates will likely worsen the vulnerabilities. There is a scarcity of information concerning Gaborone's water resources and climate change. To improve urban policy-making and planning, there must be studies on climate change and water security for the city of Gaborone, considering the already scarce nature of water in the country.

1.4 Study Goal

To investigate Gaborone and its surroundings' water security and its supply system's vulnerability to anthropogenic climate change up to the year 2090.

1.5 Research Question

The research question is: What will be the water availability from the Gaborone Dam and consequently for Gaborone city and surroundings, in the coming decades under anthropogenic climate change?

1.6 Research Aim

1. To evaluate the sensitivity of Greater Gaborone's water supply system and demand to the projected climate change and population growth, through the lens of the Gaborone Dam, taking into account the uncertainty of projections of future climate.

Objectives:

- To investigate variability in water availability in the Gaborone Dam and its main drivers.
- To analyse the projected rainfall and potential evaporation for the Gaborone Dam catchment area and assess the future water balance of the Gaborone Dam under these projected rainfall and potential evaporation, taking into account the uncertainty of climate projections.
- To assess the effects of the projected population of Greater Gaborone in the coming decades (till the end of the 21st century) on the water demand from the Greater Gaborone water supply system.
- To evaluate policy provisions for urban water security in Botswana.

1.7 Structure of the thesis

Chapter 2 describes the study area and its parent water supply system. It details the dam's vulnerabilities and present engineering interventions and the role of the water policy.
Chapter 3 provides a review of the literature and earlier studies providing context to the understanding of water security issues faced by Gaborone in particular, but Botswana in general. It also outlines the role of climate models and simulations (GCMs and RCMs) in studying future water security under anthropogenic climate change.
Chapter 4 details the research design and general approach to conducting the water security study. It outlines the data and methods used in researching water availability for the city.
Chapter 5 describes the study results and their analyses. It describes water and climate models' output, and Policy documents findings with respect to climate change.
Chapter 6 discusses Greater Gaborone's water security in terms of projected future climate, population growth, and relevant legal framework.
Chapter 7 is the study conclusions and recommendations concerning the study goal and findings.
Chapter 8 outlines study limitations and ethical considerations.

2 CHAPTER 2: STUDY AREA

The study focuses on the Gaborone Dam, which is part of the water supply system to the so-called Greater Gaborone. Gaborone Dam dams the Notwane River, which is a part of the upper Limpopo basin. The sections below describe the geography and climate of the Notwane River catchment, and subsequently the Greater Gaborone Water Supply System (GGWSS).

2.1 Greater Gaborone

Greater Gaborone is a cluster of towns and villages in the south-eastern part of Botswana that includes the city of Gaborone, Mochudi, Mogoditshane, Tlokweng, Ramotswa, Lobatse (Alemaw et al., 2016), and their surrounding villages. In 2022, Gaborone's population was 244 107 and the population of Greater Gaborone was at least 500 299 (Statistics Botswana, 2022). From Table 2.1, it can be observed that the population growth rate of the towns and villages in the Greater Gaborone has generally been positive (population growth) in the past years, 2011 to 2022, and this is likely to put pressure on the Greater Gaborone water supply system.

Table 2.1: Historical population and growth rate of Gaborone and its surroundings

PLACE	2011 CENSUS	2022 CENSUS	GROWTH RATE (%)
Gaborone	231,592	244,107	0.5
Lobatse	29,007	29,457	0.1
South East District	85,014	111,474	2.6
Tlokweng	36,323	55,517	4.1
Ramotswa	28,952	33,275	1.3
Kgatleng District	91,660	121,411	2.7
Mochudi	44,815	49,845	1.0
Mogoditshane	58,079	88,098	4.0

Adapted from, Statistics Botswana (2022)

2.2 Notwane River Catchment

The Notwane River catchment area is part of the Limpopo River Basin (Matlhodi et al., 2021, Figure 2.1). The Notwane catchment area is 18 263 km^2, while the Gaborone Dam catchment (Figure 2.2) area is approximately 4300 km^2 although exact values vary between 4000 – 4500 km^2 depending on the source (Alemaw et al., 2016; Fleischer et al., 2016; Kenabatho and Parida, 2005; and Moatlhodi et al., 2021). The Notwane River is the primary drainage channel of that basin (Matlhodi et al., 2021).

The region is semi-arid (Batisani and Yarnal, 2010; Byakatonda et al., 2018b) and on average experiences summer temperatures of 33ºC and winter temperatures of 20ºC (Matlhodi et al., 2021). The mean annual rainfall is in the region of 475–525 mm/year mostly falling in the summer months (November to March), and annual potential evaporation rates of about 2000 mm/year (Parida et al., 2006) which is significantly higher than the mean annual rainfall (Matlhodi et al., 2021; Meinhardt et al., 2018).

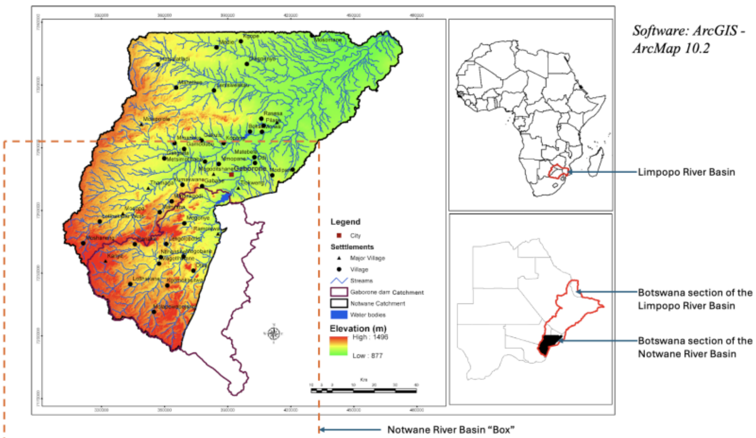


Figure 2.1: Botswana part of the Notwane catchment of the Limpopo River Basin

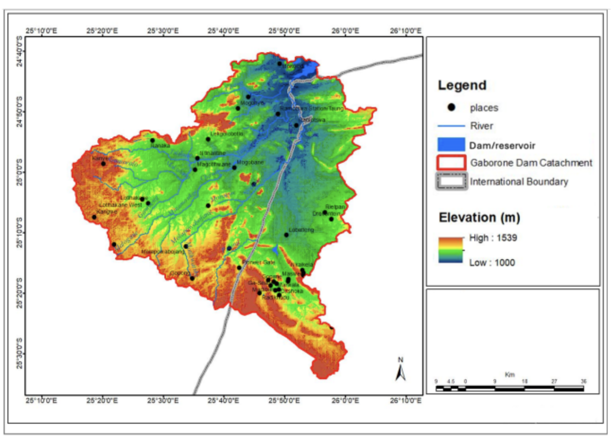
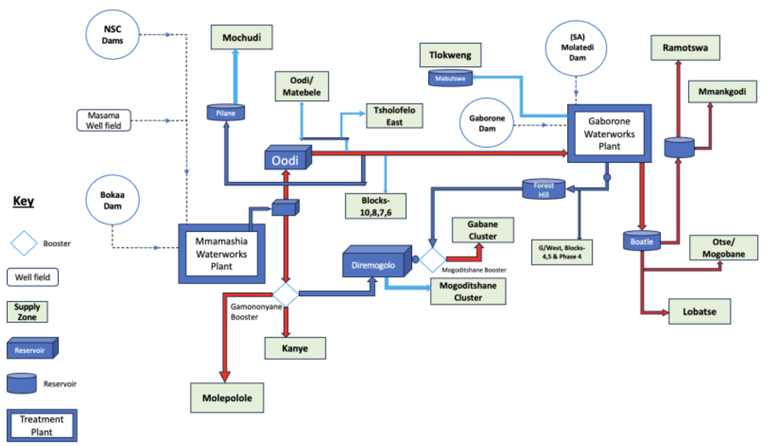


Figure 2.2: Gaborone Dam Catchment Area

2.3 Greater Gaborone Water Supply System

This section synthesises the information on the Greater Gaborone water supply system available from a number of sources, supplemented by an interview with the relevant personnel of the Water Utilities Corporation (WUC). The Greater Gaborone water supply system (Figure 2.3 and Table 2.2) services 14 supply zones from two waterworks plants.

GREATER GABORONE WATER NETWORK



From Interview materials, WUC (2023)

Figure 2.3: Schematic representation of the Greater Gaborone Water Network

Table 2.2: Dams supplying water to the Greater Gaborone area

DAM & Water Carrier	CAPACITY (MCM)	YEAR COMMISSIONED
Dikgatlhong (*NSC dam*)	400.0	2012
Molatedi (in South Africa)	201.0	1986
Gaborone Dam	141.4 (since 1984)	1965 & raised in 1984
Letsibogo (*NSC dam*)	100.0	1997
Bokaa Dam	18.5	1993

Source: Statistics Botswana (2017), Water Utilities Corporation (2022)

The water supply system for Greater Gaborone is a complex system in that it has several water sources (*see* Figure 2.3 and Table 2.2). There are five surface water reservoirs and one groundwater source in the water network. Of the five reservoirs, two dams (Dikgatlhong and Letsibogo) are in the northern part of Botswana, supplying the area via the North-South Carrier (NSC) pipeline. The NSC water project has two phases (WUC, 2023). Phase I conducts water (primarily) from the Letsibogo dam and was completed in 1991 (Farrington, 2015). Additionally, Phase II is ongoing and primarily transfers water from Dikgatlhong Dam. The NSC's key purpose is to ease pressure on the Gaborone Dam.

The other three GGWSS dams are in the south, with the Molatedi Dam situated outside the country in neighbouring South Africa. It is only the Gaborone and Bokaa Dams that are located within Greater Gaborone. Further, the system's non-surface water reservoir supply is the Masama well field, which contributes groundwater to the system and its waterworks.

The system's waterworks are the Gaborone Waterworks and the Mamashia Waterworks. The Gaborone Waterworks is supplied by the Gaborone Dam and Molatedi Dam. The Mamashia Waterworks is supplied by the Bokaa Dam and from the Dikgathlong and Letsibogo dams through the North-South Water Carrier, as well as from the Masama wellfield (Figures 2.3 & 2.4).

The unconstrained water demand imposed on the various elements of the system as per the year 2021 is presented in Table 2.3:

Table 2.3: 2021 water demand imposed on various elements of the GG water supply system (based on Table 22 from Water Utilities Corporation - Botswana, 2021)

Source	**Demand Allocation (MCM/year)**
Dikgathlong+Letsibogo (through NSC)	40.23
Masama Wellfield	9.82
Bokaa	3.1
Gaborone	21.83
Molatedi	4.06
other small dams and wellfields	~3

As per the network schematic in Figure 2.4, water from the Gaborone and Molatedi dams is distributed to parts of the Greater Gaborone through the Gaborone Waterworks, while that from the other sources - through the Mamashia waterworks (WUC, 2023). The Gaborone waterworks' daily demand allocations and supply zones (WUC, 2023) are presented in Figure 2.4.

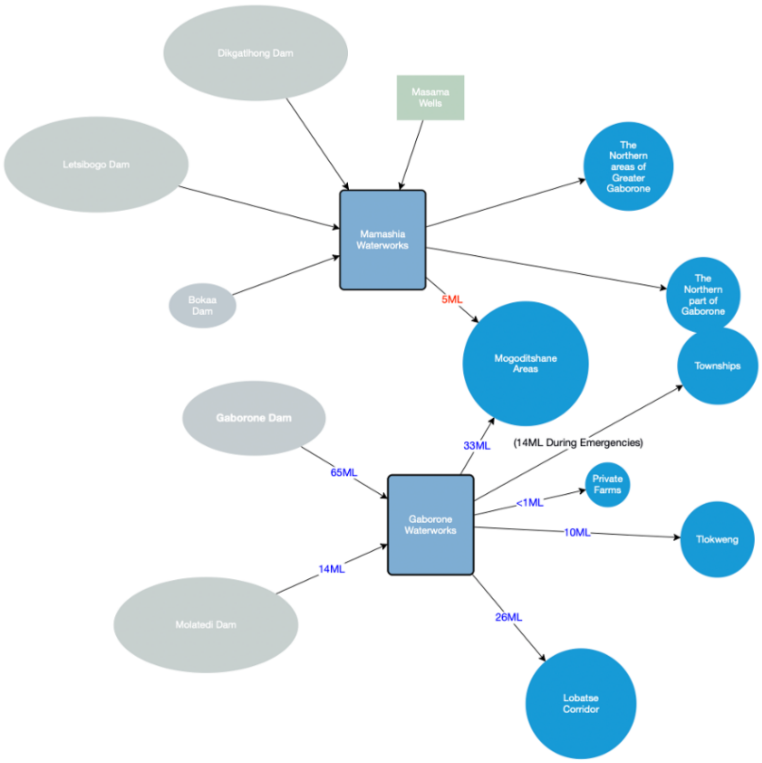


Figure 2.4: Greater Gaborone 2023 water allocation schematic - Values in ML per day (source: Interview with WUC staff)

2.4 The Gaborone Dam

One of the key surface reservoirs of the GGWSS is the Gaborone Dam. The Gaborone Dam is an earthcore dam with a capacity of approximately 140 MCM (Figures 2.5 and 2.6). The dam was constructed in 1963, commissioned in 1965 and raised to its current capacity in 1984. As mentioned earlier, the GGWSS imposes a water supply-demand (demand allocation) limit of 21.83 MCM/year on that dam. As Table 2.3 illustrates, the Gaborone Dam is able to supply only a part of the water demand of the entire Greater Gaborone area.

Source: https://earth.google.com/

Figure 2.5: Google Earth satellite image of Gaborone Dam

by author, taken on 2023.01.23

The Gaborone Dam level is low enough to see Old Lobatse Road.

Figure 2.6: Old Lobatse Road in the Gaborone Dam

When the Gaborone Dam is capable of safe yields, the operating guidelines are to meet all (100%) of the water demand. (Water Utilities Corporation - Botswana, 2021; WUC, 2024). Alemaw et al. (2016) provide a summary of the Gaborone Dam operational guidelines as applied in their modelling (Table 2.4).

Table 2.4: Operating rules of Gaborone Dam (after Alemaw et al. 2016)

Water level (ASL)	Stored volume	% Capacity	Operation
>998m	>140 MCM	100	open spillway
>983m	>4.6 MCM	3 –100	release 0.63 m^3/s to the supply system
<983m	<4.6 MCM	<3	no release

The Gaborone Dam reservoir's historical volume of water stored and the corresponding surface area are illustrated in Figure 2.7.

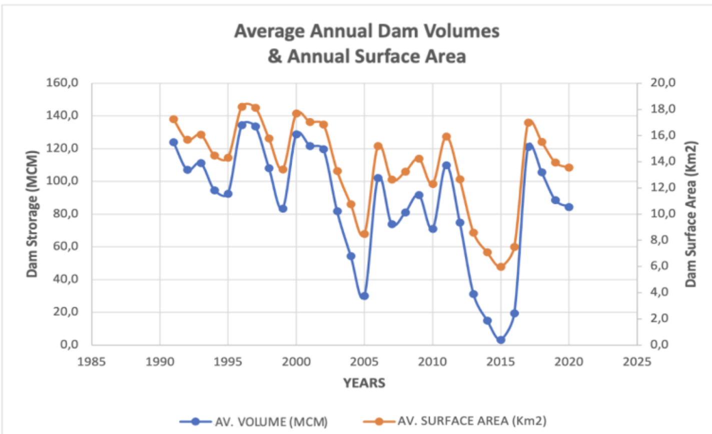


Figure 2.7: Gaborone Dam average annual volume of water stored and surface area from the year 1991 to 2020

The dam's stored water volume experiences fluctuations consistent with normal seasonal and interannual variations (Figure 2.7). However, the years 2015 and 2016 saw the dam operating at critical levels with resulting curtailment of supply, and this was recorded in some works of literature (Farrington, 2015; Fleischer et al., 2016; Kadibadiba et al., 2018).

There are a number of dams in the Notwane River catchment upstream from the Gaborone Dam :

- Notwane Dam (Figure 2.8) constructed in 1960, which currently plays the role of a siltation dam for the Gaborone Dam,
- three main dams for local (mostly agricultural) use (Table 2.5), and
- approximately 200 small farm dams (Fleischer et al., 2016, Figure 2.9).

The upstream dams are reported to decrease inflow to the Gaborone Dam by 12% in typical years, and more than 20% in extremely dry years (Fleischer et al., 2016).

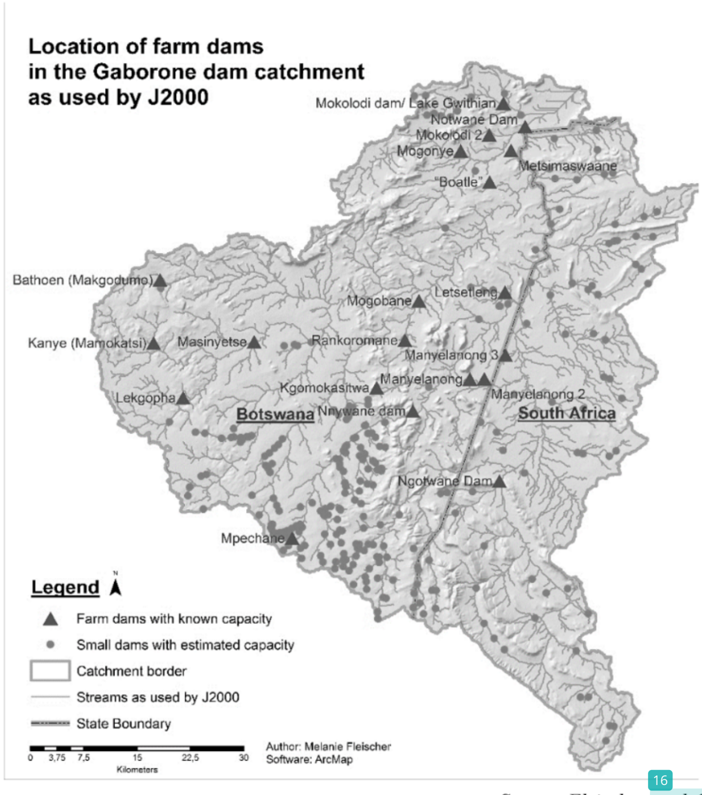
The Notwane Dam has a surface area of ~ 0.5 km^2. It is situated between 23°S and 25°S and 25°E and 27°E, in the upper catchment of the Notwane River. It is a check dam designed to capture sediment for the Gaborone Dam (Franchi et al., 2020).

Figure 2.8: The Notwane Dam (by author, taken on 2023.01.23)

Table 2.5: Main dams in the Notwane River catchment upstream from the Gaborone Dam

Dam name	**Country**	**Catchment Area (km^2)**	**Active Storage (MCM)**	**Year of Construction**	**Use**
Nnywane	Botswana	238	2.3	1970	Domestic
Mogobane	Botswana	418	Unknown	Unknown	Irrigation/conservation
Ngotwane	South Africa	518	19.1	1982	Irrigation

Adapted from: Altchenko et al. (2016)



Source: Fleischer et al. 2016

Figure 2.9: Map showing the other dams in the Gaborone Dam catchment area

3 CHAPTER 3: LITERATURE REVIEW

3.1 The City of Gaborone & surroundings' Water and Drivers of Water Scarcity

Gaborone and its surroundings are primarily supplied by the Gaborone Dam (Mphoeng, 2021; Tsheko, 2003), therefore, the dam's water stresses directly affect Greater Gaborone's water security. The dam's vulnerability in terms of adequate water supply is primarily due to operational, human and climatic factors (Alemaw et al., 2016). The human factor includes population growth and prevailing urbanisation, contributing significantly to the increasing water demand. Considering the climate change factor, Gaborone Dam is expected to have a reduced flow of water from its catchment in the coming years (Alemaw et al., 2016). This all means supply from the dam is expected to decline in the coming years.

3.1.1 Stressors of the Gaborone Dam (Notwane) Catchment Area

Climate change and land use changes can stress catchments, leading to increased surface runoff, evapotranspiration, and increased agricultural water usage. Investigating hydrological responses is crucial for effective water resource management and planning (Duan et al., 2017). Duan et al. (2017) emphasise the importance of assessing and predicting temperature, rainfall, and surface water levels to prevent future hydrological disasters like floods and water quality issues. In addition to extreme weather events, the Gaborone Dam catchment area is also stressed by relatively smaller reservoirs such as the Mogobane Dam (Farrington, 2015). Further, there is also a concern about the possibility of unauthorised dams in the catchment area (Farrington, 2015). Studying the hydroclimatology, changes in mean conditions (temperature and rainfall primarily), and human activities in catchment areas is crucial for understanding water quality and quantity reduction. This study sought to assess the catchment's water availability as impacted by historical and future climate.

3.1.2 Vulnerability of the Gaborone Dam

As the Gaborone Dam receives inflows from the catchment, understanding the dam's structure is important in its vulnerability assessment. The dam was constructed in 1963 and subsequently raised in 1984 (Alemaw et al., 2016). The wall was raised by an additional 25 metres, and the project ended in 1986 (Meinhardt et al., 2018). It is an earthcore fill dam type. Its capacity is about 141.5 MCM with a surface area of 19 km^2 (Alemaw et al., 2016).

Surface reservoirs in semi-arid areas are vulnerable to significant water losses owing to evaporation (Kenabatho and Parida, 2005; Du Plessis and Rowntree, 2003). Botswana's surface reservoirs lose more water due to evaporation, especially when their capacity is below 50% (Kenabatho and Parida, 2005). Further, on average, the evaporation rate is higher in the southern catchments of Botswana compared to the northern ones. Furthermore, the Gaborone and Bokaa dams (in the southern part of Botswana) have mean evaporation losses of 24% and 54% of the dam capacity volume, respectively. In comparison, mean evaporation losses for Shashe and Letsibogo (dams in the northern part) were 20% and 11% of the dam capacity volume, respectively. One of the factors contributing to Botswana reservoirs' high evaporation losses is the relatively shallow and wide dams owing to the country's general flat topography (Kenabatho and Parida, 2005).

Another vulnerability of reservoirs is that of sedimentation over the years, which is likely to reduce the storage capacity of the Gaborone Dam (Alemaw et al., 2016; Perkins & Parida, 2022). For instance, due to sedimentation, the Gaborone Dam is estimated to have a residual storage capacity of about 133.9 MCM by 2030 (Alemaw et al., 2016). Alemaw et al. (2016) concluded that Gaborone Dam's water supply resilience and dependability in all future scenarios are lower than they were historically, suggesting a potentially bleak water future.

3.1.3 Vulnerability of the Dam due to the Greater Gaborone Population

Greater Gaborone is the most densely populated area of the country. The mean population annual growth rate for Greater Gaborone for the period 2001 - 2011 was 4.45% (Alemaw et al., 2016). Using readily available population data, the population specific to the city of Gaborone is such that the 1991 population census was 133 468 (Republic of Botswana, 1995), 165 343 in 1995 (Republic of Botswana, 2002), 186 007, 231 592 and 244 107 for the years 2001, 2011 and 2022 respectively (Statistics Botswana, 2022). For the other key places of Greater Gaborone, in 2022, the population census of Mogoditshane and Tlokweng were 88 098 and 55 517, respectively. This means there are more than 387 722 people (Gaborone, Mogoditshane and Tlokweng alone) that demand water in the Greater Gaborone area, and this adds pressure to the Gaborone Dam. Up to the year 2100, the expected population growth of Gaborone and its surroundings is placed at around 2.2% to 3.4% growth rate and would have increased by about 10 times the present number by the turn of the century (Mphoeng, 2021).

3.1.4 Vulnerability of Urban Water Security due to Urban Growth

Urban development patterns and water shortage is a subject matter worth investigating (Heidari et al., 2021). Population growth and urbanisation are expected to significantly reduce Gaborone Dam's water supply reliability (Alemaw et al., 2016). Urban growth patterns (especially in the Global South) is perhaps a study area that must also be inserted into the conversation of water security and governance. If a city sprawls as opposed to densification, we are likely to have a situation where there is extensive pipework (water pipes covering longer distances) required to service areas in the urban 'periphery'. However, in Gaborone and the surroundings, a significant amount of water is lost owing to water pipe leakages (Mphoeng, 2021). The way a city develops or its growth pattern affects how the water infrastructure also develops, and this has a bearing on the water supply system.

3.2 Present Urban Water Security Interventions

3.2.1 The Intervention of the North-South Water Carrier Project

In pursuit of water security in the south-eastern part of the country, where the capital city is, and indeed, a huge population, the Government of Botswana engaged in a huge engineering-infrastructure project termed the North-South Water Carrier Project. The North-South Water Carrier Project was conceived in the early 1990s (Banks, 1998). The objective was to carry water from the Letsibogo Dam toward the greater Gaborone area through a 361 km pipeline in its first phase (Ministry *of* Minerals Energy and Water Resources, 2012). The second phase involves water drawn from another dam in the north, a duplicate of the Phase 1 project (Ministry *of* Minerals Energy and Water Resources, 2012).

The transfer of water from the northern part, where it is relatively more abundant, to where it is comparatively scarce, no doubt helps with the water supply in Greater Gaborone. This being the case, the issues raised by other studies (Mphoeng, 2021, for example) of Botswana's surface water and water pipelines have to be considered. The concerns of pipe leakages for such a long pipeline must be evaluated, as there is a potential for the great loss of the already scarce resource. The high rate of evaporation for open dams is also a critical concern, especially concerning the projected hot and drier climate for Botswana (Nkemelang et al., 2018; Alemaw et al., 2016) and therefore, there must be studies assessing NSWC dams and other major dams' evaporation situations. This study assesses Gaborone Dam's evaporation.

Before the services of the NSWC, about 80% of Botswana's domestic water supply was met by relying on groundwater (Ministry *of* Minerals Energy and Water Resources, 2012). However, specific to urban places such as Gaborone and Francistown, surface water resources constitute 90% of urban water supply (Alemaw et al., 2016). Critically, Greater Gaborone is supplied by 5 surface water resources (Table 2.3).

3.2.2 Water Legal Framework – National Water Policy

Water security interventions are driven by policy. The Botswana National Water Policy guides the management of water in Botswana and all that is incidental to it (Ministry *of* Minerals Energy and Water Resources, 2012). There is a recognition of the importance of water as a resource to the country's development endeavours. The Policy gives direction and guiding principles for the creation of future National Development Plans. The policy will give the economy as a whole a framework for achieving the country's objectives of economic expansion, diversification, and the eradication of poverty (Ministry *of* Minerals Energy and Water Resources, 2012).

Water is a good that improves people's livelihoods and is very critical to national development. Under the Strategies section (8.1.7), the National Water Policy aims to ensure that all water usage is effective and suitable for its intended use, finding it necessary to assess the water balance of all developments holistically, taking into consideration all supply avenues. To the best of the author's knowledge, there is no policy explicitly addressing future urban water balance and security under climate change. It is therefore very important that studies of Botswana's water bodies be increased and that there be a clear picture of the water security level in the country and its urban areas. From these studies, an informed legal framework can be developed/improved to inform the country's water governance.

In *summary, the* literature outlines many stressors to water availability in the Greater Gaborone (sections 3.1 to 3.2) affecting the Gaborone Dam. These stressors are a mix of operational, human, and climatic factors: pipe-work leaks, sedimentation of the dam, numerous smaller farm dams in the catchment, urbanisation, consumers' water use behaviours, population growth, and climate change. This study zooms in primarily on climate change and factors in the effects of population-driven demand and water policies affecting the Gaborone Dam. There was therefore a need to look at more literature on climate change and water security.

3.3 Conceptualising Climate Change - A Water Security Driver

3.3.1 The African and Regional Climate Change Context

In this era, planet Earth is dealing with climate change significantly affected by anthropogenic activities (IPCC, 2022). There is an increase in Global Mean Surface Temperature (GMST) above pre-industrial levels due to anthropogenic activities (Nkemelang et al., 2018; UNFCCC, 2016). The planet is warming and its climate is significantly changing due to the effects of Greenhouse gases (GHGs), largely owing to many human activities such as those in the energy, industry, and agriculture sectors.

Relative to the 1850–1900 period, the 2010–2019 period realised a GMST increase of 1.07 °C and a climate change that adversely affected many sectors such as the food and water sectors (Lee et al., 2023). As with other regions of the world, the continent of Africa is very vulnerable to climate change and extreme events caused by anthropogenic global warming (Nkemelang et al., 2018). The extreme events here refer to heat waves, intense precipitation, floods, and droughts. It is to be understood that the likelihood of more frequent, intense precipitation or rainfall does not necessarily mean more water is available for necessary ecological and livelihood needs. Intense precipitation tends to lead to runoff and floods. At the same time, increased mean temperature could drive higher levels of evapotranspiration and an increase in the frequency and intensity of droughts. The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) reports that these adverse effects of climate change are already one of the drivers of displacement on the African continent (Lee et al., 2023).

Southern Africa is already very vulnerable to climatic and weather extremes as it is (Nkemelang et al. 2018). As with most of Africa, 75% of mainland Southern Africa has an arid to semi-arid climate (Nhemachena et al., 2020; Nicholson et al., 2018). The region has an annual rainfall of below 650 mm. Further, Southern Africa experiences highly variable rainfall, which can range from 100 to 2000 mm annually. Because of the degree of aridity and highly variable rainfall, 75% of Southern Africa experiences low mean annual runoff and water scarcity (Nhemachena et al., 2020). Global warming will only exacerbate the water scarcity of the region. Although governments under the Paris Agreement (UNFCCC, 2016) undertook to keep global warming way below 2.0°C, and preferably not exceed 1.5°C, it is likely that the 1.5°C mark could be exceeded by the year 2026 (Nkemelang et al., 2018). The imminent threats of climate change due to anthropogenic-driven global warming necessitate that specific studies be done, particularly in the world's most disadvantaged areas (Nkemelang et al., 2018). From the literature, climate projections are part of the conventional way of doing studies concerning anthropogenic climate change.

3.3.2 Projecting Future Climate

3.3.2.1 Climate modelling experiments

Evaluating a range of potential climate outcomes/futures substantially aids in planning adaptations and aids in the assessment of climate change risk. These potential futures are depicted by climate predictions that take into account the social, ecological, and economic factors/scenarios (Daniels et al., 2012). These potential futures are termed projections. Climate modelling simulations are the technology by which climate projections are made (Cubasch et al., 2001). The climate models used are state-of-the-art atmosphere-ocean general circulation models (AOGCMs) which are part of the Coupled Model Intercomparison Project of the WCRP. These models are from many institutions in several countries (Knutti et al., 2010). About every six years, the IPCC publishes its Assessment Reports. The IPCC is on its sixth report, AR6 (IPCC, 2024). The IPCC relies on CMIP climate change experiments and outputs for its reports, and as such, CMIP phases traditionally align with the IPCC reports, i.e., AR6 is aligned with CMIP6. CMIP can be best described as a global modelling project whose mandate is to provide a better understanding of past, current, and future changes in the Earth's climate (CMIP, 2024). Essentially, CMIP projects and associated databases of climate projections were created to support the IPCC process.

For the IPCC's fourth assessment report of climate variability and change, as well as a significant amount of peer-reviewed publications, the Coupled Model Inter-comparison Project Phase 3 (CMIP3) multimodel dataset was relied upon (Taylor et al., 2012). The Coupled Model Inter-comparison Project Phase 5 (CMIP5) is aligned with the fifth assessment report (AR5) by the IPCC (Oo et al., 2019; Taylor et al., 2012). It is the phase with more robust models than the CMIP3, having the capacity to answer more scientific questions (Taylor et al., 2012). Succeeding the CMIP5, the sixth phase of the Coupled Model Intercomparison Project - Phase 6 (CMIP6) is expected to lay a significant foundation for climate change research into the future and is a vital component of the Intergovernmental Panel on Climate Change's (IPCC AR6) sixth assessment report (Li et al., 2020). The CMIP6 is a climate multi-model project whose output is accessible through the Earth System Grid Federation (ESGF). These projects use multiple models in the assessment of climate change owing to natural, unforced variability and climate change in response to changes in radiative forcings (Eyring et al., 2016).

3.3.2.2 Future socio-economic and greenhouse gas emission climate scenarios

Climate scenarios offer a credible forecast of potential future outcomes by making some well-reasoned assumptions about the main driving forces of anthropogenic climate change.

Although scenarios are useful for comprehending potential future developments, they cannot foretell events (Krey, 2014). The baseline situations vary greatly in terms of some assuming no climate policy at all, others reflecting the policies enacted and a situation where only some of the planned climate policies are enacted. To date, the analysis of potential future climate change, impacts, and response options in subsequent IPCC Assessment Reports (ARs), has been informed by four generations of emission scenarios that have been fed into climate models and scenario-based research (Pedersen et al., 2022). The fourth and currently widely used is the Shared Socioeconomic Pathways-Representative Concentration Pathways (SSP-RCP) framework.

The framework includes the Shared Policy Assumptions (SPA), which describe trends in climate policy, the Representative Concentration Pathways (RCP), which express radiative forcing scenarios, and the Shared Socioeconomic Pathways (SSPs), which express socioeconomic developments (Pedersen et al., 2022; Kebede et al., 2018). The RCPs focus on the biophysical change in climate due to forcings, while the SSPs include the prevailing or relevant socio-economic impacts, and the SPA covers the environmental policy narratives (Kebede et al., 2018). Furthermore, RCPs consist of a series of global climate scenarios that take land use changes and greenhouse gas and other air pollutant emissions into account (van Vuuren et al., 2011). They include the paths for the global climate system's "radiative forcing," which quantifies how variations in the atmosphere's composition, such as those brought on by greenhouse gas emissions, affect the system's energy balance (Kebede et al., 2018). On the other hand, the SSPs, at the global and major regional levels, describe credible alternative tendencies in the evolution of natural systems and society during the twenty-first century. They are made up of two components: a collection of quantitative development metrics and a narrative plot (O'Neill et al., 2014). Global circulation models (GCMs) make projections based on these climate scenarios.

3.3.3 The Botswana Climate Change Context

It is important to study country-specific climate change and be able to draw out the best knowledge towards mitigation and adaptation plans, for instance. Botswana is under-researched as far as climate change and global warming are concerned, despite being extremely vulnerable to the effects of climate change (Nkemelang et al., 2018). There are, however, a number of publications (Alemaw et al., 2016; Batisani and Yarnal, 2010; Boikanyo and Levers, 2017; Byakatonda et al., 2018b; *list not exhaustive*) discussing Botswana and climate change and related topics such as drought and rainfall. From these publications, the projected climate change is likely to exacerbate extreme events and lead to water insecurity.

Extreme temperatures and rainfall patterns under RCP8.5 may increase water insecurity in vulnerable Botswana, but may also provide relief in some cases due to flash floods (Nkemelang et al., 2018). The Gaborone Dam catchment area is a "semi-dry system" and as such requires flash floods to fill the reservoirs even during decent wet/rainy years, as was precisely the case with Cyclone Dineo in 2017 (Nkemelang et al., 2018; Siderius et al., 2018).

The cyclone's induced heavy rainfalls led to the much-needed filling up of the Gaborone Dam. Before Cyclone Dineo, Botswana (along with most of Southern Africa) was already experiencing droughts and drying of the Gaborone reservoir, only to be exacerbated by the 2015/2016 El Niño. Furthermore, this drying of the Gaborone reservoir led to the disturbance in water supply in Greater Gaborone, which had worsened by the mid-2000s such that water rationing was resorted to from time to time (Sidzerius et al., 2018). The negative effects of climate change on water security compromise Sustainable Development Goals (SDGs) (Lee et al., 2023), and a developing country like Botswana cannot afford to have its development plans compromised or be climate illiterate.

3.3.4 Climate Change Literacy and Interest in Botswana

About half of Batswana claimed to be aware of climate change, but only about 38% of those who are aware of it attribute it to anthropogenic activities (Nonjinge, 2018). Furthermore, of those who are aware of climate change, 60% have the view that climate change is making life difficult. Since available literature points to Botswana being vulnerable to climate change, the question has to be asked about the level of interest in attending to the issue. What is termed psychological distance to climate change has a bearing on the likelihood of policymakers and or policy influencers responding to climate change (Steynor et al., 2020). Based on Harare, Gaborone, and Blantyre, the dominant perception amongst policymakers is that climate change is indeed happening, especially looking at the many extreme climatic events experienced in these cities (Steynor et al., 2020).

Although the study was based on preliminary findings (Steynor et al., 2020), it does suggest that there is a keenness to tackle climate change in Gaborone. Therefore, policymakers should be aided with the best possible climate change knowledge for suitable policymaking.

3.4 Botswana Studies: Climate Change And Water Security

3.4.1 Historical Climate and Water Security

For an appreciation of the climate and water security of the Gaborone Dam, several studies have assessed the roles of climate and other factors affecting historical water availability in the dam. For instance, Farrington (2015) assessed how different variables contributed to the water crisis of 2014. Farrington (2015) studied the variables that, throughout the previous ten years, had contributed to the Gaborone Dam's volume reduction. One of the proposed factors affecting inflows of the Gaborone Dam is that the dam is not the only reservoir within the catchment area. There are other relatively smaller dams upstream of the Gaborone Dam (Fleischer et al., 2016; Farrington, 2015). It is, therefore, necessary to assess the water balance of the Gaborone Dam and inflows from the catchment however, this is limited by the lack of data on the amount of rainfall needed to produce runoff for instance, lack of adequate data on specific years' population numbers precise to Greater Gaborone and, water consumption data (Farrington, 2015).

Despite limited data concerning the Gaborone Dam and its catchment, a number of studies attribute the dam's historical water challenges to climate. For example, Farrington (2015) concluded that the amount of water that can accumulate in the Gaborone Dam depends on the catchment area's climate and other abstractions from the catchment. The climate events of key interest are temperature and rainfall. Historically, from 1981 to 2011, the annual temperature increased on average by 0.089 °C/annum and consequently, increasing temperatures resulted in increasing evaporation losses over the country's surface reservoirs (Moalafhi et al., 2012). Further, Moalafhi et al. (2012) claim that from 1926 to 2011, rainfall was found to be decreasing by an average of 0.861 mm/annum. However, this amount of decrease has not been highlighted by other studies.

On the other hand, based on long-term yearly rainfall data collected at 11 synoptic stations throughout Botswana between 1961 and 2003, it can be concluded that rainfall was rising until 1981, at which point the annual rainfall pattern began to diminish (Parida and Moalafhi, 2008). A general decrease indicates that there has been a significant drop in rainfall amounts in recent years, or after 1981(Parida and Moalafhi, 2008). Another source citing Botswana's historical rainfall decline is Batisani and Yarnal (2010). Botswana's daily, monthly and annual rainfall trends for the period 1975 to 2005 (31 years) also indicated that rainfall is generally decreasing across the years as well as monthly. Furthermore, the country has seen a decrease in the number of rainy days over the 31 years assessed (Batisani and Yarnal, 2010). Other papers with a different conclusion were not found.

The historical decrease in rainfall has resulted in more droughts. The Limpopo (along with the Okavango) catchment indicate that the river system is heading towards drying conditions (Byakatonda et al., 2018a), and during dry spells, the Notwane River has a history of being less reliable (Farrington, 2015). The analysis of long-term drought was carried out for the period 1960 to 2016, and Botswana has a historically drying trend (Byakatonda et al. 2018b). The reduction in rainfall and drying of the catchment means a reduction in inflows to the Gaborone Dam. The dam has experienced inflow reduction since 2002 and consequently, a significant reduction in stored volumes (Fleischer et al., 2016). Therefore, with a historically growing Greater Gaborone population, there will be pressure on water resources, and an increase in unmet water demand is a possibility (Mphoeng, 2021). Mphoeng (2021) examined the capacity of surface resources to provide water to the supply area amidst the historically growing city population and urbanisation, juxtaposed with climate change.

In *summary,* these studies used climate and hydrological modelling and drought analysis indices. Some of the models used were JAMS/J200 (Jena Adaptable Modelling System), MAGICC/SCENGEN software and HEC-ResSim (Hydrologic Engineering Center - Reservoir Simulation model). Furthermore, some of the drought analyses were carried out using the Standardised Precipitation Evapotranspiration Index (SPEI) and Standardised Flow Index (SFI). Mphoeng (2021), for instance, utilised the Water Evaluation and Planning System (WEAP) and Soil and Water Assessment Tool (SWAT) to investigate the Notwane River's historical flows under climate change. However, not all the studies relied on modelling and analysis indices. For instance, Farrington (2015) inferred climate change to have had a role in the 2014 Gaborone Dam water crisis, but does not offer concrete dam-water-climate analyses nor any modelling. Finally, even though there exist analyses of historical climate, some of the literature assessed future climatic conditions as well, relying on projections.

3.4.2 Climate Change Projections and Water Security

Of the literature that used climate change projections, a drier future was the outcome using various scenarios. Based on a climate change scenario of decreased rainfall and increased temperature from the historical means, there is likely to be a reduction in rainfall by about 20% and a reduction in inflows in Botswana, in line with a 3°C rise in air temperatures (Alemaw et al., 2016). The Alemaw et al. (2016) simulations were up to the year 2050, and the water supply reliability of Gaborone Dam is expected to reduce by about 44%. Water supply reliability here refers to a metric that quantifies the percentage of time the dam can meet the required water demand. Other simulations indicated that, by 2050, the temperature is expected to increase by 2.5°C and the corresponding increase in potential evaporation/evapotranspiration is likely to decrease river flows by 4.4% (Moalafhi et al., 2012). Furthermore, rainfall is expected to decrease by 5%, likely resulting in a 7.9% reduction in river flows (Moalafhi et al., 2012).

Another study exploring the effects of global mean surface temperature (GMST) warming of 1°C, 1.5°C and 2°C above pre-industrial levels (1861 – 1900 base period) on the country's projected climate up to 2100, also indicated a decline in rainfall. Further, the increase of GMST by 1°C, 1.5°C and 2°C will result in Botswana's temperature also increasing while the mean annual rainfall decreases, and it is projected that the dry-spell length will increase with each GMST level increase (Nkemelang et al., 2018).

The studies on Botswana's projected climate and water resources used a range of models and approaches. These models included: the HEC-ResSim and Reservoir Reliability Analysis model (Alemaw et al., 2016), the MAGICC/SCENGEN model based on CMIP3 data (Moalafhi et al., 2012), and the 24-member ensemble models based on CMIP5 (Nkemelang et al., 2018). Other models used in assessing Botswana's water resources, as affected by future climate change, were the Water Evaluation and Planning System (WEAP) and the Soil and Water Assessment Tool (SWAT) hydrological models (Mphoeng, 2021). Some of the inputs needed for some of these models included catchment rainfall data and historical river flows. The models that carried out climate projections relied on future scenarios such as the high emissions scenario Representative Concentration Pathways-8.5 (RCP8.5), for example, Nkemelang et al. (2018).

The studies into Botswana's projected climate impacts on water resources offer great insight into the subject matter however, there are gaps that this study can consider. For instance, while the Nkemelang et al. (2018) study conducted a relatively comprehensive evaluation of projections of climate, these were not translated in any way into hydrological and water resources responses to changing climate. Further on water resources, instead of modelling hydrological responses, Moalafhi et al. (2012) constructed a simple statistical link between rainfall and dam inflows. The Moalafhi et al. (2012) model, MAGICC/SCENGEN, used a downscaling method and was driven by a set of now-outdated forecasts (CMIP3 from the 1990s), and it ultimately utilises one value for the drop in temperature (2.5°C) and rainfall (5%).

On the other hand, Alemaw et al. (2016) do model future water resources in the Notwane River catchment, but base it on a very generalised quantification of climate change—a single value of a 20% reduction in rainfall and an increase in PE corresponding to a 3°C rise in air temperatures. As for Mphoeng (2021), single-model projections have unknown provenance (the study does not describe the source of projections in any way). Although the study comprehensively models water resources until the end of the century, it does not account for the uncertainty of projections. Additionally, it appears that apart from Nkemelang et al. (2018), none of the studies considered the uncertainties of climate change projections.

This present study is similar to the Mphoeng (2021) study, but there are significant differences. The difference between this study and Mphoeng's is that this study aims to highlight the use of comprehensive climate change projections in the modelling of water balance/water supply deficit. Mphoeng (2021) seemingly uses a single-model projection, while this study uses a multi-model ensemble, so as to get a better overview of the uncertainty of future climate. Further, there is a difference in the type of model or approach in that Mphoeng (2021) models the entire system of 5 reservoirs, while this study models only one—the Gaborone Dam. It has to be noted, of course, that Mphoeng (2021) does not model/consider the NSWC directly. This study uses a simple water balance model. Furthermore, this study uses gridded data for temperature, for its historical water balance analyses and the multi-model ensemble data are also used for the future water balance of the Gaborone Dam, specifically as explained in the methodology section of this study. However, similarly, this study examines unmet water demand in the coming years. This current study aims to enhance knowledge of Greater Gaborone's urban water security through various methods, focusing primarily on the Gaborone Dam.

In *summary*, based on the evaluated literature, there is consensus in the studies that Botswana's future climate is likely to have raised temperatures and reduced rainfall. The projected climate is expected to lead to reduced dam inflows. In light of the available literature, this study's contribution is that it employs the most recent, current set of projections, namely CMIP6 (in addition to CORDEX projections), and acknowledges the uncertainty of climate projections, as evidenced by the spread of the multi-model ensemble of projections. Similar to the study of Nkemelang et al. (2018), the conventional approach to doing climate-related research is to employ a multi-model ensemble. The goal of this study's analysis and interpretation of the data is to communicate projection uncertainty or the range of potential system reactions to future climate change. To conclude, this study used multi-model ensembles and assessed the Gaborone Dam water balance up to the year 2090.

4 CHAPTER 4: METHODOLOGY AND MATERIALS

4.1 Research Design

The study used quantitative techniques and a minor policy review.

The assessment of the study area's past and future climate, focusing on rainfall and temperature as well as the evaluation of future water deficits, is based on statistical analyses of observed climate data and outputs of global and regional climate models, and water balance modelling.

A minor policy keyword search was carried out to assess what keywords emerged regarding climate change and water security. An interview was conducted with WUC to assist in filling the gaps in the data and literature regarding the Greater Gaborone water supply, which includes the Gaborone Dam.

4.2 General Approach

The objectives of this work revolve around assessing, via the analyses focusing on Gaborone Dam, how sensitive GGWSS and water demand are to projected climate change and population rise.

As described above - the GGWSS is complex and utilises a number of water sources, including a number of surface water reservoirs and wellfields, some of which are located ~400 km to the north of Gaborone, and which are linked to it by means of the NSC. A fully comprehensive evaluation of the functioning of the entire system is beyond the scope of an MSc-level research project.

Instead, the work focuses on the Gaborone Dam and its catchment. Analysing only this part of the system does not inform about the performance of the entire system under climate change, as different parts of the system can, to a certain extent, compensate for deficiencies in the functioning of its other parts. It is assumed here, however, that such analysis is informative from the perspective of the stress imposed on the system by anthropogenic climate change, and in particular, is able to highlight the level of uncertainty around that stress resulting from the uncertainty of projections of future climate.

Quantitative analyses implemented in this thesis towards its objectives include:

- Development of a simple catchment runoff and dam water balance model to establish a relationship between water availability in Gaborone Dam and climate variables.
- Evaluation of changes in rainfall, temperature and potential evaporation projected by a multi-model ensemble of global and regional climate models.

- Simulations of water availability under current and future climates using a water balance model.

These analyses are supplemented by interviews with key resource persons regarding the GGWSS and policy analyses considering climate change and water security issues.

4.3 Data

4.3.1 Gaborone Dam volume and water use data

The Gaborone Dam data was obtained from the Water Utilities Corporation (WUC). This was the water level and volume data for January 1980 – February 2022, and the Gaborone Dam percent water levels for July 2001 to July 2022. The other material obtained was the present dam's daily supply data (WUC, 2023) presented in Figure 2.4.

4.3.2 Historical climate data

This study considered observed monthly rainfall data from five weather stations in the Notwane Catchment provided by the Department of Meteorological Services, Botswana (Figure 4.1). The data were for Lobatse, Otse, Ramotswa, Gaborone and Mochudi, covering the period 1980/81 to 2020/21. Further, the temperature (minimum and maximum) was obtained for Sir Seretse Khama International Airport (SSKA) for the period of 1990/91 to 2020/21. Potential evaporation (Class A Pan) data were obtained for the Sir Seretse Khama International Airport (SSKA) station for the period of 1971/72 to 1996/97.

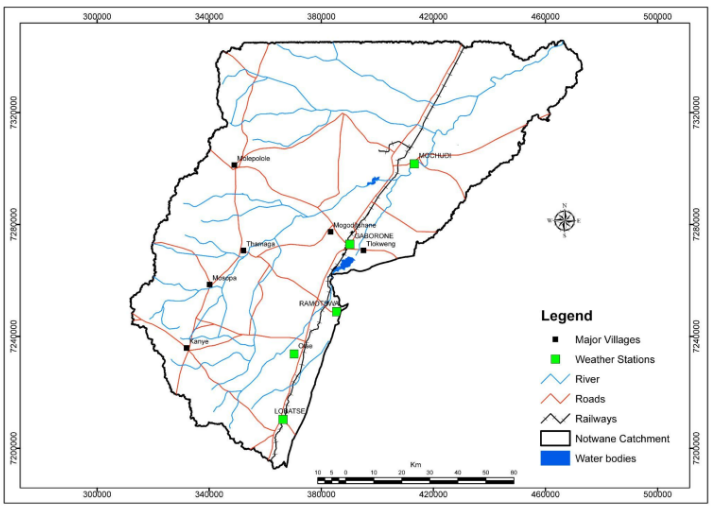


Figure 4.1: Location of meteorological stations in the study area

In order to perform quantitative analyses and water balance modelling to establish a relationship between climate variables and water in the Gaborone Dam, climate data required for water balance calculations, namely rainfall over the dam and catchment and potential evaporation/evapotranspiration, have to be available for the period overlapping with the available dam water level data for at least 30 years, i.e. 1991–2020.

In view of that requirement, a different source of potential evaporation data had to be found, as station data were available only for the period of 1971–1997. Additionally, since the study intended to perform analyses of future climate projections, there was a need to obtain potential evaporation from climate model data, as this is not a variable that is available for climate model simulations. It was thus decided to derive potential evaporation from air temperature data, using the Hargreaves (Hargreaves, 1994) approach. That data can be sourced from station observations, but also from gridded historical temperature data and gridded climate model data. The approach is described in the methodology section, sub-section 4.4.3.

During preliminary analyses, it appeared that there is relatively little temporal coherence between the rainfall data from the 5 stations (Figure 4.2), which is unexpected in the relatively small region with low topographic relief, indicating possible issues with data quality. Additionally, the preliminary attempts at calibration of the water balance model with station-based data did not yield acceptable results (Appendix, Figure A-F.1), further confirming data quality problems. Upon inspection, it was revealed that individual stations contain numerous missing data, as well as data points with a value of 0, which is often found in months during a rainy season, while other stations sometimes have substantial rainfall during that month. This suggests missing data that have been substituted by a 0. In-situ measurements from meteorological stations and rain gauges are, in principle, the most reliable source of temperature and rainfall data as they constitute a direct measurement of temperature and rainfall reaching the ground. However, they tend to lack consistency and continuity, and are often of short duration, especially in less developed countries/regions (Alsilibe et al., 2023; Mulungu and Mukama, 2023; Baseri et al., 2023), as was the case with this study.

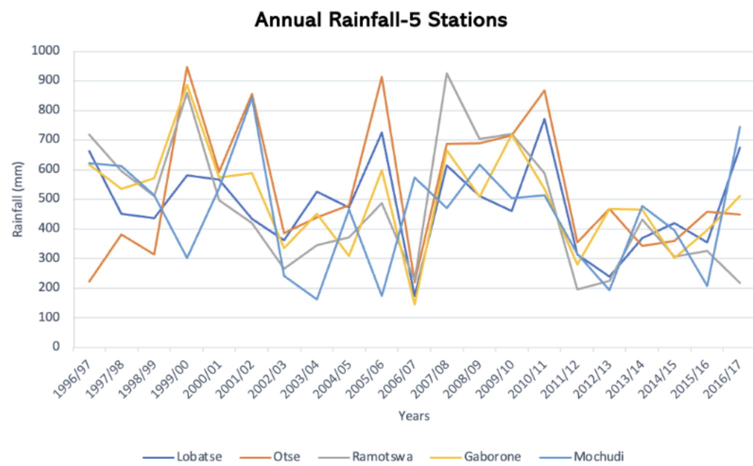


Figure 4.2: Annual rainfall time series for the 5 analysed stations

Addressing data quality problems was beyond the scope of this research, and as a result, similarly to PE, it was decided to search for an alternative source of rainfall data representing the entire catchment. One of the alternatives was CHIRPS (as it has been used in a number of studies as an alternative, for example: Siderius et al., 2018 and Franchi et al., 2020). However, model performance comparisons have revealed that a model using data from only the Gaborone station (instead of the average of all 5 available stations) outperforms that using CHIRPS. This is not unexpected as Gaborone's observed rainfall is of reasonable quality compared to the other stations, i.e. it has fewer gaps. It was thus resolved to use it to represent the catchment area's rainfall in the modelling analyses. When there is scarce station data in a catchment, single-good-station data can be used to represent the entire catchment (Vaze et al., 2011; Walega and Ksiazek, 2016).

Concerning temperature data, as mentioned above, due to the limited availability of station data for this study, a decision was taken to utilise secondary climate data from a global gridded dataset, as these data are continuous in time and space.

As a substitute for the observational temperature data, the CRU gridded dataset was thus considered:

- Minimum and maximum monthly air temperature data from CRU 4.05 (version 4.05 of the Climatic Research Unit gridded Time Series - CRU TS, Harris et al., 2020). This is a global gridded dataset with a resolution of 0.5° by 0.5° latitude and longitude grid. The data is interpolated from observations of networks of weather stations and covers the period from January 1901 to December 2022.

The data accessed in the gridded dataset were the monthly minimum (TN) and maximum temperature (TX) for the study area.

4.3.2.1 Climate change projections data

Multi-model ensemble (MME) climate projections by Global Climate Models (GCM) sourced from the CMIP6 archive, and Regional Climate Models (RCM) from the CORDEX project, were used to analyse future climatic conditions affecting the Gaborone Dam. GCMs and RCMs are used simultaneously in this study because CMIP6 are the most recent projections with the most up-to-date models, but are not appropriate in terms of resolution and nature for analyses at the scale of the Notwane catchment. CORDEX data are more appropriate, however, they downscale the previous CMIP generation.

CMIP6 is the sixth phase of the Coupled Model Intercomparison Project supporting the IPCC AR6 report (Eyring et al., 2016), and providing simulations with state-of-the-art global climate models performed in the late 2010s (IPCC, 2023). That project succeeds the CMIP5, which provided simulations with the previous generation (early 2010s) of climate models. CMIP6 provides data from over 30 different global climate models (the exact size of the ensemble varies depending on the experiment). Here, data from three CMIP6 experiments are used:

- historical - providing simulations under historical (observed) GHG concentrations over the period of 1860–2015,
- SSP 2 4.5 - providing simulations under the GHG projected under the so-called SSP 2 4.5 emissions scenario over the period of 2016–2100.
- SSP 5 8.5 - providing simulations under the GHG projected under the so-called SSP 5 8.5 emissions scenario over the period of 2016–2100.

Details of this scenario and justification for its choice are provided below.

CORDEX (Coordinated Regional Downscaling Experiment) downscales coarse GCM data from the CMIP5 generation of projections over a number of regions in the world (Gutowski Jr et al., 2016). CORDEX Africa's domain covers the entire continent and comprises a 21-member multimodel ensemble. Downscaled data have a spatial resolution of 0.44° (~50km). Similarly to CMIP6, data from three experiments are used here:

- historical - providing simulations under historical (observed) GHG concentrations over the period of 1951–2005,
- RCP4.5 - providing simulations under the GHG projected under the RCP4.5 emissions scenario over the period of 2006–2100.
- RCP8.5 - providing simulations under the GHG projected under the RCP8.5 emissions scenario over the period of 2006–2100.

The CMIP6 and CORDEX MME data are for the Notwane region, a rectangular block of latitude 26.5°S – 23.0°S and longitude 24.0°E – 28.0°E (Figure 2.1) and includes data for rainfall and air temperature. The time series used in the analyses covers the period from 1981 to 2099 and was obtained by merging historical experiment data with the future scenario data.

The projections selected for this study are in contrast to those used in earlier studies that used CMIP3 and CMIP5 data, which were produced by climate models that were available in the 1990s and 2000s, respectively (e.g. Moalafhi et al., 2012; Mphoeng, 2021). These earlier studies used a single, synthesised value or scenario that represented future conditions in a deterministic way. Here, the full ensemble is used that captures the uncertainty of future climate projections related to the so-called model uncertainty, i.e. uncertainty arising because of differences between climate models. Since two different types of models are used, this study provides a very comprehensive overview of the uncertainty of future climate projections.

One of the factors contributing to the uncertainties surrounding the future climate is future greenhouse gas emissions. Of note is that the nomenclature of emissions scenarios has changed between the CMIP5/CORDEX and CMIP6 ensembles. While the former was limited only to greenhouse gas emissions reflected by the so-called level of radiative forcing at the end of 21st century (so RCP4.5 denotes radiative forcing of 4.5 W/m^2 in 2100), the latter extends that to include associated socio-economic development scenario, and it becomes for example SSP2-4.5, where SSP2 denotes socio-economic pathway 2, i.e. a set of socio-economic constraints prevalent in the world, under which the nominal radiative forcing is reached at the end of 21st century.

RCP4.5 and RCP8.5 were the two scenarios used in the earlier (prior to CMIP6) experiments. In this study, these scenarios are used in conjunction with the SSP2-45 and SSP5-85. The RCP4.5 and RCP8.5 (for CORDEX data) correspond to the shared Socioeconomic pathways SSP2-4.5 and SSP5-8.5 for CMIP6 data, respectively (IPCC, 2023; Ajjur and Al-Ghamdi, 2021). For the RCP4.5 and SSP2-4.5 scenarios, the radiative forcing is 4.5 Watts per square metre ($W.m^{-2}$) while the radiative forcing of RCP8.5 and SSP5-8.5 is 8.5 is 4.5 Watts per square metre ($W.m^{-2}$). Furthermore, the predicted global surface temperature increase of SSP2-4.5(RCP4.5) is 2.1°C – 3.5°C by the turn of the century (21^{st} to 22^{nd}). On the other hand, the global surface temperature increase of SSP5-8.5(RCP8.5) is 3.3°C – 5.7°C by the turn of the century (IPCC, 2023).

The RCP4.5 scenario is an intermediate mitigation scenario, middle-of-the-road development (Riahi et al., 2017) or simply the medium pathway (Deutsches Klimarechenzentrum, 2023). Its corresponding SSP scenario, SSP2-4.5, communicates a business-as-usual world where the socioeconomic trends of recent history prevail and there is a steady decline in reliance on fossil fuels (Iyakaremye et al., 2021). Further, this scenario assumes moderate global population growth, income trends in different countries varying significantly, and a degree of Environmental Systems “degradation” (Deutsches Klimarechenzentrum, 2023). Significantly, in this scenario, the assumption is that there are climate protection policies in place. The RCP4.5/SSP2-4.5 scenario is primarily focused on for this thesis’s conclusions as it is more plausible under the prevailing circumstances of our times (Hausfather and Peters, 2020).

The other scenario, i.e. RCP 8.5/SSP5-8.5, explored in earlier studies (*such as in* Mphoeng, 2021; Nkemelang et al., 2018) is considered to be implausible (Burgess et al., 2022). Scenarios that propose a catastrophic climate future, though widely appearing in many scientific studies, are a less probable climate future (Burgess et al., 2022; Hausfather and Peters, 2020). This is in view of all the interventions that have already happened in the area of climate change and global warming. Nonetheless, they are still considered in this thesis to obtain a 'worst-case scenario' for the study area.

In *summary*, given that climate projections contain additional sources of uncertainty, in particular model uncertainty, represented by the spread of model ensembles, it is ideal to consider a variety of potential future conditions rather than just one, as was the case in the previous studies. The previous studies took into account GHG emission scenarios as a source of uncertainty. However, this approach is less suitable as we are becoming locked into a specific future trajectory—that is, SSP2-4.5/RCP4.5, which is more realistic, while SSP5-8.5/RCP8.5 is less likely.

4.4 Methods

4.4.1 Data preparation and pre-processing

Station rainfall, temperature, and dam water level/volume data, obtained from various sources in various formats, were organised in structured Excel spreadsheets.

Gridded air temperature data and global climate model data were obtained from the Climate System Analysis Group (CSAG) archive of the University of Cape Town. These data were provided in the form of CSV files containing area average data for the "box" representing the Notwane River Catchment upstream from Gaborone Dam (Figure 2.1). For further analyses, these data were organised in structured Excel spreadsheets.

4.4.2 Evaluation of gridded data

The gridded dataset was evaluated for its suitability for this study. One example of a study on Botswana that also relied on CRU gridded data is Maoyi and Abiodun (2021). Therefore, using CRU data for a study in Botswana is not new. However, Maoyi and Abiodun (2021) used CRU as a substitute for observed temperature patterns over southern Africa, seemingly without evaluating its suitability for the study area. In order to determine whether the gridded dataset is suitable to use in the study at a smaller scale, an evaluation of the dataset against available in-situ measurements is carried out.

In order to assess the suitability of CRU air temperature data, a visual inspection of time series figures was carried out, and the following accuracy statistics were calculated:

1. Pearson correlation coefficient (r)
2. Mean Absolute Error (MAE)
3. Root-Mean-Square Error (RMSE).

The correlation coefficient (Eq. 4.1) value range is -1.0 to +1.0 and indicates the strength and direction of correlation between datasets (Gogtay and Thatte, 2017). Values of 0.5 to 1.0 indicate a positive and strong correlation.

Mean Absolute Error reflects a systematic difference, or bias, between the two datasets. It is expressed in units of the analysed variable and thus more difficult to interpret objectively, although some interpretation can be facilitated if MAE is expressed as a percentage of the mean value of the target variable.

RMSE expresses the magnitude of deviations of individual measurements between the two datasets. Similarly to MAE, it is expressed in units of the analysed variable and thus difficult to interpret objectively, unless it is expressed as a percentage of the mean.

Pearson's correlation coefficient (r):

$$r = \frac{\left(\sum_{i=1}^{N} X_i - \frac{1}{N}\sum_{i=1}^{N} X_i\right)\left(\sum_{i=1}^{N} Y_i - \frac{1}{N}\sum_{i=1}^{N} Y_i\right)}{\sqrt{\left(\sum_{i=1}^{N} X_i^2 - \frac{1}{N}\left(\sum_{i=1}^{N} X_i\right)^2\right)\left(\sum_{i=1}^{N} Y_i^2 - \frac{1}{N}\left(\sum_{i=1}^{N} Y_i\right)^2\right)}} \tag{4.1}$$

Mean absolute error (MAE):

$$\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N} |X_i - Y_i| \tag{4.2}$$

Root mean square error (RMSE):

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (X_i - Y_i)^2} \tag{4.3}$$

In the above, *Y* is the temperature estimates from CRU for the study area, *X* is the observed station data from the catchment, and *N* is the sample size.

4.4.3 Derivation of potential evaporation from climate data

Calculations of dam water balances and rainfall-runoff relationships require knowledge of actual evaporation and evapotranspiration, respectively. Several methods could be employed to derive these variables. These computation techniques fall into three primary categories: analytical techniques based on climate variables, empirical estimations, and hydrologic or water balance techniques (Vangelis et al., 2013). Hydrologic or water balance techniques are, however, for a laboratory setting and for assessing actual evaporation. Empirical methods, which mostly rely on temperature and other atmospheric variables that influence evaporation and transpiration, have become more popular because they need less information. Due to the outlined limited data, this study relied on an empirical approach.

The Penman-Monteith equation for potential evapotranspiration (ET_o) is based on mass and energy balance and is regarded as very accurate and therefore widely accepted in the region

(Moeletsi et al., 2013). However, this requires data that are not often routinely available, namely net radiation, vapour pressure and wind speed, which makes the use of the Penman-Monteith less suitable for many places in southern Africa, and also in this study.

Of the empirical approaches, the Hargreaves method offers a suitable alternative for estimating potential evapotranspiration (ET_o) as it only requires temperature inputs (Song et al., 2024). The Hargreaves approach is generally suitable for semi-arid climates as present in Southern Africa (Moeletsi et al., 2013) and in Botswana in particular. However, it has to be factored in that the Hargreaves method (with 0.0023 - the empirical coefficient) might lead to an underestimation of Penman-Monteith/actual values (Ngongondo et al., 2013). But, proper calibration requires long-term, high-quality local meteorological data (e.g., radiation, wind speed, and humidity), whose availability or reliability for the study area was limited. Calibration might improve historical estimates but could introduce site-specific biases that limit broader applicability.

For the reasons above, the empirical Hargreaves method was used to calculate potential evaporation using available observed station (SSKA) temperature data, and from gridded historical and MME climate projections datasets.

While formally there is a difference between potential (or reference crop) evapotranspiration and open-water evaporation (Xiang et al., 2020), the paucity of available data does not allow us to differentiate between those in this study. In this study, the potential evapotranspiration derived from the Hargreaves method is taken to be equivalent to the potential evaporation (PE) over the dam.

The formula for Hargreaves' PE (Hargreaves, 1994; Hargreaves and Allen, 2003) is as follows:

$$\mathrm{ET_{oH}} = 0.0023 R_{\mathrm{a}} (T + 17.8) \sqrt{T_{\max} - T_{\min}} \tag{4.4}$$

where,

ET_{oH} - computed reference evapotranspiration/evaporation (mm/d)
R_a - the water equivalent of the extraterrestrial radiation (mm/d)
T_{min}, T_{max} and T - daily minimum, maximum and mean air temperature in degrees Celsius (°C)
T - is calculated as the average of Tmin and Tmax
0.0023 - the empirical coefficient (Hargreaves and Allen, 2003).

The calculations were implemented in the SPEI package in R-Studio (Pyrgou et al., 2019). The inputs were only Tmin, Tmax and a latitude of -24.55 (latitude of the Gaborone Dam).

4.4.4 Water Balance Model of the Gaborone Dam

Analysis of the reliability of a water supply system requires a mathematical model of that system. Such a model would involve accounting for hydrological processes in catchments that generate runoff, accounting for water balances in dams, accounting for water transfers between dams, and for water offtakes to supply water demand and its drivers. An off-the-shelf model of the Greater Gaborone Water Supply System was not available for this study, and the development of such a model is beyond the scope of this project. Instead, a simplified approach was adopted that involved the development of a model of the Gaborone Dam, or in fact two sub-models - a model of the dam and a model of the catchment. This model can thus be used to evaluate the availability of local resources under future climates, as projected by climate models under different greenhouse gas emission and socio-economic development scenarios.

The complexity of modelling might vary depending on the study's objectives and the data's accessibility. Importantly, the accuracy of the model does not always increase with model complexity (Baseri et al., 2023). Additionally, numerous climatic, hydrological, and human factors may impact how well the model functions (Zhang et al., 2020). Limited data dictates that the model be a simple one with fewer inputs.

Calculating a reservoir water balance is challenging when the reservoir levels and weather/climate (i.e., rainfall and temperature of the catchment) data are the only observational data available. The data for the other hydrological processes, such as inflow from upstream of the catchment, outflow data of surface evaporation, and spillway water release, are often not available or very limited (Song et al., 2022). Only when two of the three terms or variables—inflow, water level, and dam outputs (e.g., offtakes, evaporation and infiltration)—are known can the water balance equation be solved. In data-scarce regions, the best variable to estimate a reservoir water balance is typically water level data (Song et al., 2022).

In the case of the Gaborone Dam, the availability of hydrometric data is very limited. According to WUC (2023), there are no measurements of inflow or outflow from the dam, and only water level measurements are available. Also, a continuous time series of offtakes from the dam for water supply to the Greater Gaborone water supply system is not available. In addition, to the best of the author's knowledge, there are no studies or measurements of the fluxes between the dam and the surrounding groundwater.

In view of the above, the development of a detailed, comprehensive model of the dam and its catchment with all the relevant processes is not possible, and hence, a simple water balance model of the dam, accompanied by a simple conceptual rainfall-runoff model of the Notwane (Gaborone Dam) catchment, was established. The Schematic of the model is illustrated in Figure 4.3. Both models operate on a monthly time step.

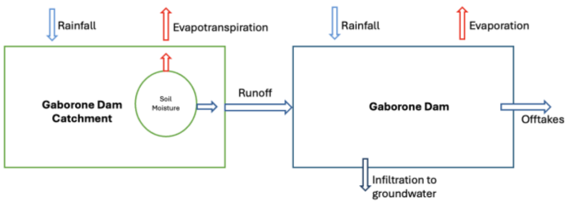


Figure 4.3: Schematic diagram of catchment runoff and reservoir water balance

4.4.4.1 Water balance model of the Gaborone Dam

Dam water balance is expressed using the following water balance equation (Shahin, 2007):

$$\Delta S = P + Q_{in} - E - Q_{inf} - Q_{out} - Q_{use} \quad (4.5)$$

where:

ΔS - change in dam storage
P - rainfall on the dam surface
E - evaporation from the dam surface
Q_{in} - surface inflow to the dam
Q_{out} - surface outflow from the dam (including spillway release)
Q_{inf} - infiltration loss
Q_{use} - offtakes to satisfy water demand.

When considering that at any time step, months in this study, change in dam storage ΔS is equal to the difference between some initial ($V_{(t)}$) and a final ($V_{(t+1)}$) reservoir volume, and factoring large dam surface area (Guntner et al., 2004), equation (4.5) can be written in the following way:

$$V_{(t+1)} = V_{(t)} + (P_{(t+1)} \cdot A_{(t)}) + Q_{in\,(t+1)} - (A_{(t)} \cdot PE_{(t+1)}) - Q_{inf\,(t+1)} - Q_{out\,(t+1)} - Q_{use\,(t+1)}$$
(4.6)

where subscript t and t+1 denote values of individual variables at the beginning of a time step and during or at the end of that time step, respectively. The Gaborone dam water balance model implements equation 4.6 with a monthly time step.

To implement this water balance model, the following was considered:

1. Rainfall over the dam (P) corresponds to the rainfall measured at the Gaborone DMS station.

2. E over the dam when unconstrained by water availability, i.e. when there is water in the dam, is equal to PE. It will be equal to 0 if there is no water in the dam.
3. Both P and E are calculated over the actual water surface area of the dam.
4. The water surface area is calculated from the volume-area relationship, i.e:

   $A = aV^{b}$

   where coefficients a and b characterise dam geometry. Those coefficients are a=0.7 and b=0.66, obtained from the volume-area curve sourced from Moalafhi (2023).
5. Infiltration to groundwater is a fixed proportion of the volume of water stored in the dam i.e., $I_{gw} = K \cdot V_{dam}$ (relationship deduced from Estácio et al., 2024; Dhunagan and Wang, 2020). K is one of the calibration coefficients of the model. While in reality, infiltration is a complex variable driven by water levels, antecedent conditions and potential evapotranspiration, there is no data to support such complex parameterisation. The approach adopted here is a simplification that is consistent with available data and has, for example, been used in modelling the Gaborone Dam by Alemaw et al. (2016).
6. The offtakes from the dam are equal to the unconstrained supply capacity of the dam (100% demand), if there is water available, otherwise they are limited to the amount of available water, i.e., $Q_{use} \leqslant WD_{unconstrained}$
7. Outflow from the dam is considered to occur only when the dam is at full capacity, and then it is equal to the amount that is needed to keep the dam at full capacity after accounting for offtakes, evaporation and infiltration.

4.4.4.2 Rainfall-runoff model of the Notwane Catchment

The rainfall-runoff model used here is a simplified version of the model called HBV (Bergström and Lindström, 2015). The model is based on the following water balance equations:

Catchment water balance (Dingman, 2015):

$$Q_{out} = P - Q_{int} - Q_{inf} \quad (4.7)$$

where:

Q_{out} - surface outflow from the catchment

P - rainfall over the catchment

Q_{int} - Interception of rainfall by vegetation contributing to evapotranspiration

Q_{inf} - infiltration to soil moisture

Soil water balance:

$$\Delta S = Q_{inf} - ET \quad (4.8)$$

where:

ΔS - change in soil moisture storage
ET - evaporation/evapotranspiration from the soil moisture

In the Notwane catchment rainfall-runoff model, Eq. 4.7 and 4.8 are implemented as follows:

1. Qint is considered to be a constant value, or threshold. It is one of the calibration parameters.
2. Qinf is considered to be a function of soil moisture, as in the original HBV model (Bergström and Lindström, 2015), namely:

$$Q_{inf} = P * (SMmax, inf - SM)^{beta}$$

where SM is actual soil moisture, $SM_{max,inf}$ is the soil moisture storage at which the soil is saturated and there is no more infiltration, and beta is a coefficient. $SM_{max,inf}$ and beta are model calibration coefficients.

3. ET is considered to be a function of soil moisture and potential evapotranspiration, as in the original HBV model (Seibert, 2005), namely:

$$ET = PET * (SMmax, pet - SM)$$

where:

PET is potential evapotranspiration, SM is actual soil moisture, and $SM_{max,pet}$ is the soil moisture at which ET is equal to PET. $SM_{max,pet}$ is one of the calibration parameters of the model.

Such a formulated model is relatively simple, but it accounts for the most important factors that affect runoff in a catchment, namely:

- It expresses the dependence of runoff on antecedent moisture conditions in the catchment. This is captured by the partitioning of rainfall into runoff and infiltration, which is a function of soil moisture.
- It expresses the role of vegetation and the nature of soils and topography on the water balance of the catchment. This is expressed by the interception coefficient and the dependence of evapotranspiration on the status of soil moisture.

In *summary,* the two models formulated in this way have numerous simplifications and processes, the most important of which are:

- The inflow to the dam is simulated using a simple rainfall-runoff approach based on observed rainfall data (Gaborone) and calculated PET (CRU-Hargreaves calculated), rather than employing a complex hydrological model. The approach is a compromise due to data limitations and the scope of this study.
- The unconstrained water demand is considered to be constant in time, both seasonally and on an annual basis. In reality, abstractions from the dam vary, for example, during 2018–2021 offtakes were 23.70 MCM, 21.53 MCM, 20.89 MCM and 19.38 MCM. While it would be more realistic to use actual water abstraction data or relate the level of abstractions to, for example, climatic conditions driving water demand, information

supporting this is not available, and a simple approach that is consistent with operational rules for the dam was adopted.

- Actual evaporation from the dam is estimated using potential evaporation (PET) as a proxy for atmospheric water demand, consistent with the Hargreaves approach for PET estimation.
- Infiltration to groundwater is modelled as a proportion of the volume of water stored in the dam, using a commonly applied linear relationship in dam water balance studies.
- The model does not explicitly account for long-term changes in catchment characteristics (e.g., land cover changes) or dam conditions (e.g., siltation), though these may influence the water balance over time.

Importantly, these simplifications are commensurate with the nature and quality of available data and constitute a limitation to the interpretation of the results of this modelling exercise.

4.4.5 Modelling of future water supply under climate change scenarios

In order to evaluate future water security, the calibrated (chapter 5, sub-section 5.2) Gaborone Dam water balance model is used to simulate dam storage under future climates. As mentioned in the data section - the multi-model ensemble of future projections used is CMIP6 and CORDEX, and two scenarios of greenhouse gas emissions are considered SSP2-4.5/RCP4.5 and SSP5-8.5/RCP8.5. Two future periods are considered, namely the near future: 2031–2060 and the far future: 2061–2090, with changes evaluated against the historical period of 1991–2020.

The approach adopted to run the model with future climate is based on the so-called “change factor” or “delta method” (Lopez‐Cantu et al., 2020; Daniels et al., 2012). This approach applies the average (mean) climate model-projected change from a future time (for example, the monthly mean for 2031–2060) to observed corresponding values from a baseline period (for example, 1991–2020) (Daniels et al., 2012).

In this study, historical observed climate data used in the model are adjusted by a change factor that reflects a change in climate simulated by climate models between a future period and a historical period. The change factor is calculated for each calendar month, i.e. there are 12 different change factors calculated for each climate variable. The formula used to derive the change factor differs for different variables.

To calculate the future change in rainfall (P) between periods (historical, near and far future), the percentage change was used:

$$Percentage\ Change_P = \frac{(P_f - P_i)}{P_i} \times 100\ (\%) \qquad (4.9)$$

Where P_f is the mean monthly precipitation/rainfall in the future period, and,

P_i is the mean monthly rainfall in the historical period.

To calculate the change in temperature, the absolute difference was used:

$$Absolute\ Difference_T = T_f - T_i \tag{4.10}$$

Where T_f is the mean (maximum or minimum) temperature for a given month in the future period, and

T_i is the mean (maximum or minimum) temperature for a given month in the historical period.

Once monthly change factors are calculated from climate model data, they are used to modify the historical time series of observed climate variables - rainfall and minimum and maximum air temperature. The modified air temperatures were, in turn, used to calculate potential evaporation. That, together with the modified rainfall, was used as input to the calibrated water balance model. This allowed us to derive a time series of dam storage that reflected water availability under the future climate.

An index used to evaluate the impact of climate change on water availability was chosen to be the number of months over the 30-year simulation period, during which the amount of water stored in the dam would impose stress on the Greater Gaborone water supply system. The dead storage of the Gaborone Dam is 5% (source: correspondence with WUC staff). To the best of the author's knowledge, there is no clear safe yield threshold/value (though Table 2.4 offers operational parameters); a threshold of 10% of the total dam capacity was therefore set for this study, which is 14 MCM. This value is twice the dead storage value and caters for potential siltation challenges in the future.

4.5 Supplementary Analysis

4.5.1 Interview

The water structure of Greater Gaborone was not satisfactorily coming out in the literature, hence short interviews with WUC personnel were carried out to fully understand the water system. The questions/guidelines were primarily focused on understanding the water supply of Greater Gaborone. Interview questions/guidelines (Appendix B) were prepared beforehand, and then engaged the WUC personnel responsible for water production and the responses were recorded on a notepad. The responses were processed and used in NVivo to create the Greater Gaborone daily water supply dynamics schematic representation (Figure 2.4). Through the interviews with the WUC staff, a schematic diagram of the water supply network was shared and subsequently adapted to create the GGWSS schematic Figure 2.3.

4.5.2 Policy Review - Desk Research

In conducting secondary research in terms of a Policy Review, a similar methodology to that of Wang et al. (2023) in their Policy Review was adopted for this study. The study used NVivo (Version 14.23.0 (13)) to analyse the Water Policy of Botswana and other relevant legal framework documents. The aim was to have a rough assessment of how the Policy addresses the climate change issue. The Google search engine was searched using **keywords** A. "Botswana National Water Policy", B. "national water master plan Botswana" and C. "Water Act AND Policy Botswana", and the results obtained were: the (i) Water Policy from (https://www.water.gov.bw/). Other legal documents that appeared were: (ii) Water Act of 1968 (https://faolex.fao.org/docs/pdf/bot42103.pdf), (iii) Borehole Act of 1956 (https://faolex.fao.org/docs/pdf/bot42106.pdf), (iv) Botswana National Water Master Plan (NWMP) (yielded *the Water Policy*), (v) Water Utilities Corporation (WUC) Act (https://faolex.fao.org/docs/pdf/bot91880.pdf), (vi) Botswana Integrated Water Resources Management & Water Efficiency Plan (https://faolex.fao.org/docs/pdf/bot175091.pdf), and (vii) Waterworks Act from (https://www.wuc.bw/). The search was then narrowed down to search online specifically for the 7 (i–vii) documents.

The "principles of authority and comprehensiveness" (Wang et al., 2023) were used to narrow the list of search findings to two key documents; the (i) Water Policy and (ii) Botswana Integrated Water Resources Management & Water Efficiency Plan. These two documents were analysed in NVivo concerning the study's fourth objective. Further, the study included the cited legal framework (Tables 4.1 and 4.2) in the National Water Policy, which did not originally appear in the search.

Table 4.1: Botswana Water Legal Framework - Policies

POLICIES	*Available Online*
Vision 2016	No
National Development Plan 11	Yes
Water and Wastewater Sector Tariff Strategy (2010	No
National Energy Policy (2011)	Yes
National Master Plan for Sanitation and Wastewater (2003)	No
Wastewater and Sanitation Management Policy (2001)	No
Waste Management Strategy (1998)	Yes
National Policy on Natural Resources Conservation and Development (1990)	Yes
Community Based Natural Resources Management Policy (2007)	Yes
Game Ranching Policy (2002)	Yes
Tourism Policy (1990)	No
Integrated Support Programme for Arable Agriculture Development (2010)	No
Livestock Management Infrastructure Development (2007)	No
National Master Plan for Arable Agriculture Development (2002)	Yes
Agricultural Water Development Policy Implementation Guidelines (1993)	No

Table 4.2: Botswana Water Legal Framework - Acts

ACTS	***Available Online***
Water Act, Ch. 34:01	Yes
Boreholes Act, Ch. 34:02b	Yes
Waterworks Act, Ch. 34:03	Yes
Aquatic Weeds (Control) Act, Ch. 34:04	Yes
Wildlife Conservation and National Parks Act, Ch. 38:01	Yes
Forest Act, Ch. 38:03	Yes
Local Government Act, Ch. 40:01 (repealed)	Yes
Townships Act, Ch. 40:02 (repealed)	Yes
Fire Service Act, Ch. 40:04	Yes
Consumer Protection Act, Ch. 42:07	Yes
Waste Management Act, Ch. 65:06	Yes
Environmental Impact Assessment Act, Ch. 65:07	Yes
Water Utilities Corporation Act, Ch. 74:02	Yes
Public Health Act, Ch. 60:01 (2013)	Yes

4.5.3 Data analysis

With regards to the policy documents, the focus was on using keywords and text search to have a rough picture of the words and text that have the highest frequency in the legal documents. This was done to gauge the importance of keywords such as climate to Botswana's principal water legal instruments that were readily available online. Of the 15 policy documents, the 7 available online and the 14 Acts were considered.

5 CHAPTER 5: RESULTS

5.1 Evaluation of historical climate data used as input to the water balance model

5.1.1 Observed Historical rainfall (Pr) for the study area

Figures 5.1 and 5.2 below show observed station data from the 5 study stations.

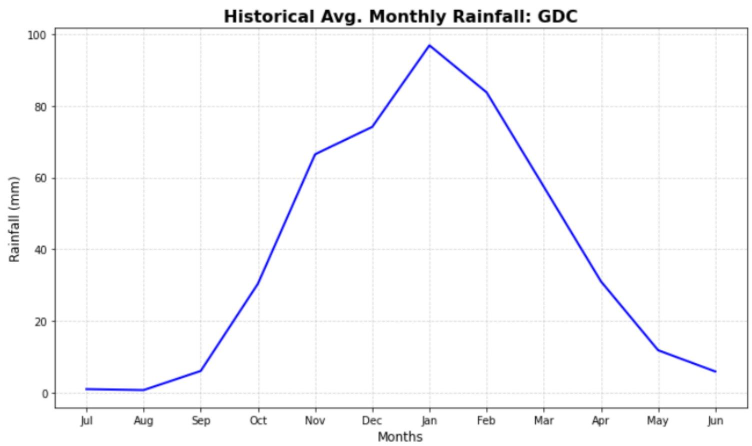


Figure 5.1: Observed mean monthly rainfall for Gaborone Dam catchment - average of 5 stations

The average study area rainfall (Pr_{av} - *Gaborone Dam catchment*) was calculated over a period for which there was corresponding available data from all 5 stations, i.e. 1996/97 to 2016/17. The unweighted average of these stations is taken to represent rainfall over the Gaborone Dam Catchment. While some of the stations are located outside of that catchment, they were included to increase the robustness of the estimate, and this approach is compatible with the level of quality of rainfall data.

As expected, the wettest months are December, January and February (DJF) while the driest months are June, July and August (JJA) (Figure 5.1). Historically, the country's wet season is from October to April (Andringa, 1984; Segobaetso et al., 2022). Further, the catchment area and Gaborone's annual rainfall (in brackets) from 1996/97 to 2016/17 ranges between 284(145) mm and 643(886) mm per annum (Figure 5.2). Since the available observed data did not cover the entirety of the baseline period, 1991–2020, and there were missing rainfall measurements from some stations, Gaborone data became essential in representing the entire catchment.

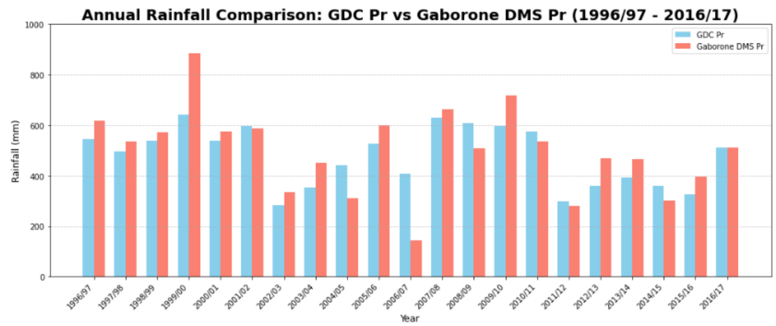


Figure 5.2: Observed GDC 5-Stations average rainfall and Gaborone DMS rainfall

5.1.2 Observed Station and Gridded Temperature - CRU validation results

A visual inspection of Figures 5.3 to 5.5 indicates that CRU temperature is closely aligned with observed station maximum and minimum temperatures for the period 1990/91 to 2020/21. This was true for both the annual (Figure 5.3) and monthly (Figure 5.4) temperature assessments.

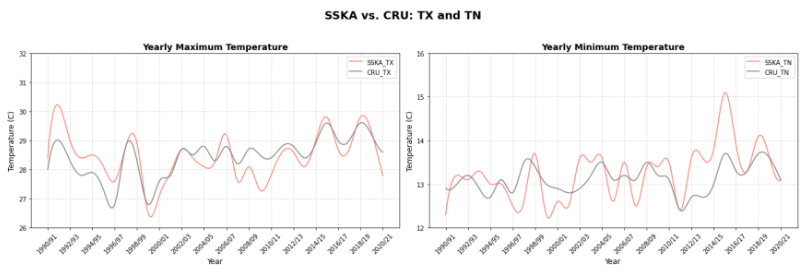


Figure 5.3: Observed mean yearly temperature compared with CRU gridded temperature data

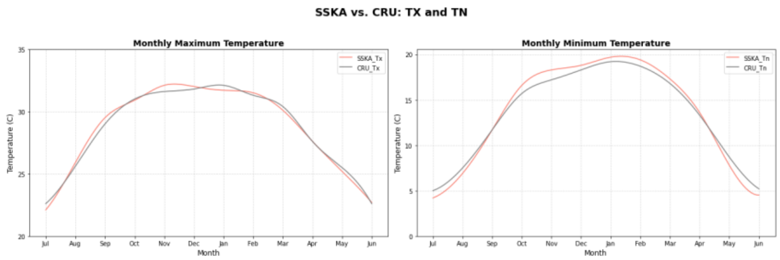


Figure 5.4: Observed mean monthly temperature compared with CRU gridded temperature data

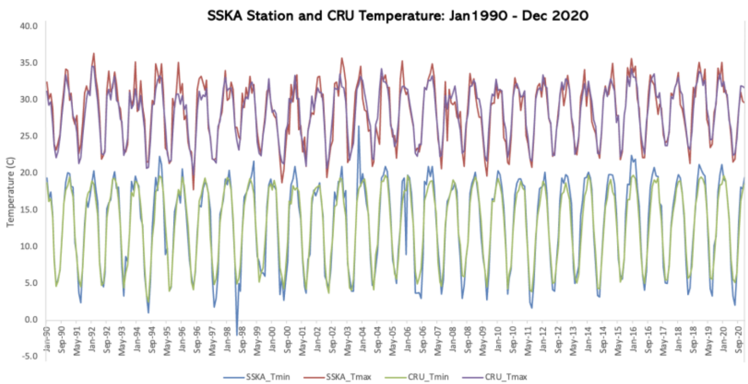


Figure 5.5: Meteorological station - temperature compared with CRU temperature

Table 5.1 shows that CRU monthly maximum temperature (Tx) correlates acceptably with SSKA Tx, and the same applies to monthly minimum temperature (Tn). Based on MAE and RMSE, there is also minimal error between CRU and station data. Therefore, due to low bias based on **visual inspection** (Figures 5.3 to 5.5) and Table 5.1 below, CRU is considered to be acceptable as a basis for calculations of PE using the Hargreaves method.

Table 5.1: CRU's accuracy validation against observations at SSKA - monthly data over the 1990–2020 period.

Temperature -T, (°C)	**correlation (*r*)**	**MAE**	**RMSE**
T-minimum	0.97	1.18	1.60
T-maximum	0.93	1.12	1.48

5.1.3 Gridded Temperature: Hargreaves-Method Historical Evaporation

Hargreaves' potential evapotranspiration was calculated using the R-Studio Hargreaves package for both station and CRU data. Figure 5.6 presents a comparison of the monthly time series of PE from these two data sources, and in addition, Class A Pan potential evaporation data over the years of overlap, ie, 1986/87 to 1996/97.

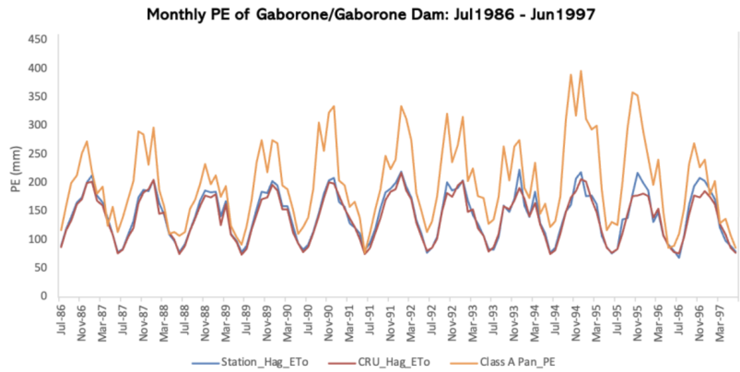


Figure 5.6: Comparison of 3 datasets for Gaborone/Gaborone Dam's PE

Overall, there is a very good correspondence between the Hargreaves ET_o from the station and gridded data, but both these variables are significantly different from Class Pan A measurements, both in terms of overall values and month-to-month pattern. This is not unexpected, as Class A Pan measurements provide a maximum possible evaporation value (small oasis effect), and are also very location-specific (Chapman et al., 2021; Simba et al., 2013). On a monthly basis, Class A Pan measurements correlate well with observed SSKA temperature Hargreaves calculated ET_o ($r = 0.85$), and gridded CRU temperature Hargreaves calculated ET_o ($r = 0.86$). As the ET_o calculated from climate variables is the only way of accounting for the influence of future climate on water resources that can be used in this study, it was decided to accept the possibility that this data possibly underestimates actual evaporation, especially under water-limited conditions. The goal of this study is not to perfectly replicate observed Class A Pan data, but to assess future water availability under a consistent methodological framework.

5.2 Calibration of the Gaborone dam runoff and water balance models

5.2.1 Model calibration procedure

The runoff and water balance models were calibrated using a trial-and-error method (manual calibration). Some of the model parameters were considered structural and were fixed (Table 5.2). The remaining parameters were adjusted so that the model outputs replicated the observations. (Tables 5.2 and 5.3).

Table 5.2: Structural and Calibration parameters - dam water balance model

Structural Parameter	**Coefficient/Threshold**
Volume area coefficient (a)	0.7
Volume area coefficient (b)	0.66
Calibration Parameter	
Infiltration factor	0.01 (fraction of volume)

Table 5.3: Accepted values of the calibration parameters - catchment runoff model

Parameter	**Coefficient/Threshold**
Rainfall threshold	30 mm
Maximum soil moisture	220 mm
Beta	0.9
Soil moisture maximum evaporation	225 mm

Two rainfall data sources were used in the development of the model, and calibration was run simultaneously for both models. The calibration target was the stored volume of the Gaborone dam.

5.2.2 Calculated Dam stored volume

After the trial-and-error calibration process, the accepted values of the calibration parameters are shown in Table 5.2 and Table 5.3, and a comparison of observed and dam storage modelled with CHIRPS rainfall data is presented in Figure 5.7 (for the benefit of comparison) while that for dam modelled with rainfall from station data (Gaborone DMS) is in Figure 5.8. The model was able to simulate the observed historical storage of the Gaborone Dam generally closely with a r = 0.71 correlation coefficient and RMSE = 28.1 for CHIRPS and r = 0.74 and RMSE = 27.4 for weather station rainfall data. Neither of the results is able to replicate the observed dam volume perfectly, but the model with both datasets is able to simulate the principal characteristics of the variability of the reservoir volume, namely:

- the seasonal rises and declines of reservoir volume reflecting the annual rainfall cycle,
- the slow decline in volume over several years with lower rainfall, such as 2002–2006,
- the rapid replenishment of the volume in years with higher rainfall, such as 1987, 1995–96, 2006 and 2017.

Unexpectedly, the model with neither dataset, CHIRPS data and the Observed Gaborone data (Figure 5.7 and Figure 5.8) is able to simulate the effects of the 2015–2016 drought accurately - i.e. in neither of the models, the dam dries in that period. However, overall, the model with Gaborone (DMS) data comes closer to adequate simulation as compared to

CHIRPS (i.e., $r_{DMS} > r_{CHIRPS}$ & $RMSE_{DMS} < RMSE_{CHIRPS}$) and it will be used as the basis for the climate change impact assessment.

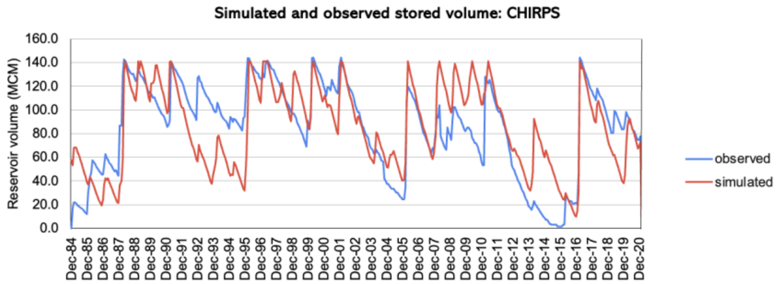


Figure 5.7: Calculated and observed reservoir volumes for Gaborone Dam - CHIRPS rainfall

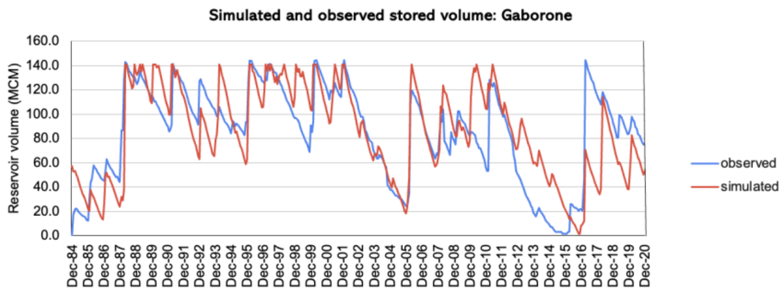


Figure 5.8: Calculated and observed reservoir volumes for Gaborone Dam - Gaborone rainfall

The other diagnostics of the model, namely catchment runoff and actual evaporation, are presented in Figures 5.9 and 5.10 below. The simulated historical Gaborone Dam catchment monthly flows (streamflow/runoff) vary between near-zero (0) values and values greater than 30 MCM/month, even reaching 216.2 MCM in February 2000 (Figure 5.9).

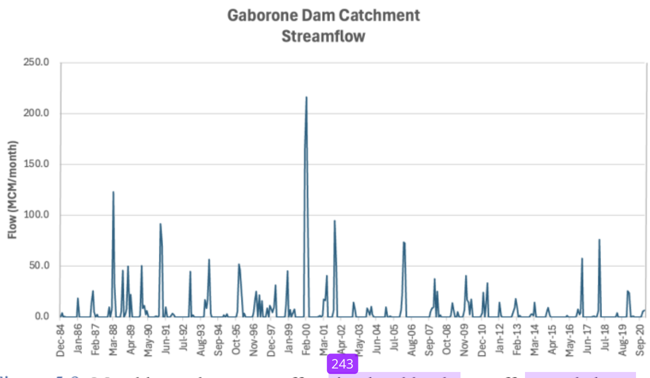


Figure 5.9: Monthly catchment runoff as simulated by the runoff–water balance model

The simulated actual evaporation varied between near 0 MCM/month and 3.7 MCM/month values. The highest and lowest values occurred in December 1997 and November 2016, respectively.

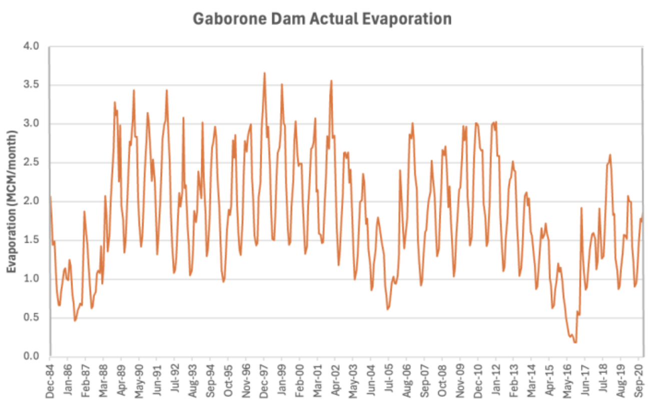


Figure 5.10: Monthly actual evaporation from Gaborone Dam, as simulated by the water balance model

While there are no data available that would allow for validation of runoff and actual evaporation simulated by the Gaborone dam model, the obtained values appear realistic.

5.3 Future changes in water demand

5.3.1 Greater Gaborone population-driven demand

In the historical period, there has been an increasing water demand largely due to population and industry growth (Matlhodi et al., 2021). Numerous factors influence water demand, but they tend to have a complex and nonlinear interaction with water demand. However, the most important factor affecting water consumption is population (Ou et al., 2023). As Greater Gaborone's population grows, it is to be expected that the water demand will increase, and this study simply estimates water demand to be at a proportional rate to the increase in population. This is due to the complexity that would be involved in trying to account for the nonlinear interaction of water demand and factors affecting it.

5.3.1.1 City of Gaborone Population Trends

The city of Gaborone has the largest population in the GG area. Population census values starting in 1991 were obtained for the city. The study's baseline 30-year period begins in 1991, and therefore, this study searched for values prior to the 2011 and 2022 censuses presented in Table 2.1 of **Chapter 2**. The city of Gaborone's 1991 population census was 133 468 (Republic of Botswana, 1995), 165 343 in 1995 (Republic of Botswana, 2002), 186 007, 231 592 and 244 107 for the years 2001, 2011 and 2022, respectively (Statistics Botswana, 2022). The historical population trends of the city of Gaborone are presented in Figure 5.11 below and show an increasing city population.

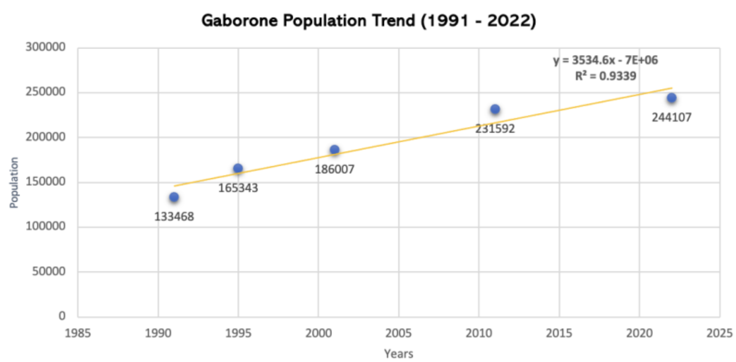


Figure 5.11: Gaborone population trend for study base period

5.3.1.2 Greater Gaborone Population Trends

There are many towns/villages in Greater Gaborone; however, their specific population statistics are not reported in all censuses by Statistics Botswana. For a rough estimate of the population trend in Greater Gaborone (Gaborone included), population statistics for major towns (villages) were used based on their available census data Figure 5.12. These are Mochudi, Mogoditshane, Tlokweng, Ramotswa and Lobatse. These places have generally had an increase in their population in the past decades.

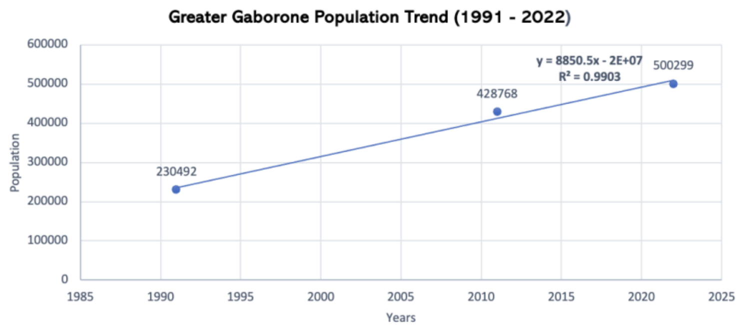


Figure 5.12: Population trend of Greater Gaborone

At the time of this study, Botswana's official population projections were only up to 2026 (Statistics Botswana, 2015). However, population projections up to the year 2090 were needed for this study, and therefore, estimations were made using a simple approach.

Statistics Botswana uses four scenarios, high, medium, low, and HIV/AIDS, for its population projections, each representing a different fertility and mortality assumption, due to specific problems with the demographic statistics needed to generate such projections (Statistics Botswana, 2015). The key components of population statistics are fertility, mortality and migration; however, the scope of this study only requires a base estimate of population growth rate, and therefore these factors will not be discussed. Only total population census figures will be considered for a simple estimation of future populations.

Population projections were made using Equation (5.1) (Statistics Botswana, 2020; Lundquist et al., 2014):

$$P_t = P_o (1+r)^{t} \quad (5.1)$$

Where P_t = population at time t

P_o = is the base population at time o

r = annual growth rate

t = interval time

In this study, an estimated - calculated growth rate, calculated based on the generalised GG population from 1991 to 2022, was used. This formula is the annual constant population growth rate (PGR) derived from Figure 5.12. It is the Compound Annual Growth Rate (Nassar et al., 2014) applied to population:

$$\text{PGR} = \left(\frac{\textit{End value}}{\textit{Start value}}\right)^{\frac{1}{(Periods-1)}} - 1 \tag{5.2}$$

= [(500 299/230 492) ^ (1/(32-1)] − 1

= 0,025314478 [*multiply by 100, for percentage*]

= 2.53%

This study's growth rate is lower compared to the 4.45% annual growth used by Alemaw et al. (2016), but that growth rate was only for 2001 to 2011. From Table 2.1, the average growth rate calculated from the 'Growth rate' column for all the cited towns/villages is 1.83%. This is lower than this study's growth rate however, it was only for the period 2011 to 2022.

The limitation of this study is that there was no official specific growth rate for the Greater Gaborone cluster, as even some of the cluster's villages were not included in the Statistics Botswana population reports. A calculated value covering the entire baseline period was therefore necessary—from 1991 to 2020.

5.3.1.3 Greater Gaborone population projections

The population projections of GG up to 2090 in 10-year intervals are presented in Table 5.4. If Greater Gaborone were to experience population growth at a constant annual rate of 2.53%, then the population is expected to be about 610 994, 1 292 903 and 2 735 865 by the years 2030, 2060 and 2090, respectively (Table 5.4). The 2030–2090 projected population far exceeds the present Greater Gaborone population of at least 500 000 people.

Table 5.4: GG Population projections up to 2090 at a 2.53% growth rate

Year	Population Projections
2030	610 994
2040	784 417
2050	1 007 063
2060	1 292 903
2070	1 659 876
2080	2 131 008
2090	2 735 865

5.3.1.4 Greater Gaborone Population Growth and Water Demand

Population growth-driven water demand was estimated based on PGR and represented in Figure 5.13 below. The estimated GG water demand is based on Table 5.5 monthly demand for 2020. The total of Table 5.5 certainly underestimates Greater Gaborone water demand as not all of the towns/villages of the area are accounted for, for example, Lobatse. However, the monthly total available is still suitable to establish a rough estimate of the water consumption in GG and is therefore used in this study.

Table 5.5: Available Greater Gaborone water demand (2020)

Greater Gaborone Area	~ Monthly Demand (MCM)	~ Annual Demand (MCM)
Gaborone	3.30	39.56
Tlokweng	0.22	2.68
Mogoditshane	0.44	5.36
Kumakwane	0.01	0.16
Mmopane	0.05	0.62
Metsimotlhabe	0.02	0.29
Gakuto	0.03	0.31
Mmatseta	0.01	0.16
Gabane	0.10	1.16
Mokolodi Village	0.01	0.11
Tloaneng	0.01	0.11
Ramotswa	0.26	3.07
Taung & Boatle	0.01	0.06
Police College	0.01	0.16
Otse	0.04	0.51
Mogobane	3.6×10^{-3}	0.04
TOTAL	**4,53**	**54,35**

Source: WUC (2024)

5.3.1.5 Greater Gaborone Unmet Water Demand

If the average water supply (Q_{use}, during safe yields) from the GGWSS of ~6.84 MCM/month (established in **Chapter 2,** Table 2.3) is assumed to have remained relatively constant, similar to Alemaw et al. (2016), for the projections years starting with the reference year of 2020, then an increase in unmet water demand is as presented in Figure 5.13.

For the unmet water demand of the supply area, the formula below, adapted from Unto (2024), was used:

$$WD_{unmet} = WD - Q_{use} \quad (5.3)$$

where:

WD_{unmet} - water demand unmet from the Gaborone Dam,

WD - unconstrained water demand of Greater Gaborone

Q_{use} - offtake from the GGWSS for water use, i.e. actual water supplied to users.

From Table 5.5, the 2020 water demand values are used to calculate the unmet water demand. The 2020 water demand monthly average was about 4 529 437 m^3/month = **4.53 MCM/month**. For simplicity, ~ 4.5 MCM/month is taken to be the unconstrained water demand. In 2021 (based on Table 2.3), it is known that the system was able, in theory, to adequately supply all the demanded water, i.e., ~ 4.5 MCM/month (Q_{use}).

Taking average water demand (WD) to be 4.5 MCM/month (in 2020), for the reference year, and the average actual water supplied to users/offtake (Q_{use}) from the GGWSS to also be 4.5 MCM/month (in 2021), then, there was no unmet water demand:

$$WD_{unmet} = WD - Q_{use}$$

$$WD_{unmet} = 4.5 \text{ MCM/month} - 4.5 \text{ MCM/month}$$

$$WD_{unmet} = 0\ MCM/month$$

Since the average allocated water/potential offtake ($Q_{pot.use}$) from the GGWSS was 6.8 MCM/month (in 2021), it means there was a surplus of water in the system when the demand was 4.5 MCM/month.

To then establish the water surplus of the system, but still being able to adequately meet the GG demand, under current system capacity, mathematically, we can consider the difference between the system's allocated water and present demand. If we take the average water demand (WD) to be 4.5 MCM/month (in 2020), for the reference year, then:

$$W_{surplus} = Q_{pot.use} - WD$$

$$W_{surplus} = 6.8 \text{ MCM/month} - 4.5 \text{ MCM/month}$$

$$W_{surplus} = 2.3\ MCM/month$$

Surplus water of **2.3 MCM/month** means more than an adequate amount of water is available for Greater Gaborone from the Gaborone Dam and other GGWSS sources in

2020/21. However, it has to be established as to how long there will be a surplus and project the potential future unmet demand.

In order to estimate the future water demand-water supply balance, it was considered that the future water demand growth rate will be equal to the population growth rate - 2.53% as calculated above.

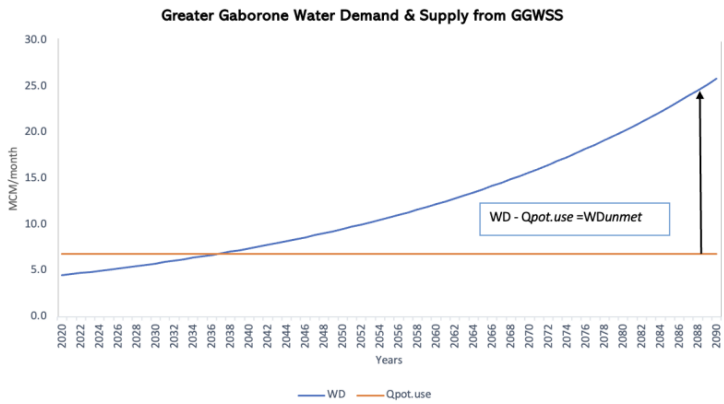


Figure 5.13: Projected unmet water demand after supply from GGWSS

From Figure 5.13, there is presently no unmet water demand. As it was evident in 2016, in a situation of drought, that condition was not met, and the NSC was not yet at a stage where it could satisfactorily ease pressure on the Gaborone Dam. In any case, the NSC is primarily supplied by surface reservoirs, and it can be inferred that the whole system, GGWSS, was probably vulnerable to the drought. Further, from projection, the positive balance of allocated water resources and water demand is, however, likely to change around the year 2037. It will call for GGWSS to increase its supply capacity from that year onwards.

5.4 Projections of future water availability under climate change

5.4.1. Projections of future climate variables affecting water resources

An examination of the MME temperature projections shows that relative to the baseline period temperature, the minimum (Tn) and maximum temperature (Tx) are expected to increase in the future (Table 5.6). This is true for both the GCMs and RCMs outputs. When considering the middle-of-the-road scenarios, i.e. SSP2-4.5 and RCP4.5, compared to the baseline period, the near future minimum and maximum temperatures are expected to increase by 0.9 – 2.2°C (1.0 – 1.8°C) and 0.6 – 3.1°C (0.8 – 2.0°C) respectively. As with the near future, the far future temperatures are expected to be significantly higher compared to the historical climate. The CMIP6 models display more variability compared to their regional CORDEX models counterparts. Further, the CMIP6 MME showed hotter temperatures compared to those projected by the CORDEX ensemble (Table 5.6).

Table 5.6: Absolute Difference between historical and future mean temperatures

Period	Scenario	Temperature Difference (°C)	Median (°C)
		CMIP6	
Near Future (2031 – 2060)	Tn_SSP2-4.5	0.9 – 2.2	1.4
	Tx_SSP2-4.5	0.6 – 3.1	1.6
Far Future (2061 – 2090)	Tn_SSP2-4.5	1.3 – 3.3	2.3
	Tx_SSP2-4.5	1.1 – 4.4	2.6
Near Future (2031 – 2060)	Tn_SSP5-8.5	1.2 – 2.6	1.8
	Tx_SSP5-8.5	0.8 – 3.2	2.0
Far Future (2061 – 2090)	Tn_SSP5-8.5	2.6 – 5.9	4.1
	Tx_SSP5-8.5	2.3 – 6.5	4.2
		CORDEX	
Near Future (2031 – 2060)	Tn_RCP4.5	1.0 – 1.8	1.3
	Tx_RCP4.5	0.8 – 2.0	1.3
Far Future (2061 – 2090)	Tn_RCP4.5	1.6 – 2.9	1.9
	Tx_RCP4.5	1.5 – 3.2	2.1
Near Future (2031 – 2060)	Tn_RCP8.5	1.2 – 2.5	1.7
	Tx_RCP8.5	0.9 – 3.0	1.7
Far Future (2061 – 2090)	Tn_RCP8.5	2.7 – 5.3	3.6
	Tx_RCP8.5	2.7 – 5.5	4.0

As expected, with the rise in future temperatures, an increase in PE is also expected (Table 5.7). For instance, the SSP2-4.5(RCP-4.5) near future (2031–2060) projected PE percentage increase is between 0.5 – 11.4**%**(1.2 – 9.6**%**).

Table 5.7: Percentage difference (ensemble range and median) between historical and future mean PE

Period	Scenario	Percentage Difference (%)	Median (%)
		CMIP6	
Near Future (2031 – 2060)	SSP2-4.5	0.5 – 11.4	5.4
Far Future (2061 – 2090)	SSP2-4.5	2.5 – 14.7	8.3
Near Future (2031 – 2060)	SSP5-8.5	0.9 – 12.1	6.4
Far Future (2061 – 2090)	SSP5-8.5	5.2 – 21.8	13.4
		CORDEX	
Near Future (2031 – 2060)	RCP4.5	1.2 – 9.6	4.8
Far Future (2061 – 2090)	RCP4.5	3.2 – 13.2	6.9
Near Future (2031 – 2060)	RCP8.5	1.7 – 9.4	5.4
Far Future (2061 – 2090)	RCP8.5	6.3 – 19.0	11.2

On the other hand, both the CMIP6 and CORDEX multi-model projections under the chosen emission scenarios show no clear direction of change when it comes to rainfall (Table 5.8). This is to say that both drier and wetter future conditions are possible under the SSP2-4.5/RCP-4.5 and SSP5-8.5/RCP-8.5 scenarios for the near and far future. The multi-model median splits the ensemble so that 50% of models project higher change, while the other 50% project lower change. In the case of rainfall, ensemble medians indicate consistently negative medians in projected rainfall change, except for one. This provides an indication that, despite inter-model variability, the dominant climate signal points towards reduced rainfall in the future. The magnitude of that reduction is, however, minimal - in the order of 1-2%, increasing to 3-5% in the far future under the SSP585/RCP85 scenario.

Table 5.8: Percentage Difference between historical and future mean rainfall

Period	Scenario	Percentage Difference (%)	Median (%)
		CMIP6	
Near Future (2031 – 2060)	SSP2-4.5	-19.5 – 12.2	- 0.6
Far Future (2061 – 2090)	SSP2-4.5	-18.7 – 10.4	- 1.3
Near Future (2031 – 2060)	SSP5-8.5	-17.0 – 17.1	- 1.2
Far Future (2061 – 2090)	SSP5-8.5	-35.0 – 10.5	- 3.5
		CORDEX	
Near Future (2031 – 2060)	RCP4.5	-13.4 – 14.7	- 1.6
Far Future (2061 – 2090)	RCP4.5	-20.5 – 5.7	- 4.7
Near Future (2031 – 2060)	RCP8.5	-16.3 – 14.4	1.8
Far Future (2061 – 2090)	RCP8.5	-24.8 – 8.3	- 1.8

5.4.2 Projections of water availability in the Gaborone dam

Results of simulations of future water availability in the Gaborone dam under the projected future climate are presented in three forms:

- Figures 5.14 and 5.15 illustrate the time series of projected stored volume (in MCM) across multiple models for two future periods (near future: 2031–2060 and far future: 2061–2090) under two climate scenarios for CMIP6 and CORDEX ensembles, respectively. This illustrates how individual models simulate time series of dam storage.
- Figures 5.16 and 5.17 present the ranges of stored volume for individual models in the form of boxplots. This illustrates an overall change in the range and average of stored volume, but also highlights the differences between individual models, and thus model-related uncertainty of projections.
- Finally, Figures 5.18 and 5.19 present the number of months in the simulation period of 30 years with critical dam volumes for each of the models, with the dam's critical level/volume considered to be 10% of the dam's full capacity, which is ~14 MCM. This illustrates the level of unmet water demand or reliability of supply, as water supply will be severely restricted or impossible during such months.

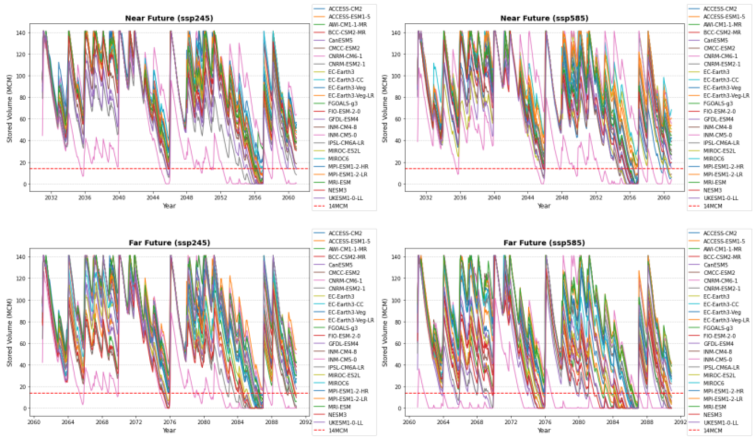


Figure 5.14: Gaborone Dam future stored volume changes simulated by CMIP6 MME

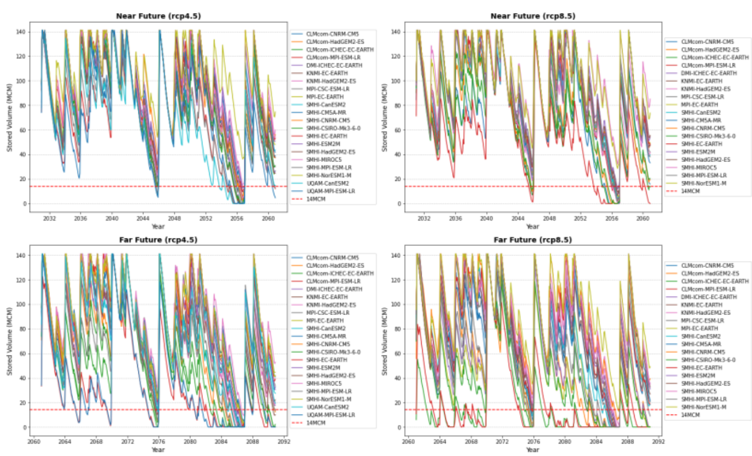


Figure 5.15: Gaborone Dam future stored volume changes simulated by CORDEX MME

The simulations of stored volume under projected climate for the near future (2031–2060) and far future (2061–2090) under the SSP2-4.5 and SSP5-8.5 scenarios by both analysed ensembles - CMIP6 (Figures 5.15 and 5.17) and CORDEX (Figures 5.16 and 5.18) reveal the following:

- There are notable differences between the different climate models in projected water availability relative to the reference period (1991–2020). The model-to-model differences reflect the uncertainty of projected water storage.

- Those model-to-model differences are smaller in the near future than in the far future, and smaller under the SSP2-4.5 and RCP4.5 scenario than under the SSP5-8.5 and RCP8.5 scenario. Those patterns are similar in both the CMIP6 and CORDEX ensembles.

- Generally, projected volumes display greater variability than the observed data modelling, as indicated by wider interquartile ranges and more outliers.

- Median values in: near future (SSP2-4.5/RCP45 and SSP5-8.5/RCP85): 23 out of 46 and 23 out of 44 models, respectively; far future (SSP2-4.5/RCP45 and SSP5-8.5/RCP85): 33 out of 46 models and 39 out of 44 models, respectively, fall below that of the observed record, implying potential future overall declines in dam stored volume. This observation is more pronounced in the far future than in the near future. Also, the median values under SSP5-8.5 tend to shift downward, suggesting a higher likelihood of reduced water availability compared to SSP2-4.5.

- There are, however, several models that project an increase in water availability. That number is 15 in the far future compared to the near future, and 4 under SSP5-85/RCP85 than under SSP2-45/RCP45.

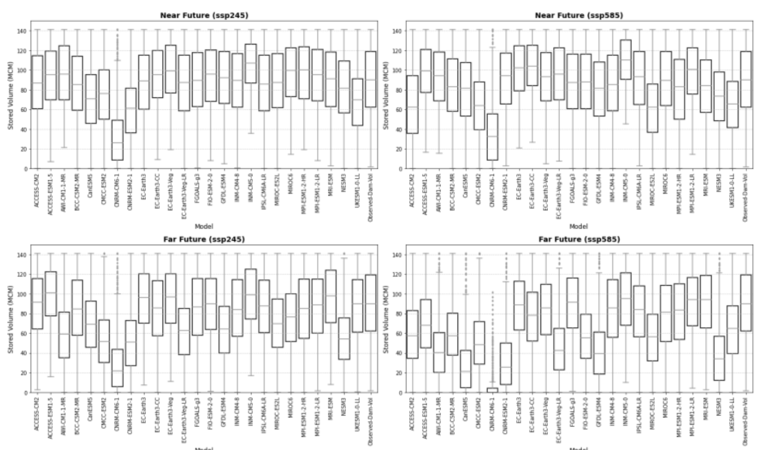


Figure 5.16: CMIP6 MME - Boxplots of the future dam water volume under the climate simulated by each model. Dam water volume under observed rainfall is shown in the last boxplot in each of the panels.

- In summary, the CMIP6 and CORDEX scenario medians show broadly similar patterns in projected water availability. Notably, both RCM and GCM indicate slightly higher medians in the far future compared to their near future periods. However, the variability across models remains substantial, highlighting the uncertainty in future water availability projections.

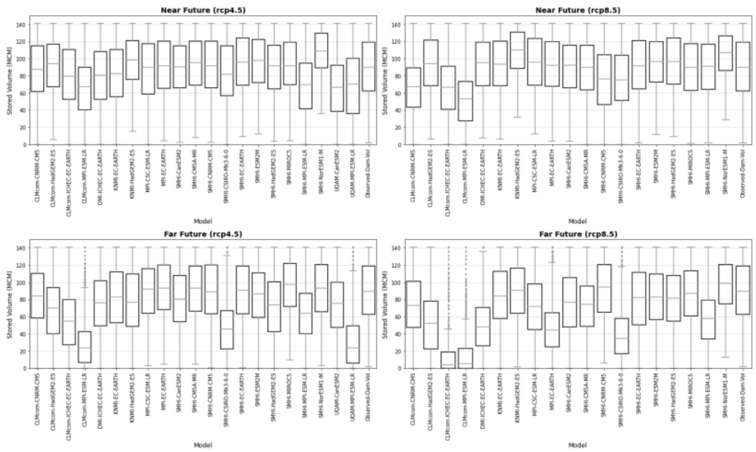


Figure 5.17: CORDEX MME - Boxplots of the future dam water volume under the climate simulated by each model. Dam water volume under observed rainfall is shown in the last boxplot in each of the panels.

In order to evaluate the reliability of water supply under the projected climate, the number of months was counted for each model simulation with dam storage below 10% of the storage (14 MCM)(Figure 5.18 and Figure 5.19). The baseline period (1991–2020) had 11 months (in the simulation period of 360 months) with a stored volume of 14 MCM and below. The number of models detailing the reliability of water supply is displayed in Figures 5.18 and 5.19 below, and the specifics are presented in Table 5.9

In the near future (SSP2-4.5), most models show a relatively low frequency of low storage months, indicating more reliable water supply conditions. However, a few models exhibit elevated counts, suggesting a decrease in reliability. The Near Future (SSP5-8.5) scenario generally reveals an increase in the number of low storage months compared to SSP2-4.5, reflecting the more severe impacts of the high-emission pathway on the reduction of reliability of supply and water resources in general. Concerning the far future (SSP2-4.5), the frequency of low storage months becomes more pronounced for several models, indicating that even under a middle-of-the-road scenario, water storage issues are likely to intensify over time. The far future (SSP5-8.5) scenario shows the most concerning results, with multiple models projecting significantly higher counts of months with critically low storage, emphasising the increasing risks associated with severe climate change trajectories.

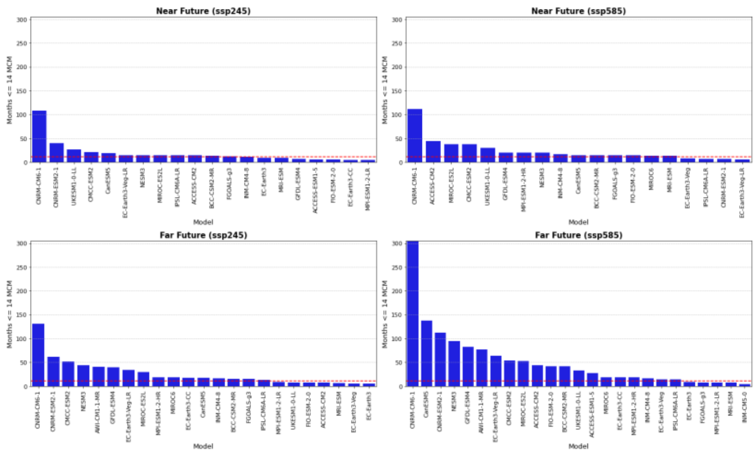


Figure 5.18: CMIP6 MME - future months with critical dam volumes

The CORDEX MME display similar patterns to the CMIP6 output. However, in all the scenarios and time periods, the CORDEX models generally recorded lower values than the CMIP6 models.

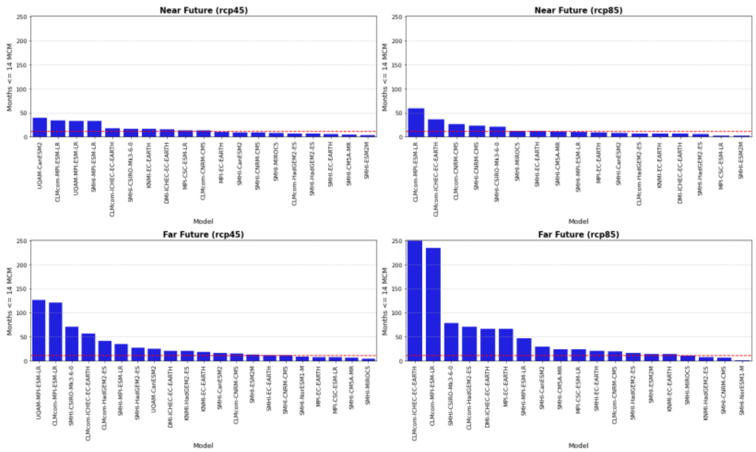


Figure 5.19: CORDEX MME - future months with critical dam volumes

The table below (Table 5.9) provides an analysis of the likelihood of the Gaborone Dam experiencing limited supply capacity exceeding the historical baseline of 11 months with stored volumes below 14 MCM. The likelihood is calculated as the percentage of models in each scenario that predict water supply stress levels greater than 11 months. This percentage represents the probability that the Gaborone Dam will experience stress levels exceeding the historical baseline. A higher likelihood suggests a greater risk of prolonged water scarcity, whereas a lower percentage indicates a lower risk. A lower likelihood means that fewer models predict the reservoir will experience frequent periods of water scarcity. All the scenarios, future periods and ensembles, however, indicate a higher likelihood of the dam (and thus GGWSS) operating under conditions of constrained water supply.

Table 5.9: Likelihood of critical dam months - GCM and RCM ensembles

Ensemble	Scenario	Models Above threshold	Total Models	Likelihood (%)
CMIP6 (GCM)	ssp245 NF	12	20	60.0
	ssp585 NF	15	19	78.9
	ssp245 FF	21	25	69.6
	ssp585 FF	20	25	80.0
CORDEX (RCM)	rcp45 NF	10	19	52.6
	rcp85 NF	7	17	41.2
	rcp45 FF	16	21	76.2
	rcp85 FF	15	19	78.9

In *summary,* comparing the CMIP6 GCM outputs with the CORDEX RCM outputs, both sets reflect increasing uncertainty and potential reductions in stored volume over time, particularly under high-emission scenarios (RCP8.5 and SSP5-8.5). There are pronounced instances of extremely low storage conditions in the far future, especially under SSP5-8.5/RCP8.5. The RCP4.5 and SSP2-4.5 pathways, representing moderate emissions, generally align in indicating relatively low uncertainty of future storage compared to their high-emission counterparts. This comparison underscores the overall consensus across different sources that higher emissions lead to a higher risk of reduced stored volumes in the long term. However, the MME presents uncertainty in future projections as displayed by model-to-model differences in the same scenarios.

A clear rise in water storage vulnerability is evident as emissions increase and time progresses. The SSP5-8.5/RCP8.5 scenarios consistently produce more months with critically low storage compared to SSP2-4.5/RCP45, both in the near and far future periods. Models generally display more months with stored volume below the threshold under the far future scenarios. Additionally, the far future scenarios exhibit a broader range of outcomes across models, highlighting the increasing uncertainty and potential severity of future water shortages under changing climate conditions. This suggests that higher emissions scenarios and extended future periods pose greater risks to reservoir storage, emphasising the importance of adaptation measures to safeguard water resources.

5.5 Reconciling population projections with climate projections

In this section I asses how the population-driven demand projections compare to changes of water availability due to changing climate

To do so, it is considered that the change in mean stored volume of the Gaborone Dam as simulated by the dam model under future climate reflects a change in available resources. That change is assessed separately for each climate model in relative terms, i.e. as a percentage of the mean stored volume simulated by the model when it is run with the observed rainfall. In order to account for the uncertainty of climate projections - the "wettest" and "driest" models are selected for each of the ensembles and scenarios.

Demand from Greater Gaborone arising due to population growth is projected to rise significantly - by nearly 29% in 2030, 171% in 2060, and 476% in 2090, relative to the 2020 baseline (4.5 MCM) (Table 5.10).
As for projected water availability, in the CORDEX ensemble under RCP4.5, the "wettest" model indicates a 21.1% increase in water availability by 2045 (near future), and this is insufficient to meet even the modest 2045 demand increase. On the other hand, the driest model indicates a 25.2% decrease, and this is likely to result in significant unmet water demand should Gaborone rely only on water resources available in 2020. CMIP6 ensemble under SSP2-4.5 scenario offers a slightly more optimistic wettest-case projections of 19.3% increase in available water by 2045, and this aligns closely with the 2030 demand increases

but falls short of the 171% increase projected for the 2060 demand, and beyond. In the far future, 2075, availability increases by 11.5%, but this too falls well below projected demand.

Projections, far future, under SSP5-8.5/RCP8.5 show greater disparity, with a median decline of -16.7 to -27.5% and a driest model decline of -80.5 (under CORDEX) to even -91.4% (under CMIP6). A projection of -91.4% means a complete loss in dam yield. This is a serious concern for water security in the far future under high emissions scenarios.

Overall, the wettest projections briefly align with immediate future (present time to near future) demand increase, however, median and driest projections consistently suggest water availability will increasingly fail to meet population-driven demand. This underscores the importance of addressing uncertainty in water planning and management, seek efficient demand management policies, and, more importantly - plan for the development of any not yet available water resources.

Table 5.10: Projected demand increases - relative to 2020 demand (4.5 MCM)

Year	Population	Projected Demand (MCM)	Percent increase from 2020
2030	610 994	5.8	28.9%
2045	888 795	8.4	86.7%
2060	1 292 903	12.2	171.1%
2075	1 880 747	17.8	295.6%
2090	2 735 865	25.9	475.6%

Table 5.11: Percent change in water availability - GCM and RCM ensembles

Ensemble	Scenario	Wettest Model Change (%)	Driest Model Change (%)	Median Model Change (%)
		Near Future		
CMIP6 (GCM)	SSP2-4.5	19.3%	-58.6%	-0.3%
	SSP5-8.5	22.4%	-57.2%	-2.7%
CORDEX (RCM)	RCP4.5	21.1%	-25.2%	0.4
	RCP8.5	21.0%	-38.4%	3.0
		Far Future		
CMIP6 (GCM)	SSP2-4.5	11.5%	-62.7%	-5.2%
	SSP5-8.5	6.2%	-91.4%	-27.5%
CORDEX (RCM)	RCP4.5	8.2%	-63.7%	-9.5%
	RCP8.5	9.0%	-80.5%	-16.7%

5.6 Botswana Water Legal Framework

Of the 7 policies and 14 Acts searched (Tables 4.1 and 4.2), the top 100 most frequent keywords (including those repealed) are in Figure 5.20 below. Of these, the top 10 with their word count were: water (3603), followed by Botswana (2384), may (1773), government (1508), development (1466), point (1393), health (1352), person (1281), management (1277) and, act (1135). Because these are the government of Botswana documents dealing with water, it is unsurprising that these words appear the most. The word may is a modal verb that appears commonly in Acts of Parliament (Law). It can be inferred that developments are highly considered in these documents. It can also be noted that urban/city and climate, or similar words, do not appear within the most frequent (100) word search/query.

Figure 5.20: Word cloud of the key Legal Framework documents

The keyword searches were for climate and evaporation. Climate, and specifically climate change, is not mentioned enough in documents that manage the country's water (Table 5.10) and does not even appear in the other documents that form part of the water legal framework for the country (Table 4.1 and 4.2). Since these are national documents, there is no reason to assume that there exist special documents specifically for the city of Gaborone or Greater Gaborone. As for 'evaporation'**,** only the IWRM mentions it. There are **14** references therein (0.02% coverage). They include phrases such as:

1. "*...there are few suitable dam sites and most dams are shallow, and have high evaporation loss*".
2. "*Most of the runoff cannot be captured due to the lack of suitable dam sites, high variability of runoff in time as well as high evaporation*".
3. "*The sustainable yields of dams are low as compared to their capacity due to erratic river flows, high rates of evaporation… and limited dam site suitability*".
4. *"Gaborone Dam with a capacity of 144.2 MCM (Mm^3), has an evaporation of 38 MCM/year"*.

Table 5.12: Appearance of the word 'climate' in key Water Legal Frameworks

Document	References	Coverage
IWRM	65	0.06 %
National Energy Policy	6	0.02 %
NDP 11	57	0.03 %

6 CHAPTER 6: DISCUSSION

The findings of the projected future dam water balance are discussed concerning (1) the water dynamics/situation of Gaborone and its surroundings, (2) what literature states about the projected population dynamics of the city of Gaborone and surroundings, and associated water demands of the area, and (3) what literature, including, the legal framework (Policies) says about Gaborone city's water security presently and in the coming years under anthropogenic climate change. The key objective was to consider the uncertainty of projections in assessing water availability (dam volumes) in the study area, in this century, under anthropogenic climate change.

The study findings are such that historically, over the past 20 – 30 years, Gaborone Dam has experienced drying periods, and the question remains if this will continue in the future under anthropogenic climate change. Historically, there has been a consistent decline in the Gaborone Dam's volume since 2002 (Meinhardt et al., 2018; Farrington, 2015). During the baseline period, the dam water balance model implemented here simulated many years of runoff into the dam, with near-zero (0) values. Concurrently, the model simulated many months of actual evaporation (AE) with values of more than 1.0 MCM/month. With low inflows into the dam and higher evaporation from the dam, this suggests that historically a key driver of the dam's water availability was climate - rainfall and PE driven by temperature. A dam's filling due to the catchment area's surface inflows into the reservoir hinges largely on rainfall. Throughout their research period, Byakatonda et al. (2018b), as with previous research by Kenabatho et al. (2012), found rainfall has been trending downward in every region except for the east at Francistown and the west at Ghanzi. This supports the understanding that increasing greenhouse gas concentrations globally result in less rainfall over Botswana. The Gaborone Dam catchment is in a region of said declining rainfall. Declining rainfall and high evaporation rates will put pressure on the Gaborone Dam and GGWSS' water availability.

The driving factor of high evaporation is high temperature. Concerning temperature, the findings of this study are consistent with the other studies on the same subject as outlined in Section 2 (Literature Review). As the temperature increases, PET/PE over the catchment and the reservoir surface is expected to increase with time this century. Historically, Gaborone Dam area's PE, from the literature and the study model, was higher than rainfall by a magnitude of at least 3 (Byakatonda et al., 2018b; Meinhardt et al., 2018), making the dam very vulnerable to climate conditions.

With a historically vulnerable dam, water availability, it was then necessary to establish if the same could be the case in the future. In assessing the projected rainfall and potential evapotranspiration/evaporation in the Gaborone Dam catchment area and consequently, assessing the uncertainty of future climate and water availability, this thesis considered rainfall and temperature-driven PE under the SSP2-4.5/RCP4.5 and SSP5-8.5/RCP8.5 scenarios. If the projected rainfall declines or increases, the expectation is that so does the runoff into the dam. The same is true for temperature and evaporation. The projected PE for the study area was found to be significantly higher than the rainfall. Surface evaporation of the reservoir, causing dam water loss, should lead to the drying of the dam, but, for instance, SSP2-4.5/RCP4.5 (SSP5-8.5/RCP8.5) PE changes relative to the past only reach 0.5 – 11.4% (0.9 – 12.1%) and 2.5 – 14.7% (5.2 – 21.8%) increases for near and far futures, respectively. The near and far future water availability of Gaborone Dam under projected rainfall and PE is such that the multi-model ensemble suggests a probability of a wetter or drier future, while PE increase is relatively small to lead to significant water loss compared to the base period. However, for all the scenarios used in this thesis, for both the near and far future, the likelihoods of critical dam volume per month above historical times were all above 50%.

The projections underscore the compounding effect of a high-emissions pathway over time, emphasising an increased risk of water scarcity towards the end of the century. However, notably, there is substantial inter-model variability in each scenario. Even when considering the same emission pathway, SSP2-4.5, for instance, some models project relatively wetter futures with sustained higher storage volumes, while others suggest drier conditions and more severe volume declines. This spread illustrates the uncertainty inherent in climate projections, owing to differences in how individual models simulate key climate processes such as rainfall and temperature, factors that directly influence evaporation and inflow into the dam. Having both wetter and drier models' outputs within each scenario underscores the importance of using a multi-model ensemble; it provides a more extensive picture of plausible futures rather than relying on a single projection. Overall, while the ensemble mean points toward increasing water stress, especially under SSP5-8.5, the uncertainty envelope includes both optimistic and pessimistic outcomes.

Stored volumes tend to decrease from the near to the far future, particularly under SSP5-8.5, as compared to SSP2-4.5, highlighting the potential long-term consequences of unmitigated climate change on water resources storage. The models' outputs, in the coming years up to 2090, highlight a growing risk of water scarcity, particularly under continued high-emissions trajectories.

This study used a conservative assessment of growth rate and used population growth as a proxy for rising water demand. The reason for this, as already mentioned earlier, is that there is no official growth rate for Greater Gaborone for the period 1990–2020. What is available is the Alemaw et al. (2016) mean population growth rate for Greater Gaborone for the period 2001–2011 and Statistics Botswana for the period 2011–2022. With a population growth rate of 2.53%, the water demand for the study area is expected to increase significantly. The total amount of water required for an adequate municipal supply increases as cities' populations grow. As cities hunt for new, sufficient, reasonably pure water sources as a result of the overall rise in municipal water demand, this can result in the development of occasionally highly complicated urban water infrastructure systems (McDonald et al., 2014). This is precisely the case with Greater Gaborone. Additionally, Gaborone is growing outwardly (Kent and Ikgopoleng, 2011), and the urbanisation of many rural areas is likely to persist for many years, therefore placing more demand on the GGWSS.

To contend with the growing water demands of Gaborone and its surroundings, the North-South Carrier Water Project (NSC-WP) was proposed and subsequently implemented, with phase I of the project commissioned by the year 2000 (WUC, 2023). As already outlined in this thesis, the NSC-WP is an engineering water project that transfers water from other regions of Botswana (primarily the North) into the Greater Gaborone region. Botswana is seemingly addressing, or at least attempting to address, its water scarcity issues, which include Greater Gaborone's water security.

Historically, the ratio of water supply from the Gaborone Dam and the NSC projects is 1:1 (WUC, 2023). This is consistent with Byakatonda et al. (2018b), which records the main source of the city's water supply as the Gaborone Dam and Alemaw et al. (2016) stating that 56% of the GG's water supply is from the Gaborone Dam. However, as presented in **Chapter 5** (5.3.1.4-5), the Gaborone Dam presently accounts for ~29% of the total supply of GGWSS. This is still a significant contribution. The projected rainfall and relatively small increases in PE over the reservoir in the future may still be adequate to render the Gaborone Dam able to have significant yields and retain its significance.

Climate change certainly introduces significant uncertainty in available water from the Gaborone Dam, however, even the optimistic-wettest projections may not meet future demands. The scale and near-certainty of population growth seem to outweigh the contribution of climate impacts in the coming decades. With projected demand rising sixfold by 2090, GG population-driven demand presents the greatest vulnerability to the Gaborone Dam and thus the GGWSS.

Before the turn of the century, rapid urbanisation is projected. Extreme weather events promote the temporary migration of farmers and agriculture-based workers to urban places (Seiyefa, 2019). As a means to adapt to climate change in rural areas, some people move to towns and cities such as Selebi Phikwe, Francistown and Gaborone in search of employment (Mugari et al., 2020). Another social implication of water insecurity is that of job losses due to water-dependent industries shutting down or relocating from a water-scarce place (Farrington, 2015). Water-intensive industries such as breweries are cited as vulnerable to water scarcity. Sound urban water security policies are a necessity and must be based on appropriate studies for the country.

At present, the majority of the country's potable water is from groundwater sources. The challenge, however, is that Botswana's groundwater capacity is limited in both quantity and quality. It is for this reason that surface water is preferred. However, owing to a lack of surface water in most parts of the country, to date groundwater has been the most utilised source for local water supply in many places (Ministry *of* Minerals Energy and Water Resources, 2012). Since the groundwater is limited in quantity and quality, with increasing demand, attention has to switch towards surface water resources, as is the current scenario with Greater Gaborone. The challenge, however, with surface water resources in the country is that they are hard to utilise due to their location concerning where the demand is. Further, the majority of surface water resources in Botswana are transboundary. There are complexities to utilising transboundary resources.

Botswana has five major drainage basins, all of which are transboundary (Ministry *of* Minerals Energy and Water Resources, 2012). This means the country's water plans within its borders have a direct impact on its neighbouring countries and vice versa (Boroto, 2001). About 95% of Botswana's surface water resources are located in the northern region of the country and it is 'housed' in the transboundary Chobe and Linyanti rivers, and the Okavango Delta (Ministry *of* Minerals Energy and Water Resources, 2012). Since Botswana's key water basins are transboundary, reliance on them has to be in a manner that is mindful of not jeopardising national sovereignty (Ministry *of* Minerals Energy and Water Resources, 2012). There are limited water resources in the Greater Gaborone region. It is these water dynamics that add to the vulnerability of the GG's water.

Potential future reductions in rainfall and the rise in temperature (minimum and maximum) have to be discussed in terms of what measures emerge from policies to manage these. To reduce the disastrous effects of extreme weather events, policymakers need comprehensive, up-to-date information on regional variations in precipitation [and temperature] to develop appropriate adaptation and mitigation policies (Lim Kam Sian et al., 2021). With about a 50 % potential for reduction in rainfall for the future and an anticipated rise in PE due to an anticipated increase in temperature, a reduction in streamflow is likely. Additionally, droughts are endemic to Botswana, and as such, Water Security Policies must incorporate adaptive measures for climate change. Unfortunately, a preliminary look into water-related legal framework documents shows that climate change is not frequently mentioned. In the National Water Policy, there is not even a single mention of climate change. This possibly suggests that climate change has not been one of the key factors of consideration when it comes to the country's water security plans, and this would also mean GG's water security plans. If the projected decline in rainfall and river inflows is realised, it means Botswana will continue to grapple with water security for decades to come. In the past, part of Botswana's water-saving 'policy' encompassed water-rationing and rainwater harvesting (Alemaw et al., 2016; Lund Schlamovitz and Becker, 2021). The question must then be asked if this is an adequate policy measure to ensure water security in this century.

Water security policy development has to be anchored on comprehensive climate-water-population studies. In this thesis, just like the Zhang et al. (2020) study, this study did not include many meteorological and human activity parameters that could significantly impact runoff formation and improve future projections. For instance, urbanisation may alter baseflow generation and stream flow drainage times. For future applications, with better data, there ought to be a consideration for including all the parameters that were excluded. For instance, dealing with ungauged streamflow and evaporation meant relying on assumptions and calculated/estimated values. There are errors and uncertainties involved in estimating water balance parameters (Baseri et al., 2023). As with the Zhang et al. (2020) study, determining/acknowledging the importance of key components that are not extensively represented, and providing direction for future research, can be accomplished with the use of accurate uncertainty quantification. It would be prudent to study the NSC dams with the aforementioned parameters catered for and obtain a more holistic assessment of Greater Gaborone's water security up to the turn of the century.

In *summary,* from the study, it emerges that it cannot be stated with high confidence that climate change will adversely impact the dam's water availability in the coming years. However, there is a marginally greater likelihood that water availability will decline, which would lower supply reliability rather than boost it. This study presents the uncertainty that is involved with future water availability projections. This is different from studies such as Alemaw et al. (2016) and Moalafhi et al. (2012), which projected only a drier future.

Importantly, even if Gaborone Dam were to be compromised, it may be possible that the city's (and surroundings) water can be safeguarded by supply from the North via the NSC, which already supplies at least 50% of GG water. It would then mean to fully assess Greater Gaborone's water security or vulnerability, this study needs to be replicated with the assessment of NSC dams to more adequately inform water security policymakers. Policymakers have to prepare for either future water availability scenarios - a wetter or drier future, as this is the uncertainty emerging from the MMEs.

7 CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The goal of the study was to investigate Greater Gaborone's water security under anthropogenic climate change through investigating the variability and future projections of water availability in the Gaborone Dam, with a focus on climate-induced change in rainfall and evaporation. This study highlights the uncertainty surrounding climate projections and their implications for future water balance. Additionally, the research examines how projected population growth may affect water demand and urban water security in Greater Gaborone. This thesis, therefore, concludes that there is uncertainty concerning the projected future water availability (stored water) under climate change, however, a drier future cannot be ruled out, especially with a growing population-driven water demand.

The more plausible SSP2-4.5/RCP4.5 scenario's analyses of the projected rainfall, temperature and, potential evaporation (evapotranspiration) for the Gaborone Dam catchment area are such that: there is a 50% chance of a drier or wetter near and far future; SSP2-4.5(RCP4.5) minimum and maximum temperatures are projected to increase by 0.9 – 2.2°C (1.0 – 1.8°C) and 0.6 – 3.1°C (0.8 – 2.0°C) respectively, in near future relative to baseline period. In the far future, relative to the baseline period, the projected minimum and maximum temperature increases are 1.3 – 3.3°C (1.6 – 2.9°C) and 1.1 – 4.4°C (1.5 – 3.2°C), respectively; The potential evaporation increases by less than 15%. An assessment of the future water balance of the Gaborone Dam under this projected rainfall and potential evaporation, taking into account the uncertainty of climate projections, generally indicates little but significant vulnerability to climate change compared to the baseline period.

As far as the Gaborone Dam water balance showed, climate change is less likely to result in the dam's severe water stress, i.e., less availability of water. Simulations for both the future study periods - near and far futures - showed stored volumes of more than 14 MCM for the majority of months. Even though the temperature and PE findings of this study are consistent with other studies done on Botswana's climate in the past and coming years, an increase of less than 15% did not significantly affect the model, i.e., dam water availability. Furthermore, since it is difficult to categorically state if rainfall is likely to increase or not, it can be concluded that, the likelihood of the dam being adversely impacted is considerable, however, there is also a chance that the water availability/stored will be comparable to or even better than it was in the past, due to anthropogenic climate change in the coming decades—near and far future(s) under the more plausible SSP2-4.5/RCP4.5 scenario. This scenario is highlighted precisely to consider a world with some degree of climate policy towards climate adaptation and mitigation measures.

However, when considering the worst-case scenario, SSP5-8.5/RCP8.5, the results are more pessimistic—a more vulnerable water availability. The presence of low extremes in several models highlights possible scarcity risks in the future. The discrepancy between the projected and observed distributions highlights the mounting strain on the sustainability of dam storage. In the drier future projections, particularly - worst-case scenario, this is very concerning.

Furthermore, since hotter conditions in the city of Gaborone, as with the rest of the country, are projected, potential evaporation higher than rainfall consistent with the historical period can still be expected. This means a drier future cannot be ruled out under climate change, especially since, although there is a significant spread among models, particularly with regard to rainfall, the general trend is toward future water stress. Furthermore, based on the study findings, another vulnerability is that Greater Gaborone's water system is complex due to having several water sources, some of which are transboundary, and the majority being outside the city region (NSC dams). Cross-border activities may affect flows in the Gaborone Dam transboundary catchment.

From the above, this thesis successfully achieved the *first two* objectives of investigating the variability in water availability in the Gaborone Dam by analysing projected rainfall and potential evaporation, assessing future water balance, and considering climate projection uncertainties. The *third* thesis objective of assessing the effects of the projected population of Greater Gaborone in the coming decades, till the end of 2090, on the water demand from the Greater Gaborone water supply system was achieved. Due to the effects of Greater Gaborone's population growth, the area is still at risk of water insecurity. Although there is presently no unmet water demand in GG, this is probably going to change by 2037. For the Gaborone Dam to retain its supply significance to GGWSS, it will need to supply ~11 MCM/month by the year 2090. This is significantly higher than the present ~2 MCM/month, and factoring in the maximum annual abstraction limitation of 21.83 MCM/yr. Water demand due to urban population increase may occur at a far greater pace than GG's water system can supply.

With water scarcity being a long-standing concern, the key city water security intervention at present is the NSC project, with water being brought into Greater Gaborone from the relatively water-rich northern part of Botswana. Even if the Gaborone Dam were to be distressed, as was the case in 2015–2016, it is well possible that Greater Gaborone's water demand can, at least in the immediate future, be satisfied. This is not to say there will be no unmet water demand, however, a separate study on the capacity of the NSC would be required to research that question. This is especially important considering the expected high urban population increase. A water-insecure Global South urban population has a propensity to exacerbate social inequalities, and this is a concern that Policymakers should be made aware of.

This thesis's *fourth* objective of evaluating policy provisions for urban water security in Botswana was satisfied. Based on evaporation and climate as the key search terms, the country's water management documents do not adequately address climate, and climate change in particular. They do not even mention it in the other documents that make up the country's water law framework, such as the Water Utilities Corporation Act and the

Waterworks Act. There is very little on climate change and water security policy for the country, let alone its urban areas.

In *conclusion,* the study's objectives were primarily to analyse the dynamics of Greater Gaborone's water supply and research how vulnerable Gaborone Dam's water availability and supply are to anticipated anthropogenic climate change and increases in Greater Gaborone's population. Historically, the dam has had a significant reduction in water levels, and this study's findings cannot categorically state if GG's principal reservoir's water availability under anthropogenic climate change (under SSP2-4.5/RCP4.5) will be critically reduced. The greater threat seems to be continued population growth and hence rising water demand. Further, regarding the National Water Policy of Botswana concerning the city's water security, it appears to be currently ill-equipped to tackle matters of water security, factoring in the effects of climate change.

Finally, using runoff and water Balance models for the Gaborone Dam with inputs from climate MMEs, the study shows that in the coming decades, especially, under a more plausible scenario, there is still a chance that there will be more water but, there is a higher chance of there being less water, consequently making Gaborone city and Greater Gaborone water insecure. However, climate change will bring about a higher degree of uncertainty, especially when considering the worst-case scenario; therefore, more studies into the water availability of Greater Gaborone, for the present and future water security, are necessary to safeguard Greater Gaborone's future in the Anthropocene. Knowledge building in this sphere will prove most useful for policymakers towards mitigation and adaptation plans.

7.2 Recommendations

- That an Act or Policy dealing specifically with the country's surface water dams be developed
- That there be gauges to adequately monitor Gaborone Dam inflows (river inflow) and outflows (spillages) and direct evaporation
- That there be an adaptation strategy for Gaborone Dam's evaporation losses.

8 CHAPTER 8: LIMITATIONS AND ETHICAL CONSIDERATIONS

8.1 LIMITATIONS

There are certain limitations in doing these types of studies. Some of the limitations are concerning historical data. The quality of historical meteorological and hydrological data for weather stations in the study catchment area was low. There were gaps, and at times, data were missing for large periods. Further, the study was limited in the sense that the quality of the water-use data was low. For instance, there was no abstraction data (continuous) for the Gaborone Dam for more than five (5) years. Adequate abstraction data could have improved water balance calculations for the Gaborone Dam, the main dam of interest for the study.

The other limitation of the study was in establishing a simplified approach to adequately represent a complex water supply system for the city of Gaborone and its surroundings. The other challenge was the limited understanding of surface water-groundwater dynamics and their role in water balances for the study area. Also, it proved challenging to have a simplified representation of surface water balance and rainfall-runoff processes in the catchment. Further, the model appeared to be less sensitive to changes in PE, due in part to the study not taking into account the influence of PE on runoff from the catchment. The reason is that the simple runoff accounts for high rainfall months but does not account for the role of antecedent moisture.

A study such as this one has climate projection uncertainty as one of its limitations. There is an inherent limitation to using climate modelling, and indeed, most models for that matter. For local climate events, the models may underestimate climate extremes (Muradás et al., 2020).

8.2 ETHICAL CONSIDERATIONS

Essentially, the study utilised data from public databases and Global Climate Models (GCMs), a desk (literature) review and an interview of key informants from Water Utilities Corporation (WUC) that does not use personal identifiers. Further, Ethical Clearance was obtained for part of the study that involved conducting an Interview. The Ethics Clearance approval code is **FSREC 004 – 2023** (Appendix A). All precautions will be taken to use the data and study findings in the most ethical manner possible.

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10 APPENDICES

10.1 APPENDIX A - Ethical Clearance

UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

Faculty of Science
University of Cape Town
Rondebosch
South Africa 7701

E-mail: melissa.densmore@uct.ac.za
Tel: 021 650 4315

8 February 2023

Thusego Sebastian Setswammung
ACDI -Environmental & Geographical Science

Projected Hydro-climatological conditions of Gaborone Dam catchment area: assessing Gaborone's water vulnerability to anthropogenic climate change up to the year 2100

Dear Thusego Sebastian Setswammung

I am pleased to inform you that the Faculty of Science Research Ethics Committee has approved the above-named application for research ethics clearance, subject to the conditions listed below.

- Restrictions on involving human participants in research must be adhered to, given current concerns about the spread of Covid-19. Please ensure that you are aware of and comply with UCT policy on this, as communicated by management.
- Implement the measures described in your application to ensure that the process of your research is ethically sound; and
- Uphold ethical principles throughout all stages of the research, responding appropriately to unanticipated issues: please contact me if you need advice on ethical issues that arise.

Your approval code is: **FSREC 004 – 2023**

I wish you success in your research.

Yours sincerely

A/Prof Melissa Densmore
Chair: Faculty of Science Research Ethics Committee

10.2 APPENDIX B

Interview Guiding Questions

DEPARTMENT OF ENVIRONMENT & GEOGRAPHICAL SCIENCE

UNIVERSITY OF CAPE TOWN
PRIVATE BAG X3
RONDEBOSCH 7701
SOUTH AFRICA

RESEARCHER/S: Thusego S. Setswammung
TELEPHONE: +27-63-552 2330
E-MAIL: ststhu001@myuct.ac.za
URL: https://science.uct.ac.za/department-egs

Informed Voluntary Consent to Participate in Research Study

Project Title: Projected Hydro-climatological conditions of Gaborone Dam catchment area: assessing Gaborone's water vulnerability to anthropogenic climate change up to the Year 2100

Invitation to participate, and benefits: You are invited to participate in a research study conducted with water managers/experts. The study's aim is to assess the city of Gaborone's water vulnerability to climate change and population growth in the coming years. I believe your experience would be a valuable source of information, and I hope that you may gain useful knowledge by participating.

Procedures: During this study, you will be asked to narrate the city's water dynamics; supply & demand

Recording: We may take photographs of the study area as part of the study. These will be used to enhance the text output of the research. If you object to this, please indicate below.

Risks: There are no potentially harmful risks related to your participation in this study.

Feedback: You will receive feedback about the results of this research in the following manner: A PowerPoint presentation.

Disclaimer/Withdrawal: Your participation is completely voluntary; you may refuse to participate, and you may withdraw at any time without having to state a reason and without any prejudice or penalty against you. Should you choose to withdraw, the researcher commits not to use any of the information you have provided without your signed consent. Note that the researcher may also withdraw you from the study at any time.

Confidentiality: All information collected in this study will be kept private in that you will not be identified by name. Confidentiality and anonymity will be maintained.

What signing this form means: By signing this consent form, you agree to participate in this research study. The aim, procedures to be used, as well as the potential risks and benefits of your participation has been explained verbally to you in detail, using this form. Refusal to participate in or withdrawal from this study at any time will have no effect on you in any way. You are free to contact me, to ask questions or request further information, at any time during this research.

I agree to participate in this research (tick one box) ☐ Yes ☐ No ________ (Initials)

Name of Participant	Signature of Participant	Date
Name of Researcher	Signature of Researcher	Date

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Title

Projected Hydro-climatological conditions of Gaborone Dam catchment area: assessing Gaborone's water vulnerability to anthropogenic climate change up to the year 2100.

Abstract

Botswana is a landlocked semi-arid Southern African country with present water challenges (scarcity). Given the projected climate and increase in population especially in the city, water resources are likely to be even more vulnerable. There seems to be little research regarding this specific to Botswana and Gaborone city itself. Furthermore, water is paramount for Sustainable Development (National Water Plan); hence, its insecurity jeopardises the country's sustainable development ambitions.

Research Question:

What is likely to be the water stress level of Gaborone Dam and consequently of Gaborone city in the coming decades under Anthropogenic climate change?

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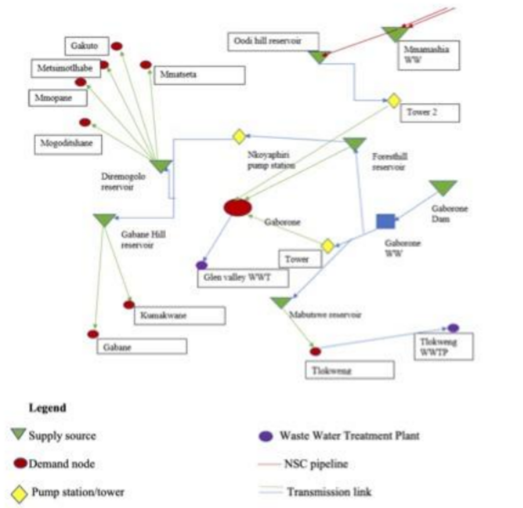
E-MAIL: ststhu001@myuct.ac.za
URL: https://science.uct.ac.za/department-egs

TITLE: Water Supply Dynamics of Gaborone and Greater Gaborone

Date: 26.04.2023 **Interviewee: WUC Personnel**

1. Discuss the Greater Gaborone Water System regarding Mphoeng's (2021) schematic diagram (Figure 1 below).

Is this an accurate representation of the Greater Gaborone water network?



Source: Mphoeng, 2021

Figure 1: Schematic representation of the Greater Gaborone water network

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E-MAIL: ststhu001@myuct.ac.za
URL: https://science.uct.ac.za/department-egs

Answer:

____

____

2. **Discuss Inflows and Outflows of the Gaborone Dam:**

I. Does the dam get recharged by the Bokaa dam from time to time?

Answer:

____

____

II. What territory does the dam supply?

Answer:

____

____

III. If it is not the only source, what are the supply dynamics?

Answer:

____

____

IV. What percentage of the supply area does it supply?

Answer:

____

____

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V. What is the role of the Molatedi Dam (The nature of the bilateral agreement in place)?

Answer:

VI. What is the role of the NSC?

Answer:

VII. When was the First Phase (NSC/NSWC) completed?

Answer:

VIII. What is the role of the Mamashia Waterworks?

Answer:

IX. What is the role of Masama Well Fields?

Answer:

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3. What are the major water security concerns over the supply territory especially the city?

Answer:

____

____

4. What are the effects of Climate Change on the Gaborone Dam?

Answer:

____

____

5. Are there any future plans for the city water security (this century at least)?

Answer:

____

____

6. Is dam siltation a major challenge to the Earth dam (Gaborone Dam)?

Answer:

____

____

7. What are the different categories/levels of water restrictions (such as those of "August 2012, level 2 water restrictions were imposed")?

Answer:

____

____

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8. **What is the purpose of the National Water Plan?**

Answer:

____

____

9. **Reflections (if any) on the 2023 Government of Botswana Budget Speech.**

Answer:

____

____

10. **Are there other matters incidental to Gaborone city water security in the era of Anthropogenic climate change one should be mindful of?**

Answer:

____

____

Thank you!

10.3 APPENDIX C

Table A.1: CMIP6 Multi-model GCMs

Name of GCM	**Long Name/Institution**	**Experiment**
ACCESS-CM2	Australian Community Climate and Earth System Simulator - Coupled Model	The multi-model simulations provide a more accurate estimation of the signals of climate change linked to aerosol and greenhouse gas forcings from anthropogenic activity. These simulations cover the years 1850–2014 (hindcast) and 2015–2100 in future projections (Rashid et al., 2020). For more details on ACCESS-CM, see also Bi et al. (2020)
ACCESS-ESM1.5	Australian Community Climate and Earth System Simulator - Earth Systems Model	*As with ACCESS-CM above*
AWI-CM-1-1-MR	*The* Alfred Wegener Institute Climate Model	A more recent addition to the CMIP6 project that generally performs better than CMIP5 models (Semmler et al., 2020)
BCC–CSM2–MR	Beijing Climate Center - Climate System Mode - medium-resolution	The model effectively depicts the global energy balance and can replicate the primary patterns of wind, precipitation, sea surface temperature (SST), land surface air temperature, and atmospheric temperature (Wu et al., 2021).
CAMS-CSM1-0	Developed by: Chinese Academy of Meteorological Sciences (CAMS)	Simulations of the atmosphere, ocean and land, including the equatorial tropics (Rong, 2019)
CanESM5	The Canadian Earth System Model version 5	The Multi-model's contribution to CMIP6 is to generate seasonal and decadal predictions and to model past climate variability and change, as well as to project future climate spanning hundreds of years. The model utilises radiative forcing caused by specific greenhouse gases (GHGs) in its application (Swart et al., 2019).
CMCC-ESM2	Developed by: Euro-Mediterranean Centre on Climate Change (CMCC) - Earth System Models - version 2	The purpose of the models is to produce accurate estimates of climate variability and its reaction to changes in the atmosphere's chemical composition and surface modifications (Lovato et al., 2022).
CMCC-CM2-SR5	*Euro-Mediterranean Centre* on Climate Change - coupled climate model	The CMCC-CM2-SR5 is the standard configuration of CMCC-CM2 (Cherchi et al., 2019)
CNRM–CM6–1	Multi-model by: Centre National de *Recherches Météorologiques* (CNRM) and *Cerfacs* for the sixth phase of the Coupled Model Intercomparison Project 6 (CMIP6)	The multi-model is utilised in a lot of MIPs, which require a lot of diagnostics to be generated following a particular CMIP6 format and standards (Voldoire et al., 2019).
CNRM–ESM2–1	CNRM-*CERFACS* -Earth system (ES) model of the second generation	When it comes to model complexity, CNRM-ESM2-1 is more advanced than CNRM-CM6-1 in that it includes interactive ES elements such as atmospheric chemistry, aerosols, and the carbon cycle (Séférian et al., 2019).

EC–Earth3	Developed by: European research consortium. For Earth system research	This is the Institution's model standard configuration. The experiments cover the atmosphere, land and ocean (Döscher et al., 2022)
EC-Earth3-CC	Developed by: European research consortium. For Earth system research: Carbon Cycle *description* Configuration	The simulations are run with emissions forcing rather than just prescribed concentrations. With this configuration, a single carbon tracer in the atmosphere is used (Döscher et al., 2022).
EC–Earth3–Veg	Developed by: European research consortium. For Earth system research: Vegetation Configuration	This is a setup that uses the interactively connected *2nd generation dynamic* global vegetation model to expand EC-Earth3 (Döscher et al., 2022)
EC-Earth3-Veg-LR	Developed by: European research consortium. For Earth system research: Vegetation - Low Resolutions configuration	Low Resolutions configuration of EC–Earth3–Veg (Döscher et al., 2022)
FGOALS–g3	Flexible Global Ocean‐Atmosphere‐Land System Model: Grid‐Point Version 3-low-resolution	The experiments focus on the climate mean state, its variations and changes in the climate (Li et al., 2020)
FGOALS-f3-L	Flexible Global Ocean–Atmosphere–Land System Finite-Volume version 3	
FIO-ESM-2-0	*The* First Institute of Oceanography- Earth System Model -version 2.0	Aim at understanding changes in the climate system as well as forecasting future trends. This model version has fewer biases than previous models (Bao et al., 2020)
GFDL–ESM4	Geophysical Fluid Dynamics Laboratory- Earth System Model Version 4.1	The experiment involves a coupled carbon-chemistry-climate simulation. Emphasises how comprehensively Earth system interactions are understood (Dunne et al., 2020).
IITM-ESM	Indian Institute of Tropical Meteorology – Earth System Models	Experiments that look at long-term climate change and variability, particularly concerning the monsoon in South Asia (Krishnan et al., 2021)
INM–CM4–8	Institute for Numerical Mathematics - *model output* -4-8	Uses CMIP6 protocol forcings to have experiments that evaluate the concentration of greenhouse gases, anthropogenic aerosol emissions, volcanic aerosol concentrations, solar constant, and solar radiation distribution, based on observations made over the years (Volodin et al., 2018).
INM–CM5–0	Institute for Numerical Mathematics - *model output* -5-0	The climate model INM-CM5 is used to simulate changes in climate from 1850 to 2014. The model accurately captures some key historical climate events/periods. Further, the exact reproduction of global warming slowdown is a substantial advance over the previous version of the model (Volodin and Gritsun, 2018).
IPSL–CM6A–LR	Developed by: *Institut Pierre-Simon Laplace* (IPSL) for CMIP6	The experiments are for the unpredictability of the natural climate and how it responds to the forcings of both natural and anthropogenic types. The interest is in the depiction of the physical climate as well as the key elements of the global carbon cycle (Boucher et al., 2020).
KACE-1-0-G	Korea Meteorological Administration - Advanced Community Earth-System	The model relies on the coupled Earth System Model's component parts, which accurately depict biogeochemical processes (Lee et al., 2020).

	model	
MIROC6	Model for Interdisciplinary Research on Climate - 6	Future climate projections and seasonal to decadal climate predictions are part of the MIROC6 experiments. The climate sensitivity, internal climate variability, and simulated mean climate are assessed (Tatebe et al., 2019).
MIROC–ES2L	Model for Interdisciplinary Research on Climate - Earth System version 2 for Long-term Simulations	An Earth system model (ESM) that incorporates several biogeochemical cycles for the ocean and carbon-nitrogen cycles for the land. It is for projecting future climate change among ESMs in the CMIP6, having good performance in reproducing historical climate and biogeochemical changes (Hajima et al., 2020)
MPI–ESM–1–2–HR	Max Planck Institute for Meteorology Earth System Model – High-Resolution	There is an assessment of the relationship between the representation of vertical mixing in the ocean and the climatic mean states of the ocean and atmosphere when the horizontal model resolution of the Max Planck Institute Earth System Model (MPI-ESM 1.2) is increased. The experiments offer climate simulations at several horizontal resolutions higher than the CMIP6 (Gutjahr et al., 2019)
MPI–ESM–1–2–LR	Max Planck Institute for Meteorology Earth System Model – Low-Resolution	Earlier version and Lower resolution than the MPI–ESM–1–2–HR
MRI–ESM2–0	Meteorological Research Institute - Earth System Model version 2.0	The model has made significant improvements on its precursor; improvement of the atmospheric, oceanic, and chemical models' vertical resolution. Among other things, a focus on enhancing aerosol and cloud processes has been made (Yukimoto et al., 2019).
NESM3	Nanjing University of Information Science and Technology (NUIST) Earth System Model version 3	The focus is on making sub-seasonal-to-seasonal predictions, estimating future changes in Earth's climate and environment, and offering a numerical modelling framework for interdisciplinary Earth system experiments (Cao et al., 2018).
NorESM2–LM	*Coupled* Norwegian Earth System Model- Second version -Low-Resolution (LM)	The model's capacity to replicate the historical climate under the CMIP6 forcings is evaluated, as is the stability of the pre-industrial climate and its sensitivity to an abrupt and gradual quadrupling of CO2 (Seland et al., 2020).
NorESM2–MM	*Coupled* Norwegian Earth System Model- Second version -Medium-Resolution (MM)	
TaiESM1	Taiwan Earth System Model	Some of the key simulation contributions of the model include the portrayal of how rainfall systems begin, the representation of how "clouds covers shade", how aerosols form and disperse, and how "topography reflects sunlight" (Wang et al., 2021).
UKESM1–0–LL	U.K. Earth System Model – First Version	Models the interaction of land, ocean and atmosphere processes, assessing biogeochemical cycles (Sellar et al., 2019).

10.3.1 Adapted from Lim Kam Sian et al. (2021)

10.4 APPENDIX D

Table A.2: CORDEX - 21-member ensemble multi-model experiments

No	RCM-GCM Simulation Downscales	Institution
1	DMI-HIRHAM5.v2-ICHEC-EC-EARTH.r3i1p1	Danish Meteorological Institute
2	UQAM-CRCM5.v1-CCCma-CanESM2.r1i1p1	Universite du Quebec a Montreal (UQAM)
3	UQAM-CRCM5.v1-MPI-M-MPI-ESM-LR.r1i1p1	Universite du Quebec a Montreal (UQAM)
4	SMHI-RCA4.v1-CCCma-CanESM2.r1i1p1	Swedish Meteorological and Hydrological Institute (SMHI)
5	SMHI-RCA4.v1-MIROC-MIROC5.r1i1p1	Swedish Meteorological and Hydrological Institute (SMHI)
6	SMHI-RCA4.v1-MPI-M-MPI-ESM-LR.r1i1p1	Swedish Meteorological and Hydrological Institute (SMHI)
7	SMHI-RCA4.v1-CSIRO-QCCCE-CSIRO-Mk3-6-0.r1i1p1	Swedish Meteorological and Hydrological Institute (SMHI)
8	SMHI-RCA4.v1-NOAA-GFDL-GFDL-ESM2M.r1i1p1	Swedish Meteorological and Hydrological Institute (SMHI)
9	SMHI-RCA4.v1-MOHC-HadGEM2-ES.r1i1p1	Swedish Meteorological and Hydrological Institute (SMHI)
10	SMHI-RCA4.v1-ICHEC-EC-EARTH.r12i1p1	Swedish Meteorological and Hydrological Institute (SMHI)
11	SMHI-RCA4.v1-CNRM-CERFACS-CNRM-CM5.r1i1p1	Swedish Meteorological and Hydrological Institute (SMHI)
12	SMHI-RCA4.v1-IPSL-IPSL-CM5A-MR.r1i1p1	Swedish Meteorological and Hydrological Institute (SMHI)
13	SMHI-RCA4.v1-NCC-NorESM1-M.r1i1p1	Swedish Meteorological and Hydrological Institute (SMHI)
14	CLMcom-CCLM4-8-17.v1-MPI-M-MPI-ESM-LR.r1i1p1	Climate Limited-area Modelling Community (CLMcom)
15	CLMcom-CCLM4-8-17.v1-MOHC-HadGEM2-ES.r1i1p1	Climate Limited-area Modelling Community (CLMcom)
16	CLMcom-CCLM4-8-17.v1-ICHEC-EC-EARTH.r12i1p1	Climate Limited-area Modelling Community (CLMcom)
17	CLMcom-CCLM4-8-17.v1-CNRM-CERFACS-CNRM-CM5.r1i1p1	Climate Limited-area Modelling Community (CLMcom)
18	MPI-CSC-REMO2009.v1-MPI-M-MPI-ESM-LR.r1i1p1	Climate Service Center Germany (GERICS)
19	MPI-CSC-REMO2009.v1-ICHEC-EC-EARTH.r12i1p1	Climate Service Center Germany (GERICS)
20	KNMI-RACMO22T.v1-ICHEC-EC-EARTH.r1i1p1	Royal Netherlands Meteorological Institute (KNMI)
21	KNMI-RACMO22T.v2-MOHC-HadGEM2-ES.r1i1p1	Royal Netherlands Meteorological Institute (KNMI)

10.5 APPENDIX E - Change Factors

For projections of monthly averages, covering the 30 years, months can be expected to show negative, positive or zero Percentage Change (%). This would mean that relative to the reference period - baseline, some months could experience a decrease in rainfall, others an increase, while others experience no change.

The MME projections vary largely between negative and positive; 50% change factors (Figures AE.1 & AE.2). Considering the rainfall change (Relative Change), the ensemble multi-models show no clear direction of change. This is to say that both drier and wetter future conditions are possible when using the SSP-245 scenario for the near and far future. Additionally, the CORDEX RCP4.5 MME (Figure AE.2) projections also show no clear direction in rainfall for the near and far future periods relative to the baseline period. However, it can be noted, for CMIP6 MME, that roughly 50% of models show an increase in rainfall for the future, relative to the baseline, during the wet months, December, January and February noticeably (Figure AE.11). Interestingly, a significant percentage of CORDEX models show an increase in rainfall for the dry season (Figure AE.2).

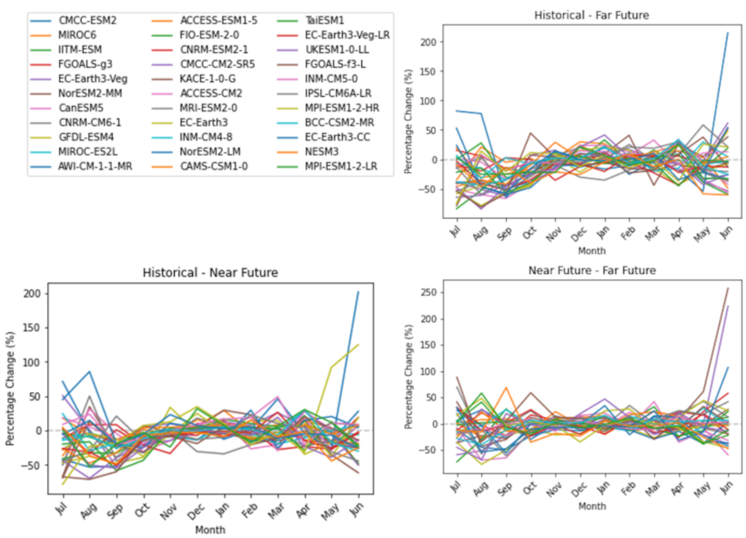


Figure AE.1: Notwane area rainfall changes simulated by CMIP6 MME

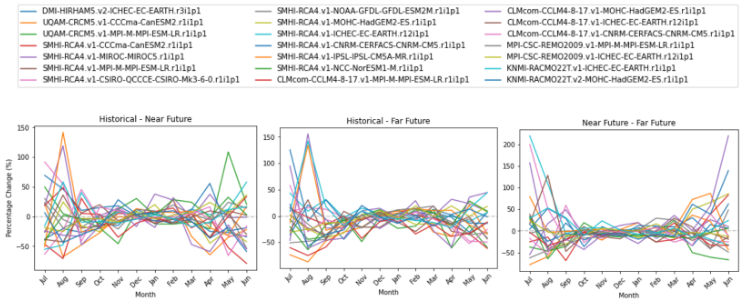
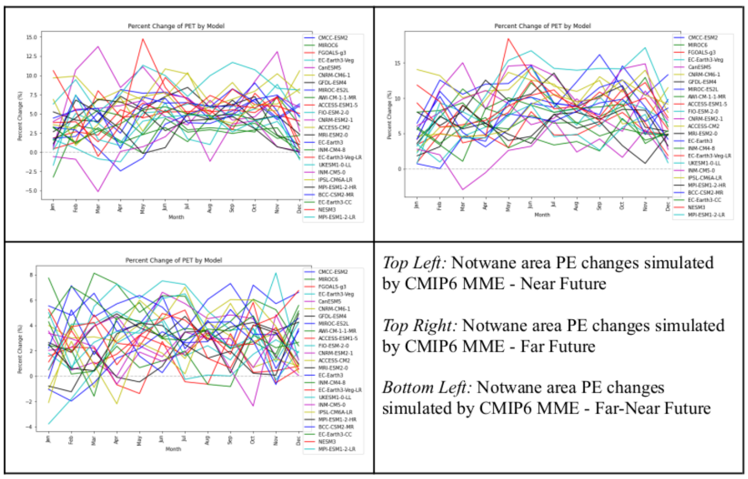


Figure AE.2: Notwane area rainfall changes simulated by CORDEX MME



Top Left: Notwane area PE changes simulated by CMIP6 MME - Near Future

Top Right: Notwane area PE changes simulated by CMIP6 MME - Far Future

Bottom Left: Notwane area PE changes simulated by CMIP6 MME - Far-Near Future

Figure AE.3: Notwane area PE changes simulated by CMIP6 MME - Future

Figure AE.3 illustrates changes in PE calculated from model air temperature data using the Hargreaves approach. Most models show a general increase in PE for the future period of no more than 15% (Figure AE.3). With the projected increase in temperature, this is to be expected. The CMIP6 projected temperature-based PE calculations (Hargreaves Method) show that there is to be an increase in PE in the coming decades relative to the baseline period. Due to the CORDEX temperature data being generally lower than the CMIP6, the calculated PE is expected to be lower than that of the CMIP6 models. As with the near future period, the CMIP6 MME generally shows an increase in PE for the far future period.

10.6 APPENDIX F

Table A.3: Available Greater Gaborone Water Demand in cubic meters

Greater Gaborone Area	Monthly Demand (m^3)	Annual Demand (m^3)
Gaborone	3,296,394	39,556,727
Tlokweng	222,939	2,675,268
Mogoditshane	446,871	5,362,448
Kumakwane	13,194	158,329
Mmopane	51,737	620,838
Metsimotlhabe	24,082	288,984
Gakuto	25,968	311,616
Mmatseta	13,652	163,824
Gabane	96,546	1,158,550
Mokolodi Village	8,838	106,056
Tloaneng	8,795	105,540
Ramotswa	255,467	3,065,601
Taung & Boatle	5,116	61,388
Police College	13,460	161,520
Otse	42,823	513,878
Mogobane	3,555	42,662
TOTAL	**4,529,437**	**54,353,229**

Source: WUC (2024)

The 5-station data (Lobatse, Otse, Ramotswa, Gaborone and Mochudi) had stations with significantly limited data that required a lot of gap filling. In any case, simulations using the average catchment rainfall were correlated at $r = 0.64$ and RMSE of 31.3.

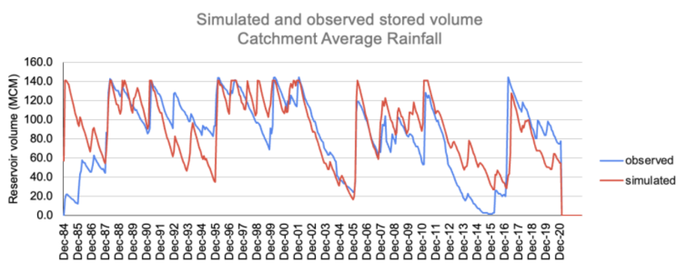


Figure AF.1: Calculated and Observed Reservoir volumes for Gaborone Dam - Gaborone Dam catchment mean rainfall

10.7 APPENDIX G - CHIRPS as an alternative data source

Rainfall data from CHIRPS v2.0 (Climate Hazards Group InfraRed Precipitation with Station) offers precipitation data that are blended gauge-satellite precipitation estimates, i.e. based on satellite observations that are adjusted so that they fit available observations. CHIRPS provide a continuous record of rainfall spanning January 1981 to the present (data till October 2022 are used here) for most parts of the world (Funk et al., 2015). It has a resolution of 0.05° by 0.05° (Funk et al., 2015).

Gridded rainfall data were obtained from the Climate System Analysis Group (CSAG) archive of the University of Cape Town.

The suitability of the gridded dataset in the region and in Botswana has been evaluated in numerous earlier studies (e.g. Kibii and Du Plessis, 2023; Gwatida et al., 2023; Pitman and Bailey, 2021 for CHIRPS rainfall). The outcome of the evaluation is that, generally, CHIRPS performed well as a substitute for station data. Where CHIRPS is overestimated or underestimated, it is within acceptable values compared to station data for the region.

To assess the suitability of CHIRPS data, a visual inspection of time series figures was carried out and the following accuracy statistics were calculated:

1. Pearson correlation coefficient (*r*)
2. Mean Absolute Error (MAE)
3. Root-Mean-Square Error (RMSE).

10.7.1 Gridded Historical Rainfall (P) for the Study Area

To compensate for the limited observed station rainfall data and poor data quality, comparisons of observed station data and gridded historical data were analysed on a monthly and annual basis.

10.7.1.1 CHIRPS validation results

Whereas there are other stations in the Gaborone Dam catchment, i.e., Ramotswa and Otse stations, there are significant gaps in their measurements as opposed to the Gaborone Station (Table A.4). It is for this reason that CHIRPS' accuracy validation was based primarily on Gaborone's historical rainfall from January 1981 - June 2021.

Table A.4: Details of in-situ Rain Gauges of key relevance to the study area

Rainfall Gauge	Location	Latitude	Longitude	Elevation	M.A.P.[i]	Missing	Years
Meteorology Headquarters	Gaborone	24° 40′ S	25° 55′ E	983 Metres	479 mm	0.4%	1981 - 2021
SSKA	Gaborone	24° 42′ S	25° 55′ 12′′ E	975 Metres	466 mm	*	1985 - 2021
Mochudi Police Station	Mochudi	24° 23′ S	26° 8′ E	945 Metres	424 mm	0.4%	1981 - 2021
Ramotswa Police Station	Ramotswa	24° 52′ 48′′ S	25° 52′ 12′′ E	–	520 mm	1.0%	1986 - 2021
Lobatse Police Station	Lobatse	25° 15′ S	25° 39′ E	1192 Metres	464 mm	*	1981 - 2021
Moeding College	Otse	25° 1′ 12′′ S	25° 43′ 48′′ E	1103 Metres	554 mm	4.4%	2001 - 2019

i. *M.A.P: Mean Annual Precipitation (mm/year)*
* *No missing data – the possibility of gaps filled or excellent recording*

For the meteorological years (July to June) of 1981/82 to 2020/21 for the study area's stations, the in-situ rain gauge details are detailed (Table A.4). This is the location of the gauges, the elevation of the station, the mean annual rainfall of the place and the percentage of missing measurements for the period data was available.

For CHIRPS' accuracy assessment compared to the study area's monthly station historical rainfall, CHIRPS was found to reasonably well represent the in-situ rain gauges' rainfall (Table A.5). The best performing were the two Gaborone stations and the Lobatse station. The other three, Ramotswa, Otse and Mochudi, were relatively less accurately represented by CHIRPS, but the agreement was still acceptable.

Table A.5: CHIRPS' Accuracy Validation for the study area

Rainfall Gauge	ES [ii]	Years	Correlation (*r*)	MAE	RMSE	Range (mm/month)
Meteorology Headquarters	484	1981 - 2021	0.85	16.27	28.34	0 – 280
SSKA (Gaborone)	438	1985 - 2021	0.84	16.29	27.50	0 – 285
Mochudi Police Station	484	1981 - 2021	0.62	24.19	41.73	0 – 327
Ramotswa Police Station	417	1986 - 2021	0.55	28.42	67.82	0 – 697
Lobatse Police Station	486	1981 - 2021	0.84	16.31	28.61	0 – 389
Moeding College	204	2001 - 2019	0.74	23.76	48.55	0 – 437

ii. *ES: Effective sample (the original sample, monthly entries, minus the missing measurements)*

Since CHIRPS reasonably represents observational rainfall of the in-situ rain gauges closest to the Gaborone Dam, i.e., SSKA and Meteorology Headquarters stations, CHIRPS would serve as a suitable alternative to station data. However, this study's models performed better with Gaborone rainfall than with CHIRPS, therefore making Gaborone rainfall station data suitable, especially since it has few gaps.

11 Glossary - Water Management

This is a glossary of key water management terms for the Gaborone Dam and GGWSS, as used in this thesis.

Term	Explanation
Abstraction	Water withdrawal from the dam. It corresponds to dam offtakes (Q_{use}) and the dam water supply
Allocated water/ Demand allocation	This is the maximum, safe yield, a dam can supply towards the end-user demand. It is essentially potential water supply from the dam formally assigned to users or sectors through legal, institutional, or policy frameworks
Critical Level/volume	Dam level/volume at which production/abstraction is compromised due to very low dam volumes
Dead storage	The dam's volume that is inaccessible; cannot be abstracted
Delivery supply / Actual supply	The volume of water physically delivered to users, accounting for system constraints and losses
Residual Dam Storage Capacity	The quantity of water a dam can still store after a specific amount of operation, accounting for things like sediment buildup.
Safe yield	The reliable withdrawal/abstraction rate that can be achieved from the dam without compromising dam operations
Supply Zone	An area supplied by water from the Waterworks
Unconstrained demand	The total water demand that would be required by users if there were no limitations on water availability
Unmet demand	The portion of the total water demand that cannot be fulfilled due to supply limitations
Water demand	The volume of water required or requested by users (e.g. agriculture, domestic, mining) over a given period

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