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Surface water demand and supply of Gaborone city and surrounding areas under climate change and population growth

MSc thesis Submitted to the Faculty of Science in Partial Fulfilment of the
Requirements for the Award of the Degree of Master of Science in
Environmental Science of BIUST

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Declaration

I, the below mentioned, declare that the dissertation hereby submitted by me for the degree of Master of Science (Environmental Science) at the Botswana International University of Science and Technology, Palapye, Botswana is my own independent work and has not been submitted by me to another University and/or Faculty in order to obtain a degree.

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Certification

I, the undersigned certify that I have read and hereby recommend for acceptance by the Faculty of Science a thesis titled: "*Surface water demand and supply of Gaborone city and surrounding areas under climate change and population growth*" in fulfilment of the requirements for the degree of Master of Science in Environmental Science in BIUST.

______________________________ Date___02/06/2021____________

Professor. Dr. Gizaw Mengistu Tsidu (Supervisor)

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May the grace of the Almighty God be with you.

Abstract

The adequate supply of the ever-increasing demand of fresh water continues to be a global challenge due to increase in population. The anticipation for better lifestyles and improved water supply has resulted in an increase in migration from rural settlements leading to an increase in the populations of many cities globally. This study therefore investigates the variability and trends in the surface water demand and supply of the city of Gaborone and surrounding areas in response to anticipated population growth and climate change using the Water Evaluation and Planning (WEAP) model for future periods. The model was run with the current accounts and reference period set at 2014 and 2015-2100 respectively to predict their possible impacts on the water balance and allocation of the region due to varied water demands. Moreover, the study includes analysis of population trends, water production and consumption rates, hydrological information as well as projected rainfall over the catchment supplying water to Gaborone Dam. The rainfall data over the catchment, simulated in the frame work of Coupled Model Intercomparison Project Phase 5 (CMIP5) by Max Planck Institute Earth System Model Mixed Resolution (MPI-ESM-MR) for scenario periods, are statistically downscaled using the high resolution Worldclim data to spatial resolution of 1 km^2 and bias corrected against Global Climatology Precipitation Center (GPCC) precipitation. The downscaled rainfall data are then employed in WEAP model and climate trend analysis. The stream flow of Notwane River has decreased from 0.65 MCM in 2006 to 0.53 MCM in 2016. The change is consistent with decrease in rainfall in the area. The WEAP simulated flow of Notwane River station with the observed flow gives an EF (Coefficient of Efficiency) of 0.91 which is a good correlation. The analysis shows that the projected population of Gaborone, Mogoditshane and Tlokweng using the high population growth rate of 3.4% will be about 4106670, 1029877, and 644092 by the year 2100 respectively. Under both RCP (Representative Concentration Pathway) 4.5 and RCP8.5 scenarios, the reservoir inflow indicates that the level of reservoirs at Foresthill, Diremogolo, Gabane hill, Oodi hill and Mabutswe will be reduced during 2080-2098 period. The unmet water demand of the whole study area will be 88.04 MCM (Million Cubic Meters) in 2050 as compared to 3666 MCM in 2100 under RCP 8.5 climate and high population growth scenarios. However, the unmet demand under RCP 4.5 climate and high population growth scenarios will be 84.65 MCM in 2050 as compared to 3569 in 2100. The climate under RCP 8.5 emission scenario will be drier than that of the RCP4.5. On the other hand, the unmet water demand will be 25.9 MCM in 2050 as compared to 355 MCM in 2100 under the RCP4.5 climate with low population growth rate of 2.2% scenario. In contrast, the unmet demand is as high as 26.8 MCM in 2050 and 373 MCM in 2100 under the RCP 8.5 climate with low population growth rate. The unmet water demand in both high and low population growth and the dry climate of RCP8.5 climate scenario will lead to shortage of water in the city. These changes in water supply and demand of the city under various scenarios show that there is a need for various forms of water loss control interventions. For example, if the current 39% loss through leakage is reduced to 0% by 2100, the unmet water demand will reduce from 3569 to 422 MCM under RCP4.5 climate change scenario. Similarly for the RCP 8.5 climate change scenario, the unmet water demand will reduce from 3666 MCM to 436 MCM. These estimates show that mitigation of impact of climate change on water resources is possible but needs aggressive and robust interventions.

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List of acronyms and abbreviations

DMS Department of Meteorological Services

DWUC Department of Water Utilities Corporation

EF Coefficient of Efficiency

EWR Ecological Water Requirements

FAO Food and Agricultural Organisation

GCM Global Circulation Model

GDP Gross Domestic Product

GMC Gaborone water Management Centre

IPCC Intergovernmental Panel on Climate Change

IWRM Integrated Water Resources Management

MCM Million Cubic Meters

ME Mean Error

MCP Marginal Cost Pricing

MSE Mean Square Error

NSC North South Carrier

RCP Representative Concentration Pathway

SADC Southern African Development Community

SWMM Storm Water Management Model

SWAT Soil and Water Assessment Tool

SWRRB Simulator for Water Resources in Rural Basins

UN United Nations

UNDP United Nations Development Policy

UNFCCC United Nations Framework Convention on Climate Change

USEPA United States Environmental Protection Agency

WEAP Water Evaluation And Planning Model

WWTP Waste Water Treatment Plant

Nomenclature

B_r Bottom level branch

Ds Demand site

K_c Crop coefficient

LAI Leaf Area Index

mm millimetres

PET Potential Evapo Transpiration

Rrf Runoff resistance factor

S_R : Total amount of release from reservoir storage.

S_C : Conservation storage

S_F : Flood storage

S_b : Buffer storage

CHAPTER 1: Introduction

1.1 Background

Water is a multipurpose resource on which people rely for various benefits such as drinking water, manufacturing, development of wealth, employment, good health as well as leisure opportunities (Bjornlund et al., 2013). It thus contributes a critical portion in driving the economy of many countries worldwide. However, supply of water to highly populated centres such as urban areas is challenging despite the fact that three quarters of the Earth's surface is covered by water (Mullen, 2012).
A number of studies have concluded that rapid population increase, hydrological conditions, urban rural migration, increased water consumption per capita, water pollution, excessive water extraction and the change of climate are major factors that control availability of water globally (e.g., Bell, 2013; Kujinga et al., 2014). Urbanisation in semi-arid regions is escalating rapidly and putting added pressure on the water system and its management (Grimm et al., 2008). The urbanization process has impacted local water through altering hydrological regimes such as river and ground water regimes (Wakode et al., 2018). For example, flooding could lead to increased soil sealing whereas increased water consumption and pollution lead to water shortages.

Climate change caused by human beings is anticipated to affect the amount and water quality supplies and that needs improvements in the management of the water resource (Roy et al., 2010). Human activities now have a huge contribution in modifying the quality and amount of stream water mainly in various ways. That is, anthropogenic activities are modifying water-shed characteristics linked to the biogeochemical processes operating in the watershed (Ayivi and Jha, 2018). As a result, integrated management and satisfactory distribution of water resources among various consumers are major challenges considering the ever changing land use and climate conditions. (Simonovic, 2002).

Hundred (100) million people in the Southern African Development Community (SADC) region do not have access to potable water (Kujinga et al., 2014). Furthermore, the UN predicts that by the year, 2025 almost one third of the world’s population will experience severe water shortages with the present utilisation levels (Kujinga et al., 2014). Therefore the impact of human activities and climatic conditions on the quality of surface water and stream hydrology needs to be investigated. This can be tackled by increasing the number of field explorations as well as use of hydrologic models (Haverkamp et al., 2005). In particular, effective Integrated Water Resource Management (IWRM) models are needed to address complicated problems in the successful planning and management of water resources. IWRM models should be designed such that they provide proper tools for water managers. Moreover, the models should provide inputs for development of policy instruments that can be used in water supply and demand management so as to acquire fair usage of water, environmental protection as well as determining fair allocation in water resources that are shared (Van Loon and Droogers, 2006). The Water Evaluation and Planning System version 21 (WEAP21) is amongst many of the IWRM models utilised in various river basins with the tools that link supply and demand site requirements (Ayivi and Jha, 2018).

WEAP is a model that is based on water balance which requires hydrological, climate, water supply and water demand data for the assessment of the available water resources together with their exploitation in a given watershed (Dimova et al., 2014). Since WEAP couples watershed hydrology with the water planning process, population increase effects, economic developments and changes in climate on the water balance can be suitably assessed. For example, Arsiso et al. (2017) utilised WEAP to evaluate the effects of climate change and population increase on the supply and demand of surface water in Addis Ababa, Ethiopia. This kind of modelling exercise is important in places like southern African savannas where the climate controls the availability of water through degree of persistence of high temperature and its link to evaporation levels thereby dictating the extent for the amount of growth and development in the region (Pallet et al., 1997). However, difficulties in obtaining enough model input data are the major constraints of research in the water sector. In Africa, shortage of skilled manpower and research funding are additional barriers to conduct such water resource assessments.

As a result, the water policy brief by the United Nations Development Policy (UNDP) are being made to bridge these gaps created by lack of skilled manpower and limitations in availability of observational data in developing countries. In addition, institutions mandated with provision of water to the community releases water accounting reports annually as a way of tracking the water demand and supply patterns in various water management centres. For example in Botswana, Water and Climate Digest issued by the Botswana Environment Statistics is a report which is produced on a quarterly basis with the aim of providing data needed in water management and monitoring of climate trends.

However, such information is inadequate for water planning and management of major urban centres such as Gaborone which has experienced rapid growth in the Southern Africa regions. Moreover, the city is located in semi-arid part of Southern Africa under the influence of the erratic rainfall and limited surface water resources (Botswana Environmental Statistics Water Climate Digest, 2014).

1.2 Problem statement

The prolonged surface water stress experienced in Botswana as a whole has been one of the most critical issues facing the Botswana government. The proximity of the country to the southern hemisphere's subtropical high-pressure belt makes up its largely arid or semi-arid climate regime (Botswana Enviromental Statistics report, 2006).

Gaborone as an urban area is also prone to facing such problems due to its rapidly increasing population which eventually over flows to its neighbouring villages. In 2001 the Gaborone Water Management Centre (GMC) was home to over 261 000 people as compared to 361 379 people in 2014 which is a major challenge to the water supply system (Botswana Water Sector Policy Brief, 2012). Gaborone Dam and Mmamashia Water Works (which gets water from the Letsibogo and Dikgatlhong dams) are faced with periodical water shortages. The total capacity of Gaborone dam is 141 million cubic meter (MCM). However it witnessed a continuous drop in the volume of water over the years at a higher pace than other dams in Botswana. In 2014, the dam had the lowest levels of 12.8 % of its capacity which was quite insufficient to satisfy the water needs of the whole management centre. The Department of Water Utilities Corporation therefore freely imports water from Molatedi dam in South Africa during times of severe water scarcity as per agreement between the two countries in view of the dams in a shared watershed on the South African portion of the Notwane and Limpopo catchments (Botswana Enviromental Statistics Water Climate Digest, 2014).

This is a clear indication that the water supply and demand of Gaborone and its surrounding areas need to be analysed in order to come up with water allocation policies and guidelines for the current and future periods. The relationship between water use and water resources is vital for the implementation of the principles of water allocation. As a way of addressing this problem, this study focuses on finding out the effects of climate change and population increase on the supply and demand of surface water resources in Gaborone and its neighbouring villages. Therefore in this study, the WEAP hydrological model is applied to make this assessments. The two main elements in WEAP simulation experiment are the supply and demand. The demand component consists of projections based on population while the supply aspect consists of the hydrological evaluation of the Gaborone water management centre with the main supply components being the Gaborone Dam and Mmamashia Water Works. Upon accomplishment, the results of the study could be utilised for making decisions in water management, developing appropriate climate change mitigation measures, most importantly for raising awareness and educational purposes.

1.3 Rationale

This study is a case study on the current and future impacts of climate change and population increase on the supply and demand of surface water in Gaborone and surrounding areas. The aim of the study is to determine the potential extent of the future impact of the two factors on the availability of surface water and to recommend possible options of mitigation and adaptation in the water sectors.

1.4 Research objective

The general objective of this study is to investigate the surface water demand and supply prospects of the city of Gaborone and its neighbouring villages (Gaborone Management Centre) through the application of the WEAP model based on scenarios of population growth and climate change.

The specific objectives are to:

- Assess the population trends of Gaborone and surrounding areas and their effect on the demand of surface water.
- Investigate the future impacts of climate change on reservoir inflows and their impact on unmet water demand.
- Address possible solutions to the projected water supply deficits.

1.5 Scope of the study

The study was designed to establish the link between climate change and population increase and the supply and demand of surface water in Gaborone and surrounding areas.

1.6 Structure of the dissertation

The thesis is structured such that Chapter 1 covers introduction, Chapter 2 provides water resource, availability, water sector challenges in Botswana, and Chapter 3 gives overview of hydrological models used in water management; Chapter 4 deals with data and methodologies used in the study. Results and discussion are presented in Chapter 5 while summary and conclusions are given in Chapter 6 and finally recommendations are presented in Chapter 7.

CHAPTER 2. Water resource, availability and water sector challenges in Botswana

Water supplies in Botswana consist primarily of surface water (dams of various capacities, in rivers and pans) and underground water in aquifers. The country has eight dams and the largest of all dams is the Dikgatlhong dam with a capacity of 400MCM (Fig. 1). Botswana shares also river basins such as Zambezi, Okavango, Shashe-Limpopo and Orange-Senqu with neighbouring countries. However, Botswana's storage capacity has proven to be one of the lowest in the Southern region due to its flat terrain. The scarcity of water is attributed to various factors such as recurrent drought, high evaporation rates from dams that supply Botswana, low and unreliable rainfall, high costs of extraction of the current surface water supplies and rapid increase in human population (increased demands) (Botswana Water Sector Policy Brief, 2012). Botswana's access-to-drinking water was 99.5% in 2001 for the urban areas and 83.5 % in rural areas (Botswana Water Statistics, 2009). The majority of rural areas get borehole water while almost all the urban places are supplied with water from the dams. In this chapter, a review of surface water availability, water needs in various economic sectors, water supply, management and other challenges like climate change, population growth, and construction of water infrastructure is presented.

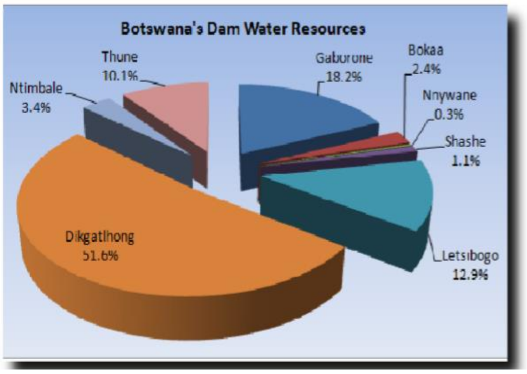


Figure 1. Dams available in Botswana and their percentage capacities (taken from Botswana Water Sector Policy Brief, 2012).

2.1 Water resource

Water is considered as a basic human need and the key driver of any economic growth; its sustainable use is very important (Majelantle, 2015). It is also essential for both agriculture and social developments and in attaining reliability and sustainability in production systems.

Botswana’s water resource is a shared and scarce resource with uneven spatiotemporal distribution (Du Plessis and Rowntree, 2003). The country has few surface water supplies primarily because of low rainfall, high evaporation rates and high seepage due to sandy soils. Surface water, residing mainly in dams, rivers, lakes and wetlands, depend mostly on atmospheric precipitation or rainfall. In Botswana, rainfall is erratic because of the arid to semi-arid climate conditions and influence of recurrent drought (Botswana Environmental Statistics report, 2016). Both of these conditions severely affect availability of surface water. As a result, most of the rivers, in Botswana (Fig. 2), flow during very wet to extremely wet seasons.

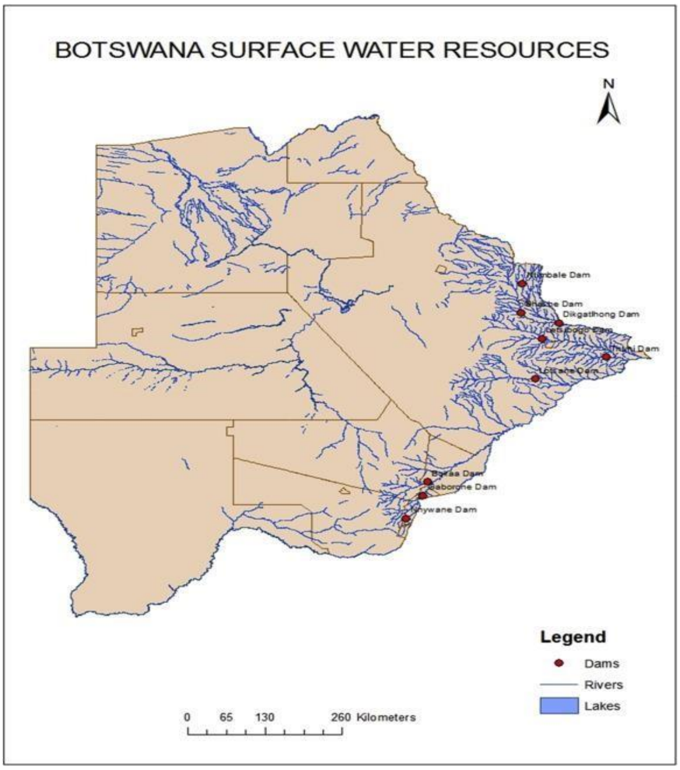


Figure 2. *Few surface water resources available in Botswana (taken from Setlhogile et al., 2017).*

Botswana’s surface water development is facing limitations due to a number of reasons which include its low and unpredictable rainfall, high evaporation levels and lack of available dam sites, (Du Plessis and Rowntree, 2003). Nevertheless most of the overall water supply in cities is from surface water (Kgathi, 1999). Table 1 shows the dams that provide water to Gaborone and surrounding areas.

Name of dam	Full supply Capacity in million cubic meters (MCM)
Gaborone	145
Dikgatlhong	400
Letsibogo	100
Molatedi	201

Table 1. Dams that supply the Gaborone management centre (taken from Botswana Environment Statistics: Water and Climate Digest, 2016).

2.2. Water availability and challenges

2.2.1. Changes in population and climate

Continued exposure of the biosphere to extreme events like drought, increased saltiness of soils, extremely high temperatures, oxidative stress and toxicity of chemicals induces imbalances to environment's natural state (Lisar et al., 2012). Increasing demands for water from the economic sectors and domestic users puts exuberant pressure on water supply. This can therefore cause a situation whereby the ecological water requirements (EWR) are no longer met and environmental degradation and loss of biodiversity occur (Botswana Integrated Water Resources Management & Water Efficiency Plan, 2013). For instance, water stress causes a reduction in water levels in the surface resources which decreases the levels of biodiversity; eliminates a number species fish species and therefore tempering with the natural inhabitants such as including birds, plants and other species. Therefore, water cannot simply be allocated to satisfy the basic increased demand from Agriculture, industry and other competitive sectors but must also fulfil aquatic environment requirements and the ecosystem (Levite et al., 2003).

Over 50% of the population of Southern Africa depends on the agricultural sector (FAO, 1989). The agricultural sector in Botswana accounts for 3 percent of the national GDP (Dube, 2003) but withdraws water for irrigation to unsustainable levels (Bjornlund et al., 2013). Water stress in plants leads to growth inhibition and reproductive failure (Lisar et al., 2012). This limited supply of water for irrigation and poor water quality decreases agricultural yields which in turn will cause changes in productivity and prices, changing the economic system, crop mix, production, food demand and consumption.

Botswana's economy is largely dependent on the mining sector. Access to water has proven to be one of the growing challenges in the mining sector. The use of open water-bodies such as rivers, lakes and dams for tourism will be adversely affected by lack of water (Botswana Water Sector Policy Brief, 2012).

Rapid population growth is a major challenge for resources such as land, water, flora and fauna upon which the basic needs of human beings depend. One of the main reasons for the rapidly increasing population in urban areas, is rural urban migration. That is, growth of towns in African countries has intensified in the recent decades, contributing to environmental problems of a different sort. In addition to the typical environmental issues that are often associated with poor health, there are also current problems caused by traffic and heavy industry (Jonsson, 2004). New developments in Gaborone city such as real estate housing, the growth of production and other service sectors have contributed towards pressure on water resources during the past decades. Increased developments are directly proportional to the rate of rural urban migration or population growth in cities. In most cases, the tendency to migrate is directly linked to the sought for improved life styles such as good water supply, education, improved health facilities and many others. The migration of people from rural to urban areas is therefore common in Botswana. However, these differences between rural and urban areas are not great enough in Africa context. For example, nearly 40 percent of the population have no access to adequate water supply and sanitation (Hutton et al., 2004).

According to population censuses, the population of Gaborone has rapidly increased to the extent that the population has even over flowed to the neighbouring sub cities such as Tlokweng, Mogoditshane, Gabane, Kumakwane, Metsimotlhabe and Mmopane. This study will therefore focus on the Gaborone Management Centre (MC) which includes Gaborone and these sub-cities. Table 2 shows the populations of the study areas from the past population censuses of 1991, 2001 and 2011.

Place	Population -1991	Population -2001	Population -2011
Gaborone	133,468	186,007	231,592
Tlokweng	12,512	21,133	36,323
Mogoditshane	14,246	32,843	58,079
Gabane	5,975	10,399	15,237
Kumakwane	-	3,139	5,545
Metsimotlhabe	-	4,056	8,884
Mmopane	-	3512	14655
Gakuto	-	89	1831
Mmatseta	-	201	513

Table 2. Population trends of the Gaborone Management centre from the last three population censuses (taken from Botswana Central Statistics Office, 2015).

Figure 3 shows the spatial variability of water consumption within the country. The differences in water consumption between the regions are quite significant and reveal the dependence of consumption on population density. At local level, it can be noted that highly populated towns and cities like Gaborone MC, Selibe-Phikwe MC, Francistown MC and Lobatse MC experience the highest consumption rates. Tsabong MC has the lowest consumption due to its arid nature. The difference in consumption is because the bulk of the population resides in the eastern part of Botswana. The Gaborone MC supplies the highest population amongst all MCs relying on various sources of water, including the Gaborone dam, Molatedi dam transfers and North-South Carrier transfers.

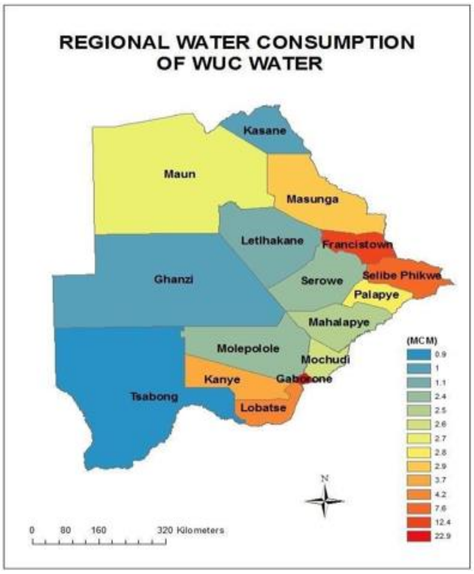


Figure 3. Water consumption by management centres (taken from Botswana Water Accounting Report for 2014/2015).

There are significant human impacts on the climate system and recent anthropogenic greenhouse gas emissions are highest in history. Emissions of greenhouse gas emissions have increased mostly due to economic and population growth and are now higher than ever (IPCC, 2014). Globally population and economic growth continue to be the primary driving forces of CO_2 emissions from fossil fuel combustions. For example, the Morupule coal fired power plant, located in Palapye, Botswana generates electricity for both domestic use and industry in Botswana. In addition to these anthropogenic sources, (Maikano, 2012) alludes that in Botswana, the fire season from July to September is the source of greenhouse gases. About 10% of wild fires are caused by natural processes such as lightning. However, the contribution of Botswana specifically and Africa in general to the overall burden of greenhouse gases is quite small as compared to developed nations where heavy industries consume huge energy generated from fossil fuels.

This emissions led to the development of different scenarios under the Special Report on Emission Scenarios (SRES) and Representative Concentration Pathways (RCPs). The fifth Assessment Report (ARS) of the IPCC has been developed using a new set of scenarios that replace the SRES (Wayne, 2014). Such pathways include RCP 4.5 and RCP 8.5. RCPs are trajectories based in greenhouse gas emissions, land use changes and aerosols developed for use by the climate modelling community as a uniform basis for the near term and long term experiments of climate modelling (Moss, 2010). RCP 4.5 consists of low to moderate future emissions while RCP 8.5 includes very high future emissions.

IPCC assessments based on some of the above scenarios show that climate change will cause more rainfall variability over Southern Africa's central-semi arid land mass, which mostly covers Botswana. UNFCCC (2007) report shows that runoff and water availability are expected to decrease over most of the dry tropics of which some are currently water stressed areas. As a result drought prone areas (like Botswana) and extreme precipitation prone areas may likely increase. The increased flood intensity or frequency of occurrence in some areas and increased occurrence of extreme droughts in other areas (e.g., see Fig. 4 for example) are manifestation of climate change, both of which severely affect the local and regional water resources (Bahri, 2012). These extreme events destroy the food security, lead to the extinction of some species and disturb farming. Floods among other things destroy the country's infrastructure, transport and human health which bring about economic set back to many countries. House-Peters (2011) has also shown that changing climatic conditions are projected to intensify the stresses on water supply systems as catchment water yields are likely to decrease in many areas of the world due to climate change. Some studies also show that changes in climate are going to accelerate the speed of the global hydrological cycle as well as rising global temperatures and shifts in precipitation patterns (Rochdane et al., 2012). Recent studies (e.g., Arsiso et al., 2017 and references therein), have shown that stream flow and the subsequent storage volume of reservoirs can be invariably influenced by the changes in rainfall intensity and frequency.

Figure 4. Gaborone dam in 2005(left) and 2015(right) (taken from Mmegi newspaper, 2015).

2.2.2 Limitations in infrastructure development and water management

One of the factors that influences water stress is the tremendous water losses experienced in Botswana. Most of this water is lost through pipe leakages and bursts (Fig. 4). Water leakage usually occurs in poor sections of transmission pipes, service pumps, fire hydrants and water reservoirs (Kholoma, 2011). Leakage causes include mechanical damage, incorrect backfill, and improper maintenance of valves, insufficient corrosion control, age and poor construction of pipes; most of which are linked to inadequate evaluation and management of these infrastructures (Arntzen, 2006). Therefore, conservation of water should begin with regulation of the water loses through proper maintenance of these infrastructure (Lambert and Mackenzie, 2002).

Figure 5. *Water leakages on a chlorination plant located in Foresthill (Kgale) (left) and losses through water pipes located at Diremogolo reservoir, Gabane (right).*

There are less dam development sites in Botswana mainly due to its flat terrain. The high cost of dam developments is also one of the major limitations in the water sector. On average, the cost of constructing a 30 million cubic meters reservoir is approximately 3.5 million BWP, which is quite expensive (Maforaga, 2019). Which could slow construction of reservoirs in many cities. Moreover, construction of dams could potentially displace a large population. Re-location efforts associated with the development of dams frequently leads to high population elsewhere, thus greater conflicts over acquiring land (Brown et al., 2008). This then leads to a prolonged decision making process of dam construction, which then leads to a prolonged period of less water supply.

The government could promote water saving through seasonal water price increment. Some users however, can use water beyond what they need since they can afford to pay high consumption tariffs. Tariffs are thus in some cases not suitable tools for water conservation. Water reticulation facilities must be routinely maintained to minimise water losses and unaccounted for water. Also, careful monitoring of water use via meter readings and keeping daily records to pick up gaps and demand trends are important means of water demand management. Re-use is another tool for water management. For example, water used for irrigation may be reused for more than one purposes. Therefore reuse has the ability to reduce the supply requirement. To curb the problem of deficiencies in water supply and the climate change effects on reservoirs storage volume, upgrading as well as increasing the capacity of reservoirs could be the best option. The more the capacity of reservoirs, the more the chances of storing more rainwater. Another tool in water management is education of citizens through civic society and schools about the importance and scarcity of water. This tool is vital as schools are largest consumers of water in Botswana and ironically water management is not properly practiced (Botswana Integrated Water Resources Management & Water Efficiency Plan, 2013). Therefore teaching children about the importance of saving water is of outmost importance as it shall help in reducing future water demands.

2.3 General water allocation principles and guidelines

The ever-increasing water demands for humanity, development of the economy and questions about environmental water demands exacerbate the necessity to distribute it properly. While objectives and strategies have changed overtime, in the end water resources allocation has basically remained as the process of deciding how much water is available for human consumption and how that water should be distributed between competing regions. However water allocation and planning has been affected by a number of challenges which include growth in water extractions, basin closures, lack of sites for development of water infrastructures and climate change (Speed et al., 2013).

Dinar et al., (1997) found out that there are four fundamental institutional strategies of water distribution namely; public distribution and water markets allocation, marginal cost pricing (MCP) and user based allocation. Public administrative allocation is commonly used in countries where water is seen as a public commodity and water authorities give licences to consumers looking at physical standards and political factors (Dinar et al., 1997). On the other hand, water markets consist of lucrative possible benefits which include distributing reliable water rights to consumers, offering opportunities for efficient use of water and earning additional income by selling stored water (Dinar et al., 1997). The MCP targets a price of water to equal the marginal cost of supplying the last unit of that water while user based allocations require collective action institutions with water rights decision making bodies.

The government of Botswana is currently using the water markets allocation principle. The department of Water Affairs via the water act allows for existing water rights to be suspended in the event of a water shortage or due to drought or where water is required for public purposes

(Rahm et al., 2006). The Act provides penalties for pollution and for altering and interfering with water flow as well as requirement to dispose waste water with minimal pollutants (Rahm et al., 2006). However such efforts are sometimes failing because people choose to pay for the penalties and continue with the same behaviour they are being penalised for.

CHAPTER 3. Hydrological models for water management

Water resource models are vital to make knowledge-based decisions on water availability, ecological restoration and water management in diverse regional systems (Loucks, 2008). Computer based decision support systems based on water resource models are valuable tools for water resource management since they enable the user to predict and analyse the effects of various potential upcoming developments and management strategies prior to full implementation (Ayele, 2016).

The following sections give a brief description of several models that are used to analyse the water balance of various watersheds and utilised as tools that support decision making in the development and management of water resources.

3.1 Soil and Water Assessment Tool (SWAT)

SWAT is a model built from continuous modelling exercises in the Agricultural sector and other areas during the last 30 years (Singh, 2013). Due to its robustness, this method has acquired international recognition as a strong interdisciplinary tool for modelling watersheds. The model, a continuous-time, semi-distributed process based river basin model, was developed as part of the US Environmental Protection Agency (USEPA) and is being used by many institutions globally to determine the effects of alternative water resource management decisions. Moreover, it is used to simulate rainfall-runoff and the effects of land use and land management activities as well as climate change on the hydrology and water quality of watersheds.

Recently, Uniyal et al. (2015) utilised it to evaluate climate change impacts on the water balance of starved Upper Baitarani River Basin in Eastern India. The twelve independent climatic scenarios considered in the study indicated a decrease in the surface runoff spanning a range of 2.5 to 11 % under a change of temperature from 1 to 5 °C, while the rise in rainfall by 2.5 to 15 % led to an increase of 6.67 to 43.42% in surface runoff above the baseline (Uniyal et al., 2015). The implications of this study is such that future climatic changes would most likely have notable impacts on the area’s stream flow.

Ayivi and Jha (2018) utilised SWAT in the Reedy Fork-Buffalo Creek Watershed in North Carolina to estimate its water balance and water yield as well as for assessing the performance of the model in capturing the observed monthly stream flow using statistical model performance parameters such as the Nash–Sutcliffe Efficiency (NSE) and the coefficient of determination (R^2). SWAT performance was very good as confirmed by strong correlation, high NSE and R^2 exceeding 0.7 for the calibration and validation data (Ayivi and Jha, 2018). Further analysis of the impact of potential land use changes on runoff and water reveals interesting results implying the importance of the SWAT model as a decision support tool for water balance and water yields for sustainable water resource management in watersheds.

Narsimlu et al. (2013) also carried out a study to assess the potential impacts of climate change on Upper Sind River Basin's water resources using the SWAT model driven by meteorological parameters obtained from PRECIS (Providing Regional Climates for Impact Studies) model under IPCC A1B emission scenarios for future period. The observed monthly stream flows and simulated flows were also in good agreement as determined by several statistical performance measures. Moreover, the model yields interesting results under A1B emission scenarios. For example, the average annual streamflow for the mid-century could rise by 16.4 % and a substantial rise of 93.5 % by the end century. The findings also indicate that potential increase streamflow during monsoon season in contrast decrease in non-monsoon period due to climate change under A1B scenarios.

However, SWAT has some limitations. It is difficult to manage and modify when there are hundreds of input files because the watershed is so large and divided into hundreds of hydrologic response units (Gao and Li, 2014). The model does not simulate detailed events based on flood and sediment routing. Also, during spring and winter months, it has difficulties in modelling flood plain erosion and snowmelt erosion (Hamlett and Peterson, 1998).

3.2 Simulator for Water Resources in Rural Basins (SWRRB) model

The SWRRB model was designed to simulate hydrological processes in rural basins (Williams et al., 1985). The model is customized such that the effects of management options on water and sediment yields can be simulated with fairly good accuracy for ungauged rural basins. Arnold et al. (1987) utilised the SWRRB to model the impacts of urbanisation on basin water yield and reservoir sedimentation of the white rock lake.

Williams et al. (1985) has tested the model several big watersheds and the author has shown that the model is quite dependable as it accurately simulated water and sediments under a wide variety of soil conditions, climatic conditions, land use, topography and land management practices.

Ghanbarpour et al. (2012) used the SWRRB model to simulate stream flows in northern Iran's Kasilian watershed. The results show that corelation between the observed and simulated monthly and annual stream flows is generally adequate in the calibration period. It was also noted from the analysis that model simulated the stream flow more accurately in the dry seasons than in times of rainy and high flow rate periods.

Though, the SWRRB model is capabale of modelling large and complex watersheds, its main limitation is that it is incapable of simulating instream processes when the input and output files are massive (Adu and Kumarasamy, 2017).

3.3 Storm Water Management Model (SWMM)

SWMM is a detailed statistical model that simulates urban runoff in storm and mixed sewer systems (Huber et al., 1992). The model can simulate all aspects of the urban hydrologic cycles including surface runoff, transportation through the drainage network, storage and treatment.

Campbell and Sullivan (2002) used SWMM to simulate flow and changes in water level for a portion of the Stephens Gap Cave in Jackson County, Alabama. The simulation was aimed at estimating losses from a surface stream into the cave. According to SWMM, the calculated losses to Stephens Gap Cave varied as h1.8 (Campbell and Sullivan, 2002). Such depth dependency is mostly common of flowing over a weir than through a pipe. The losses measured by SWMM to Stephens Gap Cave did not display any hysteresis (Campbell and Sullivan, 2002). Simple models like CLG or weir flow model can hardly simulate loss curves with significant hysteresis. An SWMM model of a simple hypothetical cave indicated however that the storage in Stephens Gap Cave is way below that required for hysteresis.

Jun et al. (2010) used SWMM to predict the long-term stream discharge of the Gapcheon watershed in Korea in relation to the escalating rates of groundwater usage. The model runs were designed to find out the relationship between the long-term stream discharge and the changes in groundwater usage and to establish their future relationship. The annual runoff discharge is influenced by the annual rainfall in contrast to the annual base flow which is less influenced.

Just like other models, the SWMM has some limitations. The SWMM engine is slightly more unstable than other hydrological models (United States Environmental Protection Agency, 2015). Also, the SWMM cannot model manhole or inlet loss directly. That is, the model is not able to represent inlet or outlet losses as true point losses. Lastly, the model is an analytical tool and not a design tool (United States Environmental Protection Agency, 2015).

3.4 Water Evaluation and Planning (WEAP) model

WEAP is a water resource planning model that provides a robust framework for water balance scenario formulation, planning and policy analysis (Dimova, 2013). The model can be used in a wide range of systems from single watershed to large transboundary river basins. As a result, there are provisions for simulation of water system operations within a river network with simple water accounting principles on a custom-defined time step and computing water mass balance for every demand node and link in the system (Hamlat et al., 2013). In addition, WEAP can simulate a wide variety of natural and engineered components such as rainfall run-off, base flow and groundwater recharge, demand analysis, water saving, water allocation priorities, hydropower generation, reservoir operations, water quality and pollution, ecosystem needs and vulnerability evaluations (Ayele, 2016).

As a model used in policy analysis, it explores a wide variety of water supplies and conservation options under the presence of numerous and competing uses of water resources. Arsiso et al. (2017) employed WEAP to assess impacts of climate change and population growth on surface water supply and demand of Addis Ababa Ethiopia. The authors have shown that the population of Addis Ababa using high population growth rate of 3.3% will approximately be 7 million by the year 2039 under which the unmet water demand with the dry climate of RCP 4.5 scenario will be higher than RCP 8.5 scenario. The water conservation required to alleviate high levels of unmet water demands can be achieved through increases in water tariffs, improving the efficiency of house hold machines and water harvesting (Arsiso et al., 2017)

Mounir et al. (2011) utilised WEAP to evaluate future water demands of the Niger River. Under three scenarios the authors concluded that the unmet water demand can be experienced under the two scenarios of high growth rate of population and variable climate. Under these scenarios, proposed remediation to counteract the unmet water demand is construction of hydroelectric dam on the Niger River. The dam can regulate the flow of water and low water levels in the river and ensure reliable water supplies.

Hamlat et al. (2013) also used WEAP to simulate water resources in Western Algeria watersheds in order to assess the current balance and potential future scenarios under various operating policies and factors that may influence demand by 2030. The author concluded that demand management and the creation of living standards are the important procedures for proper management of the existing resources.

Despite the ease of use of the model and its user-friendly interfaces, its main limitations include its reliance on the development of scenarios that can be quantified, without notifying how these scenarios should be developed and placing the actors deliberately outside the system's architecture (Haddad et. al 2007). Also, data needs to be imported into the model, which can be quite handy.

CHAPTER 4. Data and Methodologies

This chapter describes the data and methodologies utilised in the study. Its main focus is the hydrological and demographic aspects of the catchment, meteorological data and population and climate scenarios developments.

4.1. Description of the study area

4.1.1 Geography

The city of Gaborone is located in the southern part of Botswana at 24^{o} 40′ S, 25 55′E, (Jonsson, 2004). It is known to be situated between Kgale and Oodi hills near the convergence of Notwane and Segoditshane rivers. Botswana’s terrain is mainly high plateau (table land) and so is Gaborone. Gaborone dam is the primary water supply source for the city and its surrounding areas. Gaborone dam is situated on the south side of the city and covers around 225 square kilometres. It is drained by Notwane River, Metsemaswaane River and others. At about 15 kilometres north of the city is the Mmamashia Water Works which welcomes water from the Dikgatlhong and Letsibogo dams through the north south carrier (NSC) pipes.

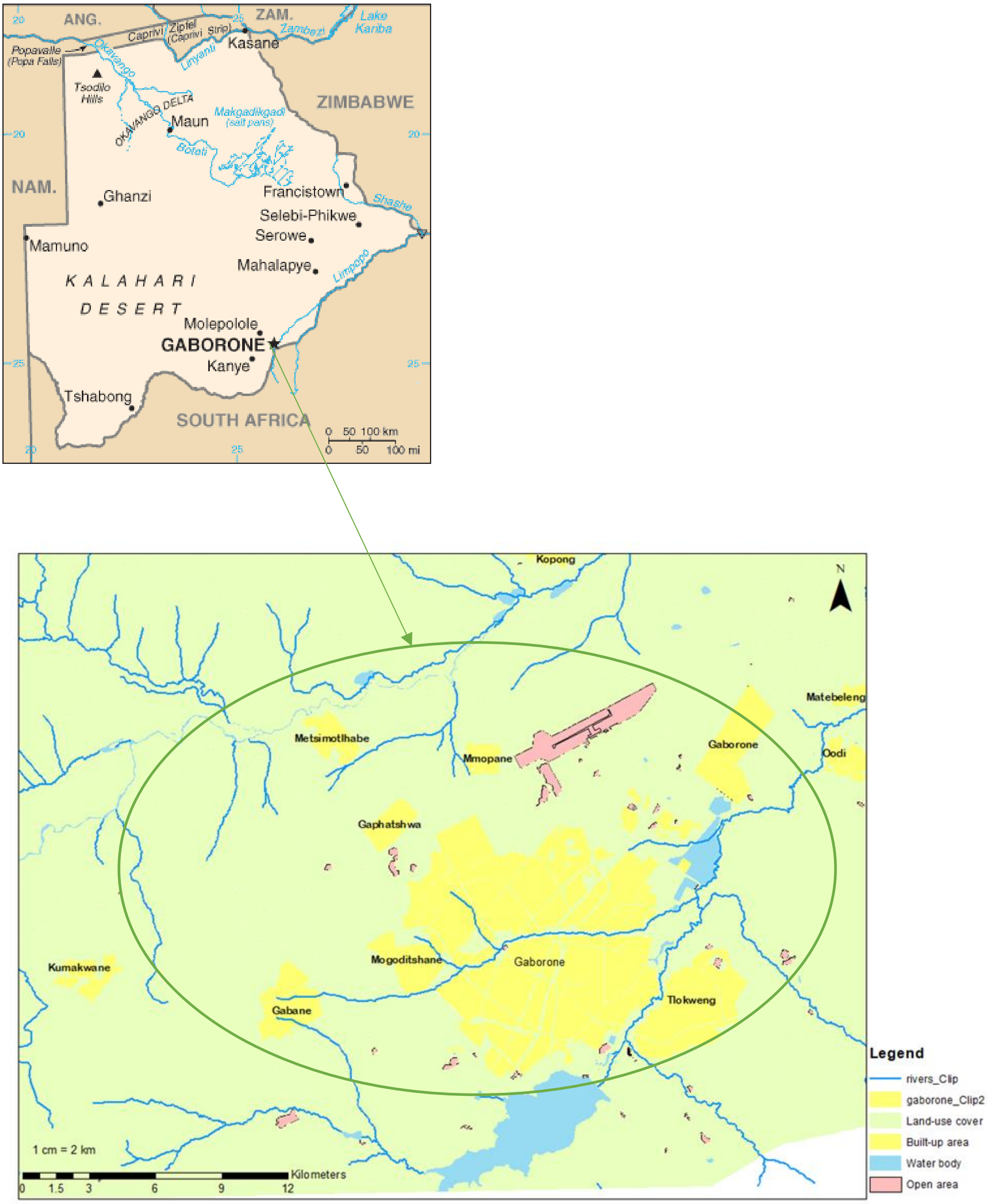


Figure 6. Hydrological map of the study area.

The study area includes places in the greater Gaborone such as Mogoditshane, Tlokweng, Gabane, Kumakwane, Gakuto, Metsimotlhabe, Gabane and Mmopane (Fig. 6).

4.1.2 Climate

Gaborone's climate and that of Botswana in general is of hot and semi-arid as per the Koppen Climate Classification. The climate is therefore dominated by the subtropical high pressure belt which creates dry winters with a high daily temperature range and wetter summers (Fig. 7).

The city has an average annual temperature and precipitation of 20.7 ^{o}C and 538 mm (Jonsson, 2004). It is also characterized by windy and intense insolation during day time, which causes occasional heavy convection and turbulence during summer (Givoni, 1992). The mean wind speed attains its peak and minimum in November and April respectively (Jonsson, 2004).

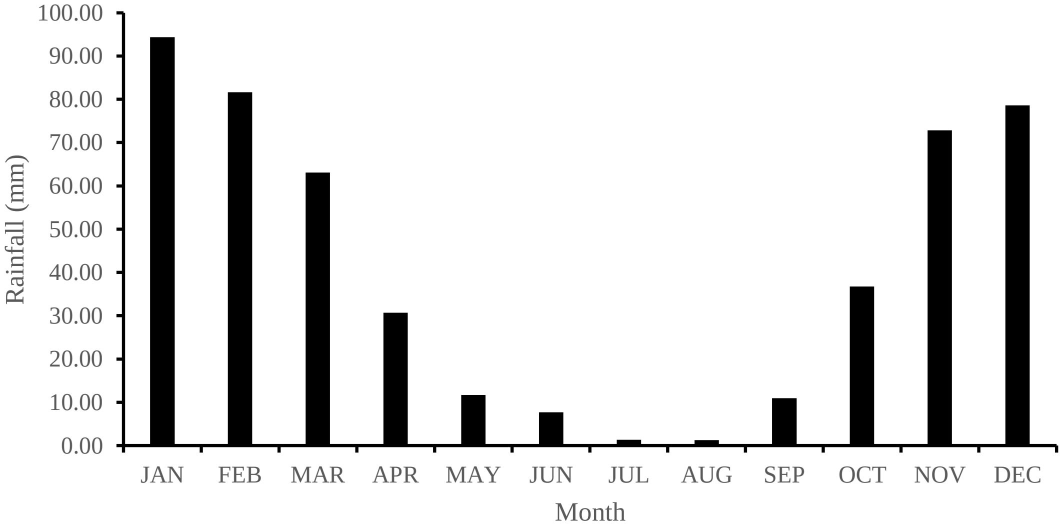


Figure 7. Monthly total rainfall recorded at Gaborone meteorological station obtained from DMS Gaborone for the period (1980-2017).

4.1.3 Population

As the capital city of Botswana, Gaborone consists of 231,626 inhabitants according to the 2011 census. The figure is approximately 10% of the population of Botswana. Table 3 indicates villages included in the Gaborone water management centre, their distance from the city centre, location and population as per the 2011 census.

Place	Location/coordinates	Distance from Gaborone (Km)	Population as per the 2011 Census
Tlokweng	24.66° S, 25.97° E	15	36,323
Mogoditshane	24 .37° S, 25. 51° E	9	58,638
Kumakwane	24°39′23″S, 25°41′55″E	15	5,901
Mmopane	24.56° S, 25.87° E	20	17,843
Metsimotlhabe	24.55° S, 25.81° E	20	9,265
Gakuto	24.47^{o}S, 25.78^{o}E	15	1,831
Mmatseta	24.51^{o}S 25.86^{o}E	15	513
Gabane	24.66° S, 25.78° E	15	16,671

Table 3. Location and populations of the villages included in the Gaborone Management Centre (GMC) and their distance from the city (taken from Central Statistics Office).

4.2. Data

The data used in this study were obtained from government institutions on the water supply and demand of the study area and from published reports. Annual and monthly water production and consumption data for the study area (9 demand sites) were acquired form the department of Water Utilities Corporation. The main water supply elements are the Gaborone dam and Mmamashia Water Works which acquire water from Letsibogo and Dikgatlhong dams and reservoirs. Yearly and monthly data from Gaborone rainfall station for the period 1980 to 2017 were collected from the Department of Meteorological Services. The hydrological data of the 5 reservoirs (Foresthill, Gabane hill, Oodi hill, Diremogolo and Mabutswe) were also collected from Water Utilities Corporation. Hydrological data includes monthly inflows and storage capacities of different reservoirs for the period of 2014. Annual population growth rates for the nine demand nodes were acquired from Statistics Botswana .The water supply design norms, parameters and recommendations were collected from the water utilities corporation (DWUC). These are given in Tables 4-6.

Table 4 indicates the monthly average water consumption rates (%) for Gaborone and surrounding areas for base year 2014. Table 5 indicates the monthly average inflows (MCM/s) of the reservoirs that supply the study area during the base year 2014. Table 6 tabulates the storage capacities of the reservoirs and dams.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gabane	5	3.21	2.9	2.85	1.8	2.7	2.6	3.1	2.91	3.5	3.1	3.6
Gaborone	74	73	72	55	37	67	69	69	74	71	66	59
Gakuto	0.05	0.05	1.75	0.07	0.04	0.1	0.09	0.06	0.1	0.14	0.15	0.14
Kumakwane	0.43	0.7	0.7	0.61	0.63	0.68	0.6	0.66	0.76	0.67	0.62	0.6
Metsimotlhabe	1.3	1.29	0.56	2.9	1.9	2.2	2.3	2.6	2.5	2.9	2.5	0.29
Mmatseta	0.04	0.03	0.05	0.06	0.04	0.06	0.06	0.06	0.05	0.06	0.05	0.13
Mmopane	0.5	0.57	0.6	0.7	0.4	0.6	0.6	0.5	0.3	0.4	0.7	0.9
Mogoditshane	9.1	12.2	13.22	25.7	1.7	1.6	1.56	13.7	10	13.9	13.1	22.2
Tlokweng	7.7	7.8	7.2	10.3	6.8	9	0.8	9.3	8.3	5.9	12.1	11.6

Table 4. Monthly average water consumption rates per demand node for the base year 2014.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Diremogolo reservoir	0.26	0.32	0.35	0.50	0.31	0.34	0.34	0.30	0.23	0.31	0.30	0.38
Foresthill reservoir	2.62	2.45	2.50	1.86	2.52	2.00	2.05	2.05	2.15	2.12	2.13	1.63
Gabane Hill reservoir	0.15	0.09	0.09	0.07	0.07	0.07	0.07	0.08	0.08	0.09	0.08	0.07
Mabutswe reservoir	0.21	0.19	0.19	0.19	0.20	0.18	0.17	0.19	0.18	0.13	0.26	0.19
Oodi reservoir	0.99	0.91	0.92	0.52	0.94	0.68	0.72	0.71	0.80	0.76	0.71	0.49
Gaborone dam	1.99	2.33	1.93	1.99	2.24	0.17	1.51	1.62	1.39	1.45	1.36	0.90
Mmamashia Water Works	2.70	2.34	2.24	1.92	2.42	1.97	2.08	2.17	1.96	2.11	1.98	1.32

Table 5. Monthly average reservoir inflows for the base year 2014 as provided by the department of Water Utilities Cooperation.

Reservoir name	Storage capacity in MCM
Oodi reservoir	18.5
Diremogolo	30
Mabutswe	30
Gabane hill	5
Forest hill	49
Gaborone dam	145
Mmamashia	80

Table 6. Reservoir storage capacities as provided by the department of Water Utilities Cooperation (WUC).

4.3 WEAP model

4.3.1 Model layout and setup

The WEAP model is comprised of five different views represented by unique icons. These are icons for the schematic, data, results, scenario explorer and notes (see Fig. 8). All activities in WEAP are reflected in the schematic view (SEI 2011). The data view is where the model is built as it allows data entry of various variables. Assumptions and estimates using mathematical expressions are also done on the data view and it can also be dynamically linked to excel. The data and assumptions can be documented in the notes view. On the other hand, the results view shows detailed and calculated model outputs in various forms including charts, tables and maps. The scenario explorer allows tuning of WEAP by altering scenario data variable until the sought effect on user-selected key results is attained.

The most vital functions of the program are found at the top part of the screen, usually termed as the ‘main menu’. At the bottom part of the screen is the status bar.

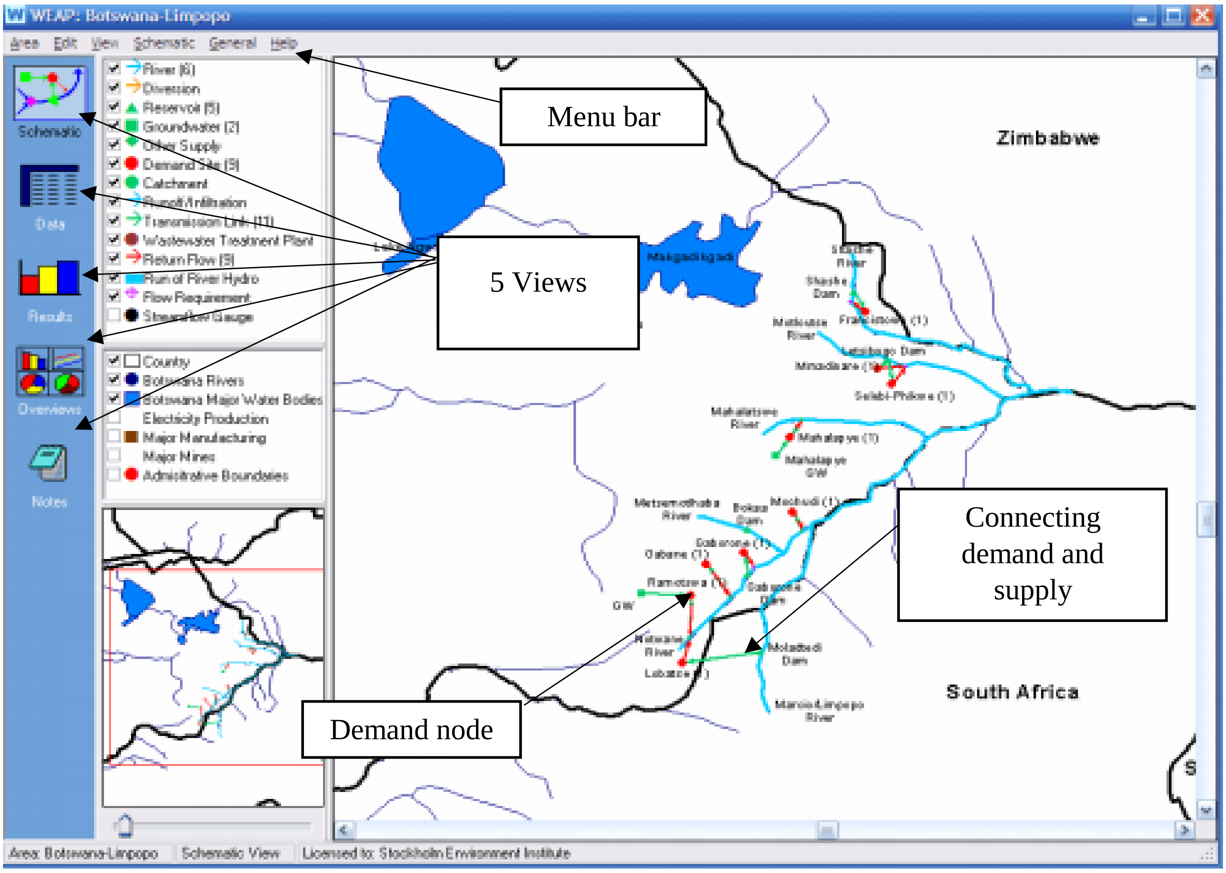


Figure 8. WEAP screen views, menu bar schematic view (taken from (Sieber, 2015) .

The WEAP work flow chart is given in Fig. 9.

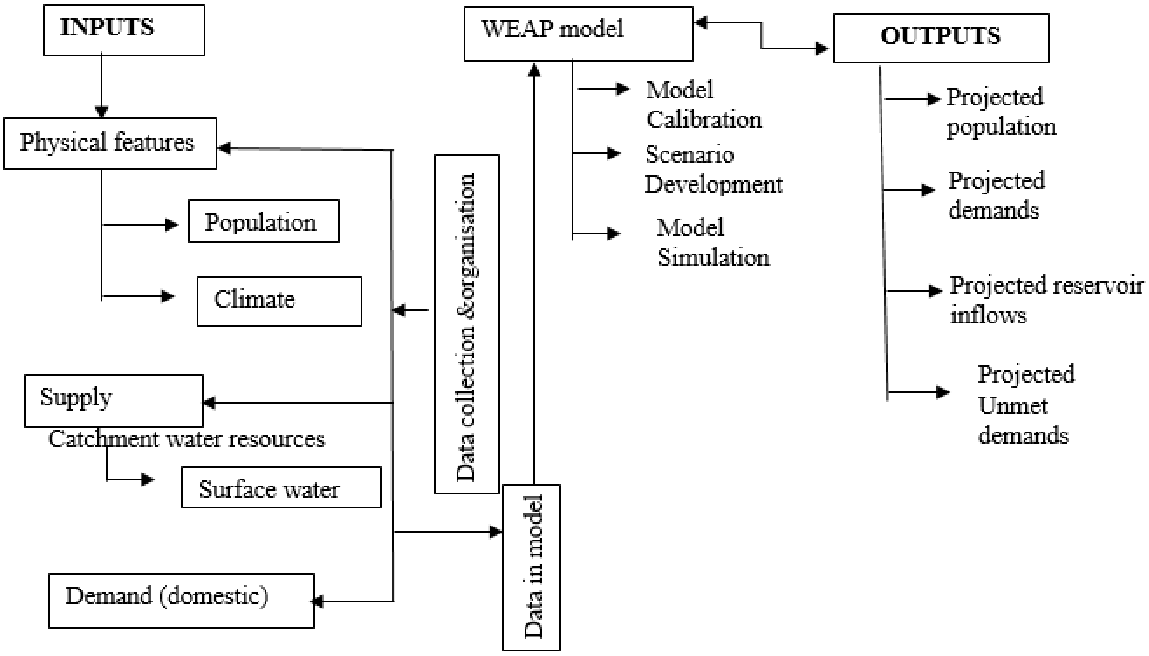


Figure 9. Model processes flow chart

The most important aspect in WEAP is the water demands in the catchment. Nine (9) demand sites were considered for this catchment as shown in Fig. 10.

Every demand site in the model is denoted by a node and connected to the supply sources available (Fig. 10).

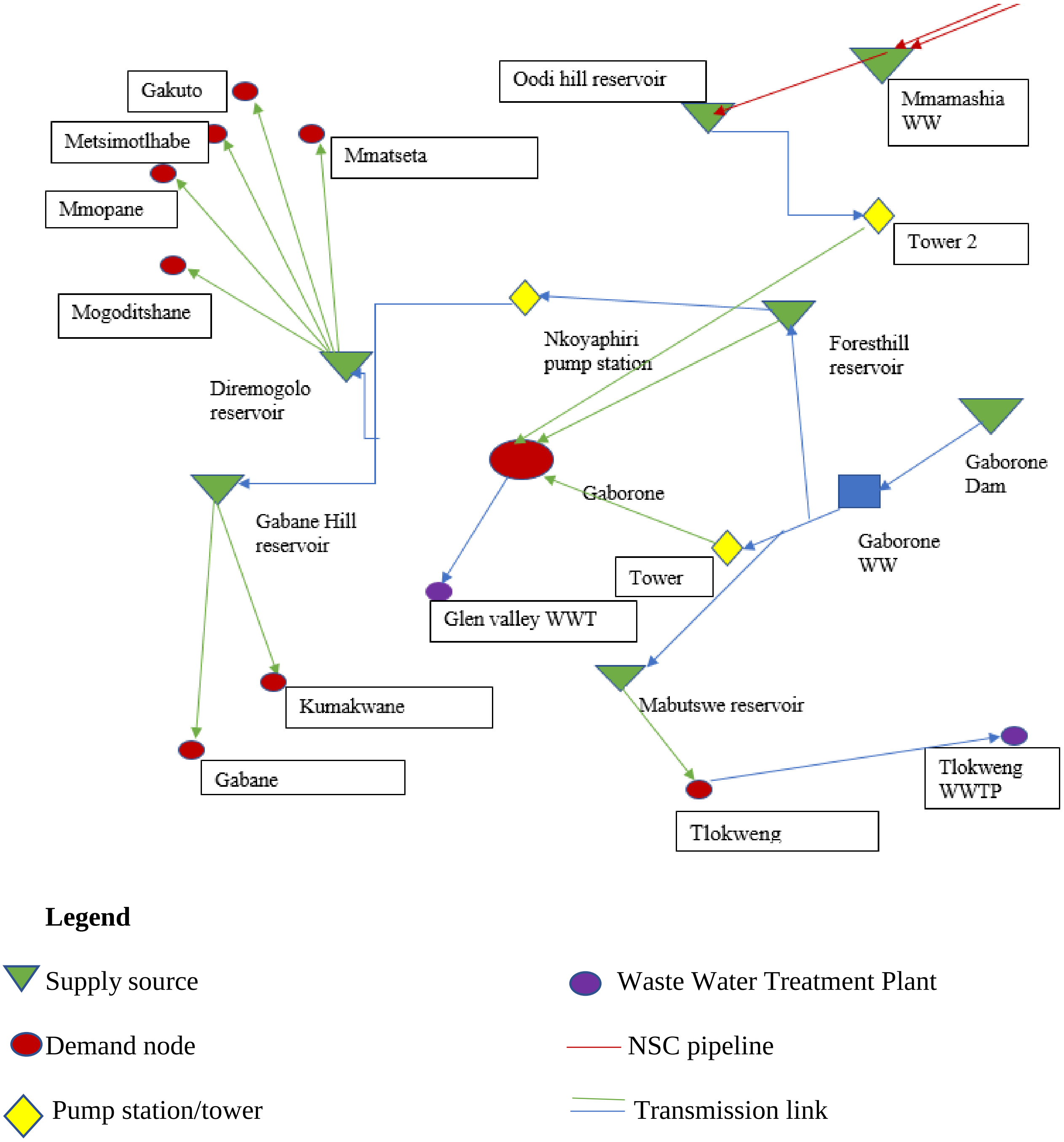


Figure 10. Schematic description of network in WEAP modelling process showing reservoirs, demand sites and nodes.

For this study, demand sites at Gaborone, Mogoditshane, Tlokweng, Gabane, Mmopane, Metsimotlhabe, Gakuto and Kumakwane were all given first priority. Using the WEAP model, a transmission link (green/blue lines in Fig. 10) was used to connect the various supply sources to each demand site from the various supply nodes (inverted green triangle, Fig. 10) to the demand sites (filled red circle, Fig. 10) so that each demand node's demand is met. The overall quantity of water to be supplied to the demand sites is equal to the amount to be abstracted minus the possible losses (see also Arsiso et al., 2017). This means that WEAP integrates both water demand and supply by placing the demand-side issues on an equal footing with the supply side dynamics.

All flows are assumed to happen instantaneously; this means that water extraction from the reservoir, consumption and return of excess water to a receiving body by the demand site occur concurrently. The topology of the network could constrain the model to distribute water to satisfy any particular demand in the system, regardless of travel time. As a result, the model time step should be at least as long as the time of residence of the study area. Also, WEAP21 operates on a monthly time step from the first month of the current accounts year through to the last month of the last scenario year (Yates et al., 2005). Each month is independent of the previous month, except for reservoir and aquifer storage. Thus, all of the water entering the system in a month (e.g. head flow, groundwater recharge or runoff into reaches) is either stored in an aquifer or reservoir or leaves the system by the end of the month (e.g. outflow from end of river, demand site consumption, reservoir or river reach evaporation, transmission and return flow link losses). Thus a demand site can withdraw water from the river, consume some, return the rest to a wastewater treatment plant that treats it and return it to the river. This return flow is available for use in the same month to downstream demands (Yates et al., 2005). In view of this, the monthly and yearly time steps were used for this study.

The key considerations about water demand, water supply and management of water for this project are:

(i) The population growth rates of 2.2% and 3.4% are assumed to represent low and high population growth rate scenarios.

(ii) Technology improvements will lead to reduction of water loss via leakages and pipe bursts from the current 39% to 0% by the year 2100.

(iii) Agricultural re-use has been assumed to be 5% every year starting with the base year (2014) until 2100.

In addition, the following steps are considered during the model setup:

1. Setting area boundaries, mapping and data entry. The data needed are population, historical flow of the river, rainfall, catchment characteristics and present water supply;

2. Establishing current accounts and providing the actual water demand, resources and supplies for the system. The year 2014 was set as the current accounts for this study;

3. Creating scenarios based on future assumptions; and

4. Assessing the water balance and allocation with respect to scenarios.

4.3.2 WEAP hydrology and water management modules

WEAP provides three methods for simulating watershed hydrological processes. These are the Soil moisture method, Rainfall Runoff as well as the simplified coefficient approach (Sieber, 2015). This study therefore utilised WEAP’s Soil Moisture Method to assess the rainfall run-off processes throughout the study area. The soil moisture module in WEAP assumes the study area as a continuous collection of sub catchments covering the whole river basin (World Bank, 2017).

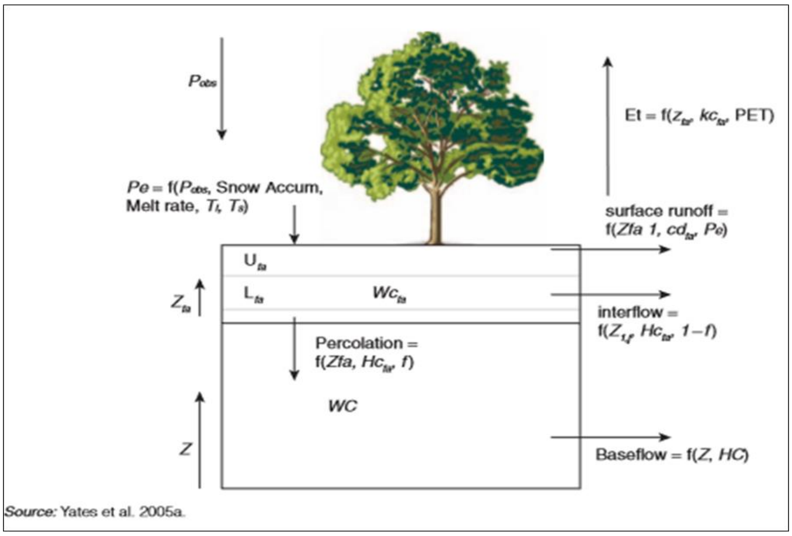
Each sub catchment (SC) is fractionally subdivided in to a distinctive collection of independent land use/land cover classes. Every SC is characterized by a uniform climatic data sets of relative humidity, precipitation, wind speed and temperature.

WEAP considers the hydrological response of each fractional area within a SC by portioning water into surface runoff, infiltration, evapotranspiration, interflow, percolation and base flow components as shown in schematics in Fig. 11.

For the application of the model on the catchment, the balance was calculated considering each fraction of area j, depending on the type of land or soil cover. Also, the climate was assumed to be the same in each fraction of area j. The mass balance is therefore written according to equation 1.

$$Sw\frac{dz_{1,j}}{dt} = P_e(t) - PET(T)K_{c,j}(t)\left(\frac{5z_{1,f} - 2z^2{}_{1,f}}{3}\right) - P_e(\mathrm{t})z_{1,j}{}^{\frac{LAI}{2}} - f_j k_j Z_{1,j}^2 - (1 - f_j)k_{z,j} Z_{i,j}^2 \text{.............................}(1)$$

Where Sw is the soil water holding capacity, $P_e\ (t)$ is the effective precipitation with respect to time, evapotranspiration from the fractional area, j is given by PET which is referred to as PenmanMontieth reference crop potential evapotranspiration in mm/day and $K_{c,j}$ is the plant coefficient for every fractional land cover. Term three indicates surface runoff, where LAI is the Leaf and Stem Area Index (LAI). While terms four and five indicate the interflow and deep percolation terms, respectively, where the parameter k_j , is an estimate of the upper storage conductivity (mm/time) and f_j is a quasi-physical tuning parameter related to soil, the type of land cover, and terrain that fractionally distributes water either horizontally, f_j or vertically$(1 - f_j)$.



Source: Yates et al. 2005a.

Figure 11. WEAP's water balance model (taken from Yates et al., 2005).

Water balances for each reservoir are calculated as:

$$S_j^t - S_j^{t-1} = \ Q_{in,j}^t - Q_{out,j}^t - L_j^t \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (2)$$

where S_j^t is the volume of water in reservoir j at time t in MCM, $Q_{in,j}^t$ is the j reservoir inflow in period t in MCM, $Q_{out,j}^t$ is the release from reservoir j in period t in MCM and L_j^t is the losses from reservoir j at time t in MCM. WEAP then integrates the results of the two balance equations to come up with the amount of water available and supplies it to the demand sites.

Annual demand and monthly variation data were used to acquire each demand node's water demand. Water demand was calculated as follows:

$$Total\ demand = Total\ Activity\ Level \times Water\ Use\ rate \ \ldots\ldots\ldots\ldots \ (3)$$

Using WEAP, water demand is computed as the summation of the demands of demand sites (DS) for all the demand site's bottom-level branches (Br):

$Demand\ Annual$ = $\sum_{Br}$(Total activity levelBr′,× Water use rate Br" × …) …….. (4)

where Br is the bottom-level branch, Br′ is the parent of Br, Br″ is the grandparent of Br, etc.) (Sieber, 2015). Bottom-level branch is the sum of the activity level for the product of the activity levels for all branches from the bottom of the branch back up to the demand node branch.

For every water demand there is a supply requirement given by:

$Supply\ requirements = (Demand_{Dsm} \times (1 - Reuse\ rate_{Dsm})$ ×(1−$DSM\ savings_{Ds}$))/(1−$Loss\ rate_{Ds}$)………………….. (5)

where DS refers to a demand site and DSM refers to the demand side management strategies. That is, the supply requirement takes the demand and regulates it to account for internal reuse, demand side management strategies in order to reduce demand, and internal losses.

The amount supplied to a demand site (DS) is the total amount of inflows from its transmission links i.e.

$Demand\ Site\ Inflows_{Ds} = \sum_{Src} TransmissionLink\ Outflow_{Src,Ds}$ ……………………. (6)

Where the demand node's inflow from a supply source (Src) is described as the outflow from the transmission link that connects them. That is, the net of any leakages along the distribution line or the transmission link

Demand site inflow should be equal to its supply requirement unless if there are shortages of water caused by hydrological, climatic, physical, contractual or any other constraints i.e.

If $Demand\ site\ Inflows_{Ds} \geq Supply\ requirements_{Ds}$ then the supply is considered as adequate.

If $Demand\ site\ Inflows_{Ds} < Supply\ requirements_{Ds}$ then the supply is considered as inadequate. It is also referred to as unmet demand.

Demand site return flow links transport wastewater from demand sites (DS) to either rivers or waste water treatment plants. This can be expressed mathematically as

$Demand\ site\ Return\ flow_{Ds} = Demand\ Site\ Inflow_{Ds} - Consumption_{Ds} - Demand\ Site\ Reuse\ Outflow_{Ds}$………….. (7)

Two large reservoirs and five small reservoirs are considered in this study to assess the impacts of applying regulation rules on the supply of water to consumers. The reservoirs are Gaborone dam, Mmamashia, Diremogolo, Gabane hill, Foresthill, Mabutswe and Oodi hill. In the case where priority value for filling water in a reservoir is lower than the downstream requirements, the model will allow for a release of only as much of the available storage as is required to meet the demand and environmental flow requirements at the same time considering releases from the sources (Yates et al., 2005). All reservoirs were assigned the lowest demand priority of 99 for this study. This lowest priority value of 99 implies that the reservoirs can only be filled up when all the rest of the demands are met.

The rules governing reservoir operation splits the reservoirs into water-level related sections as shown in Fig. 13. If the level of water reaches the flood control zone, it is released. Water is abstracted as needed to satisfy the demand in the conservation level. Below the conservation zone, buffer zone limits the supply of water to avoid over abstraction (Yates et al., 2005). The inactive zone is where it is impossible to use the water except to satisfy the resevoirs's evaporation and seepage losses.

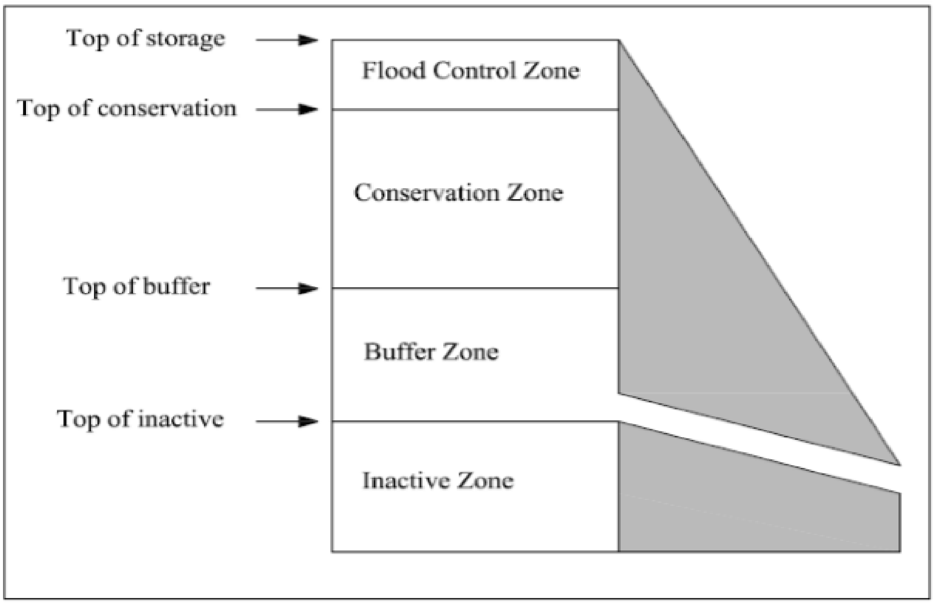


Figure 12. Reservoir storage zones (taken from Yates et al., 2005).

Eq. 8 indicates the calculation for the amount of water available to be extracted from the reservoir:

$$S_R = S_C + S_F + (b_c \times S_b) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(8)$$

where S_R the total amount of release from reservoir storage is, S_C is the conservation storage, S_F is the flood storage and S_b is the buffer storage.

4.3.3 Calibration of the WEAP model

The aim of calibration is to change or tune the parameters such that the model solutions optimally match the observations (Hamlat, 2013). Brunner (2008) defines calibration as the modification of the parameters of the model like roughness coefficients, hydraulic structures etc., in order for the model to produce observed simulated data at a reasonable degree of precision. The calibration of the WEAP model consists a quantitative assessment of the hydrological response of the Notwane River in order to match simulated data with the observed flow data at a reasonable accuracy. Parameters like hydraulic conductivity, runoff resistant factor, soil water capacity and root zone conductivity are needed by the model for calibration and validation of the historical river stream flow data (Ayele, 2016). Based on scientific assumptions, the crop coefficients for maize (K_c), runoff resistant factor (RRF), soil water capacity, root zone capacity, deep conductivity and observed climate (precipitation, temperature, relative humidity and wind speed) data were used for the calibration of the model. The data was entered manually on monthly and yearly time series where applicable. The model was then run so as to assess whether it represented or simulated the catchment water balance well. The correlation of the observed stream gaged Notwane river flow data with the simulated stream flow data was generally tested using two general approaches as stated below.

These approaches are the objective function and the subjective criteria (Ahamad et al., 2007). Objective evaluation is based on error measures such as the mean error (ME), mean square error (MSE) and the model coefficient of efficiency (EF) (Ahamad et al., 2007). The MSE calculates the average of the squares of the errors, which is distinction between the observed flow values and the ones being simulated by the model. The Nash-Sutcliffe coefficient, (EF) is utilised to evaluate the skill of hydrological models (Tefsaye, 2014). A value of 1 for EF is indicative of perfect model where observed discharge is perfectly modelled. The modelled discharge and the observed data is indicated by an output value of 1. On the other hand, an efficiency value of 0 shows that the model can simulate utmost the mean observed data. Subjective criteria is however the visual analysis of the difference between the simulated results and the observed data.

The ME, MSE and EF are defined by Eqns. 9-12

$$E_Q \ = Q_m - Q_o \qquad (9)$$

$$ME = \sum_{i=1}^{n} \frac{(Q_m(i) - Q_o(i)}{n} = \sum_{i=0}^{n} \frac{EQ(i)}{n} \qquad (10)$$

$$MSE = \sum_{i=1}^{n} \frac{(Q_m(i) - Q_o(i)}{n^2} = \sum_{i=0}^{n} \frac{EQ(i)}{n^2} \qquad (11)$$

$$EF = \left[\!\left[1 - \frac{MSE}{S_{Q_O}^2} \right]\!\right] \qquad (12)$$

CHAPTER 5. Results and Discussions

For this study, the WEAP model was run up to the year 2100 with the baseline year being 2014. Two population (2.2% and 3.4%) growth rates and climate change (RCP 4.5 and RCP 8.5) scenarios were combined to produce four population-climate scenarios.

5.1 Model performance

In order to generate the water balance results, the climate data, area, the Crop coefficient (maize), soil water capacity (range 0-100mm), deep water capacity (range 0-1000mm) , runoff resistance factor (range 0-1000) , root zone conductivity (range 0-20 mm), deep water capacity (range 0-1000 mm), deep conductivity (range 0.1-20 mm) , initial (Z_1 and Z_2 , range (0-100%) were entered manually into the WEAP model on an elevation of 1000-1500 m. All of the parameters were entered per specific land cover using the monthly time series wizard except the deep water capacity, deep conductivity and Z_2 which were entered using the yearly time series wizard at 10 mm/month, 500 mm and 50% respectively. The land cover included the Agriculture, forest, grassland, wetland, urban, shrub land, barren or sparse vegetation and open water. Climate data (precipitation, temperature, humidity and wind speed) were assumed to be uniform throughout the catchment. The climate data were acquired from the department of meteorological services while the values of the above tuning hydrological parameters for the different land cover types are based on literature. Seasonal variation of the parameters are also considered based on the climatology of the region.

Fig. 13 below shows the WEAP water balance output for the catchment area for the base year of 2014. The model was run on different values of the parameters and it was deduced from the analysis of the several runs that, of the water balance components, the surface runoff is mostly influenced or sensitive to the runoff resistance factor, soil water capacity and the root zone conductivity while other parameters showed little or no effect to it. More runoff is experienced in summer while less in winter because of little or no rainfall. It is assumed that most rainfall seeps into the upper soil layer and later evaporates with very little contribution to the ground water recharge. Hence little base flow is experienced as shown in Fig. 13.

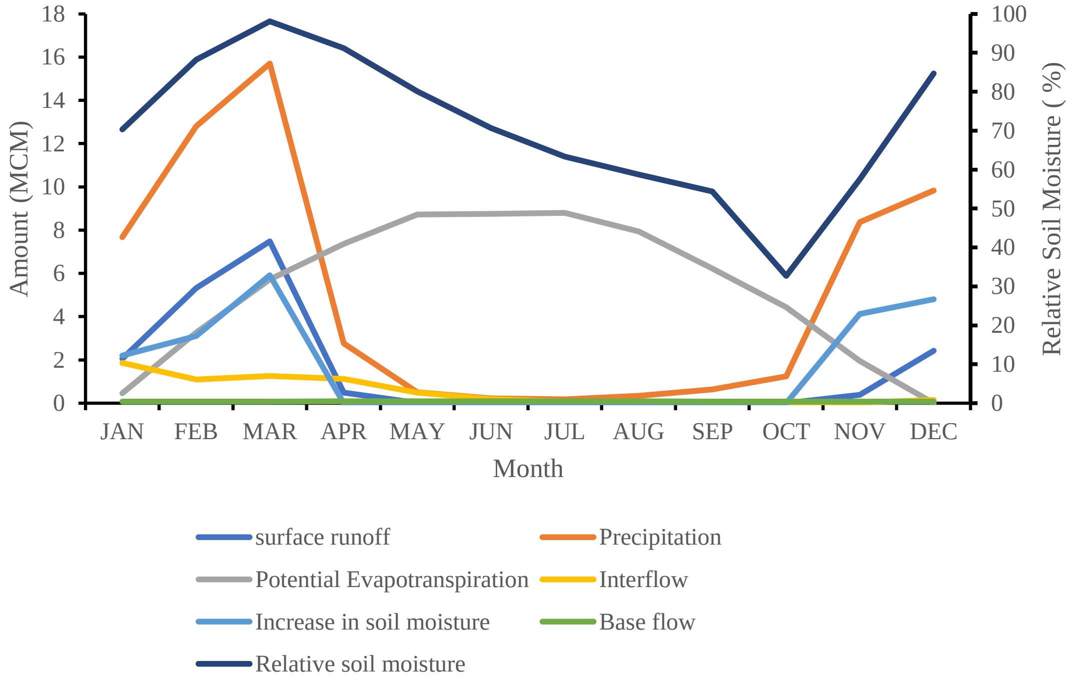


Figure 13. WEAP model water balance outputs for the base year 2014.

The WEAP model has been tested on a monthly and yearly time step basis. The performance of the model performance was also assessed using statistical parameters such as the mean error (ME), mean square error (MSE) and the model coefficient of efficiency (EF). Observed stream flows recorded at the Notwane gauging station are compared to the simulated flows produced by the model. Results show that simulated flow at Notwane gauge station with the observed flow gives an EF of 0.91. Comparison of observed and simulated stream flow is one way of determining if the model accurately represents the hydrological system. Table 7 shows that the simulated flows of Notwane River match the observed values relatively well.

River	Statistical parameters			
	Mean **Q_o (MCM)**	Standard Deviation **STDEV**	Mean Square Error **MSE**	Coefficient of Efficiency **EF**
Notwane	1.09	0.73	0.00025	0.91

Table 7. Statistical analysis of observed and simulated flows of the Notwane River.

Fig. 14 illustrates a relatively good correlation between the simulated and observed monthly stream flow values for the Notwane River. However much of the strong correlation comes from the seasonal cycle since the model simulates systematically a bit of higher stream flow than observations.

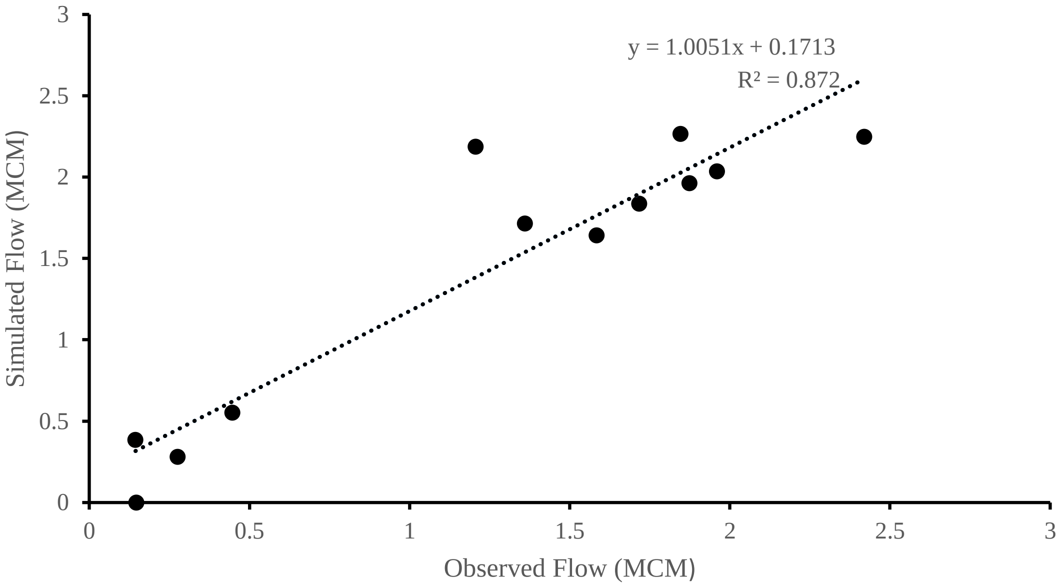


Figure 14. Mean observed and simulated flow at the Notwane gauge station for the account base year.

The observed flows at gauged station covers for the period between 2014 and 2016 (Fig. 15). WEAP simulation has captured the seasonal cycles in the stream flow fairly well. However, the magnitude of the simulated stream flow is a bit higher particularly for the years 2015 and 2016 during the peak seasons. This could be attributed to either interannual differences in the model tuning parameters or the selected parameter values during model calibration for the base year were not sufficiently optimal. We assume that the latter is more likely as the changes in the hydrological parameters such as root zone conductivity, run-off resistance etc. within a year or two are unlikely to occur.

Figure 15. Comparison between the observed and simulated flows of Notwane River.

5.2 Water consumption and availability of the base year 2014

Fig. 16 shows high consumption rates in the highly populated areas like Gaborone, Mogoditshane, and Tlokweng. That is, the more the population the higher the water consumption rates.

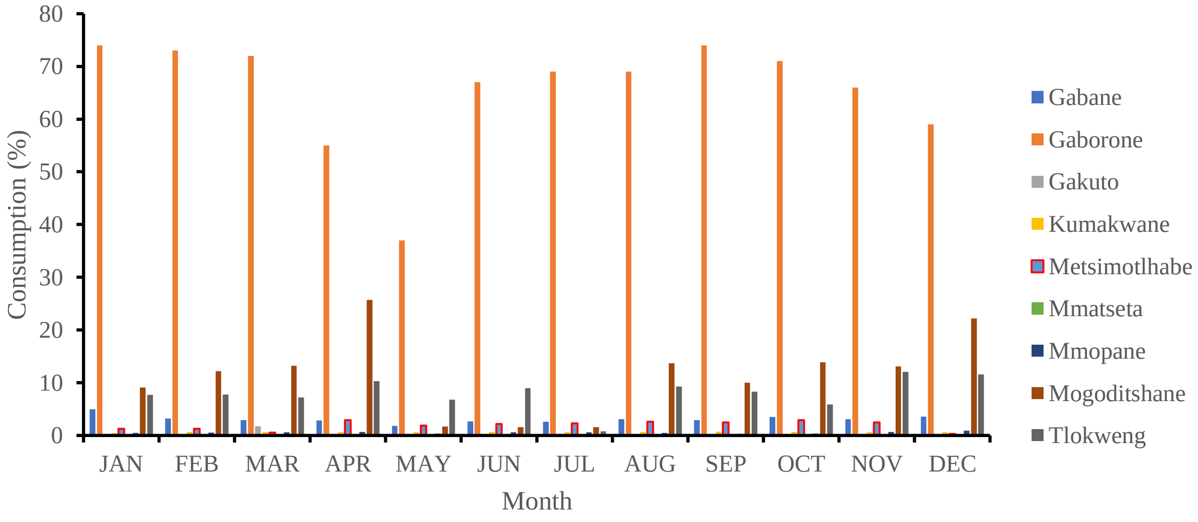


Figure 16. Water consumption rates per demand node during reference year 2014.

Annual water demands calculated using WEAP for the current year (2014) are given in Table 8. Gaborone has the largest water demand mainly because of its high population leading to the highest water use rates. The total annual demand for the GMC was 7.20 MCM in 2014 with Mmatseta and Gakuto being the lowest in water demand because of their low population.

Demand site	Population	Water demand (MCM)
Gaborone	231,592	2.61
Mogoditshane	58,079	1.62
Tlokweng	36,323	1.71
Gabane	15,237	0.72
Metsimotlhabe	8,884	0.23
Kumakwane	5,545	0.02
Mmopane	14,655	0.10
Gakuto	1,831	0.14
Mmatseta	513	0.06

Table 8. Population and water demands of Gaborone and surrounding areas in 2014.

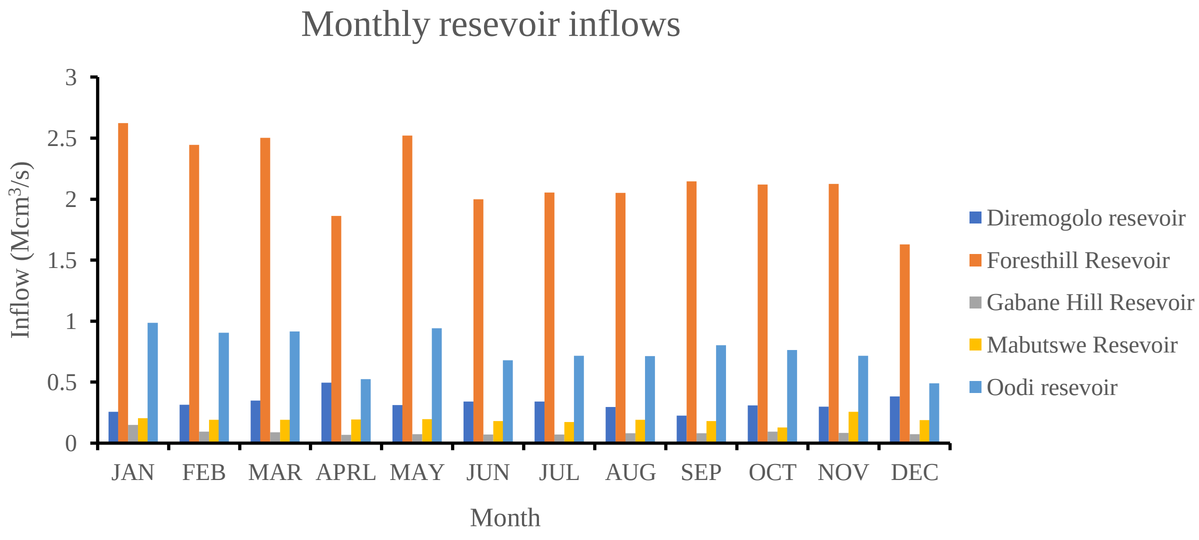


Figure 17. Monthly inflows of reservoirs.

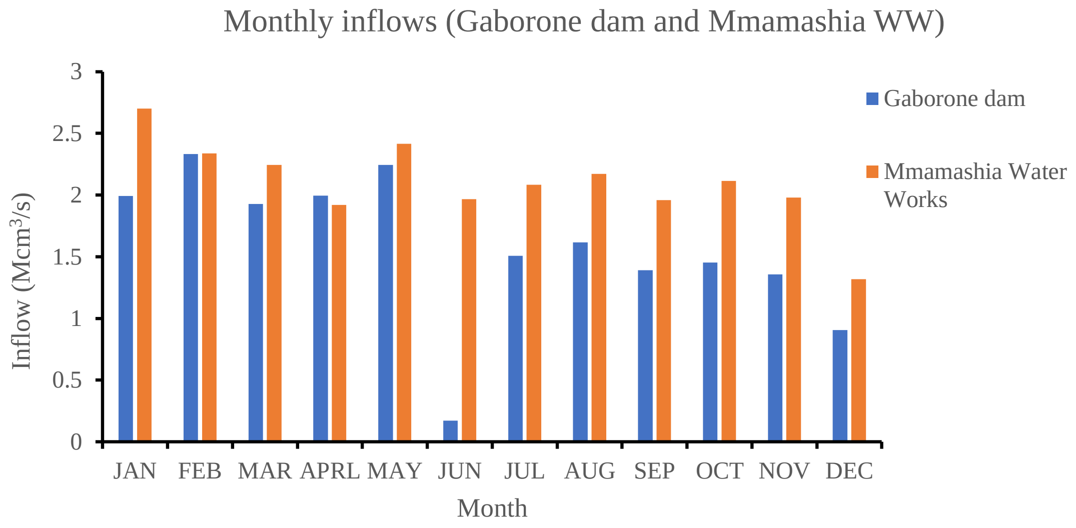


Figure 18. Monthly inflows of Gaborone dam and Mmamashia water works.

Fig. 17-18 indicate the monthly inflows of the reservoirs which supply demand sites. It is to be noted that these reservoirs depend mainly on rain water for refill. Consistent with the 1980-2017 monthly rainfall trend (Fig. 7), that there is low inflow mostly in the dry months of June, July, and August. The rainy season in Botswana ranges from October to March. Hence a bit of higher inflows during those months although due to some delay the rainfall peaks do not concide with inflow peaks. Foresthill reservoir receives more inflow than all the other reservoirs. Figure 18 shows that Mmamashia water works receives more water than Gaborone dam. It receives water from the northern dams (Dikgatlhong and Letsibogo dam) which also depend on rain water for accumulation in agreement with the fact that the northern part of Botswana receives more rainfall than the southern part of Botswana.

5.3 Population and climate projections and future unmet water demands

The Statistics Botswana calculated the high population growth rate for Gaborone to be 3.4% and the low population growth rate to be 2.2%. The population growth rates shall therefore be applied for the whole of Gaborone water management centre (GMC). Fig. 19 shows the projected populations under reference and high population growth scenarios respectively.

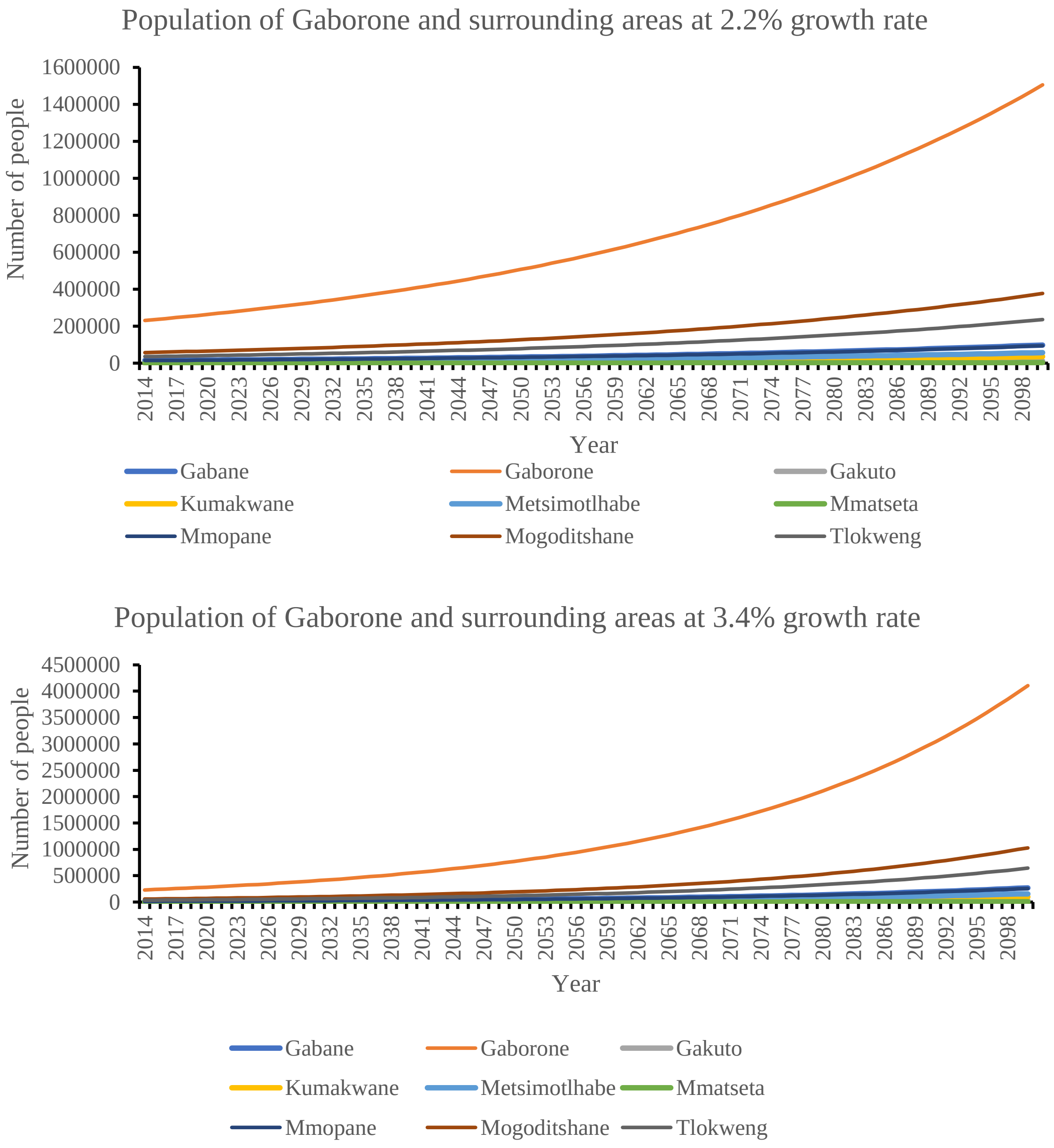


Figure 19. Projected population growth at 2.2% growth rate (top) and 3.4% (bottom) growth rate.

Fig. 19 indicate growth in the populations of Gaborone and its surrounding areas in the next 95 years. At 2.2% growth rate the population of Gaborone, Mogoditshane and Tlokweng shall increase from (231,592 to 1,504,875), (58,079 to 377,395) and (36, 323 to 236,025) people between the years 2014 and 2100 respectively. And at a higher population growth of 3.4% there will be a higher population increase for the city and all the other villages. Even small villages like Mmopane, Gabane and Kumakwane shall increase from (14, 655 to 259,867), (15, 237 to 270,187) and (5,545 to 98,325) people respectively. Gaborone shall also experience a population increase of (231, 592) to (4,106,670) at 3.4% growth rate. However, it is important to underline that change in population size over a century period may not be realistic particularly at 3.4% growth rate. The importance in the scenario analysis is to get extreme scenarios that encompass the most likely scenario for water resource planning and management. Therefore, based on the extreme scenarios, one can obtain the extreme water supply requirements and demands from which interventions options are formulated including technology and management options.

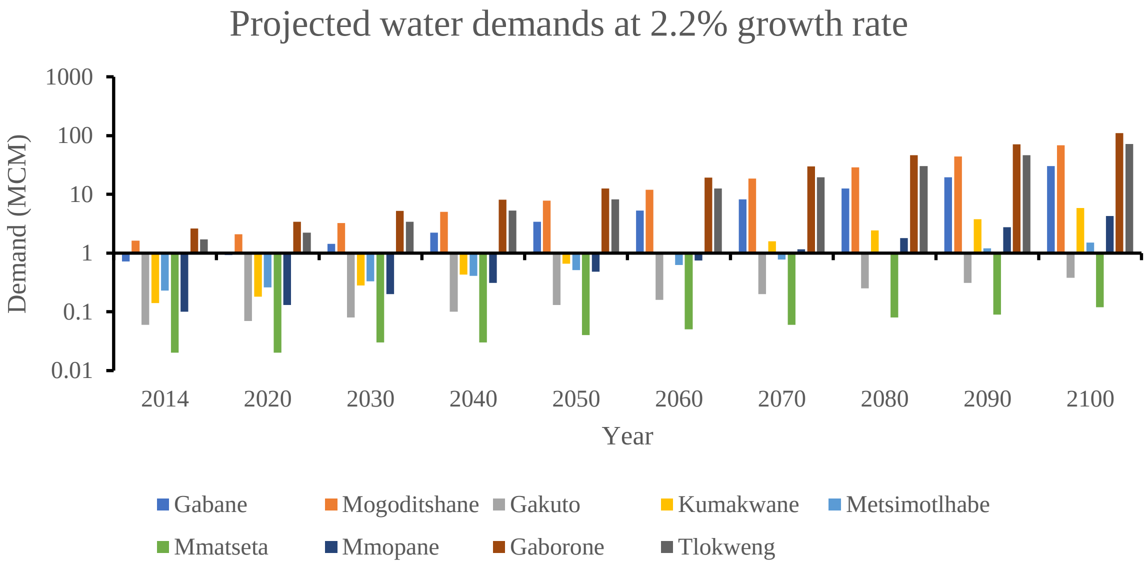


Figure 20. Projected water demands in MCM for all demand sites under the low population growth 2.2% reference scenario for all demand sites, 2014-2100 –WEAP model results.

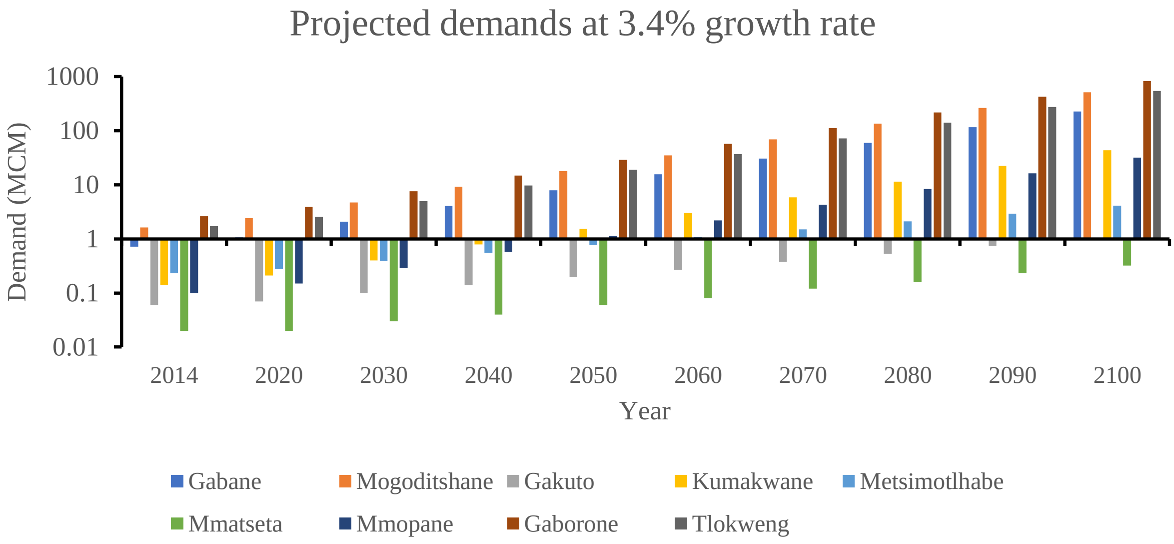


Figure 21. Projected water demands in MCM for all demand sites under the high population growth 3.4% reference scenario for all demand sites, 2014-2100 –WEAP model results.

Figures 20-21 show the future water demands of each demand node under the low and high population growth rates respectively. Taking Gaborone as a sample demand node under the low population growth scenario, the demand will increase from 2.61 MCM in 2014 to 19.35 MCM, 29.90 MCM, 46.21 MCM, 71.41 MCM and 110.35 MCM in 2060, 2070, 2080, 2090 and 2100 respectively. While under the high population scenario the demand for Gaborone will increase from 2.61 MCM in 2014 to 56.64 MCM, 110.54 MCM, 215.75 MCM, 421.07 MCM and 821.80 MCM in 2060,2070,2080,2090 and 2100 respectively. The future water demands are mainly driven by population growth and economic developments in the catchment and irrigation industries (Ayele, 2016).

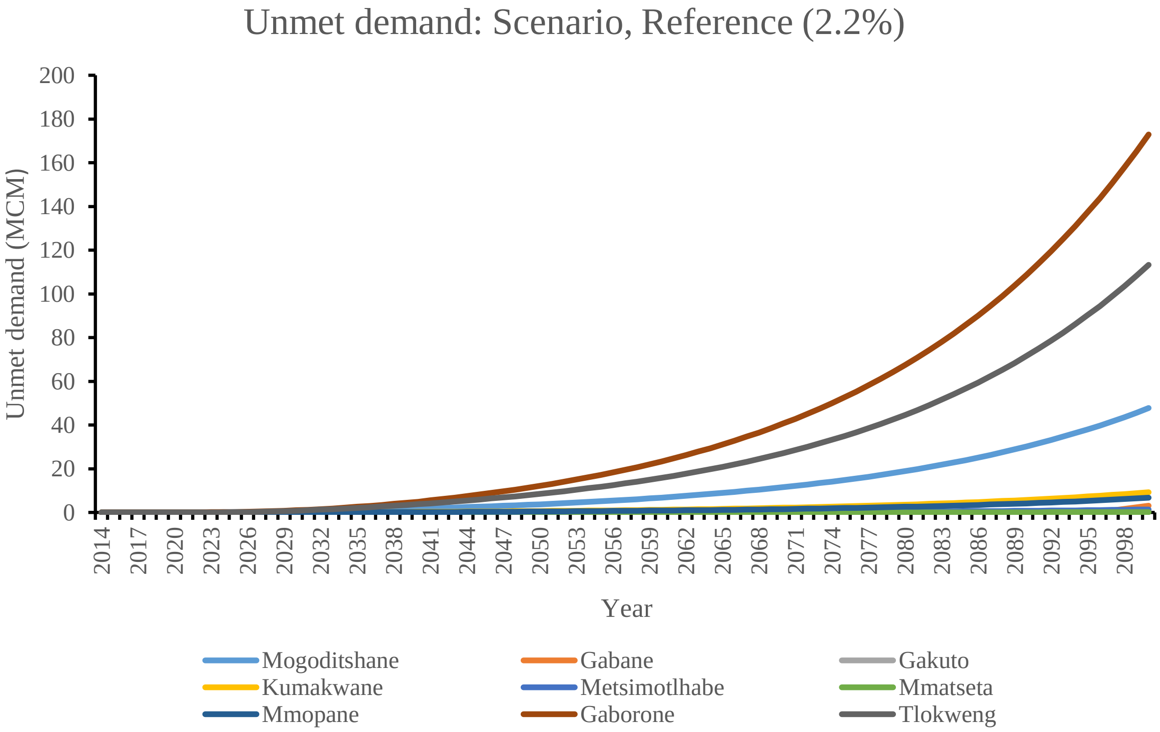


Figure 22. Unmet demand at low population growth rate.

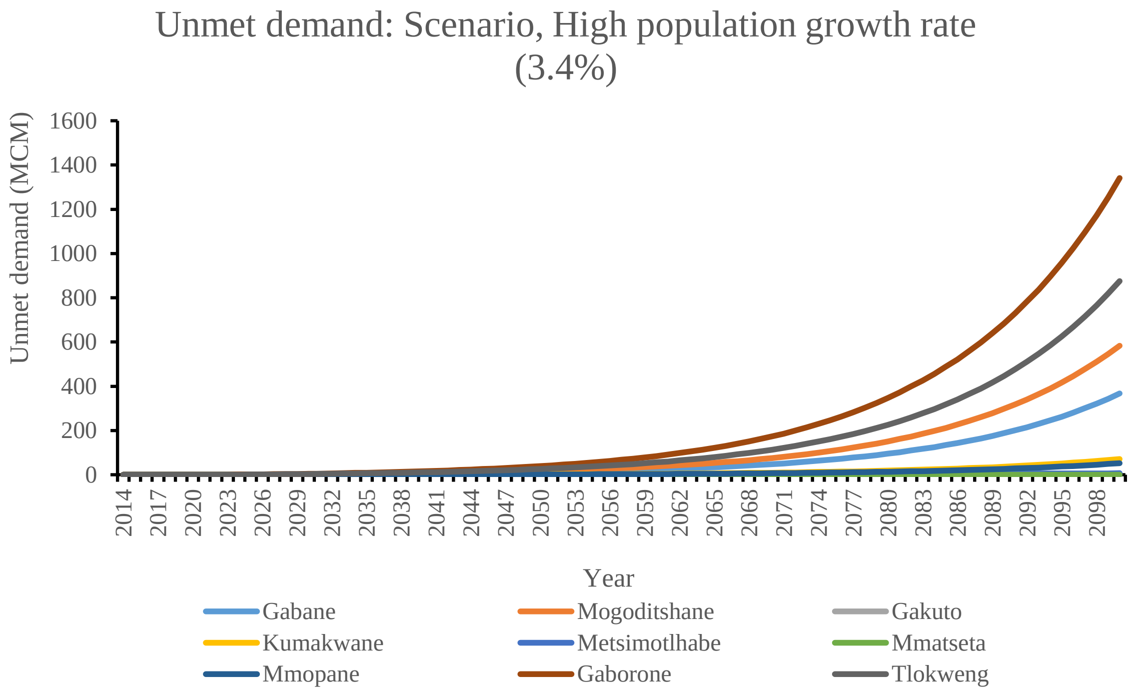


Figure 23. Unmet demand at high population growth rate.

Figs 22-23 show the unmet water demand for all the demand sites at low and high population growth rates respectively. At low population, the unmet water demand for Gaborone is going to be 50 MCM and 172 MCM by the years 2074 and 2099 respectively while at high population growth rate the unmet water demand shall be 229 MCM and 1340 MCM by the years 2074 and 2099 respectively. This indicates that with increasing population, it is going to be difficult for the government to meet the water demands of the growing population.

Climate changes affect many factors like reservoir inflows. Impacts of climate change under low population growth rate are assessed using the RCP 4.5 (low emission) and RCP 8.5 (high emission) climate scenarios for the period reference of 2015-2100.

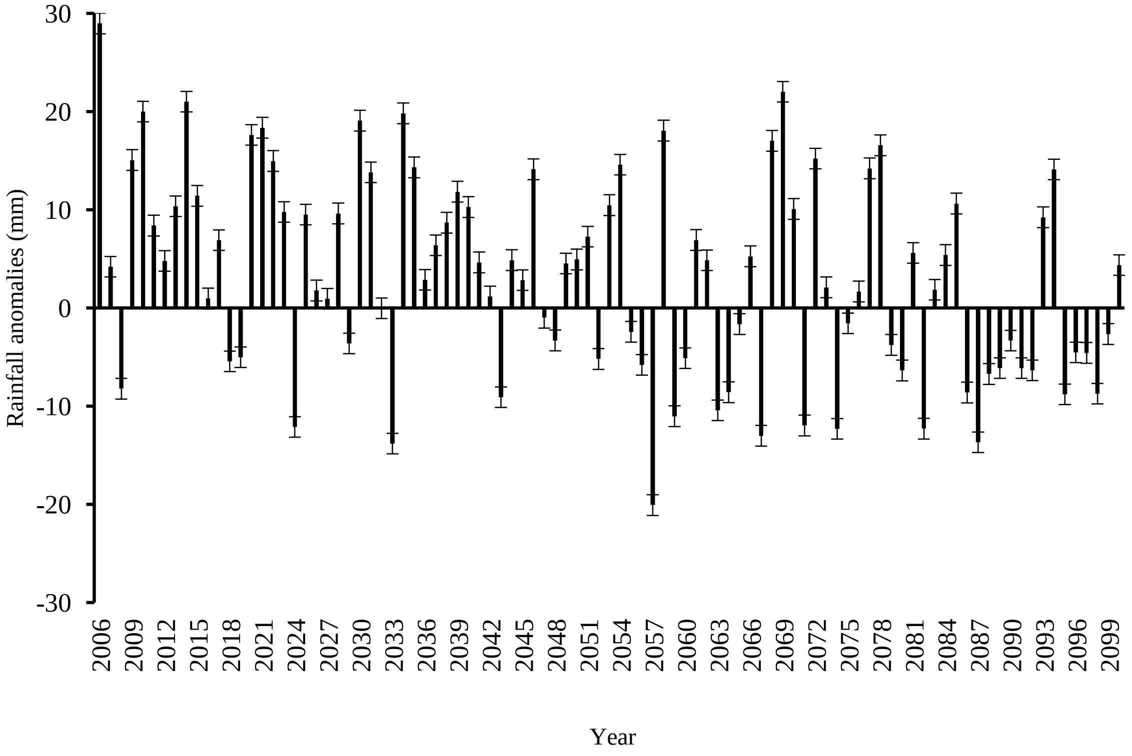


Figure 24. RCP 4.5 rainfall anomalies from the mean (1981-2020).

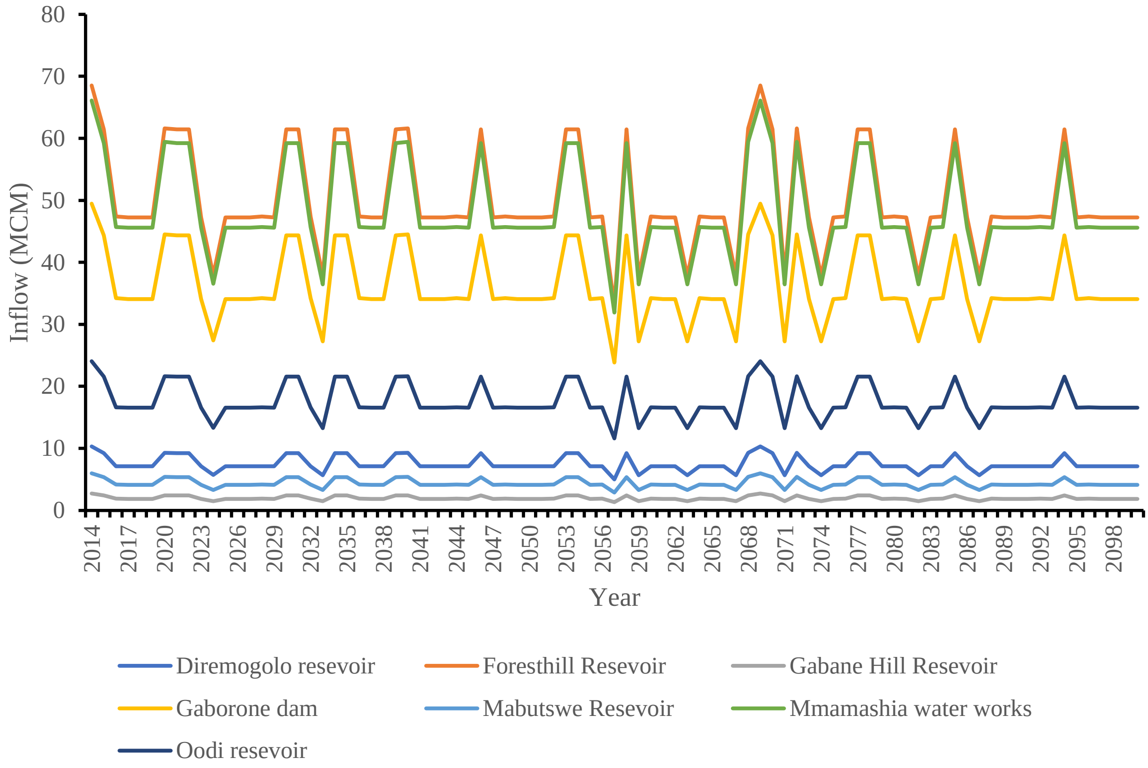


Figure 25. RCP 4.5 future reservoir inflows.

Figs 24-25 indicate the rainfall anomaly under RCP 4.5 scenarios from the mean of (1981-2020) and projected reservoir inflows under the RCP 4.5 climate scenario respectively. The RCP 4.5 anomalies indicate that there will be fluctuations in the reservoir inflows particularly between the years of 2070 and 2100. This trend will therefore affect the future reservoir inflows as depicted in Fig.24. Gaborone dam for example shall experience fluctuating inflows of 34.09 MCM in 2050, 27.28 MCM in 2070, 34.08 MCM in 2090 and 34.0 in 2100. These fluctuations in inflows could be attributed to climate change.

Fig. 26 shows the monthly average reservoir inflows with respect to the RCP 4.5 climate scenario at low population growth rate for the midterm period of 2030-2050 (a) and the long term period of 2070-2100 (b) respectively. The highest reservoir inflows will be expected from January to May while the lowest shall be in June. However, there will be a significant downward shift on the monthly reservoir inflows between the midterm period and the long term periods.

For example Gaborone dam will experience an average inflow of 3.9 MCM in January in the midterm while it shall experience reduced inflow of 3.7 MCM during the end term.

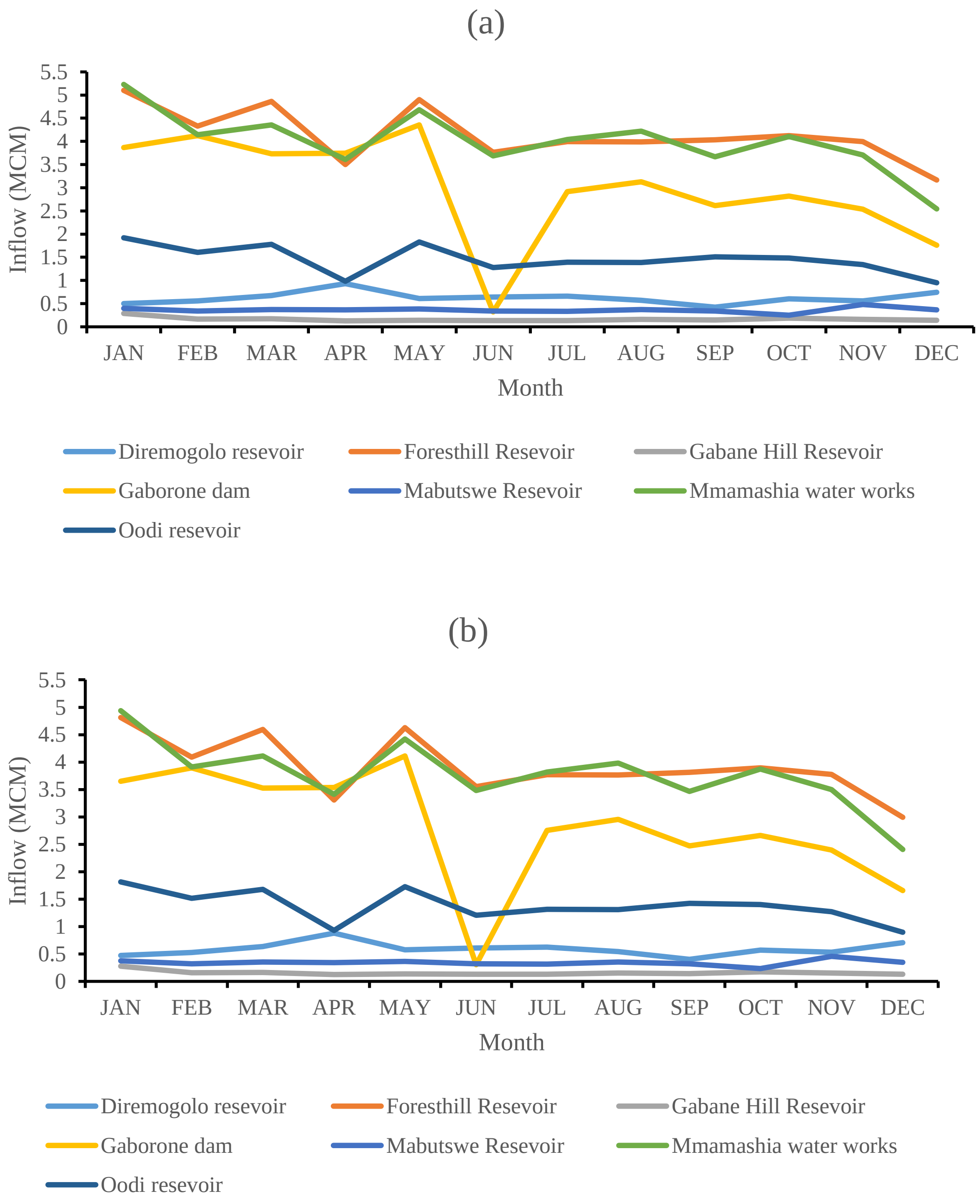


Figure 26. RCP 4.5 monthly reservoir inflows 2030-2050 (a) and 2070-2100 (b).

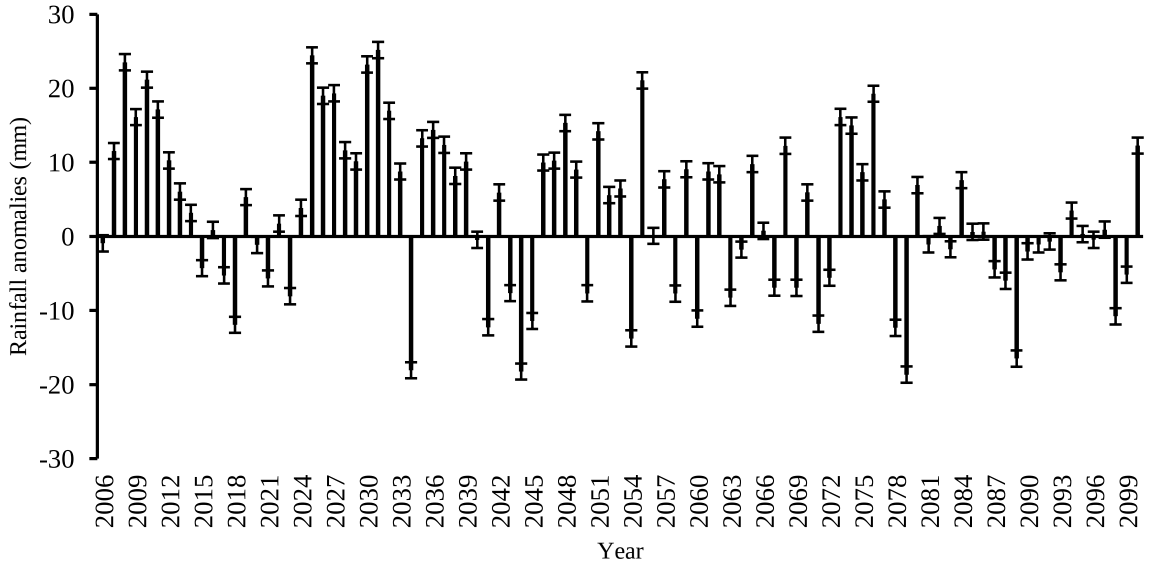


Figure 27. RCP 8.5 rainfall anomalies from the mean of baseline period (1981-2020).

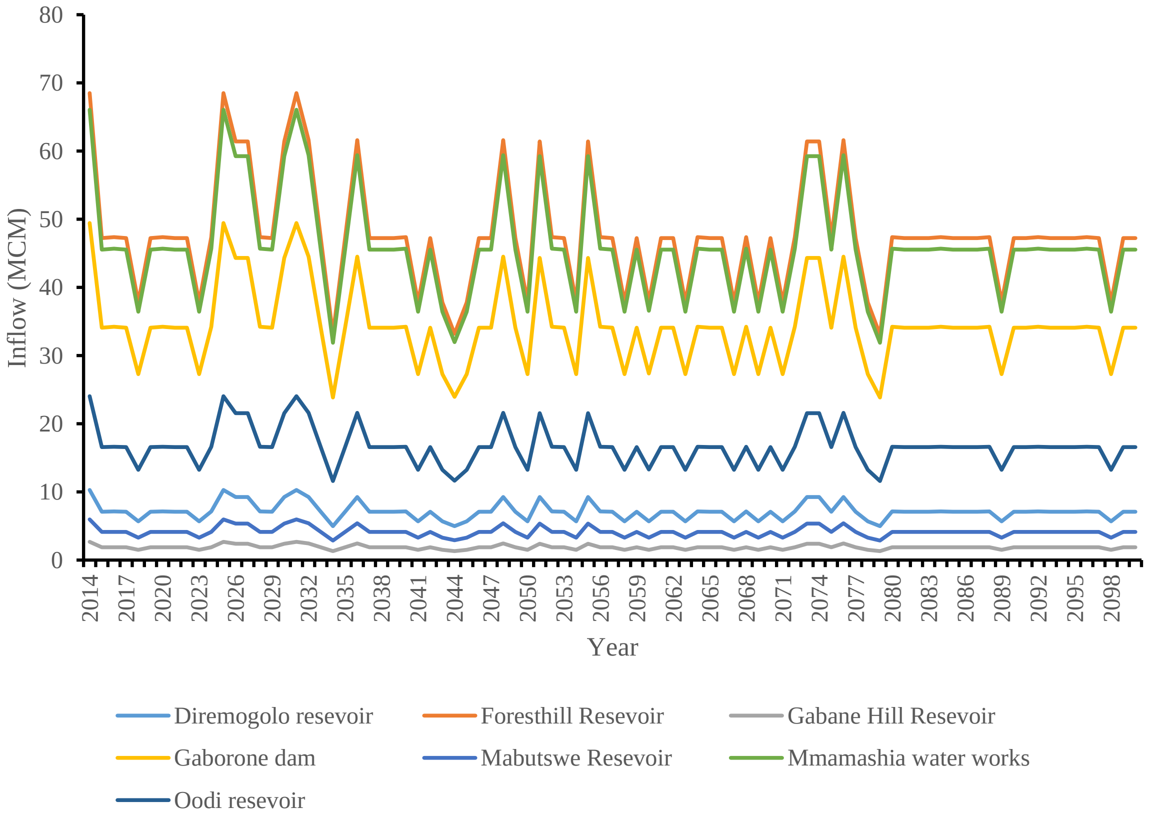


Figure 28. RCP 8.5 future reservoir inflows.

Rainfall anomalies under RCP 8.5 show a dry trend towards the end of the century (Fig. 27). However the rainfall under RCP 8.5 appears to be dryer than under RCP4.5. This is also depicted by the reservoir inflows which show a reduction in the inflows (Figs 28-29). For example Gaborone dam inflows shall be 27.3 MCM in 2050, 34.1 MCM in 2070, and 33.0 MCM in 2090 and 34.0 MCM in 2100.

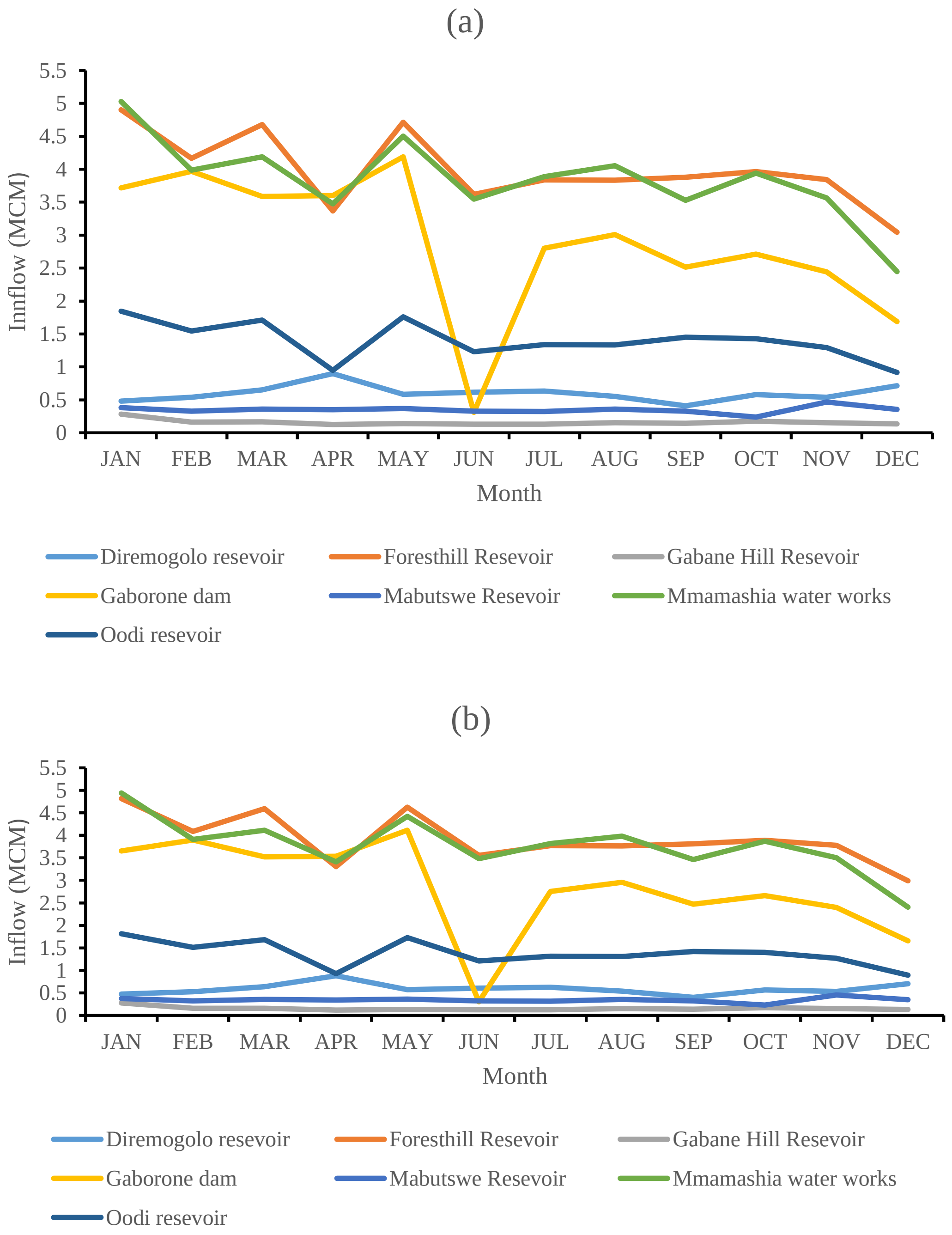


Figure 29. Mean monthly reservoirs inflow under RCP 8.5 during 2030-2050 (a) and 2070-2100 (b).

The monthly average inflows under RCP 8.5 show even more reduction compared to the RCP 4.5.In January, Gaborone dam is expected to experience an average inflow of 3.65 MCM for the midterm period (2030-2050) compared to 3.51 MCM for the long-term period.

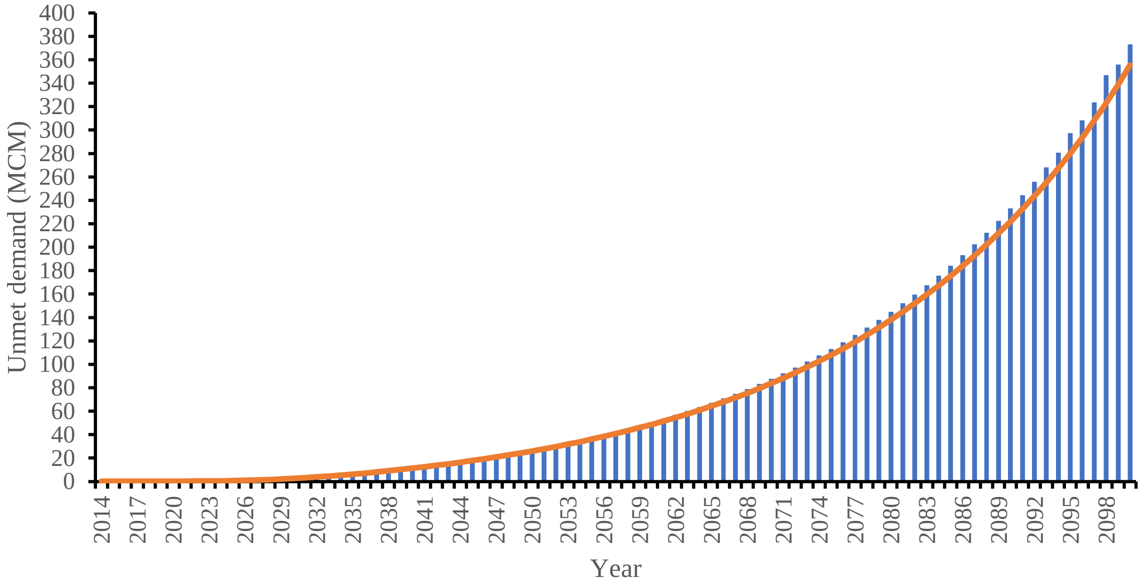


Figure 30. Unmet water demands at low population growth rate under RCP 4.5 (red) and RCP 8.5 (blue).

As illustrated in Fig. 30, the fluctuations and reductions in reservoir inflows lead to unmet water demand. The result of the RCP 4.5 climate scenario at low population growth rate for the whole study area indicate that the unmet water demand will increase from 25.9 MCM in 2050 to 355.2 MCM in 2100. For the RCP 8.5 the unmet water demand shall increase form 26.8 MCM to 373.2 MCM

Figs. 31-34 show the future reservoir inflows versus unmet water demands for all the demand sites for both the RCP 4.5 and 8.5 climate scenarios at high population growth rate. The high population growth scenario under RCP 8.5 shows that the unmet water demand of the whole study area will be 88.04 MCM in 2050 as compared to 3666.11 MCM in 2100. However that of the RCP4.5 scenario indicates that the unmet demand will be 84.65 MCM in 2050 as compared to 3569.95 MCM by the year 2100. These results therefore are consistent with the fact that the RCP8.5 emission scenario is drier than RCP4.5. The whole results therefore clearly indicate that the unmet water demand in both high population growth and the dry climate of RCP8.5 climate change scenario will lead to severe shortage of water in the city and its surroundings.

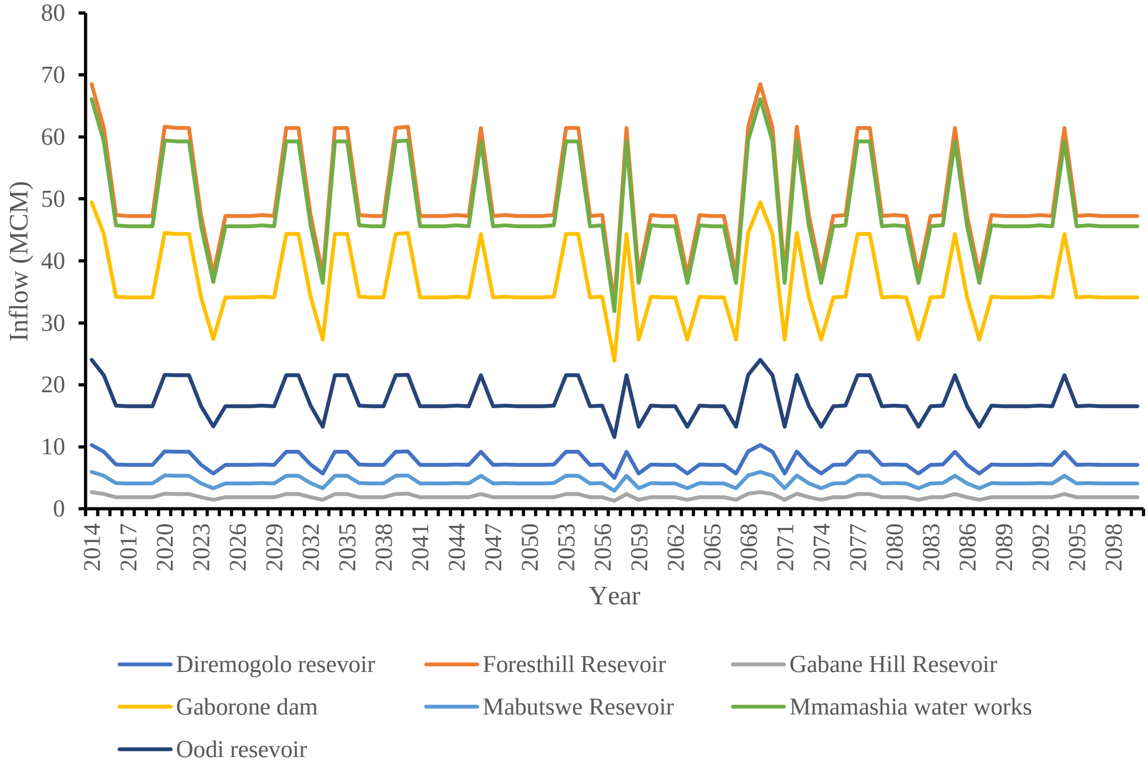


Figure 31. RCP 4.5 Future reservoir inflows at high population growth.

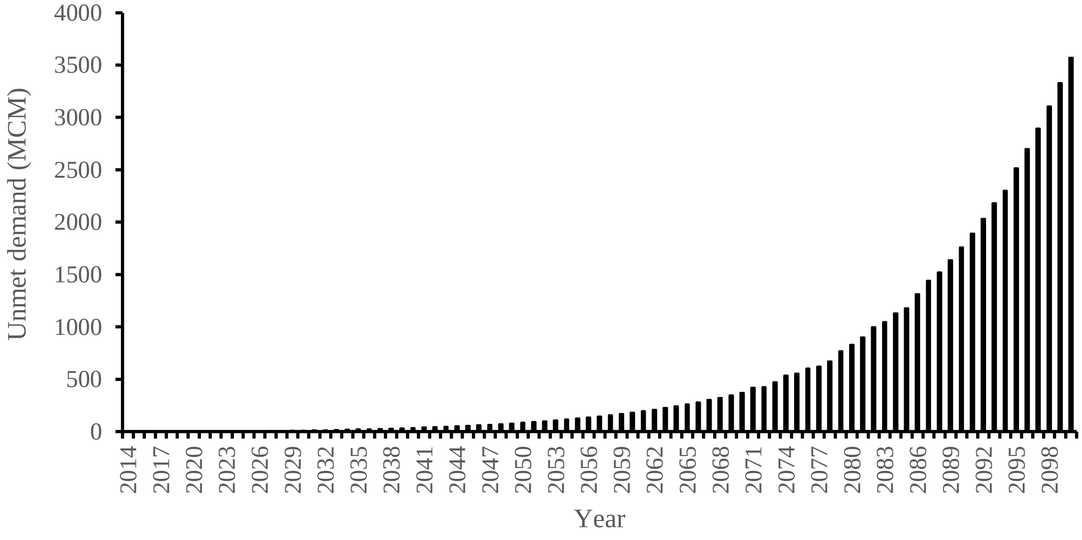


Figure 32. Unmet water demand under the RCP 4.5 climate scenario with high population growth rate.

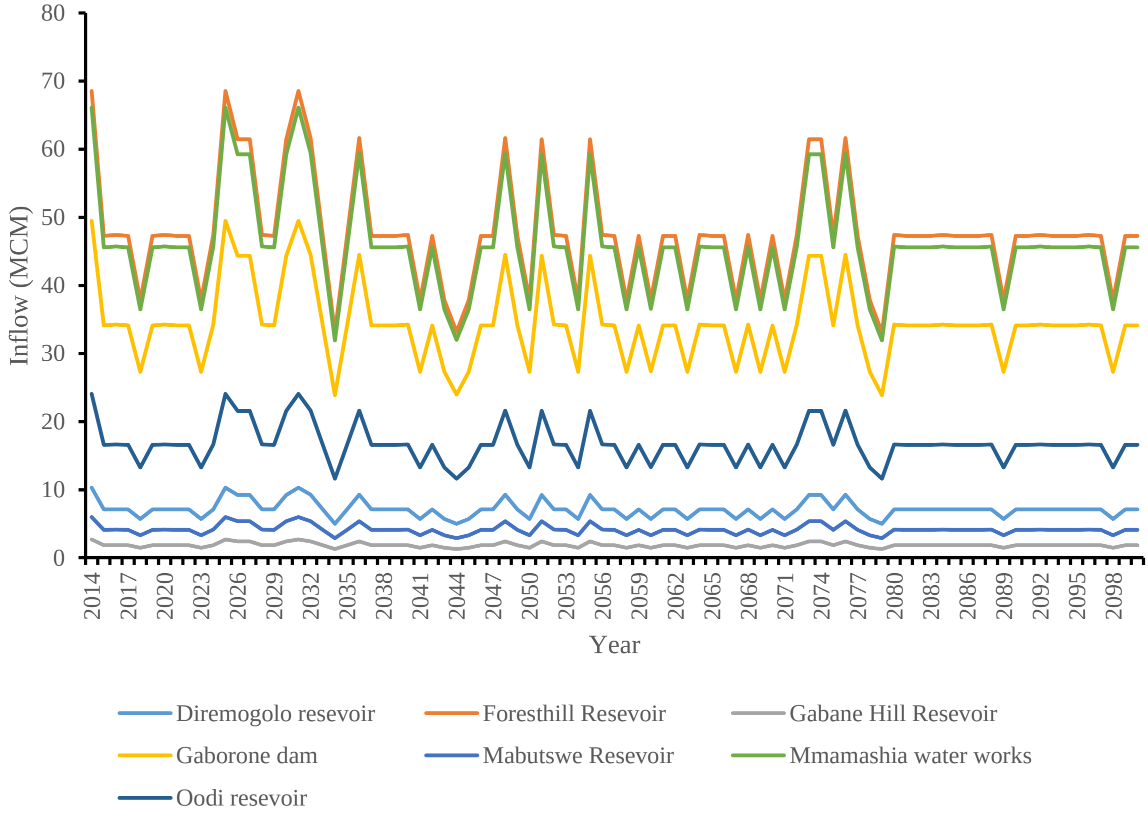


Figure 33. RCP 8.5 future reservoir inflows under high population growth rate scenario.

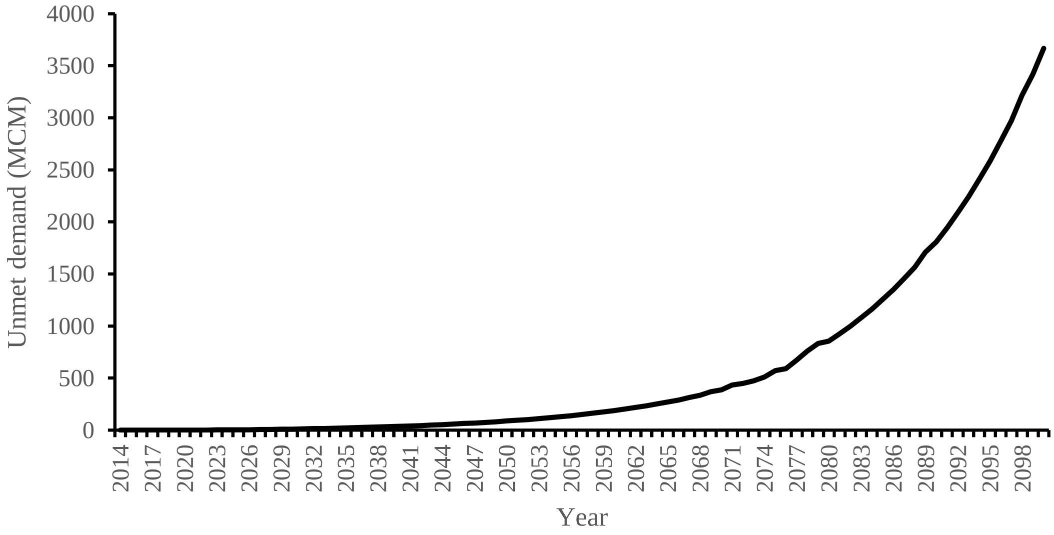


Figure 34. Unmet water demand under RCP 8.5 climate and high population growth scenarios.

It is vital to comprehensively understand water consumption behaviour as it is necessary for the establishment of effective water use strategies. Water usage habits are processes that are affected by a number of factors such as seasonal fluctuations and water availability , restrictions in water supply , use of water tariffs and pricing , household characteristics and water conservation attitudes and intensions (Fan et al., 2013). Such factors influence water usage patterns (Jorgensen et al., 2009).

These results show that Gaborone as an urban city experiences higher consumption rates than any other demand node. This is because of factors such as high population numbers, increase in industrialisation (for example, construction of more commercial and business districts (CBDs) to increase business opportunities), irrigation for agriculture and many others. All of these factors combined lead to the increment of water demand.

Water reservoirs are the basic elements of water supply. Reservoir inflows are mostly affected by the world’s hydrologic cycle and meteoric factors such as rainfall, snow, topography and geology of watersheds, vegetation cover and natural disasters such as extreme droughts and floods (Imanshoar et al., 2014). In a system, all basic functions of a reservoir can be used for water conservation, flood monitoring, and treatment of water and aquatic ecosystems. Gaborone water management centre depends mostly on the Gaborone dam, Mmamashia water works, Diremogolo, Gabane hill, Foresthill, Mabutswe and Oodi reservoirs. Reservoir storage capacity and the inflow volume are considered to be directly proportional. That is, the higher the reservoir capacity, the higher the inflow volume. As such, Gaborone dam and Mmamashia water works receive the highest inflows as they are of a bigger capacities than the rest of the reservoirs. Mmamashia water works receives water from dams such as Dikgatlhong and Letsibogo which are on the northern side of the country and they depend mostly on rainfall for water accumulation. The inadequate supply of water by these water reservoirs leads to an increase in unmet water demands. Unmet water demand is caused by poor supply of water which is influenced by numerous such factors such as water losses through poor infrastructure i.e. pipe bursts and leakages which reduce the amount of water in the pipes before it reaches its final destination and climatic factors such as precipitation and others. Increase in population also leads to increased unmet water demand. The consumption rates remain higher over the years due to the observed consistent growth in population as well as improvements of lifestyles resulting in higher levels of consumption. That is, the growing population and industrialization rates will soon overpower the ability of the water utilities corporation to adequately supply water. This may therefore lead to death of people and plant species from lack of water. This therefore calls for various water demand management strategies such as water re-use.

Water demand models are critical tools needed for analysing and forecasting urban water demand. In many cases, models are utilised as decision making tools. These models however their own uncertainties have and therefore need to be validated. The WEAP model was utilised for this study. For calibration, parameters such as crop coefficients for maize (K_c), hydraulic conductivity, runoff resistant factor, soil water capacity, root zone conductivity and observed climate data were used so as to assess the model's ability to adequately simulate the catchment's water balance. Parameters such as surface runoff, precipitation, relative soil moisture and base flow were simulated well by the model with seasonal variations captured very well. For validation, the observed streamflow of Notwane River was compared with the WEAP simulated stream flow and a good correlation between the two was observed. This therefore is an indication that WEAP is generally a model that performs well and can be relied upon for decision making.

Population or demographic assessments are of outmost importance as they help decision makers to predict demand based on the assumptions that the existence of certain characteristics or circumstances is an indication of future demand for services. Population forecasts are an important data source in predicting future needs and placing those needs within the context of general population change. For this study, the baseline period was 2014 and the population was projected at both 2.2% (low population) and 3.4% (high population) growth rates as per the Central Statistics office, Botswana.

Currently, Gaborone experiences higher water consumption rates than other areas in the Gaborone water management centre. This is mainly because of its higher population and industrialisation rates. However, Mogoditshane is more urbanised than other villages i.e. has more or high water consumption as compared to other major villages. This may be because Mogoditshane serves as a satellite settlement for Gaborone city, hence the population is higher compared to other surrounding villages. Another reason for Mogoditshane high water consumption could be the presence of commercial and industrial institutions like the Botswana Defence Force (BDF).

Therefore these projected population figures will lead to a deficiency in the availability of water in most of the demand nodes. At lower population growth rate, Gaborone shall have unmet water demand of 12 MCM in 2050 (mid-term) and 172 MCM in 2100 (long term). This therefore calls for the government and water authorities to come up with water efficiency plans that will help tackle such future situations.

Climate change disrupts the water cycle and precipitation hence affecting the supply of fresh water in most parts of the world. It has been recently found out that most of the climate change is influenced by anthropogenic activities that release greenhouse gases into the atmosphere. The RCP 8.5 scenario is viewed as the worst scenario in which emissions continue to grow at a higher rate throughout the early and mid-parts of the century (Furphy, 2015). This dry trend in RCP 8.5 scenarios will therefore affect the future annual reservoir inflows. The effect of climate change on reservoirs storage volume should be controlled and mitigated by supply measures that include enhancing the current reservoirs capacity and building new reservoirs. Water authorities have to device ways of storing both rain and storm water. Collection of rain water at house hold level and awareness about the advantages of such a system should be encouraged. Paved cities like Gaborone should have storm water dams that can be utilised for various purposes depending on the quality of water. The storm water may then be diverted to these dams using a network of storm drainage systems available.

5.3 Possible interventions to the projected water supply deficit

5.3.1 Loss control via technology advance

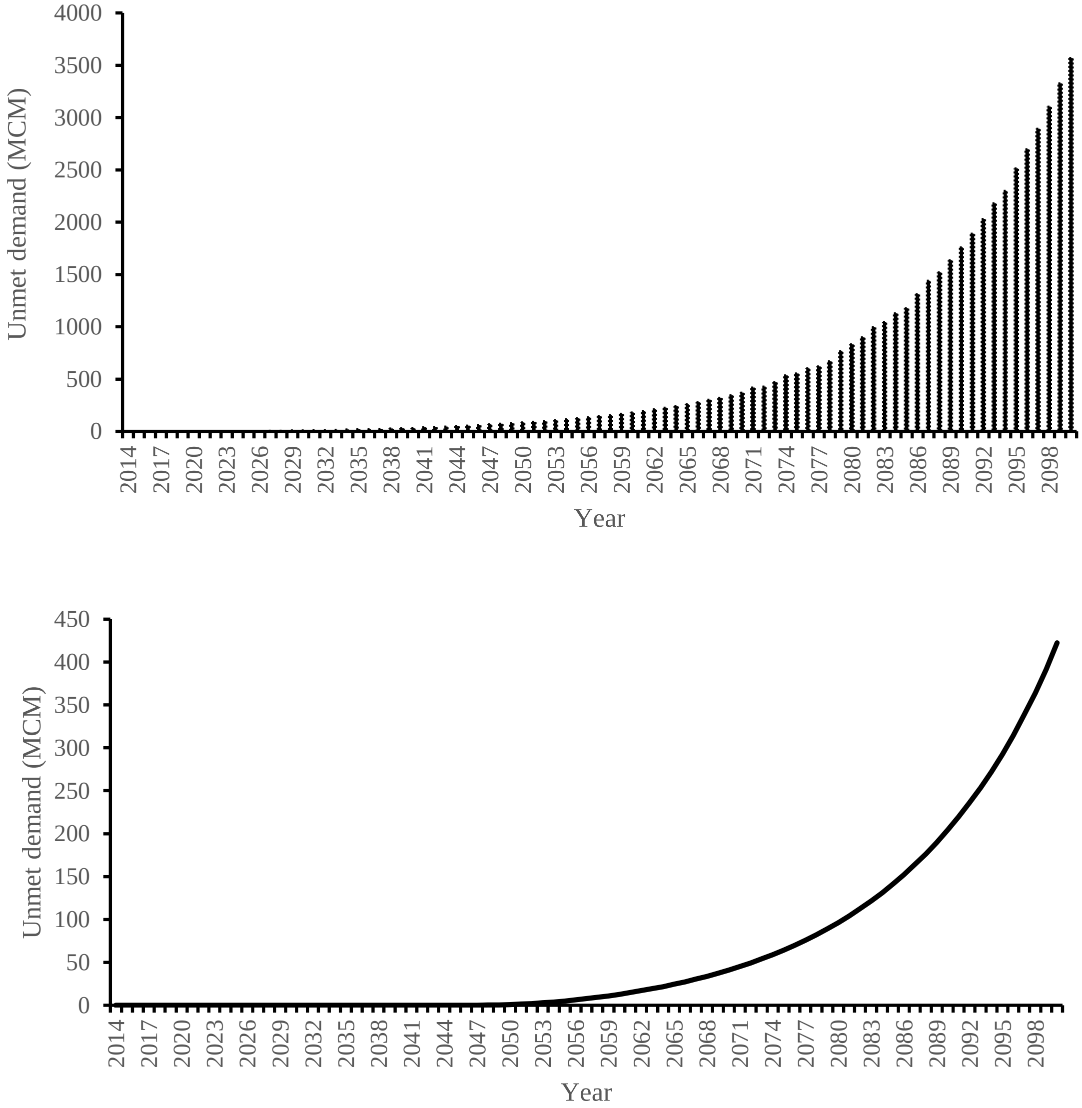


Figure 35. Unmet water demand under the RCP 4.5 at high population growth scenarios before loss control (top) and after loss control (bottom).

Fig. 35 shows the unmet water demands for the RCP 4.5 climate scenario (under high population growth) before (top panel) and after (bottom panel) water loss control efforts. It is clear that after reducing leakages in water transmission lines from the current 39% to 0% in 2100 there is a significant decrease in unmet water demand which suggests that it is possible to adapt to future climate change impacts. The unmet water demand could reduce from 3569 MCM to 422 MCM by the year 2100. This is an indication that with the constant efforts of reducing water leakages via proper pipeline and meter replacement strategies, unmet water demand could be reduced to some extent.

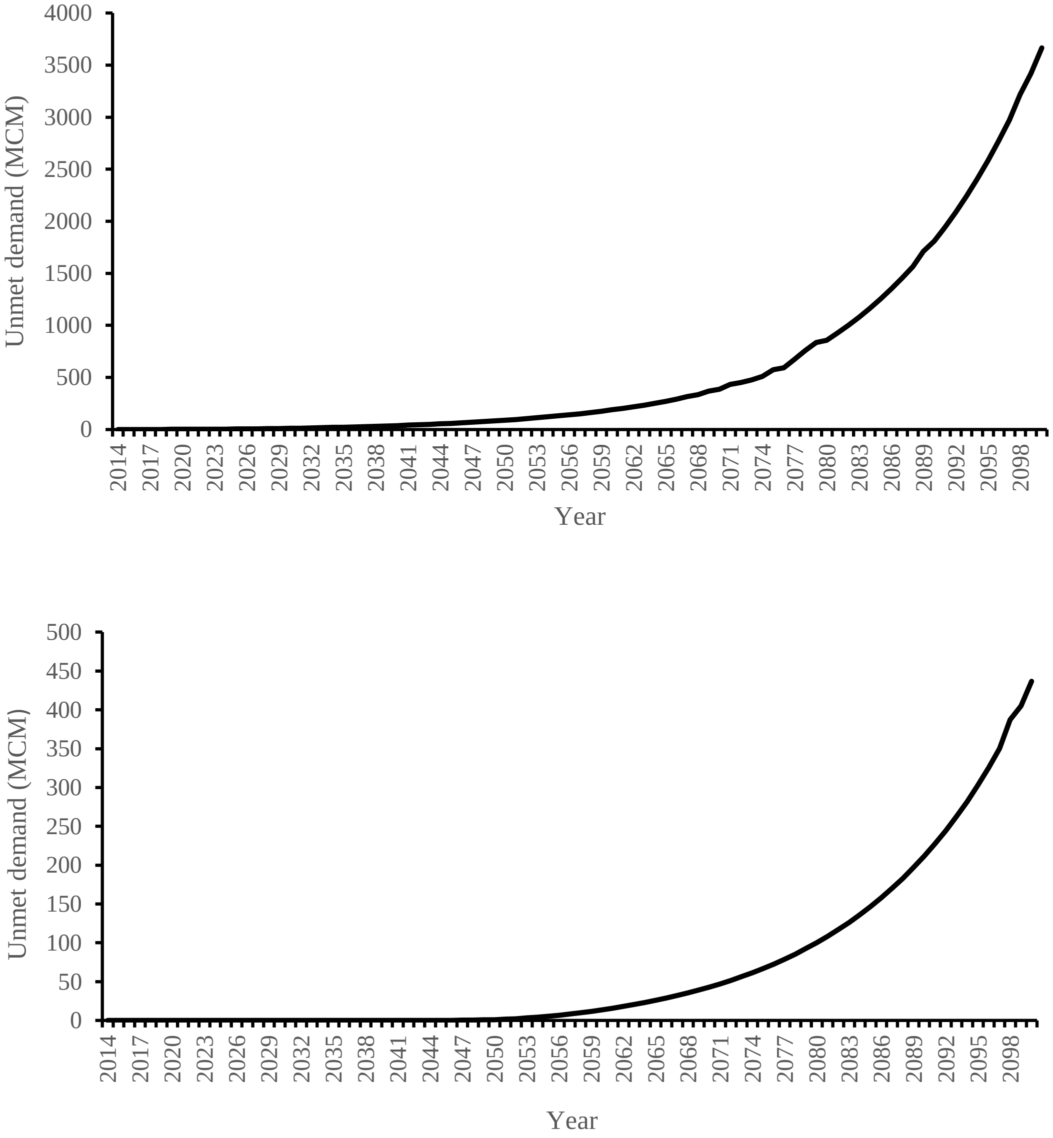


Figure 36. Unmet water demand under RCP 8.5 and high population growth before loss control (top) and after loss control (bottom).

Fig 36. shows the unmet water demand before (top panel) and after (bottom panel) loss control for the entire study period for the RCP 8.5 climate and population growth scenarios. The unmet water demand shall reduce from 3666.1 MCM to 436.89 by the year 2100. There is a tremendous opportunity of reducing water demand through proper maintenance of infrastructures. Evaporation loss control via placing concrete on top of water reservoirs is also an effort.

5.3.2 Water recycling

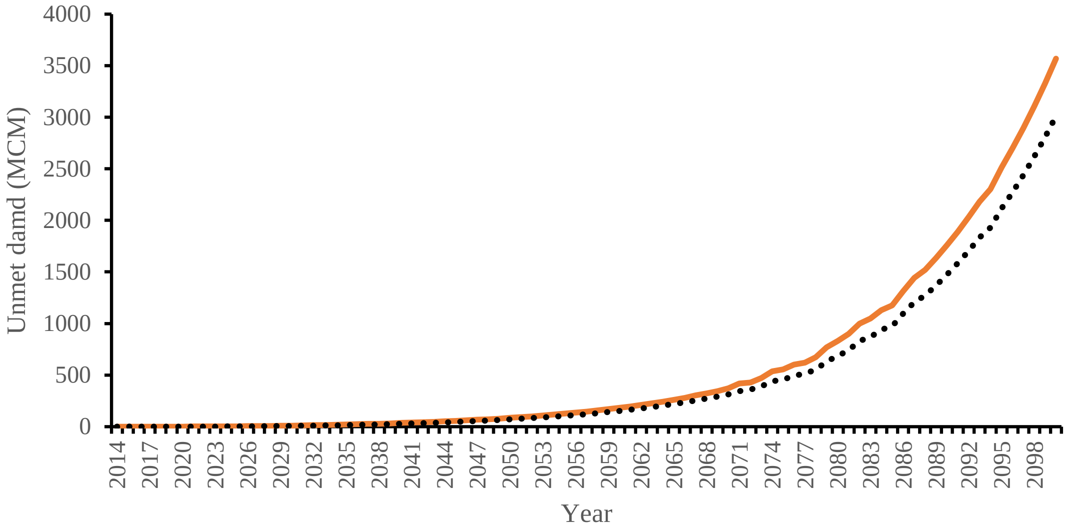


Figure 37. Unmet water demand under the RCP 4.5 climate and high population growth before (red) and after (dotted) recycling efforts.

Fig. 37 shows the projected unmet water demand before and after re-use under RCP 4.5 climate and high population growth scenarios. The unmet demand after re-using waste water by 5% each year could reduce from 3569.95 to 3012.87 MCM by the year 2100. According to a recent study, recycling waste water for agricultural purposes can outweigh the costs involved and reduce the overall demand of fresh water.

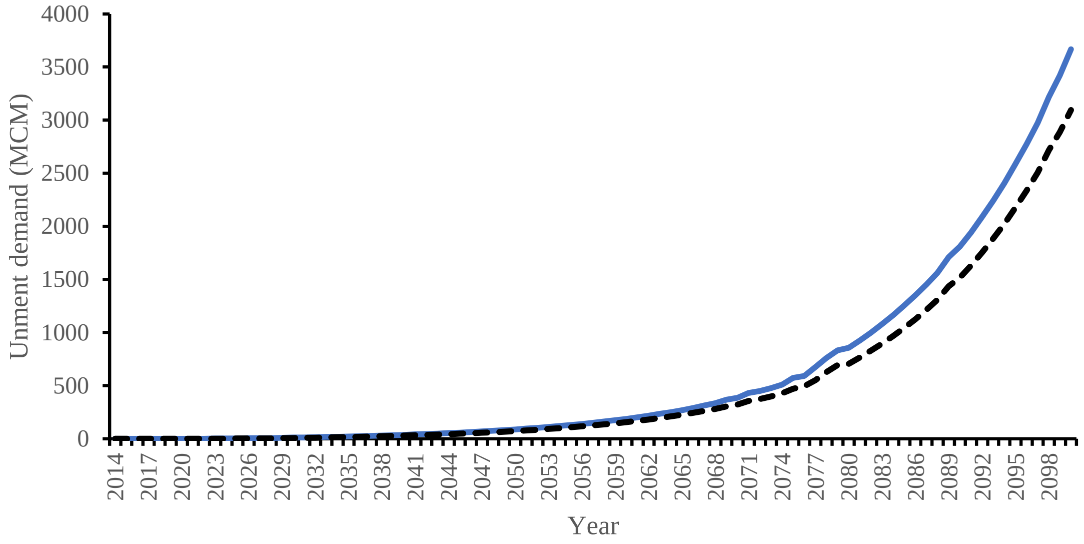


Figure 38. Unmet water demand under RCP 8.5 climate and high population growth scenarios before (blue) and after (black) recycling efforts.

Fig 38 shows that under the RCP 8.5 climate scenario with high population growth rate, the unmet demand for the whole study area shall reduce from 3666.11 MCM to 3094 MCM after re-use as a water demand management option.

Water losses also form part of the great water supply deficit that is experienced in most parts of the country. Higher water losses are experienced in bigger areas like Gaborone, Mogoditshane and Tlokweng. Gaborone experiences most of water losses followed by Mogoditshane and Tlokweng respectively. These areas are relatively larger than all the other areas, therefore the longer the distance water has to travel, the higher the chances of it being lost to the ground through pipes. Arntzen (2006) and Hambira (2007) linked the problem of the inefficiency of the distribution systems to inadequate infrastructure assessment and management. Weimer (2001) asserts that losses exceeding 15% are high and calls and need to be reduced. Coming up with water loss reduction measures could help with the constant efforts of reducing water leakages via proper pipeline and meter replacement strategies, unmet water demand could be reduced to some extent. To manage the ever increasing shortage of water, updating water tariffs would be a resolute action with seasonal increment of water prices. Since Botswana has ran out of dam sites, increment of the capacity of the available or existing water reservoirs is encouraged. Rain and storm water harvesting should be practiced at all possible times and people should be educated on the importance and scarcity of water at an early age.

CHAPTER 6. Summary and conclusions

As part of the efforts to evaluate sustainability and environmental integrity of the current surface water resources, this study has given a great deal of information on surface water resources, availability, potential demand and supply options under two climate and population scenarios for the city of Gaborone in the near, mid and long term time horizon. The study has also indicated possible mitigation options for the high water supply demand under the various scenarios. The two options indicated in this study are water loss control which is currently at 39% and increase in waste water reuse at annual rate of 5%. The fidelity of the data generated using WEAP model based on these scenarios has been ensured through model calibration based on observed stream flows. Generally the model has the potential of being a useful tool for water allocation decision making.

There is a critical need for a model validation process that can be utilised to asses model performance and create trust in the suitability of a model for decision making (Hassan, 2006). For validation, observed streamflow gauged data was compared with WEAP modelled stream flow data for the Notwane River. The results show that the WEAP simulated flow data of Notwane River station with the observed gauged data flow gives an EF of 0.91. Which means that a relatively good correlation between the modelled data and the actual data was observed. This therefore is an indication that WEAP is generally a model that performs well and can be relied upon for decision making.

Climate change disrupts the water cycle and precipitation hence affecting the supply of fresh water in most parts of the world. For this study, the RCP 4.5 (low emissions) and RCP 8.5 (higher emissions) climate scenarios were utilised to assess the impact of climate change on the supply of water. The results show that both the climate scenarios indicate dryness in the near future however the RCP 8.5 scenario appears to be drier between the years of 2080 and 2100. The RCP 8.5 rainfall anomalies from the mean of (1981-2020) shows a prolonged period of dryness of as low as (0mm to -24.3 mm) between those years. On the other hand, the RCP 4.5 shows that though it is going to be dry, there will be a bit of wetness ranging from (2 mm to 23 mm) as anomalies from the mean between the years of 2080 and 2100. This dryness will therefore affect the future annual reservoir inflows.

The result of the future reservoir inflows for the RCP 4.5 under low population growth rate show fluctuating inflows for most reservoirs. Gaborone dam for example shall experience fluctuating inflows of 34.09 MCM in 2050, 27.28 MCM in 2070, 34.08 MCM in 2090 and 34.0 MCM in 2100. Analysis of the monthly average reservoir inflows with respect to the RCP 4.5 climate scenario at low population growth rate for the midterm period of 2030-2050 and the long term period of 2070-2100 show that the highest reservoir inflows will be expected from January to May while the lowest shall be in June .There will be a significant downward shift on the monthly reservoir inflows between the midterm period and the long term periods. For example Gaborone dam will experience an average inflow of 3.9 MCM in January in the midterm while it shall experience reduced inflow of 3.7 MCM during the end term. The result of the RCP 8.5 under low population growth rate shows that Gaborone dam inflows shall be 27.3 MCM in 2050, 34.1 MCM in 2070, and 33.0 MCM in 2090 and 34.0 MCM in 2100. The result of the RCP 4.5 climate scenario at low population growth rate for the whole study area indicate that the unmet water demand will increase from 25.9 MCM in 2050 to 355.2 MCM in 2100.For the RCP 8.5 the unmet water demand shall increase form 26.8 MCM to 373 MCM.

The result of the future reservoir inflows for the RCP 4.5 under high population growth rate is still the same fluctuating inflows for most reservoirs. Gaborone dam for example shall experience fluctuating inflows of 34.09 MCM in 2050, 27.28 MCM in 2070, 34.08 MCM in 2090 and 34.0 MCM in 2100. Similarly the result of the RCP 8.5 under low population growth rate shows that Gaborone dam inflows shall be 27.3 MCM in 2050, 34.1 MCM in 2070, and 33.0 MCM in 2090 and 34.0 MCM in 2100. However the result of the unmet demand under both scenarios with high population growth shall increase. The high population growth scenario under RCP 8.5 shows that the unmet water demand of the whole study area will be 88.04 MCM in 2050 as compared to 3666.11 MCM in 2100. However that of the RCP4.5 scenario indicates that the unmet demand will be 84.65 MCM in 2050 as compared to 3569.95 MCM by the year 2100. These results therefore are consistent with the fact that the RCP8.5 emission scenario is drier than RCP4.5. The whole results therefore clearly indicate that the unmet water demand in both high population growth and the dry climate of RCP8.5 climate change scenario will lead to severe shortage of water in the city and its surroundings.

These possible future unmet water demands therefore call for strategic water management strategies. The results show that with the efforts of water loss control via technology advance (reducing leakages in transmission lines from the current 39% to 0% by 2100) the unmet demand under RCP 4.5 with high population growth scenario could reduce from 3569 MCM to 422 MCM in 2100. Similarly for the RCP 8.5 under high population growth scenario, the unmet demand could reduce from the 3666.1 MCM to 436 MCM. This is an indication that there is a tremendous opportunity of reducing water demand through adequate maintenance of infrastructure. Water recycling is another good way of dealing with increasing water demands. The result of the RCP 4.5 with high population growth scenario show that future unmet demand could reduce from 3569 MCM to 3012 MCM by 2100. That of the RCP 8.5 under high population growth scenario shows that the unmet demand could reduce from the 3666.1 MCM to 3094 MCM after water recycling efforts.

Given the increasing rates of industrialisation, rural urban migration, reduced mortality rates due to medical advancements, increases in birth rates and many others, the population of Gaborone and surrounding is expected to increase by more than 10 fold by the year 2100. This increase in population will then lead to increased water consumption and demand. However, it is observed that more water is consumed during the winter season than any other seasons. Therefore more water management options should be considered at that time of the year. Water reservoir inflows and outflows are also influenced by the climate of Botswana, in which more inflows are experienced during the rainy season of October to March.

For the study area, the RCP 8.5 scenario is found to be drier than the RCP 4.5 scenario. The effects of climate change on reservoir inflow should be managed by building more reservoirs and increasing the capacity of existing reservoirs to increase more chances of rainfall harvesting. Water loss is also one of the major concerns in the Gaborone water management centre which should be significantly reduced with proper infrastructural and pipeline management. This modelling study has clearly shown that loss control can offset the unmet water demand due to impact of climate change and population growth significantly. Other management options include, tariff increments, encouragement of water re-use and educating people about climate change impacts and ways of mitigating it and the importance and scarcity of water. In this study, it has been demonstrated that appreciable quantity of water can be saved by implementing water reuse procedure and mechanisms in various economic sectors. In other studies, water tariff can also be used as a control tool to reduce unnecessary waste of water.

CHAPTER 7 Recommendations

As the study has provided useful information on future water resource management for the City of Gaborone and its surrounding areas, the following recommendations could be considered:

- When unmet demand increases, water supply coverage will decline. This therefore is an indication that dependence on surface water resources alone is not sufficient to satisfy the demands. Therefore the encouragement of waste water re-use, use of ground water resources and construction of ground water resources should be part of the solutions for long-term water use sustainability.
- Water reticulation facilities should be maintained on a regular basis to reduce water losses. Moreover, education about the value and scarcity of water among citizens is also essential for increased efficiency.

- Finally, more studies may be required using additional water demand management models such as MODISM (modular simulator model), RIBASIM (River Basin Simulation Model), REALM (Resource Allocation Model) and many others. The use of several models will help to identify suitable model(s) for Botswana in terms of their performance. Moreover, Intercomparison of models can also help in understanding key processes that affect water resource availability and usage.

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