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Simulation and Evaluation of Water Supply Reservoirs Using HEC-ResSim Model and RRV Indices in the Notwane Catchment

A Thesis Submitted to the Department of Geology in Partial Fulfilment of the Requirements of the Master of Science Degree in Hydrogeology

by:

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DECLARATIONS

I declare that this work is my original work and references have been made where ideas have been borrowed from other sources and the respective authors acknowledged. I declare that this work has never been submitted anywhere for any award.

Signature of Author..

Edmore Otsile Keaitse

Date.......................................

This dissertation has been submitted for examination with my permission as a University of Botswana supervisor.

Signature of the Supervisor..

Prof. B.F. Alemaw

Date……………………………………

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ABSTRACT

Botswana has gradually developed its water resources at great expense but it is estimated that as much as half of it is wasted through leakage, lack of water demand management, knowledge gap, inefficient management and operation practices and policies. Reservoirs are one of the most valuable tools for integrated water resource development and management. However, their operation and management are still a challenge for integrated water resource development and management. With the increasing population and rapid development of the economies, the function and operation of reservoirs has become more and more important to help meet society's energy and water requirements. Models are usually developed and used in order to facilitate decision-making.

Simulation models strive to fill the knowledge gap, cross check analyses, support and address water resource development and management decisions. HEC-ResSim Model is one such model used to simulate the water resource system in the Notwane River Basin. It is a public domain model that enables easy sharing of knowledge and data among researchers. The base line scenario is configured in such a way to represent the current infrastructure and known management practices and calibrated with historical hydrological regime. The model is calibrated and its performance is checked using Nash-Sutcliffe efficiency and Coefficient of Determination, (R^2), at key stations. The model calibration is satisfactorily accepted as the values for R^2 and for NS coefficient for the fit of the daily water levels for the calibration period are 0.81 and 0.60 respectively and 0.62 and 0.27 and 0.54 and 0.39 respectively for the Bokaa, Gaborone and Nnywane dams in that order.

Different scenarios including climate change, population growth, sedimentation and operation schemes for each dam have been simulated for the period of 2015 to 2050. These scenarios are analyzed and evaluated by comparing the reliability, resilience and vulnerability indices (RRVs) on the dam's release capabilities. As introduced by Hashimoto et al. (1982), RRV metrics measure different aspects of a water resources system performance. Together, RRV metrics provide one of the most comprehensive approaches for analysing the probability of success or failure of a system, the rate of recovery of a system from unsatisfactory states, as well as quantifying the expected consequence of being in unsatisfactory states for extended periods. Assessing these comprehensive metrics at current (baseline) and future scenarios provide insight into system performance in changing or varying conditions. Outputs from the HEC-ResSim model were then used to define criteria over which the RRV and other metrics were evaluated. Results from the simulation indicates that the scenario of Population Growth greatly lessens the reliability of the Gaborone, Bokaa and Nnywane reservoirs by 66, 2 and 49 % respectively on average while sedimentation on the dams negatively affect the reliability of water supply by 30, 1 and 4 % respectively. The resilience of all scenarios for all the dams is very low expressing the low speed of recovery of the dams from failure states to satisfactory states. This is evidenced by a large number of days of maximum of unsatisfactory duration (demand not met) of about 284, 107, and 133 days for Gaborone, Bokaa and Nnywane dams. Lastly, the results indicate that the Bokaa dam is the least vulnerable followed by Nnywane and Gaborone dams. The significance of the study results will help in coming up with policies and rules which, if implemented, will promote efficient and sustainable planning, management and operation of reservoirs in the Notwane catchment.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND SYMBOLS

C	Criterion of the water system perfomance
BNWMPR	Botswana National Water Master Plan Review
CAR	Centre for Applied Research
cms	Cubic meters per second
CSO	Central Statistics Office
CZ	Central Zone
DEA	Department of Environmental Affairs
DGS	Department of Geological Surveys
DMS	Department of Meteorological Services
DRI	Drought Risk Index
DWA	Department of Water Affairs
EHES	Engineering, Hydrological and Environmental Services
E_t	Evaporation during period t
GWP	Global Water Partnership
GUI	Graphical User Interface
HEC	Hydrologic Engineering Centre
I_t	Inflow at period t
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
km^2	kilometre squared
LMB	Limpopo Mobile Belt
Ma	Million years
MAR	Mean Annual Rainfall

masm	metres above mean sea level
MCM	Million Cubic Meters
MLG	Ministry of Local Government
Mm^3	Million Cubic Meters
MMEWR	Ministry of Minerals, Energy and Water Resources
MOA	Ministry Of Agriculture
NSC	North South Carrier
NWMP	National Water Master Plan
NWMPR	National Water Master Plan Review
SMEC	Snowy Mountains Engineering Corporation
SMZ	Southern Marginal Zone
SUI	Sustainability Index
USACE	US Army Corps of Engineers
WEAP	Water Evaluation And Planning
WUC	Water Utilities Corporation
WR	Water Resources

CHAPTER 1

INTRODUCTION

1.1 Importance-background of the study

Surface water resources are the main source of water supply for urban areas in Botswana. Around 34 percent of the total water supply is from surface water, whereas the remainder (66 percent) is from groundwater (CSO, 2009). However, surface water accounts for 90 percent of the total supply of water in urban areas such as Gaborone, Lobatse, Francistown, and Selibe-Phikwe. According to Central Statistics Office (CSO, 2009), water from reservoirs and rivers yields about one-third to national water consumption.

Reservoirs are one of the most valuable tools for integrated water resource development and management. However, their operation and management are still a challenge for integrated water resource development and management. With the increasing population, climate change and rapid development of the economies, the function and operation of reservoirs has become more and more important to help meet society's energy and water requirements (Guo et al, 2011).

Hence simulation and optimization models are very essential. Models are usually formulated, developed, evaluated, analysed and utilized in order to facilitate decision-making. Various reservoir simulation, optimization and operation models and methods have been, are being proposed, and reviewed by numerous authors, nevertheless it is difficult to come up with a unique model or technique to solve the operation of reservoirs. The models are created to add to a better understanding of the real-world processes and provide invaluable information to aid decision-making processes. One of the scenarios in which these models can be applied is in simulating water resource systems in river basins rules and aid in the development of efficient and sustainable water management options policies for reservoirs. This research centers on contributing to the management and operation of the Gaborone, Bokaa and Nnywane dams by coming up with a fitting mechanism to augment and enhance the overall management of the reservoirs through the use of a simple simulation model (HEC-ResSim) to simulate different scenarios and its evaluation using reliability resilience and vulnerability (RRV) indices.

1.2 Problem Definition

The population of Botswana is growing rapidly from 941 027 people in 1981 to 1 326 796 people in 1991 and 1 680 863 in 2001 to 2 024 787 people in 2011, (CSO, 2012 and Statistics Botswana, 2011). The population of Botswana is growing (Table 2.4) and consequently the water demand is escalating, however supply sources are running out and sites for future development are more distant and therefore more expensive (DWA, 2013). Botswana has gradually developed its resources at great expense but it is estimated that as much as half of it is wasted through leakage, lack of water demand management and inefficient management and operation practices, (DWA, 2013). Currently population growth, climate change, rapid urbanization and development require proper water management tools to assist planning decisions and management of water resources infrastructure.

1.3 Research Objectives

The overall objective of the study is to simulate the operation of dams in the Notwane river basin to promote understanding and aid in their management and the evaluation of their performance.

1.4 Specific Objectives

- To come up with a simulation tool that can be used to easily and quickly identify good alternatives for reservoir management that can then be further refined or used in design and operational decision making.
- To simulate the impacts of climate change on the reservoirs of the catchment
- To assess the effect of population growth on the capability of the dams to meet the demand
- Look at the problem of an ever increasing sedimentation and its impact on storage
- Evaluate the readiness or reaction of the dams to an increase and decline of inflows
- To identify or suggest strategies or policies for management and operation of the water resources in the Notwane catchment
- To evaluate and compare the performance of the dams in the catchment using performance indicators.

1.5 Organization of the thesis

This research study is structured as follows:

Chapter 2 – Study Area Description

The area of study is in the Notwane catchment. A subbasin of the greater Limpopo river basin. This chapter describes the setting, water resources situation, climate and demography of the catchment.

Chapter 3 - Geology of the Study Area

This section expounds on the geological setting of the catchment and its influence on the water resources of the area of study.

Chapter 4 – Literature Review

The literature review for this research focuses on definition of simulation and optimization models for water resources systems, comparison of WR and reservoir simulation models and previous water resources modeling systems in the catchment.

Chapter 5 – Research Methodology

This chapter covers the methods and techniques that were used in the course of the research. It focuses on the description of the HEC ResSim model and its data requirements, collection and generation.

Chapter 6 – Model Evaluation and Application

In this chapter, model calibration and verification is accomplished after which the development of scenarios/alternatives is dissected.

Chapter 7 – Results and Discussion

Reliability, resilience and vulnerability index results of the simulations and their discussion is illustrated in his chapter.

Chapter 8 – Conclusion and recommendations

Conclusions and recommendations drawn from the simulation of the Notwane catchments dams.

CHAPTER 2

STUDY AREA DESCRIPTION

2.1 Description of the Study Area

The Notwane River sub-basin/catchment is located in south eastern Botswana bounded by latitude of 23° S and 25° S and longitude 25° E and 27° E encapsulating an area of approximately 18263 km^2 (Figure 2.1 and Figure 2.2). The Notwane sub catchment is part of the greater Limpopo Basin, which has Botswana, Mozambique, South Africa and Zimbabwe as the riparian states (Figure 2.1). The Notwane sub – basin constitutes about 4.4% of the entire Limpopo basin. The Botswana part of the Limpopo basin drains into the upper Limpopo River and it consists of the Notwane, Bonwapitse, Mahalapswe, Lotsane, Motloutse and Shashe sub-basins (Appendix A).

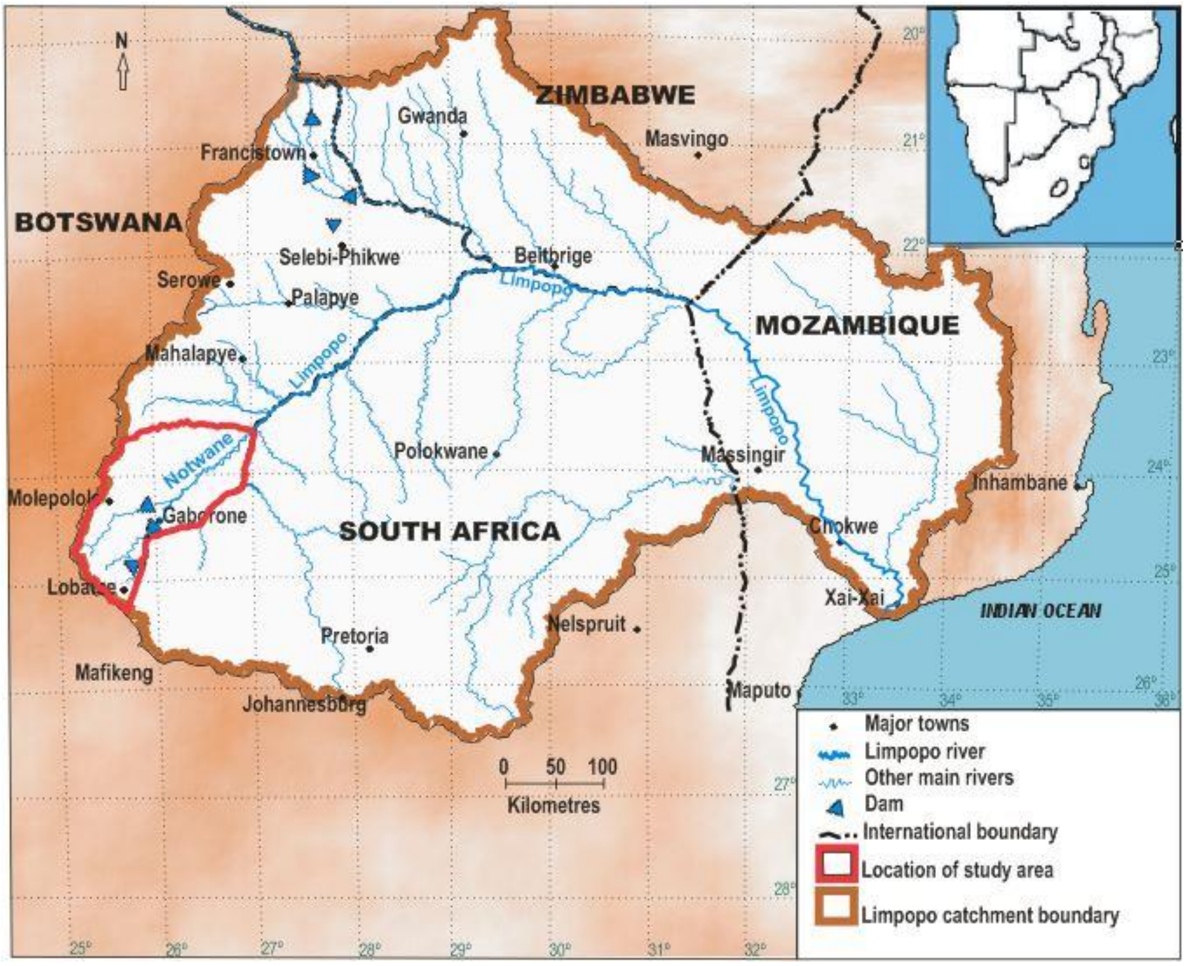


Figure 2.1: Limpopo basin hosting Notwane sub basin

The Notwane catchment has four districts, which are the Kgatleng, Kweneng, South – East and Southern districts, which host major settlements including Mochudi, Molepolole, Gaborone and Kanye respectively (Figure 2.2). In the sub basin, there are competing demands for water from domestic (both urban and rural), agriculture, mining, industrial and the now prominent environmental flows.

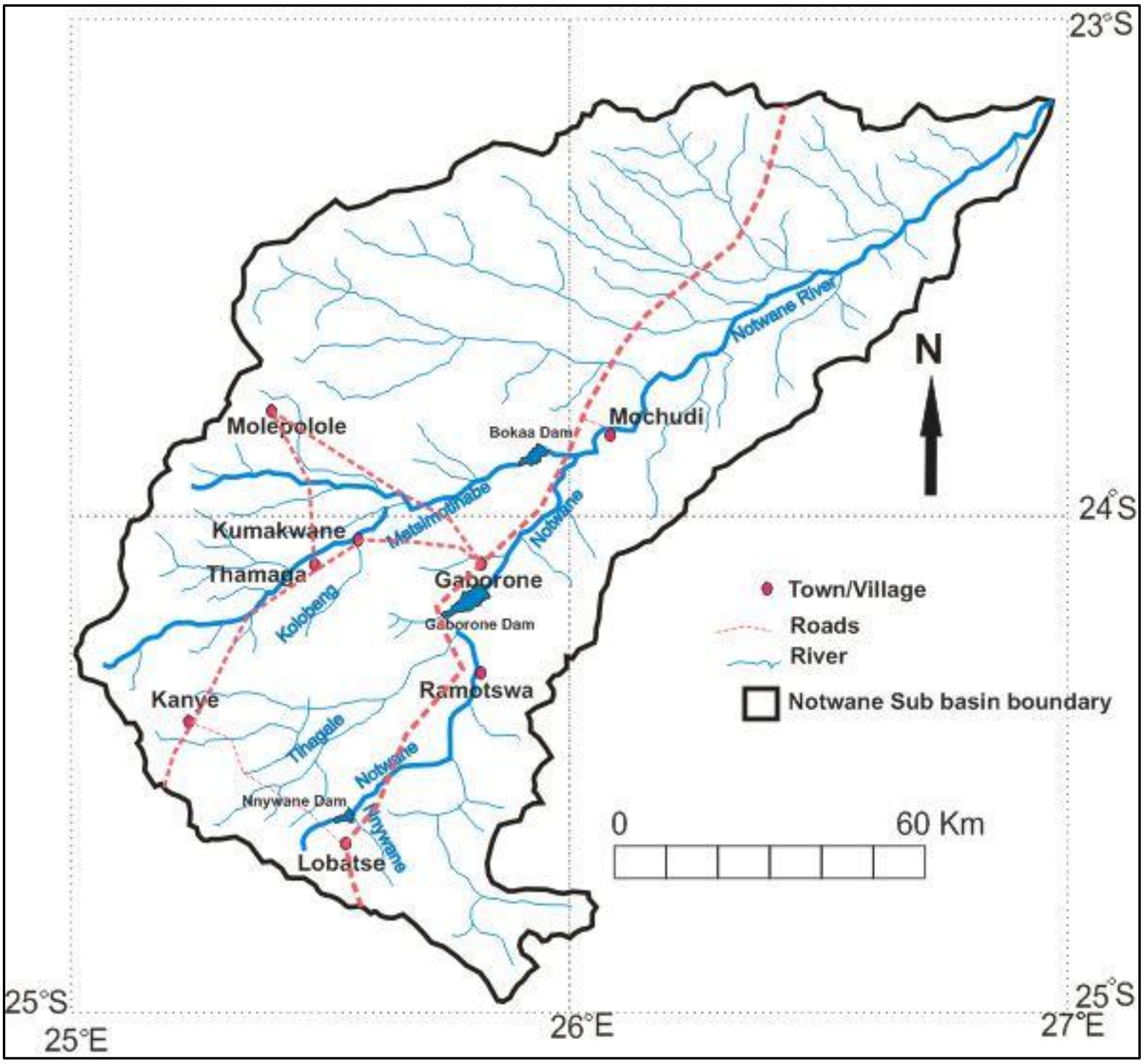


Figure 2.2: Notwane Sub basin and major towns

The Notwane sub – basin is drained by the Notwane River and its tributaries. The Notwane River stretches a distance of about 184km in a north – easterly direction where it crosses the border into South Africa, joining the Limpopo River (Figure 2.1). Along its course, the Notwane is fed by smaller tributaries including Segoditshane, Metsimotlhabe, Kolobeng and Tlhagale rivers as shown in Figure 2.2. The Notwane sub – basin hosts three dams, which are the Gaborone (141.5 MCM), Bokaa (18.5 MCM) and the Nnywane (2.3 MCM) dams, and are the main sources of domestic water supply to Gaborone and surrounding villages.

2.2 *Dams in Notwane*

The catchment has many dams of which most are small farm dams for livestock watering and small irrigation projects. The larger dams of Gaborone, Bokaa and Nnywane are managed by WUC for water supply purposes to the greater Gaborone area. Their characteristics are in Table 2.1 and their area – capacity curves are in Appendix A. Figure 2.3 shows the rivers flowing into the dams and their locations and some of the towns supplied by the dams in the Notwane catchment.

Table 2.1: Dams in the Notwane catchment and their parameters. Source: WUC

Dam Parameters			
Parameters	**Gaborone Dam**	**Bokaa Dam**	**Nnywane Dam**
Dam Type	Earthcore Fill	Earthcore Fill	Earthcore Fill
River dammed	Notwane	Metsimotlhabe	Nnywane
Year Constructed	1963, raised 1984	1993	1970
Full Supply Level (FSL)	EL 998 masl	EL 954 masl	EL 1135 masl
Spillway Length	272 m	690 m	80 m
Catchment Area	4300 km^2	3570 km^2	238 km^2
Active Storage	141.5 MCM	18.82 MCM	2.3 MCM
Surface Area (FSL)	19 km^2	6.6 km^2	1.65 km^2
Dead storage	3.71 MCM	0.25 MCM	0.002 MCM
Area supplied	Greater Gaborone	Greater Gaborone	Greater Gaborone
% contribution to area supplied	56 %	25 %	10 %
Greater Gaborone comprises: Gaborone, Lobatse, Mogoditshane, Tlokweng, Ramotswa and Mochudi			

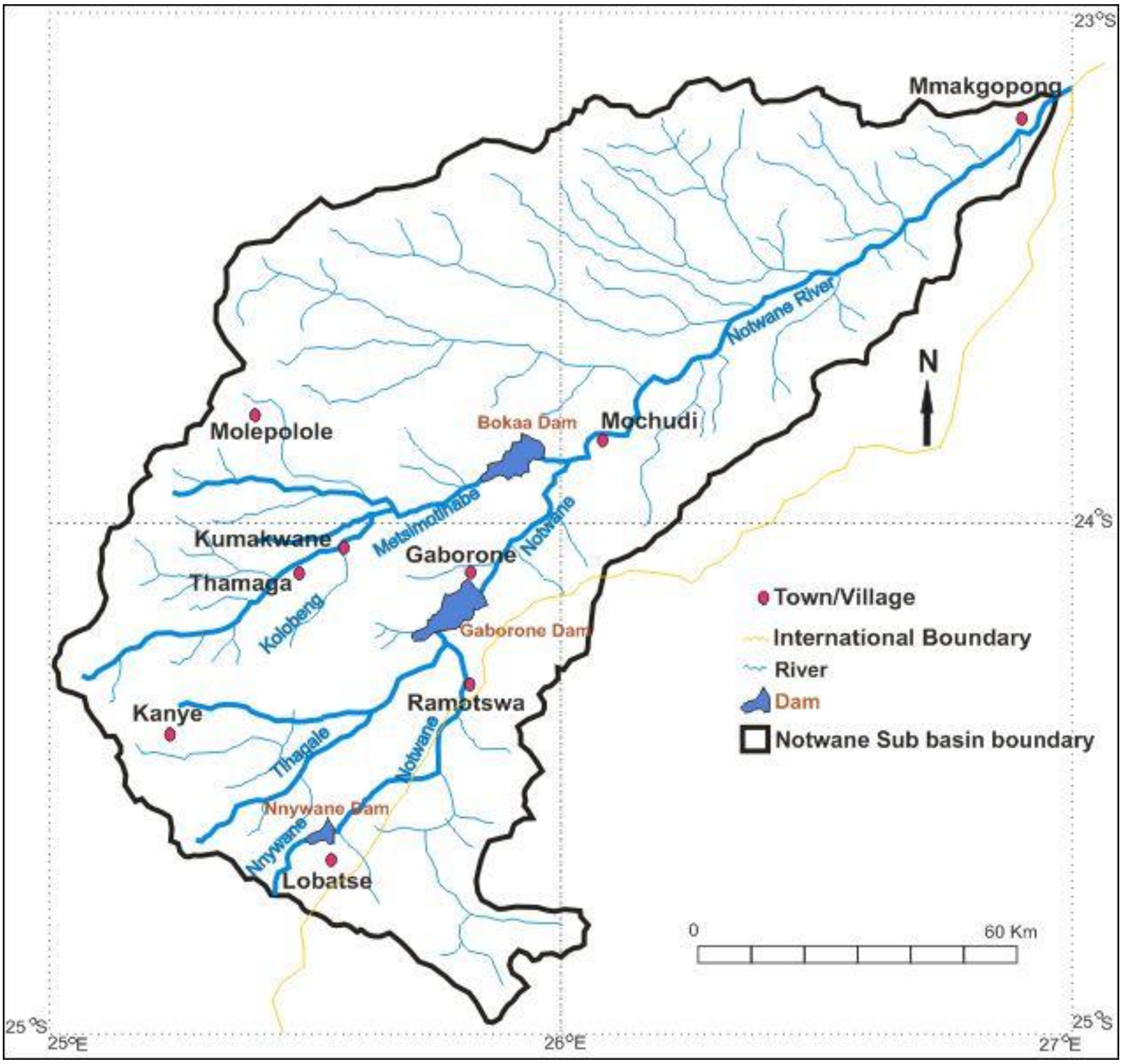


Figure 2.3: Dams and rivers in the Notwane catchment

2.2.1 Gaborone Dam

Operated by WUC, the dam has a capacity of 141.5 Mm^3 (Table 2.1) and supplies the greater Gaborone area consisting of the capital city and surrounding villages of Lobatse, Mogoditshane Cluster, Tlokweng, Ramotswa Cluster and Mochudi (Figure 2.3). Situated on the southern outskirts of the capital city, the Gaborone dam is now second largest and used to be largest in the country before the completion of the Dikgatlhong dam (Appendix A). The Notwane River is impounded to form the Gaborone dam (Figure 2.3). The average precipitation in the dam ranges between 450 mm to 550 mm. The Gaborone dam is an earthcore fill type of dam constructed in 1963 with the construction finishing in 1964. In the years between 1983 to 1985, the dam was raised by 7 m to reach a maximum height of 25 m and a length of 3.6 km. Its surface area is 19 km^2 and its catchment area is 4300 km^2 and contributes 56 % to the greater Gaborone area with the rest augmented by Molatedi in South Africa, Bokaa and Nnywane dams (Table 2.1). The dam has an annual yield of 10 Mm^3 (DEA & CAR, 2006).

2.2.2 Bokaa Dam

Bokaa dam was built in 1990/1991 across the Metsimotlhabe River, south of Bokaa village in the southern part of the country. The dam is about 20 kilometres north of the capital city of Gaborone (Figure 2.3). The Metsimotlhabe River is a tributary of Notwane River. Run by WUC, the dam was opened in 1993 with a capacity of 18.2 Mm^3 and provides water to the greater Gaborone area. The dam is an earth core fill structure and its catchment area is about 3.5 km^2 (Table 2.1). The dam wall is 14 m high and a surface area of 6.6 km^2. It was built as part of the Metsimotlhabe transfer scheme which delivers water to Gaborone Dam at a maximum rate of $11x10^6m^3/a$. The impoundment has a large surface area per unit of storage. Bokaa Dam is unable to contribute during severe droughts though generally it provides water when the inflows are high. The dam contributes about 25 % to the greater Gaborone area and its waters are injected to the NSCW pipeline. The reservoir is a habitat to most water birds, notably the special Southern Pochard (Birdlife Botswana, 2013).

2.2.3 Nnywane Dam

Nnywane dam is on the southeast of Botswana and dams the Nnywane River which is ephemeral. It is the smallest dam in the country with a capacity of 2.3 Mm^3 for purposes of water supply. The dam is closer to the town of Lobatse, which is 70 km away from the capital city Gaborone. The Nnywane River is a tributary to the Notwane River, which flows into the Gaborone dam (Figure 2.3). Opened in 1970, the dam is an earth-core fill type with a catchment area of 238 km^2 and surface area of 1.65 km^2. Managed by WUC, the dam was initially constructed to supply water to Lobatse but now supplies the greater Gaborone area.

2.3 *Water Resource Management*

The Notwane river basin supports a large population and significant economic activities in the southern part of the country. The major water user in the Notwane basin in Botswana is urban supply. The Ministry of Minerals, Energy and Water Resources (MMEWR) has the main responsibility for water resources in the catchment and the republic. The Ministry of Minerals, Energy and Water Resources (MMEWR) is responsible for policy formulation, planning, development, and management of water resources in Botswana; however, its portfolio also includes service delivery responsibilities (NWMPR, 2006a). This responsibility is discharged through the Department of Water Affairs (DWA), Department of Geological Surveys (DGS), and a parastatal, Water Utilities Corporation (WUC) and to a lesser extent the Ministry of Local Government (MLG) and the Ministry of Agriculture (MOA). DWA is the organisation indulging in the overall planning and development of water resources. The DWA is responsible for the overall water resources planning, investigation and construction including operation and maintenance of 17 major village supplies catering to 22.5 % of the country's population. It also designs and constructs rural village water schemes which are handed over to the respective district councils (DCs) for their operation and maintenance. The DGS is responsible for the overall assessment, investigation and monitoring of the groundwater resources. It interfaces on a broad front with the DWA, and maintains the database for the assessment of groundwater potential throughout the country. It also designates those drilling boreholes or conducting related operations to furnish information and records to the Director of DGS. WUC is tasked with water supply to the urban areas. There is no ‘national water resources manager’ responsible for the driving seat of Botswana’s water resources and therefore a lack of holistic approach to the water resources management (NWMPR, 2006a). The responsibility of water resources has been apportioned between these institutions for better management and planning.

2.4 *Hydrology*

The hydrology in the sub basin consists of both surface and groundwater resources. The surface water resources in the sub basin such as dams are paramount to the rapid growing capital city of Gaborone and the emerging densely populated areas of Tlokweng, Mmopane and Mogoditshane among a few surrounding the city and the other urban areas of Lobatse, Mochudi and Ramotswa. The groundwater resources are currently of supreme importance to the areas west of the catchment such as Molepolole and Kanye.

2.4.1 Surface Water Hydrology

The Notwane River is the major river in the sub basin and drains into the Limpopo River, which in turn drains into the Indian Ocean (Figure 2.1). Some sections of the river form the international boundary with South Africa. It rises south of Ramotswa and runs along the border in a north-easterly direction passing east of Lobatse and close to Gaborone. The Notwane River is dammed near Gaborone (Gaborone Dam) and provides the main source of domestic and industrial water for the city. Thereafter it joins Limpopo River 50 kilometres downstream of the confluence of the Marico and crocodile rivers. The Notwane catchment is drained by the Notwane River, Taung, Kolobeng, Tlhagale, Metsimotlhabe and Nnywane rivers which are ephemeral. The Metsimotlhabe River is the second largest river in the catchment found in the Kweneng district situated west of the catchment. It passes through the villages of Thamaga and Kumakwane south of Molepolole before being impounded at Bokaa Dam after which it joins the Notwane River near Morwa village (Figure 2.3). Nnywane River originates southwest of Lobatse and passes west of Lobatse before being impounded northeast of Lobatse to form the Nnywane Dam. After the dam the Nnywane flows into Notwane River which then enters South Africa and comes back to form the border between South Africa and Botswana before flowing north to Gaborone Dam. The three dams of Nnywane, Bokaa and Gaborone currently supply the greater Gaborone area and Lobatse however they are failing to meet the demand on their own (Table 2.1). They are assisted by the NSC water transfers from dams and Wellfields north of the country.

2.4.1.1 Water Consumption

Water consumption per capita in Mm^3 refers to the amount of water consumed over the population per year. Water consumption is an indicator for the pressure that the demand puts on the resources, however these has been fluctuating for Botswana. The major cause of these fluctuations could be climatic variations as it affects the per capita consumption [CSO] (2009). The water consumption per capita for major towns is shown in Table 2.2.

Table 2.2: Water Consumption per capita in Towns (m^3/d) (1998 – 2008) [WUC]

Year	Gaborone	Francistown	Lobatse	Jwaneng	Selibe-Phikwe	Sowa Town
1998	0.247	0.151	0.192	0.246	0.323	0.460
1999	0.175	0.115	0.148	0.175	0.252	0.263
2000	0.386	0.149	0.208	0.386	0.329	0.356
2001	0.288	0.208	0.252	0.288	0.539	0.482
2002	0.192	0.151	0.159	0.192	0.312	0.301
2003	0.255	0.159	0.205	0.225	0.471	0.332
2004	0.227	0.162	0.203	0.227	0.441	0.268
2005	0.211	0.167	0.164	0.211	0.463	0.257
2006	0.192	0.175	0.170	0.192	0.416	0.266
2007	0.208	0.170	0.192	0.208	0.422	0.214
2008	0.184	0.178	0.211	0.184	0.433	0.233

Botswana has seven operating dams which are Dikgatlhong, Gaborone, Letsibogo, Shashe, Ntimbale, Bokaa and Nnywane dams while Lotsane (capacity: 42 Mm^3); and Thune (capacity 90 Mm^3) dams are currently being constructed. Of these seven dams, four of them contribute directly and indirectly to the greater Gaborone area of the Notwane catchment and the remaining three to the areas north of the catchment.

2.4.1.2 Water Supply Operations Summary Situation

The water supply operations discussed below were elicited from discussion with a DWA official and data from the NWMPR. Releases are made as the rule curve directs. The rule curve is the designated quantity of release each month and is amended each beginning of the year. Released water from Gaborone dam is diverted to Gaborone waterworks while the water from Bokaa dam is transferred to the Mmamashia water treatment plant before transmitted to the public. It is also possible that the water from Bokaa dam may be transferred to the Gaborone water works treatment plant. No environmental flow requirements are made despite the advices of the Draft water policy and the NWMPR recommendations. Whenever reservoir level falls below the dead storage for each dam and releases cannot meet the rule curve requirement, shortage is sort from other alternative sources such as the NSC.

2.4.2 Groundwater Hydrology

Botswana has relied more on groundwater resources in the past. However according to (DWA, 2013) groundwater resources are limited in quantity and quality and the limited resources are unevenly distributed over the country with most located on the eastern part of the country (Appendix A). Most of the rural areas in Botswana rely on groundwater for water supply. Several small farm dams and numerous boreholes provide water for small-scale irrigation and stock watering in several parts of this sub-catchment. The villages of Kanye and Molepolole and surrounding areas currently depend on underground water sources for their daily water supply with their connection to the NSC water project in the pipeline. The DWA has carried out numerous studies to investigate and establish the potential yield of production boreholes in various Wellfields. (Appendix A) shows the major Wellfields in the country. Four types of aquifers are found in Botswana:

- Fractured aquifers - are found in the crystalline bedrocks of the Archaean Basement in the east and in the Karoo basalt. These have low yields with the median yield ranging between 2 and 10 m^3 per hour.
- Fractured porous aquifers - are found in Ntane and Ecca sandstones as well as in arkoses in the Karoo formation. These aquifers have the highest yields and include the Masama and Makhujwane Wellfields north of Mochudi in the Notwane sub basin.
- Porous aquifers - occur in sand rivers, alluvium and the Kalahari beds. These are usually high yielding and have a yield ranging between 10 and 300 m^3 per hour; and
- Karstified aquifers - occur in the dolomite areas and are restricted to the south-western parts of Botswana including the Notwane sub basin in areas of Lobatse, Ramotswa and Kanye. The Ramotswa aquifer is a trans boundary karst aquifer lying between South Africa and south-eastern Botswana. Due to its karst nature, it has high well yields, rapid recharge from rivers, and high vulnerability to pollution. Ramotswa Wellfield was eventually closed in 1995 due to water pollution and Ramotswa village is now supplied through the Gaborone Dam. Karstified aquifers account for only 1% of the land area of Botswana. These aquifers have a median yield of 4-20 m^3 per hour.

2.5 Shared Water Resources in the Sub basin

The majority or bulk of Botswana’s surface water resources are shared with neighbouring countries. Some of the country’s aquifers also transcend its borders. Due to the rising demand, the 2006 NWMPR (c) states that in future the extended use of shared water resources is inevitable. The Limpopo basin of which the Notwane is a sub basin of is currently used mostly by South Africa. Through LIMCOM (Limpopo Watercourse Commission) Botswana and other member states are advised on the use of the Limpopo waters, its tributaries for the protection, preservation and management of the Limpopo River. Water is transferred to the Gaborone Dam from the Molatedi Dam in South Africa following the agreement made between the governments of Botswana and South Africa. The agreement is if the Molatedi Dam storage is more than 25 % then about 7 million cubic meters per annum may be transferred, otherwise Botswana receives half of this entitled volume of water.

2.6 Climate of the Study Area

Notwane catchment and the country at large have a warm and dry tropical/subtropical climate described as semi-arid to arid. Consequently, the catchment is characterized by harsh weather conditions with huge temporal and spatial variations in rainfall, temperature, runoff, and evaporation quantities.

2.6.1 Physiography

The Notwane subbasin in Botswana is drained by the Notwane River and its tributaries and they drain a generally flat landscape with the countryside gently sloping in a north-easterly direction towards the Notwane river.

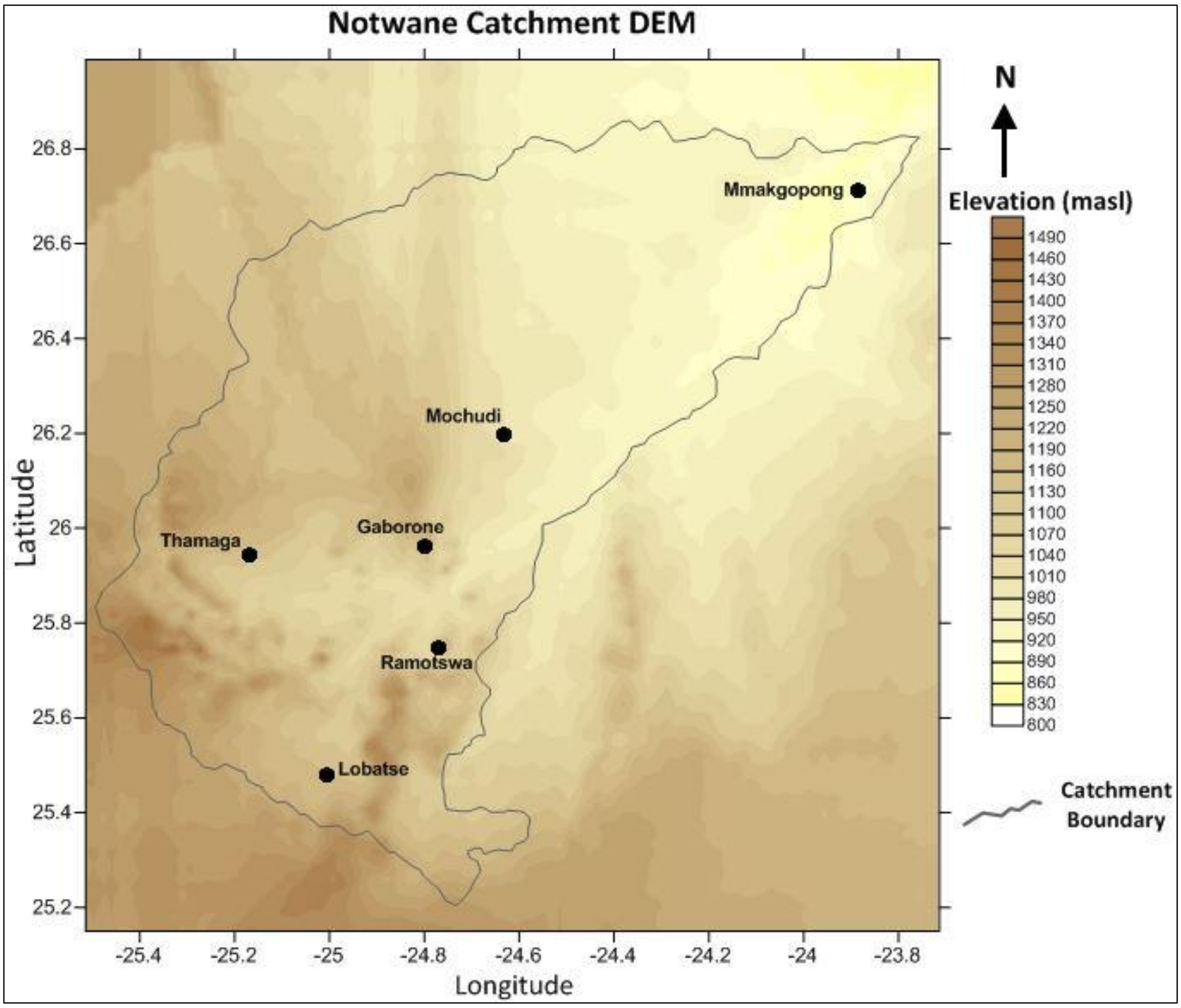


Figure 2.4: Digital Elevation Map of the Notwane catchment

The climate controls that influence the climate of an area are its geographical location and its physiography. The topography of Notwane catchment is generally flat and at an average altitude of 1000 m with elevation ranging between 850 to 1500 m (Figure 2.4). The highest point in the sub basin as well as the country is the Otse Hill near village of Otse just 24 km from Lobatse with an altitude of 1491 m. As a consequence of this flat physiography, there are no barriers to the flow of moist air and as a result, orographic influences on the development of clouds and precipitation are almost non-existent. This very flat terrain also results in very few suitable dam sites. The flat topography coupled with sandy, pervious soils makes surface water sources to be limited. The principal land cover in the catchment is natural grassland, shrubland and woodland.

2.6.2 Rainfall

According to DEA & CAR, 2006, the hydrology of the catchment can be summarised by the following factors;

Low Rainfall: the catchment receives a low and unreliable rainfall from year to year with mean annual rainfall averaging 250 mm per year. About 95 % of this rainfall falls between October and April.

Rainfall Seasonality: rainfall is seasonal hence all the rivers in the catchment are ephemeral.

High temporal variability of rainfall: Rainfall is highly variable with sometimes rainfall received in months when it is not expected or it coming earlier or later than anticipated. This high temporal variability of run-off necessitates surface water storages to be relatively large in relation to the mean annual run-off in order to host carry-over storage for recurrent droughts affecting both the inflow into dams and recharge to groundwater.

High spatial variability of rainfall: rainfall changes notably from one area to another even if it is the same catchment area. The end result of this is that often times runoff from areas with high rainfall may be absorbed in areas with low or lacking rain before it even reaches the dams.

High rainfall intensities: even though the climate is categorised as semi – arid to arid, high intensity rainfalls over a short period of time are the norm.

The rainfall seasons of the catchment and country are generally divided into four;

- Winter or Dry Season: May to August.
- Spring or Pre-rainy Period: September to October.
- Summer or Rainy Season: November to March.
- Autumn transition or Post Rainy season: April.

The Department of Meteorology (DMS) is responsible for maintaining or obtaining rainfall data. The Figure 2.5 to Figure 2.9 show the annual long-term averages of rainfall in the towns of the catchment covering the period 1971-2000.

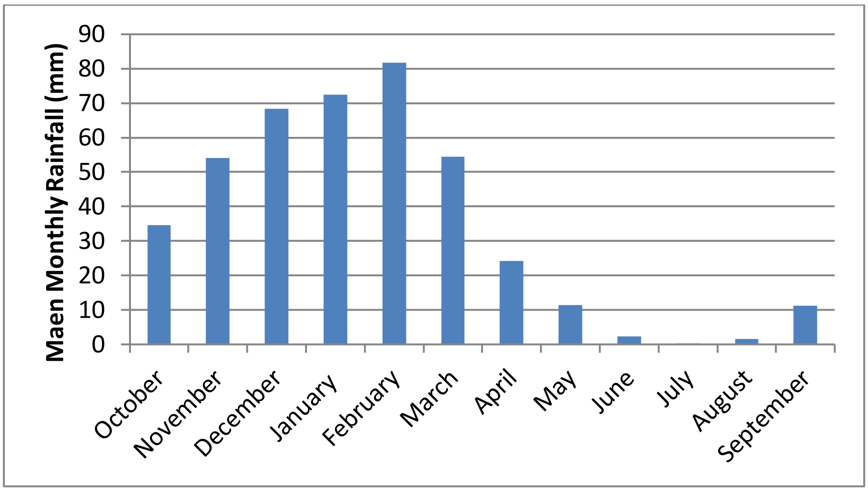


Figure 2.5: Long-term average rainfall for Molepolole

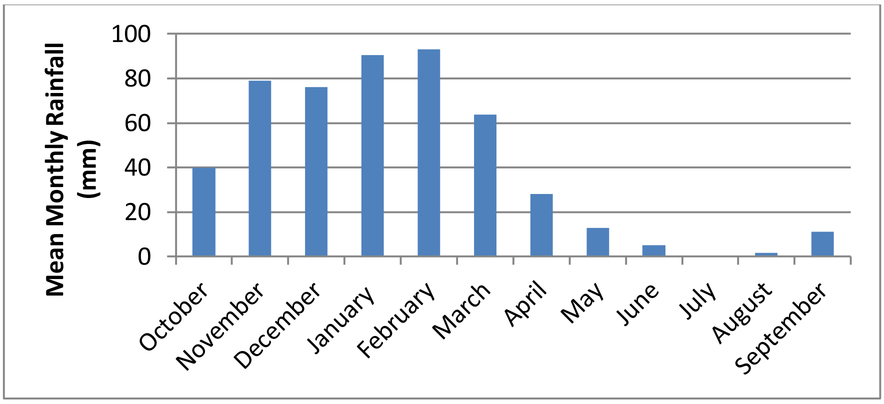


Figure 2.6: Long-term average rainfall for Gaborone

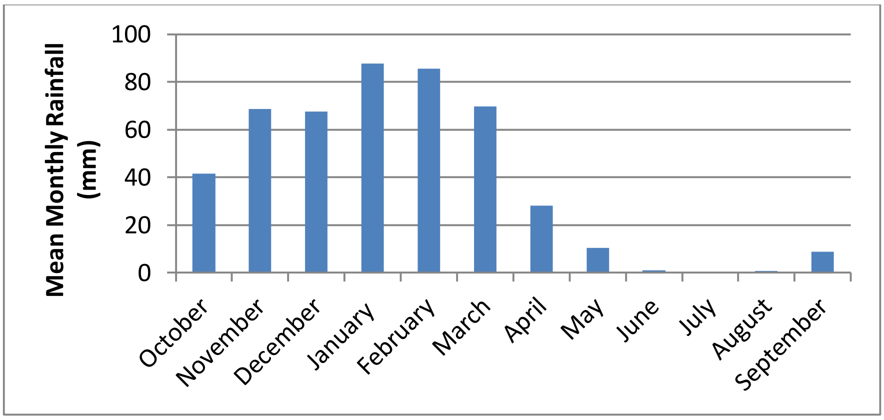


Figure 2.7: Long-term average rainfall for Ramotswa

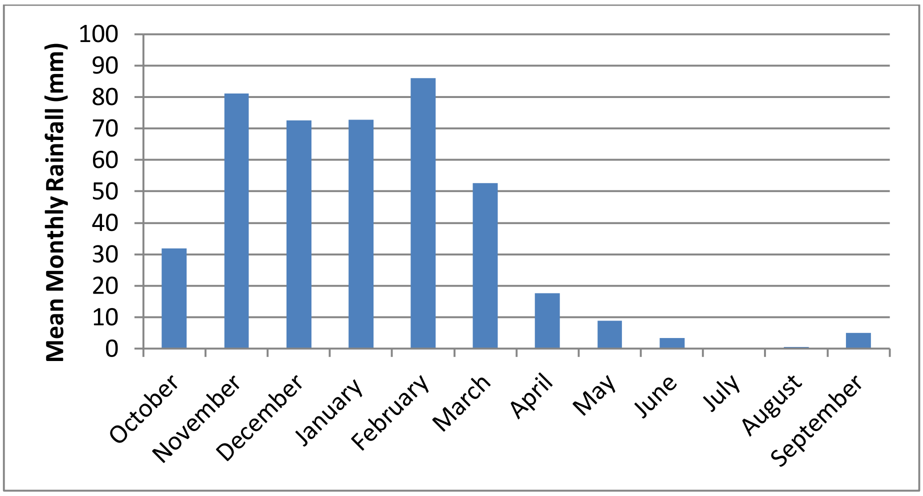


Figure 2.8: Long-term average rainfall for Mochudi

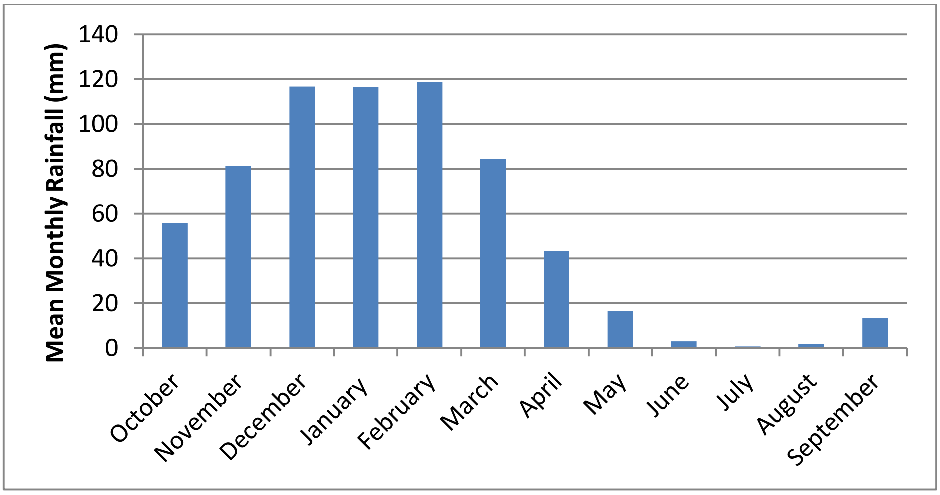


Figure 2.9: Long-term average rainfall for Lobatse

The Mean Annual Precipitation for the towns above are, 34.64; 41.78; 39.22; 26.08 and 54.31 mm for Molepolole, Gaborone, Ramotswa, Mochudi and Lobatse respectively. Long-term rainfall trends show Gaborone, Kanye, Lobatse, Mochudi and Molepolole show a trend of decreasing rainfall (NWMPR, 2006 c). This decrease in rainfall may be contributing to the observed recent low water levels in the dams in the basin.

2.6.3 Evaporation

The country has high evaporation rates. This leads to a considerable amount of storage being lost to the atmosphere by evaporation (Department of Surveys and Lands, 2002.). High evaporation rates are the order in the Notwane catchment and the country at large. According to Lange et al, (2006), more water is lost from the reservoirs through evaporation than through abstraction. The water yield/production from the Gaborone Dam calculated in accordance with the agreed safe yield criteria was 9.4 mcm/year (BNWMP 1992). This means that even with this huge storage volume (141 MCM) considered in relation to the mean annual run-off (MAR), the reliable yield is no more than about 33 % of the MAR. In the long-term about 7 % is lost as spill down the river and 60 % is lost to evaporation (BNWMP 1992). These high rates of evaporation are exacerbated by the unfavourable storage sites with a low ratio of volume of water stored to surface area leading to shallow reservoirs of wide expanse.

2.6.4 Temperature, Wind speed and Direction

The temperature of the catchment averages 31 °C in the summer months and 20 °C in winter. Diurnal temperature variation is large with warm to hot temperatures during daytime and cool to near freezing temperatures at night. The mean monthly maximum temperature ranges from 29.2 °C to 33 °C in summer, and 22.5 °C to 25.3 °C in winter while mean monthly minimum temperatures range from 16.1 °C to 19.4 °C in summer, and 4 °C to 8.1°C in winter. Temperature data is summarised in Appendix A. Wind direction in Botswana is generally east to north easterly and wind speed is considered too low (Table 2.3). Wind speed is an important factor in determining evaporation.

2.6.5 Sunshine and Humidity

The country receives a lot of sunshine with mean annual sunshine ranging between 8.6 to 10.1 hours/day (NWMPR, 2006 c). Hours of sunshine are also a key component in the determination of evaporation. The mean sunshine hours, wind speed and evaporation per month are presented in Table 2.3.

Table 2.3: Long-term climatic data for Notwane Catchment

Month	Wind Speed	Sunshine	ETO-Penman Monteith
January	104	9.3	5.7
February	95	9.4	5.4
March	78	8.6	4.4
April	78	8.1	3.4
May	60	9.1	2.5
June	69	9.1	2.1
July	69	9.5	2.2
August	95	10.0	3.2
September	121	10.1	4.6
October	156	9.6	5.7
November	130	9.0	5.7
December	112	9.0	5.7

Relative humidity is the amount of moisture in the air compared to what the air can hold at that temperature. Relative Humidity is at its highest in the early morning with about 70 % and lowest in the afternoon with 30-40 %.

2.7 Demography

According to the 2011 Population and Housing Census (CSO, 2012) the total population of people in the Notwane catchment is 907 351 contributing to 45 % of the total population of Botswana. The population of Gaborone and surrounding villages like Tlokweng, Mogoditshane, Mmopane, Ramotswa and Metsimotlhabe has grown faster than any in the country. The population and percentage growth of major towns and villages in the Notwane sub basin in Botswana is shown in Table 2.4. The rapid growth in these towns and villages especially in Gaborone and surrounding villages puts considerable pressure on water resources and water service providers to meet the growing demand.

Table 2.4: Population of towns and major villages in the subbasin.
Source: CSO, 2012

Settlement	2001	2011	% Growth
Gaborone	186,007	227,333	22.21744
Molepolole	54,561	67,598	23.89436
Mogoditshane	32,843	57,637	75.49249
Kanye	40,628	45,196	11.24348
Mochudi	39,349	44,339	12.68139
Ramotswa	20,680	27,760	34.23598
Tlokweng	21,133	35,982	70.26452
Mmopane	3,512	14,655	317.2836

2.8 Water Demand

Because of urbanization and the need for employment, more people are moving to the south – eastern part of the country, especially the capital, Gaborone to seek employment. This has resulted in the growth of Gaborone and the spill over into surrounding villages such as Tlokweng, Mogoditshane, Gabane, Ramotswa, Mochudi and Lobatse, which all make part of the greater Gaborone (DWA, 2013). This sudden increase in population has put enormous pressure on the already limited water resources. The demand projections from the NWMPR, 2006d shown in Table 2.5 below indicate a high increase in water demand. This research focuses on the fact that water resources in the greater Gaborone, which falls within the Notwane catchment area, are very limited. There is therefore a need to come up with better operating policies for the already under- pressure reservoirs.

Table 2.5: Demand (m3) projections of major villages and towns in Notwane Catchment. Source: NWMPR, 2006d

Year	**Gaborone**	**Lobatse**	**Tlokweng**	**Ramotswa**	**Mogoditshane**	**Total (m3)**
2006	25307798	3438761	1905246	57,824	3400473	34110102
2007	26317369	3544440	1936640	58,271	3525434	35382154
2008	27326660	3653165	1970805	58,722	3654448	36663800
2009	28340520	3765018	2023258	59,177	3786926	37974899
2010	29363172	3880114	2078837	59,635	3923567	39305325
2011	30276621	4062561	2127819	59,866	4047722	40574589
2012	31309055	4239001	2182026	60,097	4182463	41972642
2013	32355878	4349019	2238793	60,330	4321572	43325592
2014	33418703	4473315	2297991	60,563	4463687	44714259

CHAPTER 3

GEOLOGY OF THE STUDY AREA

3.1 Regional Geology

To better understand the controls of surface water movement, distribution and occurrence in an area, the underlying geology should be well understood. This section gives an account of the geology underlying the Limpopo Basin in Botswana beginning with the broad regional geology to the local geology of the study area. The majority of the geology of Notwane catchment is blanketed beneath a layer of Kalahari sediments.

3.1.1 Achaean Eon

Botswana hosts three major Archaean terrains namely the Limpopo belt and Kaapvaal and Zimbabwe cratons (Carney et al, 1994) and Appendix A). The 250 km Limpopo belt lies between the Kaapvaal and Zimbabwe craton and is an east-northeast trending zone of granulite facies tectonites that developed between 3.2-2.9 Ga. The belt consists of high-grade metamorphic rocks that have been completely deformed and metamorphosed at granulite and amphibolite facies leading to a variety of gneisses and migmatites. The Kaapvaal craton formed and stabilized between 3.7 and 2.6 Ga by the emplacement of major granitoid batholiths that lead to relative stabilization of the continental crust during the early stages of an arc-related magmatism and sedimentation cycle (Caney et al, 1994).The craton is a mixture of early Archaean granite greenstone terrains and older tonalitic gneisses intruded by a variety of granitic plutons. The Zimbabwe craton formed at about 3.5 Ga and consists of greenstones, granitoids and gneisses. In the late Archaean, the Kaapvaal and Zimbabwe craton collided and the three major terrains became a single crustal block, the Kaapvaal-Zimbabwe craton. Groundwater storage in these rocks is confined to fractures and cracks termed hydrogeologically as secondary porosity.

3.1.2 Proterozoic Eon

The beginning of the Proterozoic Eon [2.5 Ga -570 Ma] in Botswana commenced with the Kaapvaal-Zimbabwe craton. The development of the Kaapvaal-Zimbabwe craton was accomplished by three episodes of Proterozoic mobile belt activity namely the Eburnian (ca. 2.1-1.8 Ga), the Kibaran (1.4-1.0 Ga) and the Pan-African (650-450 Ma). During the Eburnian the entire western margin of the Kaapvaal-Zimbabwe was then deformed to form the Kheis and Magondi belts. The post-Eburnian shield was known as the Kalahari craton (Carney et al, 1994). Tectonic suturing of the Kalahari and the neighboring Congo craton later on led to the beginning of the assembly of the Gondwana supercontinent. The main Proterozoic units in Botswana are the Transvaaal and Waterberg Groups. The rock units representing the Proterozoic eon in the study area are the Waterberg and Otse groups (Figure 3.1) and Table 3.1. The groundwater found in the Waterberg Group is from fractured secondary porosity matrix or fractured porous aquifers.

3.1.3 Phanerozoic Eon

The Phanerozoic Eon begins from age of 570 Ma. Suturing of the Kalahari craton with other crustal fragments during the Proterozoic led to the formation of the Gondwana supercontinent. This became the repository for the extensive Carboniferous to Jurassic sequence represented by the Karoo Supergroup. Rifting and progressive break-up of Gondwana took place between 140 and 120 Ma ago. The Karoo Supergroup is a succession of sedimentary and volcanic rocks that unconformably overlie Archaean and Proterozoic rocks approximately 70 percent of the area as Carney et al observed. The aeolian sandstones of the Karoo are a rich source of groundwater having water stored within the matrix and as well as within fractures. The aeolian sandstones commonly referred as Ntane sandstones (Lebung Group) have dual porosity (both primary and secondary porosity) making them have high water yields thereby making wellfields in these areas very important to the catchment and country. The rocks of the Karoo Supergroup are in turn overlain unconformably by the Kalahari beds (Table 3.1). The Kalahari beds are an association of loosely consolidated deposits that are between a few metres to about 400m thick. The Kalahari accumulated in aeolian, fluvial and lacustrine environments and so comprise of a variety of sediment types (Williamson, 1996). The schematic simplifying and summarizing the geology of the Notwane catchment below the Kalahari is given below in Table 3.1.

Table 3.1: Simplified geology of the study area

Eon	**Era**	**Age (Ma)**		**Geological Units**	**Short Description**
Phanerozoic	Cenozoic	80-100		Kalahari beds	Post Karoo erosion and deposition forming the ‘African surface’
	Mesozoic	170		Dolerite Dykes	Post Karoo emplaced dykes
		180-200	KAROO SUPERGROUP	Stormberg Lava Group	Marine, glacial, lacustrine, deltaic, fluvial, terrestrial and aeolian conditions deposited sedimentary rocks later intruded by flood basalts
				Lebung Group	
				Beaufort Group	
				Ecca Group	
				Dywka Group	
Proterozoic	Mesoproterozoic	1300		Waterberg Group	Assemblage of Sandstones, shales, conglomerates and siltstones
	Palaeoproterozoic	1800		Otse Group	Red bed sequences
Archaean	Neoarchaean	2700		Lobatse Volcanic Group	Volcano sedimentary rocks
	Mesoarchaean	2850		Gaborone granite	Granitic gneisses

3.2 *Local Geology*

The geology of the Notwane sub basin lies between the Archaean to Cenozoic formations and is dominated by the Archaean (3000-2600 Ma) Kaapvaal craton. The Notwane drainage basin is underlain by four generalised types of geological terrain viz;

- Archaean- crystalline (igneous and metamorphic) basement; Gaborone granite
- Neoarchaean-Mesoproterozoic volcano-sedimentary basins and layered intrusive; Kanye Volcanic Formation, Lobatse Volcanic Group, Waterberg and Otse Groups
- Palaeozoic-Mesozoic sedimentary-volcanic sequences; Karoo Supergroup
- Post Karoo- Dolerite intrusions and Kalahari beds (Table 3.1 and Figure 3.1)

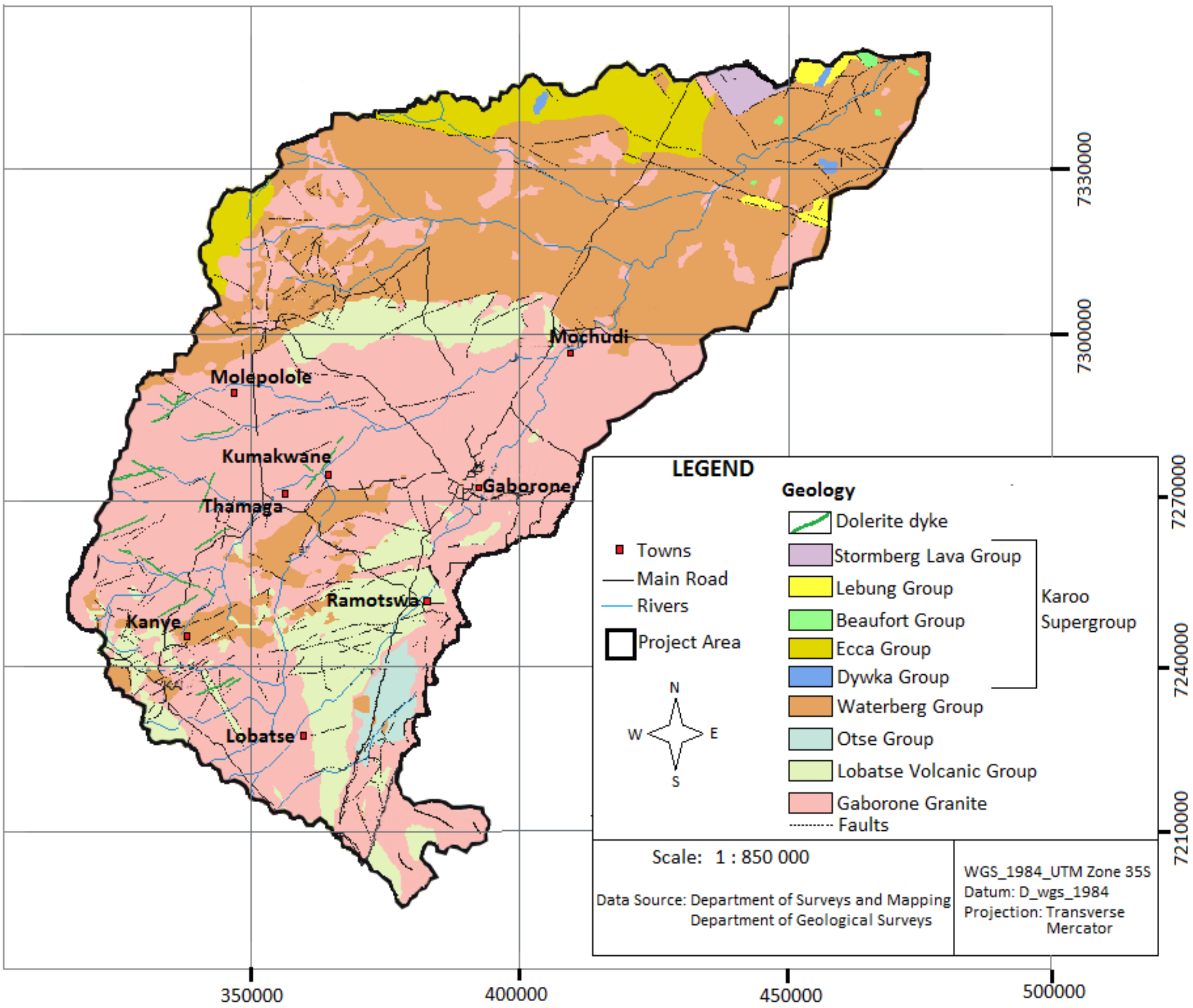


Figure 3.1: Geology of the study area

3.2.1 Gaborone Granite

The Archaean Gaborone granite was emplaced in the Kaapvaal Craton around 2850 Ma ago. The craton is a mixture of early Archaean granite greenstone terrains and older tonalitic gneisses intruded by a variety of granitic plutons. These granitoids and granitic gneisses of various types and ages account for 90 percent of the Kaapvaal craton in the Limpopo basin. The Gaborone granitic complex is believed to have been formed from a single, highly viscous magma. Key and Wright, 1982, described it as a mushroom – shaped intrusion of rapakivi type granites with a surface area of over 5000 km^2 (Figure 3.2). Internally the intrusion displays an apparent concentric distribution of three subdivisions of Thamaga, Kgale and Ntlhantlhe granites surrounded by zone of massive felsites which make up the Kanye Volcanics (Figure 3.2).

Thamaga Granite forms the core of the complex and comprises of medium to coarse grained porphyritic rapakivi textured granites. Aplite veins and dolerite dykes are common in parts of the Thamaga granite. Deformation zones are widespread in the Thamaga Granite with orthogneisses, mylonites and cataclasites.

The dominating Thamaga granite is surrounded by the Kgale Granite which is an equigranular leucocratic, homogeneous, medium grained granite which contains phenocrystal blue – grey quartz in the marginal parts of the granite (Carney et al, 1994). The mineralogy of the Kgale granite is similar to that of the Thamaga Granite only difference is the proportion of the main and accessory minerals hence the difference in grain size. The quartz and feldspar contribute around 97 % and the rest is constituted by muscovite, chlorite, sercite, biotite, zircon, apatite and fluorite.

Ntlhantlhe Microgranite is a porphyritic granophyre found as a zone between the Kanye volcanics and Kgale Granite as in Figure 3.2.

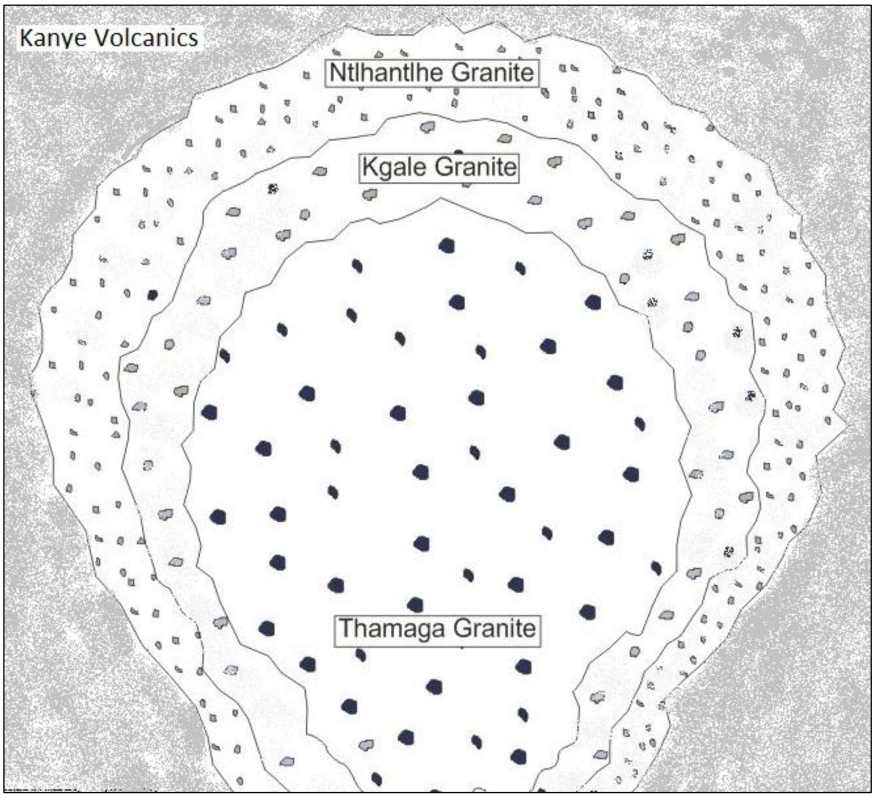


Figure 3.2: Schematic of Gaborone Granite

The Kanye Volcanics is an association of fine-grained felsitic rocks mostly rhyolites. They consist of strongly jointed, homogeneous fine grained to aphanitic rocks with sporadic feldspar phenocrysts (Stålheim, 2014). The rhyolitic groundmass has bands and streaks of intersected mineral aggregates consisting combinations of quartz, feldspar, biotite, calcite, apatite and zircon. According to Key and Wright, 1982, the Kanye volcanics are believed to represent the chilled margin of the Gaborone granite.

3.2.2 Lobatse Volcanic Group

The Neoarchaean Lobatse Volcanic Group comprises a diverse association of lavas, associated pyroclastics and fine to coarse grained sediments (Figure 3.1). It is the oldest volcano sedimentary rocks deposited on the Kaapvaal Craton in Botswana. It consists of rhyolites, volcanic breccias, siliceous shales, sandstones and grey quarzites. It is estimated to be about 2700 Ma (Table 3.1). The Lobatse Volcanic Group can be divided into two, a lower volcanic unit, namely, the Nnywane Formation and an upper sedimentary unit, namely, the Mogobane Formation. Nnywane Formation comprises of rhyolites lavas with interbedded volcaniclastic rocks such as breccias. The Mogobane Formation with an estimated thickness of about 1500 meters consists of interbedded micaceous fine-grained sandstones and siltstones with laminated mudstones. The sequence shows coarsening up and passes into sandstones containing quartz-pebble conglomerates (Carney et. al., 1994).

3.2.3 Otse Group

The Proterozoic (1800Ma) Otse group is found in an area between Ramotswa and Lobatse (Figure 3.1). Sedimentary rocks of the Waterberg Group overlie it (Table 3.1). It is a post Transvaal and pre-Waterberg assemblage and encompasses red beds, breccias, sandstone lenses, conglomerates, shales and siltstones.

The basal unit of this group is the Otse Breccia consisting of angular chert clasts in ferruginous or manganiferous matrix. The Ditsotswane Formation is contiguous to the Otse Breccia. It is a chert and dolomite-clast conglomerate supported by a red sandstone matrix. This conglomerate shows a fining upward texture. The Moeding Formation overlies the Ditsotswane Formation. It is poorly exposed and principally is a red micaceous shales and sandstones succession. Overlying the Moeding Formation is the youngest Otse Group unit termed Maladiepe Hill Formation. It is a succession of interbedded mud-clast conglomerates and subordinate sandstones. According to Carney, 1994, these strata are thought to have been deposited in a mid-alluvial plain environment.

3.2.4 Waterberg Group

The Proterozoic Waterberg Group is an assemblage of conglomerates, shales, sandstones and siltstones and one of the oldest occurrences of continental red beds sedimentation (Table 3.1). The continental red beds of the Waterberg Group suggest an evolution from alluvial fan complexes that developed as a fault controlled basin that fed freshwater lake systems of the Lokgalo and Ramotlobake Formations (Williamson, 1991). As shown in Figure 3.1, the Waterberg Group on the main outcrop north of Gaborone occupies an east west syncline. Along the margins of the syncline is the Mannyelanong Hill Formation while in the core are the Lokgalo Siltstone, Ramotlobake Siltstone and Masama Sandstone Formations.

3.2.4.1 Mannyelanong Hill Formation

This is a sequence of sand stones and conglomerates found both in the north and southwest of Gaborone near Otse village on the Mannyelanong Hill (Carney, 1994). It is about 100m thick on the hill and the sandstones are red and poorly sorted and could be classified as arkosic and lithic arenites and greywackes. Common in the hill is a basal conglomerate about 4m in thickness and includes clasts of quartz and sandstone.

3.2.4.2 Lokgalo Siltstone Formation

This unit overlies the Mannyelanong Formation and is about 190m thick. It comprises of red and pinkish siltstones thinly interbedded with shales and laminated mudstones. Williamson, 1991 believes the great thickness and lateral extent of the formation suggests deposition in a large freshwater lake.

3.2.4.3 Masama Sandstone Formation

This formation overlies the Lokgalo Siltstone Formation and is extensive around Mochudi area. It is a succession of poorly assorted arkoses, quartzites, feldspathic greywackes, shales and siltstones.

3.2.4.4 Ramotlobake Siltstone Formation

This Formation represents a return to shallow water lacustrine conditions that prevailed during deposition of the Lokgalo Formation. It is about 175m thick and the exposures are reddish-purple to pink calcareous shales, siltstones and fine grained sandstones.

3.2.5 Karoo Supergroup

These are paleozoic-mesozoic successions of sedimentary and volcanic rocks that overlie Archaean (Gaborone Granite, and Lobatse Group) and Proterozoic rocks (Waterberg Group) (Table 3.1). Mostly found north of the study area, these rocks are poorly exposed being overlain by the Kalahari beds (Figure 3.1). The Karoo Supergroup is composed of the Dywka at the base then on top of it are the Ecca, Beaufort, aeolian sands of Lebung Group and Stormberg Lava Group. The various sequences in the Karoo indicate different periods of evolutionary environments during the paleoclimate of the Gondwana continent.

3.2.5.1 Dywka Group

The Dywka Group consists of glaciogenic sediments deposited during a Permo-Carboniferous glacial episode and in the deeper valleys comprises of tillites overlain by sandstones and conglomerates succeeded by lacustrine sediments including varvites. It forms the base of the Karoo Supergroup in Southern Africa (Table 3.1).

3.2.5.2 Ecca Group

This Group of rocks were deposited in lakes, rivers and deltas in the post glacial environments right away following the retreat of the Dywka glaciers. The Group commences with argillites overlain by sandstones and occur in upward coarsening cycles in the base. In the middle of the Group coal occurs in abundance in the eastern margin of the Karoo Supergroup basin as observed by Williamson, 1991. Towards the top of the Group are carbonaceous mudstones which are overlain by the beds of the Beaufort Group.

3.2.5.3 Beaufort Group

The Beaufort Group overlying the Ecca Group, hosts massive mudstones in the Tlhabala Formation (Williamson, 1991). Thin impure limestones are found with the grey to bluish massive mudstones of the Tlhabala Formation suggesting deposition in shallow, mildly evaporative lacustrine environments.

3.2.5.4 Lebung Group

The Lebung Group is characterised by clastic rocks of the Karoo with reddish sandstones being superior. It is a succession of medium grained sandstones, coarse grained sandstones, pebble conglomerates and siltstones at the top. The upper part of the group is dominated by the Ntane Sandstone Formation with reddish sandstones massive or cross bedded with rounded grains indicating accumulation in aeolian conditions. Areas where Lebung Group sandstones provide good quality water in the catchment are Masama and Makhujwane wellfields north of Mochudi near Artesia village where in 2015 the greater Gaborone area was supplied by water from the two wellfields amounting to 20 million liters per day (Daily News, 2015)

3.2.5.5 Stormberg Lava Group

These are basaltic lavas widely distributed although they are obscured by the Kalahari beds, Figure 3.1. Karoo sedimentation ended in the Jurassic period with the outpourings of the Stormberg flood basalts onto a desert like landscape of the aeolian sands of Lebung Group. According to Williamson, 1991 the age of the lavas is estimated to be between 195 and 200Ma (Table 3.1).

3.2.6 Dolerite Dykes

Dolerite dykes emplaced post Karoo mainly following a west-northwest and east-northeast trends Figure 3.1. They form prominent lineaments on aerial photographs and give rise to strong aeromagnetic anomalies that enable their detection beneath sequences of Kalahari beds (Carney et al, 1994).

3.2.7 Kalahari Beds

These units are of Cenozoic age and are loosely consolidated deposits ranging between a few metres to about 400m thick. They rest on eroded Karoo and pre-Karoo rocks forming the African surface and the most areally extensive geological unit in Botswana (Carney et al, 1994). The Kalahari beds extend into Namibia, South Africa, Zimbabwe, Zambia, Angola and DRC. They accumulated in aeolian, fluvial and lacustrine environments therefore include a wide variety of sediment types. This includes pink and red clays, gravels, aeolian sands, calcretes, silcretes and ferricretes estimated to be between 100 and 80 Ma (Table 3.1).

CHAPTER 4

LITERATURE REVIEW

4.1 Introduction

The GWP'S mission is to support the sustainable development and management of water resources at all levels that is at local, national, river Basin, regional and trans boundary levels. IWRM as defined by GWP (2000) "is a process, which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems." In line with this definition, the draft Botswana National Water Conservation Policy [DWA, 2004] as an 'ultimate objective' has the principle "*to identify principles and strategies which, if implemented, will promote efficient and sustainable planning, management and protection of Botswana's water resources"*. In this regard, reservoir simulation is an important component in water resources planning and management.

A wide variety of analysis techniques including simulation and optimization algorithms have been developed over the last few decades to study water resources systems (Labadie 1997; Loucks et al. 1981; Simonovic 1992; Wurbs 2002). Simulations track the movement of water through a system while optimization programs search for an optimal operating policy to achieve a specific given objective. Yeh (1985) has done reviews of the state of the art examples of the two models. According to Labadie (1997), in discussing large, multi-reservoir systems, the distinction between simulation and optimization modeling is often obscured because optimization models usually embed simulation models in verifying and testing proposed operating policies. Simulation modeling offers a useful platform for explicitly testing specific possibilities for intergratively operating reservoirs and is the focus of further discussion. Simulation analysis, potential alternatives including operating rules, storage allocation, and other possible management options are reviewed. Selected simulation software models are also discussed.

4.2 Surface Water Modelling

Surface water is that part of water naturally open to the atmosphere in water bodies such as rivers, estuaries, ponds, lakes and reservoirs. A surface water model is a hydrological simplified representation of the real world with focus on surface water. Models can be physical or mathematical. Physical models were important in the past but currently mathematical or analogue models have become valuable and universally applicable and the ones with rapid development in terms of scientific basis and application (Refsgaard, 1996). Models allow complex systems, both existent and merely specified, to be understood and their behaviour predicted. A model is viewed as a coalesce between data and decision making, that is, a model generates information from data and improves knowledge which is required by decision-making. Computer based models can be applied in water resource planning and management and decision making processes as they have the potential to provide valuable information. Of these models, most of them are based on water balance equations.

The credibility and reliability of a model must be developed over a period of time and is shaped by the following aspects: a) initial stage of model development (clear model purpose), b) good quality reliable data, and c) adaptive to the dynamic changes which the physical system might undergo. However, selection of the right model, as classified by Savenije (1997), is the function of availability, objectives of the analysis, accessibility and simplicity of the data management facilities of the model.

In acknowledging the role of models in integrated water resources management process, we should also recognize and accept the inherent limitations of models as representations of any real problems as the input data together with assumptions and objectives may be contentious, dubious or uncertain (Alemaw, 2012). This means that we should not expect to have precise results in any model and embrace that the results may not be accepted or implemented. There are two basic modelling approaches:

- Simulation models (methodology/ conceptual)
- Optimization models (mathematical)

4.2.1 Simulation Model

A simulation is the imitation of real life situation, process or system over time. A simulation model relies on trial and error to identify proximate optimal solutions where decision variables are specified and the resulting objective solutions established (Loucks, et al, 1981). The main advantage of a simulation model is that it can be used as an analysis tool for predicting the effect of changes in a process, that is, it can compress a long period of time and quickly evaluate the effect of a change in a real life situation that takes place in many years. The main disadvantage of simulation models is that simulation results can be difficult to interpret and often the case simulation modelling and analysis can be time consuming and expensive. Examples of simulation models include MIKE 11, WAFLEX, COLSIM, HYDSIM, HEC-ResSim and WEAP. Their main applications in reservoir operation are; downstream flood forecasting and analysis, dam break analysis, optimisation of reservoir operation, dam management options, water allocation and hydropower requirements.

4.2.2 Optimization Model

Optimization is a process of determining the best plan (Wurbs and James, 2002). Optimization incorporates human judgement, use of simulation and/or optimization models and use of other support tools. Optimization is often used interchangeable with the term mathematical programming to refer to a mathematical formulation in which an algorithm is used to compute a set of decision variables that minimize or maximize an objective function subject to constraints. A mathematical optimization model consists of an objective function and a set of constraints usually expressed in the form of a system of equations or inequalities. Optimization techniques include linear programming, quadratic programming and heuristic programming algorithms Optimization models are used extensively in almost all areas of decision-making such as engineering design, economics, science and financial portfolio selection.

4.3 Simulation analysis

Simulation models use inflows (hydrology), operations (decision rules), and mass balance basin accounting (connectivity) to represent the hydrologic behavior of a reservoir system. System performance is quantified by selecting indicators based on system flow and/or storage whichever that the modeler feels best characterizes the key aspects and objectives of the system. Indicators in WR can include reservoir storage levels; in-stream flows; hydropower generation; water supply deliveries or shortages; hydropower revenues; flood damage; or summaries of these quantities such as firm supply, supply reliability (based on frequency analysis), resiliency (recovery analysis), vulnerability (volume shortage), expected annual flood damage, or explicit economic performance, to name a few. In order to carry out simulation analysis, the modeler first computes performance using selected indicators for a base case representing the system's existing hydrologic behavior. Next, the modeler develops a series of alternative system behaviors by changing reservoir storage allocations, operating rules, demand/abstraction levels, and/or hydrology and many others after which he/she computes performance for these hypothesized alternatives. Lastly, the modeler compares base case performance to performance under tested alternatives. The bulk of simulation work consists of formulating alternatives to test, evaluate, analyze and explicitly modeling them.

4.4 *WR and Reservoir System Simulation Software Literature*

Software used for simulating operating rules and storage reallocations has included spreadsheet programs, HEC-5, HEC-3, Stella, and other study-specific programs identified in reviews by Wurbs (2002). Stella is commercially-available and provides an object- and graphically-oriented environment in which to simulate a reservoir or multi-reservoir system. HEC-5 and HEC-3 were developed at HEC, a division of the USACE, in Davis, California. They are publicly available programs and are the most well documented and capable for performing network systems simulation analysis, including flood management, water supply, and hydropower operations.

Recently HEC has replaced the HEC-5 with HEC-Reservoir Simulation (HEC-ResSim), a next generation reservoir systems analysis software that is object, graphically, and database-oriented for real-time or planning analysis studies. HEC-ResSim also has a link to other modules for flood impact estimation, unsteady river flow, flood plain study, and ecosystems functioning within the Corps Water Management System (CWMS) software suite. HEC-3 was established in 1965 and since then, there has been a proliferation of reservoir models developed by various researchers, organizations and private companies. Simulation models exist in both public and private sectors; some are freely available to the public and others are patented and proprietary requiring monetary subscription to use or obtain them. Reservoir simulation programs are numerous, hence it is important to apply or engage one best suited to the objectives of the study. The ensuing section outlines a few of the models considered for this study and their features and characteristics. A summary is provided in Table 4.1.

Table 4.1: Summary of reservoir simulation models

MODEL	Developer	Graphic User Interface available?	Proprietary/ pay to use?	Generalized?
RiverWare	University of Colorado	Yes	Yes	Yes
MODSIM	Colorado State University	Yes	No	Yes
HYDSIM	Bonneville Power Administration	No	No	No
COLSIM	University of Washington	Yes	No	No
HEC-ResSim	USACE	Yes	No	Yes

4.4.1 RiverWare Simulation Software

RiverWare was developed through the Center for Advanced Design Support for Water and Environmental Systems (CADSWES) at the University of Colorado. Detailed description of the software is done by Zagona et al. (2001). The program features a graphical user interface (GUI) and also avails both simulation and optimization capabilities. The only hindrance of this simulation software is that RiverWare is proprietary and with limited funding for this research, this was not an option. An academic single-user license for one year costs over US $2,000 and US $1,200 for each renewal according to the CADSWES website (http://cadswes.colorado.edu/riverware) while a government or commercial license is over US $6,500.The impact of this is that certain water agencies and stakeholders could be less willing to engage or adapt the model to suit their needs. Nonetheless, the program offers most of the properties or ticks most boxes required to address the problems outlined in this study.

4.4.2 MODSIM Simulation Software

MODSIM was first developed in 1978 at the Colorado State University (Labadie, 2010). It has been applied for the analysis of the Colorado River basin and other basins. MODSIM like RiverWare employs a GUI and offers generalized simulation and optimization of any reservoir system. MODSIM is non-proprietary and can be easily obtained directly from the Colorado State University.

4.4.3 HYDSIM Simulation Software

HYDSIM (HydroSim) is used by the Bonneville Power Administration in their long-term planning studies, including studies related to Columbia River Treaty (CRT) operations (USACE et al. 2010). Its main role is to determine hydropower generation, project outflows and storage volumes at projects in the Columbia River Basin (CRB) under varying inflows, power requirements, and other system constraints. The monthly time step model was developed specifically for the CRB and does not have GUI capability. HYDSIM is a deterministic model that uses rule curves and flow/storage constraints to achieve operating objectives, especially for power, flood control, fish flows and spill, and recreation. Use of the model is non-proprietary, but it is not easily obtainable or implemented and requires authorization from both Bonneville Power Administration and BC Hydro because it is jointly developed between the U.S. and Canada for the Columbia River Treaty.

4.4.4 COLSIM Simulation Software

COLSIM, as expounded by Hamlet and Lettenmaier (1999), is a reservoir system simulation model developed by researchers at the University of Washington in 1997. Like HYDSIM, COLSIM was designed specifically for the Columbia River Basin. The model incorporates most of the large dams in the basin and operates on a monthly time step. It has a graphical user interface (GUI) and has been used extensively for analysis of climate change impacts in the basin and continues to be implemented (Hamlet et al. 2002).

4.4.5 HEC-ResSim Simulation Software

The US Army Corps of Engineers (USACE) has also developed numerous reservoir simulation tools including HEC-3 (HEC 1981), HEC-5 (HEC 1989), HEC-ResSim 2.0 (HEC 2003), and most recently, HEC-ResSim 3.0 (HEC 2007 and 2013). HEC-ResSim in particular has been successfully implemented for the analysis of multiple reservoir systems throughout the U.S. and the world (Wurbs 2012). It was designed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers specifically for aiding in decision-making processes for reservoir operations and planning (HEC 2013) and is the predecessor to the widely used HEC-5 program. The program has been updated with a number of improvements over time to allow users to control additional operational parameters and access output results in more intuitive formats. ResSim employs a GUI to allow point-and-click model construction and can function on multiple user-defined time steps. HEC-ResSim is a one-dimensional program that uses a rule-based approach to govern reservoir release and hydropower generation. Reservoirs are divided into different zones having rules associated with each and total storage is determined by a storage-elevation-area relationship. The model is purely descriptive, that is it does not have optimization capabilities. Hec-ResSim is non-proprietary and easily obtainable from the U.S. Army Corps of Engineers software website (http://www.hec.usace.army.mil/software). It is therefore free-of-charge on an ongoing basis as long as the user has the proper hardware requirements. User support documents are also easily attainable and there are plenty of Corps reports that have utilized HEC-ResSim to some degree, allowing for simple model construction and guidance. Above all, HEC-ResSim has the capacity to accomplish all tasks required to address the objectives of this study, namely simulation of the Notwane dams under different hydrologic conditions or scenarios and alternative operating strategies. For these reasons, ResSim has key advantages over the other programs mentioned above and was therefore chosen for this study.

4.5 Water System Performance Indices

If every system performance measure or objective could be expressed in the same units, then decision-making would be relatively straight forward. Such is not the case when dealing with water resources systems. Water resource systems show a high level of complexity. Many elements of water resource systems are vulnerable to temporary disruption in service due to natural hazards or human error as in the case of operational mistakes. This complexity makes it a challenge to come up with indices to evaluate water resources performance. Performance indices serve as an evaluation function. That is, they provide insights as to general effectiveness of a set of policies or a particular course of action. Generally, failures in the operation of a reservoir has many aspects: extent, number, severity (Jain, 2010.) Hashimoto et al (1982) proposed reliability, resilience and vulnerability indices (RRVs). Reliability is a metric that measures the proportion of time the reservoir can meet the stipulated demands while resilience indicates how quickly a system recovers after failure. A good system rapidly returns to a satisfactory state after failure. Vulnerability measures severity of failure if and when it occurs. Usually, these indices are computed using daily, monthly or annual data from the reservoir system. In the recent past (Loucks, 1997, Zongxue et al 1998), attempts have been to quantitavely represent sustainability of water resource managements by the composite indices made up of the combination of the three indices (RRV). Zongxue et al. (1998) suggested an integrated risk index namely the drought risk index (DRI), as a linear weighted function of reliability and resiliency and vulnerability.

$$DRI = \beta_1(1 - Rel) + \beta_2(1 - Res) + \beta_3(1 - Vul) \qquad [1]$$

Where Rel is reliability; Res is resilience and Vul is vulnerability and $\beta_1+\beta_2+\beta_3 = 1$. β_1,β_2 and β_3 are weights and no guidelines are available to select the weights. The DRI ranges from 0-1 with 1 indicating serious water shortage. Loucks, 1997 proposed the sustainability index (SUI):

$$SUI = [Rel \times Res \times (1 - Vul)]^{\frac{1}{3}} \qquad [2]$$

Where Rel is reliability; Res is resilience; Vul is vulnerability. SUI’s values vary from 0–1 and the value closer to 1 means the condition of water shortage is less serious. The SUI equation above means that if one of the performance criteria is zero, the sustainability will be zero also there is implicit weighting because the index gives added weight to the criteria with the worst performance. In this study RRV indices are chosen and applied separately without the subjective and often times biased weighting factors of the SUI and the DRI indices.

4.6 *Previous Water Resources Modelling in the catchment*

4.6.1 NWMP 1991

The Eastern Botswana model was developed during the first National Water Master Plan to evaluate the interaction between water sources and demands with appropriate consideration of transfer systems, use of groundwater and the staged development of water resources. In the model, the area modelled was set as the area south of and including Botlhapatlou/Letlhakeng groundwater aquifers, east of and including Jwaneng wellfield and diamond mine. A number of remote demands were allocated to groundwater eliminating the need to model transfer pipelines such as Gantsi and Maun were linked to the main water supply system. The main finding of the research was the recommendation of NSC linked to Dikgatlhong and Letsibogo dams.

4.6.2 BNWMPR 2006

SMEC-EHES in Volume 11 of the NWMPR, 2006 titled ‘System Modelling and Water Development Strategies’ carried out a study on system modelling and the impact of the scenarios considered on the availability of water for Urban, Mining, Major Villages and rural villages interconnected with the system in Botswana. The study examined the water resource management options available for the 30 years up to 2035 and their likely impact on water availability in Botswana. The WATHNET (Water Supply Headworks Simulation Using Network Linear Programming) model program was applied using both historic and stochastically generated flows. Six development scenarios were established in the review, the base scenario, two scenarios from sanitation and wastewater ,two agricultural scenarios and the combination scenario of the above excluding the base scenario. The base scenario concentrated on the most economic or cost-effective water resources development plan, within the limitations given by existing policies, with the main emphasis on satisfaction of domestic and industrial water demand and only including such irrigation developments that are considered to become economically viable. The two agricultural scenarios were based on NAMPAD options of economic agricultural development. The other two scenarios were formulated in association with the recommendations prepared by the National Sanitation and Wastewater Master Plan. A final scenario based on the Consultant’s recommended combination of agricultural, sanitation and water resources development was formulated also. The main findings and recommendations of the study were;

- Priority must be given to the reduction of water losses in the bulk transfer
- systems including the NSC and future pipelines to major Villages
- Inclusion of environmental flows in future water resource modelling
- Stochastic flow analysis and climate change estimates indicate that droughts worse than those observed in the historical sequence will probably occur in the future
- WATHNET is a suitable model for both steady state and rising demand modelling of water resources
- Irrigation should not be based on surface water resources in southern Botswana
- Irrigated agriculture may be encouraged in the Chobe District where water is more plentiful subject to its ability for integration with wildlife.
- Irrigation and landscaping are both acceptable uses for reclaimed wastewater.
- Industrial and Institutional Development in the Palapye/Serowe and Selebi Phikwe areas near the water resources is preferable to unrestrained development in the greater Gaborone area.
- A link between Letsibogo Dam and city of Francistown is required to provide flexible operation of the northern storages in drought years.
- High growth scenarios will require a future water source after Dikgatlhong to sustain reliable supplies to the end of the planning period.
- Groundwater mining is not able to sustainably defer future expansion of the water supply system.
- International negotiations must commence to define Botswana's water entitlements from the Limpopo (LIMCOM), Nata, and Zambezi (ZAMCOM) river systems.
- Wherever possible, groundwater resources should be allowed to recover when surface water is in abundance.

4.6.3 Parida et al., 2006

Parida et al, 2006 applied an Artificial Neural Network (ANN) model to forecast the runoff coefficients for the rapidly urbanizing Notwane catchment system in Botswana. Runoff coefficients were computed from the historical period (1978 to 2000) utilizing the water balance technique and then used in the development of the artificial neural network. The developed network was then applied in simulating runoff coefficients up to the year 2020. The study concluded that:

- Land use changes in the catchment amounted to 52 % change in runoff coefficients as compared to 48 % contribution from climatic factors;
- A 3 % increase per year of the simulated runoff coefficients for the historical period
- The forecasted runoff coefficients up to the year 2020 indicated an increase of about 1% per year revealing the likely reduction of yield in the catchment for the next 20 years.

4.6.4 Linnett N., 2014

Linnett, 2014 carried out a study titled ‘‘Development and Optimisation of a Water Allocation Model for the North-South Corridor and Limpopo River Basin in Botswana’’ to develop and optimize a water allocation model that will entail sustainable water resource management in the Shashe and Motloutse catchments. The Water Evaluation and Planning System (WEAP) model was employed, calibrated and used for analysis of various water allocation and operational scenarios of water infrastructures. The work conducted for this study, tested WEAP’s ability to simulate water allocations under normal and high population scenario in the Shashe and Motloutse catchments and assessed the impact of population growth on water resources. The study revealed that WEAP was able to simulate sufficiently water allocation for the various demand sites. This constituted a good test of its ability to model water resources allocation under high population and use of multi water sources. The results from the water allocation simulation also showed that WEAP was a useful tool for assessment of water resources development in the two catchments.

CHAPTER 5

RESEARCH METHODOLOGY

5.1 *Introduction*

This research was conducted chiefly through desk studies using long term and short term historical rainfall, evaporation, inflow, outflow, abstraction, water supply and storage data. These data was obtained from the DWA, WUC and the DMS. Before we proceed deeper, a basic reservoir system is expounded by considering a reservoir graphic below;

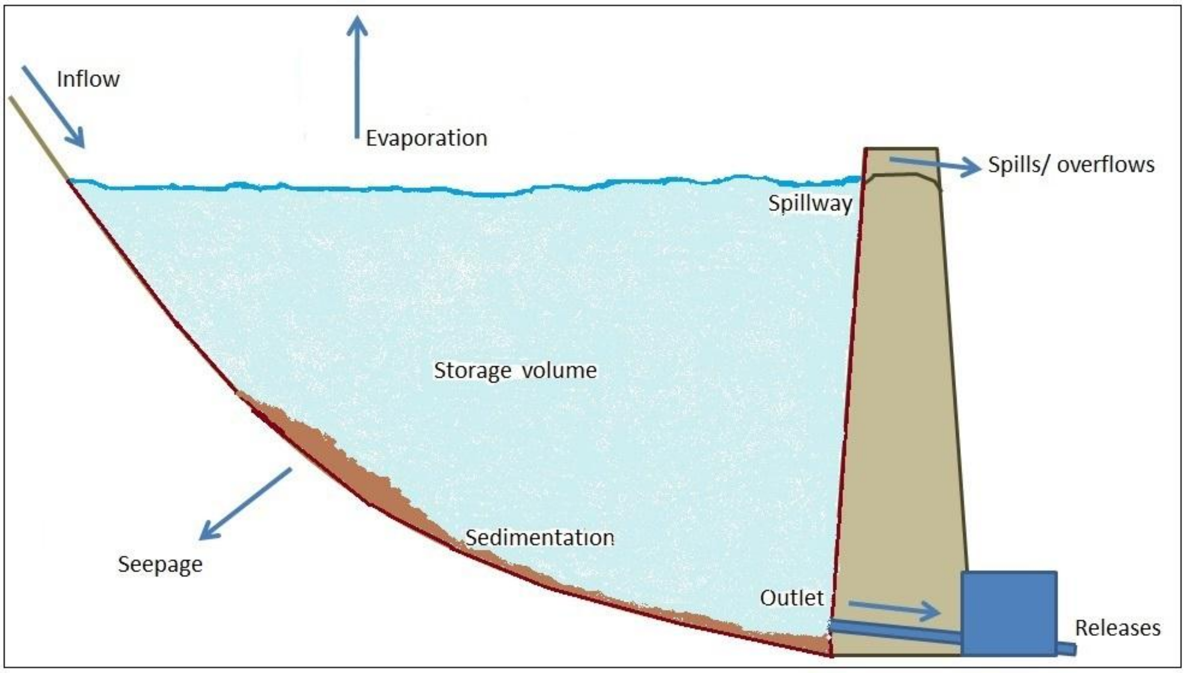


Figure 5.1: Basic reservoir system

From Figure 5.1, Water comes mainly into the reservoir from a river and this flow is termed the inflow, and is stored in the dam as storage. Part of the storage is lost as evaporation, and some is abstracted as releases, for different purposes such as water supply, irrigation and hydropower generation. Spills or overflows, occur when the reservoir is full and water keeps flowing into the reservoir so that eventually some is spilled over through the spillway.

5.2 *HEC-ResSim Hydraulic Model*

5.2.1 Introduction

Water resources management is a challenging subject and requires consideration of a broad range of social, economic, technical and environmental interests. As Botswana's water resources become increasingly stressed, effective tools for management become more important. One tool usually used in water resources management is decision support systems. Watkins and McKinney (1995) defines a decision support system as an integrated, interactive computer system, consisting of analytical tools and information management capabilities, intended to help decision makers in solving problems.

Modeling of Notwane reservoirs in operation for flood and water supply function is more challenging and encompasses modeling of reservoir storage and allocation of water through outlet groups. This sub-chapter deals with the development and application of HEC-ResSim (HEC, 2013) reservoir simulation model, as tool to assist in evaluating the existing reservoir operations and conservation storage requirements of the three dams. The intended use of the model is to promote understanding and aid in the development and application of efficient and sustainable water management options for the operations of the Notwane reservoirs.

Well modeled reservoir operation assists an engineer or reservoir operators to have the general and specific operation strategies to release water according to the current reservoir level, hydrological conditions, water demands and the time of the year. This can be attained by improving or modifying the already established reservoir operational rules through use of the existing information, forecasted climate and the ever changing hydrological conditions and advanced computational simulation models.

5.2.2 Detailed Description

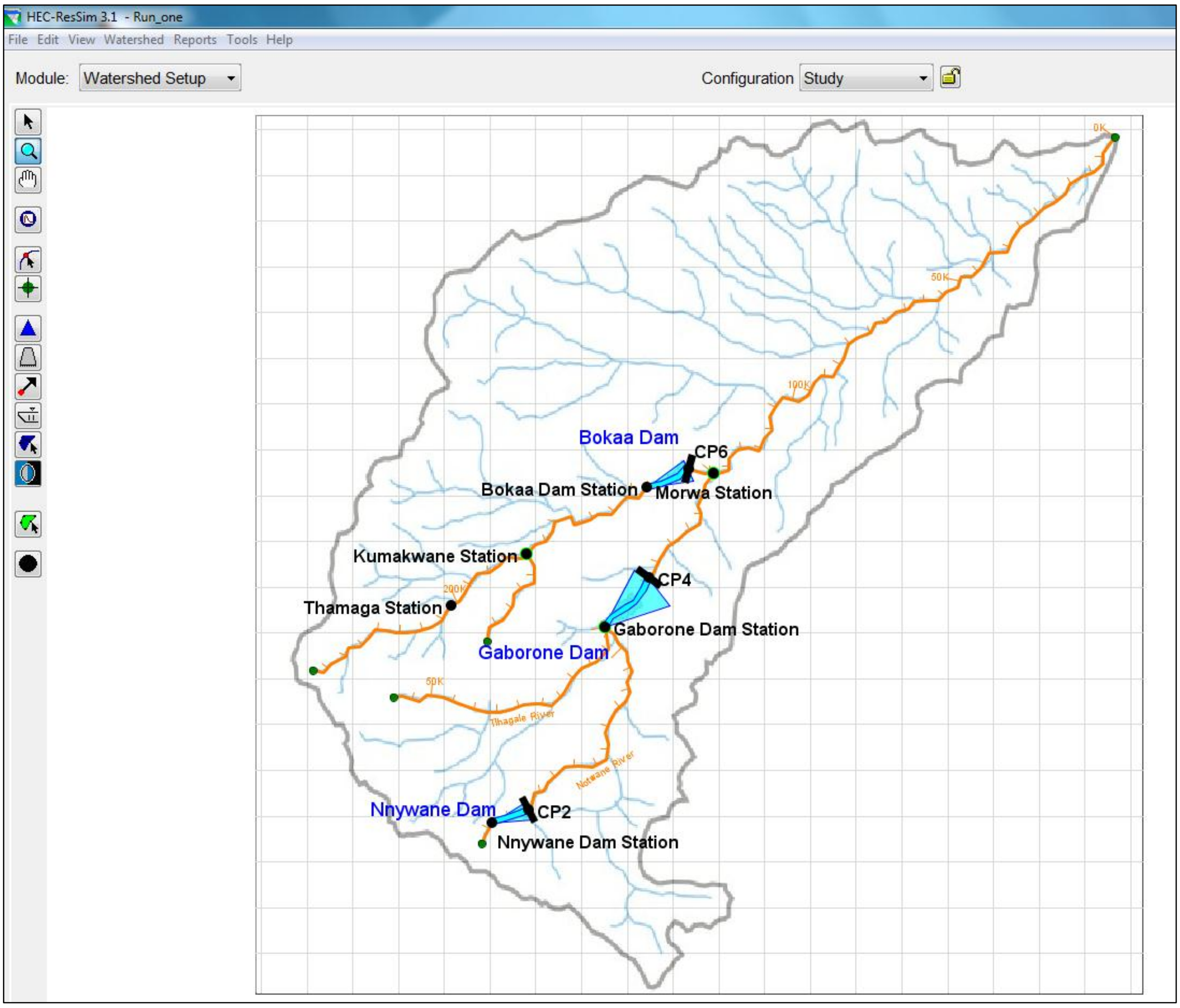
The simulation software used in modeling the Notwane reservoirs is HEC-ResSim which was created by the U.S. Army Corp of Engineers – Hydrologic Engineering Center (version 3.1, HEC, 2013). Res-Sim has a graphical user interface (GUI) for viewing, editing, and manipulating data and uses the HEC Data Storage System (HEC-DSS) for entry, storage and retrieval of input and output time-series data in the model. The model uses three types of data namely time series data, physical and operational data that are kept in HEC-DSS. ResSim is used to simulate reservoir operations including all characteristics of a reservoir and channel routing downstream. Although ResSim considers many aspects of reservoirs, it does not consider water quality.

ResSim has three main modules which are the Watershed Setup, Reservoir Network and Simulation. Each module has a specific purpose and associated set of functions which are accessible by menus, toolbars and schematic elements.

5.2.2.1 Watershed Setup Module

The foundation of the HEC-ResSim model, the watershed, is created in the Watershed Setup module. Watershed setup module allows for the creation and definition of the physical arrangement of the watershed. This includes streams alignment, reservoirs, levees, gage locations, computation points, time-series locations and some of the hydrologic and hydraulic data for the catchment. Schematic elements in ResSim allow you to represent the watershed, reservoir network and simulation data visually in a geo-referenced context that interacts with associated data. Figure 5.2 depicts the watershed setup module where streams, reservoirs, catchment boundary are drawn and added. In summary, the following model development steps in the Watershed Setup module were taken:

- The stream alignment (orange lines in Figure 5.2) was created from shape files of rivers and streams and edited to add or extend streams. The stream alignment serves as the framework for inserting reservoirs and computations points.
- The three dams were created and added to the setup (blue triangles in Figure 5.2).
- Computation Points were added to represent the DWA gauging stations and other points of interest.



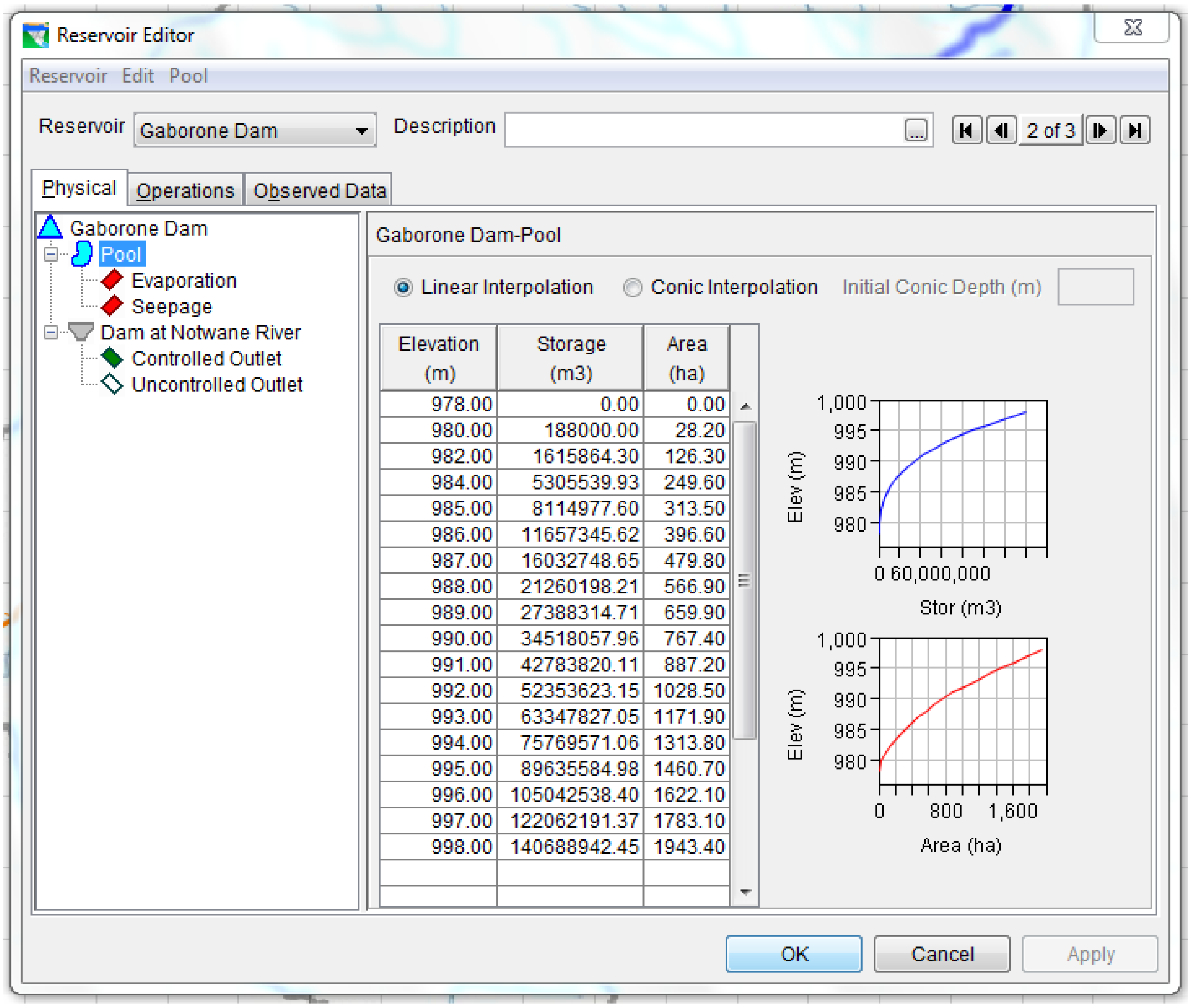
Module: Watershed Setup

Configuration Study

Figure 5.2: Watershed setup module of HEC ResSim

5.2.2.2 *Reservoir Network Module*

In this module, the reservoir network schematic is developed. The development of the reservoir network is the second most important task in building up of the model. It is made up of two major highly inter-related components, which are namely the physical and operational parts of the model.



Reservoir: Gaborone Dam

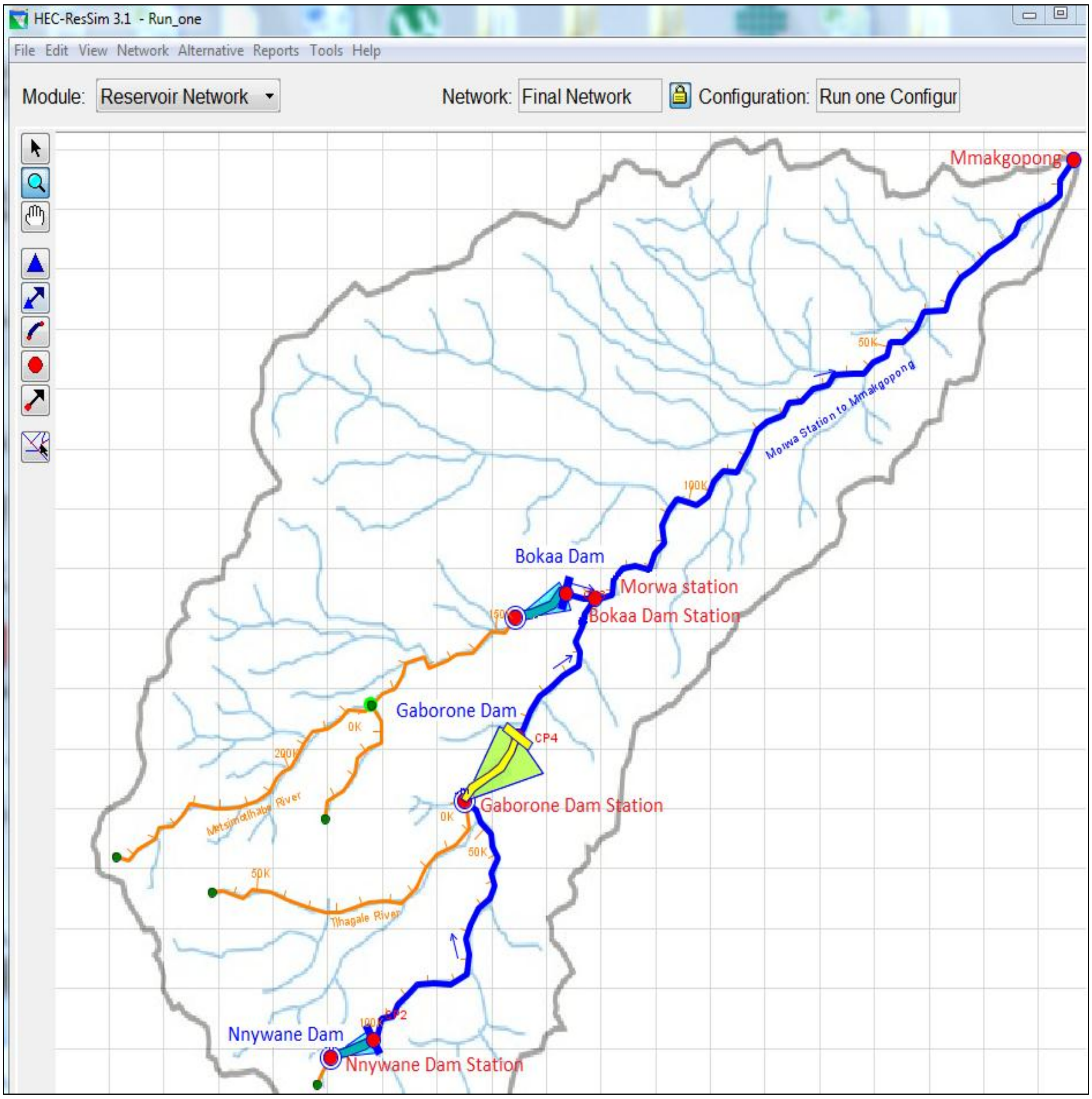
Gaborone Dam-Pool

● Linear Interpolation ○ Conic Interpolation

Elevation (m)	Storage (m3)	Area (ha)
978.00	0.00	0.00
980.00	188000.00	28.20
982.00	1615864.30	126.30
984.00	5305539.93	249.60
985.00	8114977.60	313.50
986.00	11657345.62	396.60
987.00	16032748.65	479.80
988.00	21260198.21	566.90
989.00	27388314.71	659.90
990.00	34518057.96	767.40
991.00	42783820.11	887.20
992.00	52353623.15	1028.50
993.00	63347827.05	1171.90
994.00	75769571.06	1313.80
995.00	89635584.98	1460.70
996.00	105042538.40	1622.10
997.00	122062191.37	1783.10
998.00	140688942.45	1943.40

Figure 5.3: Physical part of the reservoir network module

The physical part includes the dam and other accessory components of a dam structure like the spillways, hydropower plants and outlet groups (Figure 5.3) while the operational part (Figure 5.6) comprises reservoir release rules and a reservoir storage zone that may be divided into the inactive, conservation and flood control zones (HEC, 2013). The HEC-ResSim model requires definition of both components to yield satisfactory simulation results. The definitions of both physical and operational components necessitate intensive data in HEC-ResSim model. Reservoir pool characteristics of the projects in the reservoir network are described in detail in the ensuing sections.



Module: Reservoir Network

Network: Final Network

Configuration: Run one Configur

Figure 5.4: Junctions, reaches and reservoirs of the Reservoir Network Module

- **Junctions**

The junctions link model elements together and are the means by which flow enters the network. The junctions are at key locations to identify and manage flow across the network. They also combine flow as the outflow from the junction is the sum of the inflows entering the junction. The computation points added in the Watershed setup automatically becomes junctions in the reservoir network module, hence the main task in the reservoir network is the connection of junctions to the routing reaches. The junctions are represented as red circles in Figure 5.4. Additionally if rating curves information is available, it is added at the junctions.

- **Reaches**

The reaches route water from one junction to the next in the network from upstream to downstream. There are depicted as blue lines along the streams because routing reaches in HEC-ResSim automatically conform to the stream alignment created in the Watershed setup. Routing in HEC-ResSim is handled by a few hydrologic routing methods, which are Null (direct translation – no lag or attenuation), Variable Lag & K, Coefficient, Modified puls and Muskingum. In this study, Null routing was used as it did not require many parameters and because calibration of routing parameters can be significantly labour intensive.

- **Reservoirs**

Reservoirs are the most complex elements in HEC-ResSim. The physical data input of HEC-ResSim is handled by a pool and one or more dams. The reservoir pool comprises the reservoir's elevation-storage-area relationship (which describes the properties of the pool) and can optionally include evaporation and seepage losses if added. The dam is described by both an uncontrolled outlet and an outlet group. The top of dam elevation and length specifies the minimum parameters for an uncontrolled spillway and the dam may contain one or more controlled or uncontrolled outlets to enable the water to pass to the downstream.

Reservoir elements also host the operational data input for the reservoirs. The operational data symbolizes the goals and constraints that guide the release decision process. The operation data of the reservoir network module is grouped as a unit called an operation set. A reservoir can have multiple operation sets, but only one operation set per reservoir may be used in an alternative. The operation set comprises a set of operating zones, each of which contains a prioritized set of rules (Figure 5.6). A reservoir storage capacity can be subdivided into various zones or pools, in this study the zones are subdivided into three zones namely inactive (dead), conservation (active/live) and the flood control zones (see Figure 5.5) Inactive Pool is sometimes called dead storage zone. This zone represents the lowest operational elevation of a reservoir. By default, HEC-ResSim does not permit water releases below this elevation and rules cannot be added to this zone. Conservation pool is the storage zone between the flood control pool and the inactive pool. It is sometimes called the live or active storage as it is the storage space set aside for the purpose of water stored for water supply, hydropower, irrigation, environmental releases and other purposes. Flood control pool is defined as the zone preserved for flood control purposes. It is positioned between the maximum reservoir level and the top of the conservation pool. The flood control zone is kept as empty as possible so that it is availed to absorb or accommodate huge volumes of water during flooding hence avert or attenuate downstream flooding and damage.

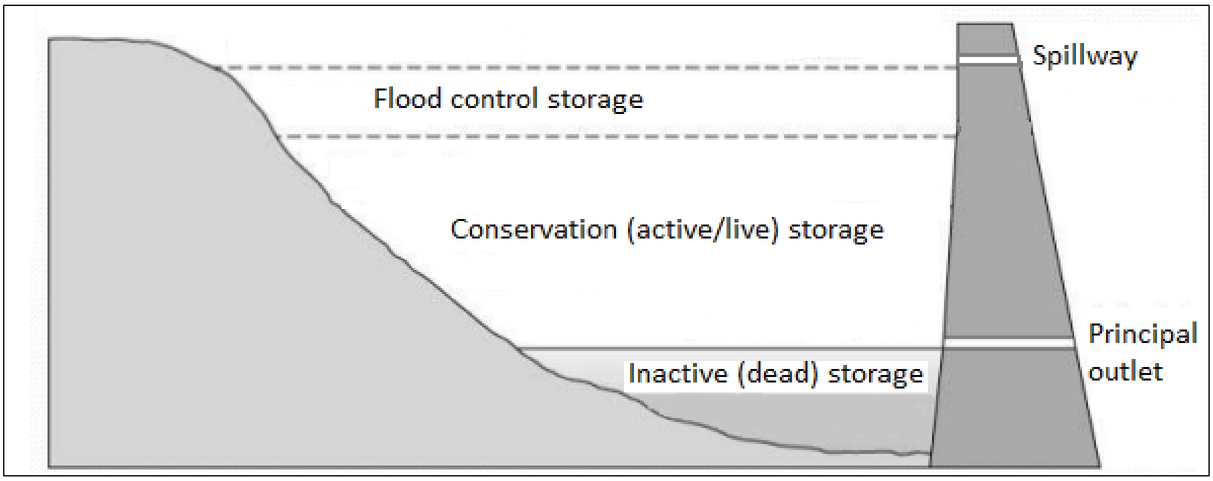
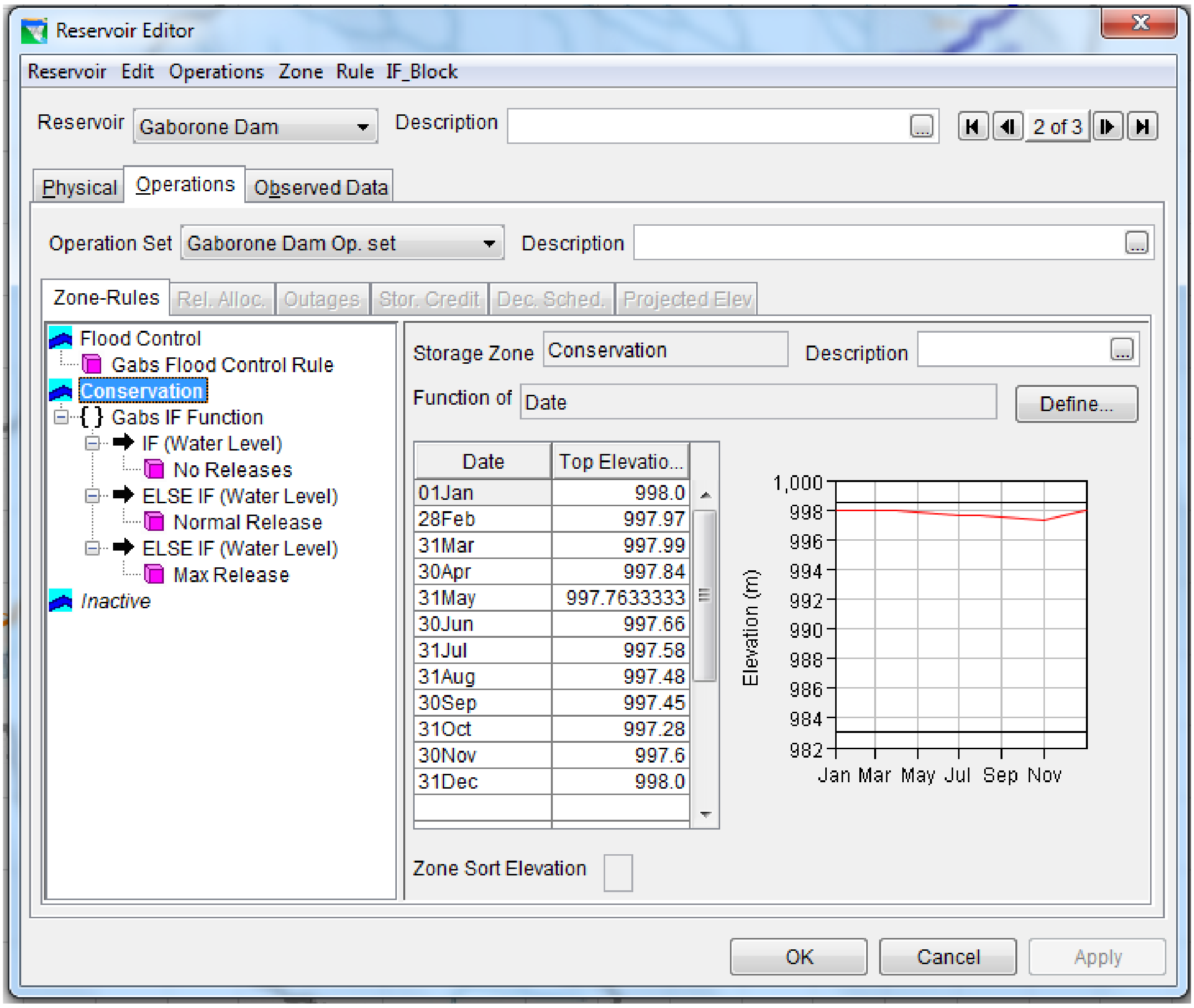


Figure 5.5: Reservoir storage zones

5.2.2.2.1 *Reservoir Operation Rule in HEC-ResSim*

Reservoir operational management requires a set of operational rules like release regulation, schedules, policy or plans that best meet a set of objectives. Rules describe a minimum or maximum constraint on the reservoir releases based on a number of variables such as reservoir water level, date, inflow, outflow and many others depending on the information you have at your disposal. The main goal of reservoir operating rules is to guide releases decisions for the reservoir operators based on the existing condition. HEC-ResSim requires every reservoir to have a target elevation. The reservoir's target elevation is called its Guide Curve and is presented as a function of time. For the Notwane dams, the guide curve was taken as the monthly maximum water elevations which make the top of the conservation zone. The storage above this guide curve is the flood control pool and the one below it is the conservation pool. The criteria for determining the release from the reservoir is then based on where the current reservoir pool elevation is in relation to the guide curve. When the reservoir pool elevation is below the guide curve in the conservation zone/pool, the reservoir reduces releases of water as possible in order to refill the pool; if the reservoir pool elevation is above the guide curve in the flood control pool, then the reservoir releases more water as possible than is entering the pool to draw down the pool (HEC, 2013).



Reservoir: Gaborone Dam

Operation Set: Gaborone Dam Op. set

Storage Zone: Conservation

Function of: Date

Date	Top Elevatio...
01Jan	998.0
28Feb	997.97
31Mar	997.99
30Apr	997.84
31May	997.7633333
30Jun	997.66
31Jul	997.58
31Aug	997.48
30Sep	997.45
31Oct	997.28
30Nov	997.6
31Dec	998.0

Figure 5.6: Operational part of the reservoir network module

The operating rules and physical limitations that are added act as constraints upon the reservoir's ability to meet the aim of bringing the reservoir pool to the guide curve elevation. Hence without rules the reservoir would be constrained only by the physical capacity of its outlets to maintain the guide curve elevation. In HEC-ResSim, the guide curve is identified by selecting the top of one of the three operational zones which in most cases is the conservation zone to represent the target elevation of the reservoir. Decisions made by reservoir operators affect the allocation of storage capacity and water releases between reservoirs and various users in different time periods. Each zone can host different set of rules as in Figure 5.6. After rules are added in a zone, the release decision process for HEC-ResSim is to determine the quantity of release for the guide curve operation. The priority of rules in HEC follows the order that the first listed rule in the storage zone has the highest priority than the one below it. Hence the release from the guide curve operation is adjusted by the program to meet each rule in their priority of which if the rules contradict each other then the higher priority rule applies or overwrites the lower priority rule. Basically the release decision can be summarized in three steps:

- The allowable release range is determined, that is the maximum and minimum physical limits of release are identified;
- then the allowable release range is narrowed by the application of rules according to their priority;
- The desired release for the guide curve operation is evaluated. This is the release needed to get the reservoir pool to the guide curve in the current (computation period) time step based on the final pool elevation of the time step before, the release before and the current inflow.

An example of reservoir storage and rules on each storage zone is depicted in operation summary tables of the dams (Table 5.1, Table 5.2 and Table 5.3). In the operation summary for the reservoirs, IF conditional statements have been used to indicate which rules apply in the reservoir release decision process.

Table 5.1: Operation summary of Bokaa dam

Name	**Item**	**Description**
Bokaa		
TOP OF DAM	954.5 m	
FLOOD CONTROL ZONE	953.5 m	
Induces surcharge	Release water from Spillway using defined release discharge	Forces flood flows over the spillway
CONSERVATION ZONE	Varies between 954 and 953.6 m	This is the range of the guide curve elevation. Calculation is done in Excel
Bokaa IF Functions	ELSE IF Bokaa Dam Pool >953.5 Maximum release of 1.5 cms	Spillways open
	ELSE IF Bokaa Dam Pool >948 and <954 m Normal release of 0.13 cms	Spillways closed Controlled outlet open
	IF Bokaa Dam pool <=948m Maximum Release of 0 cms	Spillways are closed Controlled outlet closed
INACTIVE	948 m	Dead storage, no releases below this elevation

Table 5.2: Operation summary of Gaborone dam

Name	**Item**	**Description**
Gaborone		
TOP OF DAM	998.5 m	
FLOOD CONTROL ZONE	998 m	
Induces surcharge	Release water from Spillway using defined release discharge	Forces flood flows over the spillway
CONSERVATION ZONE	Varies between 998 and 997.3 m	This is the range of the guide curve elevation. Calculation is done in Excel
Gaborone IF Functions	ELSE IF Gaborone Dam Pool >998 m Maximum release of 3.6 cms	Spillways open
	ELSE IF Gaborone Dam Pool >983 and <998 m Normal release of 0.63 cms	Spillways closed Controlled outlet open
	IF Gaborone Dam pool <=983 m Maximum Release of 0 cms	Spillways are closed Controlled outlet closed
INACTIVE	983 m	Dead storage, no releases below this elevation

Table 5.3: Operation summary of Nnywane dam

Name	**Item**	**Description**
Nnywane		
TOP OF DAM	1135.5 m	
FLOOD CONTROL ZONE	1135 m	
Induces surcharge	Release water from Spillway using defined release discharge	Forces flood flows over the spillway
CONSERVATION ZONE	Varies between 1134.5 and 1135 m	This is the range of the guide curve elevation. Calculation is done in Excel
Nnywane IF Functions	ELSE IF Nnywane Dam Pool >1135 m Maximum release of 0.15 cms	Spillways open
	ELSE IF Nnywane Dam Pool >1129 and <1135 m Normal release of 0.021 cms	Spillways closed Controlled outlet open
	IF Nnywane Dam pool <=1129 m Maximum Release of 0 cms	Spillways are closed Controlled outlet closed
INACTIVE	1129 m	Dead storage, no releases below this elevation

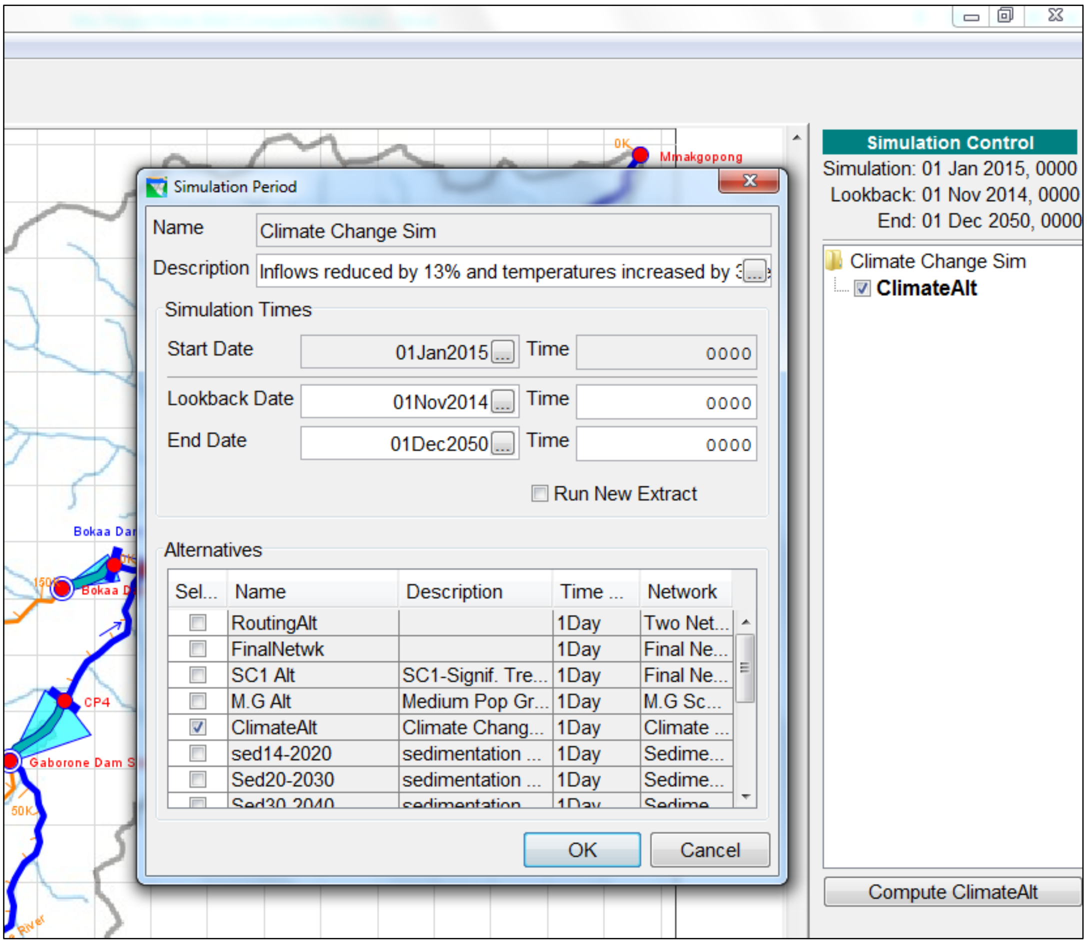
HEC ResSim allows for hydropower reservoir operation rules, however this were not formulated or applied in this study because the reservoirs of the catchment do not and are not capable of hydropower generation.

5.2.2.3 Alternatives

In HEC-ResSim, an Alternative is a platform that allows the amalgamation of a reservoir network, the selection of an active operation set for each reservoir in the network, and the specification of the initial (or lookback) conditions/values and inflow time-series data for the network.

5.2.2.4 *Simulation Module*

The simulation model isolates the output analysis from the model development process. After the catchment and reservoir network together with Alternatives are set up, computations are performed and results are viewed in the simulation module. In the simulation module the processes that include; specifying the simulation window, a computation interval and the single Alternative or group of Alternatives to be analysed are carried out (Figure 5.7).



Simulation Period

Name: Climate Change Sim

Description: Inflows reduced by 13% and temperatures increased by

Simulation Times

Start Date: 01Jan2015 Time: 0000

Lookback Date: 01Nov2014 Time: 0000

End Date: 01Dec2050 Time: 0000

☐ Run New Extract

Alternatives

Sel...	Name	Description	Time ...	Network
☐	RoutingAlt		1Day	Two Net...
☐	FinalNetwk		1Day	Final Ne...
☐	SC1 Alt	SC1-Signif. Tre...	1Day	Final Ne...
☐	M.G Alt	Medium Pop Gr...	1Day	M.G Sc...
☑	ClimateAlt	Climate Chang...	1Day	Climate ...
☐	sed14-2020	sedimentation ...	1Day	Sedime...
☐	Sed20-2030	sedimentation ...	1Day	Sedime...
☐	Sed30 2040	sedimentation	1Day	Sedime

Simulation Control

Simulation: 01 Jan 2015, 0000

Lookback: 01 Nov 2014, 0000

End: 01 Dec 2050, 0000

Climate Change Sim

☑ **ClimateAlt**

Figure 5.7: The simulation module of HEC-ResSim

Simulation window comprises starting time of the simulation, lookback (the time period required for equilibrium or 'warmup period' of the model before the starting simulation time), and end time of simulation. Once the above have been specified, ResSim creates a directory structure within the base folder of the watershed that represents the simulation. Inside this folder, there will be a copy of the watershed which includes only those files needed by the selected alternatives for the simulation. A DSS file called simulation.dss also will be created in the simulation, which will ultimately contain all the DSS records that represent the input and output data for the selected alternatives. After a successful simulation, the results can be viewed, analysed and revisions made and additional simulations performed. HEC-ResSim performs simulations on a daily time step. HEC-ResSim does not yet have the capability to perform simulations on a monthly time-step but has the capability to interpolate monthly data to daily data. The summary of the HEC-ResSim model framework is given in Figure 5.8.

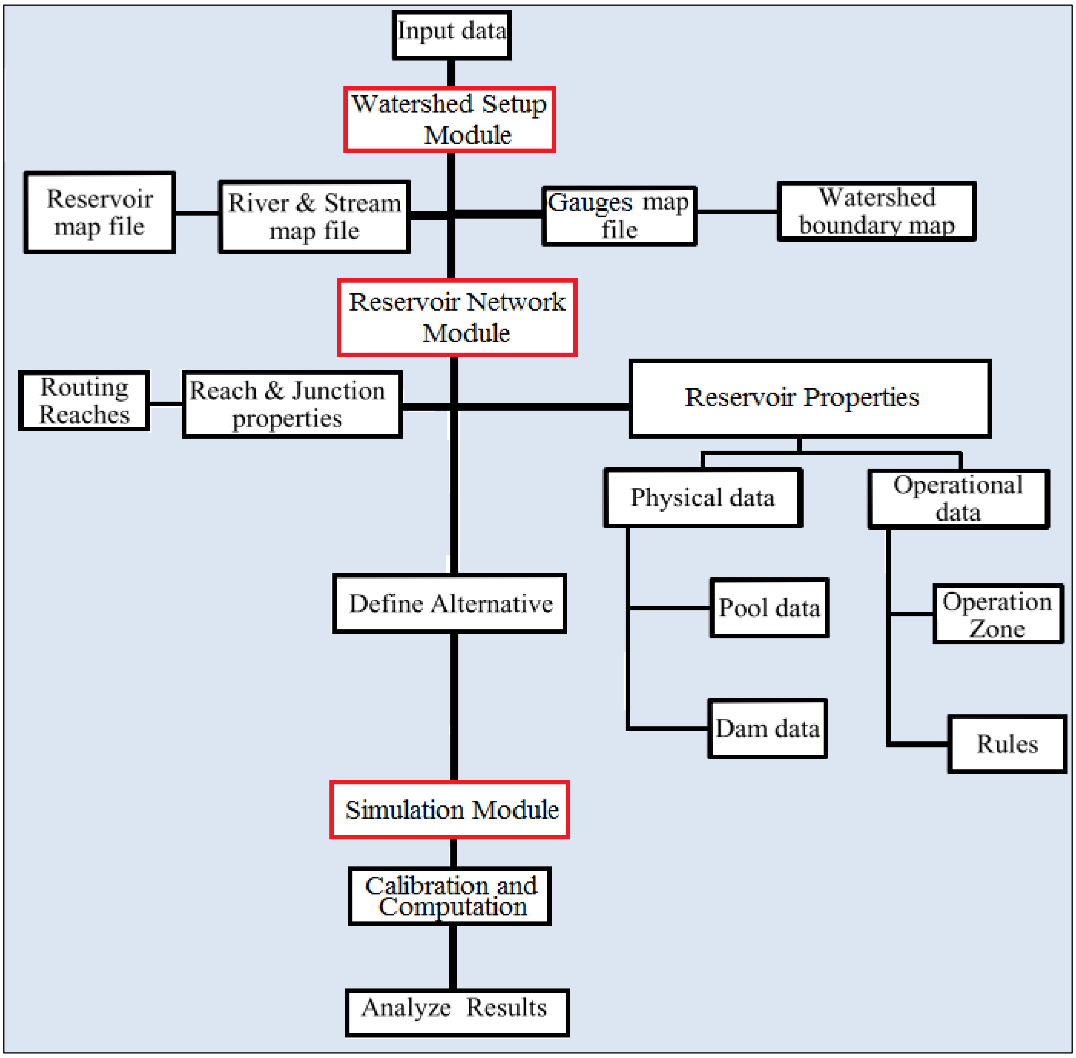


Figure 5.8: Summary of the HEC-ResSim model framework

5.3 Data Collection, Generation and Analysis

Relevant and appropriate data are very important prior to simulation of any model in order to achieve the objectives of the research. Therefore, the primary aim of this section was getting applicable information specific to the model based on the core objectives of this study. The data applied in this research were gathered from the various departments (DWA, DMS and WUC), outputs of reports, personal communication with relevant stakeholders and journals.

5.3.1 Hydrological Inflow Data

Streamflows gauging stations in the Notwane Basin are mainly maintained by the department Of Water Affairs (DWA), which process and archive data. However most of the time, data from the department for use in the design and planning of water resources projects have not always been obtainable, moreover records of hydrological data are usually short, misplaced, highly erroneous and often have large breaks in the records. the hydrological inflow data from DWA of the rivers had a few gaps of missing data and was the gaps were filled using linear interpolation method. The inflow data considered was from the stations at the three dams locations while the data at Thamaga and Kumakwane stations (Figure 5.2) were discarded as they had long breaks and were highly erroneous. The data from Bokaa Dam station was from January 1993 to December 2011 while from Gaborone Dam station was from April 1990 to September 2014 and for Nnywane Dam station was from April 1990 to July 2012. Since the inflow record or history into the reservoirs are known, i.e. there is no uncertainty about the sequence of inflows; we brand these inflows as deterministic inflows.

5.3.2 Inflows Time Series Forecasting

Time series modeling is a dynamic research field which has attracted attentions of many researchers over the last few decades. The main aim of time series modeling is to carefully study the past characteristics of a time series then establish an appropriate model which describes the inherent structure of the series. This model is then used to generate future values for the series, i.e. to make forecasts. Thus time series forecasting thus can be simply described as the act of predicting the future by understanding the past. Time series forecasting is important to numerous practical fields such as business, economics, finance, science and engineering.

As a consequence, various important time series forecasting models have been evolved in literature over many years. One of the most popular and frequently used stochastic time series models is the Autoregressive Integrated Moving Average (ARIMA), [Box and Jenkins, 1970]. The basic assumption applied to this model is that the time series is linear and follows a particular known statistical distribution, such as the normal distribution. Under ARIMA we have subclasses of other models, such as the Autoregressive (AR), Moving Average (MA), Autoregressive Moving Average (ARMA) and Seasonal ARIMA (SARIMA) [Hipel and McLeod, 1994]. The ARIMA model is highly popular due to its ability to represent several varieties of time series with simplicity as well as the associated Box-Jenkins methodology. However, the severe limitation of these models is the assumption that the considered time series is linear which sometimes is inadequate in many practical situations. To handle this problem, various non-linear stochastic models have been proposed in literature, however these are not as simple as ARIMA models and are a bit challenging. In recent years, artificial neural networks (ANNs) have solicited increasing attention in the field of time series forecasting [Zhang, 2003, Parida et al, 2006, Moalafhi et al, 2014].

Although initially biologically inspired, later on ANNs have been successfully used in various fields, especially in the domain of forecasting. The excellent feature of ANNs when used in time series forecasting problems is their essential proficiency of non-linear modelling, without any assumption about the statistical distribution of the observations. Attributable to this reason, ANNs are data-driven and self-adaptive by nature.

A time series is a sequential set of data points, measured over successive times. It is denominated mathematically as a set of vectors x (t) where t represents the time elapsed and the variable x (t) is taken as a random variable. A time series comprising records of a single variable is dubbed as univariate while if records are of more than one variable, it is termed as multivariate. A time series can be continuous or discrete. A continuous time series is where observations are measured at every instance of time (like temperature readings and flow), whereas a discrete time series involves observations measured at discrete points of time (for example, population of a town). A time series in general is characterized by four main components, which can be distinguished from the observed data. These components are Trend, Cyclicity, Seasonality and Irregularity components;

- Trend: The general tendency or course of a time series to increase, decrease or stagnate over a period of time.

- Seasonality: seasonal variations usually regular and predictable in a time series occurring every year. The seasonal variations are usually caused by; climate and weather conditions, customs, traditional habits, etc.
- Cyclicity: The cyclical variation in a time series describes the medium-term changes in the series, caused by circumstances, which repeat in cycles. The duration of a cycle extends over longer period of time, usually two or more years.
- Irregularity: Irregular or random variations in a time series are caused by unpredictable influences or events, which are not regular and also do not repeat in a particular pattern. These variations may be caused by occurrences such as war, strike, earthquake and floods. There is no defined statistical technique for measuring random fluctuations in a time series.

Generation of future inflows in this study from the last date of historical inflow to the year 2050 was realized through the Autoregressive model of order one (Equation 3). This method is picked due to the advantage mentioned in the preceding paragraphs.

Autoregressive (AR) model $$X_{t+1} = \delta + \phi_1 X_t + A_t \quad [3]$$

Where: X_t is the value of series at time t

δ is the Autoregression coefficient

Φ_1 is the order 1 serial coefficient

A_t is the error term

Autoregression coefficient $$\delta = (1 - \emptyset_1)\mu \quad [4]$$

Where μ is the mean value of X_t

Order 1 serial correlation coefficient $$\emptyset_1 = {C_1}/{C_0} \quad [5]$$

Lag 1 serial covariance

$$C_1 = \frac{1}{N}\sum_{t=1}^{N}\left(X_t - \overline{X}\right)\left(X_{t+1} - \overline{X}\right) \qquad [6]$$

Lag 0 serial covariance

$$C_0 = \frac{1}{N}\sum_{t=1}^{N}\left(X_t - \overline{X}\right)^2 \qquad [7]$$

Where;

C_1 and C_2 are the lag 1 and 0 serial covariance parameters.

$\bar{X}$ is the mean of X.

Given X (time period) and Y (inflow in m^3/s), the following steps were taken in the generation of future inflows for the dams:

1. Plot of the inflows;

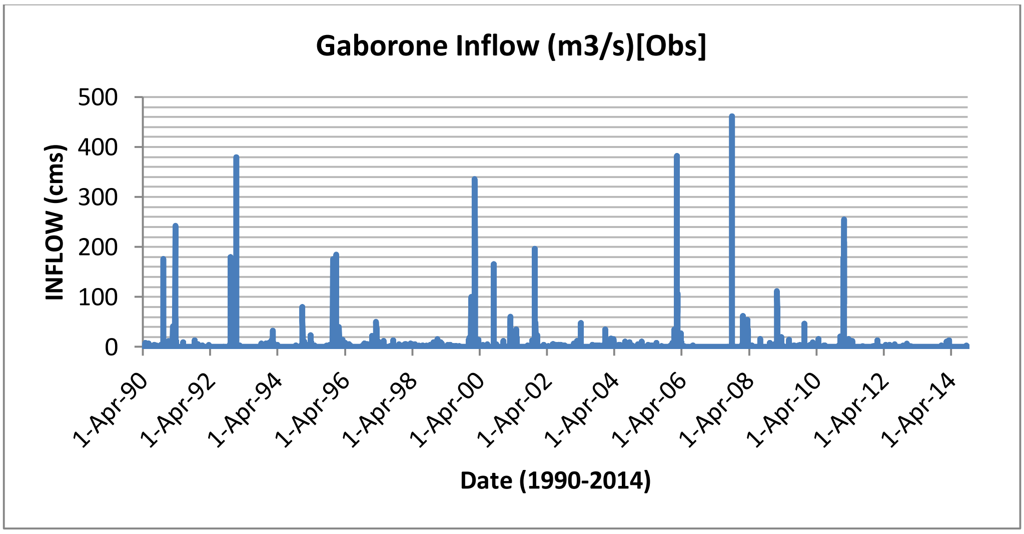
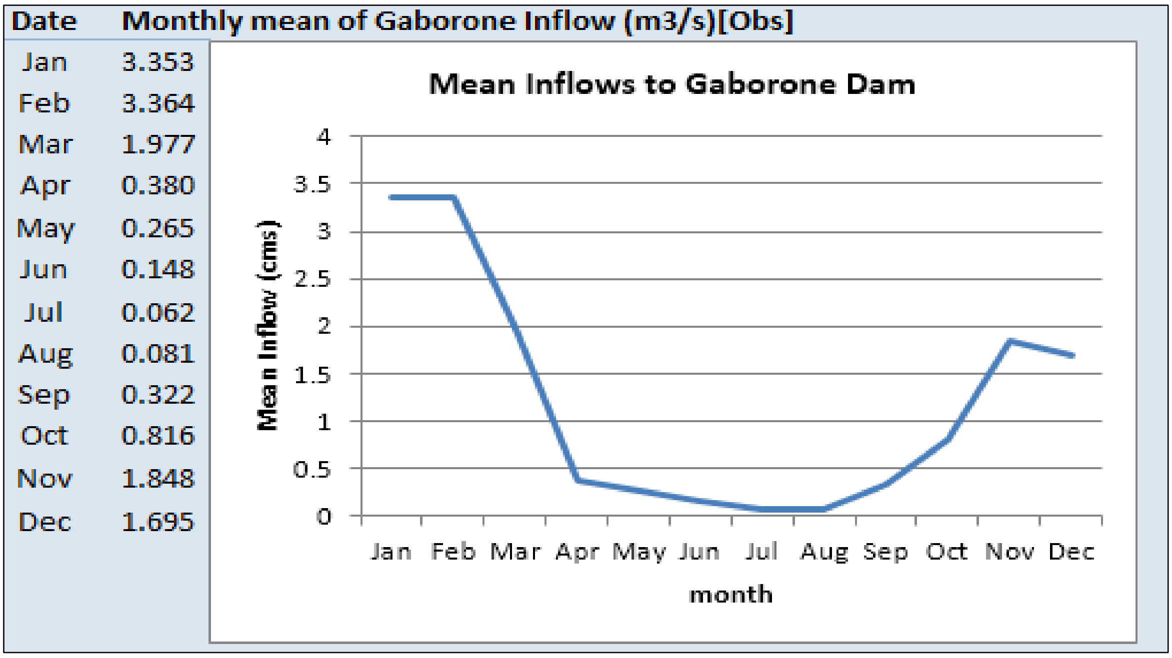


Figure 5.9: Observed inflows to Gaborone dam. Source: DWA



Date	Monthly mean of Gaborone Inflow (m3/s)[Obs]
Jan	3.353
Feb	3.364
Mar	1.977
Apr	0.380
May	0.265
Jun	0.148
Jul	0.062
Aug	0.081
Sep	0.322
Oct	0.816
Nov	1.848
Dec	1.695

Figure 5.10: Monthly mean for Gaborone inflows (1990-2014)

In Figure 5.10 is a plot of means for the 12 months of the year for Gaborone inflow. From the figure, it is clear that there is seasonality.

2. Linear Regression Analysis executed to obtain y-intercept (a) and slope of the regression line (b)

$$b = \frac{n(\sum XY) - (\sum X \sum Y)}{n \sum X^2 - (\sum X)^2} \qquad [8]$$

$$a = \frac{(\sum Y) - b(\sum X)}{n} \qquad [9]$$

3. Determination of trend component of Y using equation:

$$T = a + bx \qquad [10]$$

Where T = trend

a = intercept of y

b = slope of the regression line

4. Time series decomposition step using the additive decomposition model. This is a process to separate or decompose a time series into seasonal, trend, and irregular components. Removal of trend from Y by using the equation;

$$Y_t - T_t = S_t + R_t \qquad [11]$$

Where Y_t is inflow value at time t
T_t is the trend component at time t
S_t is seasonality component at time t
R_t is the irregular component

5. Adjustment for seasonality by the seasonality factor. The seasonality factor is subtracted from each value of Y.

6. Irregular component adjustment through the equation;

$$R_t = Y_t - S_t - T_t \qquad [12]$$

7. Determination of Autoregressive model parameters. The AR model parameters are calculated as in equations 3, 4, 5, 6 and 7. After the parameters are identified, (Table 5.4) then the time series forecast is done using equation 3.

Table 5.4: AR (1) model parameters

AR (1) model parameters	**Gaborone Inflow**	**Bokaa Inflow**	**Nnywane Inflow**
μ	0.0	0.00	0.00
$\Phi1=C_1/C_0$	0.09	0.162	0.009
$\delta=(1-\mu)*\Phi1$	0.09	0.162	0.009

5.3.3 Evaporation Data

In semi arid climates such as in Botswana, accounting for evaporation losses cannot be underestimated as most of the water is lost to evaporation (see section 2.6.3). Evaporation from open water sources is rarely measured directly, even in small water bodies. It is usually estimated by evaporation from evaporation pans or calculated by water balance, energy balance, mass transfer or a combination of energy balance and aerodynamic techniques. The technique selected usually depends on the depth of the water body and the availability of weather data or micrometeorological equipment (Jensen, 2010). The Reference Evapotranspiration (ETo) values could be considered equal to evaporation from a large body of water, such as a pond, dam or lake (Brown, 2000). CLIMWAT 2.0 is a climatic database developed by FAO to be used in combination with ETo calculator program and allows the estimation of ETo for climatological stations worldwide. This database provides long-term monthly mean of daily maximum temperature (°C), daily minimum temperature (°C) given as Tmax and Tmin in Table 5.5 , [RH] relative humidity (%), wind speed (km/day), sunshine hours per day and solar radiation ($MJ/m_2/day$). In this research, the ETo calculator software was engaged to estimate the expected evaporation from the Notwane reservoirs using the CLIMWAT 2.0 database (FAO, 2012). Since the three dams are in the same catchment the resulting evaporation values from ETo calculator program were assumed for all the dams and later modified during the model calibration. The results from the ETo calculator are given in Table 5.5.

Table 5.5: ETo values from the ETo calculator. Source: FAO, 2012

Month	Tmax (° C)	Tmin (°C)	RH (%)	Wind speed (km/d)	Sunshine (Hours)	Solar Radiation (MJ/m^2/d)	Eto (mm/d)	ET (mm/month)
Jan	32.5	19.3	59.0	104.0	9.3	25.5	5.7	176.7
Feb	32.1	19.0	61.0	95.0	9.4	24.7	5.4	151.2
Mar	30.5	17.1	61.0	78.0	8.6	21.4	4.4	136.4
Apr	26.8	13.2	66.0	78.0	8.1	17.9	3.4	102.0
May	24.5	7.6	65.0	60.0	9.1	16.4	2.5	77.5
Jun	21.7	4.1	59.0	69.0	9.1	14.9	2.1	63.0
Jul	22.0	3.6	56.0	69.0	9.5	16.0	2.2	68.2
Aug	25.1	6.5	49.0	95.0	10.0	19.0	3.2	99.2
Sep	29.5	11.5	40.0	121.0	10.1	22.4	4.6	138.0
Oct	31.3	15.7	44.0	156.0	9.6	24.1	5.7	176.7
Nov	31.5	18.2	56.0	130.0	9.0	24.6	5.7	171.0
Dec	31.6	18.5	60.0	112.0	9.0	25.1	5.7	176.7

5.3.4 Seepage

Reservoirs are prone to losses through evaporation and seepage. All earth dams have seepage due to water movement through the dam and its foundation, however, the rate of seepage must be controlled. Seepage is the slow escape of a liquid through porous material from a dam. In water resources management, seepage is a serious issue leading to water losses. For effective water management of reservoirs/dams/or small ponds, seepage calculation and estimation has become crucial. The stability of any reservoir is related to the seepage. That is if the seepage is excessive; stability is low and vice versa. Many factors affect amount of seepage water from the reservoir. These are; wall or abutment of the reservoir, slope, soil type, bedrock type, dykes and volume and pressure of water. Newly constructed reservoirs release more seepage water than old reservoirs. This is due to the good soil structure of the new reservoir. In contrast, an old reservoir has been filled with water for some time which breaks down the soil structure and long deposition of organic materials at the bottom of the reservoir that seals the soil pores at the bottom of the reservoir and reduces permeability hence low seepage rates. Although there are various factors affecting the rate of seepage, the material used in the construction and type of soil in the bed of the water reservoir are the main determinants to the rate of the seepage. Table 5.6 gives the rate of seepage losses in millimetres per day from various soil types;

Table 5.6: Soil types and their seepage rates. Source: FAO, 2014.

Natural soil type	**Seepage water losses (in mm/day)**
Sand	25.00 – 250
Sandy loam	13.00 – 76
Loam	8.00 – 20
Clayey loam	2.50 – 15
Loamy clay	0.25 – 5
Clay	1.25 – 10

To calculate quantity of water escaping as seepage, Table 5.6 and the following formula can be used;

$$\textit{Seepage water } (m^3/Day) = \textit{Seepage Losses } (m/day) \times \textit{Surface Area of dam } (m^2) \quad [13]$$

There are many methods to estimate seepage, however we use the relatively simple FAO method because of its limited data requirement. This is because there is no data available on seepage for the Notwane dams hence seepage is estimated. The HEC-ResSim model demands seepage as a constant seepage value in m^3/s. The soil type under the dams range from layers of sandy loam, loam and clayey loam, therefore seepage was taken to range from 2.5 to 76 mm/day.

CHAPTER 6

MODEL EVALUATION AND APPLICATION

6.1 Model Efficiency

The efficiency and evaluation of the calibration and verification performance of the HEC-ResSim model to estimate and reproduce historic and future reservoir behaviour was handled by two statistical parameters namely R^2 (squared correlation coefficient) and NS (Nash Sutcliffe efficiency parameter) which compare the observed and simulated values.

6.1.1 Coefficient of Determination (R^2)

The coefficient of Determination is calculated by equation 14. The range of values for the coefficient of determination between observed water levels and simulated water levels is between 0 and 1 with 0 being the worst and 1 being the best. This coefficient gives the proportion of the variance or fluctuation of the simulated water level values from the observed water level values. An R^2 value of zero means that none of the variance in the observed is replicated by the model simulated values while a value of 1 means all of the variance in the observed values is replicated by the model predictions. According to Santhi C. et al (2001), R^2 of more than 0.5 are acceptable.

$$R^2 = \frac{\left[\sum\left(WL_{o,i} - \overline{WL}_o\right)\left(WL_{s,i} - \overline{WL}_s\right)\right]^2}{\sum\left(WL_{o,i} - \overline{WL}_s\right)^2 \sum\left(WL_{o,i} - \overline{WL}_s\right)^2} \qquad [14]$$

Where $WL_{o,i}$ = observed water level for any value i.

$\overline{WL}_O$ = mean of observed water levels

$WL_{s,i}$ = simulated water level for any value i.

$\overline{WL}_S$ = mean of simulated water levels

6.1.2 Nash-Sutcliffe Coefficient (N-S)

NS is a measure of how well the simulated results predict or fit the observed data by using the mean of the observed values over the period of comparison. NS is a more strong performance test than R^2 and all the time it is smaller than R^2. The NS ranges between negative infinity and 1 with an efficiency of 1 being the optimal value as it means the modelled values are a perfect match to the observed data. Values between 0 and 1 are acceptable levels of performance as they hint at the model being a better predictor of the observed values than the observed data mean whilst values less than 0 are unacceptable and indicate that the observed data average is a better predictor of the observed values than the model predictions (Nash and Sutcliffe, 1970). The NS is calculated as follows;

$$NS = 1 - \frac{\sum(WL_{o.i} - WL_{s})^2}{\sum\left(WL_{o,i} - \overline{WL}_{s}\right)^2} \qquad [15]$$

Where $WL_{O,i}$ = observed water level for any value i.

WL_S = simulated water level.

$\overline{WL}_S$ = mean of simulated water levels

6.2 *Model Calibration*

The overall goal of calibration was to evaluate whether HEC-ResSim reliably estimates water levels as compared to observed water levels of the dams. For verification of the calibration quality of the model, two approaches were employed; namely subjective and objective assessments. Subjective assessment is based on visual graphical comparison of the observed and simulated hydrographs. Whereas objective approaches are based on calculating some quantitative statistical parameters, namely R^2 and NS.

There are various techniques designed to reduce uncertainty in the estimation of model parameters. The typical approach used was selecting an initial value within the specified range. Consecutively followed by adjusting the parameter values till the model simulated water levels closely matches the observed water levels. This process of adjustment was done manually although it can be done through use of computer-based automatic methods. The manual method was used although it's a bit tricky and time consuming, it is however generally accepted that manual calibration requires a better understanding of the hydrological processes than automatic calibration and is therefore less likely to obtain hydrologically unrealistic parameters. The calibration targets are the daily observed and computed water levels at the three dams and the calibration period was between January 1, 1994 and December 1, 2002. The model was calibrated separately for each dam using simulated and observed water levels at each dam. The comparison of the hydrographs representing simulated and observed water levels from HEC-ResSim are exhibited in Figure 6.1 to Figure 6.3.

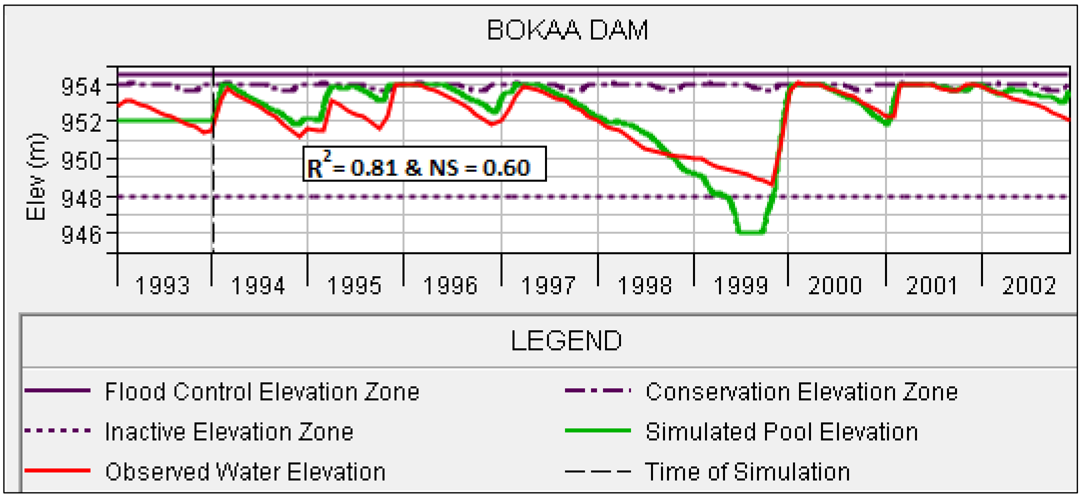


Figure 6.1: Simulated and observed hydrographs comparison for Bokaa Dam Calibration

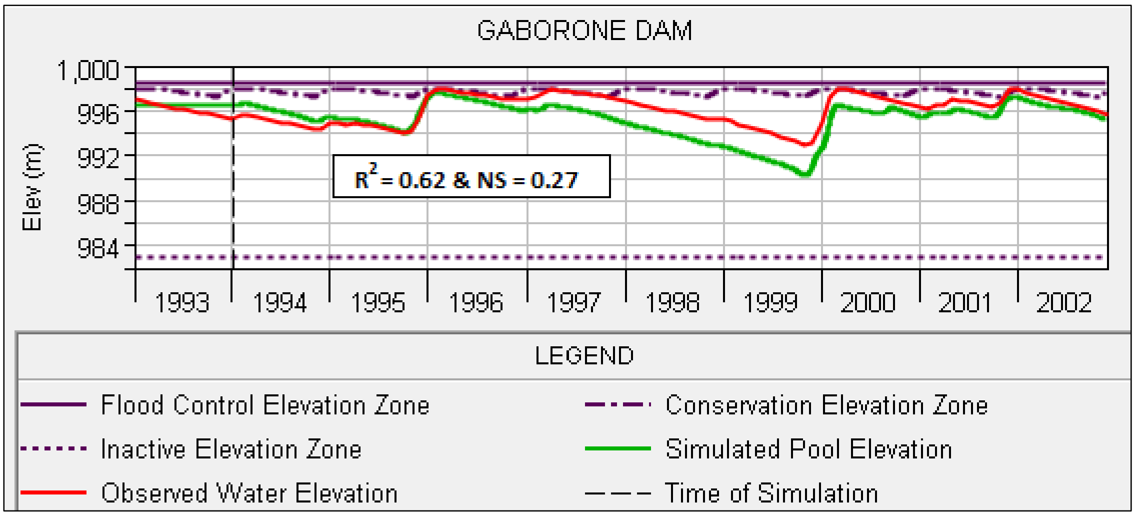


Figure 6.2: Simulated and observed hydrographs comparison for Gaborone Dam Calibration

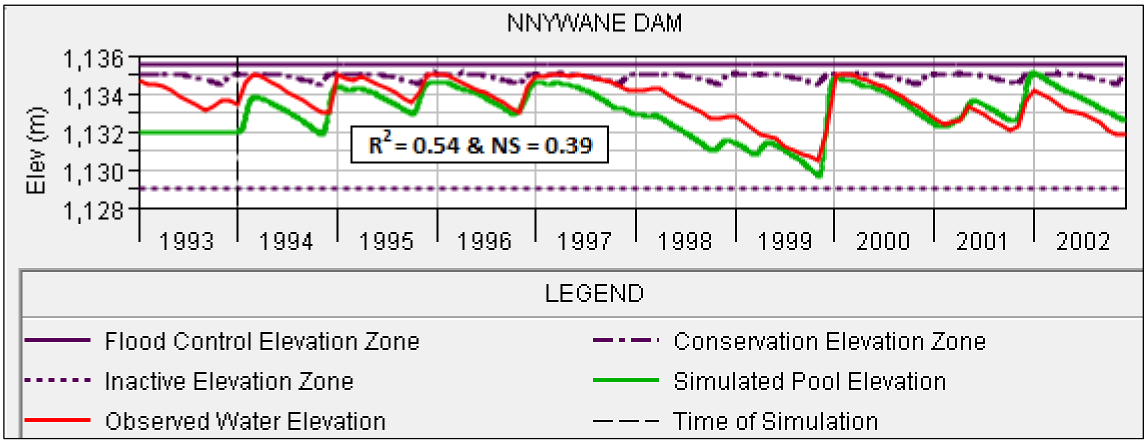


Figure 6.3: Simulated and observed hydrographs comparison for Nnywane Dam Calibration

The values for R^2 and for NS coefficient for the fit of the daily water levels (elevation) for the calibration period are 0.81 and 0.60 respectively and 0.62 and 0.27 and 0.54 and 0.39 respectively for the Bokaa, Gaborone and Nnywane dams in that order. Based on the performance statistical parameters of the model for prediction, the model calibration is satisfactorily accepted.

6.3 Model Verification

Model calibration identifies the best or at least a reasonable parameter whereas verification proves that the calibrated parameters reasonably perform well under an independent data. In verification, the model should be tested with independent data without any adjustment of the parameter values determined in calibration in order to evaluate the efficiency of the model for future predictions of water levels in the dams of the watershed. The verification period was from 1 January 2003 to 01 November 2011. Comparison of hydrographs representing simulated and observed water levels for the verification period from HEC-ResSim are shown in Figure 6.4 to Figure 6.6.

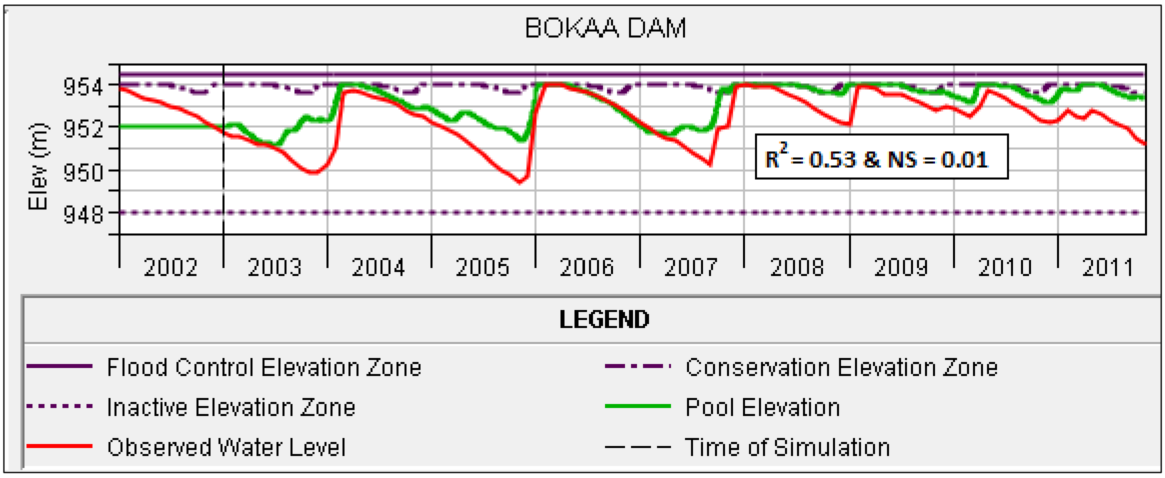


Figure 6.4: Simulated (green) and observed water level/elevation (red) for Bokaa dam verification

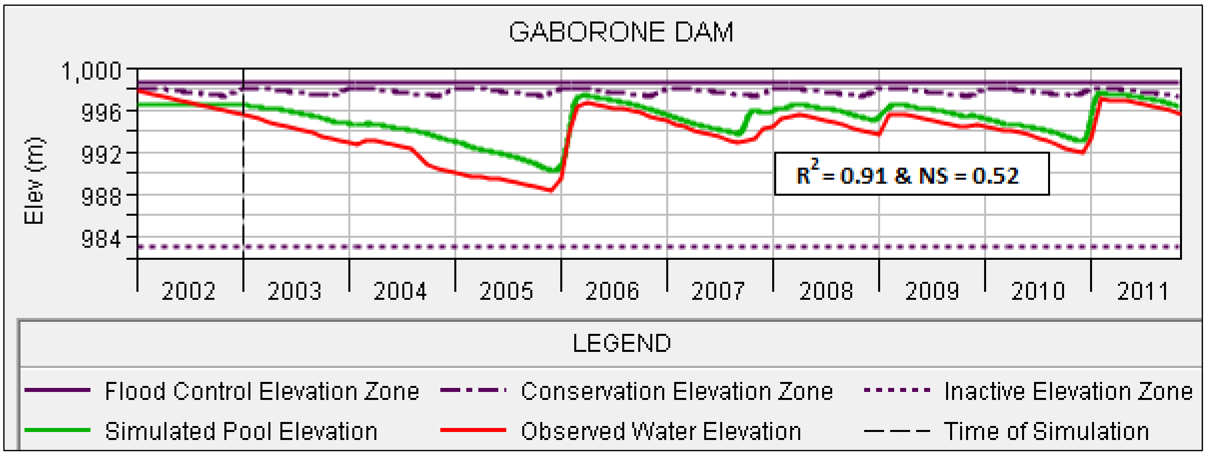


Figure 6.5: Simulated and observed hydrographs comparison for Gaborone Dam verification

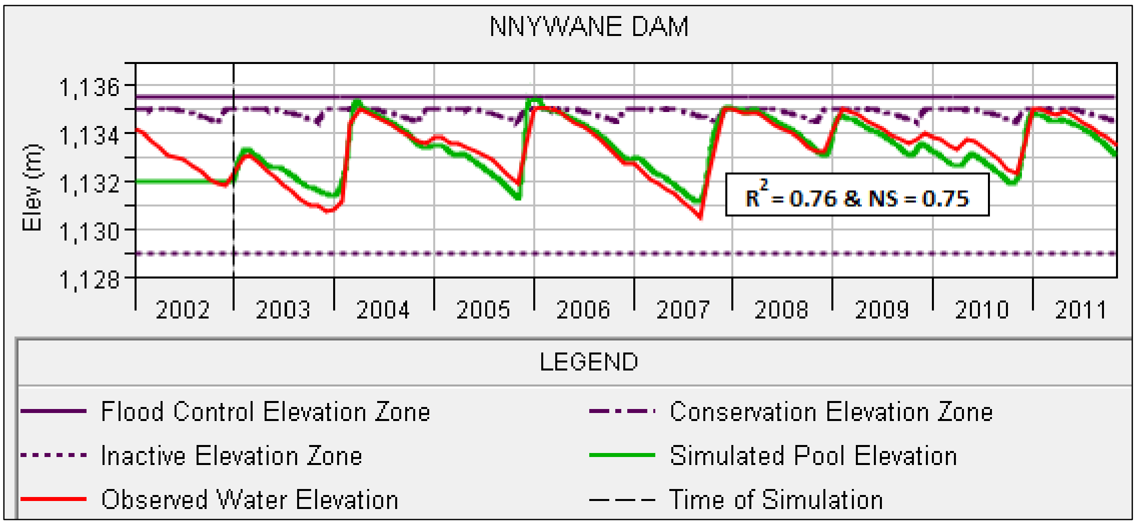


Figure 6.6: Simulated and observed hydrographs comparison for Nnywane Dam verification

Therefore, values for R^2 and for NS coefficient for the fit of the daily-simulated water levels (elevation) to the observed pool elevation for model verification are 0.53 and 0.01 respectively for Bokaa dam, 0.91 and 0.52 respectively for Gaborone dam and 0.76 and 0.75 respectively for Nnywane dam. Even though the NS and R^2 values are reasonable, there is generally underestimation and overestimation in model performance accuracy for both calibration and verification. This anomaly could be attributed to the following factors: use of mean evaporation and mean abstraction rates which does not account for the seasonal patterns of demand. To address or improve these anomalies more field observed or measured data is required through enhanced monitoring by the DWA and WUC. Despite this data shortfall, the model has been verified adequately based on the statistical parameters.

According to the statistical performance evaluation criteria by the authors in the subsequent section, overall the model is pleasing to use to represent the watershed. Hence, the set of optimised parameters can be described as the representative parameters for the dams of Notwane watershed.

6.4 *Development of Scenarios*

Scenarios were developed to evaluate the possible most likely events in the catchment. That is, what will transpire based on various conditions that may or may not change on the study area. This changes may be due to social, economic, climatic and environmental factors associated with dams. Each of the future scenarios was developed from one of, or a mixture of quantitative and qualitative information relating to one of the factors mentioned above. Using the calibrated HEC–ResSim model, the future response of the dams of the Notwane Catchment was simulated and then compared with the historical performance. Future inflow generated as described in Chapter 5.3 was used in this section. Eight scenarios were established each to be run on the three reservoirs for a period of 35 years from January 2015 to November 2050 and their results compared and scrutinized in relation to the historical baseline simulation.

6.4.1 Baseline Scenario

A time period of seventeen years was selected to create a baseline with which to compare future water availability and performance. The baseline scenario is the historical simulation from year 1994 to 2010. This period was chosen as the available data for Bokaa dam ends on midyear of 2011. In this scenario the model was run using the known inflows after which the obtained water outputs were analysed using the RRV performance indexes which are then used to compare the historical run with the future simulated scenarios. It is assumed that water demands and water system conditions, do not change over this period. That is to say the demand was assumed to be constant throughout the simulation period.

6.4.2 Population Growth

Rural and urban water demand are influenced by changes in population. In this scenario, the effect of a growing population on water resources is analysed. In order to establish the water demand up to the year 2050, population data from Central Statistics Office (CSO) and water demand information from DWA were used. The mean annual population growth rates were computed using population data from the Botswana population census of 2001 and 2011 (Table 6.1). The mean monthly abstractions is multiplied by the annual population growth rate. The annual population growth rate was determined as the average of the annual growth rates for the towns and villages in the Notwane catchment that are supplied by the dams. This is illustrated in Table 6.1.

Table 6.1: Determination of the mean annual growth rate. SOURCE: 2011 Population & Housing Census Preliminary Results Brief

GREATER GABORONE	**2001 Population**	**2011 Population**	**% Annual Growth Rate 2001-2011**
Gaborone	186 007	227 333	2.03
Lobatse	29 689	29 032	-0.22
Tlokweng	21 133	35 982	5.47
Metsimotlhabe	4 056	8 081	7.14
Oodi	3 440	5 464	4.74
Kopong	5 571	9 320	5.28
Ramotswa	2 423	27 760	2.99
Mogoditshane	2 461	57 637	5.79
Mmopane	3 812	14 655	15.4
Mochudi	2 696	44 339	1.84
Gabane	20 680	14 842	3.62
Mean Annual Growth Rate			4.45

6.4.3 Climate Change

Plenty of scientific evidence has indicated that the climate may change during the next years, decades and centuries, both globally and locally, due to increased concentrations of greenhouse gases in the atmosphere. The increase in these gases is mainly due to human activities, such as the use of fossil fuels. Botswana is among the countries which signed the United Nations Framework Convention on Climate Change at the United Nations Conference on Environment and Development (UNCED), the "Earth Summit" that was held in Rio de Janeiro, Brazil in June 1992. Botswana is a minor contributor to global warming and climate change as about 7% of the total greenhouse gases in Africa was from the country (IPCC, 1996). However, Botswana like many of the developing nations will be significantly impacted by climatic change as the predicted climate change scenarios will affect the availability and quality of water. Thus, this is a challenge to the development of the country.

The overwhelming majority of general circulation models predict a rainfall decrease in Botswana and a rise in temperatures. Temperatures are projected to rise by 1 to 3°C during the next 50 years as a result of global warming caused by the release of greenhouse gases. Hulme, 1996 predicted a 20 % decline in rainfall over the SADC region and a 13-20 % decline in inflows. Parida et al (2006) found out that climatic variables contribute about 48 % to changes in annual yields for the Gaborone dam of the Notwane river basin. The variables of interest in the study were rainfall, temperature and evaporation. Also the study revealed a decline in rainfall , a 0.132 °C per annum increase in temp and an increase in evaporation each contributing to 20, 11 and 16 % reduction in annual yields. Therefore, in this scenario inflows to the dams were decreased by 20 % while evaporation was increased in accordance with the 3 °C surge of temperatures. The demand during the simulation period of the climate change scenario was kept constant.

6.4.4 Reduced Abstractions

The Botswana National Water Act of 1968 (Water Act 1968 Cap 34.010 and the Draft water bill of 2004 have provided an enabling environment for water conservation and demand management. Limpopo Watercourse Commission (LIMCOM) has identified water conservation and demand management strategies as important tools to assist in the reconciliation of water demands and water resources in the wider Limpopo River basin catchment of which the Notwane catchment is a part of. With this in mind the Reduced

Abstractions scenario was established to aid in this endeavour of water conservation and demand management. In this scenario, the effect of water saving techniques on the dams is examined. The water saving techniques and strategies include water-rationing, rainwater harvesting, recycling, and other water conservation techniques .The water demand up to the year 2050 is kept constant in this scenario as in the baseline. It is assumed that these strategies and techniques reduce the water demand by 20 %. Therefore, in HEC-ResSim the mean abstractions are decreased by twenty percent for the simulation period.

6.4.5 Seasonal Operation

The seasonal Operation scenario focuses on operating the reservoirs according to seasons. Although the Notwane catchment has four seasons, it basically has two main seasons the wet and dry season. The wet season stretches from October to March while the dry season is from April to September. In the dry season inflows are low or none at all while in the wet season inflows are high. Since the catchment is of a semi-arid climate as described in the study area description chapter and is prone to droughts, it is common for the wet season to pass with low or no inflows at all. In this scenario, HEC-ResSim is directed to ensure that during the wet season months a higher range of abstractions is released while during the dry season months a low range of abstractions as possible are released while also meeting the demand. The abstractions from the Gaborone, Bokaa and Nnywane dams is given in Table 6.4. to Table 6.4.

Table 6.2: Gaborone dam abstractions. Source: WUC

Year	Abstraction [000 m3]	monthly Abstraction [m3/s]
2000	13573.351	0.436386028
2001	15862.379	0.509978749
2002	22372.215	0.719271316
2003	24841.659	0.798664448
2004	19605.232	0.630312243
2005	17800	0.572273663
2006	8000	0.257201646
2007	18700	0.601208848
2008	22300	0.716949588
2009	26350	0.847157922

2010	26400	0.848765432
Average (cms)		0.631

Table 6.3: Nnywane dam abstractions. Source: WUC

Nnywane Dam Abstractions		
Month	Monthly Mean abstractions (m3)	Monthly mean Abstraction m3/s
Jan	49823.33	0.0192
Feb	47836.67	0.0185
Mar	55712.33	0.0215
Apr	74034.50	0.0286
May	61735.50	0.0238
Jun	45915.00	0.0177
Jul	64066.00	0.0247
Aug	60807.00	0.0235
Sep	55270.00	0.0213
Oct	63641.50	0.0246
Nov	52779.50	0.0204
Dec	38194.50	0.0147
Average	55817.99	0.02153

Table 6.4: Bokaa dam abstractions. Source: WUC

Bokaa Dam Abstractions		
Month	Monthly Mean abstractions (m3)	Monthly Mean abstractions m3/s
Jan	161669.33	0.0624
Feb	101008.00	0.0390
Mar	312768.00	0.1207
Apr	516768.67	0.1994
May	441738.00	0.1704
Jun	347943.33	0.1342
Jul	250317.67	0.0966
Aug	308668.33	0.1191
Sep	672369.00	0.2594
Oct	526914.00	0.2033
Nov	95994.00	0.0370
Dec	200468.00	0.0773
Average	328052.19	0.12656

6.4.6 Sedimentation

The main objective of reservoirs is storing water however other substances are carried along by the water and are usually deposited inside the reservoir pool. Impounding of natural watercourses alters flow regime from flowing water to a body of stagnant water, which favours sediment accumulation. Usually on a river upstream of a reservoir, erosion and sedimentation balances each other prompting minor or no accumulation of sediments. As a river enters a dam, the flow depth increases while the velocity reduces instigating a loss in the sediment transport ability of the inflow. This loss of sediment transport ability and decrease in erosion coupled with the damming effect of the dam causes deposition and build-up of layers of sediments. Figure 6.7 illustrates this reservoir sedimentation.

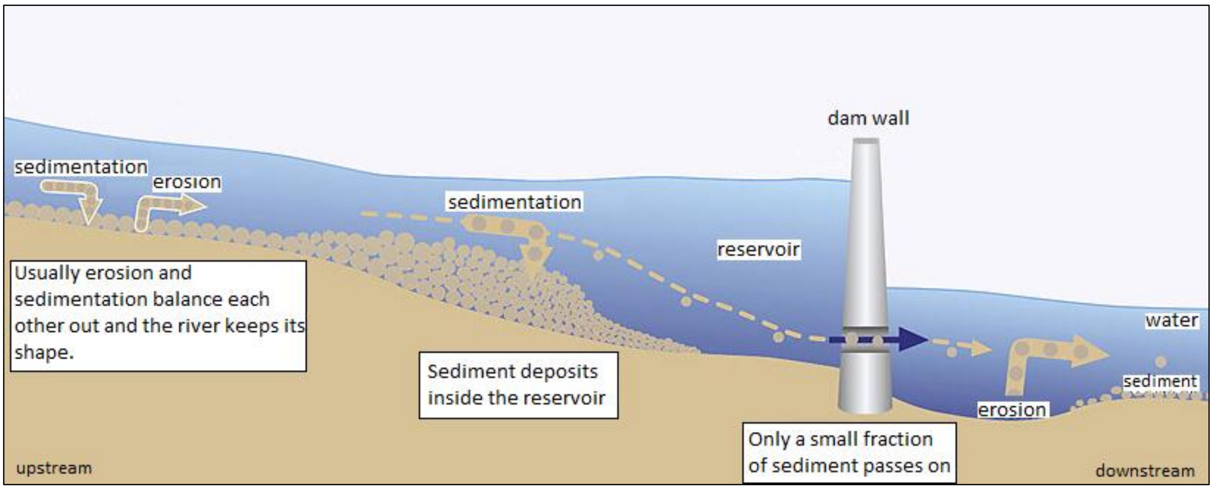


Figure 6.7: Reservoir sedimentation process

Reservoir sedimentation is a serious problem globally threatening the sustainability of reservoirs. The average age of reservoirs worldwide is now about 30 years and since majority of reservoirs have been designed with a dead storage for sedimentation of approximately 50 years, huge sedimentation problems will be experienced with about 40 percent of the storage capacity in reservoirs affected within the next 20 years (ICOLD, 2009). Sedimentation in reservoirs leads to:

- Increased flood risk on influent streams
- Loss of storage capacity with associated loss of reservoir yield

- Severe blockage of draw-off works resulting in reservoir drawdown to excavate sediment or abandonment of clogged bottom outlets
- Increased abrasion of steel hydraulic works and equipment by sediments

Sedimentation in the reservoirs of Botswana is also a growing problem as shown in Figure 6.8 as the sedimentation rate per year in the dams is now above the global average. The sedimentation rate of each particular reservoir is very variable depending on the climatic situation, the geomorphology, design and conception of the reservoir including its outlet works.

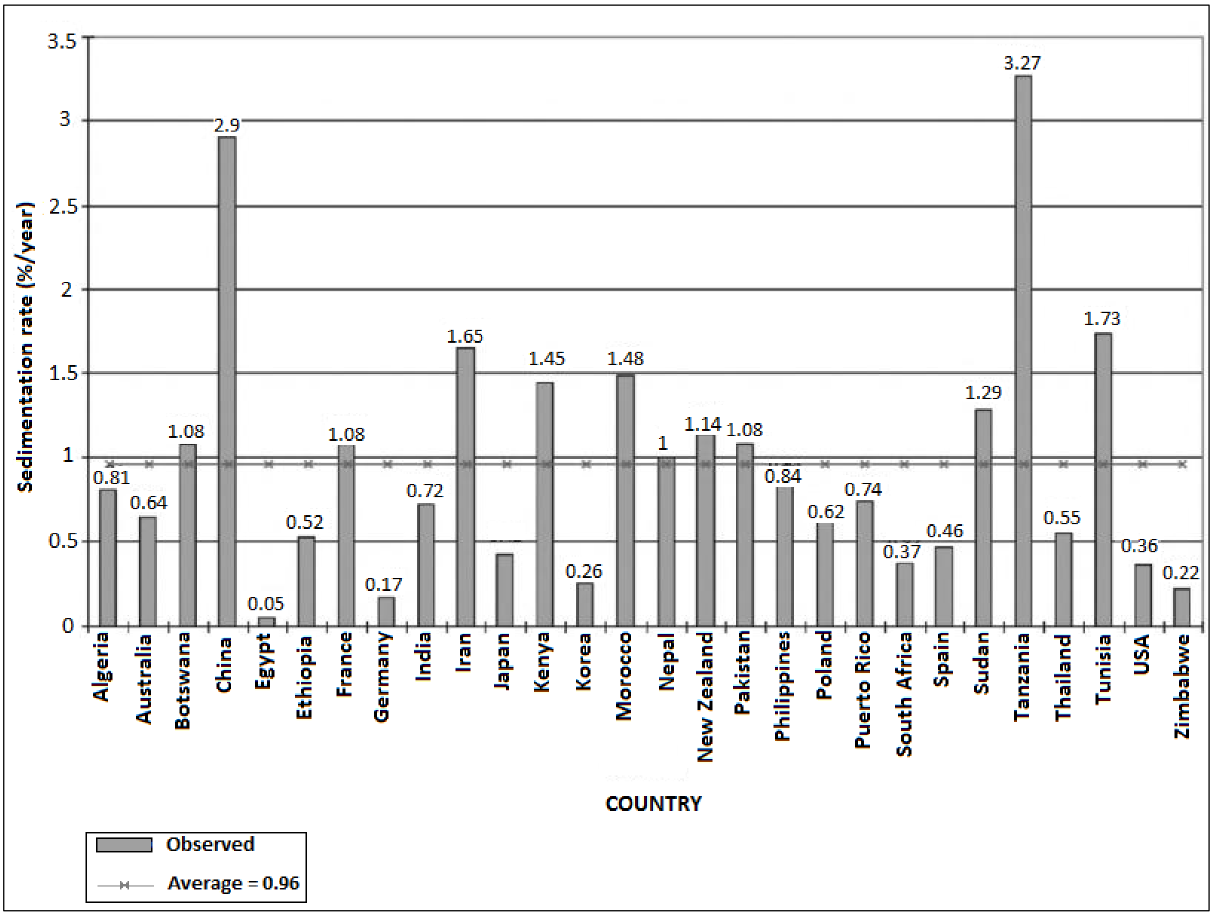


Figure 6.8: Sedimentation rates of countries. Source: ICOLD 2009.

As consequence of these, a sedimentation scenario was developed to examine the future response of dams to sedimentation. Demand or water abstractions were retained constant.

HEC-ResSim unfortunately does not contain provision for the inclusion of sedimentation directly. This has meant that the impact of reservoir sedimentation can only be assessed by examining system performance with varying storage capacity. The remaining storage of dams that was used in the simulation is presented in Table 6.5.

Table 6.5: Estimated residual storage capacity in MCM. Source: WUC and NWMPR, 2006e

Year	2000	2005	2010	2015	2020	2025	2030	2035
DAM								
Gaborone	140.5	139.4	138.3	137.2	136.1	135.09	133.9	132.8
Shashe	75.05	72	68.95	65.9	62.85	59.8	56.75	53.7
Letsibogo	104.4	102.6	100.9	99.15	97.4	95.65	93.9	92.15
Dikgatlhong	397.6	394.1	390.6	387.1	383.6	380.1		
Bokaa	18.2	17.9	17.6	17.3	17	16.7	16.4	16.1
Nnywane	2.28	2.24	2.20	2.16	2.12	2.09	2.05	2.016

The corresponding plots of the residual storage capacities at specific years for the dams and their respective extrapolation equations are depicted in Figure 6.9 to Figure 6.11.

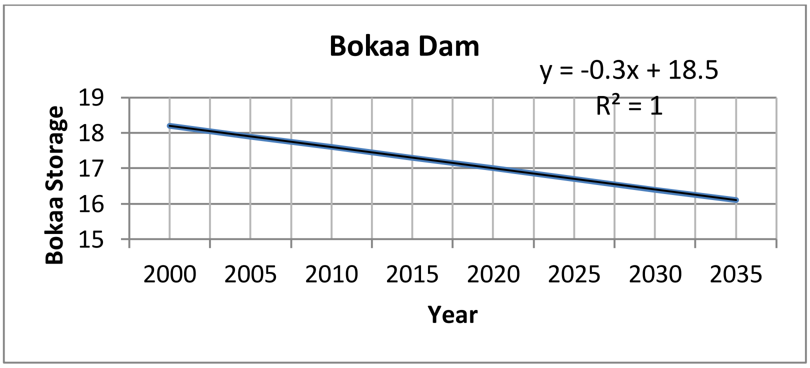


Figure 6.9: Plot of the Bokaa dam residual storage

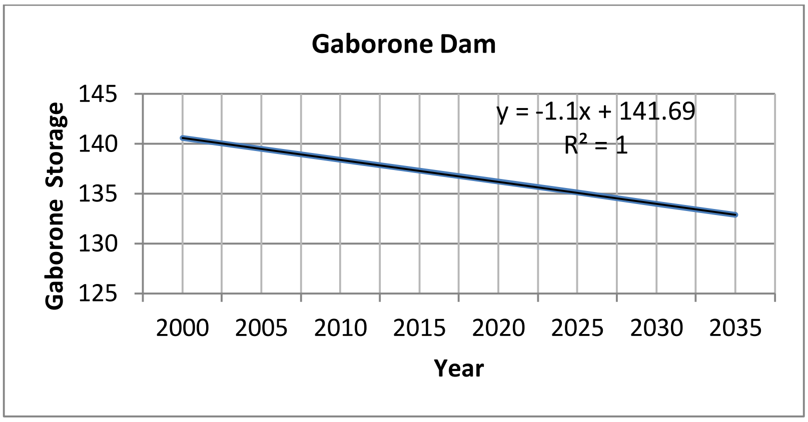


Figure 6.10: Plot of the Gaborone dam residual storage

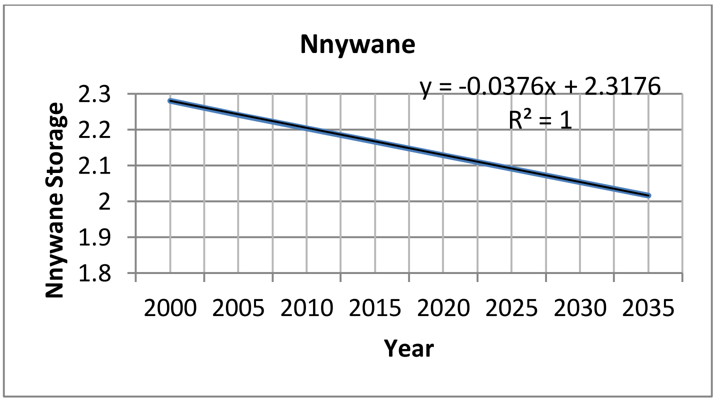


Figure 6.11: Plot of the Nnywane dam residual storage

From the three plots above and their respective equations, residual storage from the year 2015 to 2050 were extrapolated (Table 6.6).

Table 6.6: Extrapolated remaining storage of Bokaa, Gaborone and Nnywane dams.

Bokaa Dam											
Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Storage	18.2	17.9	17.6	17.3	17	16.7	16.4	16.1	15.8	15.5	15.2
% decrease					6.59	8.24	9.89	11.5	13.1	14.8	16.4
Gaborone Dam											
Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Storage	141	139	138	137	136	135	134	133	142	142	142

% decrease					3.13	3.91	4.69	5.48	6.26	7.04	7.82
Nnywane Dam											
Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Storage	2.28	2.24	2.20	2.17	2.13	2.09	2.05	2.02	1.98	1.94	1.90
% decrease					6.6	8.2	9.9	11.5	13.2	14.8	16.5

The percentage decrease in storage tabulated in Table 6.6 is used to reduce the storage capacity in the storage-area data of dams for each of the particular five- year range. This is entered in the Reservoir Network module of HEC-ResSim’s sedimentation scenario where physical data is inputted.

6.4.7 Normal Operation

The Normal Operation scenario is the business-as-usual mode of operation. Business as usual is a scenario for future patterns of activity which assumes that there will be no significant change in the people's attitudes and priorities, or no major changes in reservoir operation policies, so that normal circumstances can be expected to continue unchanged. The Normal Operation means operating the dams as they were in the historical period. This includes maintaining the mean water demands and evaporation, but the only difference is that the simulation is run using the future generated inflows.

6.4.8 Pessimistic

The pessimistic scenario is concerned at many of the things that could go wrong and tries to help decision makers plan responses to deal with these problems should they happen. These could be to loss of inflow due to diversions in the catchment, high infiltration due to human activities and land use. With that in mind, the Pessimistic scenario was developed to look at the response of dams if the inflows to the dams are lessened by twenty percent. The demand was kept constant and all the future inflows deducted by twenty percent.

6.4.9 Optimistic

The optimistic scenario introduces question as to what things or events would or could happen to result in a better than anticipated outcome and how can the reservoir operators or managers make those things happen? The Optimistic scenario indicates an increase in water availability and a constant water demand. In this scenario, the rivers inflow in the Normal Operation scenario is increased by 20 %. Human activity in the catchment is one of the factors that can increase inflow. Urbanization leading to increase in paved surfaces induces high runoff hence increased inflows. Change in land use and land management practices have great effect on the runoff yield and consequently inflows. E.g., an area with forest cover or thick layer of mulch of leaves and grasses contribute less runoff because water is absorbed more into soil. Base flow can also marginally increase inflows. Base flow is defined as the ground water that enters stream flow during dry periods. This type of flow is not normally a big contributor to stream flow but can increase inflows.

6.5 Water System Performance Indexes

The water system performance to meet the demand was assessed using Reliability, Resilience, and Vulnerability (RRV) indices (Hashimoto et al. 1982). These Indices are used to assess the performance of the Notwane catchment dams to meet the demands for the Baseline, Population Growth, Climate Change, Reduced Abstractions, Seasonal Operation, Sedimentation, Normal Operation, Pessimistic and Optimistic scenarios. The results from the HEC-ResSim model were analyzed for RRVs using Microsoft excel. It is important to note that these criteria, as defined by many authors in literature, may not be applicable to all water system cases and may need to be modified on case-by-case basis. The following description of RRV is based on the assumption that the water system under consideration at a given time t can be in either a satisfactory (i.e. non-failure) state, S, or an unsatisfactory (i.e. failure) state, U as illustrated below;

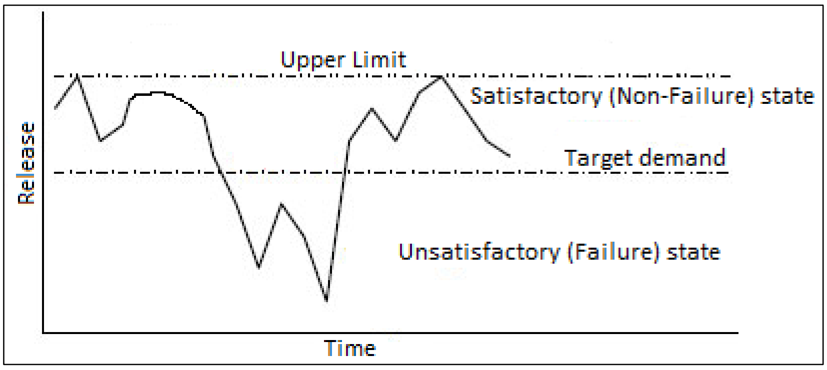


Figure 6.12: Definition of unsatisfactory (Failure) and satisfactory (Non-Failure) states. (Yilmaz & Harmancioglu, 2010).

In this study, the S state occurs when water supply is able to meet the specified water demand and, hence, the U state is when supply cannot meet demand. Moving from time step t to t+1, the system can either remain in the same satisfactory or unsatisfactory state or migrate to the other state.

First a criterion, C, is defined for each dam, where an unsatisfactory condition occurs when a certain target demand is not met. The simulated time series of parameter of interest such as reservoir water level or storage or outflow (in our case it is the dams release/regulated outflow), used as an indicator of system performance is assigned X_t to be assessed in meeting the criterion Ct which is explained as the total demand that needs to be supplied in each time step (Equation 16). Additionally, an index Z_t (Equation 16) is expounded to quantify a satisfactory (S) or unsatisfactory (U) state of the water system on the basis of the criterion, Ct (Hashimoto et al. 1982);

$$If\ \ X_t \geq C\ \ then\, X_t \in S, \qquad Z_t = 1 \qquad else\ \ X_t\ \in U, \qquad Z_t = 0 \qquad [16]$$

If the demand is met the system is in a satisfactory (S) state and Zt is one, otherwise is in an unsatisfactory (U) state and Zt is zero. Another indicator W_t, which indicates the transition from an unsatisfactory to satisfactory state;

$$W_t = \begin{cases} 1, & if\ \ X_t \in U \quad and \quad X_{t+1} \in S \\ 0, & if\ \ otherwise \end{cases} \qquad [17]$$

If unsatisfactory periods of the dam's release, X_t, are defined as J_1, J_2, …, J_N then reliability, resilience and vulnerability indices are defined (Hashimoto et al. 1982);

Reliability
$$C_R = \frac{\sum_{t=1}^{T} Z_t}{T} \qquad [18]$$

Resilience
$$C_{RS} = \frac{\sum_{t=1}^{T} W_t}{T - \sum_{t=1}^{T} Z_t} \qquad [19]$$

Vulnerability
$$C_V = mean\left\{ \sum_{t \in J_i} C - X_t \qquad i = 1, \dots, N \right\} \qquad [20]$$

6.5.1 Reliability

Reliability is the oldest and most widely used performance criterion for water resources systems as defined by Hashimoto et al. (1982), Fowler et al., 2003. Reliability is the probability that the system state lies in the set of satisfactory states. Reliability measures the frequency or probability of success of the system by simply counting the number of days that the system was in a satisfactory state compared to the total simulation length, T (Equation 15). Reliability does not evaluate other statistics of unsatisfactory states, for example the mean, variance or return periods of the unsatisfactory states. It only calculates, of the total simulation days, how many were successful. Although reliability is a widely used concept in water resources planning, it does not describe the severity or likely consequences of a failure (Fowler et al., 2003). The possible severity of failures are described by other criteria, such as resilience and vulnerability.

6.5.2 Resilience

Resilience is a measure of the speed of recovery of the reservoir from failure. It is simply a measure of how fast a system is likely to return to a satisfactory state once the system has entered an unsatisfactory state (Hashimoto et al. 1982). It is determined as in Equation 19. If failures are prolonged events and the water system recovery is slow, it implies that the system design has a flaw, and requires careful re-examination. Therefore, reservoir designers appreciate a reservoir design which can recover rapidly after a failure and return to a satisfactory state. Resilience accounts for the number of rebounds (transition from U to S state) as a percentage of total unsatisfactory days. Under resilience, we are also concerned with;

- Mean Unsatisfactory Duration (MUD): The mean of the unsatisfactory (failure) periods, i.e. how long on average the system spends in unsatisfactory state. In this study, it is measured in days.
- Maximum of Unsatisfactory duration (MAXU): The maximum period of failure events, i.e. the largest period the dam has gone without meeting the demand. It is also measured in days in this study.

6.5.3 Vulnerability

Vulnerability is a measure of the extent of failure as defined by Hashimoto et al. (1982). Vulnerability addresses how severe is the unsatisfactory state or the parameters responsible for it. As defined in Equation 20 this metric looks at only the cumulative maximum difference between criterion C and parameter of interest, X. Vulnerability can be expressed;

- as the cumulative maximum extent of system failure in volume (maximum volume deficit);
- or as the cumulative mean extent of system failure in volume (mean volume deficit);

In this study the cumulative mean extent of system failure was used (mean volume deficit). Also in this research, C is demand, therefore vulnerability would reveal the mean gap between supply and demand over a period of J. For this reason sometime it is expressed as mean deficit.

Each of the RRV metrics evaluates different aspects of a water resources system complementing each other. For that reason, the use of RRV metrics as a comprehensive performance measuring tool cannot be overemphasized. The challenge of using all three RRV metrics to evaluate water system performance is that there is no clear way of aggregating these metrics into a single value for the sake of ranking scenarios without introducing a subjective weighting factor as each metric evaluates different aspects of the water systems (Asefa et al, 2014). A sustainability index was introduced by Loucks (1997) that combines all three metrics. It consists of scaling and converting the vulnerability index to fall between 0 and 1 with higher values indicating the preferred situations and then the sustainability index is calculated as a geometric mean of the three metrics. While this approach is instinctive and subjective and makes it is easy to understand, it still requires the characterization of additional subjective weights across each metric. Consequently, for this study the three metrics were not aggregated, rather different aspects of the three metrics are discussed across scenarios. The results from the evaluation of three indices are used as a weight of evidence to support the recommended decision and or conclusion. Vulnerability is a negative measure, the smaller the better.

An efficient management and operational system should improve the reliability and resilience of the system while reducing vulnerability. Reliability and vulnerability are inversely related. As reliability of the system increases, the vulnerability of the system reduces. However, this relationship is not direct and linear; trade-off decisions often need to be made in an attempt to accommodate both factors and to find an acceptable balance between reliability and vulnerability of the system.

CHAPTER 7

RESULTS AND DISCUSSION

The results of the simulation in HEC-ResSim can be plotted as pool elevation-flow against time or pool storage-flow against time. Presentation of results as pool elevation-flow against time was selected as the performance indices evaluation in this study uses pool elevation-flow to evaluate the performance of the dams. A sample of the plot of results is displayed in Figure 7.1 and Appendix B.

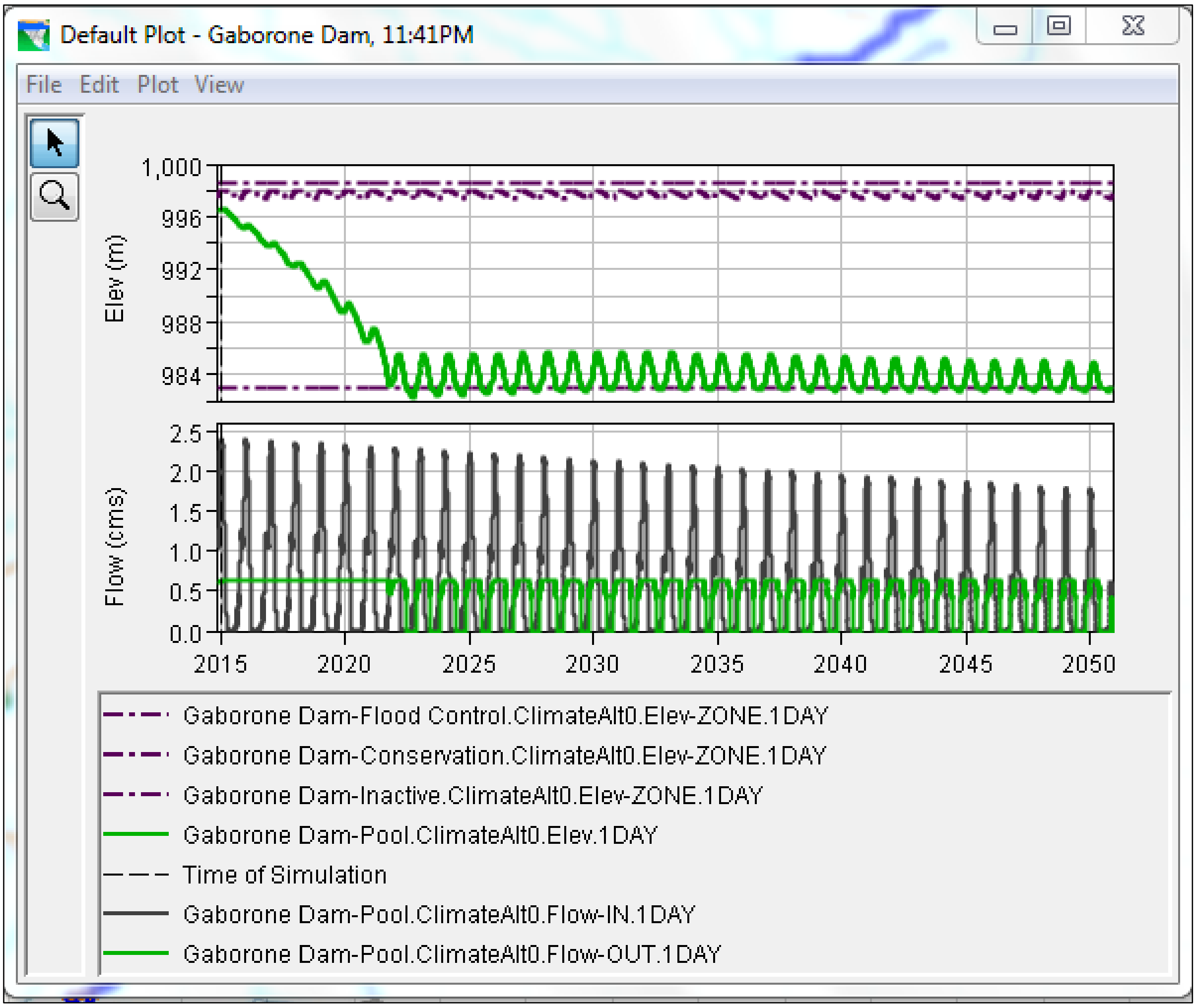


Figure 7.1: Result plot from HEC-ResSim for Climate Change scenario at Gaborone dam

From the plot HEC-ResSim offers a file containing the results in a digital format that can be exported to Excel among the many options. A sample of the result from the program is given in Appendix B. The results from HEC-ResSim were exported to excel to be evaluated using RRVs. The results from the evaluation using RRVs are discussed in the subsequent section.

7.1 Performance Evaluation Results

7.1.1 Reliability Index Results

Table 7.1: Reliabilities and percentage change of dams for various scenarios

SCENARIO	**Gaborone Dam Reliability (%)**	**% Change**	**Bokaa Dam Reliability (%)**	**% Change**	**Nnywane Dam Reliability (%)**	**% Change**
Population Growth	33.2	-66	93.3	-2	50.1	-49
Climate Change	55.2	-44	88.5	-7	86	-13
Reduced Abstractions	73.9	-25	92.4	-3	97.1	-1
Seasonal Operation	67.5	-32	99.5	5	99.5	1
Sedimentation	69.7	-30	94.4	-1	94.0	-4
Normal Operation	68	-31	99.5	5	96.3	-2
Optimistic	74	-25	99.5	5	98.8	1
Pessimistic	56.4	-43	93	-2	99.5	1
Baseline	99	0	95	0	98.3	0
Average	66.3		95.0		91.1	

The performance of the water system was evaluated for the period 2015-2050 relative to the historical period 1994-2010 using the performance indexes. Definitions and estimators of water resources system reliability (the probability that the water system will remain in a non-failure state), resilience (the ability of the water system to return to non-failure state after a failure has occurred) and vulnerability (the likely damage of a failure event) have been thoroughly investigated. Table 7.1 presents the percentage change and reliabilities of the baseline and eight simulated scenarios. Reliability is a positive water system performance index meaning the higher the percentage the better, while low values are undesirable.

7.1.1.1 Gaborone Dam Reliability

The reliability results for Gaborone dam scenarios, which is the frequency or probability of success of the system to meet the set demand, shows that the reliability for water supply for all scenarios is lower than the baseline scenario indicating a possible bleak future for the dam (Figure 7.2). This may be due to the decreasing trend of inflows expected in the future up to the year 2050. Pessimistic, Climate Change and Population Growth scenarios have lower reliabilities (averaging 38 %) indicating the significant pressure that climate change, low inflows and an increasing population places on the dam to meet demand when compared to the baseline (historical) scenario. This means for the Population Growth, Climate and Pessimistic scenarios, reliability decreases by 54, 50 and 49 % respectively as depicted in Table 7.1. Optimistic and Reduced Abstractions scenarios place less pressure or burden on the reservoir to meet demand as 70 % of the time the demand is met and reliability is slightly reduced by 2 and 7 % respectively.

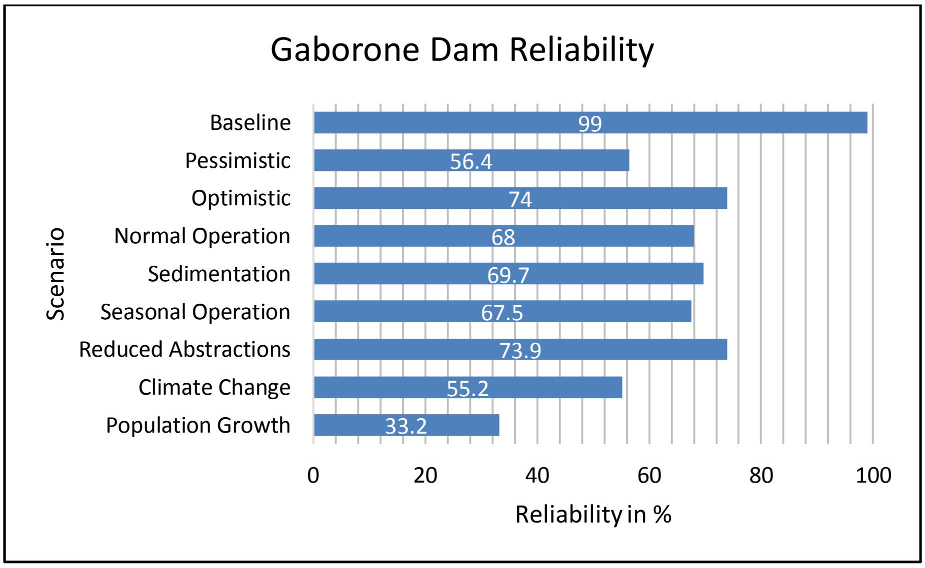


Figure 7.2: Reliability of various scenarios for Gaborone Dam

7.1.1.2 Bokaa Dam Reliability

The reliability of water supply for the scenarios of Bokaa dam indicates that the Optimistic, Normal Operation and Seasonal Operation scenarios increase reliability in comparison to the historical baseline scenario (Figure 7.3). The scenarios of Climate Change, Population Growth, Pessimistic, Sedimentation and Reduced Abstractions decrease reliability by 7, 2, 2, 1 and 3 % respectively as shown in Table 7.1. The scenario of Climate Change mostly reduces reliability implying that the reduction in inflows and increase in temperatures due to climate change will affect the dam more. It is also worth noting that the scenario of Reduced Abstractions has reduced reliability as compared to the baseline instead of increasing it, as was expected. This means that the water saving techniques and policies used to reduce abstractions from the reservoir may not have been adequate or fell short of the desired objective.

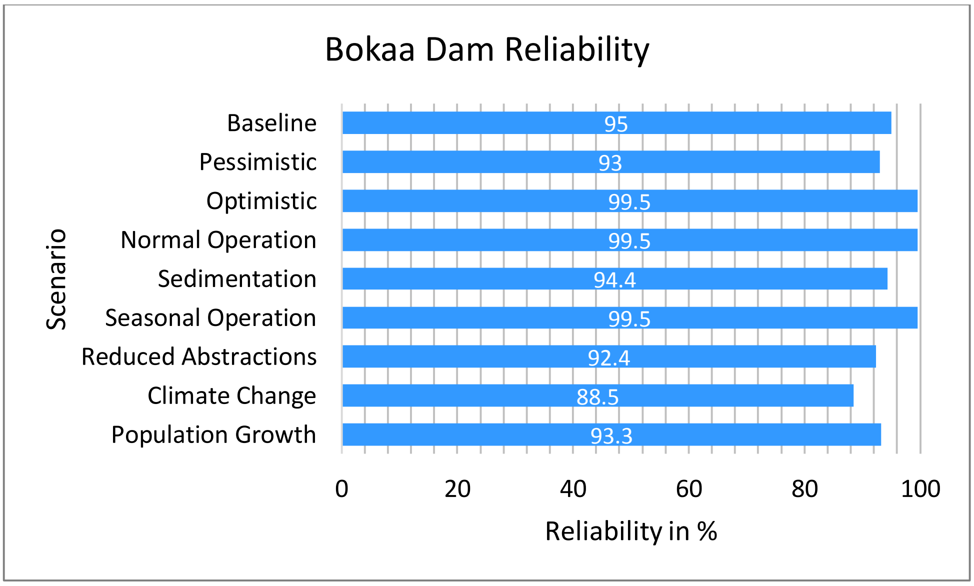


Figure 7.3: Scenarios and their reliabilities for Bokaa Dam

Seasonal Operation, Optimistic and Normal Operation scenarios respond well for Bokaa dam with positive percentage changes to the baseline reliability signifying that the continuation of normal operation and seasonally operating the reservoir bodes well for the dam.

7.1.1.3 Nnywane Dam Reliability

The reliability for water supply of various scenarios of Nnywane dam illustrated in Figure 7.4 and Table 7.1 reveal that the majority of the scenarios are below the baseline scenario reliability. Five out of the eight scenarios reduce the reliability of the dam's water supply from the baseline scenario.

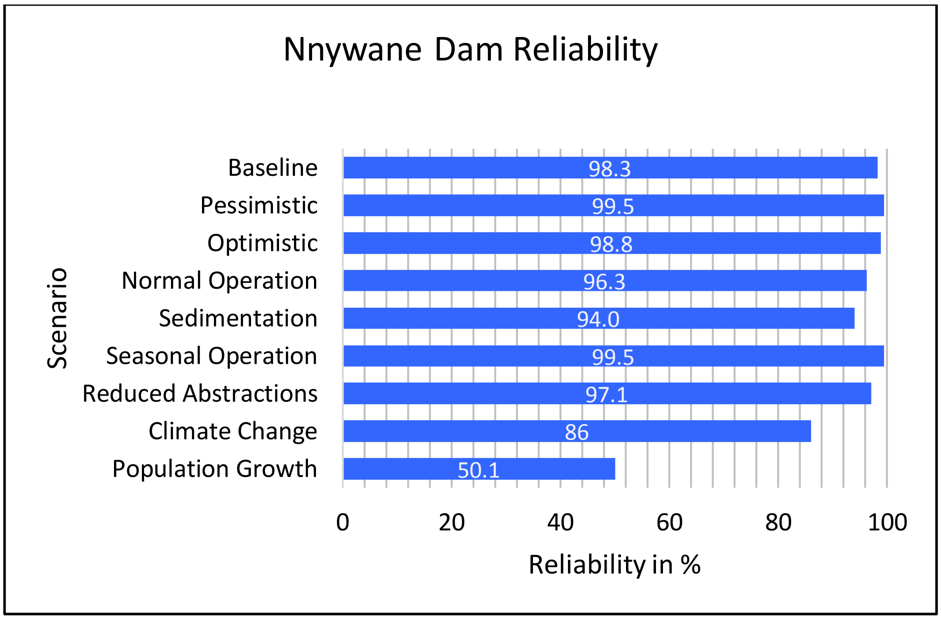


Figure 7.4: Nnywane Dam scenarios and their reliabilities

The scenarios of Population Growth, Climate change and Sedimentation greatly reduce the reliability of the dam by 49, 13 and 4 % respectively, denoting the consequence that the flow of sediments into the dam and an ever-increasing population and change in climate, place on the dam. Twenty percent reduction in inflows of Pessimistic scenario does not have a very bad effect in this dam as expected, as reliability is not reduced. Optimistic and Seasonal Operation also significantly make the dam more reliable.

7.1.2 Resilience Index Results

Resilience is a measure of how on average a system rebounds to a satisfactory state once in an unsatisfactory state. The satisfactory state is success in meeting demand while unsatisfactory state is the opposite. Resilience is a positive water system performance index therefore higher percentage values are favoured. Table 7.2 presents the resilience, Mean Unsatisfactory Duration (MUD) and Maximum of Unsatisfactory period (MAXU) of dams. An efficient dam management and operational strategy should improve the reliability and resilience of the system and reduce the vulnerability. Resilience like reliability is a positive index, the higher the better.

Table 7.2: Resilience of Gaborone, Bokaa and Nnywane dams

SCENARIO	**Gaborone Dam Resilience (%)**	**MUD (days)**	**Max of U**	**Bokaa Dam Resilience (%)**	**MUD**	**Max of U**	**Nnywane Dam Resilience (%)**	**MUD**	**Max of U**
Population Growth	0.68	144	1041	4.19	41	434	2.45	41	434
Climate Change	0.51	191	237	2.7	56	62	1.78	56	62
Reduced Abstractions	0.67	143	153	3.7	11	61	9.35	11	61
Seasonal Operation	0.63	143	181	1.64	61	61	1.64	61	61
Sedimentation	0.68	143	313	3.14	32	105	4.46	22	337
Normal Operation	0.64	151	178	1.64	14	61	7.25	14	61
Optimistic	0.67	143	157	1.64	5	61	21.5	5	61
Pessimistic	0.50	192	234	2.06	61	61	1.64	61	61
Baseline	1.64	61	61	3.85	15	61	6.8	15	61
Average	0.74	146	284	2.73	42	107	6.32	32	133

7.1.2.1 Gaborone Dam Resilience

Gaborone dam is generally less resilient with all resilience values for all scenarios less than the value 1.64 % (Figure 7.5 and Table 7.2) and low average of 0.74. All the future simulated scenarios do not perform better to the baseline as all their resilience values are lower than the baseline.

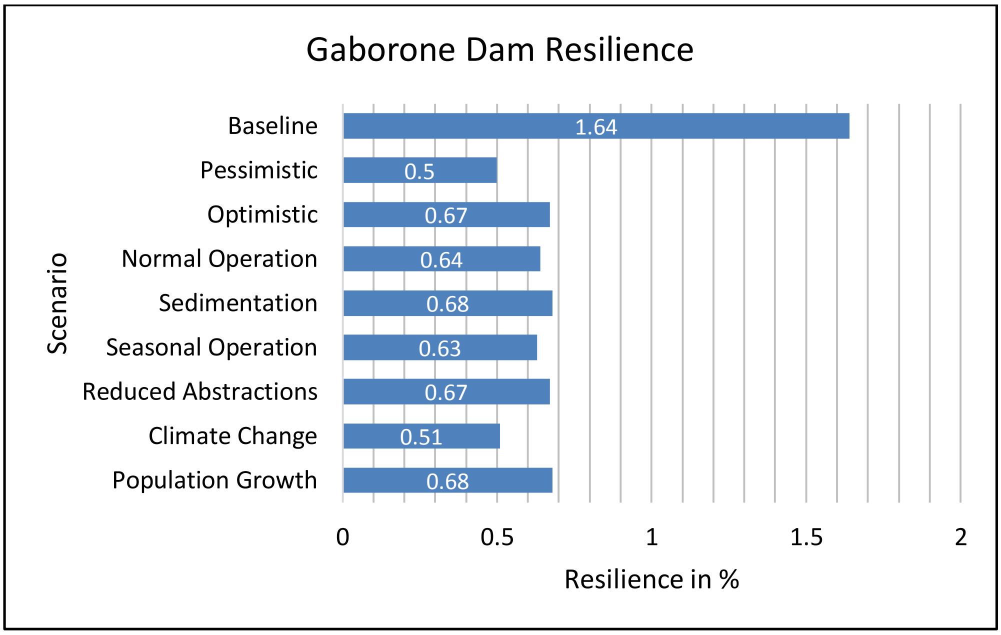


Figure 7.5: The resilience of Gaborone dam

The scenarios of Optimistic, Sedimentation, Seasonal Operation, Reduced Abstractions and Population Growth have slightly large resilience when compared to the Pessimistic and Climate Change scenarios. Sedimentation and Population Growth scenarios were predicted to have low resiliences just as Climate Change and Pessimistic but have slightly better resilience indicating their better ability to revert from failure to satisfactory (Table 7.1 and Figure 7.2).

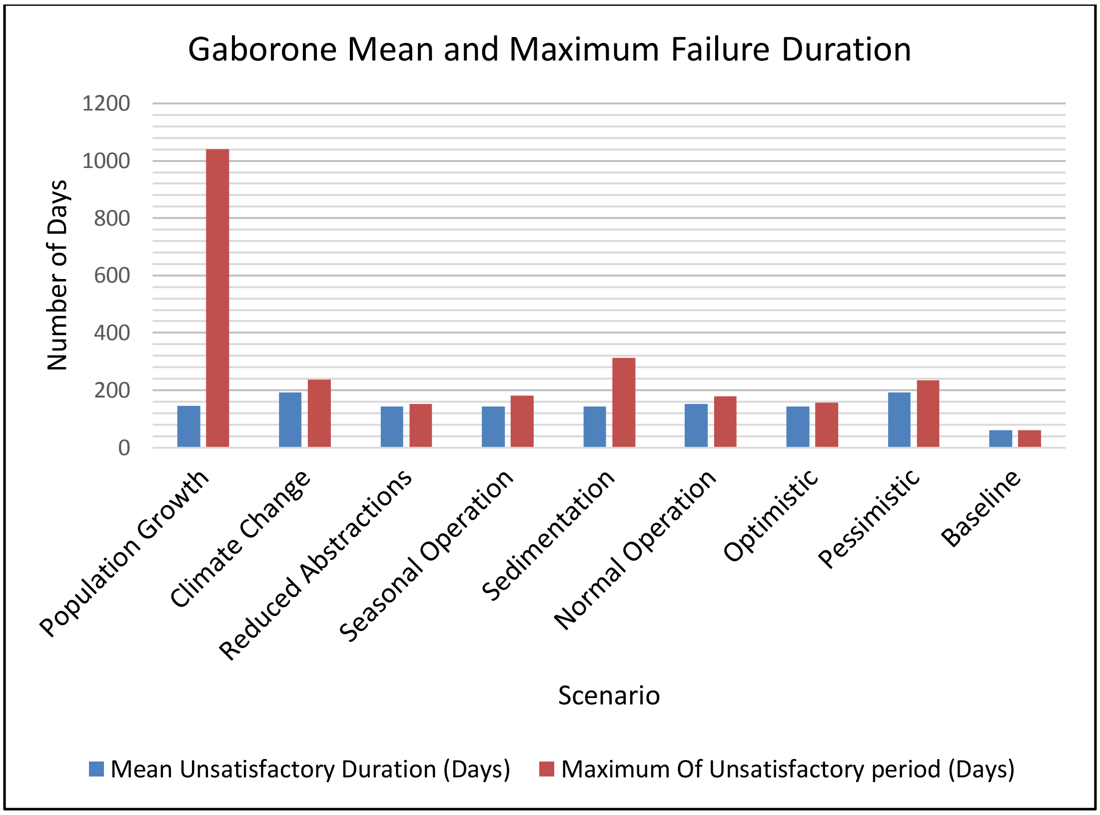


Figure 7.6: The mean unsatisfactory duration and the maximum of unsatisfactory period for Gaborone dam

The mean unsatisfactory duration (MUD) plotted in Figure 7.6 ranges between 61 and 192 days for most scenarios. The Pessimistic scenario has the highest mean unsatisfactory duration indicating more days without meeting the demand on average. Population Growth, Climate change, Sedimentation and Pessimistic scenarios have the highest maximum of unsatisfactory periods of over 200 days as displayed in Table 7.2 and Figure 7.6. Population growth heads all maximum unsatisfactory periods with over a thousand days without meeting the demand stressing the impact of a booming population on the dam.

7.1.2.2 Bokaa Dam Resilience

Simply put, resilience is the recovery rate of a system from failure to success. The resilience of Bokaa dam and its scenarios is dominated by low resiliences averaging 2.73 % as portrayed in Table 7.2 and Figure 7.7. This indicates the poor recovery of the dam when in an unsatisfactory state most of the time.

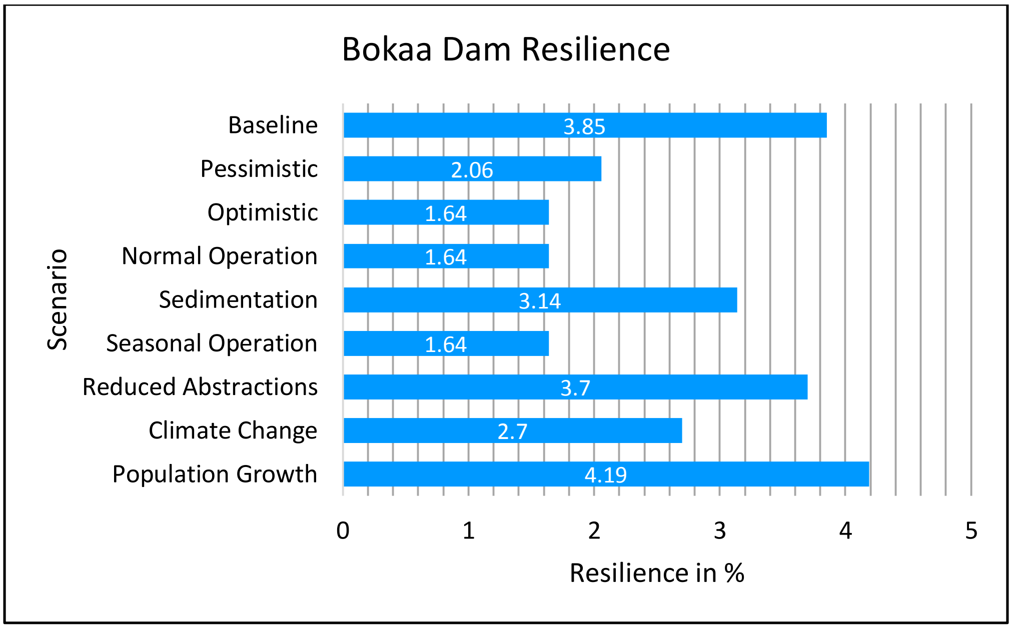


Figure 7.7: Resilience of Bokaa dam and its scenarios

Majority of the scenarios have resiliences below the baseline scenario's resilience with an exception of the Population Growth scenario. It is no surprising to also see that the Optimistic scenario, Normal Operation and Seasonal Operation have the largest mean unsatisfactory duration (MUD) of 61 days in Figure 7.8 as compared to other scenarios to attest to their low resilience. The Population Growth scenario is the most resilient expressing its better recovery rate after failure to meet demand. The scenarios of Population Growth, Reduced Abstractions, Sedimentation and Climate Change have higher maximum failure durations (MAXU) of 158, 109, 105 and 126 days respectively as specified in Table 7.2 and Figure 7.8.

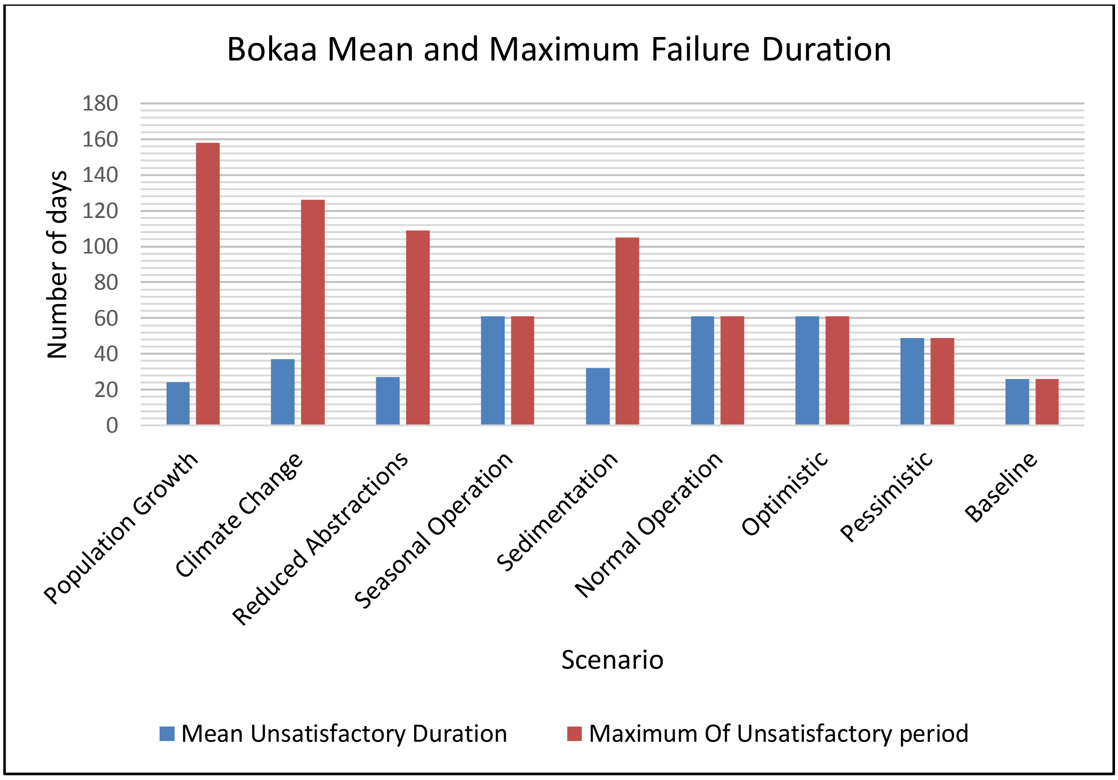


Figure 7.8: The mean failure duration and the maximum number of days of failure

7.1.2.3 Nnywane Dam resilience

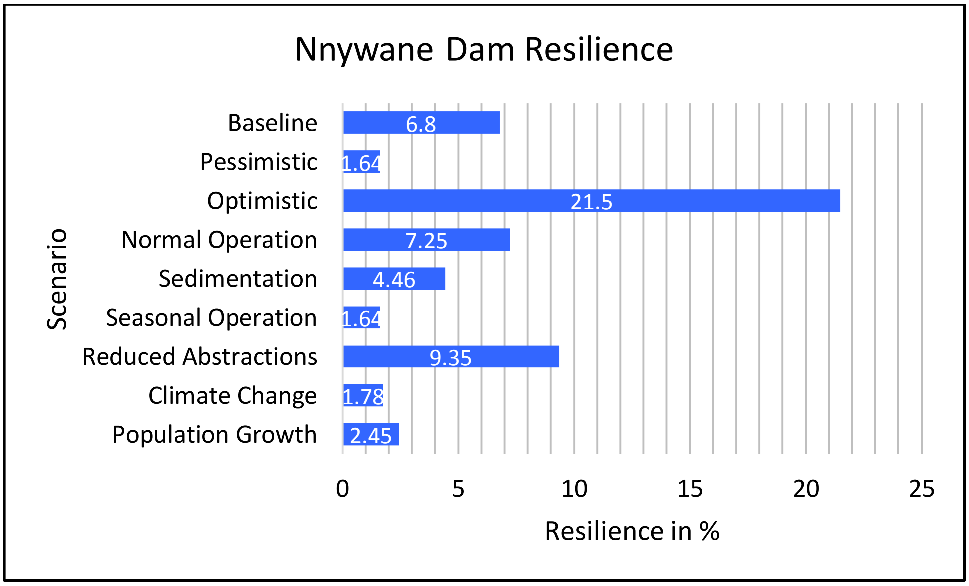


Figure 7.9: Resilience of Nnywane dam and scenarios

Table 7.2 and Figure 7.9 displays the resilience of Nnywane dam scenarios. The resilience of scenarios are mostly low, averaging 6.3 %. Most of the scenarios are less resilient than the baseline scenario; however, the Optimistic scenario is much more resilient than others while the Pessimistic and Seasonal Operation scenarios are the least resilient. The mean unsatisfactory duration for the scenarios is low with the Optimistic scenario having the lowest mean of 5 days as exhibited in Figure 7.10 and Table 7.2. The two scenarios of Population Growth and Sedimentation have very high maximums of unsatisfactory period (MAXU) of 434 and 337 days respectively (Figure 7.10). This is a huge challenge to the dam managers and water suppliers for a reservoir in a single failure period to go more than a year not meeting the demand. This indicates the pressure that the rapid population growth will place on the water resources of Notwane and the growing rate of sedimentation in the dams for the simulation period.

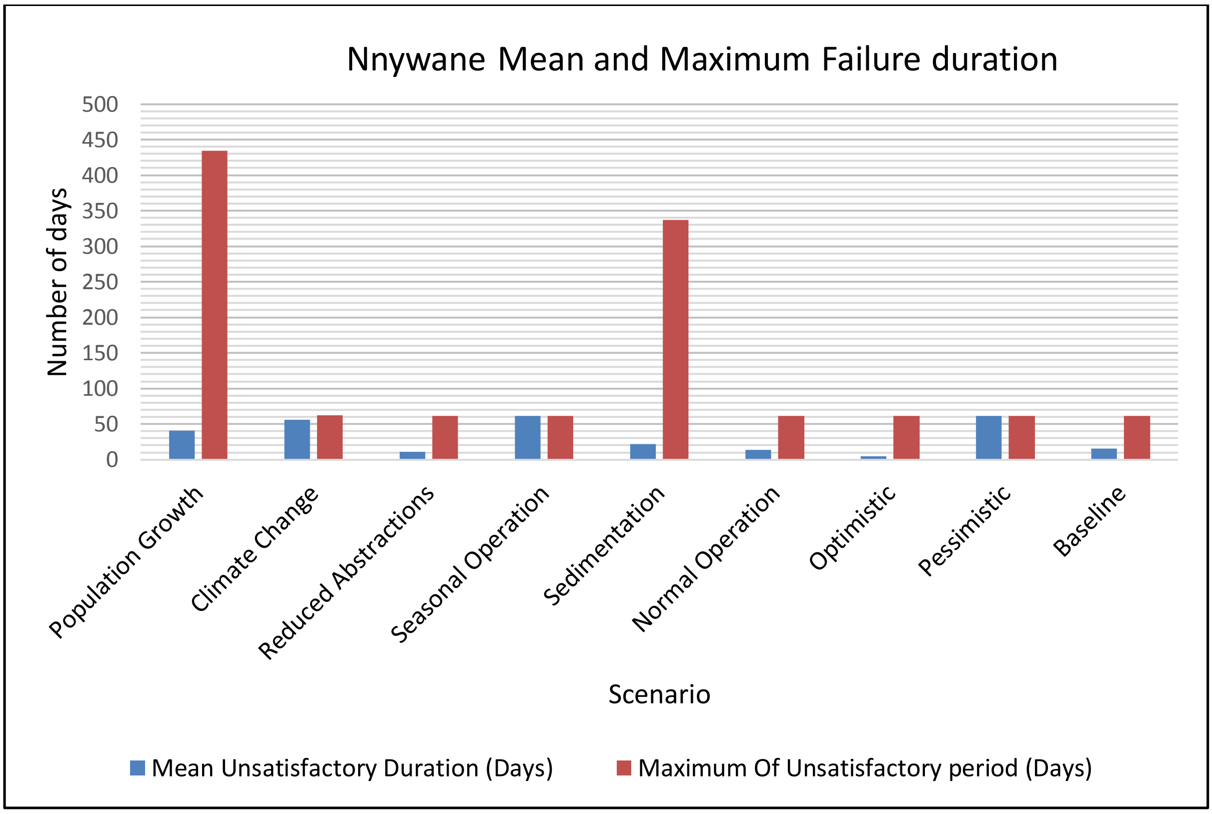


Figure 7.10: Nnywane dam mean and maximum failure durations

7.1.3 Vulnerability Index Results

Vulnerability is a measure of the extent of failure to meet demand. In this thesis, vulnerability is the average extent of water system failure expressed in volume. That is to say, it is the mean volume of all failure periods. Vulnerability is a negative water system performance index hence lower values of vulnerability are preferred. The vulnerability of dams and their scenarios is depicted in Table 7.3 and Figure 7.11 to Figure 7.13.

Table 7.3: Vulnerability of dams and their scenarios

Scenario	**Gaborone Dam Vulnerability (cms)**	**Bokaa Dam Vulnerability (cms)**	**Nnywane Dam Vulnerability (cms)**
Population Growth	0.48	0.12	0.012
Climate Change	0.44	0.12	0.020
Reduced Abstractions	0.23	0.03	0.003
Seasonal Operation	0.40	0.01	0.010
Sedimentation	0.61	0.01	0.011
Normal Operation	0.41	0.01	0.007
Optimistic	0.44	0.01	0.005
Pessimistic	0.43	0.12	0.010
Baseline	0.03	0.10	0.012
Average	0.39	0.06	0.010
Average as % of set demand	61.2	45.3	50.0

7.1.3.1 Gaborone Dam Vulnerability

The vulnerability of Gaborone dam and its scenarios is the mean volume that is required to meet the set demand. The range of vulnerability is between 0 and 0.63 cms (cubic meters per second) as 0.63 cms is the target or set demand. It can be seen from Figure 7.11 that all the scenarios except Reduced Abstractions and the baseline have high vulnerabilities. This means Reduced Abstractions scenario is less vulnerable and is a better performer while the Sedimentation scenario is highly vulnerable and a sign of poor performance.

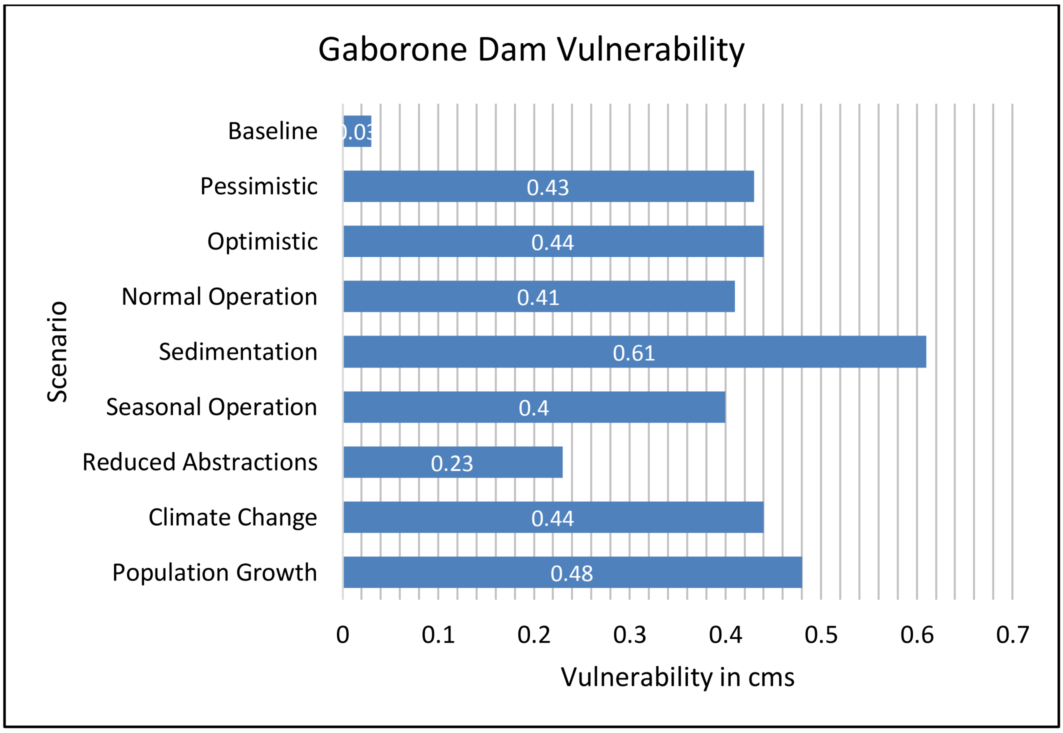


Figure 7.11: Gaborone dam scenarios and their vulnerability

7.1.3.2 Bokaa Dam Vulnerability

The range of vulnerability for Bokaa dam and its scenarios is between 0 and 0.13 cms (cubic meters per second) as 0.13 cms is the target or set demand.

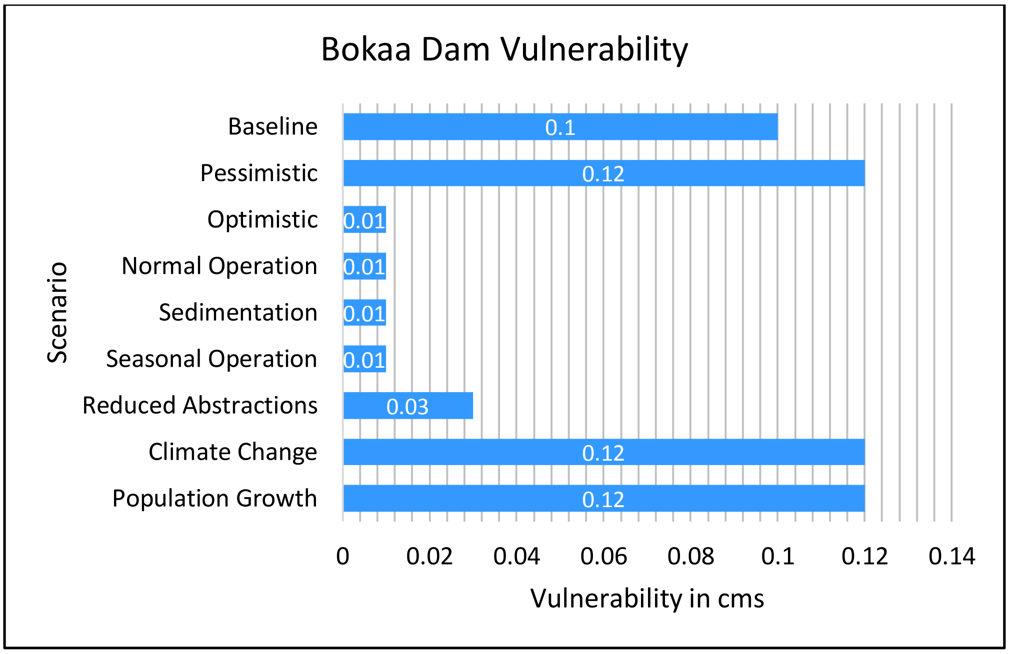


Figure 7.12: Bokaa dam scenarios and their vulnerability

The vulnerability of Bokaa and its scenarios as illustrated in Figure 7.12 and Table 7.3 show a higher vulnerability for the Pessimistic, Baseline, Climate Change and Population Growth scenarios. The other remaining scenarios of Optimistic, Normal Operation, Sedimentation, Seasonal Operation and Reduced Abstractions are less vulnerable with volumes of 0.01, 0.01, 0.01, 0.01 and 0.03 respectively which is a sign of good performance.

7.1.3.3 Nnywane Dam Vulnerability

The target demand for Nnywane dam is 0.02 cms hence the range for its vulnerability is 0 - 0.02 cms. Almost most of the scenarios in Figure 7.13 and Table 7.3 are less vulnerable while the Climate Change is more vulnerable. The three scenarios of Optimistic, Normal Operation and Reduced Abstractions have a better vulnerability of 0.005, 0.007 and 0.003 cms respectively as compared to the Baseline, Pessimistic, Sedimentation, Normal Operation, Climate Change and Population Growth scenarios with undesired vulnerabilities laid out in Figure 7.13.

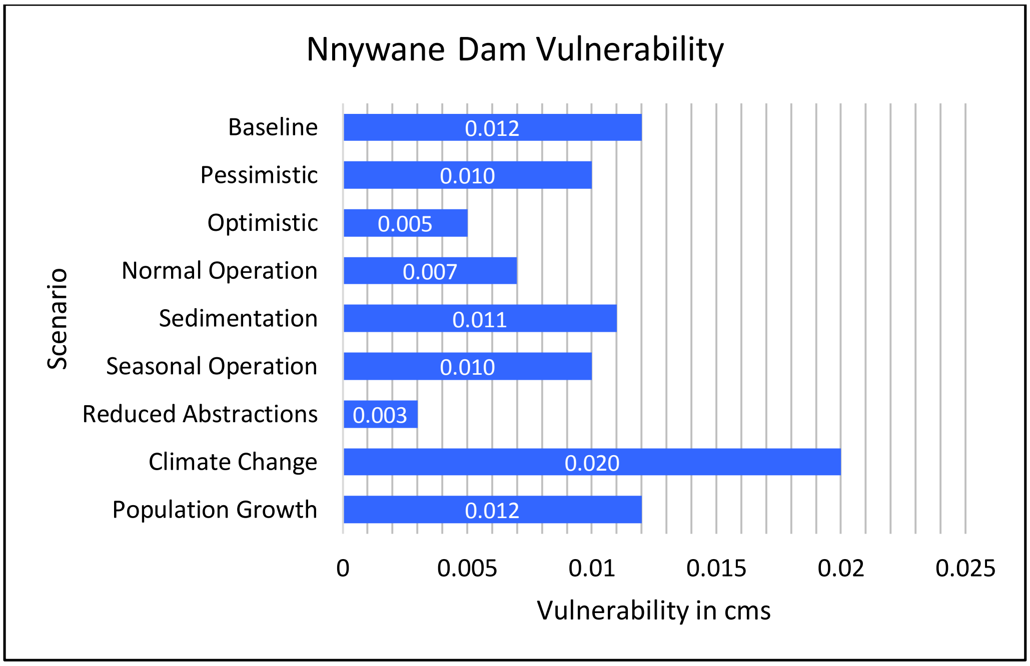


Figure 7.13: Nnywane dam scenarios and their vulnerability

7.2 Comparison of Dams

In this sub chapter, the R.R.V (Reliability, Resilience and Vulnerability) performance indexes of the three dams of Gaborone, Bokaa and Nnywane are compared to each other and analysed. The vulnerability of the reservoirs cannot be directly compared but have to be modified as a percentage volume of each reservoir relative to their volumes as showm in Table 7.2 . In Figure 7.14 the reliability of the three dams and their scenarios is compared to each other. Bokaa dam scenarios are more reliable than the other dams followed by Nnywane and lastly comes Gaborone dam whereas the scenarios of Population Growth, Climate Change and Pessimistic most of the time reduce the reliability of the dams. The average reliability for the Bokaa, Nnywane and Gaborone dams as depicted in Table 7.1 is 95, 91.1 and 66.3 % respectively.

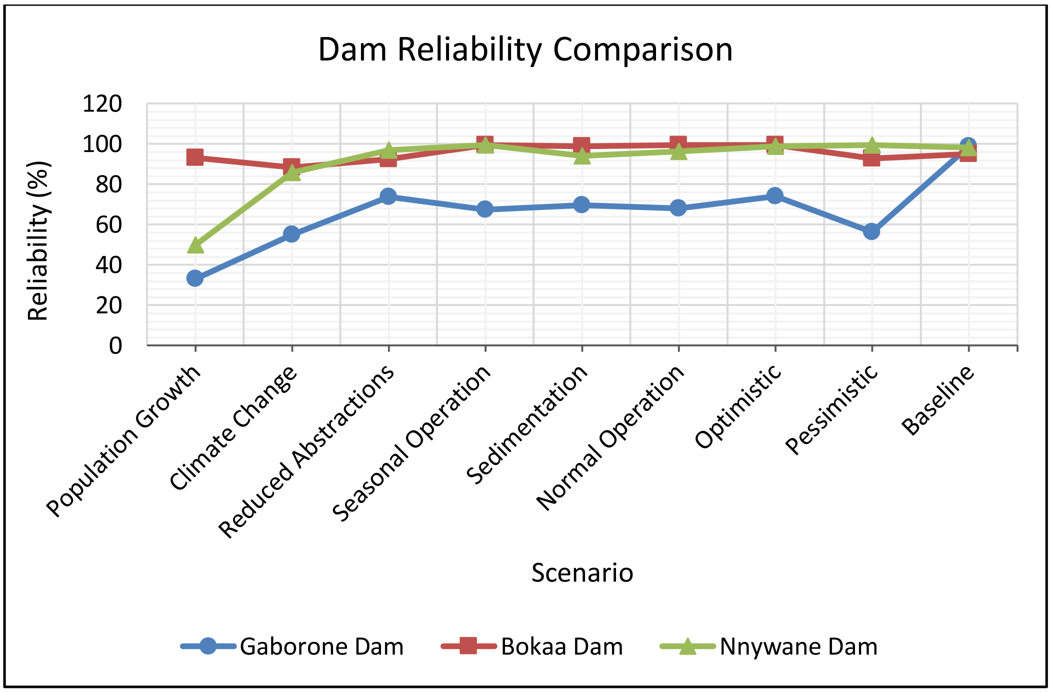


Figure 7.14: Comparison of reliability of dams

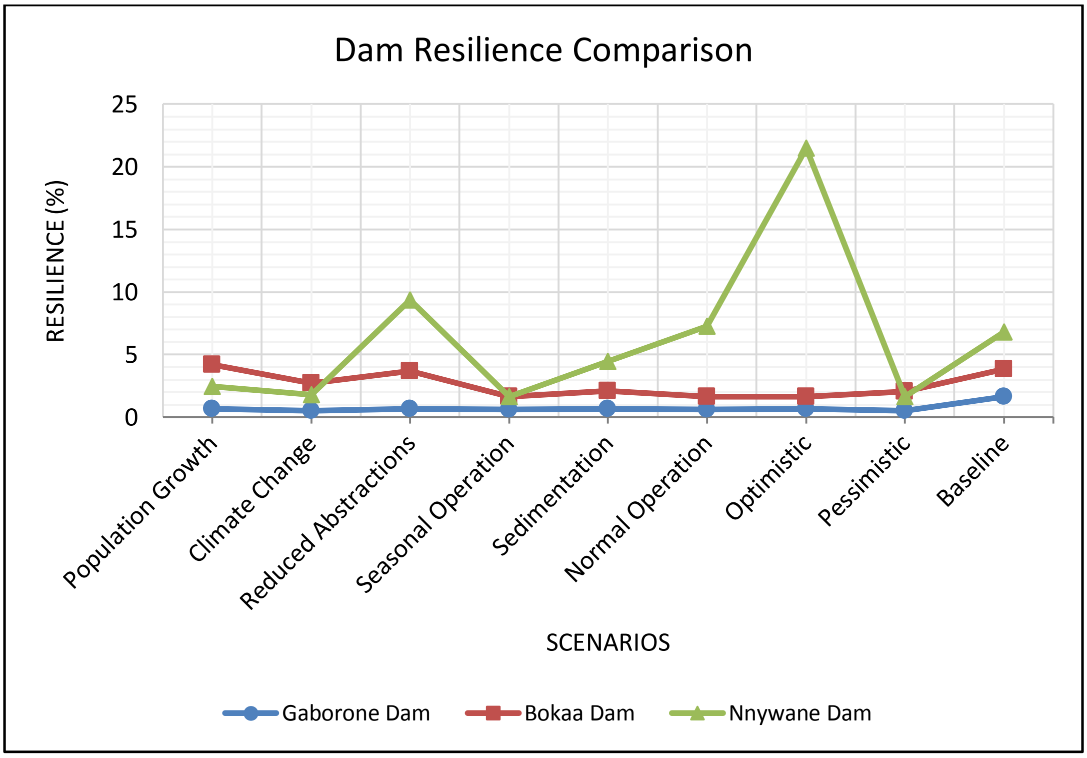


Figure 7.15: Comparison of resilience of dams

When the resilience of dams is compared in Figure 7.15, Nnywane dam scenarios come up tops followed by Bokaa and Gaborone dam in that order. The average resilience of the dams presented in Table 7.2 also confirms this with Nnywane, Bokaa and Gaborone having resilience averages of 6.3, 2.7 and 0.74 % respectively. In short, Nnywane is the most resilient dam which improves its performance rating. It was also observed that the Optimistic, Normal Operation and Reduced Abstractions scenarios are the most resilient.

The vulnerability of the dams indicates that Bokaa dam is the least vulnerable succeeded by Nnywane and lastly Gaborone dam. According to Table 7.3, the ‘average as percentage of demand row’ shows percentages of 61.2, 50 and 45.3 % for Gaborone, Nnywane and Bokaa dams. This least vulnerability of Bokaa improves the performance of Bokaa dam as compared to the other two dams because in vulnerability performance index, the lower the value the better the vulnerability and performance.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The research carried out in the catchment of Notwane has shown that HEC-ResSim has successfully simulated the operation of the major dams of the catchment. Estimators of water resources system reliability (the probability that the water system will remain in a non-failure state), resilience (the ability of the water system to return to non-failure state after a failure has occurred) and vulnerability (the likely damage of a failure event) have been thoroughly investigated. The following conclusions were drawn;

1. The reliability and resilience for water supply for all scenarios of the Gaborone dam is lower than the historical period indicating a possible dreary future for the dam.
2. The scenario of Climate Change at the Bokaa dam mostly reduces reliability of water supply from the dam by 7 %, inferring that the effects of climate change will affect the dam more than any other scenario. In addition, the reliabilities of Gaborone and Nnywane dams are also reduced by climate change by 44 and 13 % respectively as compared to the historical period.
3. The scenario of Population Growth greatly lessens the reliability of the Gaborone, Bokaa and Nnywane reservoirs by 66, 2 and 49 % respectively, signifying the detriment that an ever-increasing population and rapid urbanization place on the dam during the simulation period.
4. Sedimentation on the dams affect the storage by reducing the storage as the percentage of time the demand met is decreased. This is verified by a decline in reliability of water supply by 30, 1 and 4 % for Gaborone, Bokaa and Nnywane dams.
5. Bokaa dam scenarios on average are more reliable than the other dams followed by Nnywane and Gaborone dam respectively whereas the scenarios of Population Growth, Climate Change and Pessimistic most of the time diminish the reliability of water supply of the dams.
6. The resilience of all scenarios for all the dams is very low expressing the low speed of recovery of the dams from failure states to satisfactory states. This is evidenced by a large number of days of maximum of unsatisfactory duration (demand not met) of about 284, 107, and 133 days for Gaborone, Bokaa and Nnywane dams.

7. Nnywane dam has better resilience on average followed by Bokaa and Gaborone dams and also the Optimistic, Normal Operation and Reduced Abstractions scenarios are the most resilient.
8. Bokaa dam is the least vulnerable followed by Nnywane and Gaborone dams.

8.2 RECOMMENDATIONS

From the study the following recommendations were made:

- The stakeholders involved in water resources management must do more to encourage and promote water saving techniques/water conservation to reduce the burden on demand. Incentives should be used to encourage efficient water use, reuse and recycling.
- Environmental flows must be encouraged to sustain freshwater and estuarine ecosystems and the human livelihoods that depend on them downstream of the dams. Currently environmental flows are not being applied or adopted in the catchment.
- Increase in gauging stations and better management of these stations, frequent monitoring and better data keeping, and recording. These will improve on data gaps and erroneous data readings found in data obtained from WUC and DWA.
- Establishment of piezometers and other equipment around the dams to measure and monitor seepage from the reservoirs.
- Trapping of sediment by dams is not inevitable, at least not by all dams. However, sediment management approaches are not sufficiently used in many reservoirs in the catchment. Upstream of the Gaborone dam the DWA built a small reservoir (Notwane dam) for trapping sediments before they enter the dam, however more has to be done on this area as the Gaborone, Bokaa and Nnywane dams continue to experience this problem of siltation. Mitigation measures such as reduction of sediment production, soil erosion control and sediment traps before the dams to reduce sediment yield in the watershed. Also minimizing sediment deposition on the reservoirs by measures such as sediment bypass / diversion, mechanical excavation and drawdown routing (sluicing) should be looked at especially when the dams are empty like recently when Gaborone dam was empty.
- It is also recommend that sedimentation be explicitly addressed in planning and design documents for all proposed dams in the catchments, including quantification of upstream sediment yield to the reservoir, and with projections of reservoir sedimentation rates into the future for the conventional design approach as well as management based on more sustainable principles. Rivers vary widely in their sediment loads, and the load carried by the river should be explicitly acknowledged in planning documents. Planning and design documents should indicate how reservoir

sedimentation will be managed in the long term to contribute to sustainable development.

- The impacts of climate change in the catchment and the country must be addressed by working with partners in river basins to optimize available water supplies for competing water uses. Enhancing of climate adaptation planning through the initiation and funding of basin Studies, collaborating with stakeholders to evaluate the impacts of climate change to multiple water uses within the catchment and to identify adaptation strategies should be carried out.
- While reducing water consumption can be successful in the catchment, the loss of water from reservoir evaporation is an issue already affecting the dams especially with the possibility of decreasing precipitation occurring as a result of climate change. Hence, we suggest the water managers to look at proposals such as moving reservoir water underground into new storage areas or aquifers and the selection of future reservoir sites should be selected in such a way that the area to storage ratio is minimum. Moshe Alamaro, a Massachusetts Institute of Technology researcher, just might hold the key to reducing evaporation of reservoir water. Although the technique hasn’t been tested on a large reservoir, Alamaro proposed a monolayer film made from material extracted from vegetable oil, which would be put over a reservoir’s surface. The monolayer film can reduce evaporation up to 75 percent. Also recently the city of Los Angeles rolled out thousands of small, black plastic balls into the 175-acre Los Angeles Reservoir in Sylmar, California to reduce water evaporation from the reservoir. The black plastic balls are also used as floating covers to protect water quality by preventing sunlight-triggered chemical reactions that give birth to carcinogens, deterring birds and other wildlife, and protecting water from rain and wind-blown dust in reservoirs (see Appendix C). The 96 million balls that were deployed into the reservoir were a cost-effective investment that is expected to save the city at least $250 million in comparison to other water-saving alternatives. They are currently in place at Upper Stone, Elysian and Ivanhoe reservoirs, and come with the added benefit of reducing evaporation off the reservoir surfaces by 85 to 90 % according to a press release from LA Mayor Eric Garcetti (National Geographic, 2015).

8.2.1 Model limitations

Simulation models of surface water flow are limited in their representation of the physical system because they contain simplifications and assumptions that may or may not be valid. Results from models have a degree of uncertainty mainly because of uncertainties in many model input parameters. The main constraints in the modelling process were data gaps and poor quality of the available data. The application of the model should be constrained by the limitations inherent in the model and the knowledge and understanding of the capabilities and limitations of the model in representing real-world processes**.** Models must be carefully and meticulously applied with professional judgement and good common sense. Although the effectiveness and efficiency of a modelling study can be greatly enhanced by exploiting the capabilities provided by modelling softwares, modelling still requires significant time and effort as well as expertise.

Software limitations or weaknesses encountered include:

i. HEC-ResSim does not have the capability to perform simulations on a monthly time interval. This limits ability to make period-of-record analysis and evaluation for water supply operations.
ii. There is no way to easily define, setup, and simulate various scenarios representing changes to sets of hydrological flow conditions, physical reservoir characteristics, diversion operating rules, routing parameters, impact area, sets reference location rating curves and other user defined scenarios.
iii. In this version of HEC-ResSim (version 3.1) , scenario-based analysis is only offered for reservoir zone definitions and operating rules using operations sets defined within the Alternative Editor. This limitation hence leads to all other scenario changes to be implemented as child networks, then additional program alternatives must be freshly defined for those networks. This inadequacy exacerbates the problems stated in limitation (ii).
iv. Ability to dynamically link input and output among multiple software tools is not there. Re-computes in another module requires updating in subsequent modules followed by re-computes. Hence updating must be executed individually for each scenario in each simulation. This setup forces the user to shuffle between the various software modules and extends the time and effort needed to re-generate results.

8.2.2 Recommended Future Capabilities of HEC-ResSim

Recommended future capabilities are described for the software program:

i. HEC-ResSim must avail the ability to compute on a monthly time interval.

ii. In HEC-ResSim, further ‘set’ capabilities should be developed to allow making changes easily to sets of hydrological flow conditions, lookback conditions, physical reservoir characteristics, diversion operating rules, routing parameters, impact area sets, reference location rating curves and other user defined scenarios within a single reservoir network. These sets would be analogous to the existing reservoir ‘operation sets’ and should be accessible for user selection on a set tab within the Alternative Editor.

iii. Ability to easily replicate setup of multiple project alternatives, simulation and evaluation of multiple alternatives across a consistent set of scenarios (operations sets) must be availed. This feature should also automate the procedure for creating program alternatives and simulation and evaluation of all scenarios in one setting.

iv. HEC-ResSim must offer the capability for users to define their own evaluation indicators (e.g., firm water supply yield, reliability, vulnerability, resilience, peak flow, flow criteria met at location x, duration of inundation, DRI, SUI and other indicators.) and allow post-processing of these user-defined evaluation indicators using time-series results from multiple scenario runs. This feature could be applied using some kind of DSS-MathLogic editor or extension to DSS-Vue.

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APPENDICES

APPENDIX A- STUDY AREA DESCRIPTION

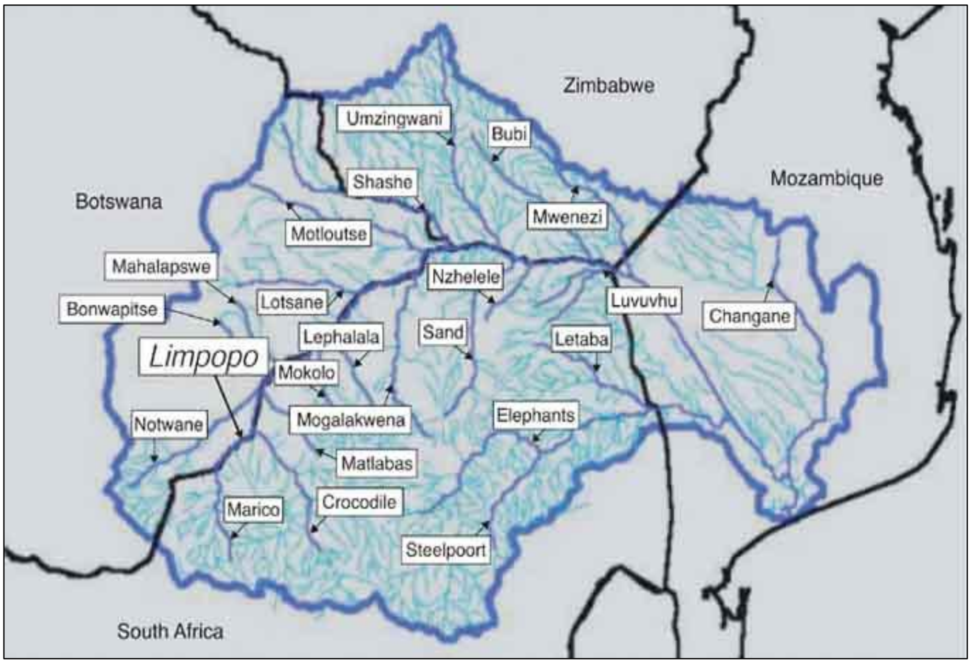


Figure 8.1: Limpopo basin and its sub basins

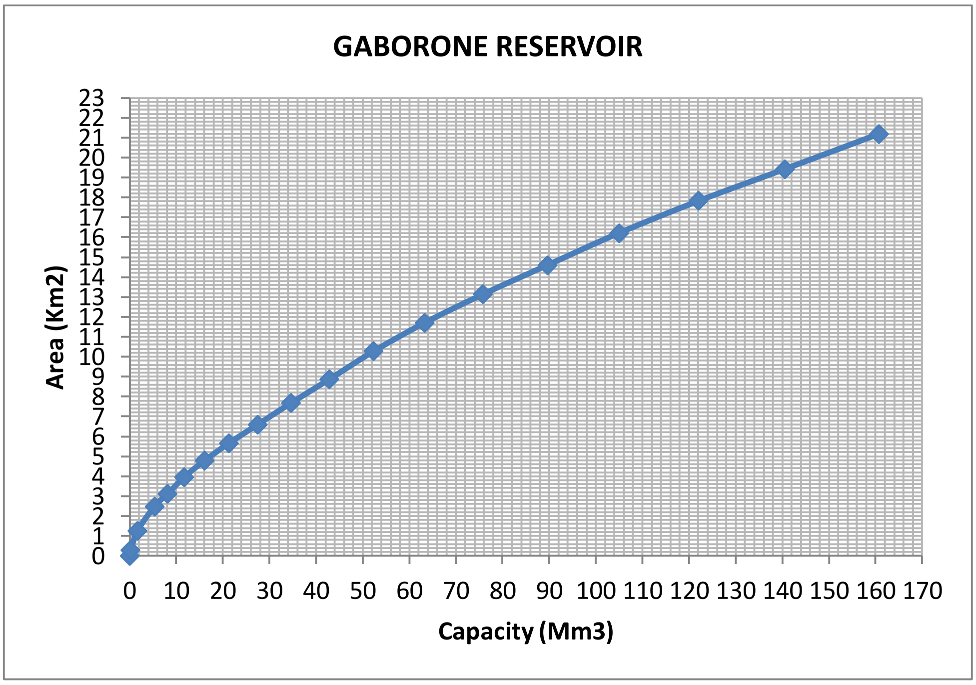


Figure 8.2: Area-capacity curve for Gaborone reservoir

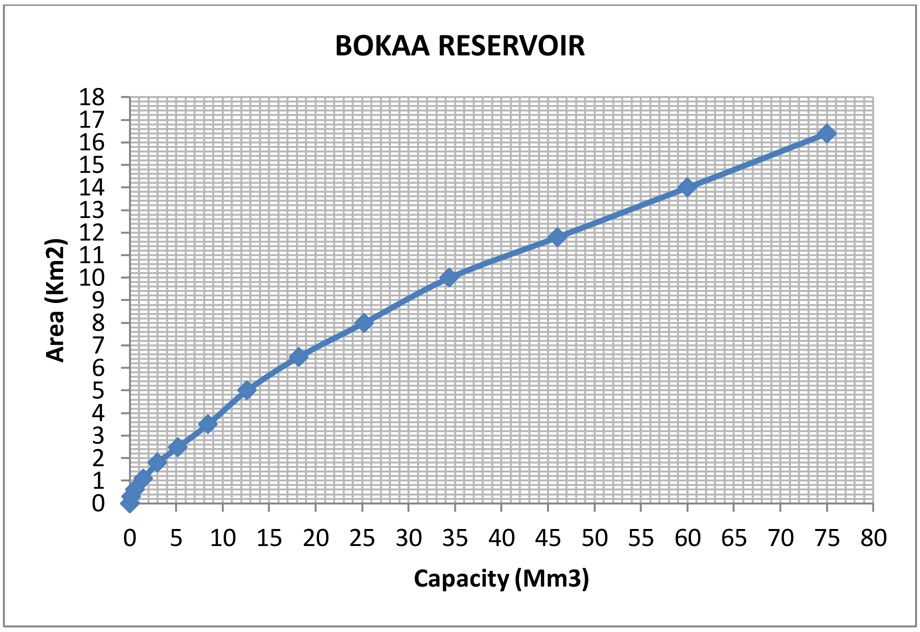


Figure 8.3: Area-capacity curve for Bokaa reservoir

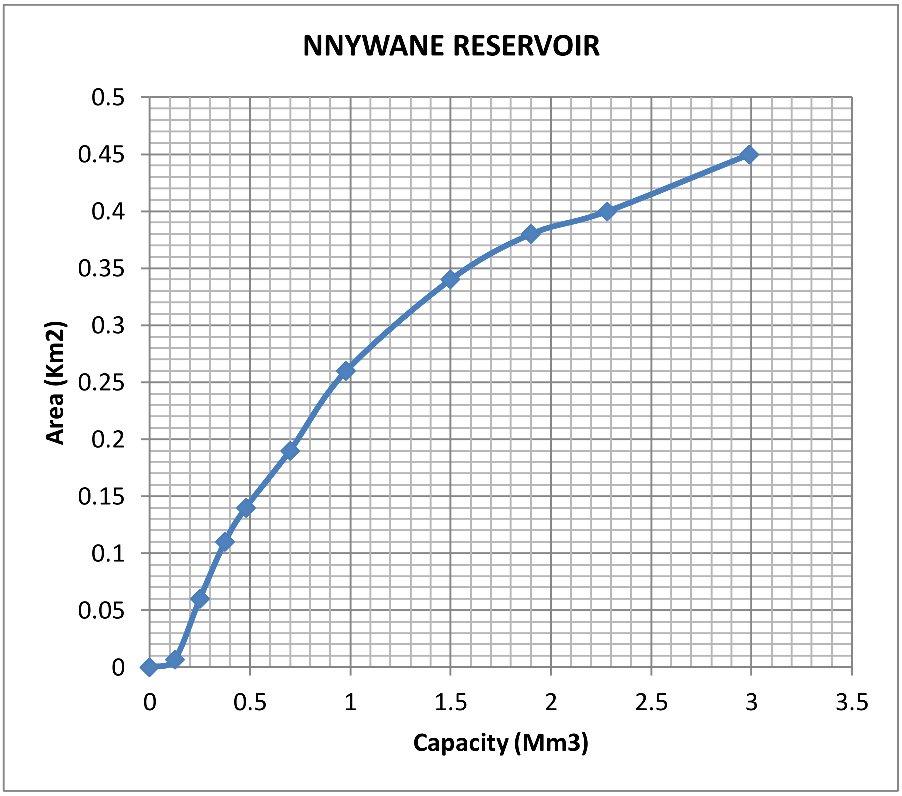


Figure 8.4: Area-capacity curve for Nnywane reservoir

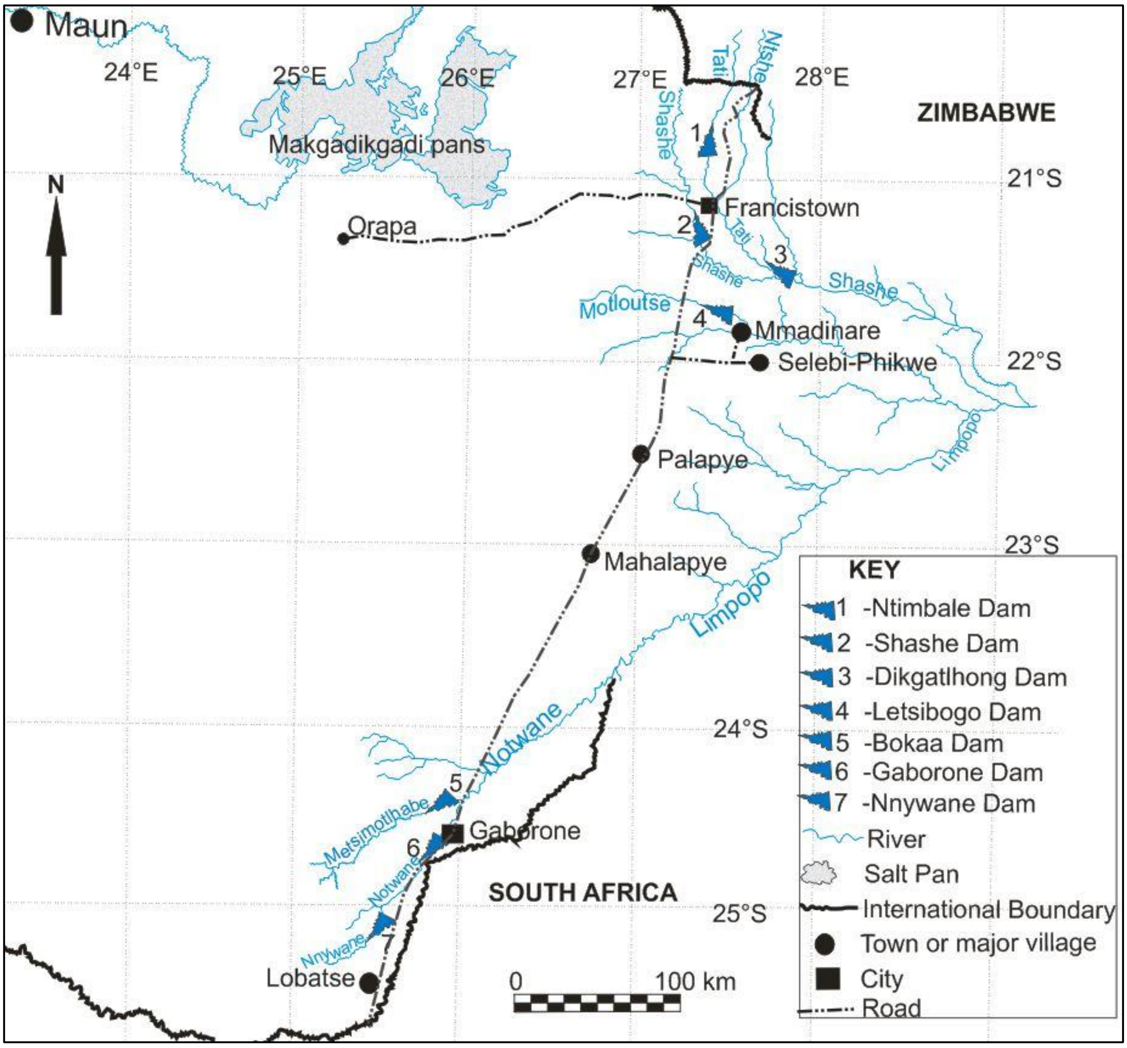


Figure 8.5: Dams and rivers of Botswana

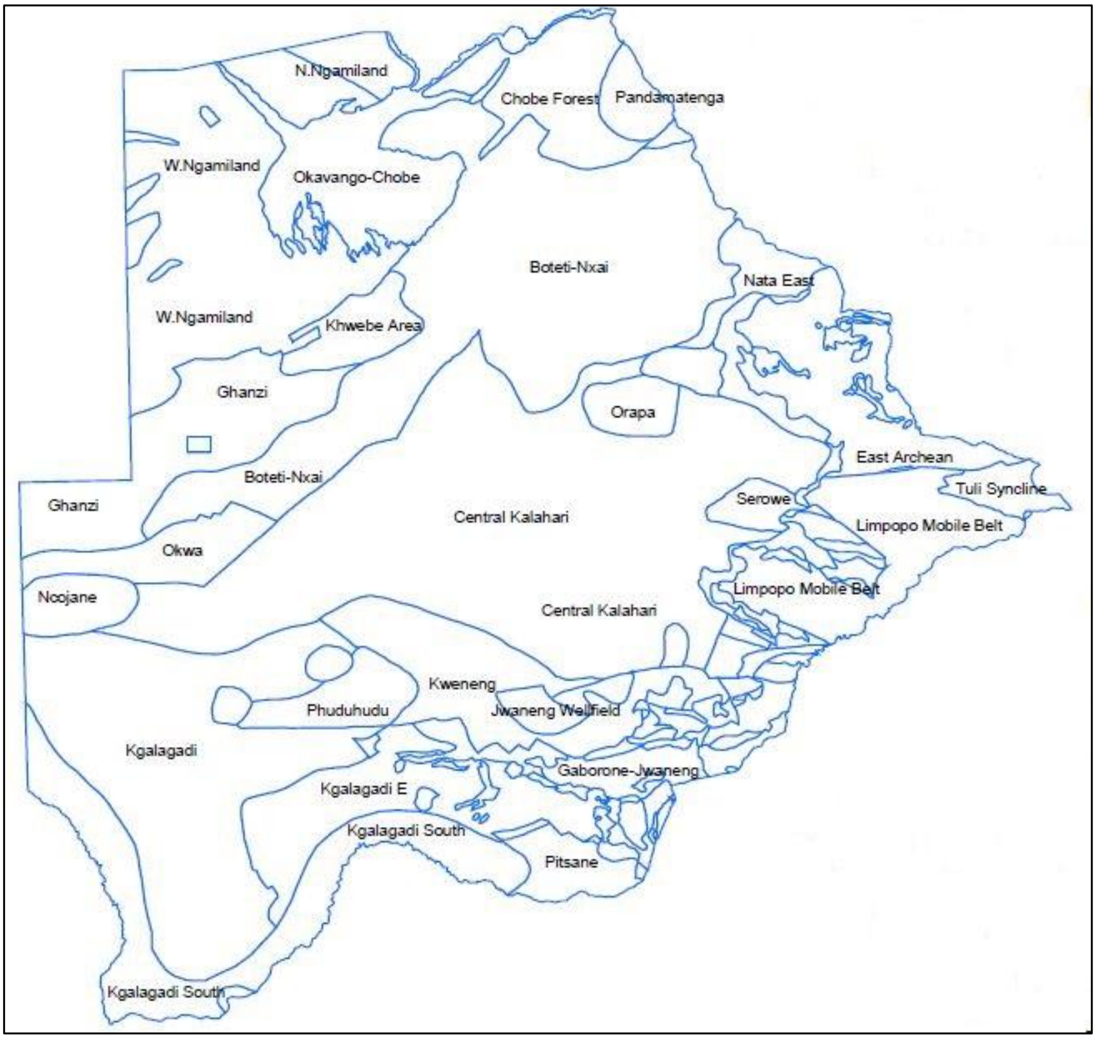


Figure 8.6: Wellfields of Botswana. Source: Dept. of Surveys and Mapping, 2001

Table 8.1: Maximum and Minimum monthly temperature for Notwane sub basin

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1986	33.8	33.2	31.9	27.9	27.3	22.9	23.5	27.2	28.6	29.8	30.2	32.7
1987	34.7	35.3	32.2	32.1	28.2	22.1	21.9	24.8	27.8	31.2	33	31.7
1988	34.4	30.3	29.5	26.1	24.8	21.9	23.8	26.4	28	29.7	30.4	30.3
1989	30.9	28.7	30.9	25.5	25.2	22.3	22.8	27.4	29.7	31	30.3	32.1
1990	32.5	30.2	31	28.9	24	23.2	24.3	25.4	29	31.5	34.3	34.1
1991	31.6	31.4	28.6	27.5	26.1	21.4	22.1	26	29.6	31.5	30.7	31.4
1992	36.2	36.5	33.1	31.7	26.8	23.3	22.9	23.6	32	33	30.2	32.6
1993	34.1	31	30.7	28.6	28.1	22.8	23.5	24.9	31.6	29.7	30.4	32.5
1994	29.1	29.2	31.9	29.1	26.2	21.9	21	24.8	30	30.8	32.6	34.4
1995	34	33.3	29.9	27.7	22.9	22.3	22.9	25.8	30.6	32.6	32.5	29.7
1996	30.1	28.7	29.4	26	23.7	22.9	21.3	25.1	29.6	32.6	30.1	31.6
1997	30	32.1	27.6	25.3	22.8	22.7	22	26.1	27.5	30.5	31.8	33.6
1998	31.2	33.2	32.7	30.5	26.5	25	23.5	25	30.2	30	31.1	30.3

1999	32.1	33.1	31.8	29.3	25.6	23.5	22.5	25.7	27.8	30.4	32.8	29.8
2000	28	27.8	28	25.1	22.8	21.2	21.3	25.8	28.7	31	33.1	29.8
2001	34.3	30.2	28.2	25.8	23.4	21.8	21.1	26.1	27.5	30.6	27.4	30.4
2002	31.7	29.4	31.8	29.9	26.3	21.3	23.1	25.9	28.4	31.9	32.1	31.6
2003	34.3	33	32.6	31.1	25.7	21.6	22.8	24.6	29.6	31.7	31.2	34.4
2004	31.8	29.9	27.9	26.5	25.7	21.5	21.5	26.7	28.1	31.8	33.4	31.9
2005	33.2	33.5	31.2	26.2	26.5	25.3	23.6	28	31.8	33.6	33.3	30.8
2006	29.9	29.1	27.1	26.1	22.8	22.1	23.8	23.8	28.6	32	30.7	33.4
Mean	32.2	31.3	30.3	27.9	25.3	22.5	22.6	25.6	29.2	31.2	31.5	31.8

Minimum Monthly Temperature for Notwane sub-catchment

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1986	21.2	18.9	18.4	15.2	10.2	5.6	5.8	9.3	13.3	16.5	17.3	19.2
1987	20.1	21.8	18.5	16.3	10.7	5	4.2	7.5	13.9	16.9	19.7	20.3
1988	21.1	15.4	18.4	13.9	8.1	3.4	3.5	7.7	11.8	15.5	14.8	17.9
1989	18.5	17.8	15	12.4	9.1	5.1	2.9	8.3	10	13.8	15.7	17.7
1990	19.4	16.6	17.5	14.4	8.5	4.7	5.6	6.8	11.3	15.9	18.8	20.2
1991	19.9	18.7	17.4	10.9	7.9	5.1	4	6.5	13	16.1	16.5	17.7
1992	20.5	19.6	19	15.2	8.3	5.1	5.3	7.4	15	17.2	16.7	19.5
1993	20.4	19.8	17.7	13.5	9.3	4.2	7	7.8	13.1	18	17.8	19.8
1994	16.4	18.3	20.1	13.2	5.9	3.2	1.5	5.9	11.8	15	19.3	19.3
1995	21.2	20.4	18.2	13.6	10	3.6	5	8.7	14	16.2	18.4	16.6
1996	19.5	18.2	14.9	12.2	8.4	4.4	2.4	6.6	11	17.1	17.1	18.5
1997	19	18.8	16.9	10.6	6.5	2.7	3.8	6.5	12.4	15	16.3	19
1998	18.7	18.9	18.1	13.9	6.3	2.9	4	6.4	12.6	15.9	17.4	18
1999	18.6	19.2	18.1	14.7	10.5	5.7	6.6	7.8	11.1	15.5	19.3	18.4
2000	17.3	18.6	17.8	11.7	6	5.8	2.8	7	11.5	15.9	19.3	18.6
2001	19.4	19.1	17.1	14.1	8	4.5	3.6	6.8	10.4	16	16.5	17.4
2002	18.3	18.1	16.6	12.9	7.8	5	2.1	9.2	11.1	15.5	16.2	19
2003	19	20.5	16.8	15.2	7.7	6.6	3.7	5.7	12.3	16.8	18.4	19.5
2004	19.6	18.6	16.9	13.5	8	4.7	3.2	7.6	9.8	15.7	19	19.6
2005	20.5	20.1	17.2	14.5	8.4	6.9	4.2	9.5	13.5	17.7	19.2	18.9
2006	20	19.3	16.7	12.5	4.1	3.5	4.8	5.5	9.8	16.4	17.1	19.9
Mean	19.4	18.8	17.4	13.5	8.1	4.6	4.1	7.4	12	16.1	17.6	18.8

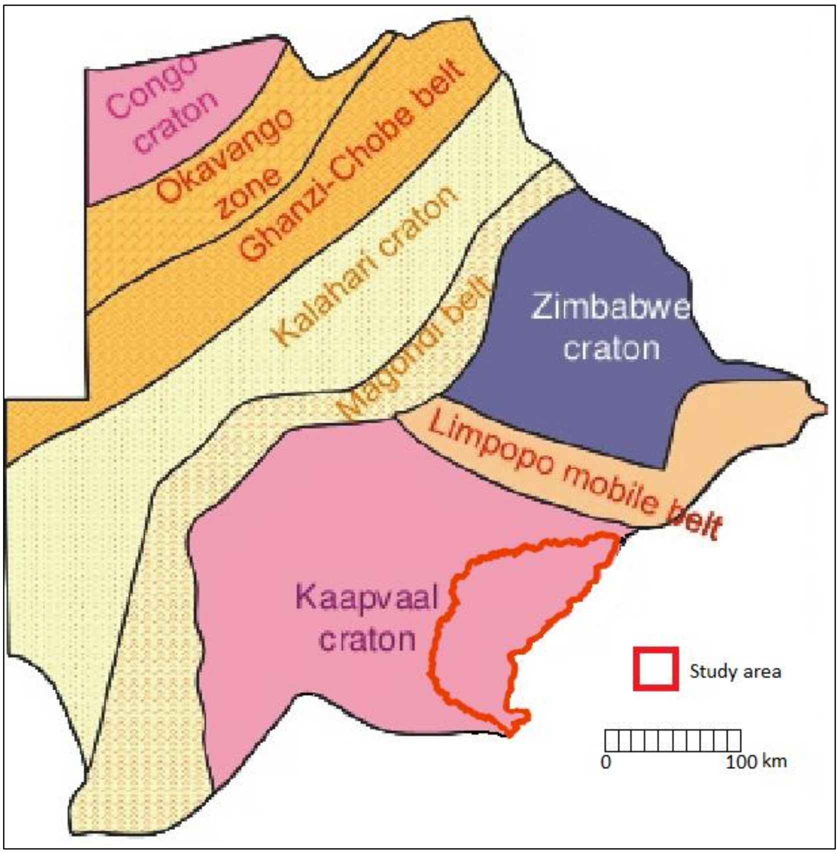
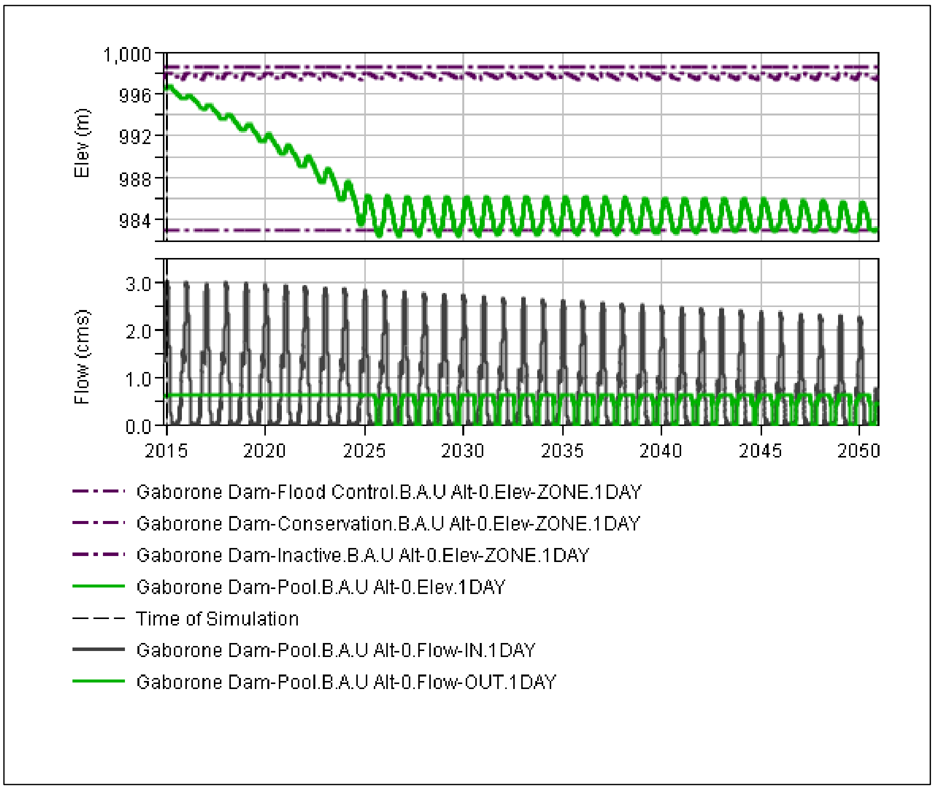
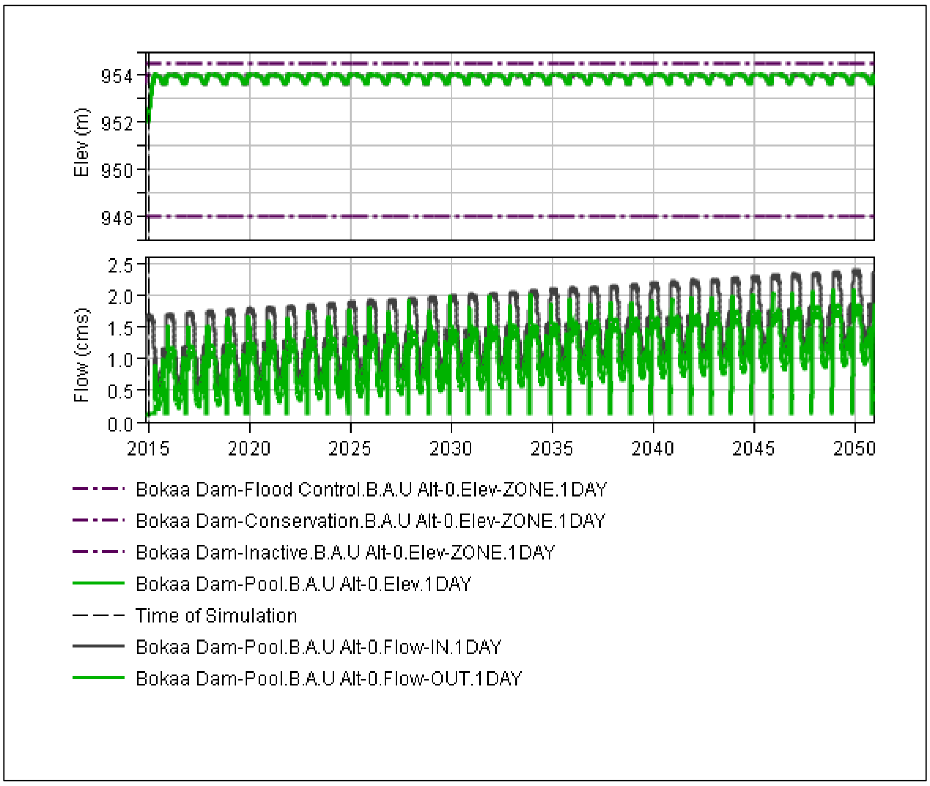


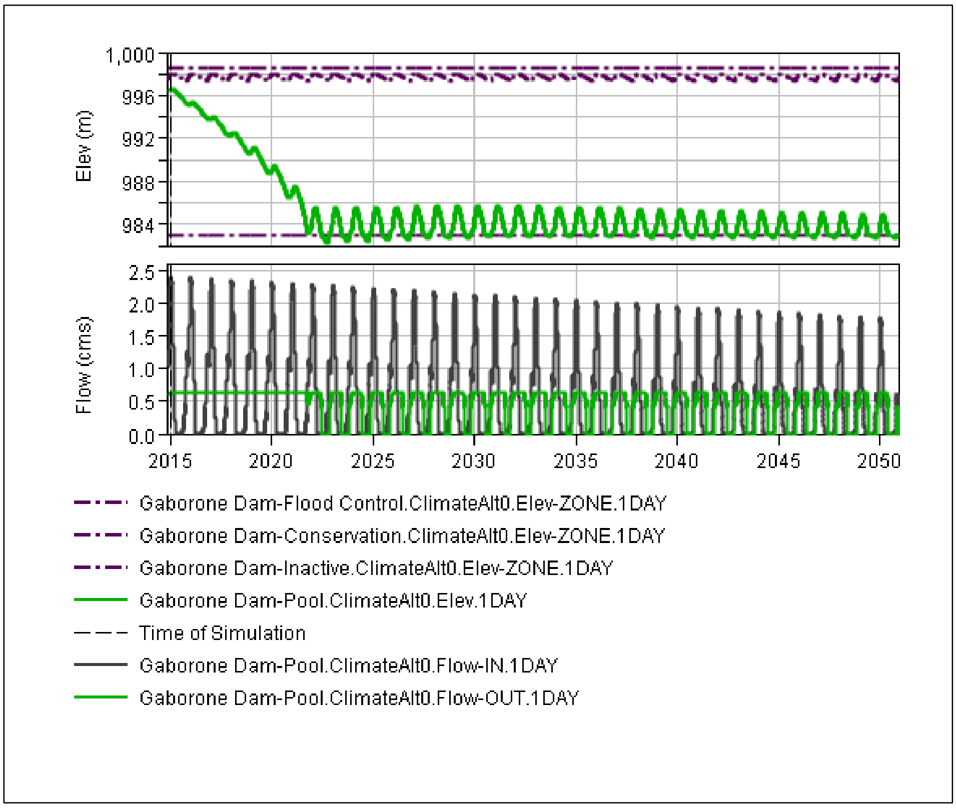
Figure 8.7: Regional Geology map

APPENDIX B- MODEL RESULTS

Results from HEC-ResSim:






Elev (m)
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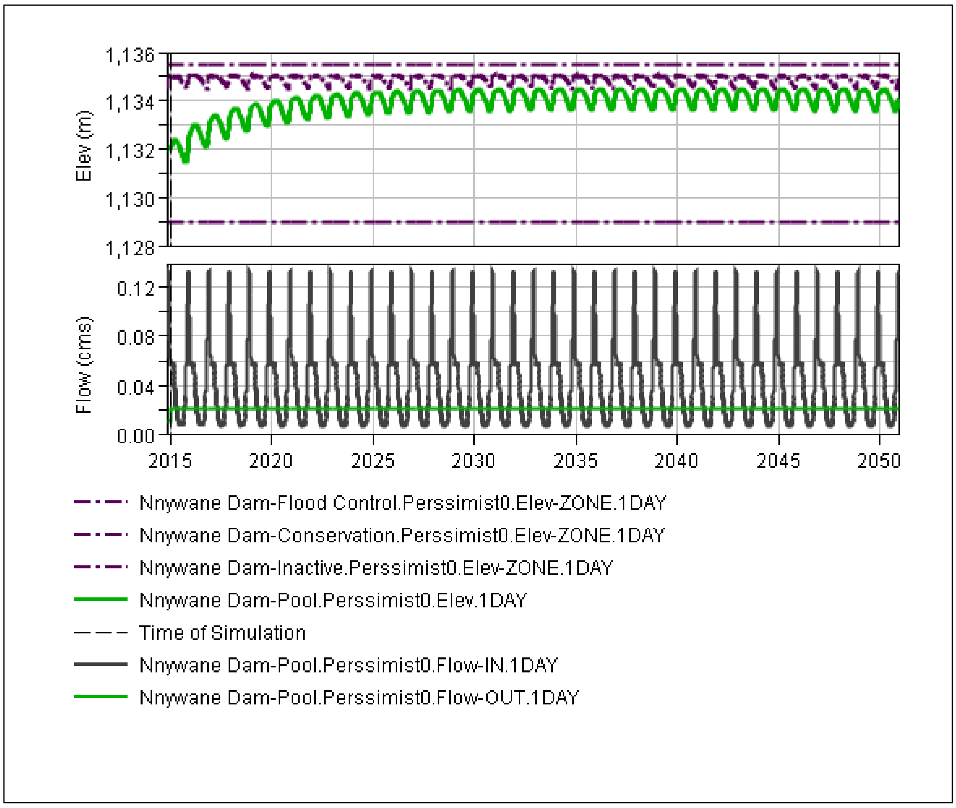
996
992
988
984
Flow (cms)
2.5
2.0
1.5
1.0
0.5
0.0
2015
2020
2025
2030
2035
2040
2045
2050
Gaborone Dam-Flood Control.ClimateAlt0.Elev-ZONE.1DAY
Gaborone Dam-Conservation.ClimateAlt0.Elev-ZONE.1DAY
Gaborone Dam-Inactive.ClimateAlt0.Elev-ZONE.1DAY
Gaborone Dam-Pool.ClimateAlt0.Elev.1DAY
Time of Simulation
Gaborone Dam-Pool.ClimateAlt0.Flow-IN.1DAY
Gaborone Dam-Pool.ClimateAlt0.Flow-OUT.1DAY


Elev (m)
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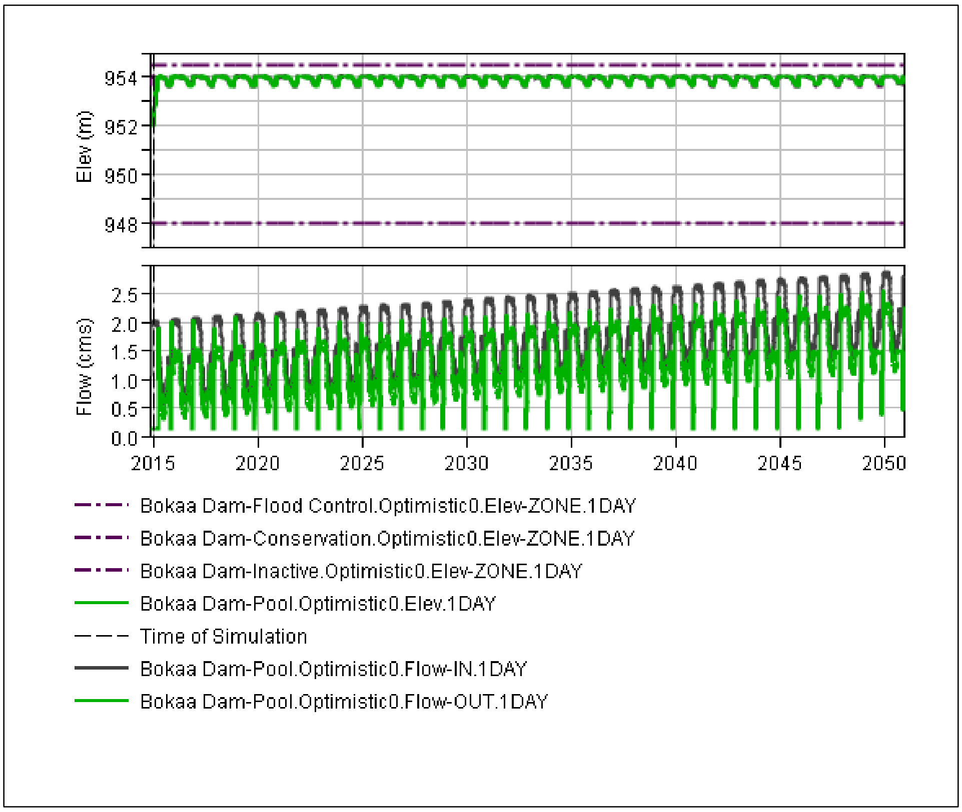
1,134
1,132
1,130
1,128
Flow (cms)
0.12
0.08
0.04
0.00
2015
2020
2025
2030
2035
2040
2045
2050
Nnywane Dam-Flood Control.Perssimist0.Elev-ZONE.1DAY
Nnywane Dam-Conservation.Perssimist0.Elev-ZONE.1DAY
Nnywane Dam-Inactive.Perssimist0.Elev-ZONE.1DAY
Nnywane Dam-Pool.Perssimist0.Elev.1DAY
Time of Simulation
Nnywane Dam-Pool.Perssimist0.Flow-IN.1DAY
Nnywane Dam-Pool.Perssimist0.Flow-OUT.1DAY


954
952
950
948
Elev (m)
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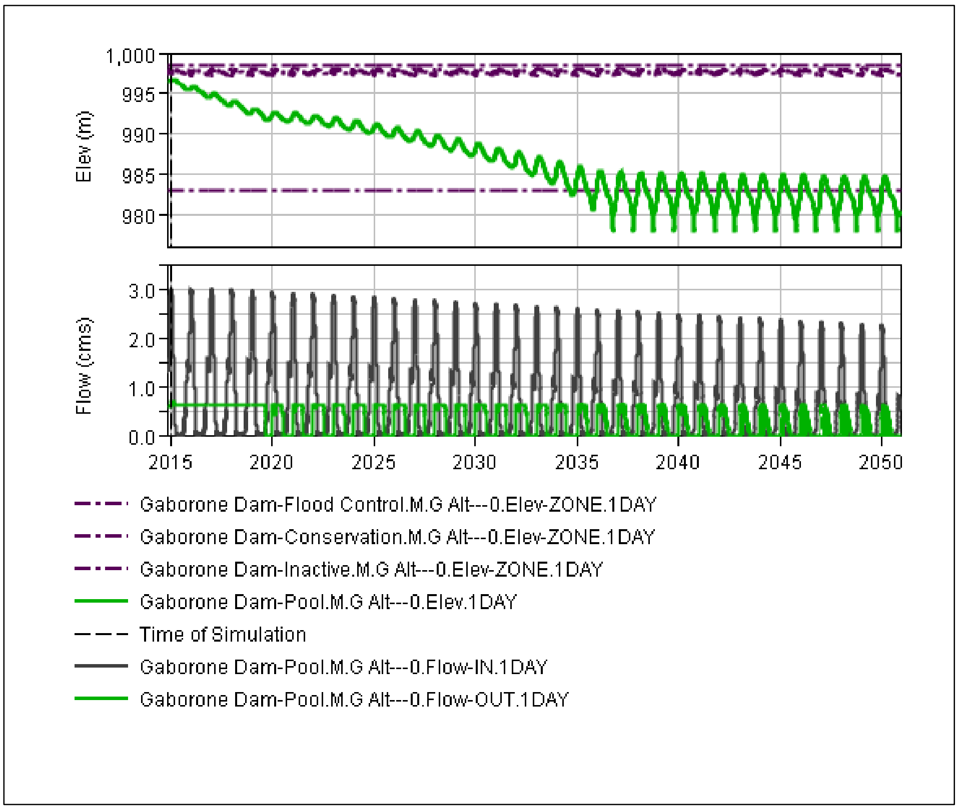
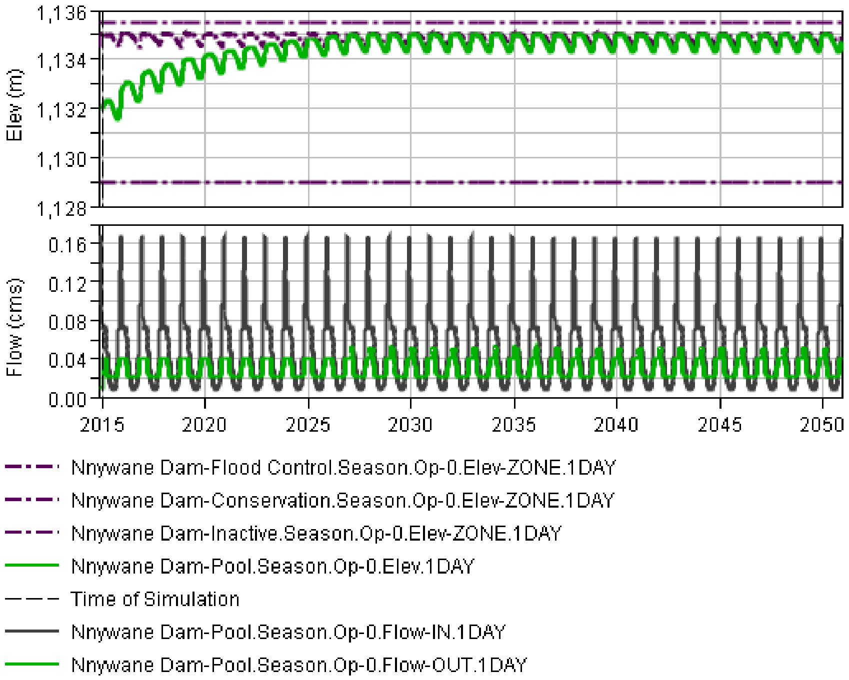
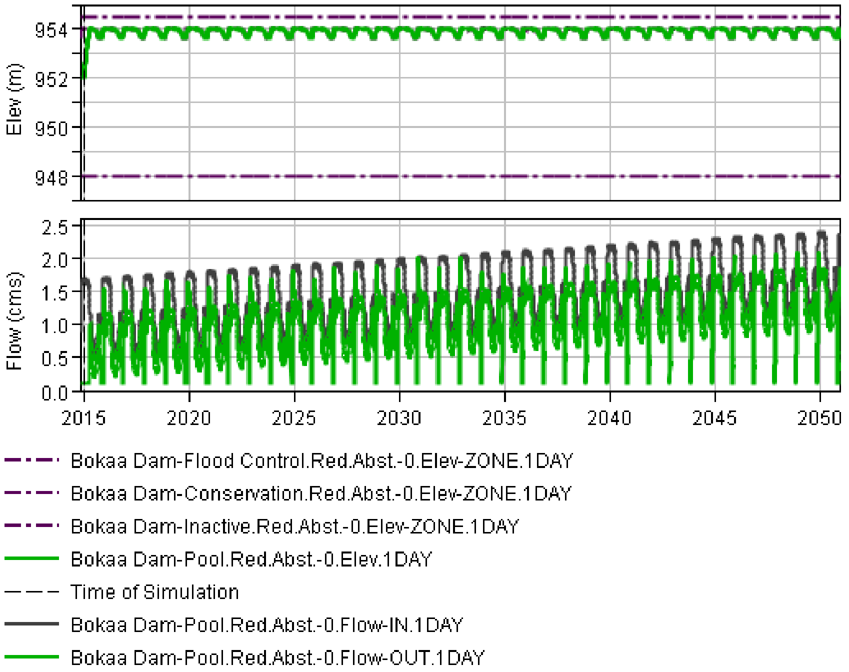
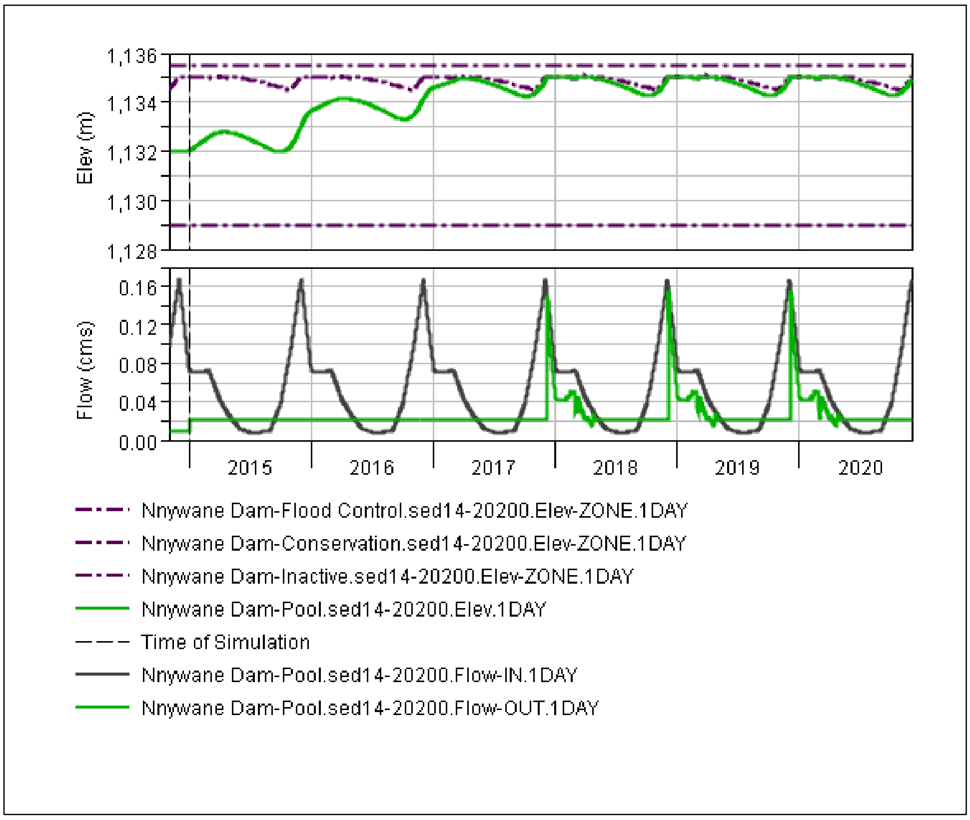
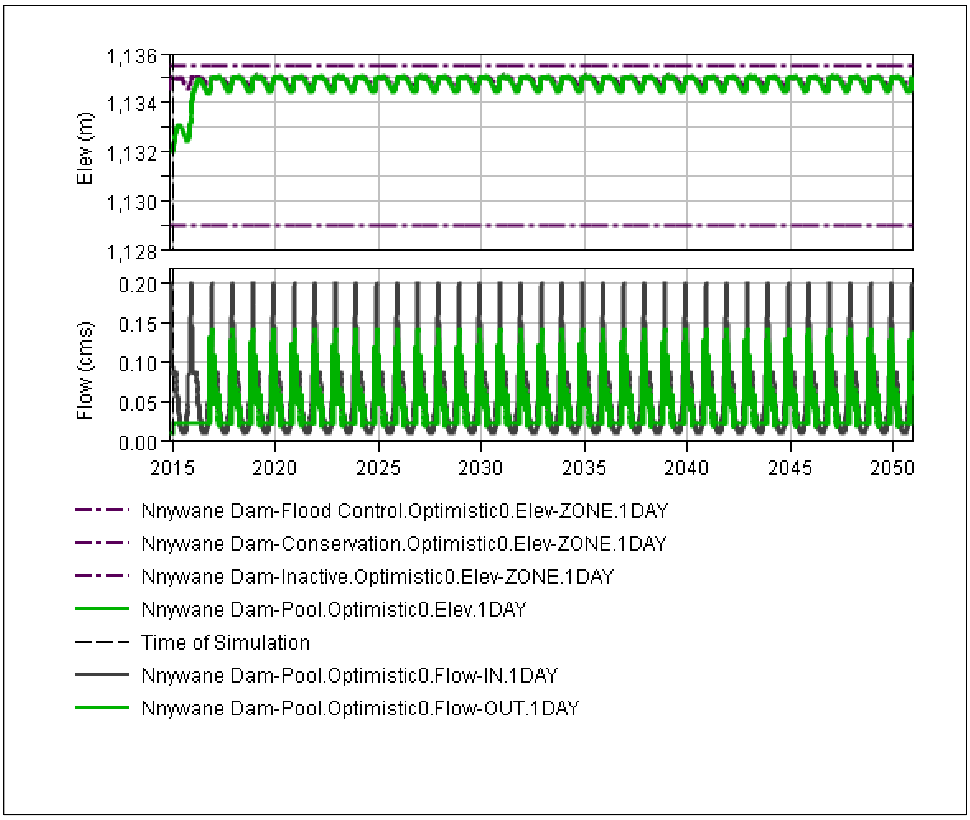
2.0
1.5
1.0
0.5
0.0
Flow (cms)
2015
2020
2025
2030
2035
2040
2045
2050
Bokaa Dam-Flood Control.Optimistic0.Elev-ZONE.1DAY
Bokaa Dam-Conservation.Optimistic0.Elev-ZONE.1DAY
Bokaa Dam-Inactive.Optimistic0.Elev-ZONE.1DAY
Bokaa Dam-Pool.Optimistic0.Elev.1DAY
Time of Simulation
Bokaa Dam-Pool.Optimistic0.Flow-IN.1DAY
Bokaa Dam-Pool.Optimistic0.Flow-OUT.1DAY


1,000
995
990
985
980
Elev (m)
3.0
2.0
1.0
0.0
Flow (cms)
2015
2020
2025
2030
2035
2040
2045
2050
Gaborone Dam-Flood Control.M.G Alt---0.Elev-ZONE.1DAY
Gaborone Dam-Conservation.M.G Alt---0.Elev-ZONE.1DAY
Gaborone Dam-Inactive.M.G Alt---0.Elev-ZONE.1DAY
Gaborone Dam-Pool.M.G Alt---0.Elev.1DAY
Time of Simulation
Gaborone Dam-Pool.M.G Alt---0.Flow-IN.1DAY
Gaborone Dam-Pool.M.G Alt---0.Flow-OUT.1DAY

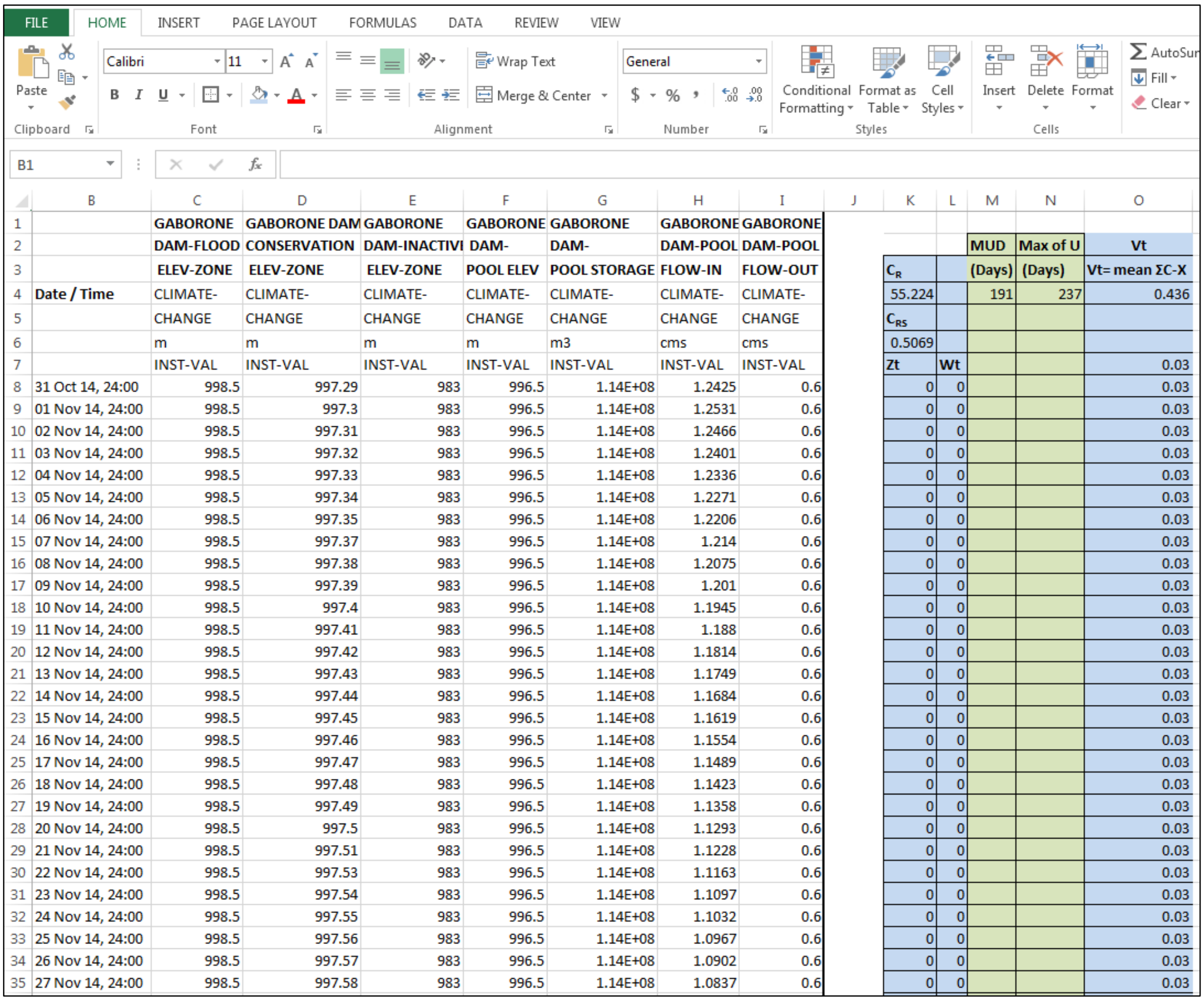

Elev (m)
1,136
1,134
1,132
1,130
1,128
Flow (cms)
0.16
0.12
0.08
0.04
0.00
2015
2020
2025
2030
2035
2040
2045
2050
Nnywane Dam-Flood Control.Season.Op-0.Elev-ZONE.1DAY
Nnywane Dam-Conservation.Season.Op-0.Elev-ZONE.1DAY
Nnywane Dam-Inactive.Season.Op-0.Elev-ZONE.1DAY
Nnywane Dam-Pool.Season.Op-0.Elev.1DAY
Time of Simulation
Nnywane Dam-Pool.Season.Op-0.Flow-IN.1DAY
Nnywane Dam-Pool.Season.Op-0.Flow-OUT.1DAY


Elev (m)
954
952
950
948
Flow (cms)
2.5
2.0
1.5
1.0
0.5
0.0
2015
2020
2025
2030
2035
2040
2045
2050
Bokaa Dam-Flood Control.Red.Abst.-0.Elev-ZONE.1DAY
Bokaa Dam-Conservation.Red.Abst.-0.Elev-ZONE.1DAY
Bokaa Dam-Inactive.Red.Abst.-0.Elev-ZONE.1DAY
Bokaa Dam-Pool.Red.Abst.-0.Elev.1DAY
Time of Simulation
Bokaa Dam-Pool.Red.Abst.-0.Flow-IN.1DAY
Bokaa Dam-Pool.Red.Abst.-0.Flow-OUT.1DAY


1,136
1,134
1,132
1,130
1,128
Elev (m)
0.16
0.12
0.08
0.04
0.00
Flow (cms)
2015
2016
2017
2018
2019
2020
Nnywane Dam-Flood Control.sed14-20200.Elev-ZONE.1DAY
Nnywane Dam-Conservation.sed14-20200.Elev-ZONE.1DAY
Nnywane Dam-Inactive.sed14-20200.Elev-ZONE.1DAY
Nnywane Dam-Pool.sed14-20200.Elev.1DAY
Time of Simulation
Nnywane Dam-Pool.sed14-20200.Flow-IN.1DAY
Nnywane Dam-Pool.sed14-20200.Flow-OUT.1DAY


1,136
1,134
1,132
1,130
1,128
Elev (m)
0.20
0.15
0.10
0.05
0.00
Flow (cms)
2015
2020
2025
2030
2035
2040
2045
2050
Nnywane Dam-Flood Control.Optimistic0.Elev-ZONE.1DAY
Nnywane Dam-Conservation.Optimistic0.Elev-ZONE.1DAY
Nnywane Dam-Inactive.Optimistic0.Elev-ZONE.1DAY
Nnywane Dam-Pool.Optimistic0.Elev.1DAY
Time of Simulation
Nnywane Dam-Pool.Optimistic0.Flow-IN.1DAY
Nnywane Dam-Pool.Optimistic0.Flow-OUT.1DAY

Result file exported to Excel and evaluation of RRVs on the right (blue and green table).



	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1		GABORONE	GABORONE DAM	GABORONE	GABORONE	GABORONE	GABORONE	GABORONE						
2		DAM-FLOOD	CONSERVATION	DAM-INACTIVI	DAM-	DAM-	DAM-POOL	DAM-POOL				MUD	Max of U	Vt
3		ELEV-ZONE	ELEV-ZONE	ELEV-ZONE	POOL ELEV	POOL STORAGE	FLOW-IN	FLOW-OUT		C_R		(Days)	(Days)	Vt= mean ΣC-X
4	Date / Time	CLIMATE-	CLIMATE-	CLIMATE-	CLIMATE-	CLIMATE-	CLIMATE-	CLIMATE-		55.224		191	237	0.436
5		CHANGE	CHANGE	CHANGE	CHANGE	CHANGE	CHANGE	CHANGE		C_{RS}				
6		m	m	m	m	m3	cms	cms		0.5069				
7		INST-VAL	INST-VAL	INST-VAL	INST-VAL	INST-VAL	INST-VAL	INST-VAL		Zt	Wt			0.03
8	31 Oct 14, 24:00	998.5	997.29	983	996.5	1.14E+08	1.2425	0.6		0	0			0.03
9	01 Nov 14, 24:00	998.5	997.3	983	996.5	1.14E+08	1.2531	0.6		0	0			0.03
10	02 Nov 14, 24:00	998.5	997.31	983	996.5	1.14E+08	1.2466	0.6		0	0			0.03
11	03 Nov 14, 24:00	998.5	997.32	983	996.5	1.14E+08	1.2401	0.6		0	0			0.03
12	04 Nov 14, 24:00	998.5	997.33	983	996.5	1.14E+08	1.2336	0.6		0	0			0.03
13	05 Nov 14, 24:00	998.5	997.34	983	996.5	1.14E+08	1.2271	0.6		0	0			0.03
14	06 Nov 14, 24:00	998.5	997.35	983	996.5	1.14E+08	1.2206	0.6		0	0			0.03
15	07 Nov 14, 24:00	998.5	997.37	983	996.5	1.14E+08	1.214	0.6		0	0			0.03
16	08 Nov 14, 24:00	998.5	997.38	983	996.5	1.14E+08	1.2075	0.6		0	0			0.03
17	09 Nov 14, 24:00	998.5	997.39	983	996.5	1.14E+08	1.201	0.6		0	0			0.03
18	10 Nov 14, 24:00	998.5	997.4	983	996.5	1.14E+08	1.1945	0.6		0	0			0.03
19	11 Nov 14, 24:00	998.5	997.41	983	996.5	1.14E+08	1.188	0.6		0	0			0.03
20	12 Nov 14, 24:00	998.5	997.42	983	996.5	1.14E+08	1.1814	0.6		0	0			0.03
21	13 Nov 14, 24:00	998.5	997.43	983	996.5	1.14E+08	1.1749	0.6		0	0			0.03
22	14 Nov 14, 24:00	998.5	997.44	983	996.5	1.14E+08	1.1684	0.6		0	0			0.03
23	15 Nov 14, 24:00	998.5	997.45	983	996.5	1.14E+08	1.1619	0.6		0	0			0.03
24	16 Nov 14, 24:00	998.5	997.46	983	996.5	1.14E+08	1.1554	0.6		0	0			0.03
25	17 Nov 14, 24:00	998.5	997.47	983	996.5	1.14E+08	1.1489	0.6		0	0			0.03
26	18 Nov 14, 24:00	998.5	997.48	983	996.5	1.14E+08	1.1423	0.6		0	0			0.03
27	19 Nov 14, 24:00	998.5	997.49	983	996.5	1.14E+08	1.1358	0.6		0	0			0.03
28	20 Nov 14, 24:00	998.5	997.5	983	996.5	1.14E+08	1.1293	0.6		0	0			0.03
29	21 Nov 14, 24:00	998.5	997.51	983	996.5	1.14E+08	1.1228	0.6		0	0			0.03
30	22 Nov 14, 24:00	998.5	997.53	983	996.5	1.14E+08	1.1163	0.6		0	0			0.03
31	23 Nov 14, 24:00	998.5	997.54	983	996.5	1.14E+08	1.1097	0.6		0	0			0.03
32	24 Nov 14, 24:00	998.5	997.55	983	996.5	1.14E+08	1.1032	0.6		0	0			0.03
33	25 Nov 14, 24:00	998.5	997.56	983	996.5	1.14E+08	1.0967	0.6		0	0			0.03
34	26 Nov 14, 24:00	998.5	997.57	983	996.5	1.14E+08	1.0902	0.6		0	0			0.03
35	27 Nov 14, 24:00	998.5	997.58	983	996.5	1.14E+08	1.0837	0.6		0	0			0.03

APPENDIX C- EVAPORATION CASE STUDY