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Presented by

Gontle Thuto RANKGOMO

TITLE: ASSESSING THE POTENTIAL OF ARTIFICIAL GROUNDWATER RECHARGE: CASE STUDY OF PALLA ROAD WELLFIELDS, BOTSWANA

Defended on 08/11/2020 Before the Following Committee:

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DECLARATION

I, Gontle Thuto RANKGOMO declare that the work contained herein is an original report of my research that has been composed to the best of my acquired knowledge. Due references have been provided for all supporting materials that were used in accordance to academic rules and ethics. I also declare that this thesis has not been submitted for any other degree or professional qualification.

Signature: Date: 14/10/2020

CERTIFICATION

I undersigned, Professor John M. Gathenya a short-term lecturer at the Pan African University Institute of Water and Energy Sciences including Climate Change (PAUWES) and Professor of Hydrology, Climate Services and Environmental Services at Jomo Kenyatta University of Agriculture & Technology, School of Biosystems and Environmental Engineering-Nairobi, Kenya certify that the thesis entitled Assessing the potential of artificial groundwater recharge in Botswana for the degree of Masters in Water Engineering (MSc) by Ms. Gontle Thuto RANKGOMO, is a record of research work carried out by her under my guidance and supervision.

Supervisor

Signature: Date: 14/10/2020

ABSTRACT

A feasibility study on the assessment of managed aquifer recharge in the Palla Road wellfields which are situated in the Bonwapitse and Serorome Catchment area, Botswana was conducted. Botswana is categorized with a semi-arid climate and most of the country's anthropogenic activities are highly dependent on groundwater which can lead to over abstraction and thus depleting the aquifers. Many countries, including Botswana need to explore several water resources in order to augment the available surface water resources and thus overcome the imbalance between water supply and water demand; one of the alternatives being Managed aquifer recharge (MAR). This research is based on spatial observations using the soil water balance and QSWAT + models to identify and assess the potential areas suitable for managed aquifer recharge in Palla Road wellfields. The following datasets were used as input files for the models: land cover, flow direction, hydrologic soil group, the soil available water capacity and climate data. The models were ran using climate data for a period of eleven years (2008-2019) respectively and the groundwater recharge was found to be prominent in three (3) years viz; 2008, 2012 and 2016 respectively in the soil water balance model. The suitable groundwater recharge zones were found to be in the central and south eastern region of the Bonwapitse and Serorome catchment area for both models. High annual groundwater recharge values, high precipitation and low values of evapotranspiration were observed in the region when using the QSWAT + model. MAR has been found to increase groundwater recharge and reduces the deficit in water supply. Therefore, implementing MAR in Botswana serves as a basis to diversify and improve the current available water resources.

Keywords: managed aquifer recharge, groundwater, soil water balance model, QSWAT + model, Botswana

RÉSUMÉ

Une étude de faisabilité sur l'évaluation de la gestion de la recharge de l'aquifère dans les sites de captage de la route Palla, situés dans le bassin versant de Bonwapitse et Serorome, au Botswana, a été réalisée. Le Botswana est caractérisé par un climat semi-aride et la plupart des activités anthropiques du pays sont fortement dépendantes des eaux souterraines, ce qui peut conduire à une surexploitation et donc à l'épuisement des aquifères. Ainsi, de nombreux pays, dont le Botswana, ont besoin d'explorer plusieurs ressources en eau afin de rétablir l'équilibre entre l'offre et la demande en eau ; l'une des options est la gestion de la recharge des aquifères (**MAR**). Cette étude est basée sur des observations spatiales utilisant le bilan hydrique du sol et les modèles QSWAT + afin d'identifier et d'évaluer les zones potentielles propices à la gestion de la recharge des aquifères dans les champs de puits du chemin Palla. Les ensembles de données suivants ont été utilisés comme fichiers d'entrée pour les modèles : l'occupation des sols, la direction de l'écoulement, le groupe hydrologique et la capacité en eau disponible du sol et les données climatiques. Les modèles ont fonctionné pendant une période de onze ans **(2008-2019)** respectivement et la recharge des eaux souterraines s'est avérée proéminente les années **2008**, **2012** et **2016** dans le modèle de bilan hydrique du sol. Les zones de recharge des eaux souterraines appropriées se trouvaient dans la région du centre et du sud-est du bassin versant de Bonwapitse et Serorome pour les deux modèles. Les valeurs annuelles élevées de recharge de l'aquifère, les fortes précipitations et les faibles valeurs d'évapotranspiration observées dans la région lors de l'utilisation du modèle QSWAT +. Il a été constaté que la **MAR** augmente la recharge des eaux souterraines et réduit le déficit d'approvisionnement en eau. Par conséquent, la mise en œuvre de la **MAR** au Botswana sert aujourd'hui de base pour la diversification et l'augmentation des ressources en eau actuellement disponibles.

<u>Mots clés</u> : gestion de la recharge des aquifères, eaux souterraines, modèle de bilan hydrique du sol, QSWAT + modèle, Botswana

Table of Contents

DEDICATION

I dedicate this thesis to my mother, Motswamasimo Rankgomo.

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In recognition to all the contribution provided to the attainment of this research. I would firstly like to express my sincere gratitude to the African Union Commission (AU) through the Pan African University (PAU) scholarships, for providing a research grant for all the proceedings of the thesis project.

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ABBREVIATIONS AND ACRONYMS

Acronym	Description
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
AR	Artificial Groundwater Recharge
ASCII	American Standard Code for Information Interchange
ASR	Aquifer Storage Recovery
ASTR	Aquifer Transfer and Storage
AWC	Available Water Capacity
BH	Borehole
BOBS	Botswana Bureau of Standards
DEM	Digital Elevation Model
DWA	The Department of Water Affairs
FAO	Food and Agriculture Organization of the United Nations
GoB	Government of Botswana
GIS	Geographical Information Systems
GWP	Global Water Partnership
HSG	Hydrologic Soil Group
IAH	International Association of Hydrogeologists
IGRAC	International Groundwater Resources Assessment Centre
NASA	National Aeronautics and Space Administration
NDP	National Development Plan
SADC	Southern African Development Community
SADC-GWI	Southern African Development Community-Groundwater Management Institute
SDGs	Sustainable Development Goals
SRTM	The NASA Shuttle Radar Topographic Mission
SWAT	Soil & Water Assessment Tool
MAR	Managed Aquifer Recharge
Mm^3	Million Cubic Meters
NSC	North South Carrier
NWAMP	National Water Master Plan
WHO	World Health Organization
QGIS	Quantum GIS
UN	United Nations
UNDP	United Nations Development Programme
USGS	United States Geological Survey

List of Tables

List of Figures

CHAPTER 1

INTRODUCTION

"Aquifer depletion is a largely invisible threat but that does not make it any less real" Lester R. Brown. Globally, water demand has been increasing over the past few decades due to population increase as well as the increasing water demand per capita. The majority of the worlds freshwater is found underground, it attributes to about 30% of the supply NGWA (2020). Groundwater also provides drinking water to about 50% of the global population and accounts to 43% of all the water that is used for irrigation. Moreover, 2.5 billion people depend on groundwater solely for their basic human needs Hassan (2018). Furthermore, groundwater plays an essential role in ensuring the attainment and implementation of the United Nations Sustainable Development Goals (SDGs). Conti (2016) affirms that groundwater is the most abstracted raw material on earth. However, globally groundwater resources are limited and they are declining in terms of quality and quantity due to contamination and climate change impacts Singh et al. (2019).

Groundwater use differs depending on its location; the country and region depending on the climate, water availability, financial resources and socio-economic development of that locality Igor (2004). Crawford (2016) categorizes Botswana as a semi-arid country located in Southern Africa with most of the country (about 70%) covered by the Kalahari Desert, with an annual rainfall average rainfall of less than 250mm. As a result, this makes the country to be classified as water stressed. Igor (2004) explained that over two-thirds of Botswana's rural and urban population, industry and livestock water demand is satisfied by using groundwater resources.

From the Dublin Rio Principles water is a precious natural resource that is vital for life, development and the environment. In addition to that, Linhe et al. (2020) explained that the potential evapotranspiration rate in Botswana at all times of the year exceeds the total rainfall due to the semi-arid climate. The World Bank WAVES (2014) document on Botswana's water accounting explains that the country's water usage had increased from 150 million cubic meters (Mm^3) annually in 1993 to slightly under 200 Mm^3 per in 2010/2011 due to increased water efficiency as well as a change in the structure of the economy. Moreover, Byakatonda et al. (2019) declare Botswana as a water scarce country with most national rivers mainly depending on the local climate despite that, there is continual increase in water demand. According to Akinyemi (2019) the intensity and frequency of drought over the whole of Botswana, particularly in the south-west and east is projected to increase. Furthermore, increased higher warming levels leads to increased evaporation that may impact the water availability in the dams causing their water levels to reduce. This has brought about 70% of evaporation losses of the drinking water in its surface dams.

The whole world is running out of water that is stored in aquifers. The rate of groundwater recharge differs depending on different parameters that is, the characteristics of the aquifer. Groundwater recharge is part of the basic hydrological cycle through precipitation Akter (2020). According to Rashid (2003) semi-arid countries such as Australia, Namibia and Botswana have put more emphasis on surface water resources although they depend mostly on groundwater resources however, gradually they are gradually recognizing groundwater. Moreover, Caroline (2017) enlightened that continual increase in population as well as climate variability experienced in Botswana has led to a great use of groundwater thus putting greater stress than ever before on groundwater resources. In addition to that, water scarcity is a major challenge for the development of Botswana therefore artificial aquifer recharge is amongst the most effective ways to store groundwater Caroline (2017).

Patel et al. (2020) consider India as the world's largest user extractor of groundwater for irrigation and domestic purposes which poses a threat in many parts of the country, particularly in the semi-arid and arid regions. In arid and semi-arid regions worldwide groundwater recharge from the views of Xu and Beekman (2018) findings is a critical process for the provision of renewable fresh water resources. Lindhe et al (2014) consider artificial groundwater recharge (AR) as an efficient technique that can be used to increase the available water quantities for water supply as well as to improve the water quality. Also, it is noted that water scarcity accentuated by urban growth, especially in semi-arid and arid regions has resulted in a growing interest in AR as a basis for water supply by collection of surface water runoff for infiltration to avoid evaporation losses.

According to Wada (2013), internationally groundwater resources have received less attention when compared to internationally shared transboundary rivers basins however they have played an important role in sustaining human needs through agriculture and the ecosystem. Water is a precious natural resource that is vital for life, development and the environment, Africa Water Vision 2025. From the Botswana national water policy (2012) groundwater is estimated to account for more than 80% of the domestic water that is supplied in Botswana. 100 km^3 of this groundwater is estimated to be extractable however, due to the hydro-climatic characteristics and geologic nature of the country only 1% of this amount is rechargeable by rainfall.

From the International Association of Hydrogeologists (IAH) website https://recharge.iah.org/ managed aquifer recharge, also called groundwater replenishment, water banking and artificial recharge is defined as the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit. According to Maliva and Missimer (2012) MAR can be used to improve water security and resilience to droughts. However, the selection of the most suitable locations is not a simple task as there are several aspects that affect the rate of groundwater recharge and have to be considered. These are inclusive of landscape characteristics, soil and aquifer properties and the availability of surface water.

Groundwater is relatively cleaner than surface water resources in terms of water quality therefore it is imperative to do an investigation of it. In addition to that, Maliva (2020) put an emphasis that groundwater quality is of good quality that is generally better than the available surface water supplies. Water Resources Institute (WRI) projections by Luo et al. (2015) indicated that Botswana water stress by the year 2040 will be high. Moreover, Botswana is facing water security challenges that have put pressure on the available water resources. Therefore, MAR serves as one of the key initiatives to improve the implemented water supply strategies. The research aims to do a feasibility study on water storage assessment and to identify aquifers that have the potential to store artificial groundwater recharge, this is important for present and future water demands and also to ensure the protection of groundwater, thus prudent water resource management will be achieved. This has led to artificial groundwater recharge to be considered by Linhe et al. (2020) among other alternatives to better water stress and its adverse effects in Botswana. The Soil Water Balance and QSWAT + model will be used for the analysis of the Palla Road wellfields, potential for artificial groundwater recharge.

1.1 Statement of the Problem

Botswana is a southern Africa country, categorized with a semi-arid climate. Also, Botswana has most of its topography relatively described as flat, with some parts of the landscape having ridges and valleys Lindhe (2014). The Botswana's water accounting (2015) report indicates that the country's water resources are unevenly distributed throughout the country. Due to this, the high demand centres (south-eastern part) have limited water resource whereas the water rich areas (Chobe and Ngamiland Districts-northern part) have low demand. Moreover, this lead to a decentralized approach to water management thus, linking the regions through water transfer schemes- The North South Carrier (NSC) which has undergone phase I and II as a means of improving the water supply particularly in Gaborone because of the drying up of the Gaborone dam.

Most of the anthropogenic activities in the country are highly dependent on groundwater resources, which is accounted to be over two-thirds (2/3). Historically, the traditional way of storing water has been through dams however, over the years good sites for dam establishment have been regarded to be scanty by the United Nations Development Programme UNDP (2011). Water shortage has increasingly been an initiative of concern for the Government of Botswana through the National Development Plan 11 (NDP 11) have a plan to include water conservation and demand management under the water infrastructure development. However results from Lindhe et al. (2014) show that the current supply system, water demand projected from the year (2013- 2035) shows that there will be water shortage.

From FAO (2016) it is noted that in order to supplement surface water supply the conjunctive use of groundwater is commonly practiced in many parts of the world. Although, the integration of it is incidental through spontaneous actions rather than a robust planned approach and Botswana is no exception of this. Hui Qian & Jianhuua Wu (2018) view groundwater and surface water management are essential for societal development. Due to this, several water resources need to be explored in order to augment the available surface resources and thus overcome the imbalance between water supply and water demand in a changing environment Sing et al. (2017). This imbalance is increasing in many parts of the world. Managed aquifer recharge (MAR) therefore serves as basis for this research.

1.2 OBJECTIVES

1.3 MAIN OBJECTIVE

To identify and assess potential areas suitable for managed aquifer recharge for storage in the Palla Road wellfields.

1.3.1 SPECIFIC OBJECTIVES

- To obtain the hydrological characteristics in the Palla Road aquifers (precipitation, evaporation).
- To evaluate managed aquifer recharge potential based on the hydrological characteristics of Palla Road aquifers.
- To identify suitable areas for aquifer recharge in Palla Road.
- To assess the variability of groundwater recharge over time in Palla Road wellfields.

1.4 RESEARCH QUESTIONS

- What is the current situation of Managed Aquifer Recharge in Botswana?
- How do other countries use Managed aquifer recharge?
- What type of artificial recharge method is mostly preferred?

CHAPTER TWO

LITERATURE REVIEW

2.1 BOTSWANA SURFACE HYDROLOGY

"Water is the medium through which human will experience the most impacts of climate change" (Sadoff C. & Muller M. 2009). Also, from the Botswana National Development Plan (NDP) 11 (2017), it is stated Botswana is restricted to ephemeral and perennial rivers. All rivers originating from the country are ephemeral and there are two perennial rivers which are the Okavango and Linyanti/ Chobe Rivers are situated in the Northern part of the country, both rivers have their sources outside the country. Therefore, the utilization of the resources is based on an agreement with other riparian states. Moreover, in total, six drainage basins are used for the design and implementation of water projects such as dams. It is also noted that during the NDP 10 Botswana experienced a major drought, therefore the Gaborone Dam which supplies the capital city (Gaborone) and towns in the outskirts had dried up thus requiring alternative water resources.

The North South Water Carrier (NSC) Pipeline which is described as an inter-basin water transfer scheme by New Partnership for African Development NEPAD (2013), that transfers water from the north-eastern part of the country to the southern part (mainly Gaborone) was then implemented. NSC pipeline was implemented in two phases, phase one and phase two in order to augment water supply in Gaborone where there is high demand of water.

2.2 BOTSWANA GROUNDWATER RESOURCES

Historically, Botswana has relied mostly on groundwater resources, Botswana Integrated Water Resources Management & Water Efficiency Plan (2013). Moreover, the Botswana National Water Master Plan (NWMP) (1992) states that traditionally groundwater has been the main source of water supply for Botswana with the exception of the urban centers of Botswana viz. Gaborone, Lobatse, Francistown and Selibe Phikwe which are supplied from surface water systems. The remaining population, mining industry and the cattle industry are almost all totally reliant upon groundwater. From The World Bank document (2017), it was denoted that groundwater accounted for about three quarters (¾) of the total water requirement in the country, particularly in the western part of the country.

Initially, the implementation of the Palla Road wellfields, according to the Botswana National Water Master Plan (2006) was to supply Mahalapye. However, in 2001 the wellfields were connected to the North-South Carrier (NSC) with an abstraction rate of about 5 000 m^3/day. Following which, the wellfield has been used intermittently to supply any shortage in the NSC.

2.3 AQUIFERS

According to Salako & Adepelumi (2017), an aquifer is described as any underground layer of water bearing rock or geological formation that yields sufficient groundwater for wells and or springs. Furthermore, the authors continue to explain that in geological terms an aquifer is permeable that is, water can easily move through to streams and wells. Also, aquifers can be classified into two broad types/ groups the confined and unconfined aquifer. However, Shekhar (2017) explained that there are four types of aquifers which are mainly: unconfined, confined, semi-confined and perched aquifer.

The Palla Road wellfields are characterized with a variety of aquifers inclusive of artesian aquifers. The water levels of randomly selected monitoring boreholes in Palla Road wellfields are shown in the results section, they range from about 7 to 70m which shows the variability of the aquifers which are found there this information was retrieved from Department of Water and Sanitation, Botswana formally known as Department of Water Affairs. Moreover, the Palla Road borehole yields are between 5 – 100 m^3/hr, with an average of 60 m^3/hr. Moreover, they have a transmissivity than ranges from 3-900 m^2/day, Botswana National Water Master Plan (2006). Transmissivity T, is a measure of how water moves in an aquifer, aquifers having $T \geq 0.015$ m^2/s are described as good aquifers (https://www.observationalhydrology.com/groundwater-.html).

2.4 PREVIOUS GROUNDWATER INVESTIGATIONS & GEOLOGY IN PALLA ROAD

Water resources management and evaluation in Palla Road wellfields has been studied for the past three decades following the borehole drilling in 1987, represented in table 2.1.

Project	Area	Client/ Consultant	Year	Comments
Palla Road Wellfield Development	Palla Road	DGS and DWA; in house	1987	Geophysical surveys; Palla Road Wellfield production and observation. Boreholes drilled and tested
Palla Road Groundwater Exploration Project Phase 1	Palla Road and Chepete	DGS/ WCS	1994	Geophysical surveys; drilling (43) boreholes; test pumping; recharge studies; numerical modelling; resources evaluation
Palla Road and Khurutse Groundwater Resources Investigation Phase 2	Chepete and Palla Road	DWA/ GCS	1999	Geophysical surveys; drilling (14 boreholes); test pumping; recharge studies; numerical modelling; resources evaluation

Kudumatse Groundwater Resources Investigation	Kudumatse	CIC/WCS [Mmamabula Energy Project]	2007	Bankable Feasibility Study; regional and ground geophysics; drilling (46) boreholes; test pumping, geophysical logging; recharge studies; numerical modelling
Bonwapitse Wellfield Development	Kudumatse and Bonwapitse	CIC/WCS [Mmamabula Energy Project]	2008	
Palla Road Model Post-Audit	Palla Road: sub regional	DWA/WRC	2013	

Table 2.1 Representing Palla Road Groundwater Investigations

The Ntane Sandstone shown in figure 2.1 below, retrieved from the Department of Water and Sanitation (2020) inception report is found to be the dominant geological formation found in Palla Road.

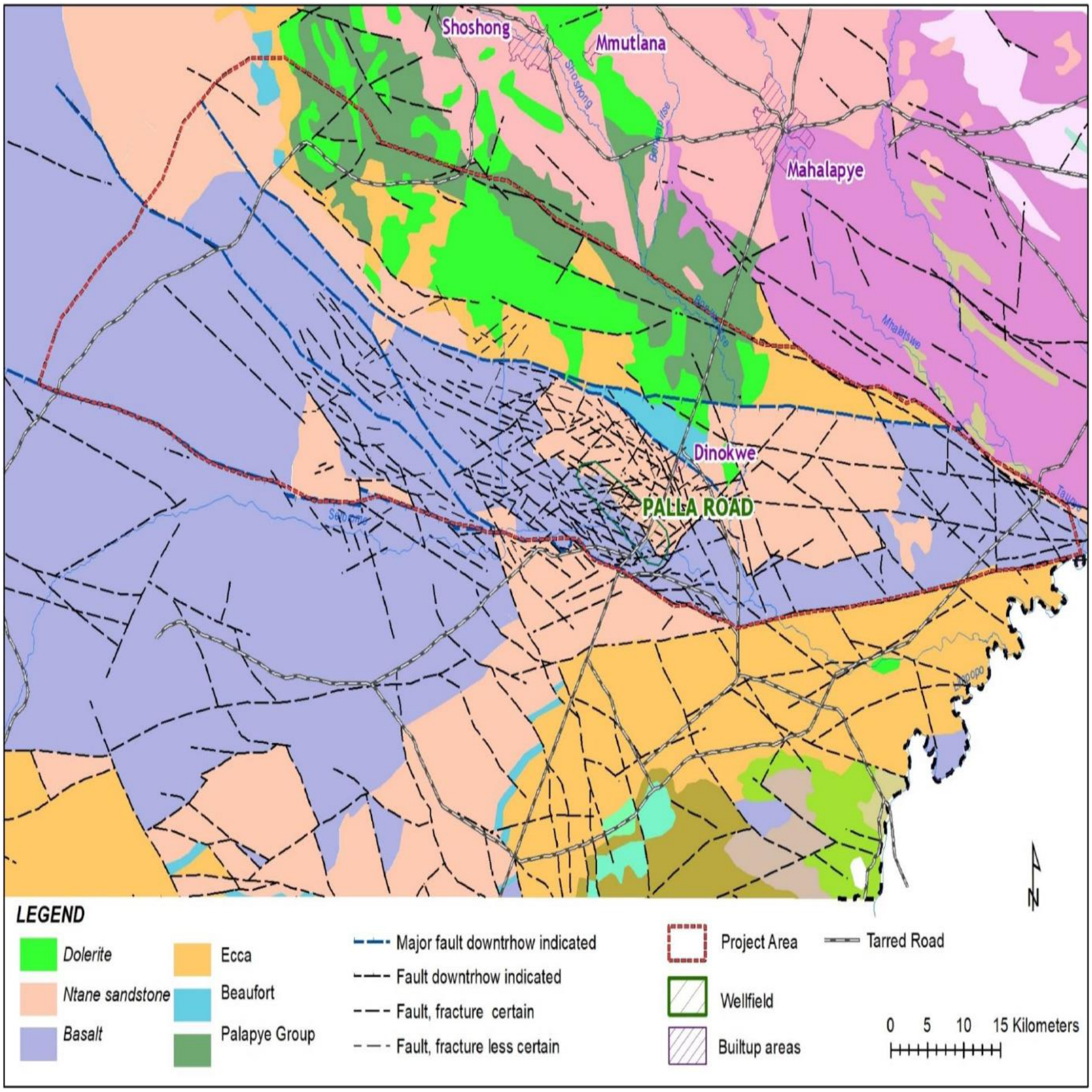

Figure 2.1 Representing Geology around Palla Road

2.5 GENERAL OVERVIEW OF ARTIFICIAL AQUIFER RECHARGE

A research carried out by Senthilkumar et al (2019) explains that globally India is the biggest user of groundwater. Moreover, groundwater accounts to more than 85% of the drinking water and more than 60% is used for agricultural activities. Artificial recharge and rainwater harvesting were considered as the possible solutions to address the issues. Furthermore the writers consider geospatial technology to have an advantage of covering vast regions of spatial, spectral and temporal availability of Earth surface. Moreover, the analysis is in a short period of time even to the most inaccessible areas for their identification as to whether they are suitable or not for artificial recharge.

Other authors Albaladejo-García and Prats-Rico (2017) justified that currently over abstraction of aquifers is regarded as one of the main causes of environmental problems and artificial groundwater recharge can lessen the adverse effects of this. In addition, from the findings of Da Costa et al. (2019) they concluded that seasonal storage of surface water in areas that have a low recharge potential can be inducted by water managers into water management strategies to improve the current water storage availabilities.

2.6 OVERVIEW OF MANAGED AQUIFER RECHARGE IN AFRICA

The use of managed aquifer recharges is increasing globally although some countries and regions have more experience than others do. MAR is not a new concept in Africa, Murray (2009). A review of the implementation of MAR by Ebrahim et al. (2020) states that globally MAR started in the 1960s and was introduced Africa in 1965 where its implementation started and is continuing to increase as time passes. This study conducted by Ebrahim et al. (2020) continues to show that MAR is concentrated in nine African countries viz., South Africa, Tunisia, Kenya, Algeria, Egypt, Nigeria, Namibia, Morocco and Ethiopia. South Africa being the country with most cases.

2.7 Examples of Case Studies in Africa

2.7.1 SOUTH AFRICA

From Ebrahim et al. (2020) South Africa is a country with the most MAR cases in Africa. MAR using treated wastewater commenced in the 1970s from https://www.artificialrecharge.co.za/casestudies/atlantis.pdf in Polokwane. Murray, R. (2009) described MAR in Atlantis near Capetown to have been operational in the past two decades were farmers built numerous earth dams for the enhancement of groundwater recharge.

2.7.2 WINDHOEK, NAMIBIA

Mupambwa et al. (2019) describes Namibia as the driest country in sub-Saharan Africa. Namibia has similar water resource problems as Botswana and has its only major perennial surface water resources in the far north BNWMP (1992). Moreover, Dupisani, P. (2011) explained that Windhoek is renowned for being the first city worldwide to operate a wastewater recycling plant for direct, portable water reuse. Moreover, Scott et al. (2018) stated that water shortages in Windhoek were cause by droughts between the years of 2013-2017 due to different factors including low precipitation in consecutive years. As a result of research and decision making

Windhoek identified MAR as the best solution to improve the water supply security by inserting water into the aquifer for storage. Murray et al. (2018) study elucidated that by the year 2050 the water demand in the city of Windhoek alone is expected to double. Furthermore, a feasibility study on MAR in a fractured quartzite aquifer proved that it serves as a water supply security option and will also play an essential role in the sustainable development as well as the socio-economic health of Windhoek. From the findings of Lewis E. et al. (2019) the Windhoek Aquifer is recharged with dual water sources viz. surface water and reclaimed water. A ratio of 3: 1 is used for the injection boreholes, where 75% of the water is from a three-dam system and 25% comes from reclaimed water both these water sources are treated to drinking water quality standards to prevent ground water contamination and to reduce recharge borehole clogging.

2.8 METHODS OF MANAGED AQUIFER RECHARGE

Sustainable groundwater using Managed Aquifer recharge can be approached using different methods depending on the variables and characteristics of the aquifer in addition to that, through an evaluation of cost benefit ratios. These aquifer recharge techniques can either be done through the surface or underground USGS (2020) https://www.usgs.gov/mission-areas/water-resources/science/artificial-groundwater-recharge?qt-science_center_objects=0#qt-science_center_objects. From the International Groundwater Resources Assessment Centre website (IGRAC) https://www.un-igrac.org/areas-expertise/managed-aquifer-recharge-mar it is stated that this serves as a main advantage for using MAR technology as it is flexible and can be used for variable scales and purposes.

According to Dillon (2005) al there are a number of methods used for managed aquifer recharge the most commonly used ones, viz., riverbank infiltration, borehole recharge, rainwater harvesting, basin infiltration and the recent trends have been observed on the use of non-conventional sources of water such as the use of reclaimed wastewater and storm water. The various methods have been illustrated in figure 2.2 and described in table 2.2 below.

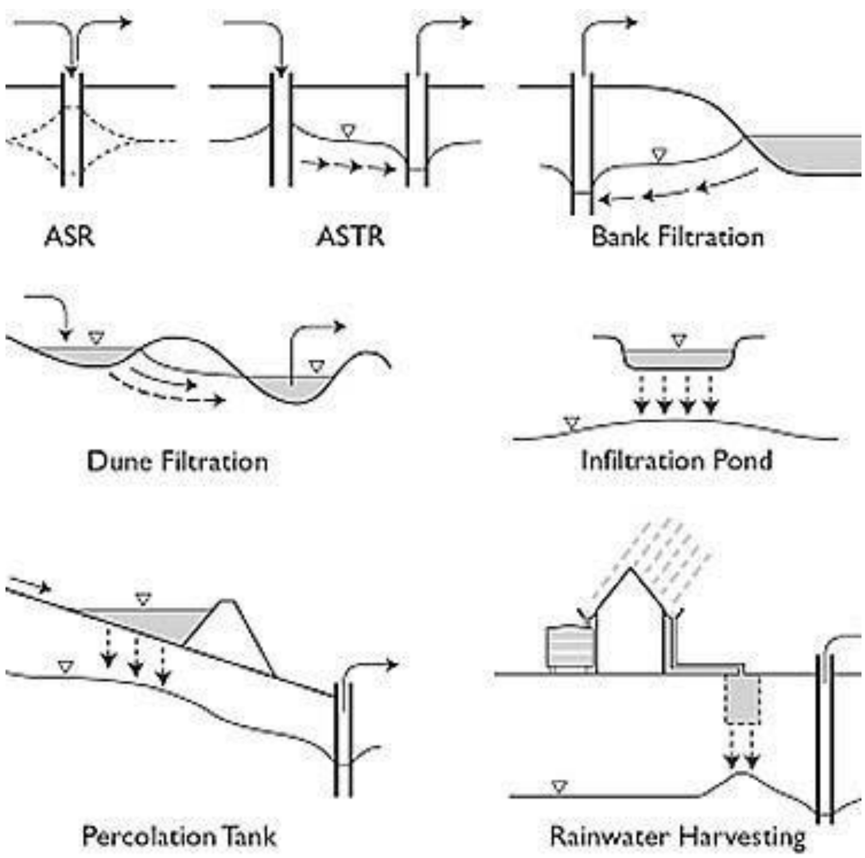

Figure 2.2 Illustration of the different schematic methods of Managed Aquifer Recharge

Most common MAR techniques Gale and Dillon (2005).ASR Aquifer Storage Recovery ASTR Aquifer Transfer and Storage

Table 2.2 A brief description of different schematic methods of MAR was derived from the Southern Africa Development Community Groundwater Management Institute (SADC-GMI) booklet by Murray, R. (2017)

Managed Aquifer Recharge Method	Description
Aquifer Storage and Recovery (ASR)	The Injection of Water into a borehole for storage and recovery from the same borehole. Suitable in both confined and unconfined aquifers.
Aquifer Storage Transfer & Recovery (ASTR)	The Injection of Water into a borehole for storage and recovery from a different borehole, generally to provide additional water treatment. Suitable in both confined and unconfined aquifers.
Infiltration Pond	Ponds constructed usually off-stream where surface water is diverted and allowed to infiltrate (generally through an unsaturated zone to the underlying unconfined aquifer). Suitable in unconfined aquifers.
Dune Filtration	The infiltration of water into a sand dune system and extraction from boreholes, wells or ponds at a lower elevation for water quality improvement and to balance supply and demand. Suitable in unconfined aquifers.
Local Rainwater Harvesting	Surface water runoff from roofs or localized paving is diverted into a borehole, well or a caisson filled with sand or gravel and allowed to percolate to the water table where

	it is collected by pumping from a well or borehole. Suitable in unconfined aquifers.
Sand Dam	Built in ephemeral streams in arid areas on low permeability lithology. They trap sediment when flow occurs and following successive floods, the sand dam is raised to create an "aquifer". Vertical boreholes or horizontal outlets to the face of the dam can be used to extract water in dry seasons

2.9 FACTORS TO CONSIDER FOR MANAGED AQUIFER RECHARGE

2.9.1 Water Quantity and Quality

In general having a variety of water sources to use is paramount for all the methods of MAR. Therefore, before selecting a source it is important to look at the water quality and quantity components of the water in order to determine its suitability for the method of aquifer recharge. Also, as per the Australasian Institute of Mining and Metallurgy website posted in October 2017 from https://www.ausimmbulletin.com/feature/managed-aquifer-recharge-mine-water-management/ the recharge water for MAR in terms of quality should be similar to, or better than the receiving water quality. The water quality standards per country and the global standards are then used to determine the quality appropriateness. For drinking water purposes in Botswana, the Botswana Bureau of Standards (BOBS) and the World Health Organization (WHO) standards are used to specify the acceptable quality. Furthermore, the source of water determines its recharge capacity based on its quantity.

2.9.2 Infiltration

Groundwater recharge is naturally supplied by the hydrologic cycle, shown in figure 2.3 below. The cycle describes the continuous movement of water on above and below the Earth's surface (www.usgs.gov). Masoud and Bahai (2019) explained that infiltration is part of the hydrologic cycle that links surface runoff to groundwater recharge. The authors continue to explain that proper understanding of the movement of the water along the unsaturated zone is a vital requirement for water conservation strategies. Furthermore, Agostinetto et al. (2013) consider infiltration as an effective contribution to groundwater recharge.

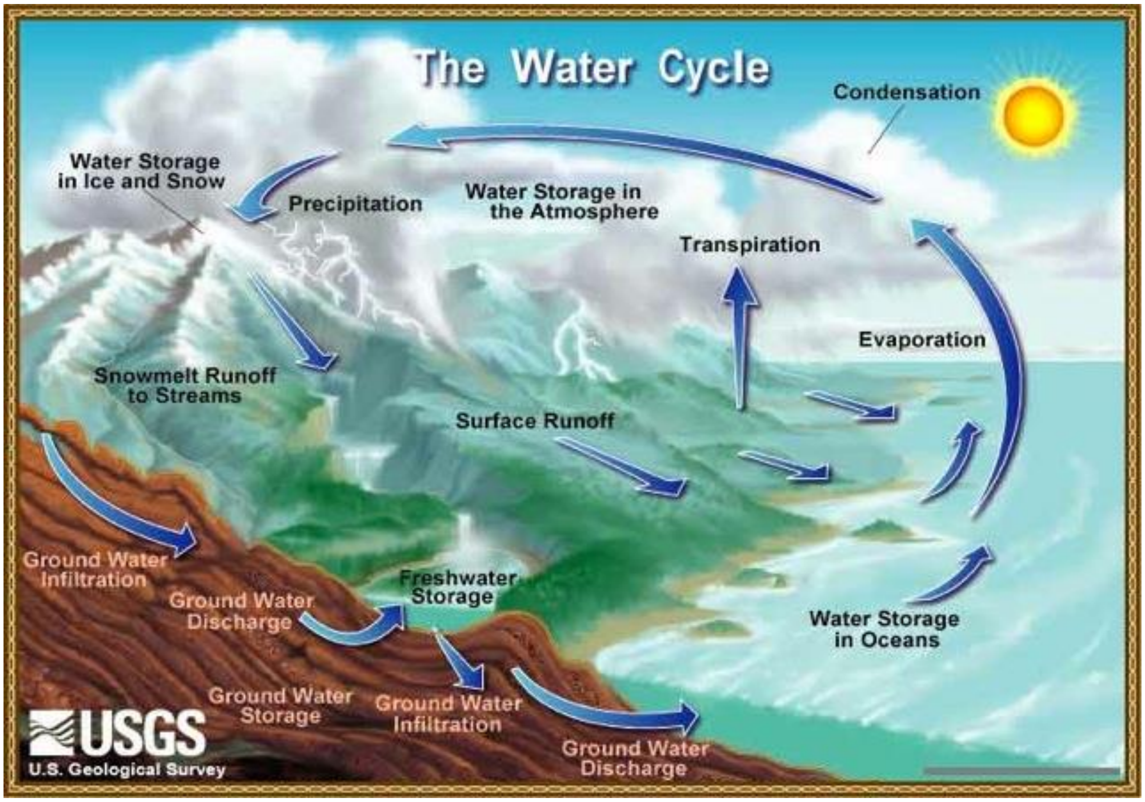

Figure 2.3 Representation of the Hydrologic cycle

Source: https://www.usgs.gov/special-topic/water-science-school/science/water-cycle

The ground serves as a storage sink for water, the rate of infiltration is determined by the environmental characteristics and the water body characteristics. Water budget description in Kansoh (2020) denotes that:

Change in storage = Inflow- Outflow (1)

$\triangle S = P + R + Q_i - G - E$ (2)

Where; $\triangle S$*= change in storage*

P= precipitation

R= surface runoff

Q_i=*drainage water*

G=groundwater

E=evaporation

2.10 MANAGED AQUIFER RECHARGE IN BOTSWANA

According to The Botswana Government National Water Master Plan (2006) three recharge projects have been carried out in Botswana, all along the Shashe River. The Shashe River is located in the Northern part of Botswana. The first project to be carried out was in 1987, with the objective to test the feasibility of replacing the 60m^3/hr abstracted from the Lower Shashe wellfield at that time. The results obtained from the study indicated that water levels rose two weeks after infiltration.

The second MAR project was conducted in 1989 where a 30*30 ridge and furrow type spreading basin and four direct injection wells. The spreading basin data is not available however, the injection wells failed as a result of a combination of intersecting clay and clogging of screens by organic matter present in the recharge water.

The third MAR study involved the construction of a 20*20 spreading basin. Following which, two tests were carried out to assess the basin design and to monitoring borehole network over a three day duration. Following which a seven day injection test was done. However a two year pilot scheme was recommended thereafter before implementing to a full scale project.

2.11 CASE STUDIES OF MANAGED AQUIFER RECHARGE

2.11.1 Jordan

Jordan, a semi-arid country which is located in the Middle East and North Africa (MENA) region. The Mena Region is the most water stressed region in the world and water resources are highly exploited Milutinović, S. (2019).Gradually, MAR is regarded as a paramount water-saving measure in order to combat the impacts of climate change on it groundwater reserves Salameh et al. (2019). According to Al (2020) Jordan is one of the most water deprived countries facing a decline in its groundwater storage due to over pumping, and by 2022 some of the wells in Amman Zarq Basin are expected to dry.

2.11.2 United States of America (USA)

Alley (2018) noted that for over a century MAR projects have been providing benefits to the USA viz., abating sea water intrusion, flood peak mitigation, preserving wetlands to mention a few. An overview of Managed Aquifer recharge in Mexico and its legal framework conducted by Cruz-Ayala et al. (2020) explain that Mexico relies on groundwater and the most important aquifers are allocated for agricultural purposes and human consumption. In general, the MAR projects are found in the arid regions which have a short rainy season and in the oceanic region that experiences rainfall all year round at a mean annual precipitation of 600mm. Bonilla Valverde et al. (2018), reported that 10 out of 33 countries in Latin America and the Caribbean are applying MAR techniques by using various methods in order to reduce the water related problems in the region and to augment water supply.

2.11.3 AUSTRALIA

Dillon et al. (2020) Lessons from 10 year experience with Australia's risk-based guidelines for MAR paper denoted that Australia in 2009 published the world's first MAR guidelines which were based on risk-management principles that underpin WHO's Water Safety Plan. Furthermore, Knapton et al. (2020) feasibility study on MAR as a strategic storage and urban water management in the Darwin rural area concluded that MAR reduces the amount of groundwater decline and increases groundwater recharge.

A case study that was done by Shirmohammadi et al. (2020) in Iran shows that the characteristics of climatic conditions in semi-arid and arid regions make them exposed to a variable environmental changes therefore an emphasis needs to be invigorated on sustainable water resources management. Marote et al. (2019) investigated the contribution of non-conventional water resources in the Segura River Basin located in south-eastern part of Spain as a means of adaptation and found out that it reduced the vulnerability of climate risk on water supply systems despite it being a drought prone area.

From the above mentioned case studies the vulnerability of water resources to exploitation is very high in arid regions and sustainable research has been carried out for water conservation. The methods of preserving water resources include its management and artificial groundwater recharge, which have now been adopted by many countries globally.

2.12 CHALLENGES OF MANAGED AQUIFER RECHARGE

There are many risks that can be associated with managed aquifer recharge. The following are examples of the technical and non-technical challenges of MAR;

2.12.1 Clogging

Artificial recharge techniques started in 1958 in Morocco, Zaidi et al. (2020). Moreover, clogging of recharge sites was found to be caused by sediment transportation during periods of high precipitation. Du et al. (2018) describe that a number of physical, chemical and biological processes can affect porous media. Clogging in general reduces and causes failure in the amount of recharge, Jeong et al. (2018). Du et al. (2014) in their research found that in MAR the most common type of clogging is the physical type which can be divided into three types: surface clogging, inner clogging and mixed clogging.

2.12.2 Contamination Risk

According to Salameh et al. (2019) a study conducted in Jordan between the years of 2012-2017 were a decline in groundwater levels and aquifer pollution was noticed. The contamination in Hidan wellfield is caused mostly by E.coli and Xanke et al. (2017) suggested that a delineation of proposed protection zones and the prohibition of livestock farming as well as controlled used of fertilizers serves as measures to remove hazards in the zone. McGill et al. (2019) findings about the Ramotswa transboundary aquifer which is located in the south-eastern part of Botswana show that during the 2013-2016 drought groundwater quality was impacted. The residents prevalently used pit latrines rather than flush toilets thus causing an increase in human waste leaking into groundwater leading to nitrate pollution in the aquifer. Furthermore, McGill & Villholth (2019) explain that although remediation and water treatment is possible, these improvements for the groundwater quality take time. In Pakistan, water pollution is one of the main threat to public health and does not meet the WHO required standards. In addition to that, the country ranks at number 80 out of 122 nation with respect to water quality standards Ahmed & Shafique (2019). Also, Solangi et al. (2019) stated that water-related diseases are common in Pakistan suggesting the contamination of groundwater.

CHAPTER THREE

MATERIALS AND METHODS

In this chapter the data sources, formats and a step by step explanation of the data processing techniques that were used for evaluating the potential sites for groundwater recharge using the Soil-Water Balance model and QSWAT + model in Palla Road are shown. Satellite data and existing data from various institutions that provide information about groundwater recharge were used. This chapter is based on the research objectives that were stated in Chapter 1.

3.1 Description of the Study Area

Palla Road also known as Dinokwe is located in the Eastern part of Botswana as shown in figure 3.1, lies between latitudes 22˚S and 25˚S and 25˚E and 28˚E longitudes. It is situated in the transboundary Limpopo River Basin, which according to the Global Water Partnership, GWP (2011) fact sheet is shared between four countries: Botswana, Mozambique, South Africa and Zimbabwe. In total, there are 72 transboundary aquifers in Africa, which cover about 42% of the land Nijsten et al. (2018). Furthermore, the Limpopo Basin is considered to be very important for water resources in Botswana as most of the dams are situated in the basin. Also, Serorome River Valley is regarded to be the most prominent topographic feature in the area, it is a broad and ephemeral tributary river channel draining towards the Limpopo River. Due to this, the Bonwapitse River is a major tributary in the Serorome river valley.

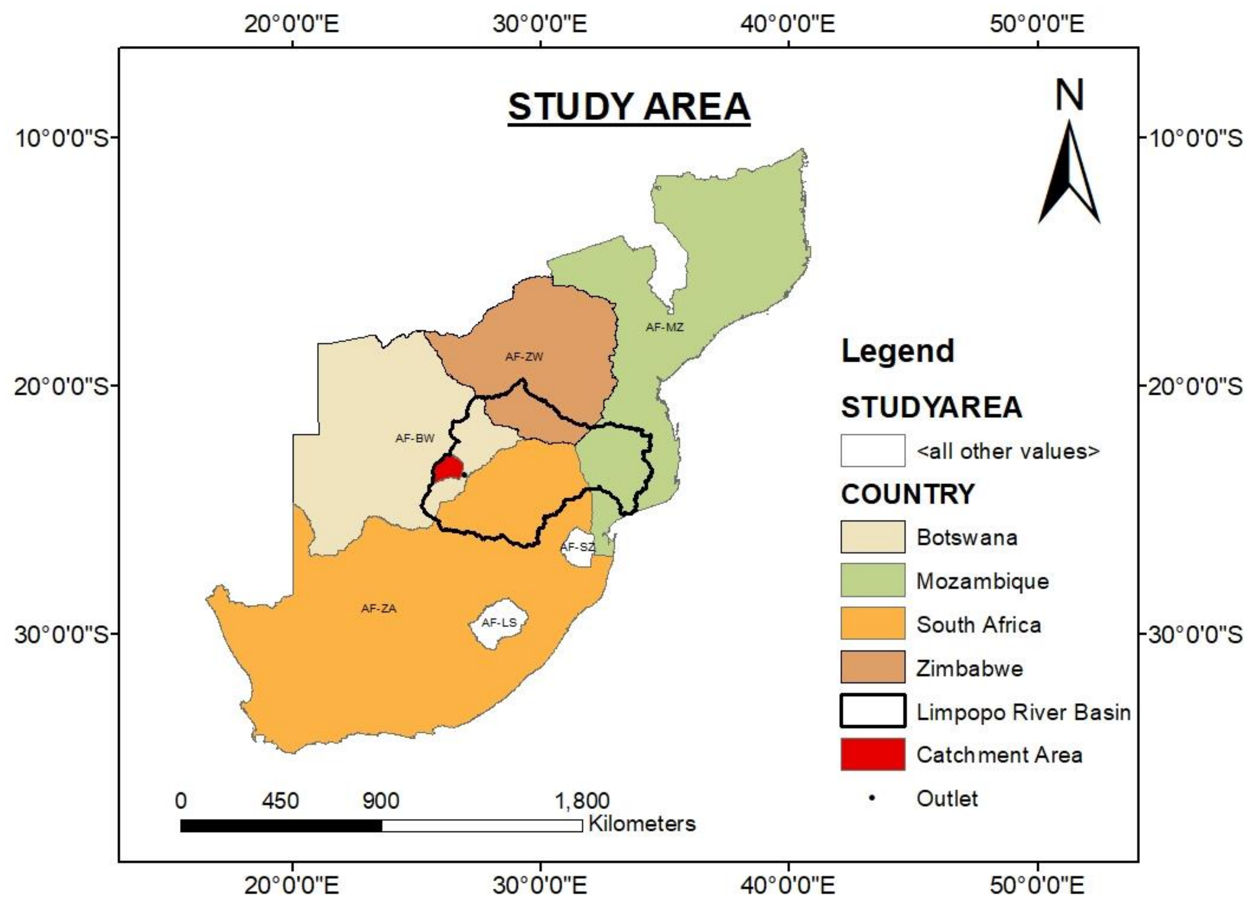

Figure 3.1 A representation of the study area

3.2 Climate

The local climate is characterized as semi-arid with cool dry winters and hot wet summers. The Mahalapye Meteorological station was used to measure the temperature. The climate is described with a graphical representation in figures 3.2 and 3.3.

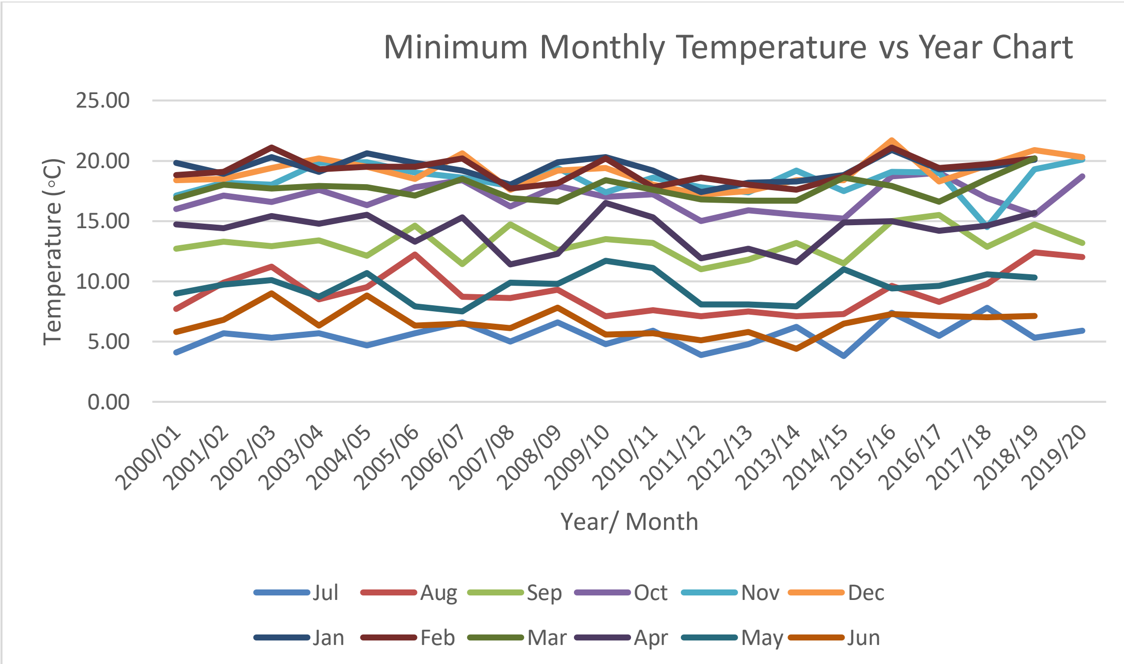

Figure 3.2 Minimum Monthly Temperature Mahalapye District

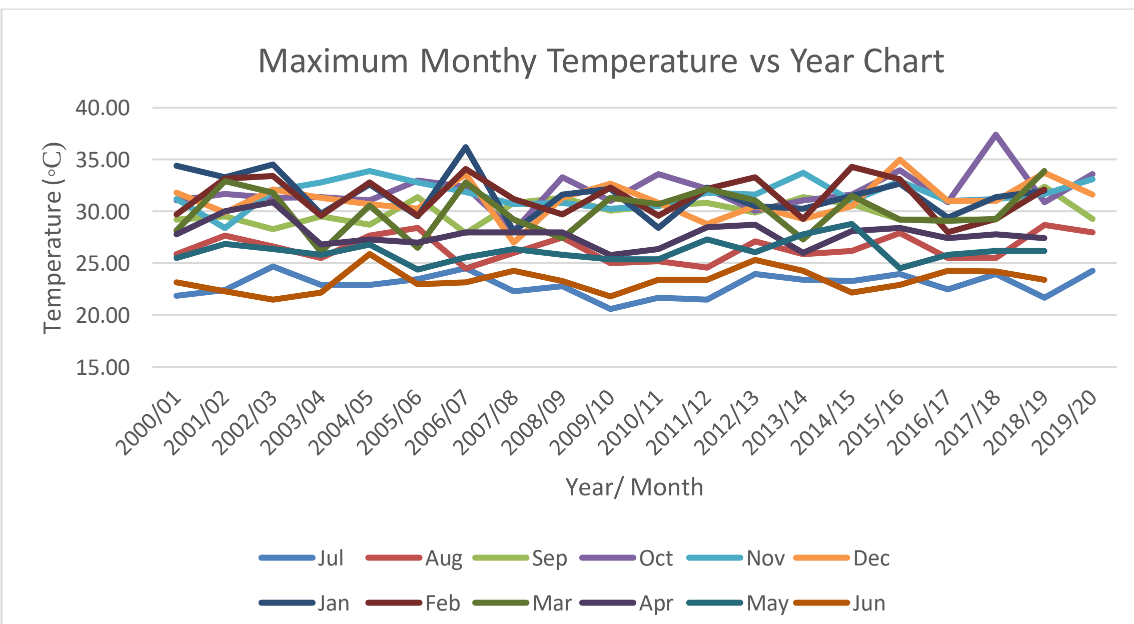

Figure 3.3 Maximum Monthly Temperature Mahalapye District

3.3 Population

Palla Road/ Dinokwe is situated in the Central District of Botswana and in the Mahalapye sub-district. Findings conducted by Statistics Botswana (2015), on the 2011 population and housing census report show that the total population of Palla Road/ Dinokwe was 1 516 with a total number of 408 households. The number recorded for males was 778 and females 738.

GIS datasets of four parameters were collected from different sources for the Bonwapitse and Serorome Valley.

Soil Water Balance Model

Table 3.1 The Soil Water Balance model requires the following data inputs which are represented below;

Data Type
Gridded (ARC ASCII or Surfer grid)
Land use/ Land cover
Flow direction
Hydrologic soil group
Available water capacity
Tabular
Soil and Land use properties lookup table
Climate at a single station
Matrix of soil-water retention for given accumulated potential water loss

3.4 Data Collection

3.4.1 DIGITAL ELEVATION MODEL

The digital elevation model (DEM) shown in figure 3.4 was downloaded from http://srtm.csi.cgiar.org/ and was used to delineate the Serorome and Bonwapitse watershed areas which are located in the vicinity of the Palla Road wellfields. DEM is described by the United States Geological Survey (USGS) Technical Support team on https://support.esri.com/en/ to be a representation of a continuous surface in which each raster cell represents the elevation at a location. The DEM was used to analyse the drainage patterns of the land surface terrain. CGIAR-CSI GeoPortal is able to provide SRTM 90m Digital Elevation Data for the entire world. The SRTM 90m DEM's have a resolution of 90m at the equator, and are provided in mosaiced 5 deg * 5 deg tiles for easy download and use. The total area of the catchment is 11 101.890267km^2.

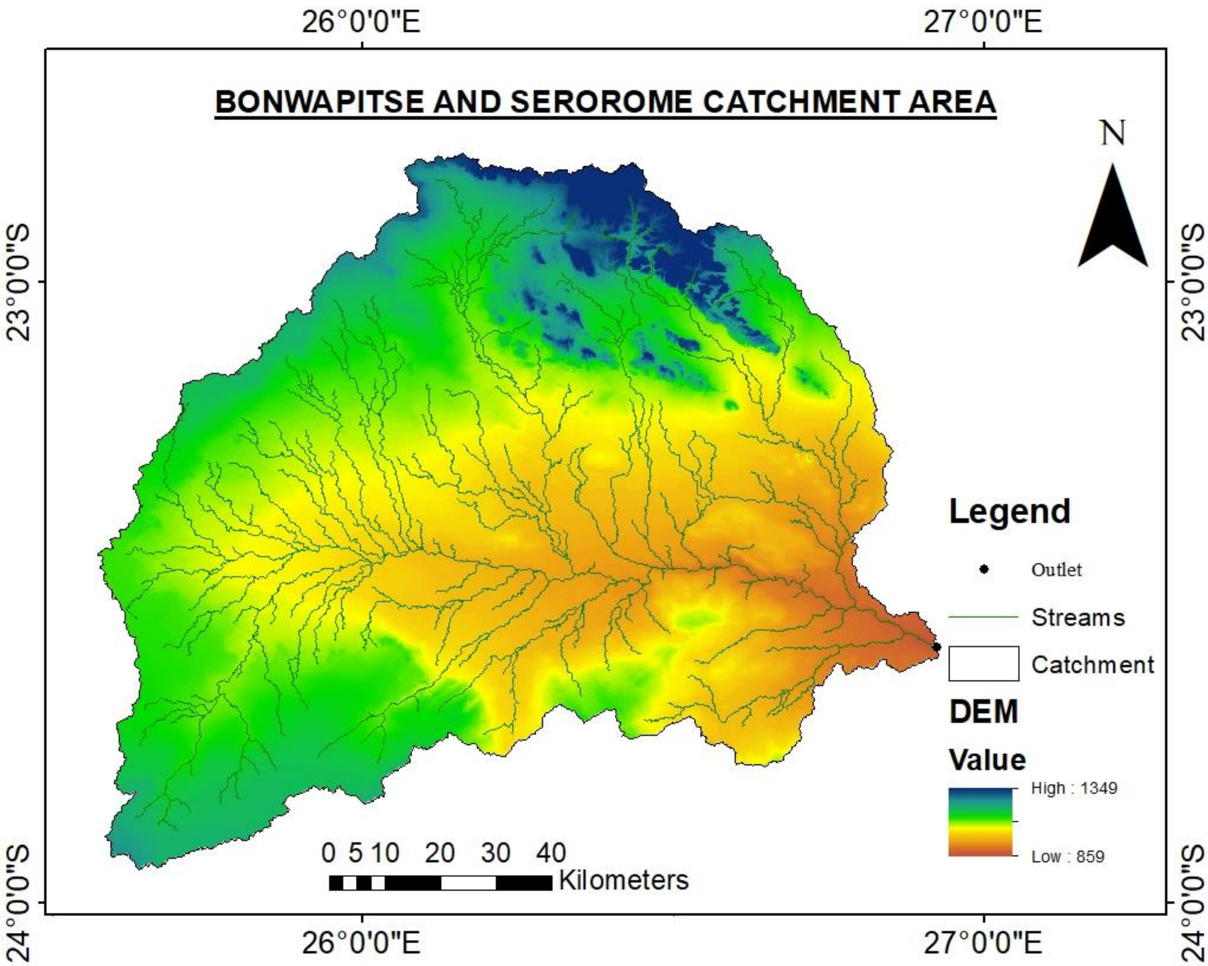

Figure 3.4 DEM and drainage network of Bonwapitse and Serorome Catchment Area

3.4.2 FLOW DIRECTION

The downloaded DEM file was imported to Aeronautical Reconnaissance Coverage Geographic Information System (ArcGIS) v10.8 ArcView in order to obtain the flow direction. The following procedure was then used thereafter.

Firstly, the Spatial Analyst extension license was used. The first tool used in the Spatial Analyst extension was the Fill tool which was explained by Arakelyan & Sargsyan (2016) to be used for certain imperfections such as sinks and peaks which DEM's often have. In addition to that, the errors are often due to the resolution or rounding of elevations to the nearest integer. Therefore, it is essential for sinks to be filled for proper delineation of basins and streams. The filled DEM created in the previous step was then used to delineate the flow direction using the flow direction tool, represented by figure 3.5 below.

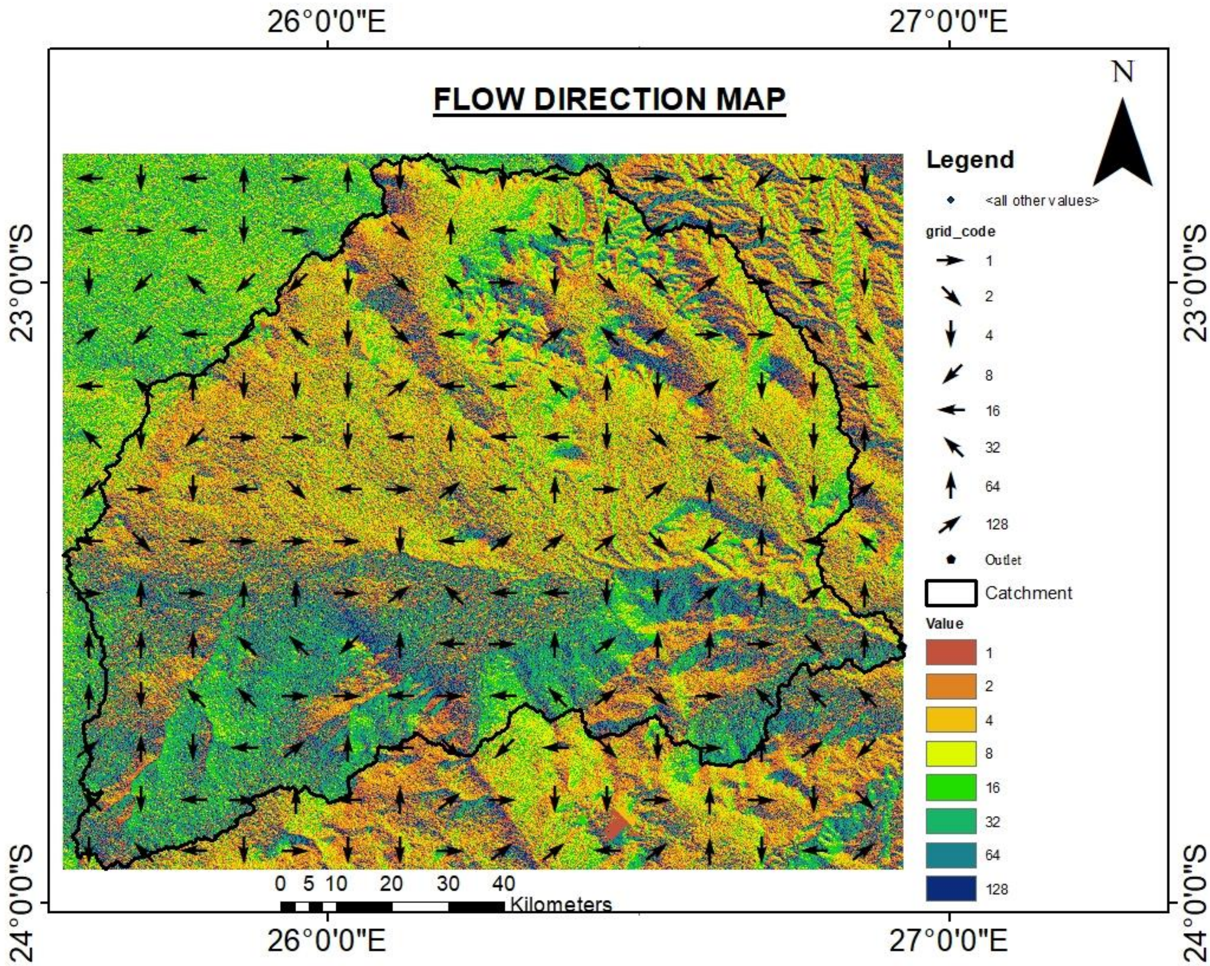

Figure 3.5 Flow direction map of the Bonwapitse and Serorome Catchment Area

Following which, the ArcToolbox conversion tool was used in order to convert the flow direction raster file to American Standard Code for Information Interchange (ASCII) file format. Also, the D8 flow direction type was used which has integer values ranging from 1-255.The values for each direction from the center are as follows in figure 3.6:

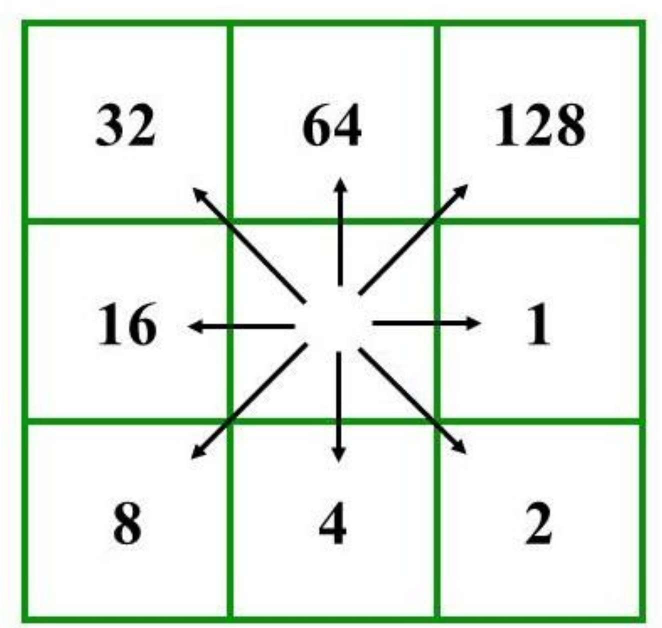

Figure 3.6 showing flow direction for D8 model

3.4.3 SOIL MAP

The preparation of the soil maps was done by extracting the digital soil maps of the world from the Food and Agriculture Organization of the United Nations (FAO-UNESCO) GeoNetwork (http://www.fao.org/geonetwork/srv/en/metadata.show%3Fid=14116). The digitized soil map of the world is at a scale of 1: 5 000 000 and in the Geographic projection (Latitude-Longitude). Lentswe and Molwalefhe (2020) elucidated that the importance of groundwater on recharge is based on the recharge capacity. The downloaded shape file (.shp) of the digital soil map of the world was then added to ArcGIS v10.8 platform. Then, a rectangular mask for the Bonwapitse and Serorome Catchment area was clipped from the digital soil maps of the world using the clip feature.

In order to categorize the soil groups from FAO soil codes in the digital soil maps of the world attribute table, the Soil & Water Assessment Tool (SWAT) 2012 soil database was accessed from (http://www.indiaremotesensing.com/p/s.html) where the user soil table was imported. Thereafter, the soil groups in the study area where identified and categorized to their respective order in the attribute table. This is represented in figure 3.6 below.

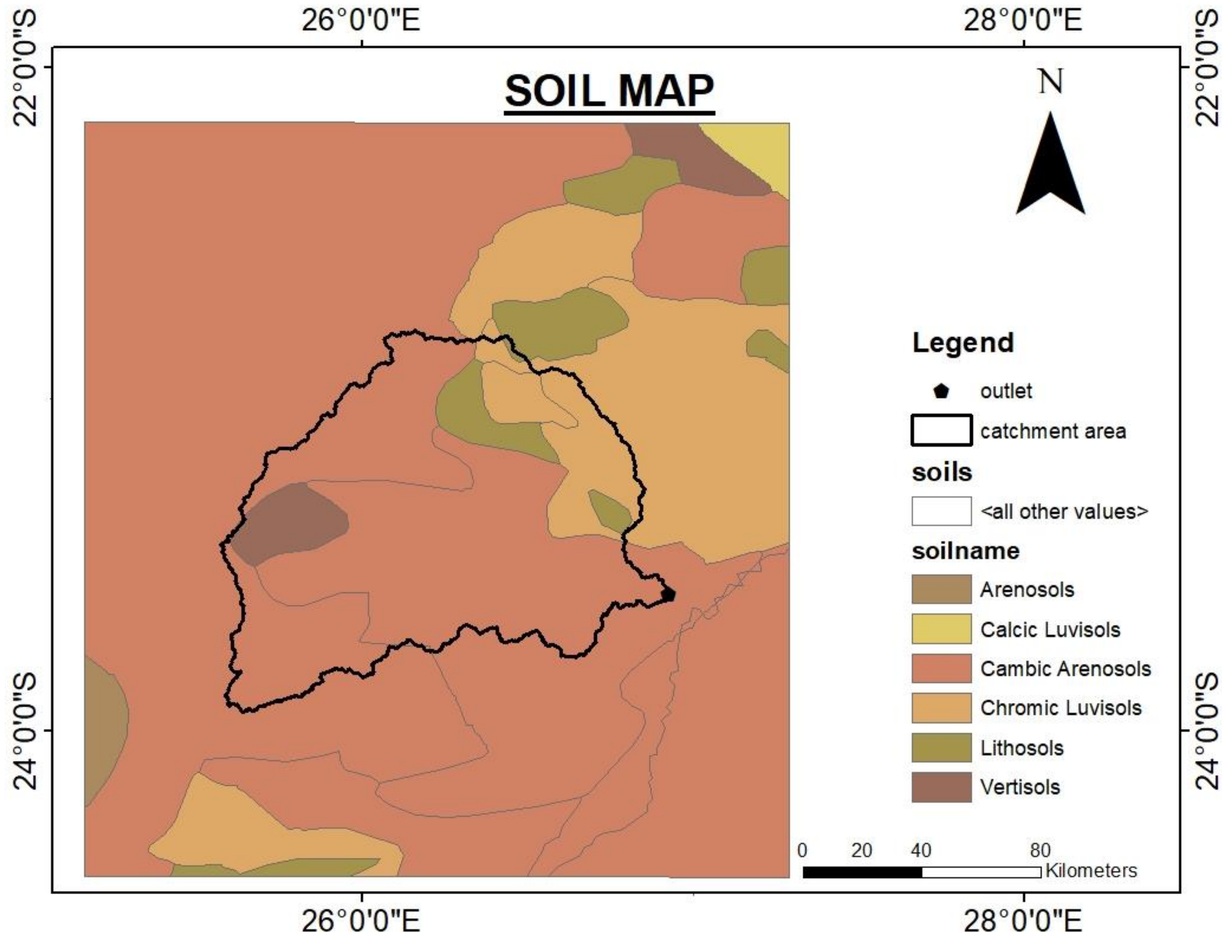

Figure 3.7 Soil map of the Bonwapitse and Serorome Catchment Area

From the figure 3.6 above it is evident that the Bonwapitse and Serorome catchment area is dominated by the Cambic Arenosol soil type which covers most parts of the catchment area. Using the ArcToolbox conversion tool, the hydrologic soil group raster file was then converted to American Standard Code for Information Interchange (ASCII) file format.

3.4.4 SOIL HYDROLOGIC GROUP

The soil hydrologic group was extracted from the user group table obtained on the SWAT soil database the table which was downloaded for the soil map classification. Firstly, the soil map on figure 3.6 above was delineated on ArcGIS V10.8, next the hydrologic group was used to classify the soil names accordingly then the different hydrologic soil groups found in the catchment area were identified. The figure 3.7 below shows a representation of the hydrologic soil groups. The dominant hydrologic soil group soils in the study area were found to be group C and D as shown below.

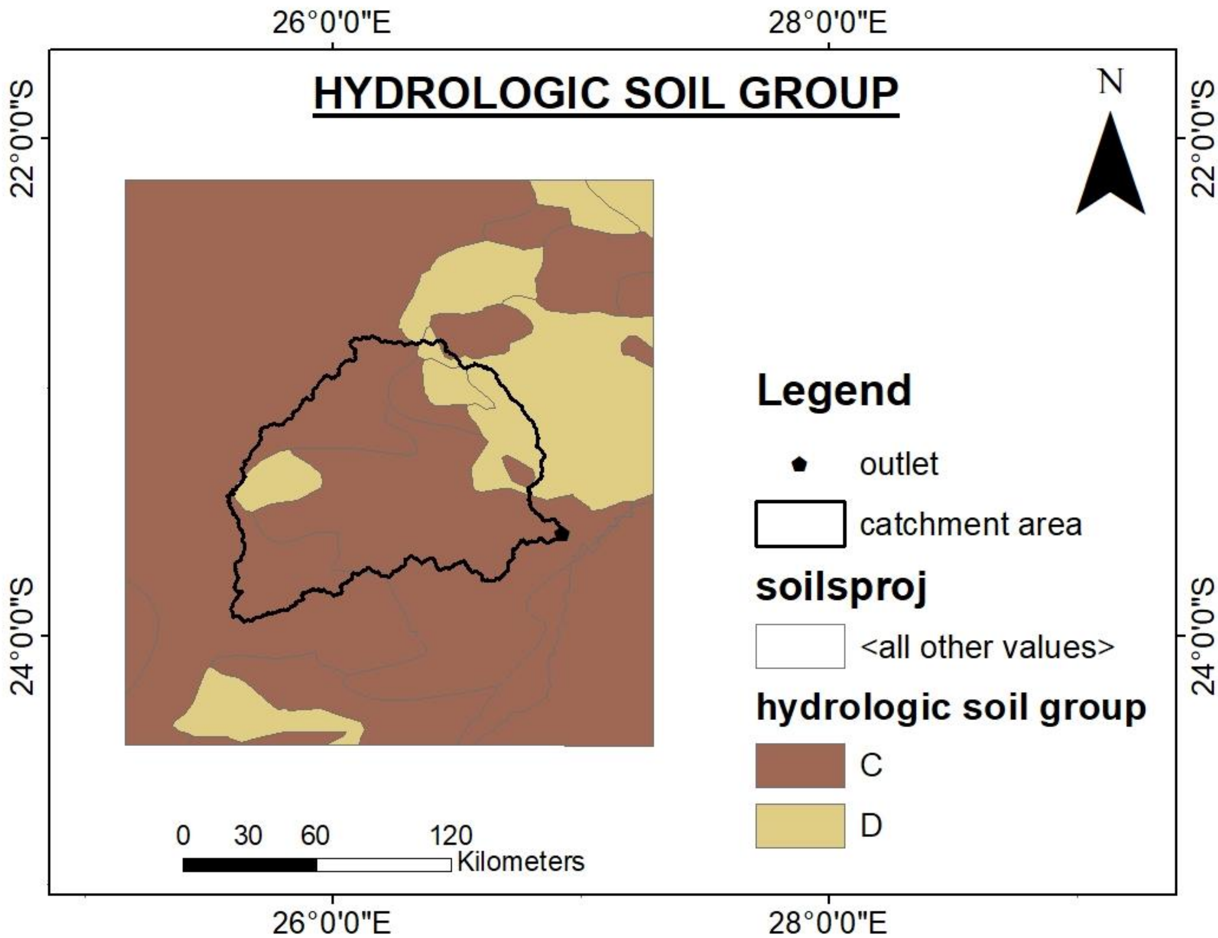

Figure 3.8 Hydrologic Soil Group of the Bonwapitse and Serorome Catchment Area

Below, is table 3.2 that is a description of the different hydrologic soil groups with their classification according to the soil texture, runoff potential and class value. The table was obtained from NASA Earth data retrieved from https://daac.ornl.gov/SOILS/guides/Global_Hydrologic_Soil_Group.html.

Textural classification was then used to create an ASCII file in ArcGIS v10.8.

Table 3.2 Classification scheme used to develop hydrologic soil groups (HSGs)

HSG	**Soil texture class**	**Runoff potential**	**Soil grids 250m texture class value**
A	Sand	Low	12
B	Sandy Loam, Loamy sand	Moderately low	9, 11
C	Clay loam, Silty clay loam, Sandy clay loam, Loam, Silty loam, Silt	Moderately high	4, 5, 6, 7, 8, 10
D	Clay, Silty clay, Sandy clay	High	1, 2, 3
A/D	Sand	High	12
B/D	Sandy loam, Loamy sand	High	9, 11
C/D	Clay loam, Silty clay loam, Sandy clay loam, Loam, Silty loam, Silt	High	4, 5, 6, 7, 8, 10
D/D	Clay, Silty clay, Sandy clay	High	1, 2, 3

3.4.5 LANDCOVER

Land cover is defined by the FAO Land Classification System on: http://www.fao.org/3/x0596e/x0596e01e.htm as the observed (bio) physical cover on the earth's surface. The land cover map was downloaded from the ESA (European Space Agency) CCI (Climate Change Initiative) LC (Land Cover) Web Viewer http://2016africalandcover20m.esrin.esa.int/download.php. The map LC map resolution is 20m over Africa and is based on 1 year of Sentinel-2A observations from December 2015 to December 2016 in GeoTIFF format. Furthermore, the coordinate reference system used for the global land cover database is a geographic coordinate system based on the World Geodetic System 84 (WGS84) reference ellipsoid. Thereafter, a rectangular mask was used to clip the study area which was then imported to ArcGIS v10.8. The color legend was then imported to the land cover map attribute table and it is shown in table 3.3 below, which presents the 10 generic classes used to describe the land surface at 20m. Thereafter, the land cover map was converted into an ASCII file.

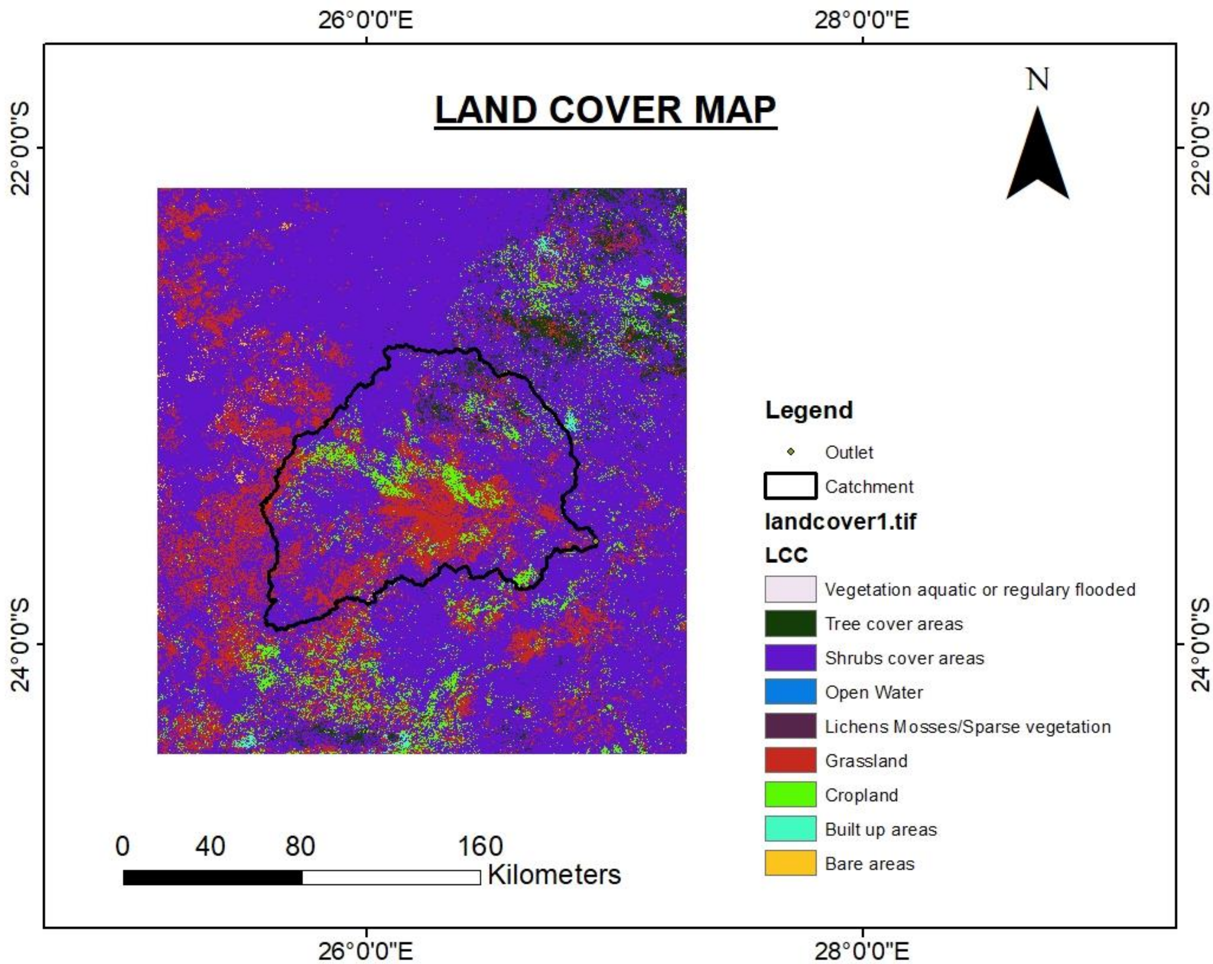

Figure 3.9 Land cover map for the Bonwapitse and Serorome Catchment Area

Table 3.3 representing the color legend used for the S2 prototype map of Africa.

Value	Label	R	G	B
0	No data	0	0	0
1	Trees cover areas	0	160	0
2	Shrubs cover areas	150	100	0

3	Grassland	255	180	0
4	Cropland	255	255	100
5	Vegetation aquatic or regularly flooded	0	220	130
6	Lichen Mosses/Sparse vegetation	255	235	175
7	Bare areas	255	245	215
8	Built up areas	195	20	0
9	Snow and/or ice	255	255	255
10	Open water	0	70	200

3.4.6 AVAILABLE WATER CAPACITY

Dobarco et al. (2019) define soil available water capacity (AWC) as the maximum amount of water that a soil can hold (store) and release to the plant roots and key for ecological and hydrological processes. The AWC data was retrieved from the User soil table which was obtained in the Soil & Water Assessment Tool (SWAT) 2012 soil database. The AWC data was then imported into ArcGIS v10.8 and categorized accordingly then, converted into an ASCII file. The figure 6 below is a representation of the AWC in the Bonwapitse and Serorome Catchment area expressed in volumetric fraction in figure 3.10 below.

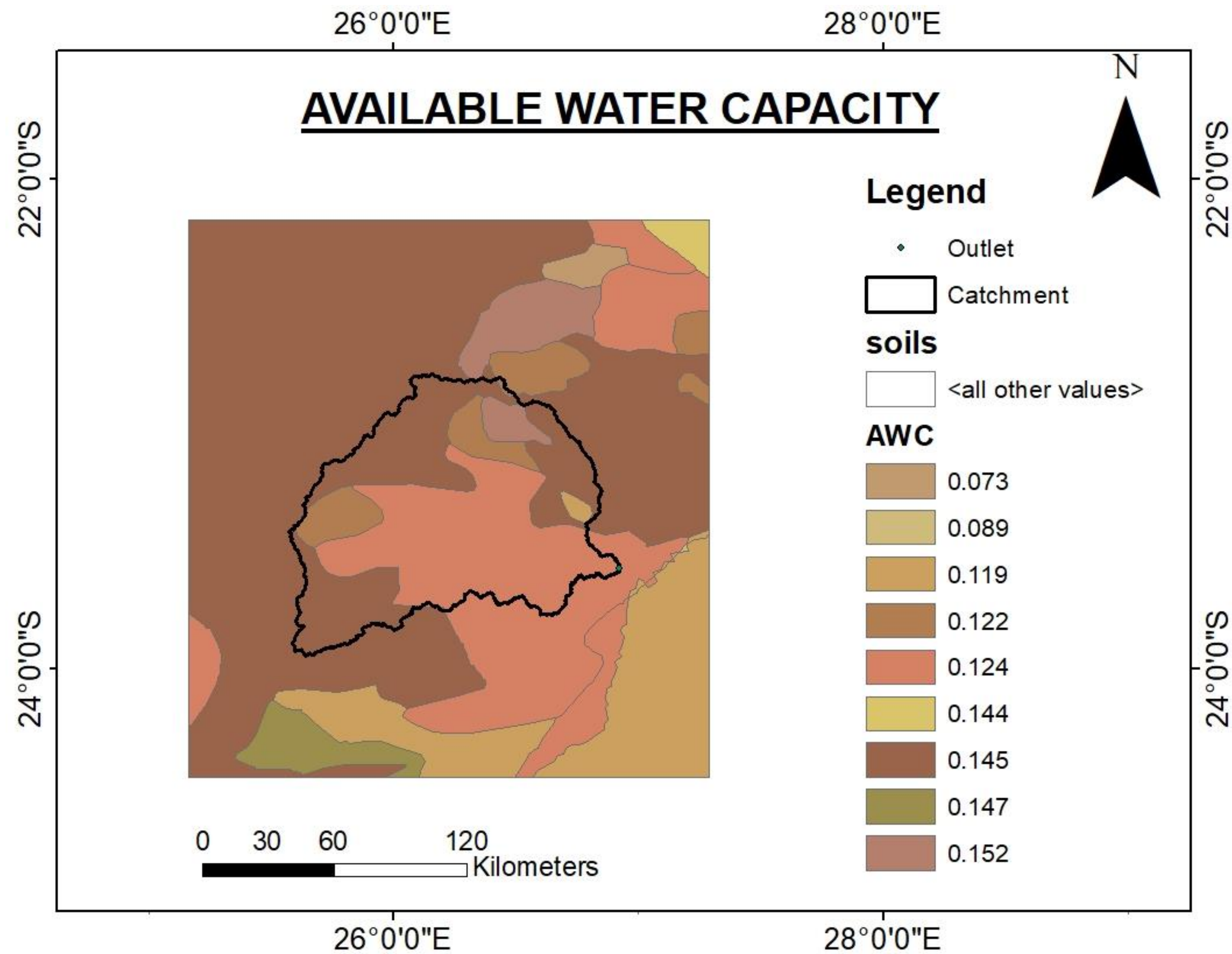

Figure 3.10 Available water capacity in the Bonwapitse and Serorome Catchment Area

3.4.7 CLIMATE

In particular, the climate variables that were examined are rainfall, temperature, sunshine (%), relative humidity and wind speed at a single point station for a period of eleven years (2008-2019). These variables were downloaded from NASA Power Data Access Viewer. (https://power.larc.nasa.gov/data-access-viewer/)

3.5 QSWAT+ Model

3.5.1 Data Collection

Digital elevation Model (DEM)

The digital elevation model (DEM) was downloaded from http://srtm.csi.cgiar.org/ and was used to delineate the Serorome and Bonwapitse watershed areas which are located in the vicinity of the Palla Road wellfields. DEM is described by the United States Geological Survey (USGS) Technical Support team on https://support.esri.com/en/ to be a representation of a continuous surface in which each raster cell represents the elevation at a location. The DEM was used to analyse the drainage patterns of the land surface terrain. CGIAR-CSI GeoPortal is able to provide SRTM 90m Digital Elevation Data for the entire world. The SRTM 90m DEM's have a resolution of 90m at the equator, and are provided in mosaiced 5 deg * 5 deg tiles for easy download and use. The total area of the catchment is 11 101.890267km^2. The DEM was imported to Quantum GIS (QGIS) V10.0 for analysis as of figure 3.4.

Land cover map

Land cover is defined by the FAO Land Classification System on: http://www.fao.org/3/x0596e/x0596e01e.htm as the observed (bio) physical cover on the earth's surface. The land cover map was downloaded from the ESA (European Space Agency) CCI (Climate Change Initiative) LC (Land Cover) Web Viewer http://2016africalandcover20m.esrin.esa.int/download.php. The map LC map resolution is 20m over Africa and is based on 1 year of Sentinel-2A observations from December 2015 to December 2016 in GeoTIFF format. Furthermore, the coordinate reference system used for the global land cover database is a geographic coordinate system based on the World Geodetic System 84 (WGS84) reference ellipsoid. Thereafter, a rectangular mask was used to clip the study area which was then imported to QGIS v10.0. Table 3.4 below is a representation of the land cover codes that were used for land cover classification which were retrieved from SWAT input/ output file documentation. The land cover map was as figure 3.8.

Table 3.4 showing the land cover codes as per SWAT model input data

Land cover map	Code
Forest	41
Rangeland	51
Pastureland	81
Agriculture	82
Wetland	91
Arid land	31
Bare land	83
Low density urban	112
Water	11

SOIL MAP

The preparation of the soil maps was done by extracting the digital soil maps of the world from the Food and Agriculture Organization of the United Nations (FAO-UNESCO) GeoNetwork (http://www.fao.org/geonetwork/srv/en/metadata.show%3Fid=14116). The digitized soil map of the world is at a scale of 1: 5 000 000 and in the Geographic projection (Latitude-Longitude). Lentswe and Molwalefhe (2020) elucidated that the importance of groundwater on recharge is based on the recharge capacity. The downloaded shape file (.shp) of the digital soil map of the world was then added to QGIS V10.0. Then, a rectangular mask for the Bonwapitse and Serorome Catchment area was clipped from the digital soil maps of the world using the clip feature.

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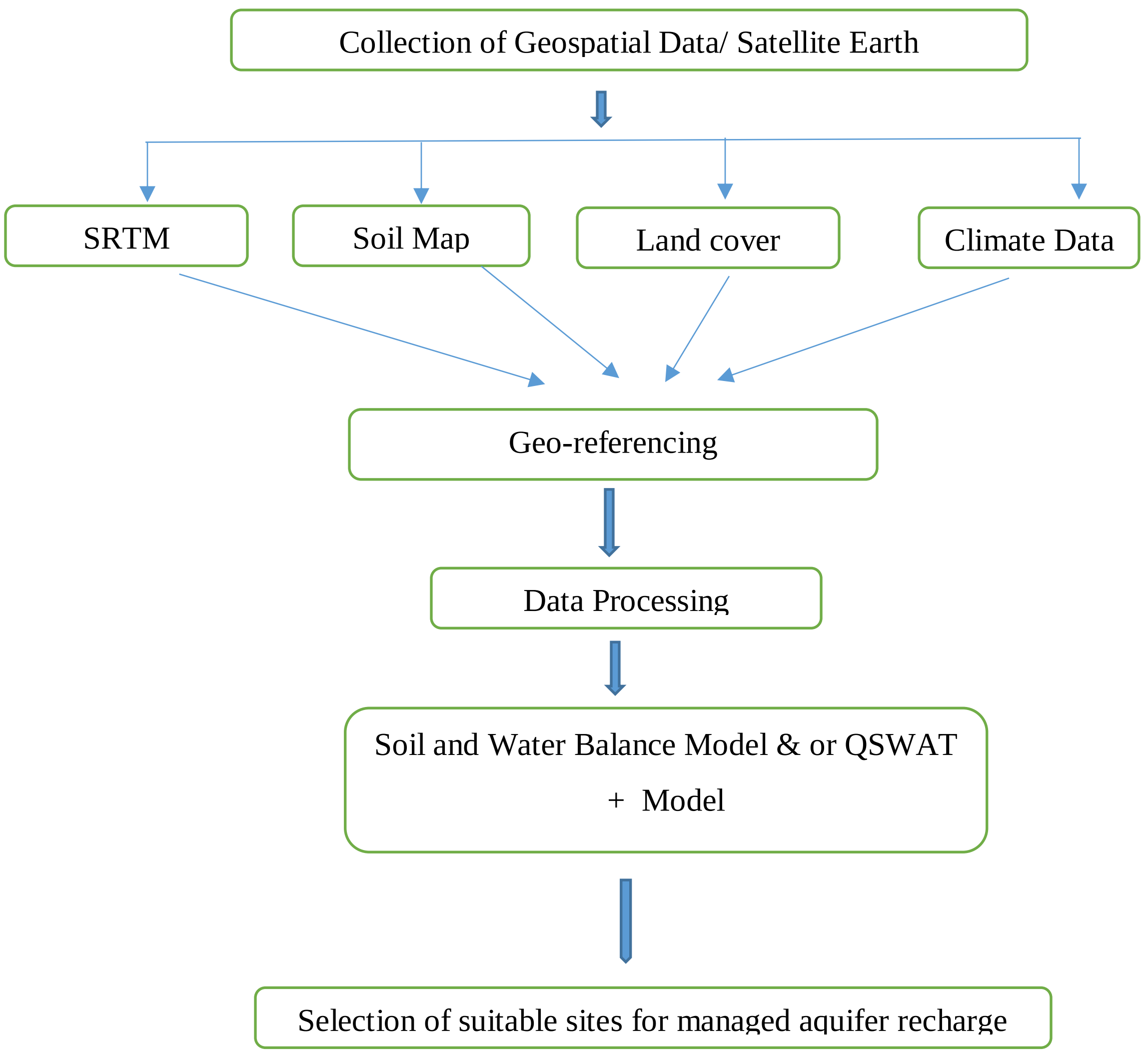
CLIMATE

In particular, the climate variables that were examined are rainfall, temperature, sunshine (%), relative humidity and wind speed at a single point station for a period of eleven years (2008-2019). These variables were downloaded from NASA Power Data Access Viewer. (https://power.larc.nasa.gov/data-access-viewer/).

Borehole Water Levels

The borehole water levels at Palla Road Wellfields were obtained from the Department of Water and Sanitation Botswana, formally known as the Department Affairs were obtained from the borehole monitoring section.

3.6 Graphical Methodology/ Data Collection and Preparation



CHAPTER FOUR

RESULTS AND DISCUSSION

RESULTS

Spatial data was used to analyze the groundwater recharge in the Palla Road wellfields. The soil water balance model was run for a period of eleven years, from (2008-2019) in order to determine the suitable zones (sites) for managed aquifer recharge at the Palla Road wellfields. Many regions in the Palla Road wellfields are considered to be suitable for artificial recharge based process, particularly in the central and south eastern regions. From the simulation the model ran in a three step time series and three recharge maps were configured for the year 2008, 2012 and 2016 respectively as shown in figure 4.1, figure 4.2 and figure 4.3 below.

The identification of suitable sites for MAR was based on the following criteria for the input files: flow direction map, soils hydrologic soil group, soils available water capacity and the land cover. The input files together with climate and other criterion represented in table 3.1 were evaluated using ArcGIS. As a result, the year 2012 showed a high value of groundwater recharge 77.37 inches= 1965.2mm represented in figure 4.2. Following which, the year 2012 which had a groundwater recharge value of 74.48 inches= 1891.8mm in figure 4.3 and thereafter the year 2008 where the recharge was 18.52 inches=470.4 mm. These figures show the suitable regions which are proposed as viable sites for MAR. The unsuitable areas with a very low annual recharge are found to be in the north eastern parts of the Serorome and Bonwapitse Catchment areas.

All of the tested criteria input files (flow direction map, soils, hydrologic soil group, soils available water capacity, land cover and climate) show that there is varied groundwater recharge over the years.

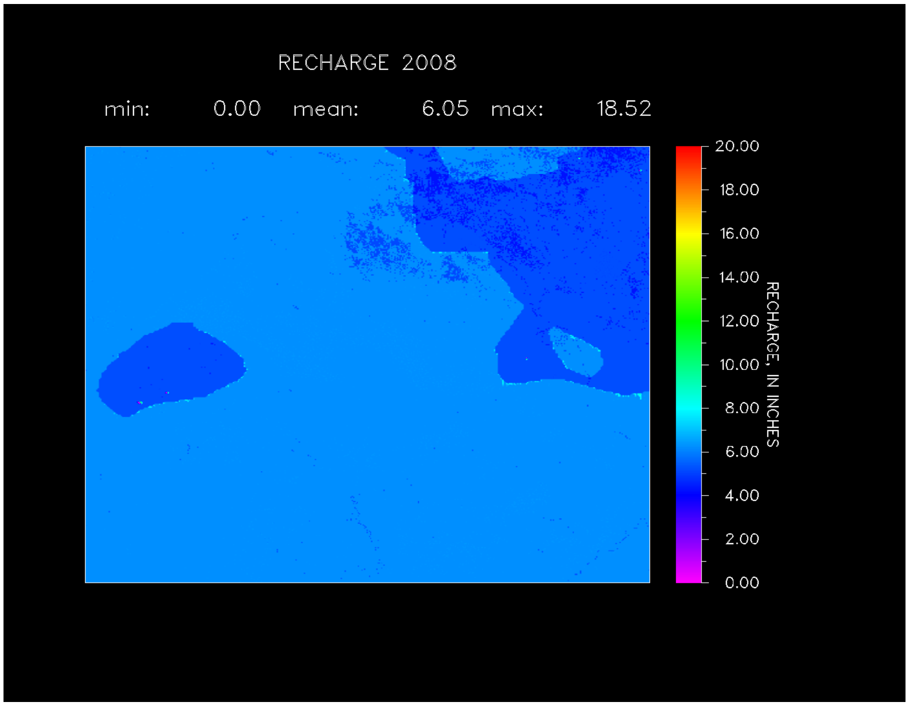


Figure 4.1 Representation of the groundwater recharge for the year 2008

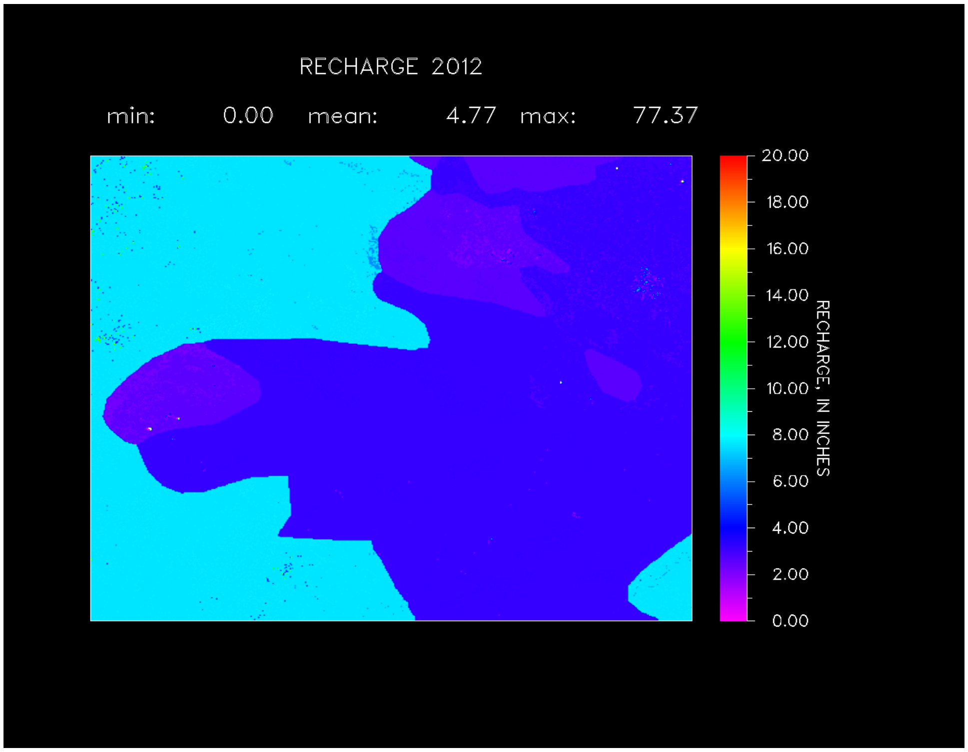


Figure 4.2 Representation of the groundwater recharge for the year 2012

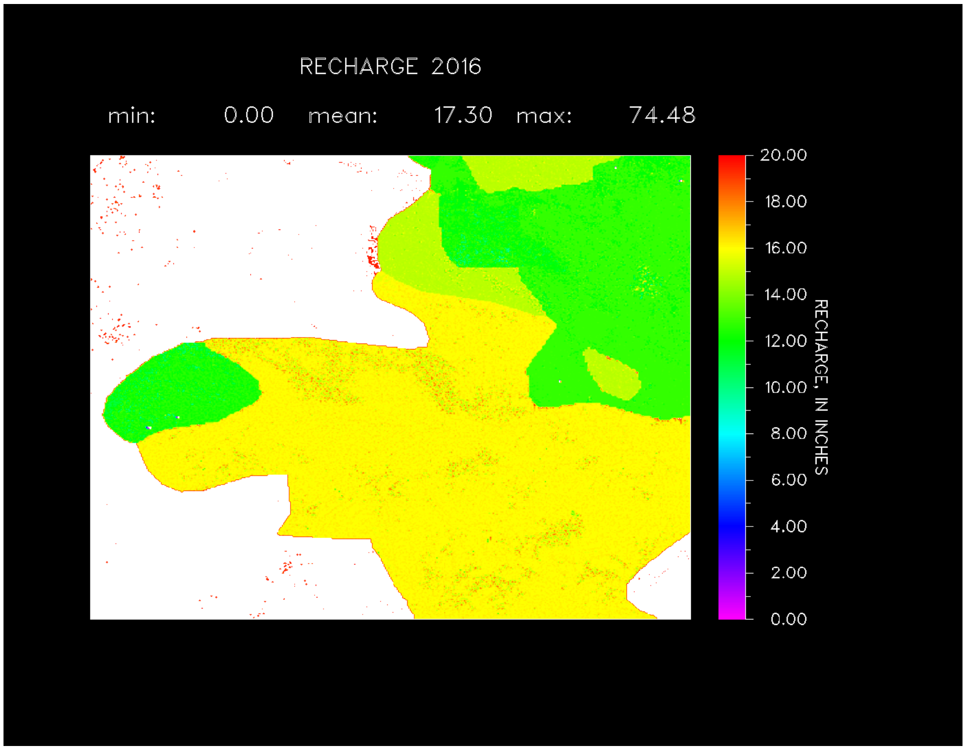


Figure 4.3 Representation of the groundwater recharge for the year 2016

Using QSWAT + Model

The QSWAT + Model was run for a period of eleven years from (2008-2019). The results show that the annual average aquifer recharge of the Palla road wellfields, located in the Bonwapitse and Serorome catchment area ranges from about 250mm to 330mm as shown in Figure 4.4 below. A simulation on the amount of precipitation for the period of eleven years was also done shown in figure 4.5, shows that there are three distinct regions of high, medium and low precipitation. High values of precipitation for a total duration of eleven years are found in the northern part of the catchment ranging at about 4750mm, medium precipitation found along the central part of the catchment has values range at around 4430mm and low values are found to be 4370mm located at the far south and western part of the catchment.

Following which, the evapotranspiration (ET) map of Bonwapitse and Serorome catchment is represented by figure 4.7, high rates of ET were observed in the northern parts of the catchment area this is also represented by the figure 4.6 showing the potential ET.

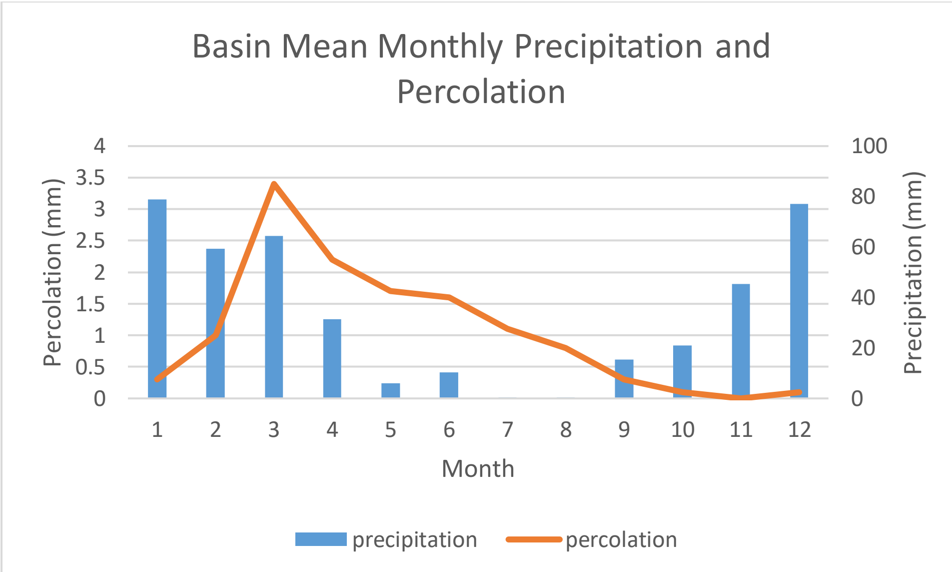


Figure 4.4 Basin mean monthly precipitation and percolation in the Bonwapitse and Serorome Catchment

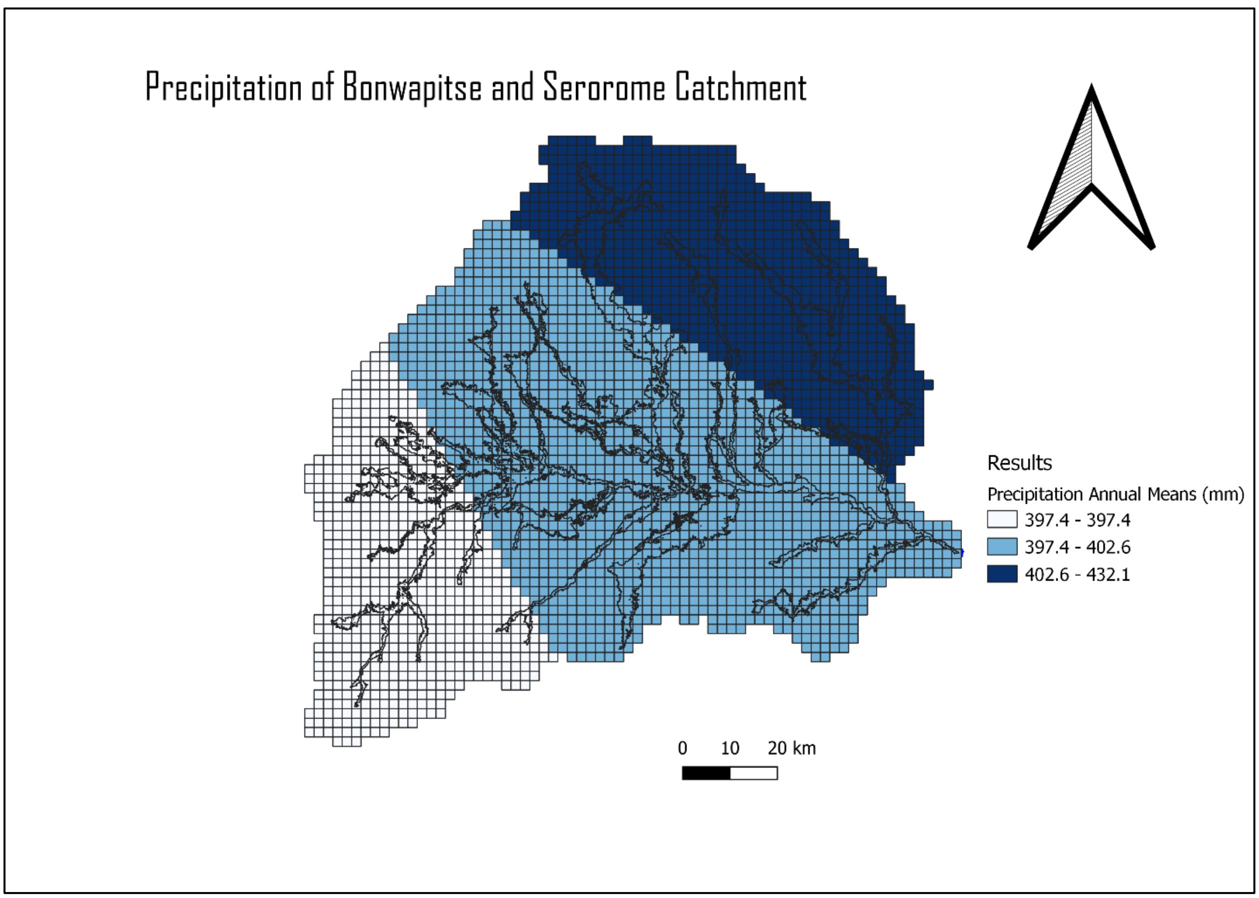


Figure 4.5 Precipitation of the Bonwapitse and Serorome Catchment

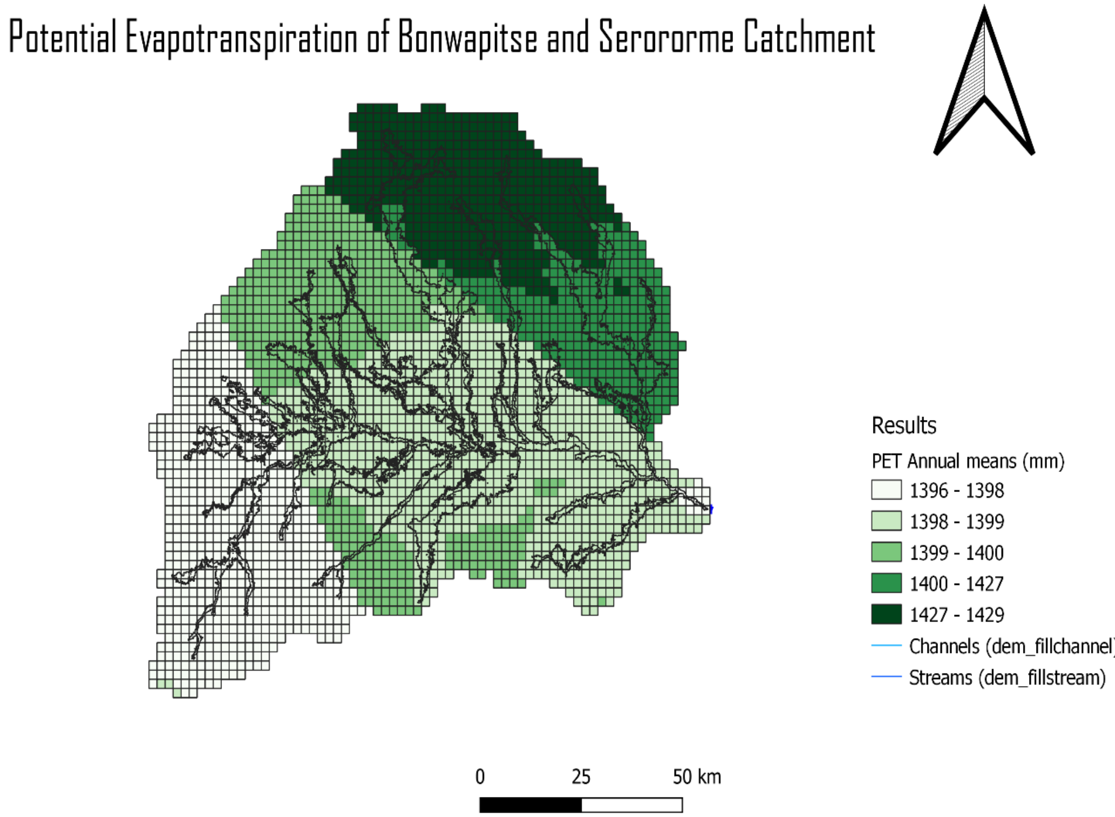


Figure 4.6 Potential Evapotranspiration of the Bonwapitse and Serorome Catchment Area

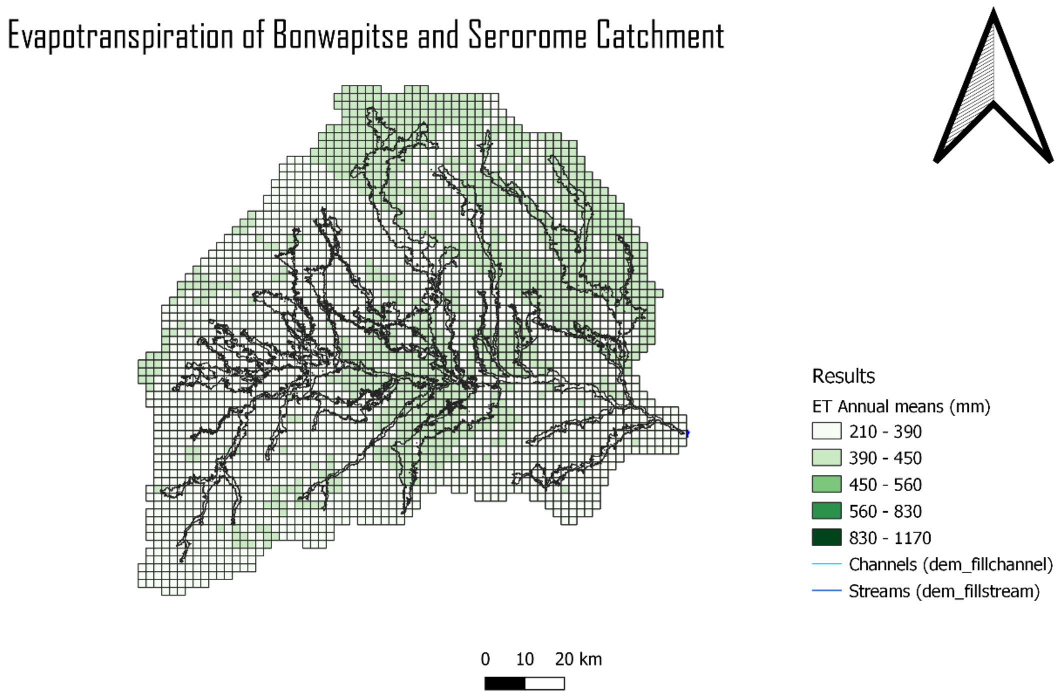


Figure 4.7 Evapotranspiration of the Bonwapitse and Serorome Catchment Area

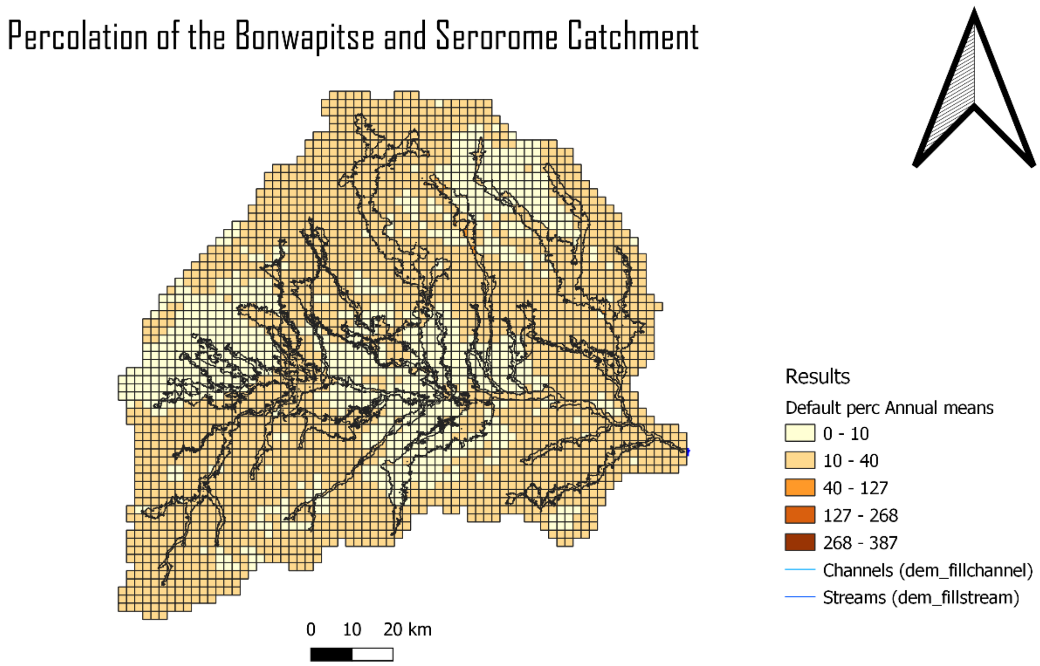


Figure 4.8 Percolation in the Bonwapitse and Serorome Catchment area

Basin Water Balance Output

The water balance output for the Serorome and Bonwapitse Catchment area are represented by the figures below figure 4.8, 4.9 and 4.10 respectively. The figures are a representation of the annual mean water balance, precipitation vs percolation chart and precipitation and evapotranspiration chart.

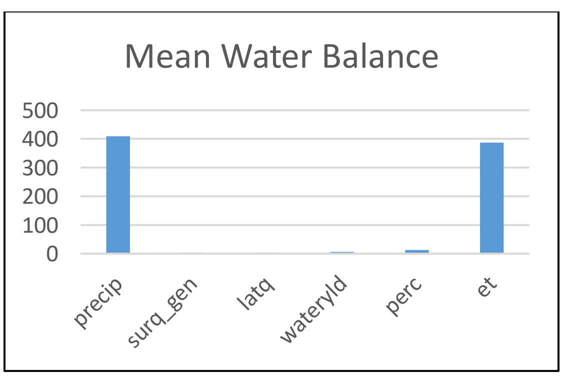


Figure 4.9 Mean Annual Water Balance (2009-2019)

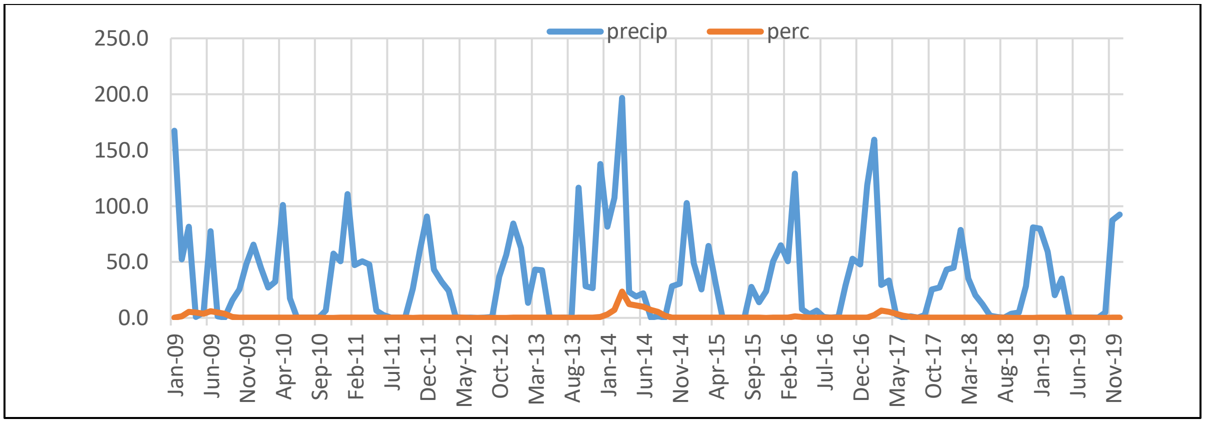


Figure 4.10 Precipitation and Percolation in the Bonwapitse and Serorome Catchment Area

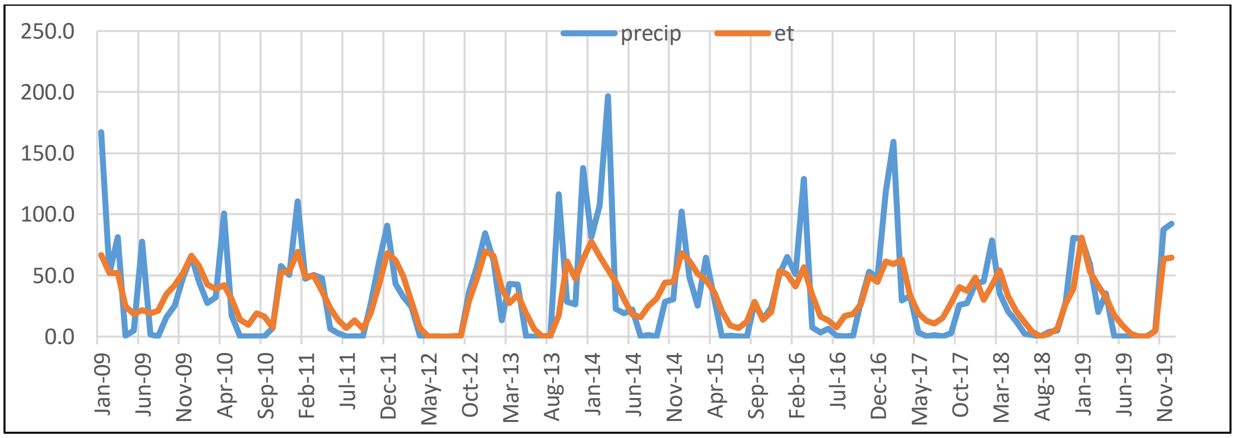


Figure 4.11 Precipitation and Evaporation in the Bonwapitse and Serorome Catchment Area

Graphical representation of the Palla Road Borehole Water Levels

The figures below are a representation of randomly selected boreholes in the Bonwapitse and Serorome Catchment area (Palla Road Wellfields).

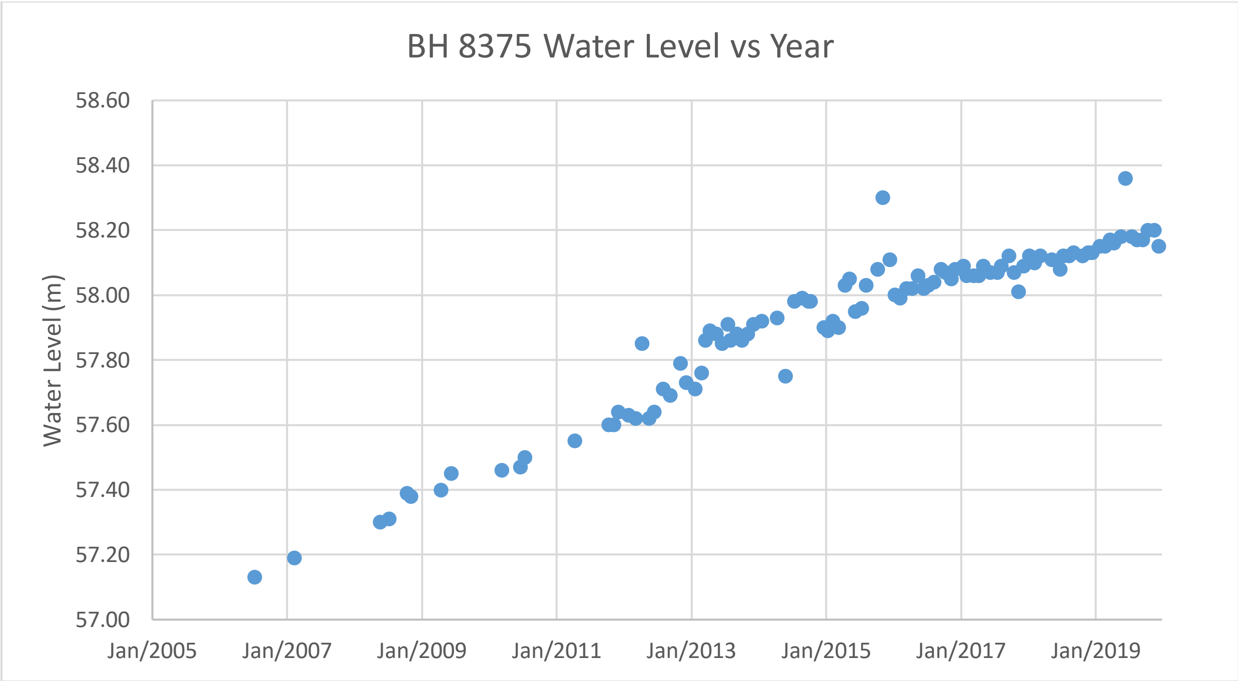


Figure 4.12 Water Level of Borehole 8375 over the years 2006-2019

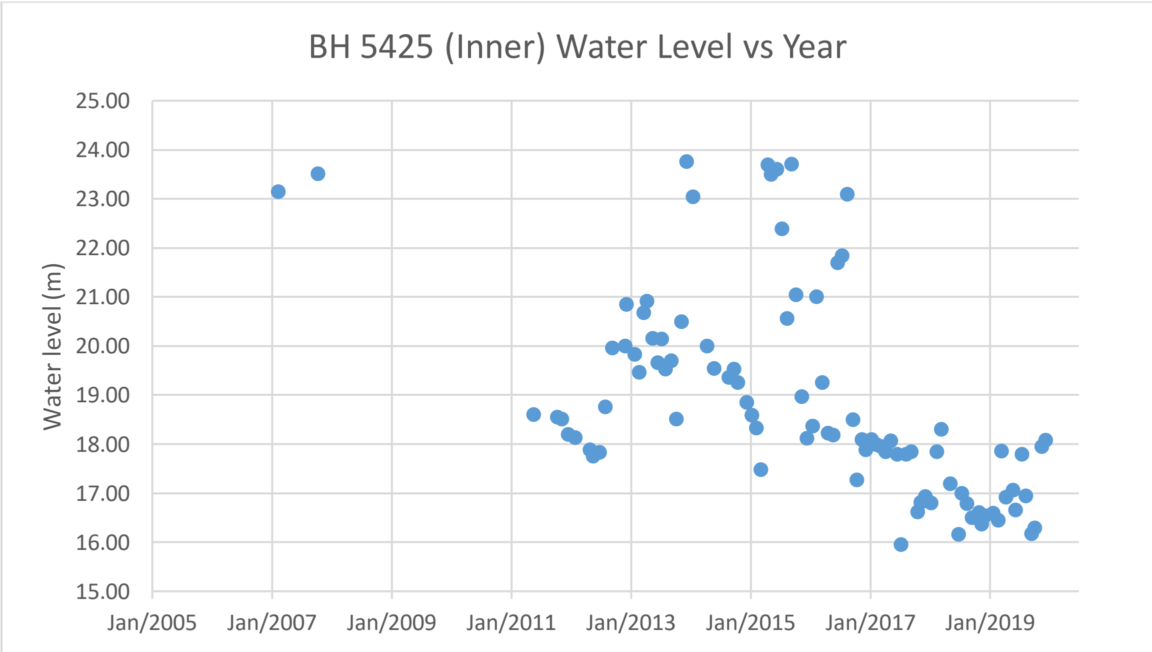


Figure 4.13 Water Level of Borehole 5425 (inner) over the years 2006-2019

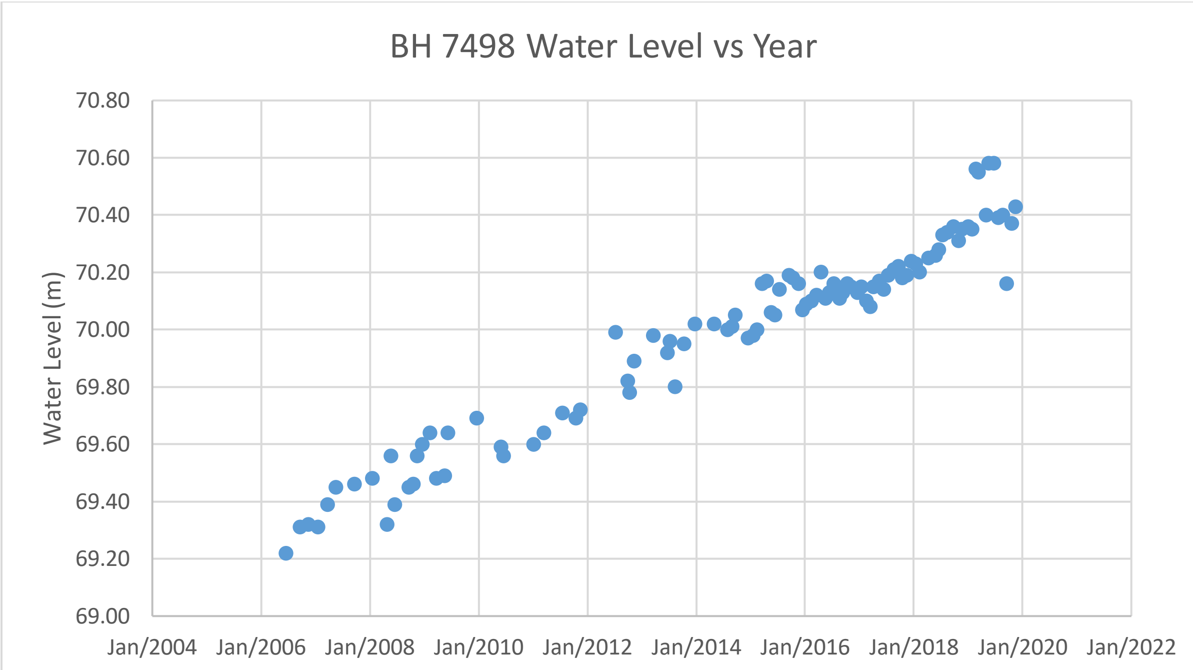


Figure 4.14 Water Level of Borehole 7498 over the years 2006-2019

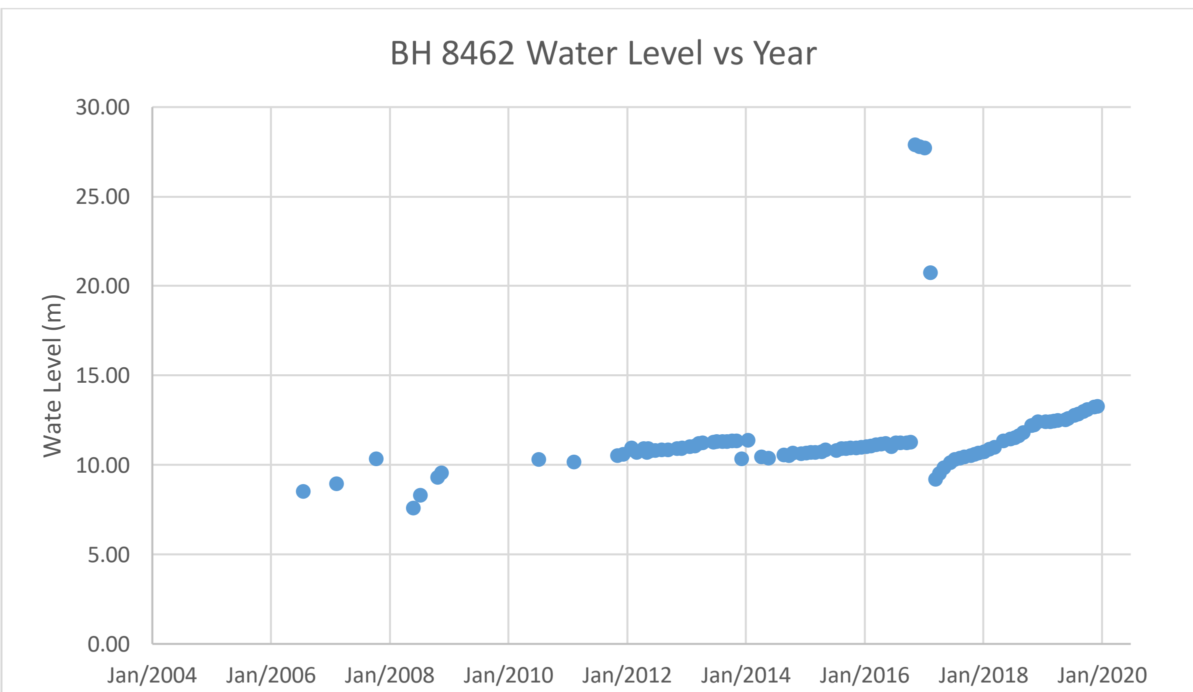


Figure 4.15 Water Level of Borehole 8462 over the years 2006-2019

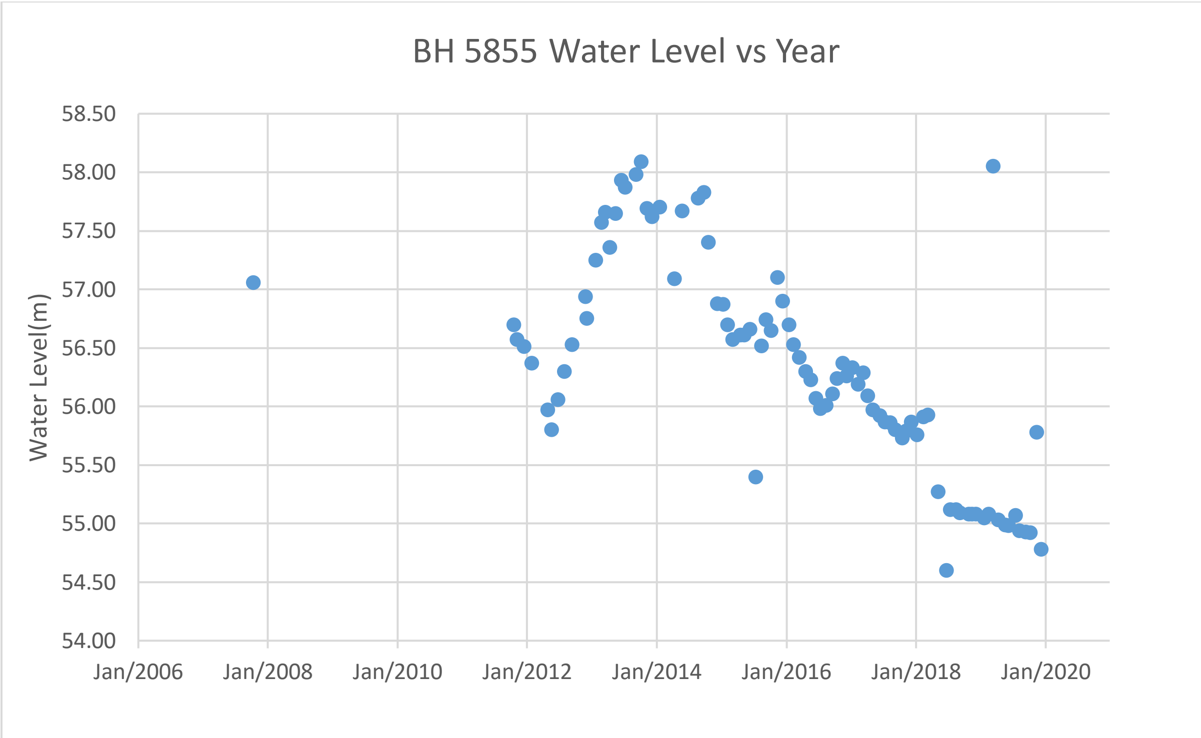


Figure 4.16 Water Level of Borehole 5855 over the years 2006-2019

DISCUSSION

The findings from this research based on the hydrological and soil properties indicate that, Palla Road wellfields have a significant potential in Managed Aquifer Recharge implementation. This serves as an opportunity to mitigate the adverse effects of low and unreliable rainfall thus translating to low natural groundwater recharge rates due to the semi-arid climate.

There has been no review of MAR in Palla Road wellfields however, MAR suitability mapping has been carried out by Ebrahim et al. (2017) for Ramotswa transboundary aquifer located in the south-eastern part of Botswana. Therefore, the limitations of the project were data availability and the lack of previous studies on MAR in Botswana. However, MAR has been used in all parts of the world, in Europe it has been used for over a century with a trial and error method and has continued to develop, Sprenger et al. (2017). Furthermore, it has been noted that the benefits of MAR could develop to it being top priority in ensuring water sustainability. As a result, it has been considered to alleviate the constant effects of climate change, salinization, and increased weather variability. Yaraghi et al. (2019), elucidated that MAR helps provide a stable and increased groundwater supply which has improved the socio-economic lives of semi-arid region inhabitants.

Modelling and assessing water resources with lack of data can be addressed by using geo-spatial data which can provide the required information. Although, when modelling groundwater resources there are minimal tools to provide the required data. Despite the limitations incurred when carrying out the project the main objective of identifying the potential of MAR in Palla Road wellfields has been achieved.

The soil and water balance showed a variance in groundwater recharge over the years with the 3 output files represented on figures 4.1, 4.2 and 4.3 although the central part represents higher recharge rates. The QSWAT + model has shown that the northern part of the catchment area has high precipitation rates but also has high evaporation. The southern side of the catchment has low precipitation and low evaporation rates. These are represented by the figures 4.5 and 4.7 respectively. Therefore, according to the water balance equation which is shown in chapter 2.9.2 and from the results section it can be seen that both models; the water balance model and the QSWAT + model suggest that the center region is most suitable for MAR. Also, it is evident from figure 4.9 which shows the annual water balance that most of the precipitation that most of the precipitation is lost through evaporation in the area. Also, the percentage evaporation ratio is 98%

which classifies the climate as Arid Steppe using the Koeppen Climate classification. This communicates that MAR could be implemented so that the water losses due to evaporation are minimized by the deliberate input of water to the ground. Moreover, the figures 4.4 and 4.8 show the groundwater recharge. Figure 4.4 shows how the precipitation and percolation are co-related and it elucidates that during the months of February and March is when most of the percolation occurs. In addition to that, figure 4.8 is more precise and specific to the regions where more percolation occurs.

The water levels from the monitoring boreholes show that in the year 2014, the water levels had reduced drastically and more recharge (percolation) occurred which is shown by figure 4.10. However, during the year 2015/2016, Botswana experienced severe drought which was an effect of El Niño and the water levels increased again. Figure 4.10 also explains that a significant amount of recharge occurs after a few years so MAR serves as a basis to quickly recharge the boreholes. Over the years the impacts of El Nino were known to have caused drastic effects on agriculture. However, the 15/16 drought has posed to be the most severe on record with dire effects on water supply, causing disruptions whereby intermittent water supply was implemented in most cities and towns also, low river levels were experienced due to the reduced runoff rates, Conway (2017). In general MAR is said to increase groundwater recharge and Fathi et al. (2020), said that it facilitates water availability and accessibility as well as reduce the deficit in water supply.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The world is gradually recognizing the value of groundwater, the United Nations World Water Day theme for the year 2022, "Groundwater: Making the Invincible Visible". Groundwater is a non-renewable resource that should be managed effectively. In this research, the soil water balance model was used in order to determine MAR suitability in Palla Road wellfields and to further improve the groundwater resource management in the area. To conclude, water is life and plays an essential role in sustainable development. Thus, groundwater management in Botswana is imperative as this resource provides water for most parts of the country. Therefore, MAR serves as a basis to ensure sufficient supply of water for the future growth of the population.

Botswana having a semi-arid climate, has never favored the country characterizing it with little or no rainfall annually therefore MAR implementation serves as a solution to diversify its available water resources. In addition to that, it increases the estimated natural recharge rate in wellfields. With regard to the knowledge, tools and techniques used in this research I recommend the launch and implementation of MAR in Palla Road wellfields. This has been proven to be a substantial investment that improves and contributes positively to the water security of countries that are already practicing different MAR technologies for example, Namibia were some of the wellfields were completely replenished and also encourages an integrated approach of water management. Furthermore, extensive research based on the hydrogeological characteristics to access the potential of managed aquifer recharge in Palla Road wellfields is needed.

5.2 RECOMMENDATION

It is evident that most rivers are dependent on groundwater, therefore its information is essential. Groundwater knowledge (capacity building) should be enforced in the general public in order to ensure that aquifers are well preserved and the risk to contamination and pollution is reduced.

Also, I suggest that The Government of Botswana needs to integrate long-term reliability mechanisms that can ensure that groundwater data is easily accessible and shared amongst other countries. Furthermore, borehole monitoring is common in many countries however, a database where all this information can be found is highly recommended for easy access and availability.

In terms of water policies in Botswana, there are gaps that need to be filled including that of the conjunctive use of use of surface water and groundwater. This will also ensure that there is open access to available data for researchers and others. Addressing the limitations that were incurred when conducting the research, further studies in this domain is also a necessity.

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APPENDICES

Appendix A

Station: Mahalapye													
Mean Monthly Minimum Temperatures													
Year	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Annual Av.
2000/01	4.10	7.70	12.70	16.00	17.10	18.40	19.80	18.80	16.90	14.70	9.00	5.80	13.42
2001/02	5.70	9.90	13.30	17.10	18.20	18.50	18.90	19.10	18.00	14.40	9.70	6.80	14.13
2002/03	5.30	11.20	12.90	16.60	18.00	19.40	20.30	21.10	17.70	15.40	10.10	9.00	14.75
2003/04	5.70	8.50	13.40	17.60	19.80	20.20	19.10	19.30	17.90	14.80	8.70	6.30	14.28
2004/05	4.70	9.50	12.10	16.30	19.90	19.50	20.60	19.50	17.80	15.50	10.70	8.80	14.58
2005/06	5.70	12.20	14.60	17.80	19.00	18.50	19.80	19.50	17.10	13.30	7.90	6.30	14.31
2006/07	6.60	8.70	11.40	18.40	18.60	20.60	19.20	20.20	18.50	15.30	7.50	6.50	14.29
2007/08	5.00	8.60	14.70	16.20	17.90	17.60	18.00	17.70	16.90	11.40	9.90	6.10	13.33
2008/09	6.60	9.30	12.60	17.90	19.40	19.20	19.90	18.10	16.60	12.30	9.80	7.80	14.13
2009/10	4.80	7.10	13.50	17.00	17.40	19.40	20.30	20.20	18.40	16.50	11.70	5.60	14.33
2010/11	5.90	7.60	13.20	17.20	18.60	18.00	19.20	17.80	17.60	15.30	11.10	5.70	13.93
2011/12	3.90	7.10	11.00	15.00	17.80	17.20	17.40	18.60	16.80	11.90	8.10	5.10	12.49
2012/13	4.80	7.50	11.80	15.90	17.40	17.50	18.20	18.00	16.70	12.70	8.10	5.80	12.87
2013/14	6.20	7.10	13.20	15.50	19.20	18.40	18.30	17.60	16.70	11.60	7.90	4.40	13.01
2014/15	3.80	7.30	11.50	15.20	17.50	18.40	18.80	18.70	18.60	14.90	11.00	6.50	13.52
2015/16	7.40	9.60	15.00	18.70	19.10	21.70	20.90	21.10	17.90	15.00	9.40	7.30	15.26
2016/17	5.50	8.30	15.50	19.00	19.00	8.30	19.30	19.40	16.60	14.20	9.60	7.10	13.48
2017/18	7.80	9.80	12.88	16.90	14.50	19.60	19.44	19.70	18.50	14.60	10.60	7.00	14.28

2018/19	5.30	12.40	14.70	15.50	19.30	20.90	20.10	20.20	20.20	15.70	10.30	7.10	15.14
2019/20	5.90	12.00	13.20	18.70	20.10	20.30							

Botswana Department of Meteorological Services

Table 1:Mean monthly Minimum Temperature

Station Mahalapye													
Mean Monthly Maximum Temperatures													
Year	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Annual Average
2000/01	21.90	25.90	29.20	31.10	31.20	31.80	34.40	29.70	28.20	27.80	25.50	23.20	28.33
2001/02	22.40	27.70	29.50	31.70	28.40	29.90	33.30	33.20	32.90	30.00	26.90	22.30	29.02
2002/03	24.70	26.60	28.30	31.30	32.00	32.10	34.50	33.40	31.80	30.90	26.40	21.50	29.46
2003/04	22.90	25.50	29.50	31.40	32.80	31.30	29.80	29.60	26.10	26.80	25.80	22.20	27.81
2004/05	22.90	27.70	28.70	31.10	33.90	30.70	32.60	32.80	30.60	27.30	26.80	25.90	29.25
2005/06	23.50	28.40	31.40	33.00	32.80	30.30	29.50	29.60	26.50	27.00	24.40	23.00	28.28
2006/07	24.50	24.50	27.90	32.40	31.90	33.60	36.20	34.10	32.80	28.00	25.60	23.20	29.56
2007/08	22.30	26.00	30.80	28.10	30.70	27.00	28.10	31.20	29.20	28.00	26.40	24.30	27.68
2008/09	22.80	27.50	31.30	33.30	30.80	31.30	31.60	29.70	27.40	28.00	25.80	23.30	28.57
2009/10	20.60	25.00	30.10	31.00	30.30	32.70	32.20	32.30	31.30	25.80	25.40	21.80	28.21
2010/11	21.70	25.20	30.60	33.60	30.50	30.80	28.40	29.60	30.70	26.40	25.40	23.40	28.03
2011/12	21.50	24.60	30.80	32.20	31.80	28.80	32.30	32.20	32.20	28.50	27.30	23.40	28.80
2012/13	24.00	27.10	29.90	30.10	31.60	30.50	30.50	33.30	31.10	28.70	26.10	25.30	29.02
2013/14	23.40	25.90	31.40	31.10	33.70	29.30	30.30	29.30	27.30	26.00	27.80	24.30	28.32
2014/15	23.30	26.20	30.70	31.60	31.00	30.50	31.50	34.30	31.50	28.10	28.80	22.20	29.14

2015/16	24.00	27.90	29.20	34.00	32.90	35.00	32.70	33.10	29.20	28.40	24.50	22.90	29.48
2016/17	22.51	25.54	29.22	30.88	31.00	31.00	29.40	28.00	29.10	27.40	25.80	24.30	27.84
2017/18	24.00	25.50	29.22	37.40	31.20	31.00	31.38	29.30	29.30	27.80	26.20	24.20	28.87
2018/19	21.70	28.70	32.40	30.90	31.70	33.70	32.00	32.10	33.90	27.40	26.20	23.40	29.51
2019/20	24.30	28.00	29.30	33.60	33.10	31.60							

Botswana Department of Meteorological Services

Table 2: Mean Monthly Maximum Temperatures

APPENDIX B: Overview of data used for thematic layers

Thematic layers	**Source**	**Link**	**Resolution**
DEM	CGIAR-CSI GeoPortal	http://srtm.csi.cgiar.org/	90m
Land cover	ESA (European Space Agency)	http://2016africalandcover20m.esrin.esa.int/download.php	
AWC	FAO-UNESCO) GeoNetwork	http://www.fao.org/geonetwork/srv/en/metadata.show%3Fid=14116	
HSG	FAO-UNESCO) GeoNetwork	http://www.fao.org/geonetwork/srv/en/metadata.show%3Fid=14116	