Using coupled atmospheric-unsaturated zone model to quantify groundwater recharge to the Table Mountain Group Aquifer system, George, South Africa

By
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In

Environmental and Water Sciences

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Declaration

I, **Nangamso Tuswa** declare that "*Using coupled atmospheric-unsaturated zone model to quantify groundwater recharge to the Table Mountain Group Aquifer system, George, South Africa*" is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name: **Nangamso Tuswa**

Signed…......................................

Date….................................

Contribution to knowledge through publication

The following final report was submitted to the Water Research Commission (WRC)

Bugan, R.D.H., Mapeto, T., **Tuswa, N**., Gush, M., Jovanovic, N., Kapangaziwiri, E., Dzikiti S., 2018. The Impacts of Commercial Plantation Forests on Groundwater Recharge and Streamflow. WRC Report no K5/2443 (Technical report). Water Research Commission, Pretoria.

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List of Abbreviations and Notations

AET	Actual Evapotranspiration
ARC	Agricultural Research Council
AWS	Automatic Weather Station
CAB	Cation-Anion Balance
CFB	Cape Fold Belt
Cl	Chloride
$\boldsymbol{Cl_{gr}}$	Chloride concentration in groundwater
$\boldsymbol{Cl_{r}}$	Chloride concentration in rainwater
CMB	Chloride Mass Balance
CV	Coefficient of Variance
CRD	Cumulative Rainfall Departure
CSIR	Council for Scientific and Industrial Research
DWS	Department of Water and Sanitation
EARTH	Extended model for Aquifer Recharge and Moisture Transport through Unsaturated Hardrock
EC	Eddy Covariance
ET	Evapotranspiration
GMWL	Global Meteoric Water Line
GWL	Groundwater Level
HM	Harmonic Mean
HPV	Heat Pulse Velocity

HRM - Heat Ratio Method

LGR - Los Gatos Research

LMWL - Local Meteoric Water Line

mamsl - metres above mean sea level

MAE - Mean Absolute Error

MAR - Mean Annual Runoff

mbc - metres below collar

mbgl - metres below ground level

NMMU - Nelson Mandela Metropolitan University

$\delta^{18}O$ - Oxygen-18 isotope (‰)

$\delta^{2}H$ - Deuterium isotope (‰)

PE - Potential Evaporation

PET - Potential Evapotranspiration

PT - Potential Transpiration

RIB - Rainfall Infiltration Breakthrough

RMSE - Root Mean Square Error

SANParks - South African National Parks

SAWS - South African Weather Services

SMOW - Standard Mean Ocean Water

SVF - Saturated Volume Fluctuation

Sy - Storativity

T - Tritium (TU)

T - Transmissivity (m^2/day)

TD - Total atmospheric chloride deposition from both rainfall and dry fall out

TMG - Table Mountain Group

UWC - University of the Western Cape

VWC - Volumetric Water Content

WRC - Water Research Commission

WTF - Water Table Fluctuation

List of Frequently used Symbols

Symbol	**-**	**Representation**	**Units/dimensions**
Δh	- -	Change in water level height Related to recharge	[L]
H	-	Water pressure head	[L]
Δt	-	Time interval	[T]
δ	-	Delta notation	
‰	-	Parts per thousand (per mill)	
ET	-	Evapotranspiration	$[L\ T^{-1}]$
MSE	-	Mean square error	$[m^3/m^3]$
pF	-	Suction pressure expressed in logarithm to the base of 10	
R^2	-	Coefficient of determination	[-] or %
S	-	Sink term	$[L^3L^{-3}LT^{-1}]$
θ	-	Volumetric water content	$[L^3L^3]$
x	-	Spatial coordinate	[L]
K	-	Unsaturated hydraulic conductivity	$[LT^{-1}]$
Kc	-	Crop factor	
Kcb	-	Basal factor	
Kr	-	Relative hydraulic conductivity	[-]
Ks	-	Saturated hydraulic conductivity	$[LT^{-1}]$

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Dedication

This thesis is dedicated to my parents for their support and encouragement during the study of my research.

Abstract

The current study aimed at providing groundwater recharge estimates in a fractured rock aquifer environment that is occupied by pine plantation and indigenous forests in order to improve the understanding of the effect of pine plantation forests on recharge. This was based on the argument that for the trees to affect recharge, they do not necessarily need to tap directly from the saturated zone, as vegetation may indirectly affect groundwater recharge by interception and abstracting the infiltrating water in the vadose zone before reaching the water table. The study was conducted along the Southern Cape coastline of Western Cape Province in South Africa. This area is 7 km east of George in an area characterized by the occurrence of the Table Mountain Group aquifer. The research presented in this thesis formed part of a Water Research Commission (WRC) project titled "The Impacts of Commercial Plantation Forests on Groundwater Recharge and Streamflow". To achieve the aim of the current study, three objectives were formulated: i) to characterize the dominantly occurring recharge mechanism ii) to determine long-term groundwater recharge estimates, and iii) to assess the effect of plantation forests on groundwater recharge. As part of characterizing the dominant recharge mechanism in the area, a conceptual groundwater recharge model of the area was developed to explain the recharge mechanism and facilitate an improved understanding of recharge estimates. The model was based on a theoretical understanding and previous investigations conducted in the study area. Methods such as environmental stable isotopes and hydrochemistry were used to refine the conceptual model by identifying the source of recharge and the dominant recharge mechanism. The occurrence and density of lineaments were used as a proxy to delineate potential recharge zones in the area. Recharge was estimated using the Rainfall Infiltration Breakthrough (RIB) and the Chloride Mass Balance (CMB) methods. Additionally, the effect of plantation forests on recharge was assessed using the HYDRUS-2D numerical model. The recharge estimates derived from the RIB and CMB techniques were verified using the published maps by Vegter (1995).

The isotope results revealed that the groundwater was recharged from local rainfall with minimal evidence of evaporation occurring prior to recharge. Based on the isotopic clustering of groundwater samples, there was a difference in signatures between samples collected from boreholes located in higher elevation areas as opposed to boreholes located in lower elevation parts which was theoretical expected. The findings provided an insight about the presence of different groundwater flow systems in the area. The hydrochemistry and isotope results also suggested interconnectivity between groundwater and the stream at the Groenkop site. The groundwater hydrochemical facies of the area was a Na-Cl type, with the dominance of the major cations in order of $Na^+ > Mg^{2+} > Ca^{2+} > K^+$. On the other hand, the anions showed abundance in the order $Cl^- > HCO_3^- > SO_4^{2-}$. Regionally, the major recharge zone of the catchment corresponded with the higher elevation areas (> 1000 mamsl) which are characterized by a dense presence of lineaments and increased annual rainfall (> 1000 mm/year). The dominant recharge mechanism was inferred to be a preferential recharge mechanism which occurred through fractures which was expected in the fractured rock environment. Recharge estimates with the RIB model ranged between 88 mm/year (10% of annual rainfall) in 2011 and 24 mm/year (5% of annual rainfall) in 2017. Recharge estimated with CMB in 2017 amounted to 40 mm/year (6.4% of annual rainfall). When dry chloride deposition from the sea spray and the forests were considered, recharge increased to an average of 108 mm/year (17% of annual rainfall). This suggested that over 83-90% of rainfall is lost through evapotranspiration, converted to streamflow and/or lost through other hydrological mechanisms in the area. The recharge values estimated using the RIB and CMB methods were in agreement with the estimates from the qualified guess method (Vegter, 1995) and were within the range of values previously estimated in the area using a GIS and Water Balance method.

These findings seem to suggest that the RIB and CMB methods can be applied fractured rock environment where pine plantations are practiced characteristics similar to the current study area. The HYDRUS-2D model provided evidence of significant higher potential recharge in the Groenkop indigenous forest when compared to the plantation forests. Over the entire simulation period, the potential recharge at the Groenkop forest site, *Pinus elliottii* site and *Pinus radiata* site amounted to169 mm, 36 mm and 14 mm respectively. The main outcomes of the study were that the model results showed that the plantation forests reduced groundwater recharge at the pine plantation. The model results further contributed to an improved understanding of recharge mechanisms and dynamics in the area. These results were in agreement with other previous studies. Findings from this study may be used to inform the basis designing action plan for groundwater conservation practices in areas where pine plantation forests exist. Since the soil moisture and evapotranspiration parameters are among the main aspects of the Hydrus numerical model, there is a need to continuously monitor them in order to improve the recharge estimates and model different recharge scenarios.

Key words: groundwater recharge**,** Rainfall Infiltration Breakthrough method, Chloride Mass Balance method, HYDRUS-2D, pine plantations, Groenkop forest, environmental isotopes

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Chapter 1: General Introduction

1.1 Synopsis of the study

Although groundwater recharge represents a major component of the water balance of a catchment, the accurate estimation of recharge is still amongst the biggest challenges for hydrogeologists (Nyagwambo, 2006; Parsons, 2014). Numerous environmental concerns have been raised on land use changes influencing the water balance of the catchment. One such concern is the effect of plantation forests on groundwater recharge. It is well acknowledged that plantation forests play a role in altering the water balance at the watershed scale. However, the effect of these forests on groundwater recharge is still a topic that is poorly understood despite being discussed in many hydrological studies (Marechal et al., 2008; Mkwalo, 2011; Dye, 2013; Fan, 2014; among others). Although groundwater recharge has received a lot of attention in the Table Mountain Group (TMG) (Hartnady and Hay, 2000, Wu, 2005, Sun, 2005), limited studies have attempted to assess the effect of vegetation on groundwater recharge in TMG dominated environments. Due to the above-mentioned knowledge gap, this study therefore aims to assess the effect of plantation forests (*Pinus elliottii* and *Pinus radiata*) on groundwater recharge using recharge estimates derived from an area occupied by plantation forests and from an area occupied by indigenous forest (reference). To achieve the aim of the study firstly, dominant recharge mechanism occurring in the area were characterized using qualitative methods such as stable environmental isotopes and hydrochemistry. Secondly, two independent commonly applied techniques, i.e. the Rainfall Infiltration Breakthrough (RIB) method and the Chloride Mass Balance (CMB) method, were both applied to estimate recharge in the area. Thirdly, the HYDRUS-2D numerical model was applied to simulate the two-dimensional water movement in the soil layers to predict the potential recharge rates under the plantation forest and indigenous forest respectively.

1.2 Background to the study

Plantation forestry is an essential economic practice in South Africa and one which the government hopes to further develop (Mkwalo, 2011). These introduced species plantations extend over approximately 1220726 ha in South Africa (Forestry South Africa (FSA), 2016), i.e. 1.1% of the country's total land area and are mainly spread over the high rainfall eastern and southern regions of the country and comprise 51% pine, 42% *Eucalyptus* and 7% Wattle (FSA, 2016). However, the disadvantage of this is that the economic benefits come at some environmental cost, especially the potential effect on water resources. The effects of tree plantations on water yield and catchment hydrology has been long recognised and discussed from as early as 1915 in South Africa (Dye, 2013) and extensive literature exists related to afforestation as a streamflow reduction activity in catchments (Scott and Lesch, 1997; Le Maitre et al., 2002; Dye and Jarmain, 2004 and Mallory, 2006). Commercial forests are estimated to have reduced the mean annual streamflow by approximately 1417 x 10^6 m^3/year or 3.2% on a national scale (Scott et al., 1998). However, there has been relatively limited published studies on assessing the effect of pine plantation forest on groundwater recharge in South Africa. Amongst the early causative factors of this gap in knowledge was the traditional separation of hydrologic science into geohydrology and hydrology which kept the investigation of tree water use in the domain of hydrologists (Le Maitre et al., 1999 and Ngobeni, 2013). By virtue of riparian zones being the ecological niche of invasive species in South Africa, many hydrology studies related to the effect of vegetation on groundwater have mainly focused on the riparian zone in alluvial aquifers and less on fractured rock aquifers (Le Maitre et al., 1999). While according to a study by Marechal et al. (2008), this gap in knowledge was also due to limited direct scientifically reliable evidence on vegetation and groundwater interaction in fractured aquifers particularly.

Plantation forests exhibit higher evapotranspiration rates when compared to that observed in indigenous forests (Chamier et al., 2012), leading to a potential reduction in streamflow and groundwater recharge. Such effects appear to vary depending on climate variability, geology and tree species (Silveria et al., 2016). Vegetation may affect groundwater recharge indirectly by rainfall interception losses as well as extraction of infiltrating water before reaching the water table/saturated zone (Fan, 2014). Limited studies have been conducted on the east coast of South Africa, which have quantified in detail the impact of different plantation forests on groundwater and the interactions with surface water. Clulow et al. (2011) studied the deep rooting impacts of *Acacia mearnsii* on soil water levels down to 5 m and concluded that the trees were “mining” soil water and groundwater reserves as their ET rates exceeded rainfall amounts. Brites and Vermeulen (2013) also conducted an investigation on the impact of different timber species (*Pinus elliottii* and *Eucalyptus Grandis Camaldulensis*) on groundwater levels in a coastal plain environment in the Nyalazi Plantation, KwaZulu-Natal. The study reported that the *Eucalyptus* forest had a significant impact on the local groundwater system, as they observed lowering of the groundwater level of between 10 and 16 m over a period of 13 years, which equates to an average decline of 1 m/year. Albhaisi et al. (2013) applied a hydrological model (WetSpa) to quantify the impacts of land use change on groundwater recharge in the Upper Berg catchment (TMG Aquifer), South Africa. Their study reported a systematic increase in recharge of about 8% per year over a 21 year period, which was due to clearing of the vegetation in the area.

While more attention seems to be given to the impact of exotic species on soil moisture, groundwater levels and recharge, the impact of natural forest on recharge is also a question of interest and which is still debated (Marechal et al., 2008). To examine such impacts, Marechal et al. (2008) conducted a study in India on the estimation of groundwater recharge in a humid tropical forest which is characterized by the fractured bedrock underneath. The study made use of the CMB method and the Water Table Fluctuation (WTF) method to estimate recharge, while geophysics and chemistry were used to understand the recharge mechanism occurring in the area. The study reported that localized and indirect recharge was 45 mm/year and 30 mm/year respectively. Evapotranspiration rates were estimated to be between 80% to 90% of rainfall (1050 mm/year) due to water availability and atmospheric demand from the forest. However, such elevated actual evapotranspiration rates from deciduous forests are seldom reported and therefore the study recommended that complementary studies be conducted for confirmation.

Fan (2014) reported that the effect of vegetation on groundwater recharge wasn't limited to direct extraction from the saturated zone only, as vegetation also uses water in the unsaturated zone which may potentially contribute to recharge. Fan (2014) also reported that little attention has been given to quantifying the water percolation processes/mechanisms in the vadose zone and correlating these with groundwater recharge in a vegetated environment. Although invasive vegetation is among the dominant vegetation species, after fynbos, which occur in TMG Aquifer environments, still very few if any studies that have been done on the effect of vegetation on groundwater recharge in the area, which provided motivation for this study.

1.3 Problem statement

To date, there have been limited studies on quantifying the effects of plantation forests on groundwater recharge to fractured rock aquifers. The lack of quantifying the recharge is a problem because uncertainties associated with evapotranspiration rates, which is often the largest outward flux in the water balance may lead to inaccurate recharge estimates and ultimately uninformed decision-making related to the availability and utilization of groundwater resources in environments dominated by pine plantation forests.

1.4 Thesis statement and research question

Literature exists on the effect of vegetation on groundwater recharge particular in the riparian zone along rivers (alluvial aquifers), where groundwater levels are relatively shallow and the root system accesses water close to the capillary fringe or directly from the water table/saturated zone. However, the present study argues that for the trees to affect recharge they do not necessarily need to tap directly from the saturated zone. The study hypothesizes that vegetation may affect groundwater recharge indirectly by rainfall interception losses as well as the abstraction of the infiltrating water before reaching the water table. The research question for the current study is: “What is the effect of the pine plantation forests (*Pinus elliotii* and *Pinus radiata*) on groundwater recharge in a fractured rock aquifer?”

1.5 Study aim and objectives

1.5.1 Aim of the study

The current thesis aims at providing groundwater recharge estimates in a fractured rock aquifer in an area which is occupied by plantations forests and indigenous forests in order to improve the understanding of the effect of pine plantation forests on recharge. Such knowledge can be used to design measures for conserving groundwater resource for its utilization in environments dominated by pine plantation forests.

1.5.2 Specific objectives

1. To characterise the dominantly occurring recharge mechanism.
2. To determine long-term groundwater recharge estimates.
3. To assess the effect of pine plantation forest on groundwater recharge.

1.6 Significance of the study

The study aims to improve the knowledge and understanding of the effects of plantation forests on groundwater recharge in fractured rock aquifers. Such knowledge can be used in groundwater resource management for groundwater utilization and protection to avoid overexploitation of aquifers in environments dominated by pine forests.

1.7 Scope and nature of the study

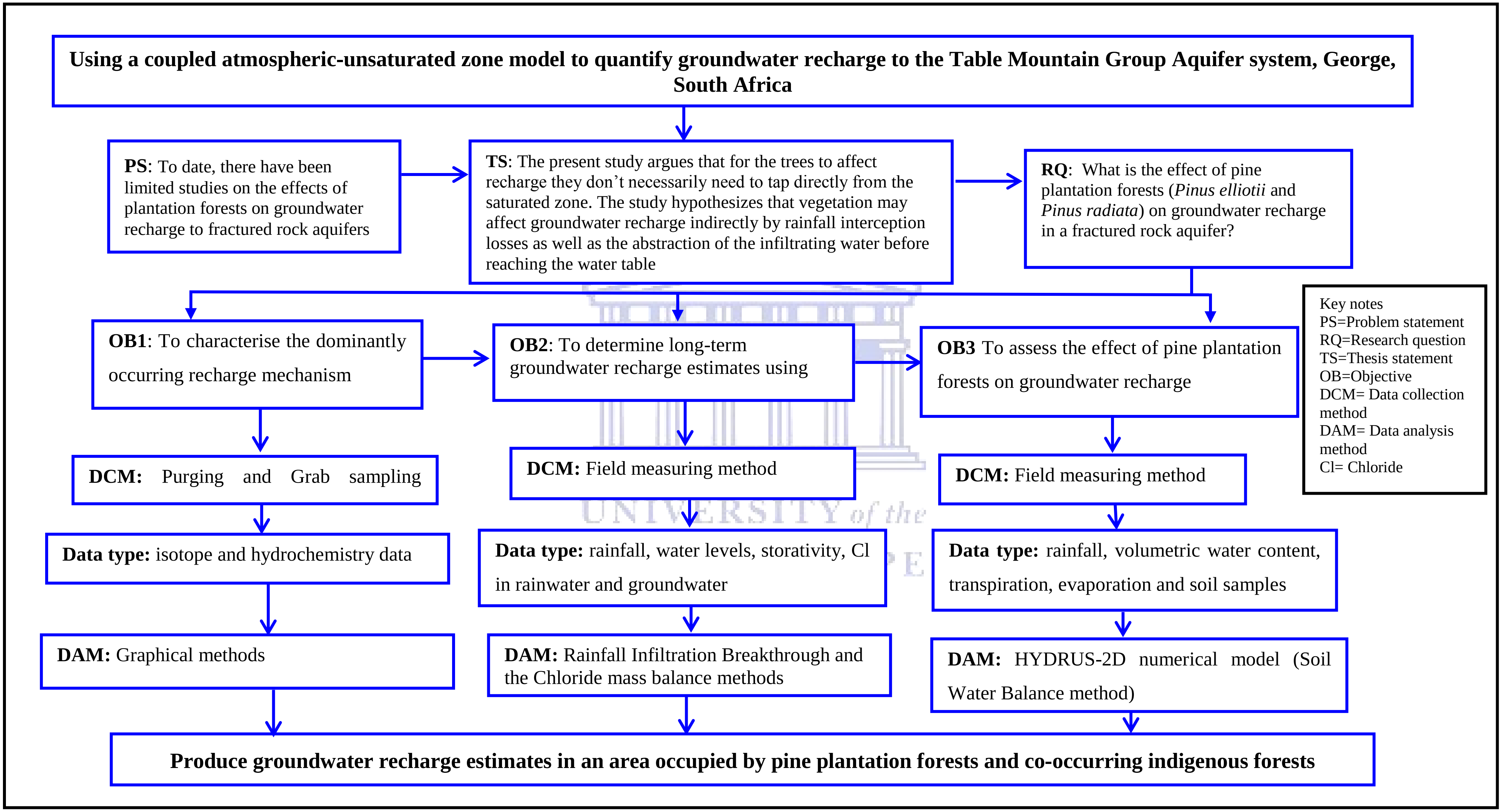
1.7.1 Scope of the study

The current study focuses on the effect of vegetation (*Pinus elliotii* and *Pinus radiata*) on groundwater recharge in a fractured rock aquifer using George as a case study. Although the study area has an area of approximately 190 km^2, the present research mainly focuses on a local scale i.e. the area with the pine plantation compartments and the Groenkop natural forest. Due to the complexity (spatial heterogeneity) of the fractured rock aquifer under investigation a conceptual model of the area was developed to explain the occurrence of the groundwater recharge flow system in the area. The model is based on theoretical understanding and previous investigation conducted in the study area. It should be emphasized that the aim of the thesis is not to develop any action plans and strategies, rather the aim is to improve the understanding of the effect of vegetation on groundwater recharge in fractured rock aquifers. Within the scope of groundwater recharge which includes natural recharge and artificial recharge, the current study mainly focuses on the natural recharge in a vegetated environment. The research presented in this thesis was part of a Water Research Commission (WRC) project titled “The Impacts of Commercial Plantation Forests on Groundwater Recharge and Streamflow”. For this thesis, attention was on the effect of pine plantation forests on groundwater recharge and using recharge estimates from the natural forest as a baseline or reference point. The study focused the following aspects of recharge: recharge zones, recharge mechanism and recharge estimations in order to address the research problem on lack of quantifying recharge estimates.

1.7.2 Description of the nature of the study

The topic of the current study is "using coupled atmospheric-unsaturated zone model to quantify groundwater recharge to the Table Mountain Group Aquifer system, George, South Africa. This topic means that the focus of the study is to quantify groundwater recharge using the coupled atmospheric-unsaturated zone model which was soil-water balance method in the Hydrus 2D Software version (2.04.580) The quantified recharge in indigenous forests was considered as a reference statistics and the quantified recharge in pine plantation forests was taken as change detection (difference between the recharge in the two forests). Therefore, by quantifying the recharge in indigenous and in pine plantation forests, the difference was interpreted to be the effect of pine plantation forests (*Pinus elliotii* and *Pinus radiata*) on groundwater recharge. The study area is located in a fractured rock aquifer system. The study utilized a physical experiment design approach whereby a fractured rock aquifer environment in George was used as a case study to assess the effect of plantation forests on groundwater recharge. In order to estimate groundwater recharge, the study reviewed the relevant existing literature on recharge estimation methods in light of their applicability in fractured rock aquifers. Appropriate methods were chosen based on the feasibility, reliability and data requirements. In order to achieve the research objectives of the study, the research incorporated three steps of research procedures whereby desktop study, fieldwork, laboratory work and data analysis were followed. The study focused the following aspects of recharge: recharge zones, recharge mechanism, and recharge estimations in order to address the research problem on lack of quantifying recharge estimates.

1.8 Framework of the study



Using a coupled atmospheric-unsaturated zone model to quantify groundwater recharge to the Table Mountain Group Aquifer system, George, South Africa

PS: To date, there have been limited studies on the effects of plantation forests on groundwater recharge to fractured rock aquifers

TS: The present study argues that for the trees to affect recharge they don't necessarily need to tap directly from the saturated zone. The study hypothesizes that vegetation may affect groundwater recharge indirectly by rainfall interception losses as well as the abstraction of the infiltrating water before reaching the water table

RQ: What is the effect of pine plantation forests (*Pinus elliotii* and *Pinus radiata*) on groundwater recharge in a fractured rock aquifer?

OB1: To characterise the dominantly occurring recharge mechanism

OB2: To determine long-term groundwater recharge estimates using

OB3 To assess the effect of pine plantation forests on groundwater recharge

Key notes
PS=Problem statement
RQ=Research question
TS=Thesis statement
OB=Objective
DCM= Data collection method
DAM= Data analysis method
Cl= Chloride

DCM: Purging and Grab sampling

DCM: Field measuring method

DCM: Field measuring method

Data type: isotope and hydrochemistry data

Data type: rainfall, water levels, storativity, Cl in rainwater and groundwater

Data type: rainfall, volumetric water content, transpiration, evaporation and soil samples

DAM: Graphical methods

DAM: Rainfall Infiltration Breakthrough and the Chloride mass balance methods

DAM: HYDRUS-2D numerical model (Soil Water Balance method)

Produce groundwater recharge estimates in an area occupied by pine plantation forests and co-occurring indigenous forests

Figure 1.1: Framework of the study

The Figure 1.1 above shows the guide for the current research that was followed in the study. The framework (guide) illustrates the perspective approach of the study and summarizes the entire research work from the problem statement, thesis argument, research question, objectives till the outcome of the study. The thesis focused on providing groundwater recharge estimates in a fractured rock aquifer in an area occupied by plantation forests and indigenous forests in order to improve the understanding of the effect of pine plantation forests on recharge. The problem that is being investigated in the current study is the lack of quantified recharge of groundwater in the pine plantation forests alongside the unknown effect of such forests on groundwater recharge estimates especially in fractured rock aquifer system. To achieve such aim, the three objectives were formulated as presented in Figure 1:1 which are characterizing the dominantly occurring recharge mechanism using environmental stable isotopes and hydrochemistry analysis methods; determining long-term groundwater recharge estimates using the RIB and CMB methods; and assessing the effect of plantation forests on groundwater recharge using a HYDRUS-2D numerical model as elaborated in section 1.7.2.

1.9 Outline of the thesis

The present study is divided into eight chapters as follows: Chapter 1 presents an outline of general introduction and background of the study, problem statement, and research question, significance of the study and scope and nature of the study. Chapter 2 provides a description of the study area with emphasis on features that are likely to influence groundwater recharge in the area. Attention is given to rainfall as the source of groundwater recharge in the area, geology as a host media of the recharge water and hydrology (surface water bodies) as a potential source of localized recharge. The chapter further highlights how vegetation, soil, slope play a role in recharge processes in the area. By inter-relating these factors, a clear description of recharge processes in the area was obtained. Chapter 3 provides the theoretical and empirical reviews including the conceptual understanding that guided the study. In addition, chapter 3 presents the reviewed literature in an analytical and systematical manner in order to provide what is known and unknown about recharge and the effect of pine plantation forests on groundwater recharge in South Africa and internationally. Chapter 4 describes the research design and methodology that was applied in collecting and analyzing the data during the study, highlighting their advantages and disadvantageous. Chapter 5 presents and discusses results on conceptual recharge model and the application of qualitative methods i.e. environmental stable isotopes and hydrogeochemistry, on assessing the recharge mechanism occurring in the area. Chapter 6 presents and discusses the recharge estimations produced with the RIB and CMB methods. Chapter 7 presents and discusses results of the effect of pine plantation forests on groundwater recharge using the HYDRUS-2D numerical model. Chapter 8 provides the main conclusions and suggested recommendations based on the findings of the study. The Appendices provides supplementary documentation in support of the findings of the study.

Chapter 2: Description of study area

2.1 Introduction

This chapter presents the study area description with emphasis on features that are likely to influence groundwater recharge in the area. Attention is given to rainfall as the source of groundwater recharge in the area, geology as a host media of the recharge water, hydrology (surface water bodies) as a potential source of localized recharge. The chapter further highlights how vegetation, soil and slope play a role in recharge processes in the area. By inter-relating these factors, a clear description of recharge processes in the area was obtained.

2.2 Location of study area

The study area is located on the Southern Cape coastline of South Africa about 7 km east of the town of George within the Western Cape Province (Figure 2.1). The area falls within quaternary catchment K30C that is approximately 190 km^2 (Figure 2.2). The catchment is located between latitudes 33º56'27.38" S and 33º 56'24 .13"S, and longitudes 22º33'47.34"E, and 22º28'46.24"E.

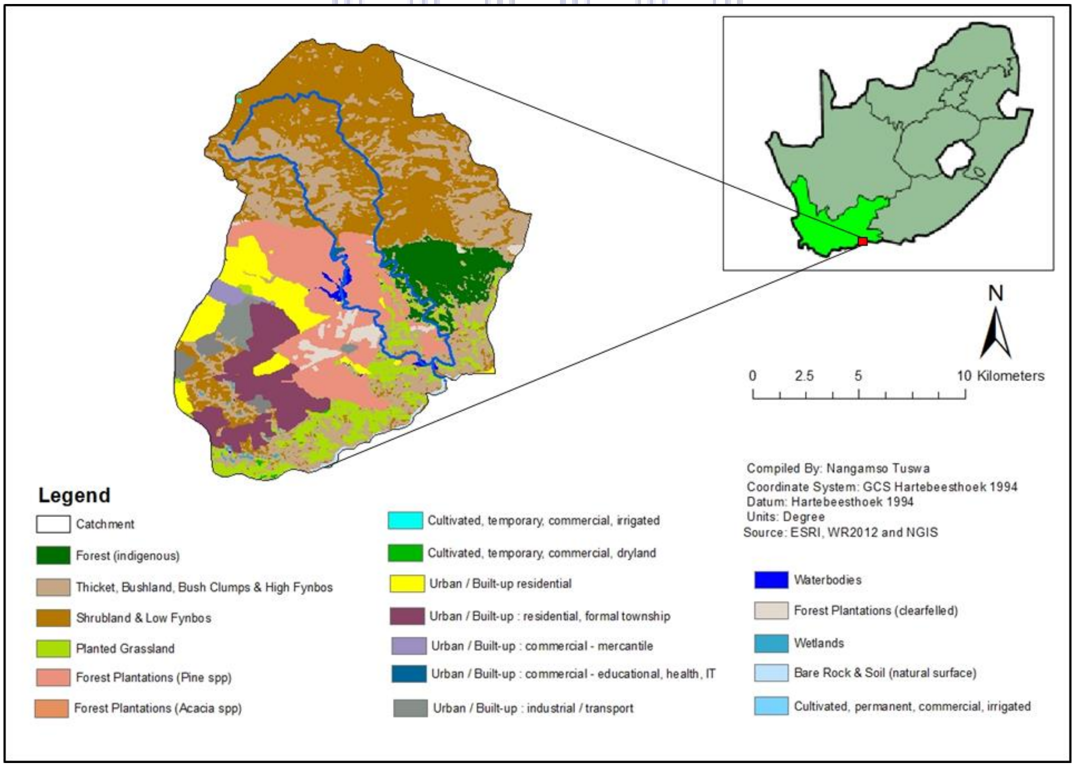


Figure 2.1: Study area map with various land uses within the catchment

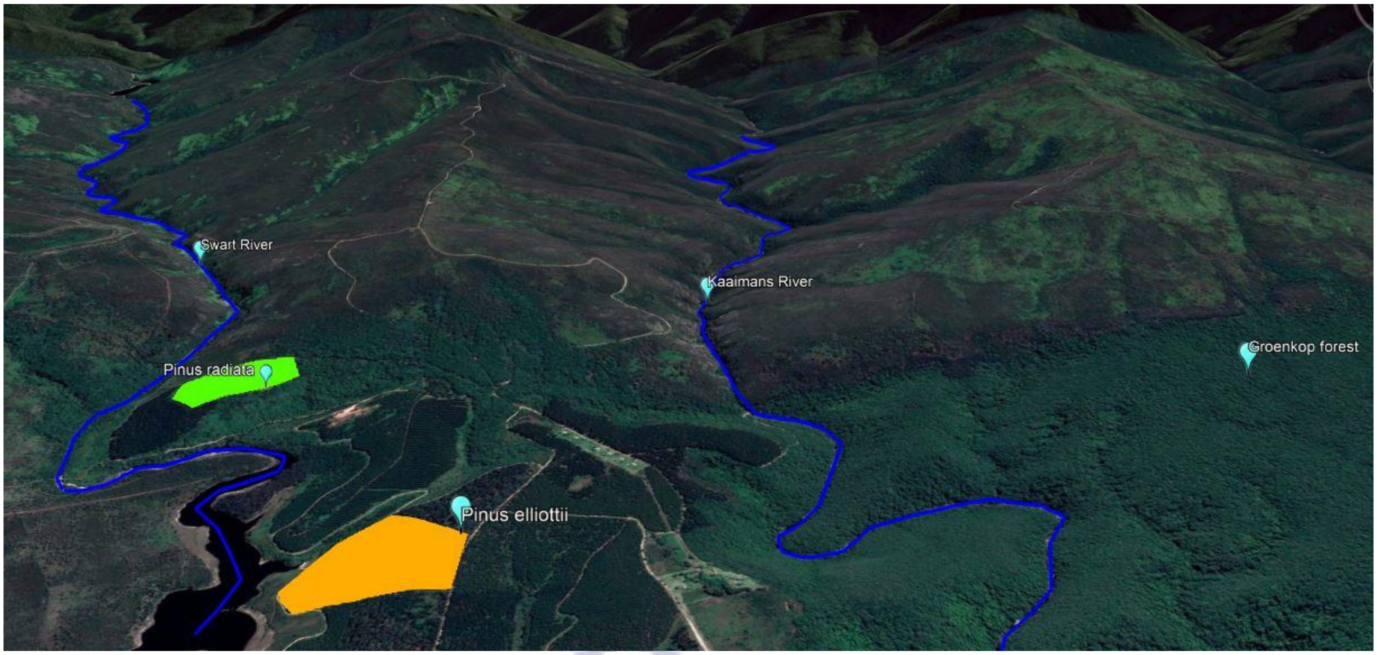


Figure 2.2: Study area map, the polygons delineate the plantation compartments which were studied, i.e. *Pinus elliotii* (brown) and *Pinus radiata* (green). (Source: Google Earth Pro, 2016)

2.3 Influence of climate on recharge

In this study, climate mainly refers to rainfall and evapotranspiration as they are the meteorological parameters that primarily influence recharge in the area. The Southern Cape is located in the transition zone between the winter rainfall Mediterranean climate of the Western Cape and the Subtropical summer rainfall characteristics of the rest of the country (Parsons, 2014). The area experiences a mean annual precipitation (MAP) of 863 mm with rainfall events being distributed throughout the year (Figure 2.3, Schulze and Lynch, 2007). Rainfall peaks generally occur during autumn (March) and early summer (October - November, Geldenhuys, 1991). The occurrence of rainfall in the area is generally a result of cold fronts from the south-west, while the area is also subjected to orographic rainfall from the high lying areas of Outeniqua Mountain Ranges which is an important source of recharge in the area.

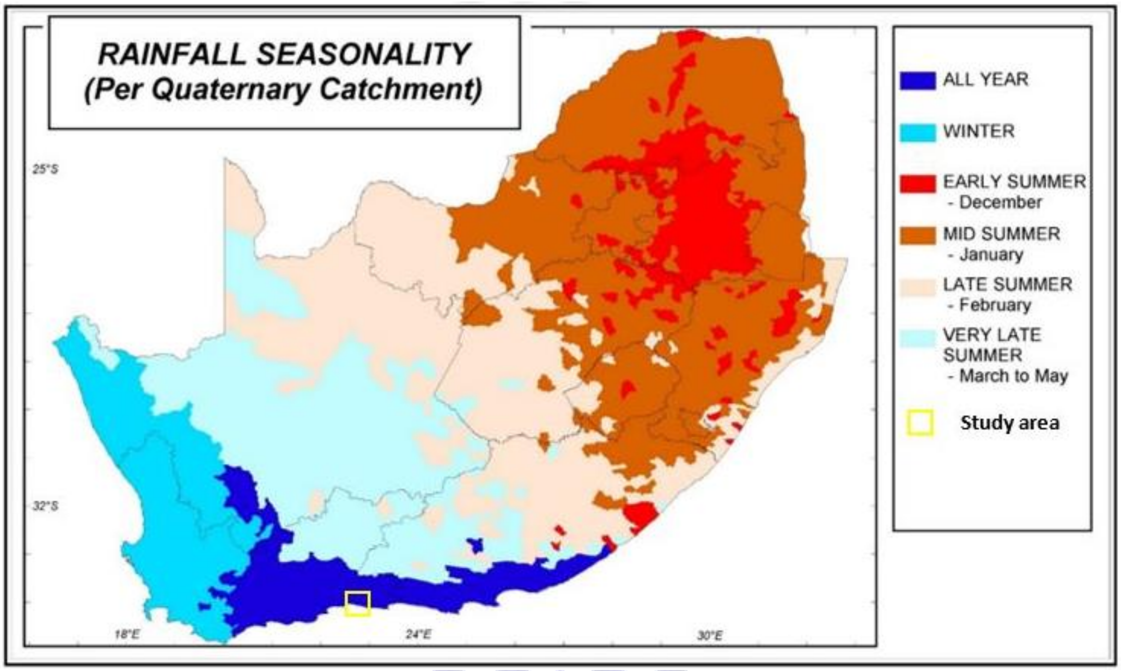


Figure 2.3: Rainfall seasonality per quaternary catchment in South Africa (Schulze, 1997)

Figure 2.3 above shows the rainfall seasonality per quaternary catchment in South Africa. The yellow square on the map represent the study area where the current research is undertaken. From the map it can be observed that the study area does not have distinct dry and wet season, rainfall is generally distributed throughout the year.

2.4 Geomorphological influences on recharge

2.4.1 Influence of vegetation on recharge

Influence of vegetation on groundwater recharge can be appreciated in various ways, vegetation can influence recharge by interception and transpiration (Wu, 2005). However, decaying roots can provide preferential flow channel which can enhance recharge (Healy, 2010). The vegetation in the catchment mainly consists of Groenkop indigenous vegetation, fynbos, pine plantation (Saasveld plantations) and some cultivated areas (Figure 2.1). The Saasveld plantations are dominated by numerous compartments of *Pinus elliotii*, *Pinus radiata* and *Eucalyptus* species. The *Pinus* species may be classified as mid-rotation (8 - 12) years (Figure 2.2). These are mainly harvested at the age 25 years and are used for making pinewood furniture. The forest is described as a medium, moist afrotemperate forest, and a total of 87 species have been recorded in the forest (Gush, 2011). The effect of timber plantation species on groundwater resources has been reported, where pine trees use enormous soil water thereby preventing aquifer recharge or by extracting water direct from the capillary fringe (Brites and Vermeulen, 2013). Therefore, groundwater recharge is expected to be less or reduced at the pine plantation than at the natural forest.

2.4.2 Influence of soils characteristics on recharge

Soil hydraulic conductivity and permeability play a role in regulating the timing and magnitude of recharge rate. The soils in the area are generally derived from the weathering of quartzitic sandstone of the TMG which produces fine sandy soils (Figure 2.4), while the shale rock weathers into more clayey structured soils (Schafter, 1992). The soils in the area are described as deep duplex loams to deep colluvial sandy and clay loams, with a clay subsoil commonly occurring at 400 - 600 mm depth restricting soil moisture (Figure 2.5) and drainage to the lower horizons (Schafter, 1992). Therefore, the clay horizon is expected to limit or delay infiltration rates from rainfall and ultimately recharge in the area.

Figure 2.4: Vertical soil profile at *Pinus elliottii* compartment plantation. The sandy loam soil is derived from the weathering of the quartzitic sandstone of the TMG

Figure 2.5: Soil profile at the *Pinus radiata* compartment illustrating the dominant soil types (sandy loam and clay) and root system

2.4.3 Influence of slope type on recharge

The catchment extends from the Outeniqua Mountain range mountain, which is approximately > 1000 meters above mean sea level (mamsl), down towards the coastline. The area is mainly dominated by seaward-dipping stratus with slopes decreasing in a southerly direction towards the sea (Figure 2.6). The landform of the area is mainly controlled by the structures and lithology of TMG outcrops and the Kaaimans Group. Wu (2005) reported that effective recharge in the outcrops of TMG area occurs in slopes less than 30° whereas strata dipping in the opposite direction hampers the recharge. Although the study area is on a hillslope, minimal overland flow occurs due to the dense vegetation and soil properties. Therefore, high infiltration and subsequently high recharge is expected to occur especial during the season when evapotranspiration rates are low.

2.5 Hydrological influences on recharge

In this study, the focal point of reviewing the literature on surface water bodies is drawn from the notion that accumulation of rainfall in surface water bodies may infiltrate and subsequently percolate and recharge aquifers, if conditions permit (Xu and Beekman, 2003). The study area is located in quaternary catchment K30C, which is drained by two main rivers which are the Swart River and Kaaimans River. Both rivers rise in the Outeniqua Mountain Range and flows southwards, topographically down gradient, towards the Indian Ocean. The Swart River feeds the Garden Route Dam, which is the primary water source for the town of George (DWAF 2004a). The Kaaimans and Swart River (Figure 2.6) are perennial and ephemeral rivers respectively (Riemann and Black 2010).

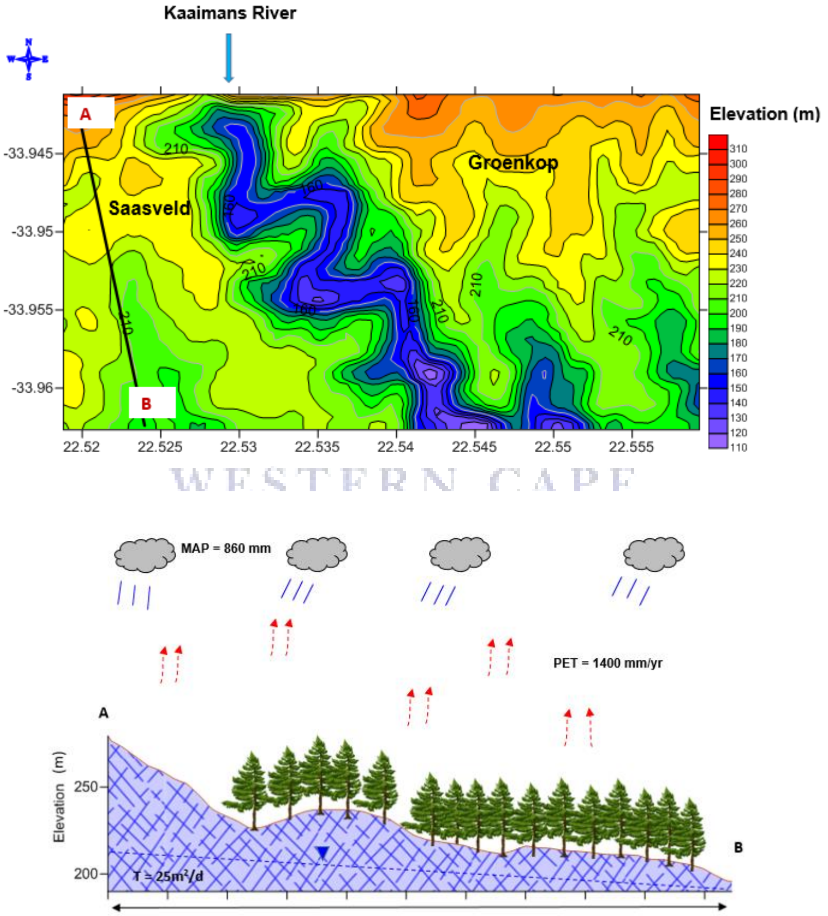


Figure 2.6: A transect along the Saasveld site (A-B) illustrating the dominant seaward-dipping stratus with slopes decreasing (260m to 190m) in a southerly direction towards the sea

2.6 Geological influences on recharge

The study area falls within the Cape Fold Belt, where three different geologically formations exist. The upper part of the study site falls within an area characterized by Peninsula Formation Sandstone, which is part of the TMG (Figure 2.7). The Peninsula Formation comprises mainly of quartic sandstone as well as minor shale and conglomerate. The middle part of the catchment, where the two different *Pinus* species are planted, is mainly made up of the Kaaimans Group which is a metamorphosed sedimentary sequence that exceeds a thickness of 2250m and that is comprised mainly of quartzite, phyllite and schist politic-psammitic rock (Fortuin, 2005). The lower, western part of the catchment primarily consists of the Cape Granite. Since the area mainly consists of fractured rock material, therefore hydraulically connected fractures in this area are expected to enhance rainfall infiltration and preferential recharge. However, the area is mainly covered by vegetation therefore, the aperture of these fractures in the shallow zone might be reduced.

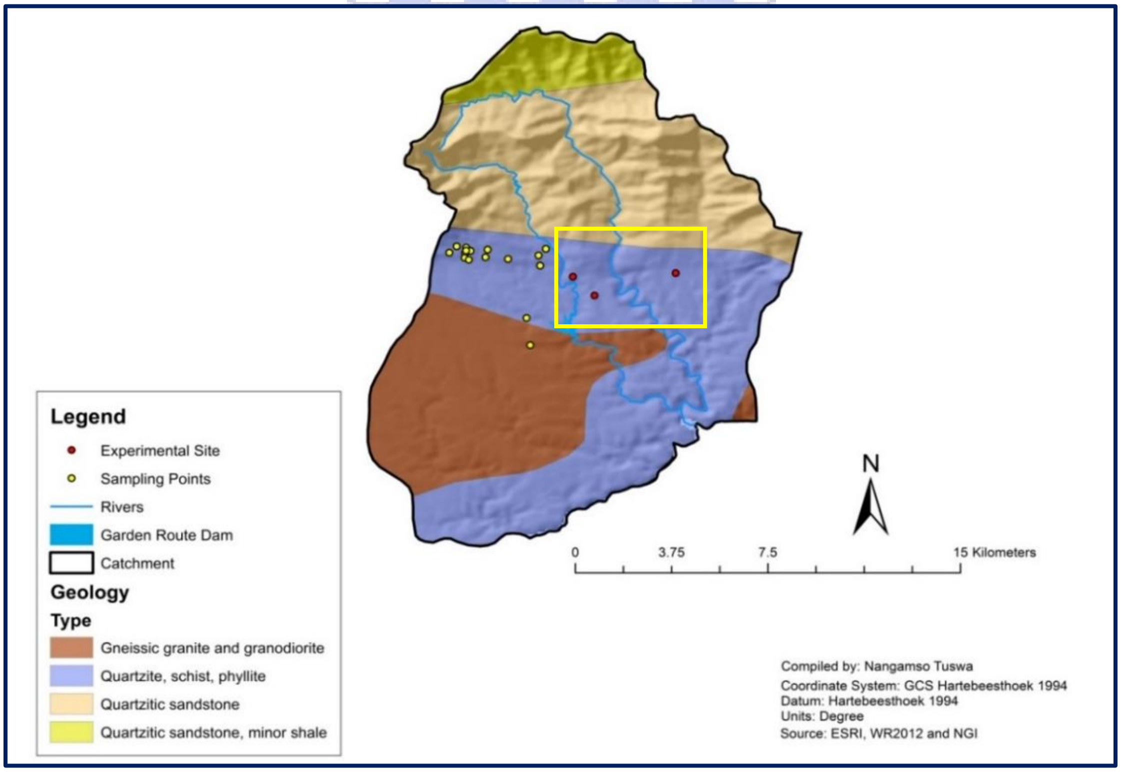


Figure 2.7: Geology map of the study area

Figure 2.7 above shows the geology of the study area with boreholes, the upper part of the site comprises of sandstone while lower part is mainly quartzite, phyllite and schist. The yellow square on the map represent the approximate study area where the current research is undertaken. The red points represent the newly drilled boreholes at Saasveld where the effect of the pine plantation forests was assessed. The yellow points represent additional municipality boreholes that were also used to get more insight about the occurrence of groundwater recharge in the area.

2.7 Hydrogeological setting and Recharge

George falls within hydrogeological unit 15 which is part of the fractured TMG aquifer (Wu, 2005). The unit is bounded by a watershed in the north, by a coastline boundary in the south, drainage boundary on the west and Outeniqua fault zone on the east (Wu, 2005). The study area comprises of two major water-bearing rocks namely the sandstone rock from the Peninsula and Skurweberg Formation (TMG) and the fractured shale rock aquifer from the Saasveld Formation. However, the granite rocks may also form minor aquifers if subjected to faulting and fracturing or where weathered basins occur. Transmissivity values in the sandstone are approximately 100 m^2/day while in the shale rock they approximately 25 m^2/day (Figure 2.8). The borehole yields generally correlates with the lithology and transmissivity, the sandstone rock aquifers generally yield about 0.5 - 2l/s, while the shale and the intergranular- fractured granite rock yield about 0.1- 0.5l/s (Figure 2.8). Groundwater electric conductivity (EC) in the upper catchment ranges from 13 - 14 mS/m while boreholes drilled within the Saasveld formation (quartzite, schist and phyllite) reflect ranges from 36 - 114 mS/m. There is progressive increase in EC and total dissolved solids (TDS) from the upper part of the catchment down gradient towards the lower southern coastal part of the catchment as groundwater moves and interacts with minerals in the bedrock. The rugged outcrop sandstone mountains in the area is regarded to be a recharge. According to Fortuin (2005), Wu (2005) and DWAF (2006) recharge in the area is about 17×10^6 m^3 year/9.4% of MAP, 8.075 Mm^3 and 7-10 Mm^3/year respectively.

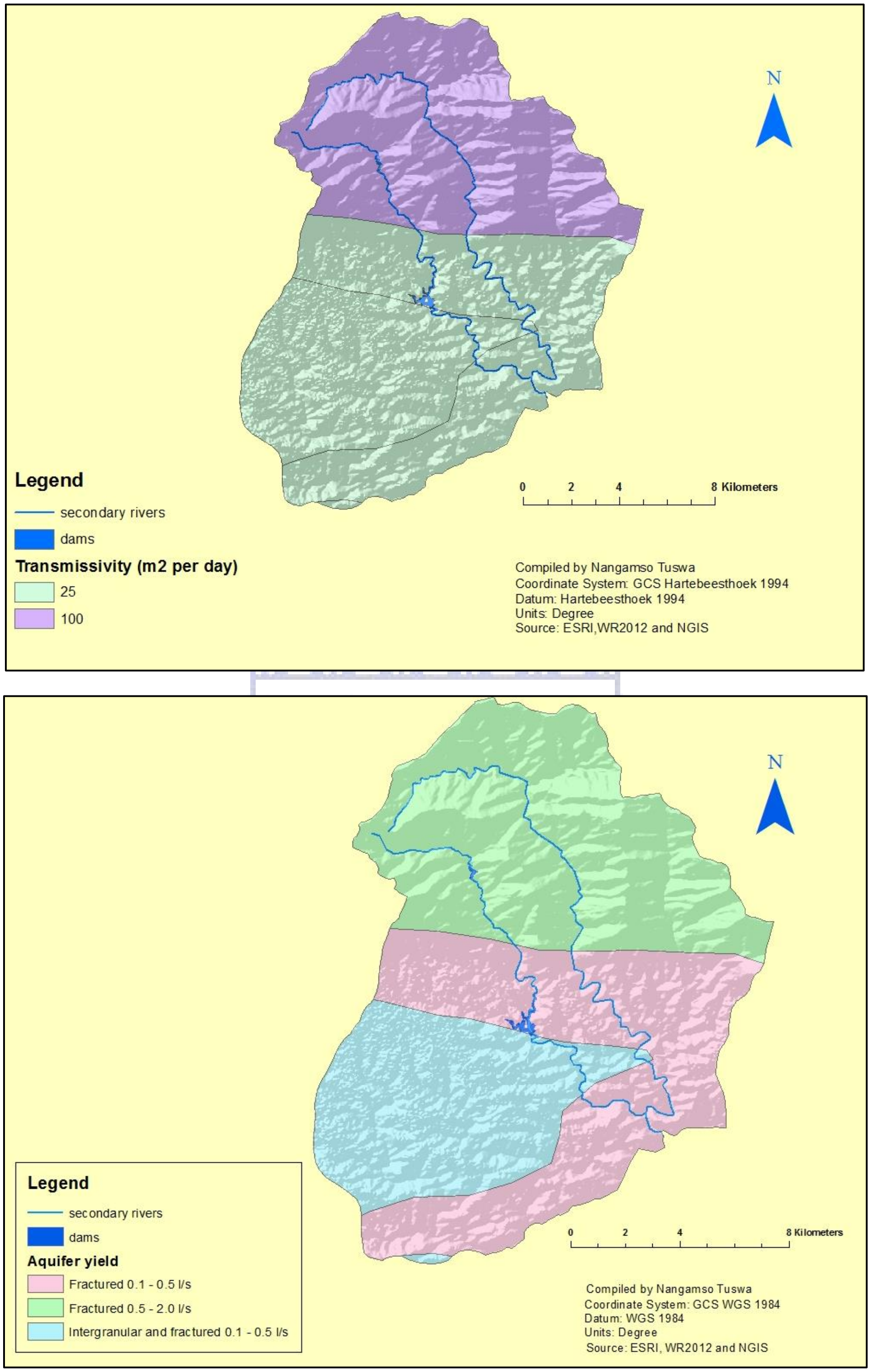


Figure 2.8: The transmissivity ranges (top) and aquifer yields (bottom) map in the catchment

Chapter 3: Literature review

3.1Introduction

This chapter presents related literature and studies about recharge methods and estimations, both local and international. A gap analysis was conducted and attention was also given to the methodological approach used to investigate groundwater recharge in similar hydrogeological environments. The chapter firstly presents and discusses the theoretical information and a conceptual guide of the concept of groundwater recharge for better comprehension of the study. It further presents a literature review in an analytical and systematic manner to highlight what is known and not known about groundwater recharge methods and estimations in South Africa and internationally.

3.2 Theoretical and conceptual framework of the study

3.3.1Theoretical framework of the study

Groundwater recharge is based on the theory of infiltration (Freeze and Cherry, 1979), which is the theory that underpins the current study. The theory involves the movement of water from precipitation, rivers, lakes, or artificial through soil profiles into the saturated zone. The theory of infiltration has been extensively studied by Horton in the early 1930s, however, it is essential to recognize that recharge and infiltration are two separate but related processes that influence water within the groundwater portion of the hydrological cycle. Infiltration is the entry of water into the subsurface (Healy, 2010), while recharge is the residual proportion of infiltration that further percolates through the vadose zone and add water to the aquifer. Infiltration will occur during any day when water is made accessible to the unsaturated zone, whereas most of that water that infiltrates may not reach the water table of the aquifer. Some of the water may be used to replenish soil moisture deficit and some may be returned back to the atmosphere through evaporation/evapotranspiration. As a result, the two terms have been coined in recharge studies, namely potential recharge and actual recharge. In this study, the theory of infiltration is applied or inferred during the interpretation of the results. Where if the unsaturated zone material is permeable and the soil water exceeds field capacity infiltration and recharge is expected to occur. While if vadose zone material is impermeable (clay content) less or delayed infiltration and recharge rates are expected., The present study does however appreciate that the recharge process is a complex process as it is influenced by various aspects such as rainfall duration, intensity, antecedent moisture conditions, soil and geology, hydraulic conductivity and depth to water, amongst others (Parsons, 2014).

3.3.2 Conceptual framework of the study

The concept that is guiding the current research study is groundwater recharge. Groundwater recharge as used in this study is defined as a downward flow of water through the unsaturated zone and reaching the water table (Lerner et al., 1990, Healy, (2010) and Freeze and Cherry, (1979). However, the present study also uses HYDRUS-2D numerical model (see objective 3) which approximates or equates potential recharge to groundwater recharge when the soil moisture exceeds field capacity, infiltration is in excess of evapotranspiration and soil layers are permeable. Groundwater can be recharged naturally through precipitation, rivers, canals, lakes, or by man-induced or artificial which occurs through activities of irrigation and storm drainage system in urban areas (Obuobie, 2008). This process is usually expressed as a percentage of annual precipitation or as an average rate of water in mm/year, while its volume can be expressed as cubic meters per year.

Groundwater recharge can occur through diffuse and focused mechanisms, where diffuse recharge is the recharge that is distributed over a large area in response to precipitation percolating and ultimately reaching the aquifer, whereas focused recharge is the flow of water from surface water bodies and streams to the aquifer beneath (Healy, 2010). Recharge can also be further classified (i) based on the source of recharging water i.e. direct or indirect recharge, (ii) based on the flow mechanisms process i.e. piston or preferential recharge, (iii) based on the area of occurrence i.e. point or areal recharge and (iv) based on the time scale for example present-day, short term or long term recharge. The two major flow mechanisms in arid and semi-arid regions are piston flow, and preferential flow (Figure 3.1), although, in many areas both types of flow mechanisms occur simultaneously, with one may dominate the other (Obuobie, 2008). Piston/ translator flow is when the precipitation stored in the vadose zone is displaced downwards by the next infiltration/ percolation event without disturbance of moisture distribution (Xu and Beekman, 2003). Whereas preferential flow is the flow via preferential pathways and macro-pores (Xu and Beekman, 2003). In this study, understanding the concept of recharge and how it occurs will facilitate a better interpretation of the recharge results.

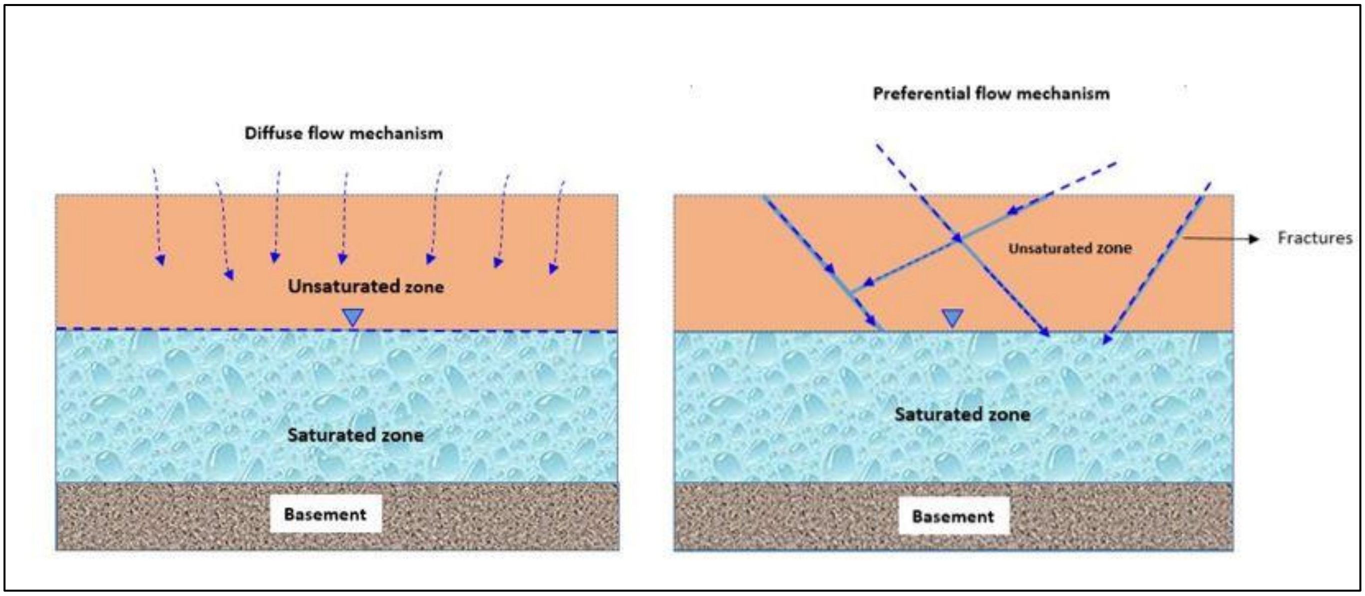


Figure 3.1: Diffuse flow mechanism, (left) and Preferential flow mechanism (right)

Figure 3.1 above shows the diffuse flow mechanism where percolation through the vadose zone occurs over a wide area and tends to be slow and preferential flow mechanism where uniform flow occurs through preferential pathways such as fractures, and tends to be localized and rapid compared to diffuse flow.

3.4 Review of groundwater recharge estimation methods

Numerous researchers (Bredenkamp et al., 1995, Scanlon et al., 2002, Kinzelbach et al., 2002, Van Tonder and Xu, 2001, Xu and Beekman, 2003, Adams et al., 2004, Healy, 2010 among others) across the world have been devoted in developing recharge estimation methods and from time to time recharge equations/algorithms or methodologies have been revised to improve the estimations. As a result a wealth literature exists on recharge methods, with each method having its own limitations (Sun, 2005). Recharge methods can be classified according to hydrologic zones namely surface water methods, unsaturated zone methods and saturated zone methods (Bredenkamp et al., 1995, Scanlon et al., 2002 and Xu and Beekman, 2003) while within these hydrologic zone these categories can be further divided into physical methods, chemical (tracer) and numerical methods (Adams et al., 2004). Surface water and unsaturated zone methods are based on the concept of potential recharge, while saturated zone methods estimate the actual recharge (Xu and Beekman, 2003). It is beyond the scope of this study to review in detail and assess every recharge method. Table 3.1 adopted from Beekman and Xu (2003), compares the commonly used recharge methods in Southern Africa For publications that deal exclusively with recharge estimation methods, the reader is referred to Bredenkamp et al., 1995, Kinzelbach et al., 2002, and Xu and Beekman, 2003, Healy, 2010). For the purpose of this recharge study, particular focus is given to the most promising methods in arid and semi-arid Southern Africa namely the CMB, the Cumulative rainfall departure (CRD) method, Extended model for Aquifer Recharge and soil moisture Transport through the unsaturated Hardrock (EARTH) model, the WTF method, Groundwater models and the Saturated volume fluctuation (SVF) method (Xu and Beekman, 2003).

Table 3.1: Review of common recharge estimation method used for semi-arid Southern Africa (adopted from Beekman and Xu, 2003)

Zone	**Method**	**Limitation**	**Applicability**			**Rating**		
			Flux mm/year	Area (km^2)	Time (years)	Acc.	Ease	Cost
SW	Baseflow	Emphermal rivers	400-4000 (0.1-1000)	10^{-4}-1300 (10-1000)	0.3-50 (1-100)	2	2	1-2
	CWB	Inaccurate flow measurements	100-5000	10^{-3}-10	1d-1yr	2-3	2	3
	WB	Emphermal rivers	1-400	10^{-1}-5×10^{5}	1d-10yr	2	2-3	3
Unsaturated	Lysimeter	Surface runoff	1-500	0.1-30m^2	0.1-6	1-2	3	3
	UFM	Poor known relationship between hydraulic conductivity- moisture	20-500	0.1-1m^2	0.1-400	3	2	2
	ZFP	Subsurface heterogeneity, periods of high infiltration	30-500	0.1-1m^2	0.1-6	3	2	2
	CMB	Long term atmospheric deposition unknown	0.1-300 (0.6-300)	0.1-1m^2	5-10000	2	1	1
	Historical	Poorly known porosity; present ^{3}H levels almost undetectable	10-50 (10-80)	0.1-1m^2	1.5-50	2-3	2-3	3
Saturated - Unsaturated	CRD	Deep (multi-layer) aquifers, sensitive to Specific yield (Sy)	(0.1-1000)	(1-1000)	(0.1-20)	1-2	1-2	1
	EARTH	Poorly known Sy	(1-80)	(1-10m^2)	(1-5)	1-2	2	1
	WTF	In/outflow Sy usually unknown	5-500	5×10^{-5}>10^{-3}	0.1-5	2	1	1
	CMB	Long term atmospheric deposition unknown	0.1-500	2×10^{-6}–>10^{-2}	5->10000	2	1	1
	GM	Time consuming, poorly known transmissivity, sensitive to boundary	(0.1-1000)	(10^{-6}-10^{9})	(1d–20yr)	2	3	2-3

Saturated		Conditions						
	SVF	Flow-through region; multi layered aquifer	(0.1-1000)	(1-1000)	(0.1-20)	1-2	1-2	1
	EV-SF	Confined aquifer	(0.1-1000)	(1-100)	(1-100)	1-2	1-2	1-2
	GD	^{14}C,^{3}H/^{3}He, CFC: poorly known porosity / correlation of dead carbon contribution	^{14}C: 1-100 ^{3}H/^{3}He, CFC: 30-1000	^{14}C, ^{3}H/He^{3}, CFC: 2*10^{-6}->10^{-3}	^{14}C: 200-200000 ^{3}H/He^{3}, CFC: 2-40	3	2	3

HS: Hydrograph Separation – Baseflow

CWB: Channel Water Budget

WM: Watershed Modelling

UFM: Unsaturated Flow Modelling

ZFP: Zero Flux Plane

CMB: Chloride Mass Balance

CRD: Cumulative Rainfall Departure

EARTH: Extended model for Aquifer Recharge and Moisture through Unsaturated Hardrock

WTF: Water Table Fluctuation

GM: Groundwater modelling

SVF: Saturated Volume Fluctuation

EV-SF: Equal Volume - Spring Flow

GD: Groundwater Dating

Concerning the applicability of the techniques, data was adopted from a study by Scanlon et al. (2002). Regarding rates, the approach of accuracy rating was adopted from the study by Kinzelbach et al. (2002) where: Class 1: difference from true value within a factor of 2, Class: 2: within a factor of 5 and Class 3: within a factor of 10 or more (Xu and Beekman, 2003). Ease of application is related to data requirements and data availability and is rated from 1: easy to use to 3: difficult to use i.e. requires experienced and skilled human resource. Cost is rated from 1: inexpensive i.e. few parameters to be collected and analysed, in-house laboratories and etc. to 3: expensive i.e. many parameters to be collected and analysed, specialized sampling equipment required, commercial laboratories and etc. (Xu and Beekman, 2003).

3.4.1 Chloride Mass Balance (CMB) method

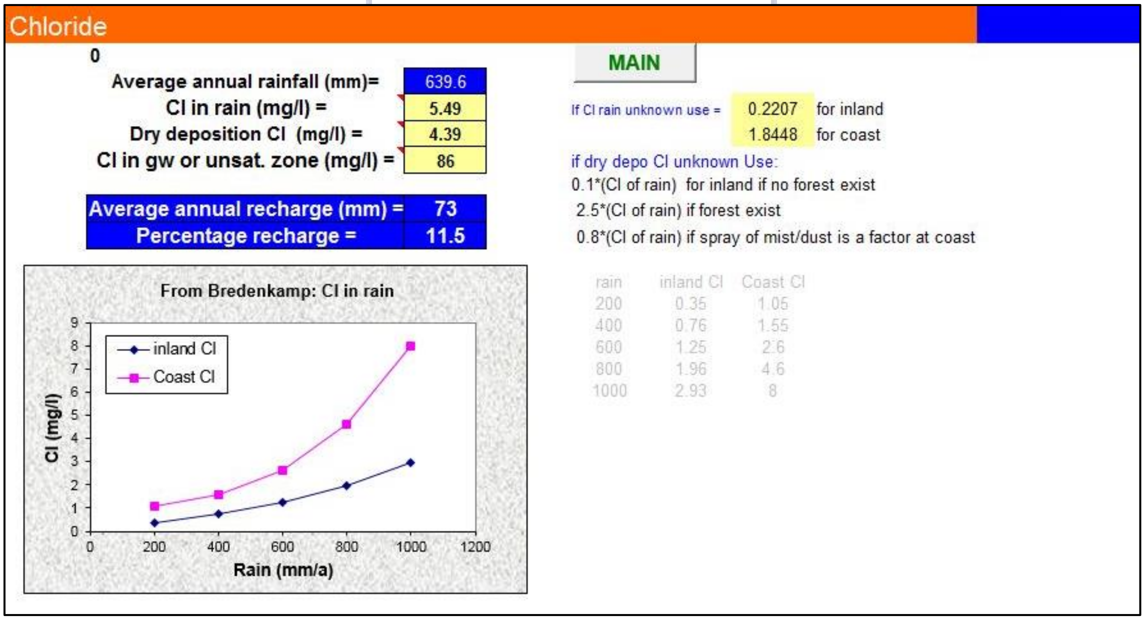
The CMB method is a tracer technique that was first applied by Eriksson and Khunakasem (1969) in the saturated zone of the coastal plain of Israel to estimate groundwater recharge. The technique was later modified by Allison and Hughes (1978) and since then it has been used by numerous researchers including Dettinger (1989), Bredenkamp et al., (1995), Wood (1999), Van

Tonder and Xu (2001), Weaver and Talma (2005), Healy (2010), Van Wyk (2010) and Parsons (2014).

The method is based on the premise that the ratio of the chloride concentration in rainfall to that in unsaturated zone or groundwater is proportional to recharge. This is based on the principle that the chloride ion is highly soluble and non-absorbing during transportation from rainfall through the soil to the aquifer system. The method gained widespread application due to its simplicity and relatively low cost of application (Adams et al., 2004). The graphical user interface of the CMB method (after Van Tonder and Xu, 2000) is presented in Figure 3.3. The general equation for estimating recharge with the CRD method can be written as follows:

$$\textbf{Recharge (mm/yr)} = P \times \left(Cl_{\boldsymbol{r}}/Cl_{\boldsymbol{gr}}\right) \tag{3.1}$$

Where P is the total rainfall, Cl_r (mg/L is the chloride concentration in rain and Cl_{gr} (mg/L is the chloride concentration in groundwater.



0

Average annual rainfall (mm)= 639.6
Cl in rain (mg/l) = 5.49
Dry deposition Cl (mg/l) = 4.39
Cl in gw or unsat. zone (mg/l) = 86

Average annual recharge (mm) = 73
Percentage recharge = 11.5

If Cl rain unknown use = 0.2207 for inland
1.8448 for coast

if dry depo Cl unknown Use:
0.1*(Cl of rain) for inland if no forest exist
2.5*(Cl of rain) if forest exist
0.8*(Cl of rain) if spray of mist/dust is a factor at coast

rain	inland Cl	Coast Cl
200	0.35	1.05
400	0.76	1.55
600	1.25	2.6
800	1.96	4.6
1000	2.93	8

Figure 3.2: The graphical user interface of the CMB method

Figure 3.2 above shows the graphical user interface of the CMB method developed by Van Tonder and Xu (2000). The model is applied in an Excel spreadsheet platform, the model programme code calculates groundwater recharge both from unsaturated and saturated zone using the CMB equation, and in a case of absence of dry deposition chloride data the model has a function of approximating the value.

Although the method is relatively straightforward, Wood (1999) reported that a lack of understanding of the assumptions and boundary conditions on the correct application of the method exists. In addition, although the method is among the most promising techniques in arid and semi-arid Southern Africa (Xu and Beekman, 2003), according to a study by Bean (2003) there are numerous cases in Southern Africa were recharge estimates derived from the technique were found to be unrealistic due to the many limitations of the method. As a result, some authors have suggested that the CMB-derived estimates should always be cross-checked with other methods, and where it is used alone the estimates should be considered as first estimates (Adams et al., 2004, Wu, 2005 and Holland, 2011). Nevertheless, it should be appreciated that many researchers have developed algorithms to incorporate or solve most of the problems associated with the method (Allison and Hughes, 1978, Gieske, 1992, Wood and Sanford, 1995, Wood, 1999, Xu and Van Tonder, 2003; among others). Recharge rates within the TMG aquifer system estimated from the CMB method ranges from 5 - 55% of MAP (refer to Table 3.2). According to a study by Weaver and Talma (2000) maximum recharge values of 55% MAP derived with the use of the CMB method in the TMG aquifers were related to cases where the unsaturated zone was absent. In this present study, CMB method will also be used conjunctively with the RIB method. The method was regarded appropriate as it works independent from a storativity which is difficult to accurately estimate in fractured rock as in the study area.

3.4.2 Cumulative Rainfall Departure (CRD) method

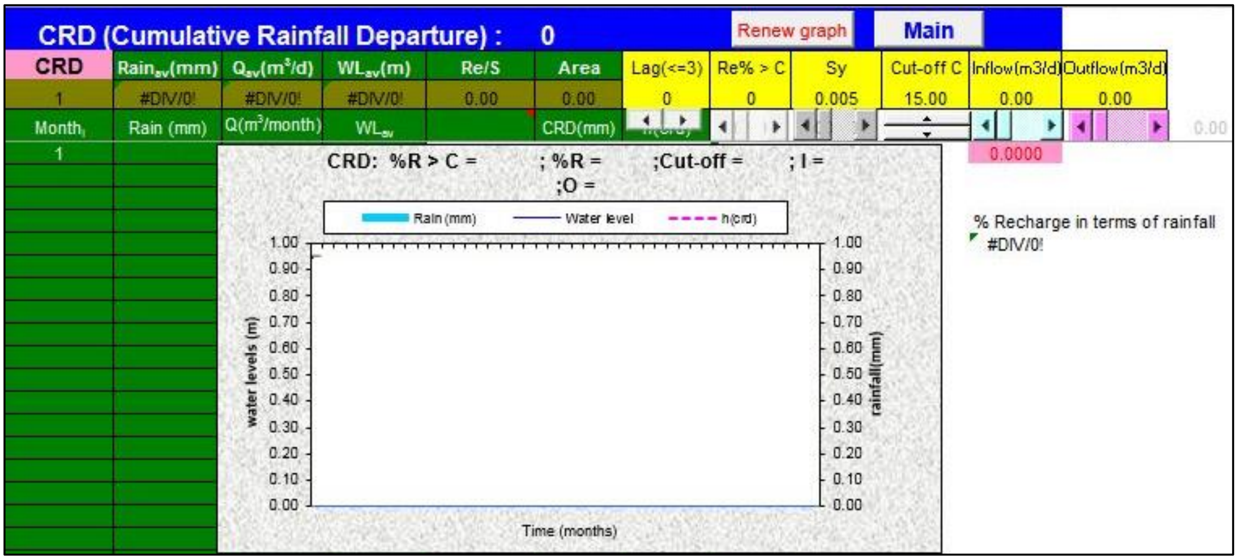
CRD is a method that uses the relationship between groundwater levels and the rainfall pattern to estimate recharge. The technique was introduced 70 years ago (Parsons (2014) and was later described and applied in dolomitic aquifers by Bredenkamp et al., (1995). Van Tonder and Xu (2001) improved the algorithm of the method to accommodate a wide variety of trends in rainfall time series (Adelana, 2010). The method is based on the principle that despite the annual variation in precipitation, over time an equilibrium exists between the average annual precipitation and the hydrological responses such as evapotranspiration, runoff, recharge and other losses (Van Tonder and Xu, 2001, Xu and Beekman, 2003, Adams et al., 2004, Parsons,

2014) The graphical user interface of the CRD model is presented in Figure 3.3. The general equation for estimating recharge with the CRD method can be written as follows:

$$RT = rCRD_i = \mathrm{Sy}[\Delta h_i + (Q_{pi} + Q_{outi}) / \mathrm{A} \times \mathrm{S_y}] \qquad \text{with} \qquad (3.2)$$

$$CRD_i = \sum_{i=1}^{N} R_i - \left(2 - \frac{1}{Rav^i} \sum_{i=1}^{N} R_i\right) \mathrm{i} R_t$$

Where *r* denotes the fraction of a CRD that contributes to recharge, S_y = specific yield, Δh_i is water level during month *i*, Q_p groundwater abstraction, Q_{out} natural outflow, *A* represent recharge area, R_i rainfall for month *i* and R_t is the threshold value representing aquifer boundary conditions (Parsons, 2014).



CRD (Cumulative Rainfall Departure) : 0

CRD	Rain$_{av}$(mm)	Q$_{av}$(m^3/d)	WL$_{av}$(m)	Re/S	Area	Lag(<=3)	Re% > C	Sy	Cut-off C	Inflow(m3/d)	Outflow(m3/d)
1	#DIV/0!	#DIV/0!	#DIV/0!	0.00	0.00	0	0	0.005	15.00	0.00	0.00
Month$_i$	Rain (mm)	Q(m^3/month)	WL$_{av}$		CRD(mm)	h(crd)					
1										0.0000	

CRD: %R > C = ; %R = ;Cut-off = ; I = ;O =

% Recharge in terms of rainfall
#DIV/0!

Figure 3.3: The graphical user interface of the CRD model

Figure 3.3 above shows the graphical user interface of the CRD method illustrating some of the required input data. The model is applied in an Excel spreadsheet platform and has a programming code that enables to manipulate, analyse and display the data. The green colored cells are used for inserting the data while the yellow cells are functions that are used for adjusting to have a good fit between the observed and simulated water levels.

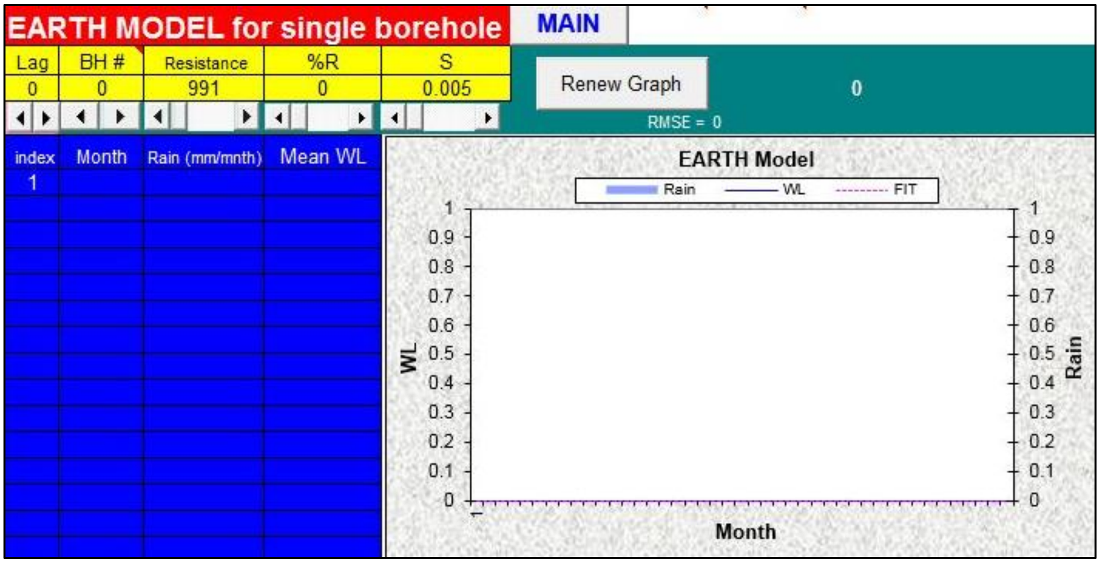
The method is best suited for aquifers with evident groundwater level fluctuations and high storativity (Adelana, 2010, Baalousha, 2005). The technique has been successfully applied in South Africa by a number of researchers (Bredenkamp et al., 1995, Bredenkamp, 2000, Bredenkamp and Xu, 2003, Adams et al., 2004) while international studies includes the work by Baalousha (2005). Although a study by Weber and Stewart, 2003 agreed that CRD concept can be useful to estimate recharge, the study exclusively discussed how misuse of CRD concepts can lead to erroneous and unsupported conclusions regarding hydrological relationships. Though the method is regarded as relatively accurate (Xu and Beekman, 2003a) and has been successfully applied by many researchers, the method is very sensitive to the small storativity in fractured rock aquifers. In a country like South Africa which consists of 90% of hard rock terrain and 10% of alluvial aquifers (Chatterjee and Ray, 2014) this might result in less accurate estimates if unrepresentative and incorrect storativity values are used. Although the hydrogeological setting of the study area conforms to the principles and assumptions required by the CRD method. The present study will not apply the CRD method due to uncertainties in estimating the inflows and outflows from the aquifer.

3.4.3 EARTH model

EARTH (Extended model for Aquifer Recharge and soil moisture Transport through the unsaturated Hardrock) is a lumped parametric model that simulates water levels by coupling climatic data, soil moisture and groundwater levels to estimate groundwater recharge (Sun, 2005). The model was designed by Van der Lee and Gehrels (1990) in Botswana and later tested under different climatic conditions. The model is based on a combination of direct and indirect methods, where the direct method estimates recharge using physical processes above the ground while indirect methods calculate the groundwater levels resulting from the recharge estimated from the direct method (Toure et al., 2016). The graphical user interface of the EARTH model is presented in Figure 3.4. The general equation for estimating recharge with the EARTH model can be written as follows:

$$Sdh/dt = R - h/DR \tag{3.3}$$

Where R is recharge (m^3/month), S is specific yield and dh/dt is change in water level head during the month, DR is the drainage resistance (site specific parameter), h is the groundwater level (Van Tonder and Xu, 2001).



Lag	BH #	Resistance	%R	S
0	0	991	0	0.005

Figure 3.4: The graphical user interface of the EARTH model

Figure 3.4 above shows the graphical user interface of the EARTH model showing some of the required input data to run the model. The model is also Excel-based software and has a programming code that enables to manipulate, analyse and display the data. The blue colored cells are used for inserting the data while the yellow cells are functions that are used for adjusting to have a good fit between the observed and simulated water levels.

The model consists of various modules namely MAXIL, SOMOS and LINRES which represent the direct parts of the model (Nyende et al., 2013). The MAXIL module represents the maximum interception loss and describes the process of interception by means of a character parameter which must be estimated experimentally. SOMOS denotes the soil moisture storage in the reservoir with soil water capacity and a thickness (root zone), while LINRES accounts for the redistribution of the percolation flux in time (Van Tonder and Xu, 2001). SATFLOW is the indirect part of the model and approximations the groundwater levels with the estimated recharge of the direct part (Nyende et al., 2013). The method has been successfully applied in South Africa (Conrad et al., 2004, Nyende et al., 2013, Parsons, 2014). One of the limitations of the method is that the model requires 11 parameters including storativity which is a problem for many physical recharge methods, hence it was not used in this present study. Although the hydrogeological setting of the study area conforms to the principles and assumptions required by the EARTH model. In this current study the EARTH model will not be adopted due to uncertainties of measuring the inflows and outflows from the aquifer.

3.4.4 Water Table Fluctuation (WTF) method

The WTF method is a technique based on the idea that the rises of the groundwater levels in the unconfined aquifer are caused by recharge arriving at the water table (Healy and Cook, 2002; Scanlon et al., 2002). The method assumes that the amount of available water in a column of the unit surface area is equal to the specific yield multiply by the height of the water in the column (Healy 2010). The method is best applied to aquifer systems with shallow groundwater levels showing quick responses to precipitation events (Yamoah, 2013). Key assumption on the application of the WTF method is that the water level rise in the aquifer is caused by only recharge and the influence of lateral flow and evapotranspiration on groundwater storage is negligible within the evaluated period of time (Adelana, 2010). Although the method is regarded as among the most simple and straightforward techniques (Kinzelbach et al., 2002), inflows and outflows are usually unknown (Xu and Beekman, 2003) while the accurate estimation of storativity is a problem. The method has been successfully applied mostly in alluvial aquifers in South Africa (Adelana, 2010 and Gomo et al., 2012), and there is a limited number of studies that have applied it in the TMG aquifer. Although the method is among the widely used technique, due the presence of lag times in the site which the method cannot accommodate the technique was regarded not suitable for the area. The general equation for estimating recharge with the WTF method can be written as follows:

$$R = \frac{Sy\Delta h}{\Delta t} \tag{3.4}$$

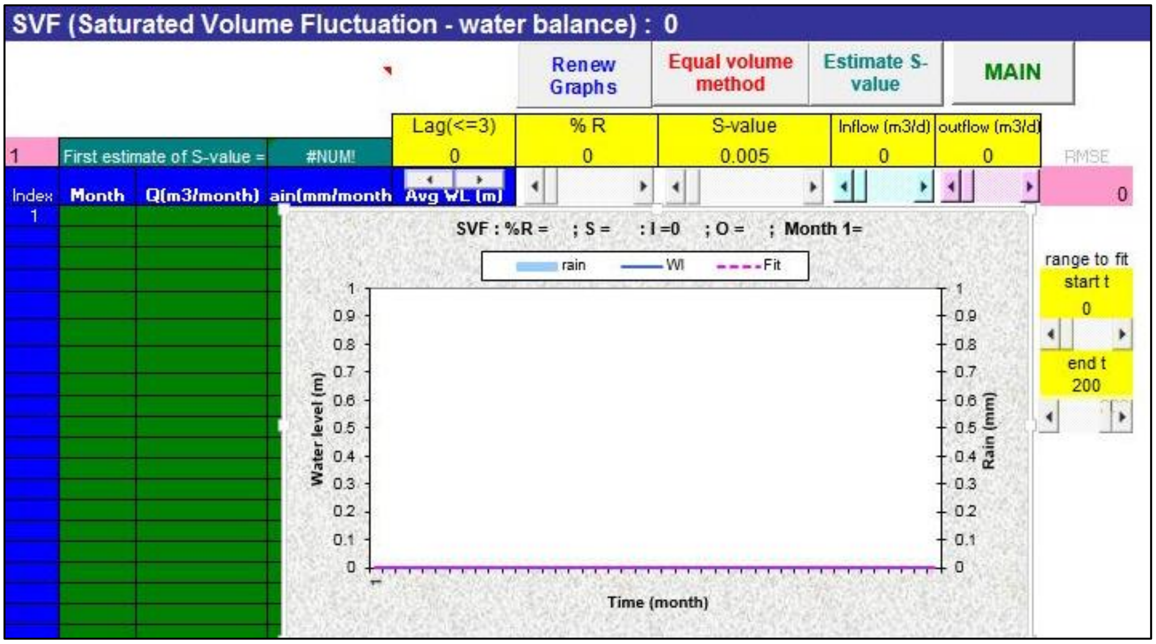
Where R is recharge, Sy is specific yield, Δh is the change in water level height and Δt is the time interval.

3.4.5 Saturated Volume Fluctuation (SVF) method

The SVF method is a lumped parametric method that considers the change in storage against recharge and abstraction (Parsons, 2014). The water levels from various observation boreholes are combined to establish the saturated volume status for the entire aquifer. This can be done by means of a grid network of elements using monitoring boreholes or points of abstraction (Adams et al., 2004). Thereafter an arbitrary value for the base thickness of the aquifer is assigned, usually in such way that saturated volumes are always positive (Van Tonder and Xu, 2001). The graphical user interface of the SVF method is presented in Figure 3.5. Lateral inflow and outflow can be assumed to be equal and if evapotranspiration rates are significant they can be incorporated in the abstraction term (Parsons, 2014).

$$R + (I - O) - Q = S\Delta V \tag{3.5}$$

Where R is Recharge (m^3/month), I = inflow into the aquifer (m^3/month), O = outflow from the aquifer (m^3/month), Q denotes withdrawal from the aquifer (m^3/month), S is Specific yield and ΔV change in saturated volume (m^3/month) (Van Tonder and Xu, 2001).


SVF (Saturated Volume Fluctuation - water balance) : 0

First estimate of S-value = #NUM!

Lag(<=3) 0

% R 0

S-value 0.005

Inflow (m3/d) 0

outflow (m3/d) 0

RMSE 0

range to fit start t 0

end t 200

Figure 3.5: The graphical user interface of the SVF method depicting the required input parameters to apply the method

Figure 3.5 above shows the graphical user interface of the SVF model showing some of the required input data to run the model. The model is also Excel-based software. The blue and green colored cells are used for inserting the data while the yellow cells are functions that are used for adjusting to have a good fit between the observed and simulated water levels.

The method is best applicable to the unconfined aquifer to semi-confined aquifer system (Xu and Beekman, 2003). The major limitation of the technique is that the measured groundwater levels must be representative for the aquifer as a whole (a good spread of the borehole through the area) and inflow value is often assumed to be equal to outflow value (Van Tonder and Xu, 2001, Sun, 2005). The method has been successfully applied in South Africa (Van Tonder and Kirchner, 1990, Adams, 2004, Conrad et al., 2004), while a study by Parsons (2014) obtained a poor fit due to the thickness of the vadose zone and possible high specific yield. While the SVF technique has been successfully applied in fractured hard rock aquifers, due to poor spreading of the boreholes in the area the present study will not apply the method.

3.4.6 Groundwater models

Numerical models are widely used in all types of hydrologic studies, and some of these models can be used to estimate groundwater recharge (Healy, 2010). These models represent the natural system in terms of simplified mathematical equations and can be applied in surface water studies, unsaturated soil zone studies or saturated zone studies. Models in surface water studies usually estimate recharge as a residual term in the water balance equation, while unsaturated zone models normally simulate the flow using Richard’s equation and estimate recharge as deep drainage (potential recharge) below the root zone in response to meteorological forcing (Chatterjee and Ray, 2014). Saturated zone models inversely estimate recharge using known piezometry, hydraulic conductivity and storativity parameters and other inflows and outflows (Xu and Beekman, 2003). The application of these models is usually time-consuming, which some of the limitations include sensitivity to boundary conditions and calibration difficulties (Xu and Beekman, 2003). In this present study unsaturated zone model i.e. HYDRUS numerical model will be applied to assess the effect of pine plantation forest on groundwater recharge.

3.4.7 Summary of recharge estimation methods

The most commonly applied techniques in the TMG aquifer system are physical and tracer methods such as CMB, CRD, SVF, EARTH model, GIS method, Base flow method, C-14 and $_2$H method, and Spring flow method (Sun, 2005). Although most of the methods discussed above are among the list of the promising techniques outlined by Xu and Beekman (2003), most of them present difficulties when assessing the effect of vegetation on groundwater recharge, principally because these methods do not integrate meteorological processes (transpiration and evaporation), surface water processes, root system depths and unsaturated zone flow dynamics in detail when estimating recharge. As a result, very few of them can account where the rest of the water went. In general, it is important to mention that very few studies have attempted to use unsaturated zone water balance model, e.g. HYDRUS numerical model to estimate recharge in the TMG area.

3.5 Previous groundwater recharge studies

The groundwater recharge topic has been the subject of many hydrogeological studies across the world (Simmers, 1987; Gieske, 1992; Scanlon et al., 2002; Healy, 2010 and others). While significant local studies include early work by Vegter (1995), Bredenkamp et al. (1995), Murry (1996), Kotze (2000), Xu and Van Tonder (2001), Weaver et al. (2002), Xu and Beekman (2003), Adams et al. (2004), Wu (2005), DWA (2006), Van Wyk (2010), Adelana (2010), Sun et al., (2013), etc. Although the topic has been thoroughly studied the accurate estimation of recharge remains one of the biggest challenges for hydrogeologists (Parsons, 2014). In TMG areas particular, various researchers have long been enthusiastic to understand and provide insights on groundwater recharge in the area owing to the foreseen influence of climate change/variability on the limited surface water resources in the area (Wu, 2005). Significant literature includes the work of Weaver (2000), Kotze (2000), Hartandy and Hay (2001), Wu (2005), Jia (2007), Sun et al., (2013), and others. The few published recharge estimations in catchment K30C (George) includes studies by Fortuin (2005), Wu (2005) and DWAF (2006). An overview of commonly employed methods with their results ranges in the TMG area and in George specifically are presented in Table 3.2 and Table 3.3 respectively.

Table 3.2: Review of Groundwater recharge estimates for the TMG aquifer (Wu, 2005)

Place	Method	Aquifer	Map (mm)	Recharge (%)	Source
Vermaaks River	Base flow	Peninsula	560	8.9	Bredenkamp, 1995
	Unknown	Peninsula	299-714	17	
	CMB	Nardouw/ Peninsula		43.5/11.1	Kortze 2000 and 2002
	SVF			3.1/19.7	
	SVF (fit)			3.4/16.4	
	CRD			3.2/14.4	
	Base flow			21.4/12.5	

		Earth			2.9/23.9	
		^{2}H Displacement			0.3/2.7	
		C Age			1.8/2.0	
		GIS	TMG		2.5/4.8	Woodford, 2002
		CMB			5	Weaver et al, 2002
Langebaan Road Field		CMB	Bredesdorp	396.4-648.9	9.7	Weaver and Talma, 2002
		CMB			11.2	
		CMB			13.5	
		CMB			11.5	
Greater Oudtshoorn		Empirical	Peninsula	165-1049	14	Hartnady and Hay, 2000
		Empirical	Nardouw		7	
Struisbaai		CMB	TMG	436	17.4	Weaver and Talma, 1999,2000
Agter Witzenberg		CMB	Nardouw	579-777	50.44	
Botriver			Nardouw	477-1546	20	
Hermanus		^{14}C		635	22(20-24	Rosewarne and Kortze, 1996
Uitenhage Artesian Basin		Spring flow	Groot Winterhoek	298- 1203	10	Kok, 1992
		CMB			25	Maclear, 1996
		CMB			55	R Parsons, 2002
Whole TMG (within a radius of 200km from Cape Town		GIS	13200km^{2} outcrop	600-2020	33	Weaver and Talma, 1999,2000
Cage	Low Rainfall	GIS	Low lying	286- 371	8	Hartnady and Hay, 2000 and 2002
	High Mountain		TMG		23	
	Mountain area				30-40	
		Isotopes			50	Weaver et al, 1999
Uitenhag, Coega aquifers		WB	TMG	460	83	Kok, 1992
		CMB	TMG		24-25	Maclear, 1996

	WB		250-850	11	Bredenkamp, 2000, Xu and Maclear

Table 3.3: Key Recharge estimates for the George area (Hydrogeological unit 15, catchment K30C)

Author	Recharge quantification	Method
Fortuin (2005)	17×10^6 m^3/year / 9.4% of MAP (86.2 mm/year)	GIS-based spatial modeling
Wu (2005)	42.5 mm/a	Water balance approach
DWAF (2006)	7 - 10 Mm^3/ year	

3.5.1 Groundwater recharge studies in the TMG Aquifer System

Fortuin (2005) carried out a study on groundwater recharge estimation in George, quaternary catchment K30C. The study applied a Geographic Information System (GIS) approach to estimate recharge, where recharge was computed based on mean annual precipitation (MAP), percentage Coefficient of Variance (CV) of MAP, terrain slope % and lithological-recharge factors. Recharge was estimated to be 9.4% of MAP. The recharge rates in the study were verified with the Harvest Potential map by DWAF. According to a study by Adams et al. (2004), the GIS technique is more a descriptive method that is less quantitative, more subjective and only assumes direct vertical infiltration. Thus, these results need to be cross-checked and confirmed with a robust quantitative method that takes potential interflow contribution into account, especially in a hill slope and fractured environment as the George area.

Watson et al., (2018) conducted a study on groundwater recharge estimation via percolation output using a rainfall/runoff model at Verlorenvlei estuarine system, west coast, South Africa. The percolation was simulated to be 3.6% of rainfall in the driest parts of the catchment, 10% of rainfall in the moderately wet areas of the catchment and 8.4% but up to 28.9% of rainfall in the wettest part of the catchment. Although the study was not on the effect of vegetation on recharge as the present study, the J200 rainfall/runoff model also estimate recharge similar to the Hydrus model i.e. the percolation or fluxes simulated at the free drainage boundary represent water that has passed through the vadose zone into the aquifer (potential recharge).

Wu (2005) carried out a study on groundwater recharge estimation in the Table Mountain Group Aquifer in the Kammanasie area. To estimate recharge the study incorporated various methods such as the Chloride Mass Balance Method, Cumulative Rainfall Departure, Regression of cumulative spring flux and the Water Balance Method. The study revealed that the recharge rates of the Kammanasie are were 1.182 - 2.027%, 0.24 - 7.56%, 3.29 - 4.01 - 4.01% and 2.32 - 4.4% respectively, using the CMB, CRD, regression of cumulative spring flux and Water Balance methods. The study recommended that recharge rates based on empirical factors in the water balance should be cross-checked with other techniques before it is used in the whole TMG area and further studies on the impact of exotic species on recharge are still necessary in the TMG area. A similar water balance approach to estimate groundwater recharge in the Table Mountain Group Aquifer in the Klein Karoo- Montague area was also conducted by Sun (2005). The study reported that recharge varied from station to station, with minimum recharge rates of 0.1 mm/year from a rainfall of 40.5 mm/year at station 0024101. While at station 0008782 recharge rates were calculated to be 3.3 mm/year related to 399.0 mm/year of precipitation. However, the study failed to cross-validate the recharge results with other groundwater recharge techniques as it is always recommended.

Challenges with the application of the water balance method alone were also emphasized during a study by Abiye (2016) in arid and semi-arid regions. Abiye (2016) reported that the water balance method could under-over-estimate recharge due to its dependence on specific meteorological parameters alone, whereas the effectiveness of recharge could be largely be influenced by aquifer characteristics. Within the TMG area, Barrow (2010) attempted to estimate groundwater recharge in a groundwater dependent ecosystem study at Oudebosch within Kogelberg reserve. The CMB method was selected as a suitable technique to estimate recharge and to incorporate dry deposition of chloride the study used the approximation by Van Tonder and Xu (2000). When a dry deposition of 1 mg/L was used recharge was estimated to be 46.3% of MAP whereas when 10 mg/L was applied recharge was estimated to be 82.3%. However, these recharge estimates were considered to be extraordinary for the area and therefore incorrect (Barrow, 2010).

Parsons (2014) estimated groundwater recharge rates in Groenvlei along the Southern Cape in a coastal environment using the CMB method and EARTH model. Permitting a Cl concentration of about 20 mg/L in the rain and harmonic mean of 135 mg/L for the Cl concentration of groundwater, the recharge rates using the CMB method was calculated to be 14.8% MAP. Estimates with the EARTH model, assuming a specific yield of 15%, ranged between 13% and 25% MAP. Although the EARTH model was successfully applied, recharge estimates with the CMB were less than expected for an area exhibiting high infiltration rates and no surface runoff and were also below the average estimated for coastal primary aquifers (Parsons, 2014). A similar recharge estimation study in a coastal environment was carried out by Conrad et al. (2004) in the northern Sandveld. The study used the CMB, SVF, CRD and EARTH methods to estimate groundwater recharge. The study reported that the groundwater recharge in the area ranged between 0.2 and 3.4%. However, the estimated recharge rates were preliminary results due to absence of extended water level time series data.

Jovanovic et al. (2012) conducted a study on reducing uncertainties of evapotranspiration and preferential flow in the estimation of groundwater recharge. The study employed the Rainfall Infiltration Breakthrough (RIB) model to estimate recharge at Oudebosch in the TMG aquifer. The RIB model and HYDRUS-1D were also used to quantify recharge in the unconfined alluvial aquifer at Riverlands and to simulate groundwater recharge under the presence of fynbos vegetation respectively. Daily simulated recharge with the RIB method ranged between 8% and 41% of MAP at Riverlands and between 5% and 26% at Oudebosch in the TMG aquifer. HYDRUS simulated the average groundwater recharge to be 25% of rainfall for five years, ranging between 3 and 15% annually.

Sun et al. (2013) conducted a study on the estimation of groundwater recharge on the west coast, South Africa. The focal point of the study was to explore the RIB method by estimating groundwater recharge in different hydrogeological and climatic areas. The background necessitation of the study was due to failure of the CMB method to provide reliable results near the coastal area. One of the case studies was conducted in the shallow unconfined Table Mountain Group aquifer at Oudebosch. Groundwater recharge rates were calculated to be 51.5% and 15.7% MAP at the daily and monthly scales respectively. Although the study was also conducted in the coastal Table Mountain Group aquifer as the present study, however, the nature of the study design is different, as the current study was conducted on recharge comparative assessment in relation to the presence of pine and indigenous plantation forest.

3.5.2 Groundwater recharge studies in South Africa

A synthesis of groundwater recharge studies in South Africa was carried out by Abiye (2016), with a focal point of reviewing and critically assessing the practicality of different recharge methods across the different climatic environments in Southern African countries. The study also tested the applicability of the Water Table Fluctuation and Baseflow separation methods in the crystalline basement rocks and metasediments close to Johannesburg. When the WTF method, was applied recharge was estimated to be 118.2 mm/year (17% of annual rainfall) in the metasediments, whereas in the fractured quartzites recharge was estimated to be 98.8 mm/year (14% of annual rainfall). When the Baseflow separation technique was applied, recharge was estimated to be 189.1 mm/year (27% of annual rainfall). Even though the WTF method was successfully applied in the area, the Base flow separation method over-estimated the recharge and as a result estimates by it were considered not to be reliable for the area.

Groundwater recharge estimations in crystalline rock aquifers were conducted by Holland (2011) in the Limpopo province, South Africa. The study applied the CMB method and estimated a recharge amount of 0.4 to 4.6% of MAP. Regardless of the fact that the CMB method is an excellent recharge technique in fractured rock aquifers (Cook, 2003), due to possibility of introducing additional sources of chloride from the weathering of rocks it is always recommended to use the method in conjunction with another method to get reliable estimates (Holland, 2011), which was beyond the scope of the study. Weitz and Demlie (2013) also attempted to estimate groundwater recharge using the CMB method in a modelling study in the lake Sibayi catchment along the coastal plain of Kwa-Zulu Natal. Groundwater recharge was estimated to be 51 mm/year which was 7% of MAP. Applying the CMB method in conjunction with other recharge techniques as recommended by other authors (Adams et al., 2004, Wu, 2005 and Holland, 2011) was beyond the scope of this study as the study was mainly on modeling groundwater-surface interaction.

Another similar hydrogeological characterization study was conducted by Leketa (2011) in the sediments of the Karoo, Bloemfontein. Among the parameters investigated to shed light on the behavior of the groundwater flow system in the area was the estimation of recharge. The study also applied the CMB method and estimated recharge to be 1.7% of MAP for the aquifer, which was low compared to the Karoo recharge value (2.6% of MAP) estimated by Woodford and Chevallier (2002). Groundwater recharge was also determined by Gomo (2011) within the same Karoo geological area of Bloemfontein. The focal point of the recharge estimation was to provide quantitative and qualitative analysis of groundwater recharge mechanisms as a component of groundwater-surface interaction. The WTF and CMB methods were selected as appropriate methods to estimate recharge in the area. When the WTF method was applied the harmonic mean recharge was estimated to be 53 mm/year and 55 mm 2010 - 2011 (rainy season) for the alluvial shallow aquifer and terrestrial aquifer respectively. The total groundwater recharge for the two aquifers was 8% of the total rainfall per year. For the CMB technique data was not sufficient to estimate annual recharge as it did not cover other rainfall seasons or events.

3.5.3 Groundwater recharge studies in Southern African Countries

A detailed study on the estimation of recharge and quantification of the flow system in the Kalahari, Namibia was done by Kulls (2000). The Water Balance model was used to estimate recharge in the area. In the vicinity of the hard rock exposure and thin sand cover recharge was calculated to be between 0.1 and 2.5% of the MAP. While within the Kalahari dominated by thick sediments recharge was calculated to be less than 1% of MAP. However, the study did not cross-check the recharge rates using other groundwater recharge methods to reduce uncertainties as it is always generally recommended. Another regional study on recharge assessments was conducted by Nyagwambo (2006) in tropical crystalline basement rock aquifers in Zimbabwe. The CMB, WTF and the Water Balance methods were selected as appropriate methods to estimate recharge in the area. The study concluded that even though the techniques estimated recharge amounts comparable to each other ranging between 8% and 15% of MAP, the CMB and the WTF methods had the weakness of over-reliance due to uncertainties in the chloride dry deposition rates in the CMB method and representativeness of the storativity of fractured rock aquifers in the WTF method.

Rwebugisa (2008) conducted a groundwater recharge assessment study in the Makutupora basin, Dodoma, Tanzania. The study made use of CMB and WTRBLN model (a computer program to estimate the water balance), EARTH model and Hydrograph analysis to estimate groundwater recharge. Groundwater recharge was estimated to range between 1 - 2% of annual rainfall (5 - 12 mm/year). Concerning the CMB method, there was human-cattle related pollution that increased the chloride content in groundwater, which resulted into underestimation of the recharge amount by the method, while lack of storativity estimates resulted in difficulties to draw concise conclusion on estimates produced through the Hydrograph analysis.

Larsen et al. (2002) conducted a preliminary analysis of groundwater recharge to the Karoo formation, mid-Zambezi basin, Zimbabwe. The study applied the CMB method to determine recharge, where direct recharge was estimated to be in the range of 10 - 130 mm/year with an average amount of 25 mm/year. The study recommended further recharge estimates due to low direct infiltration rates in the area. Sibanda et al. (2009) conducted another recharge estimation study in Nyamandhovu area, Zimbabwe. Four methods were selected to quantify recharge namely CMB, WTF, Darcian flownet computation and groundwater age dating technique With CMB, WTF, Darcian flownet and groundwater age dating recharge was estimated to range between 19 - 62, 2-50, 16 - 28 and 23 - 28 mm/year respectively. Although the estimates were not far from each other and recharge amounts from previous researchers, the study essentially reported that point recharge amounts with the CMB and WTF methods in fractured rock aquifers tend to overestimate the aerial recharge.

3.5.4 International groundwater recharge studies

Takounjou et al. (2010) estimated groundwater recharge of the shallow aquifer on a humid environment in Yaounde, Cameroon. The study applied the CMB and hybrid water-fluctuation method i.e. a combination of WTF and water balance method. The hybrid water-fluctuation method estimated a recharge amount of 87.14 mm/year which represented 5.7% of MAP, whereas the CMB method estimated recharge values ranging between 16.24 and 236.95 mm/year, with an average of 108.45 mm/year. This recharge amount represented 7% MAP in the area. Since the aim of employing two recharge methods was to assess the applicability of the CMB method using the suitable hybrid water-fluctuation method under humid environment, therefore such high discrepancy recharge amount from the CMB compared to hybrid water-fluctuation appeals to question the applicability of the CMB on forested and humid regions.

Yin et al. (2011) conducted a study on groundwater recharge estimations in Ordos Platea, China. Multiple methods including WTF, Darcian method and the water budget method were used to determine recharge in the area. The mean annual recharge amounts were estimated to be 46 - 109 mm/year, 17 - 54 mm/year and 21 - 109 mm/year using WTF, Dacian method and water budget technique respectively. Although the study claimed that these estimates were reasonable and that application of the multiple recharge methods provides a valuable range of recharge rates, some of the CMB recharge estimates in other sites were found anomalously low and were believed to be unrealistic due to the violation of the basic assumption of the method. Another similar regional recharge assessment study on crystalline bedrock aquifers was conducted by Chesnaux (2013) in Kenogami, Uplands in Canada. The study applied a one-dimensional Dupuit Forchhermer model and estimated recharge of 3.5 mm/year (0.4% of annual rainfall). Although the model was successfully applied, the study reported and acknowledged that recharge amounts by the method assume a steady state condition and does not take into consideration seasonal fluctuation of recharge.

Groundwater recharge was estimated by Hagedorn et al. (2011) in the fractured aquifer of temperate and humid semi-arid volcanic island, Jeju, Korea. The focus of the study was to evaluate the applicability of the WTF, CMB, groundwater chlorofluorocarbon (CFC - 12) ages and tritium methods for estimating recharge. The study reported that groundwater recharge was 687 mm/year, 429 mm/year, 423 mm/year and 394 mm/year using WTF, CMB, groundwater chlorofluorocarbon (CFC -12) ages and tritium method respectively. All the here applied methods underestimated recharge estimates previously quantified by Soil Water Balance (SWB) method in the area (911 mm/year) and the study concluded that these techniques cannot be used to predict average recharge amounts representative for the whole island region. Theoretically, recharge by soil water balance is usually interpreted as an upper limit recharge or potential recharge, whether these methods have underestimated recharge or SWB overestimated recharge is the predicament that needs to be cautious reviewed.

3.6 Overview of recharge estimation techniques

From the literature review, it was attested that groundwater recharge has been the subject that has been long discussed in many groundwater related studies across the world and it has been well acknowledged that very few, if any, method can measure recharge directly, hence its estimation is usually subjected to the uncertainties. The selection of method seems to be among the key predicaments that many researchers experienced as the applicability of any recharge method depends on the characteristics of the environment, availability of reliable relevant data and most essentially the cost of acquiring that particular data. From the above-reviewed studies the CMB, CRD and WTF were among the most applied methods to estimate recharge and this was in agreement with the study by Bredenkamp et al. (1995) and Xu and Beekman (2003). However, the CMB method was the main technique that seemed to underestimate and/or overestimate recharge in fractured aquifers mostly owing to unmeasured chloride dry deposition or weathering of the rock. Whereas challenges were also encountered with attaining a representative specific yield of fractured rock aquifers when using the WTF method. Many studies that were not mainly focused on recharge, but still estimated recharge to provide insight of the groundwater flow system in an area mostly failed to use recharge methods in conjunction with other recharge techniques to improve the reliability of the estimates as is recommended by various researchers. In South Africa, in particular quantifying recharge has become of paramount importance, particularly with the foreseen climate variability and limited water resources in the country.

3.7 Previous studies on characterisation of groundwater recharge mechanisms

Gomo (2011) applied stable Oxygen-18 ($\delta^{18}O$) and Deuterium ($\delta^{2}H$) to identify the source and mechanisms of groundwater recharge processes occurring in the alluvial channel aquifer in the Karoo, Bloemfontein. Groundwater $\delta^{18}O$ values ranged from 4.95‰ to - 5.25‰ while $\delta^{2}H$ ranged from - 31.28‰ to - 34.40‰. Groundwater values plotted beneath but close to Global Meteoric Water Line (GMWL) but far off and below the nearest Local Meteoric Water Line (LMWL) indicating the evaporation effect. The study inferred that groundwater in the aquifer was exposed to evaporation effects prior to or during the recharging process. Although the applied seepage technique revealed that the river is being recharged by the aquifer, the isotope signature analysis did not reflect such recharge mechanisms. A similar study on characterisation of recharge mechanisms in the similar Karoo environment was conducted by Leketa (2011) in the sediments of the Karoo, Bloemfontein. The study applied $\delta^{18}O$, $\delta^{2}H$ and Tritium to elucidate groundwater recharge mechanisms in the area. The values of $\delta^{18}O$ in groundwater ranged from-4.97‰ to -5.12‰ whereas $\delta^{2}H$ values ranged from - 32.4‰ to 34.4‰. The study inferred that groundwater may have been recharged through semi-preferred channels not from the surface water body. The Tritium values from groundwater were < 1 TU indicating that the groundwater is largely of the sub-modern water type while the river was a mixture of sub-modern and modern. However, the study reported that given that the aquifer in the area is alluvial and knowing the occurrence of groundwater fluctuation over the past 11 months, therefore, the recharge in the area should be more recent than that what tritium was revealing, therefore the study recommended other techniques to estimate the age of the water in the area.

Adams et al. (2004) characterised the recharge mechanisms of the basement aquifers of the central Namaqualand, Northern Cape, South Africa. To characterise recharge the study used stable isotopes $\delta^{18}O$ and ($\delta^{2}H$) and a radiogenic isotope ^{14}C to assess groundwater recharge processes and mean residence times of groundwater respectively. The isotope data attested that recharge was mainly indirect with direct recharge dominating the mountainous parts and the main residence time ranging from very old (> 30 000 years) to recently recharged groundwater. The groundwater of the area had a general slope of four indicating that most of the water had undergone some magnitude of evaporation. Another application of stable isotopes $\delta\ ^{18}O$ and $\delta^{2}H$ in recharge was conducted by Holland (2011) in the crystalline rock aquifer in the Limpopo province, South Africa, to gain meaningful information that will elucidate the recharge mechanisms in the area. The study reported that most groundwater samples plotted between the (GML) and the hypothetical (LML) implying a rapid recharge possibly owing to the existence of preferential pathways in the high-lying area that resulted in minimal evaporation. However, isotope rainfall samples were inadequate to analyze the rainfall sensitive between the four sites.

Acheampang and Hess (2000) conducted an isotope study on groundwater systems in a sedimentary basin of Ghana. The study applied stable isotopes and radioactive isotope to investigate the source of recharge and age of the groundwater in the area. The study reported concentration rates of 1 - 7.2 TU and 43 to 108% of tritium and modern carbon ^{14}C respectively. Whereas the tritium concentration in rainfall was below 1-4 TU. Oxygen-18 in groundwater ranged between -4.2 to -2.6 ‰ while δ^2H values ranged from -21 to -10 ‰. From the isotope graph of δ^{18}O and δ^2H, the study reported that the shallow groundwater in the area is from meteoric water that has undergone no significant degree of kinetic evaporation during recharge. No hint of paleo-recharge was inferred from the isotope results. Although the tritium results provided valuable information, its concentration was very low in the geological area. Another similar application of isotope δ^{18}O and δ^2H in groundwater recharge in fractured rock was conducted by Praamsma et al., (2008) in Canada. The focal point of the study was to use stable isotope and hydraulic head data to investigate recharge and discharge in a groundwater-surface interaction setting. An average δ^2H value of -126‰ was reported for snow samples. Oxygen-18 values for surface water ranged from -8.0. ‰ to -7.1 ‰ and δ^2H ranged from 65-56‰, while δ^{18}O in groundwater ranged -13.0 to -7.6‰ and δ^2H values ranged from -89 to 52‰. There was no hydraulic and isotopic evidence that groundwater discharges to the stream, while recharge was isotopically characterised as localized and rapid where overburden is thin and did not penetrate into the flow system on the site. One of the limitations of the study was that the rainfall isotopic signature response was beyond the error margin and snow was applied as a tracer for recharge mechanisms.

While most researchers use isotopes to characterise recharge mechanisms, Allison et al. (1984) further developed the concept of Evapo-Transpiration and Mixing Zone (ETM) moisture mobilization during episodic recharge events, suggesting an empirical method for approximating site recharge on the basis of observed displacement between ^{2}H in the vadose zone moisture and the LMWL (Bean, 2003). The general equation for estimating recharge with the δ-Displacement method can be written as follows:

$$\Delta\delta^2\mathrm{H} = \frac{C}{\sqrt{Recharge}} \qquad (3.6)$$

Where $\Delta\delta^2H = \delta^2H_{LMWL} - \Delta h_{uzm}$, C is the constant which is determined to be 20 for thick sands (Bean, 2003).

A study by Zondi (2017) applied the isotopic shift method to estimate groundwater recharge in the fractured rock aquifer of the Witwatersrand Supergroup quartzites, Johannesburg. Recharge was estimated range between 10.19 and 23.90 mm/month. Although the estimates were seen as representative of the fractured rock aquifer in the area the study suggested that more than one sample must be used to improve the estimates. Bean (2003) also conducted a study on a critical review of groundwater recharge estimation methods in South Africa. Amongst other methods the study applied the Stable shift method to estimate recharge. Groundwater values were used as an input variable due to an absence of unsaturated zone moisture data, a value of 20 was assumed for C and Δ^2H was estimated to be 8‰. Recharge of 6.1mm (1.7% of MAP) was estimated with the method and the estimates were found to be comparable with the estimates from the CMB method.

In the absence of long-term rainfall or water level data, an understanding of environmental tracers present in recharge waters can be of some benefit, particularly when investigating aquifer residence times for groundwater recharge in the aquifer (Cook et al., 2001). Tritium is produced in nature by cosmic ray interaction with the upper atmosphere, and readily oxidized to water, in which it is a conservative tracer (Abiye, 2013). Provided there is no other source of tritium on the surface and underground, and assuming that rainwater fell at 5-10 TU, then for groundwater to have a higher value it should have been recharged just recently (Leketa, 2011). Therefore based on this notion it is possible to identify the recharge period of recent groundwater by comparing its tritium content with those of present-day rainfall (Abiye, 2013). Clark and Fritz (1997) proposed tritium concentration ranges for different possible recharge period (Table 3.4).

Table 3.4: Tritium concentration and indication of groundwater recharge conditions (after Bean (2003) as referenced Clark and Fritz (1997)

Continental regions (TU)	Coastal and low altitude regions (TU)	Recharge conditions
< 0.8	< 0.8	Sub-modern groundwater (prior to 1950's)
0.8 to approximately 4	0.8 to approximately 2	Mix of sub-modern and modern recharge
5 to 15	2 to 8	Modern (< 5-10 years)
15 to 30	10 to 20	Indicates some bomb tritium
> 30	> 20	Recharge from 1960's to 1970s
> 50	-	Dominantly 1960's recharge

3.8 Overview of studies on characterization of recharge mechanism

From the literature review, it was established that the use of stable isotopes in the field of hydrogeology has been well documented across the world owing to their application from their existence as conservative nature which makes them as tracer tools. As much as there is a number of available isotopes, the most commonly used isotopes in groundwater recharge studies include the environmental isotopes Oxygen-18 and Deuterium and radioactive isotopes such as Tritium (^3H) and Radon (^{222}R). It was also noted that although the application of isotopes in the above-mentioned studies was largely successful, there were cases where isotope results disagreed with other physical techniques. It was also reported and acknowledged that since there is no further atmospheric nuclear weapon testing, the application of tritium for determining the age of groundwater is slowly reaching its limit (Holland, 2011). As much as the application of the isotopes is fundamental in groundwater studies, a lot of the isotope interpretation is usually "inferred" and mainly depends on the local knowledge of the environment.

3.9 Previous studies on the influence of vegetation on groundwater recharge

Albhaisi et al. (2013) applied a hydrological model (WetSpa) to quantify the impacts of land use change on groundwater recharge in the Upper Berg catchment (TMG Aquifer), South Africa. Their study reported a systematic increase of about 8% per year over a 21 year period, which was due to clearing of the vegetation in the area. Although the model was successfully applied the study did report and acknowledge that the hydrological model (WetSpa) requires extensive field data parameters which are conceptual in nature and difficult to obtain or assessed directly. Another related study was conducted by Ladekarl et al. (2004) on the comparative assessment of groundwater recharge and evapotranspiration for oak and heather vegetation in Central Jutland, Denmark, using a bromide tracer experiment and the Coup model (soil water model). The annual recharge rates under the presence of oak were calculated to be 390 mm/year, whereas recharge rates under the presence of heather were calculated to be 733 mm/year, which was 50% higher than for the oak. However, the recharge estimates from the bromide tracer experiment were uncertain due to spatial heterogeneity, making the three replicate samples used in the study insufficient. A similar study by Adane and Gates (2014) was also done in an environment occupied grasslands, sparse vegetation, ponderosa pine plantation and dense cedar in the Nebraska National Forest in Halsey. Instead of using a bromide as tracer the study used chloride and sulfate to estimate recharge. The study revealed that groundwater recharge in the two profile underlying the grasslands was calculated to be 27 mm/yr (17-37mm/yr; 3.4-7.5% of MAP) while at the sparse vegetation recharge was estimated to be 32 mm/yr (6.6% of MAP). At the pine and dense cedar recharge was estimated to be less than 19 mm/yr (<4% of MAP) and 4 mm/yr (<1% of MAP) respectively. Even though the CMB technique proved to be a useful and cost-effective method to estimate recharge in the study area, the study failed to consider the impact of tree canopy on chloride enhancement as reported by Deng et al. (2013).

A series of numerical simulation using HYDRUS-1D/2D were done by Fan (2014) to examine the potential effect of pine plantations and native Banksia woodland on soil moisture and groundwater recharge in the subtropical coastal sand dunes in Australia. The study attested that the annual recharge in the sparse grassland, Banksia woodland and pine plantation was 49 - 56%, 21 - 36% and 31 - 49% of net rainfall respectively. The modelled annual deep drainage (recharge) was found to be 61% of annual gross rainfall. Although the model was successfully applied and confirmed that the pine plantation extracted more groundwater through evapotranspiration than the two indigenous species, amongst the key limitations of the study was the negligence of examining the effect of root uptake in the vadose zone. While more attention seems to be given to influence or impact of exotic species on soil moisture, groundwater levels and recharge, the impact of natural forest on recharge is also a question of interest and that is still debated (Marechal et al., (2009). To examine such impact Marechal et al. (2009) conducted a study in India on the estimation of groundwater recharge in a humid tropical forest which is characterised by the occurrence of fractured bedrock underneath. The study made use of the CMB method and the Water Table Fluctuation (WTF) method to estimate recharge, while geophysics and chemistry were used to understand the recharge mechanism occurring in the area. The study reported localized and indirect recharge was 45 mm/year and 30 mm/year respectively, and evapotranspiration rate values were between 80 to 90% of rainfall i.e. 1050 mm/year due to water availability and atmospheric demand from the forest. However, such elevated actual evapotranspiration from deciduous forests are seldom reported and are unexpected and therefore the study recommended complementary studies on this value for confirmation.

Brites and Vermeulen (2013) conducted a study on the impact of different timber species on groundwater levels in Nyalazi Plantation, Kwa-Zulu Natal, South Africa. The two main plant species were *Pinus elliottii* and *Eucalyptus Grandis Camaldulensis*. The mature pine plantation had a minor impact on groundwater levels in the study area. While the *Eucalyptus* species showed a significant impact on groundwater levels, with water levels declining between 10 and 16 meters over 13 years. A similar study was conducted by Ngobeni (2013) on the impact of alien tree species in groundwater at the Dayspring Children's Village which is 66 km northwest of Johannesburg, South Africa. The aim of the study was to determine the complex interaction between the plants and structural elements of various aquifers using geophysical and hydrogeological methods. At the beginning of the study, the intention was to conduct an analysis under the presence of the bluegum tree and also take the measurement after it has been cleared to observe the change in impact. However, failing to clear the bluegum tree was the major limitation of the study, as it hindered the work plan of the study. A summary of comparative rates of groundwater recharge under different types and following the vegetation changes is presented below (Scott et al., 1998).

Table 3.5: Comparative rates of groundwater recharge under different types and following the vegetation changes in winter rainfall region of Western and south-eastern Australia and summer rainfall region in eastern Australia (spha –stem per hectare) (Scott et al., 1998)

Vegetation	Annual rainfall (mm)	Soil and water table (m)	Annual recharge (mm or % of rainfall)	Recharge method
Banksia shrubland *Pinus radiata* plantation 2200 spha 25 years old	775 (525-848 during study period)	Deep sands, 20 m	11% negligible	CMB method
Banksia shrubland *Pinus radiata* plantation	775	Deep sands, 10 m	25% 7%	CMB method
Grassland *Pinus radiata* plantation 24 years old, two sites	600-632	Deep sands, over limestone,7+ m to 40 m	63 mm 0 mm	Soil moisture
Natural *eucalyptus* forest Perennial pasture Annual pasture un/grazed Perennial Medicago *Pinus pinaster* plantation	800-900	Deep sands, over 15m to 40m	34% 20-24% 20/21-43% 8% 11%	Soil moisture
Banksia woodland *Pinus* plantation 630 spha 18 years old	747 (PET 1800 mm)	Deep sands, 4m to 12m	22-23% 15%	CMB & Soil water balance methods
Replacement of natural *eucalyptus* forest by grassland	409 mean (339-494)	Colluvium and laterite on deeply weathered granite	0.4-1.0 mm increased to 10-25 mm	CMB and Water Balance
Replacement of natural *eucalyptus* forest by grassland Eucalyptus grandis planted in grassland, 2-3 years old	800-820 1100-1220 1099 mean (739-963)	Gravel to sandy laterite on deeply weathered granite Podzolic loam	10-30 mm increase 60 mm increase 0-5 mm 2150 spha 17-23 mm 304 spha 74-79 mm 82 spha	Piezometer water levels method
Banksia woodland	525-850	Deep sands, 70-90 m	34-149 mm, 10 depth 65-80 mm, 18 depth	Soil moisture and Moisture flux model

Chapter 4: Research Design and Methods

4.1 Introduction

This chapter describes the methodologies and material adopted during the course of this study. In this section, the research design, data collection methods, data analysis methods, data quality assurance, ethical consideration and limitation of the study are presented. Under research design, the sample design and sample size are described

4.2 Research design

4.2.1Research design approach

The current study used an experimental design approach whereby the George study area was used as a case study. In order to meet the study objectives, the study incorporated four steps, namely the desktop study, fieldwork study, laboratory work and data analysis. The desktop study commenced on the 1 March 2016. This initially involved reviewing the study area reports and other relevant grey literature to get insight about the physiography of the site in order to determine the approach direction of the work research, i.e. delineating of the boundary site (critical for selecting the appropriate recharge technique), identify potential sample points, experimental set-up and among others. Existing records pertaining groundwater recharge processes and estimations were reviewed in order to establish appropriate methods to quantify recharge in the area.

Fieldwork involved multiple field visits to the site starting from July 2016 - November 2017. The first phase of fieldwork involved drilling of boreholes at the Saasveld plantation and at the Groenkop forest. Undisturbed soil samples were collected along each transect which were later analyzed for textural class and water retention curve for parameterization of the HYDRUS-2D model. This was followed by logging the borehole logs and installing data loggers and installing soil moisture sensors at different depths of the soil along each transect being investigated. The second phase was conducted in September 2017 onwards, this involved downloading daily groundwater level datasets, meteorological (rainfall and evapotranspiration) datasets and soil moisture data from the data loggers, automatic weather station and soil moisture sensors respectively. Downloading of data was done every time the site is visited. A Sampling of groundwater and streams was done for the isotope and chemistry analysis.

Laboratory work involved setting up the Sandbox and Kaolin experiment to estimate the water retention curves for parameterization of the model. Isotope samples were submitted at an accredited lab, namely iThemba Labs in Pretoria, South Africa. For groundwater chemistry (major cations and anions) analysis, samples were submitted at the CSIR Analytical Services at Stellenbosch. Soil samples were sent to Bemlab, Cape Town for textural analysis. Data analysis such as recharge estimation and modeling was conducted from October 2016 onwards.

4.2.2 Experimental set-up

The Saasveld plantation is located at about 6 km from the east of the town of George. The area lies between latitude of 33° 56'50.09"S and longitude of 22° 31'07.66"E, while the Groenkop indigenous forest is located at about 7 km from the town and lies between latitude of 33° 56'59.11" S and longitude of 22° 32'56.16"E (see Figure 4.1). The *Pinus elliottii* trees were planted in October 2006 at an original density of approximately 1111 stems per hectare (spha), i.e. 3 m x 3 m. The *Pinus radiata* trees are approximately 18 years old, after being planted in November 2000 at an original density of 918 spha (3.3 m x 3.3 m). Both compartments were actively growing at full canopy cover. Soil moisture sensors were installed at two depths of 20 cm and 40 cm at the upslope and downslope along each transect being investigated. These sites were established at the *Pinus elliotii*, *P. radiata* compartments and on the natural forest (Groenkop forest). At each site, sap flow velocities and volumetric water contents (VWC) were measured or monitored concurrently (Figure 4.1). The sap flow velocities were measured using the heat pulse velocity (HPV) of the heat ratio method technique. Data were recorded at hourly intervals and were available for the period 1 October 2016 – 31 September 2017.

Sap flow measurements

Trees were selected at each site to monitor sap flows. Each HPV system consisted of four probe sets that were inserted at breast-height around the tree circumference. The depths in which the probes were inserted varied so as to account radial variation of sap velocities. Four probe sets were positioned 110 cm above ground in the main stem of each tree and inserted to different depths below the cambium but within the sapwood to account for radial variation in sap flow velocities (cm hour-1). Sap flow velocities were recorded at hourly intervals throughout the study period. HPV1 was located within a *Pinus elliotii* stand, HPV2 was located within a *Pinus radiata* stand and HPV3 was in the Groenkop indigenous forest.

Monitoring groundwater levels

To monitor and compare groundwater levels in the vicinity of plantation forest and at the indigenous forest, three boreholes were drilled at the *Pinus elliotii* compartment, *Pinus radiata* compartment and Groenkop forest. Water levels were recorded using the Solinst level loggers were installed at SV1, SV2 and SV3 after borehole drilling. The loggers were programmed to collect data at hourly intervals throughout the study period.

Microclimate

The microclimate of the area was monitored using an automatic weather station. This station was established in Saasveld campus of Nelson Mandela Metropolitan University (NMMU) (33° 57'16.93"S, 22° 31'43.72"E) by the Council of Scientific and Industrial Research (CSIR) 2003 (Figure 4.2). The weather station was located at about 1.87 and 0.99 km from the *Pinus radiata* and *P. elliotii* compartments, respectively.

Figure 4.1: The experimental scheme in the vicinity of Saasveld. The polygons delineate the plantation compartments which were studied, i.e. *Pinus elliotii* (brown) and *Pinus radiata* (green)

Figure 4.2: An automatic weather station installed in the vicinity of the study site

4.2.3 Sample design and sample size

To characterize the dominant groundwater recharge mechanism, a total of 35 samples were collected and analysed for the oxygen-18 and deuterium concentration (16 rainwater, 16 groundwater and three surface water samples) for the year 2016 - 2017. While a total of 12 samples were collected and analysed for the major cation, anions, electrical conductivity and pH (10 groundwater and two surface water samples) for the year 2016 - 2017. The samples were collected samples for both dry and rainy/wet season so as to cover all recharge events. The number of samples was determined by the number of accessible boreholes in the catchment.

To estimate groundwater recharge using the Rainfall Infiltration Breakthrough method borehole GBHE27 which belongs to the George municipality was selected. The reason for the selection of this borehole was that it was located in the upper catchment close to the recharge zone, responded to rainfall and had less impact of abstraction from the production borehole in the site. Groundwater recharge was estimated for the year 2011- 2017. The selection of such periods was restricted by the available groundwater levels time series data from the data logger. To estimate groundwater recharge with CMB method an average chloride from the rainwater and a harmonic mean chloride from SV1, SV2 and SV3 were used. The reason for using three boreholes was to get representative recharge estimates of the catchment i.e. avoiding point estimate.

To assess the effect of plantation forest, the model simulation was carried out for over 365 days (hydrological year) which started from 1 October 2016 to 30 September 2017. The reason for such period was to again to cover all recharge events and dry and wet seasonality. In total, 16 soil samples were incised and analyzed for water retention curves (eight at the *Pinus radiata*, five at the *Pinus elliotii* compartment and three at the Groenkop forest). The number of samples in each site was mainly controlled by the challenges of auguring into deeper soil horizon due to clay horizon and root systems along each transect. The *llex mitis*, *Ocotea bullata* and *Podocarpus latifolius* from the indigenous forest were selected as species to compare transpiration rates from the plantation with (reference point) as they were the dominant natural occurring plants in the Groenkop forest.

4.3 Data collection methods

4.3.1 Data collection methods for characterizing recharge mechanism

To obtain the isotope and chemistry data to characterize groundwater recharge mechanism a purging technique, bailer method and sample grab method were employed to collect the samples from the rainwater, groundwater and from the stream for the year 2016 and 2017 respectively. During isotope sampling, caution was exercised during purging the boreholes as deeper sections of the water column may also be drained, which are possibly not in phase with the modern isotopically signature of the hydro-climate and recharge regime (Van Wyk, 2010). The samples were collected in accordance with the procedure prescribed by Weaver *et al*. (2007). The advantages of these methods are that if recommended sampling guidelines are followed, reliable data can be obtained. While their weakness is that going out to the field and visiting each sample point site and firstly purging the boreholes before sampling can be time- consuming.

Groundwater samples at the SV1 and SV3 boreholes were collected by firstly purging three borehole volumes (traditional approach) of the stagnant water with a low flow submersible pump so as to obtain samples representative of groundwater drawn from the aquifer (Figure 4.3). This was done by firstly measuring the depth to water (mbgl) and depth of the borehole (mbgl) using a Solinst Canada water level meter (dip meter). To measure the depth to water guidelines by Weaver et al. (2007) were followed. While the depth of the borehole was recorded by drillers after finishing drilling the boreholes. However, this was rechecked by using a water level (traditional approach). Therefore, the water column of the water in the borehole was calculated by subtracting the depth to water from the borehole depth, therefore the standing water in liters was estimated using the formula:

$$V = \pi \times d^2 \times h \div 4000 \tag{4.1}$$

Where V is the volume of standing water in liters

d is the diameter of the borehole in mm

h is the height of water column in meters

Thereafter, a low flow submersible pump was used to pump water out and the discharge pumping rate in l/sec was estimated using a stopwatch and a liter jar (low yield). The time it took to fill the jar was used to estimate how much time it would take to remove three well volumes of the calculated stagnant water. For the borehole SV2 the pump could not lift the water due to great depth (depth to water 43.20 mbgl). Therefore, a bailer sampling method was used to sample. This was done by lowering the bailer inside the borehole and removing 20 volumes of standing water. For the George municipality boreholes (GBHE28, GBHE3, and GBHE15) installed pumps inside production boreholes to pump water to the dams were used to sample. New 250ml sample bottles were indelibly labeled prior sampling with site name and date of sampling and all sample bottles were rinsed three times with the sampled water before collecting the samples. Prior to sending samples to the laboratory analysis samples were kept in the cooler box with ice tubes to prevent any potential evaporation and exchange of environmental gases with the chemistry of the water (Figure 4.4).

Figure 4.3: Purging process at SV3 at Groenkop indigenous forest

Figure 4.4: Photography showing the cooler box with samples from the field

4.3.2 Data collection methods for estimating groundwater recharge

Groundwater level time series data were downloaded from the installed data loggers, every time the study site was visited. This was done by removing the data logger out of the borehole and inserting it in a cable porter that was connected to a laptop and the data was downloaded. Every time after finishing downloading the data from the logger manually measurements were taken with a Solinst Canada water level meter before deploying the logger back inside the borehole. This was to validate or check any error measurement by the logger or any discrepancies between the electronic and manual measured values. For the collection of rainfall data, the automatic weather station was used to download the data, however, additional long period rainfall time series data (2011 - 2017) was requested and obtained from the Agricultural Research Council (ARC) institution. This was done through signing a disclosure agreement form. Due to low yielding of the drilled monitoring boreholes at the site, a pumping test could not be conducted to estimate storativity for recharge estimation, while the George municipality boreholes within the site were also too far apart for observing the drawdown and recovery. Therefore, the storativity value was sourced from the study previously done in the TMG aquifer by Jia (2007). The study reported the low, medium and high recommendable storativity ranges for the whole TMG aquifer. To collect chloride concentration samples for CMB method the same data collection procedures described above for obtaining groundwater chemistry was adopted i.e. purging technique and sample grab method.

4.3.3 Data collection method for assessing the effect of plantation forest on recharge

Daily meteorological datasets (rainfall, temperature, solar radiation, humidity, and wind speed) was downloaded from the automatic weather station located at the Saasveld campus of Nelson Mandela Metropolitan University, while evapotranspiration above the canopy of the plant compartments was downloaded from the Eddy Covariance flux tower. These meteorological variables were continuously measured at an hourly interval and automatically recorded by the instruments to the data logger, and the site was regularly visited on a seasonal interval for monitoring and downloading the data. Four Heat Pulse Velocity (HPV) system were installed within a vicinity of *Pinus elliottii* stand, *Pinus radiata* stand and within the Groenkop indigenous forest to monitor water uptake and transpiration rates. Each HPV system includes CR1000 data logger, a multiplexer (Model AM16/32B, Campbell Scientific Inc., Logan UT USA), a relay control module, a 70 Ah battery, 12 heaters and 24 thermocouple pairs. For analysis of soil water characteristic curve and unsaturated hydraulic properties, a total of 16 soil core samples were incised and collected at varies depth 5 - 60 cm in the vadose zone using hand auger into a 100 cc ring to attain the undisturbed sample. On each soil sample date, time, depth and compartment plantation site was recorded using a permanent marker. The soil-filled sample rings were covered with caps at the top and bottom to avoid disturbing the soil structure and preventing evaporation from the soil during transportation to the lab. Soil volumetric water content and temperature data were downloaded from the data logger which was connected to probes installed in a soil dug pits. The soil moisture probes were installed at depth of 0.2 m and 0.4 m in the vicinity of HPV1 and HPV2 at *Pinus elliottii* compartment and *Pinus radiata* compartment. At the Groenkop indigenous forest, the soil volumetric water content were monitored in the vicinity of HPV3 where water uptake and transpiration rates of *IIex mitis*, *Ocotea bullata* and *Podocarpus latifolius* trees were monitored. Another probe was installed in the vicinity of HPV4 where water uptake and transpiration of *Podocarpus falcutus*, *Curtisia dentate* and *Ocotea bullata* were monitored. At HPV3 and HPV4 the soil volumetric water content probes were installed at a various depth of 0.1 - 0.2 m and 0.3 - 0.4 m. The data were continuously downloaded to the logger at an hourly interval.

4.4 Data analysis methods

4.4.1 Data analysis methods for characterising groundwater recharge mechanism

Stable isotopes (oxygen-18 and deuterium) were analysed using a Los Gatos Research (LGR) Liquid Water Isotope Laser Analyser. All the samples were analysed in relative to a known standard, in this case standards mean ocean water (SMOW) for $\delta^{18}O$ and $\delta^{2}H$. The analytical precision was estimated at 0.2‰ for O and 0.8‰ for H. The results were reported in common delta-notation and expressed in units of parts per mil (‰) deviation from SMOW, and presented as follows:

$$\delta = \left[\frac{(R_{sample-}\ R_{standard})}{R_{standard}}\right] \times 1000 \qquad (4.2)$$

Where R denotes the $^{2}H/^{1}H$ for hydrogen and $^{18}O/^{16}O$ for oxygen, the ratio for heavy to the light isotopes. Due to the significance of geographical location and variation in seasonality in Western Cape, a Local Meteoric Water Line (LMWL) of Cape Town was used as a reference line in addition to the Global Meteoric Water Line (GMWL).

For hydrochemical analysis, a Piper diagram graphical representation method was used to support the isotope results on the possible groundwater and surface interaction and identify the predominant hydrochemical facies in the area. The Piper diagram is one of the most utilized visual graphical representation technique apart from Stiff, Durov and Schoeller diagrams (Young, 2007). The diagram has two triangle graphs one on the bottom left representing cations, one on the bottom right representing anions and an upper diamond plot in the middle. Parallel lines are then drawn from the two triangles up until they meet within the diamond plot in the middle (Young, 2007), where the lines intersect a sample point is plotted. For the purpose of this study, Ca^{2+}, Mg^{2+}, Na^{+} plus K^{+}, Cl^{-1}, SO_4^{-2} and HCO_3^{-1} were used for this analysis.

4.5.1Data analysis methods for Recharge

A range of methods are available for estimating groundwater recharge (as discussed in chapter 3, section 3.4). In this current study the RIB and CMB methods were applied to estimate groundwater recharge. The present study chose the RIB method because the study area conformed to some of the assumptions necessary for the correct application of the technique such as (i) suitable time series of rainfall and groundwater level must be available i.e. more than 3 years (ii) The water level fluctuation from the borehole should be representative of the study area i.e. close to recharge zone and away from surface water bodies (iii) relatively shallow water levels. The reason of choosing the CMB method (tracer technique) was to get quantitative recharge estimates from a method that works independently from the storativity which can be problematic to estimate in fractured rock aquifers. To make sure that the principles and assumptions for the correct application of the CMB are maintained, the present study used the modified CMB equation (Van Tonder and Xu, 2000) specifically designed for coastal regions and vegetated environment. The two chosen methods are briefly discussed below with focus on their assumptions, strength and weaknesses.

4.5.2 Rainfall Infiltration Breakthrough method

The Rainfall Infiltration Breakthrough (RIB) model is an Excel-based software (Microsoft 2007) that was developed by (Xu and Van Tonder, 2001) and later improved by (Sun et al., 2013). The model development was based on the Cumulative Rainfall Departure (CRD) method (Bredenkamp et al., 1995). The simulated groundwater recharge values by the model are based on a relationship between a series of rainfall events and groundwater level fluctuation data. The advantage of using the RIB method is that the technique. To estimate recharge the method requires rainfall data, groundwater level fluctuations, the catchment area, specific yield estimates and known sinks and sources. The RIB formula can be written as follows:

$$RIB(i)_{m}^{n} = r\left(\sum_{i=m}^{n} Pi - (2 - \frac{1}{Pav\ (n-m)} \sum_{i=m}^{n} Pi\ ) \sum_{i=m}^{n} Pt\ \right) \qquad (4.2)$$

(i=1, 2, 3,…I)

(n=i, i-1, i-2,…N)

(m=I, i-1, i-2,… M)

m<n<I

Where RIB (*i*) is the cumulative recharge from the rainfall event of *m* to *n*, *I* is the total length of the rainfall series, *r* is a fraction of the cumulative rainfall departure, P_t is the rainfall amount at i_{th} time scale (daily, monthly or annually), P_{av} is the mean precipitation of the whole time series, P_t is the threshold value representing the boundary condition (P_t ranges from 0 to P_{av}) (Sun et al., 2013). A recharge value of 0 mm represents a closed aquifer system, which implies that recharge at the i_{th} time scale only relies on the previous rainfall event from P_m to P_n, while a value of P_{av} denotes an open aquifer system, which means the recharge at the i^{th} time scale relies on the difference between average rainfall of the previous rainfall event from P_m to P_n and the average rainfall of the whole time series (Sun et al. 2013). Both r and P_t values are determined during the simulation process (Sun et al., 2013).

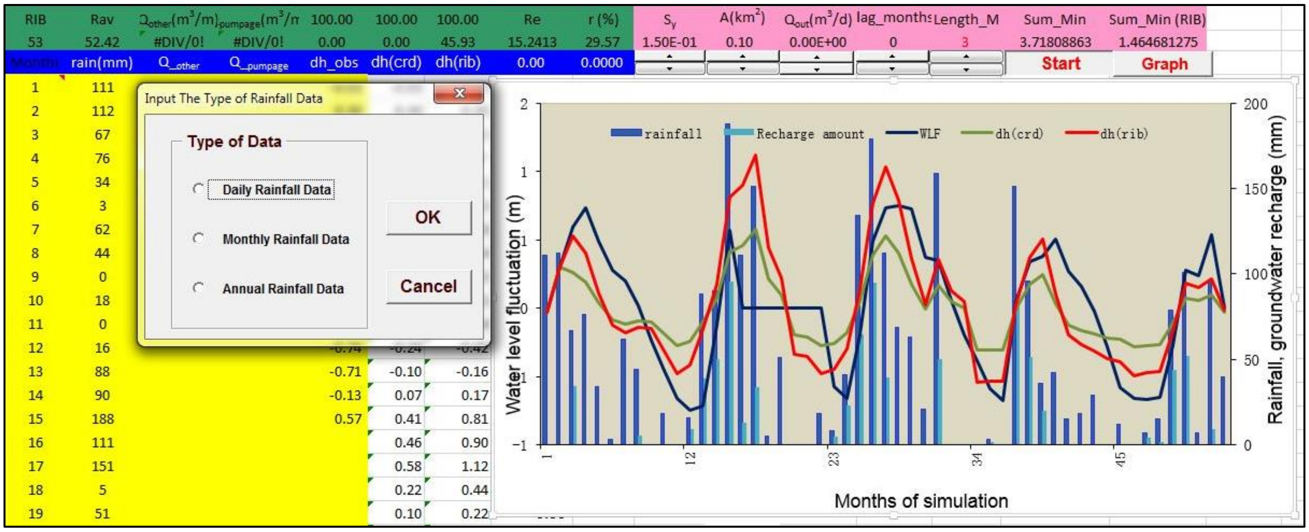
It is assumed that groundwater recharge estimated by the RIB model has a linear relationship with groundwater level fluctuations under natural conditions. The relationship between natural rainfall and groundwater level fluctuations can be described by (Sun et al., 2013):

$$\Delta h = (1\ /Sy) \times (RIB(i)_m^n) \tag{4.3}$$

Where: Δh_i is the water - level fluctuation, which is equal to the difference between the observed water level at i_{th} time scale and the mean water level of the whole time series. A positive value represents an increase of water level while a negative value implies a decrease of water level. S_y is the specific yield of the aquifer.

4.5.3 Rib software interface

The RIB model is applied in an Excel spreadsheet platform which uses Visual Basic Application (VBA) programming code to analyse and display data and groundwater estimates (Jovanovic et al., 2012). The software also incorporates a solver function that minimizes the difference between the observed water level fluctuation and simulated values using the least square method (Sun et al., 2013). Once the required input data were inserted into the software the graph button was selected on the main toolbar, then the model automatically displayed the graphs of observed water levels, CRD and RIB simulated water levels and recharge values. Figure 4.5 illustrates an example of the RIB user interface on a daily simulation scale.



RIB	Rav	$Q_{other}(m^3/m)$	$Q_{pumpage}(m^3/m$	100.00	100.00	100.00	Re	r (%)	S_y	$A(km^2)$	$Q_{out}(m^3/d)$	lag_months	Length_M	Sum_Min	Sum_Min (RIB)
53	52.42	#DIV/0!	#DIV/0!	0.00	0.00	45.93	15.2413	29.57	1.50E-01	0.10	0.00E+00	0	3	3.71808863	1.464681275
Months	rain(mm)	$Q_{\_other}$	$Q_{\_pumpage}$	dh_obs	dh(crd)	dh(rib)	0.00	0.0000							
1	111														
2	112														
3	67														
4	76														
5	34														
6	3														
7	62														
8	44														
9	0														
10	18														
11	0														
12	16			-0.74	-0.24	-0.42									
13	88			-0.71	-0.10	-0.16									
14	90			-0.13	0.07	0.17									
15	188			0.57	0.41	0.81									
16	111				0.46	0.90									
17	151				0.58	1.12									
18	5				0.22	0.44									
19	51				0.10	0.22									

Figure 4.5: Screen printout of the RIB software user interface

4.5.4 Critical assumptions on the application of RIB method

Just as any other recharge determination method, the RIB model has strengths and limitations. One of the disadvantages of the method is that theoretically it cannot be used in extremely arid conditions where rainfall is less than 100 mm/a, as groundwater recharge from the rainfall is too small to cause water level rises (Sun et al., 2013). An advantage of the model is that it requires few parameters and it is capable of filling gaps in the groundwater level record, whereby it predicts the groundwater level with available rainfall and abstraction data (Sun et al., 2013). The model is mainly suitable for unconfined aquifer conditions with shallow water levels, relatively low transmissivity and where water levels respond clearly to rainfall (Sun et al., 2013). However, according to Sun et al. (2013), the RIB method needs to be explored under different climatic and hydrogeological conditions. When applied in a fractured rock aquifer good knowledge of hydraulic properties is required as the method is sensitive to the aquifer specific yield. The technique must also be applied in an aquifer where groundwater fluctuation and specific yield is representative of the study area (Sun et al., 2013).

4.5.5 Data analysis procedures with RIB method

Firstly, a monthly time scale was defined before inserting data into the model. Rainfall data (mm) were obtained from the automatic weather station located at Saasveld. Borehole GBHE27 was selected to conduct the recharge simulation for the period of 2011 - 2017. This was among the only borehole that had less effect of abstraction on the water level data, water levels in most boreholes in the area are extensively influenced by pumping which resulted in a poor fit between observed and simulated water levels. The monthly groundwater level fluctuation values i.e. Δh (mbgl) were calculated as a difference between the average groundwater levels (mbgl) of the 12 months series data in that year minus the observed monthly average groundwater level (mbgl). A positive value represents an increase in the water level while a negative value implies a decrease of the water level. The catchment area (km^2) is also required. Specific yield (dimensionless unit) values were sourced from available literature as site-specific values were not available. The lag time and lag month values were calibrated until the simulated Cumulative Rainfall Departure (CRD) and RIB groundwater level fluctuations fitted closely with the observed groundwater level fluctuations. Therefore, when a close fit was achieved between the observed and simulated water level fluctuations by CRD and RIB, recharge estimated by the RIB model was recorded. Therefore, the better the fit between the simulated (CRD and RIB) and observed groundwater levels fluctuation the more reliable the estimated recharge by the RIB model.

4.5.6 Chloride Mass Balance method

The Chloride Mass balance (CMB) method is a tracer technique that is widely used to estimate groundwater recharge due to its simplicity and relatively low cost of application (Adams et al., 2004) (see details in Chapter 3 section 3.4.1). The CMB method is based on the premises that the ratio of the chloride concentration in rainfall to that in groundwater is proportional to recharge. The advantage of using the CMB method is that the technique is considered relatively simple, low coast, analysis can be carried out in less sophisticated laboratories, and it works independently from the storativity which can be problematic to estimate in fractured rock aquifers. While the major disadvantage of the method is that the recycling of dried salt by wind, unaccounted runoff may distort the results (Kinzelbach et al., 2002). The equation for calculating recharge with the CMB method is as follows:

$$\textbf{Recharge (\% of MAP)} = \left(Cl_r/Cl_{gr}\right) \times 100 \tag{4.4}$$

$$\textbf{Recharge (mm/yr)} = P \times (Cl_{\boldsymbol{r}}/Cl_{\boldsymbol{gr}}) \qquad (4.5)$$

Where P is the total rainfall, Cl_r (mg/L) is the weighted average chloride concentration in rain and Cl_{gr} (mg/L) is the chloride concentration in groundwater

Where weighted average (Cl_r) is calculated as follows:

$$\frac{P_1 \times C_1 + \cdots + P_n \times C_n}{P_1 + \cdots + P_n}$$

Where P_1 is the first rainfall event (mm) and C_1 is the corresponding concentration in the rainfall (mg/ℓ), for 1 to n events. Therefore to calculate the weighted average for each hydrological year, the chloride concentration of each event is multiplied by the amount of the rainfall event. The summation of these individual components is then divided by the total annual rainfall (Marei et al., 2010).

Critical assumption on application of CMB method

The CMB method may only be applied under the following conditions:

- There must be no other source of chloride other that from precipitation.
- Chloride behaves as a conservative tracer along the flow path.
- Chloride uptake by roots should be negligible.
- No recycling of chloride should occur within the aquifer system and surface runoff should be negligible.

4.5.7 Data analysis procedures with CMB method

For this study, a mean chloride concentration (mg/L) from rainwater and a harmonic mean chloride concentration (mg/L) of groundwater from SV1, SV2 and SV3 boreholes were used to estimate a spatial representative groundwater recharge in the site. Where harmonic mean (HM) was calculated as follows:

$$\textbf{HM} = \frac{n}{\frac{1}{x_1}+\frac{1}{x_2}\ldots+\frac{1}{x_n}} \qquad (4.6)$$

Where $X_1, X_2 \ldots X_n$ represents measured chloride concentration (mg/L) while n denotes the number of observations.

Due to the proximity of the ocean in the study area which is approximately 6.96 km, it was found necessary to consider chloride dry deposition in the computation of the recharge and compare the estimates when the dry deposition was not incorporated. Furthermore, forest canopy has also been reported to significantly enhance chloride deposition resulting to an enrichment of chloride in the unsaturated zone or groundwater (Deng et al., 2013).

Unfortunately, there was no chloride dry deposition monitoring network in the area, therefore the first approximation of dry deposition of Cl was determined using an approximation equation that was developed by Van Tonder and Xu (2000). Where if the dry deposition of Cl is unknown the following equation can be applied:

$$(0.8 \times Cl\ of\ rainfall) \qquad (4.7)$$

If spray of mist/dust is a factor at the coast

$$(2.5 \times Cl\ of\ rainfall) \qquad (4.8$$

If the forest exists

Therefore modifying the equation for recharge to be as follows:

Recharge = $P \times \left(Cl_r + D/Cl_{gr}\right) = P \times TD/Cl_{gr}$ (4.9)

Where the sum $P \times Clr$ and D is the total atmospheric chloride deposition from both precipitation and dry fall out.

Although the area is a hillslope, runoff is barely generated or limited in the area due to the presence of vegetation cover (refer to the conceptual model) therefore, the influence of runoff on recharge computation was ignored where recharge would be estimated as follows:

$$R = \left\{\left(Cl_p/Cl_{rw}\right) \times P\right\} + \{A_b \times Cl_{ro}/A_f \times Cl_{rw}) \times ro\} \qquad (4.10)$$

Where ro is equivalent depth of runoff (mm) with a chloride concentration of Cl_{ro} (mg/L) from a catchment with area A_b (m^2), A_f represent the area of the depression floor (m^2), the limiting assumption being all chloride in the catchment both surface and sub-surface moves to the depression (Bean, 2003). In addition, although the area is a vegetated environment no agricultural fertilizer (potassium chloride) is applied therefore impact of use fertilizer on groundwater chloride concentration was ignored, only the influence of the canopy on dry chloride deposition was incorporated (refer to equation 4.8).

4.6.1 Data analysis method for assessing the effect of plantation forest using HYDRUS-2D numerical model

With vegetation playing an important role in groundwater hydrology cycle through inception losses and extracting the infiltrating rainwater before recharging the water table, a range of models has been developed to enhance the hydrological interaction between vegetation and groundwater in shallow water table. The most utilized models include MODFLOW, HYDRUS, WAVES, and SWAP. Just as any other models these models are based on certain laws, principle and equation and have limitation. HYDRUS model is one of the most popular applied models to simulate soil water dynamics in the unsaturated zone. This is due to its ability to model flows in large varies environments from uniform to complex heterogeneity environment (Fan, 2014). HYDRUS model is finite element program that is used to simulate water movement and solute transport within the soil profiles, the model was developed to understand the main processes that influence water dynamics fluxes in the vadose zone (Fan, 2014). The main advantages of using the unsaturated zone model (solving Richard's equation) is that the technique can be adopted to any soil, weather condition or vegetation type, and the method can also account for other fluxes (transpiration, evaporation, runoff, interflow among others). In this current study the HYDRUS model was used assess the effect of pine plantation forest on groundwater recharge.

4.6.2 Water retention curve experiment

The soil water retention data were required to parameterize the initial condition of the model, boundary fluxes and most importantly to obtain the site-specific water retention characteristics of each transect. For estimation water retention curve Sandbox (hanging column) and Clay/Kaolin box experiment were used. The Sandbox is generally used in low tension (wet) range of water retention curve and measurement range is from 0 - 10 kPa while Clay/Kaolin box is used in tension range of 10 - 50 kPa (Figure 4.6). For the Sandbox experiment to get reliable water retention results the soil samples were saturated at pressure head 0 pF (Eijkelkamp, User Manual, www.eijkelkamp.com). This was done by removing the cap of the soil core sample ring and putting a piece of nylon cloth at the bottom side (sharp side) of the sample with a rubber band.

Then the soil samples were placed with the nylon cloth side inside the sandbox which was filled with water 1cm below the top of the sample (Eijkelkamp, User Manual, www.eijkelkamp.com). The sandbox basin was closed with its lid to prevent evaporation, and the samples were allowed to saturate for a week. After a week the samples were weighed and returned to the same position inside the sandbox, the suction regulator knob was adjusted to 1 pF (Figure 4.7) and the samples were left for a week, which after a week they were weighed and placed back inside the sandbox and suction regulator knob was turned to 1.8 pF. The same procedure was done until pressure head of 2 pF results were obtained. For Clay/Kaolin box, the box was filled with the same sand material as the sandbox, but the surface was covered with a layer of kaolin clay. The same procedures followed in the sandbox experiment were also done in this experiment, placing the samples on the kaolin surface and pressing them lightly downwards to form a good contact between the soil sample and kaolin. Instead of using gravitational pressure like the Sandbox, the Kaolin box experiment uses a vacuum pump to release water.

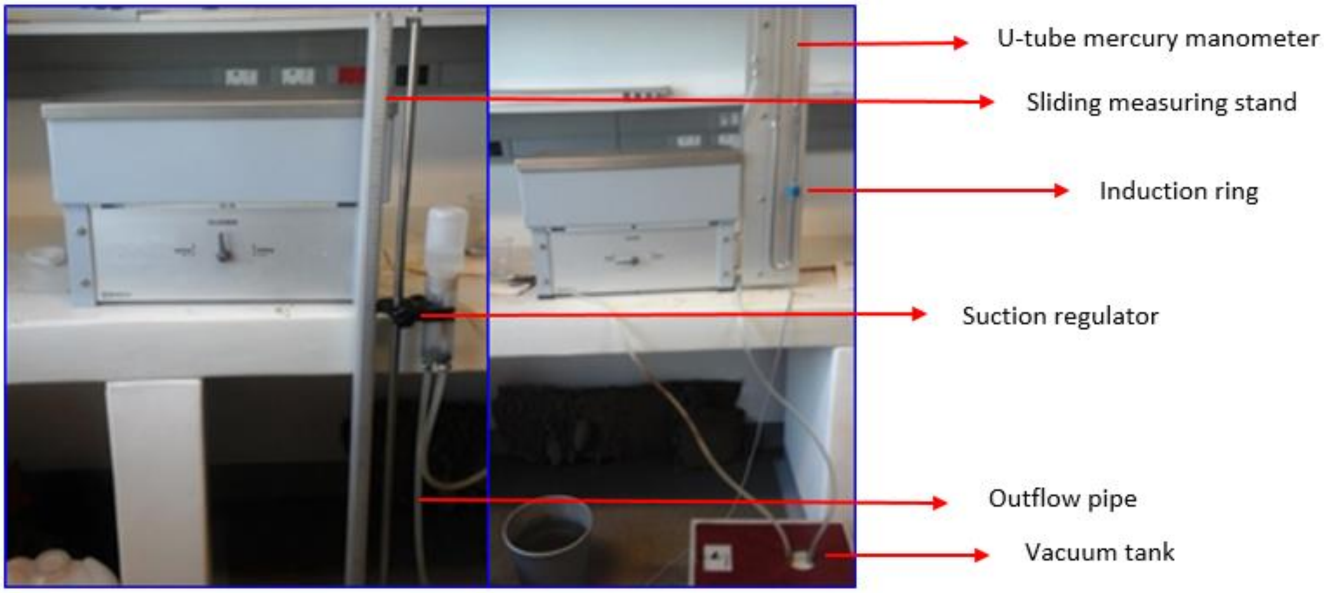


Figure 4.6: Sandbox (left) and Clay/Kaolin box experiment (right)

Figure 4.7: Sandbox experiment during pF value 1

4.6.3 Model description

HYDRUS-2D is a process based finite element model which is used to simulate water, heat and solute movement in two-dimensional variably saturated porous media (Sejna et al., 2014). The model was designed to consider the governing processes that affect water dynamics in the unsaturated zone, such as rainfall, soil evaporation, root uptake and deep drainage (potential recharge) (Fan, 2014). The model allows the user to design the geometry of the model domain and to specify initial conditions, boundary conditions and distribution of soil profile material. The model can deal with various water flow boundary conditions such as constant or variable head or flux, atmospheric boundary, free drainage, deep drainage and seepage face boundary. Water flow and transport in the model can occur in the vertical, horizontal, or in an inclined direction. The model estimate potential recharge by quantifying the deep percolation flux below the root zone in a water balance of each model domain at every time step and summing the total. This recharge is in response to meteorological parameters in the site. Figure 4.8 illustrates an example of the HYDRUS-2D user interface.

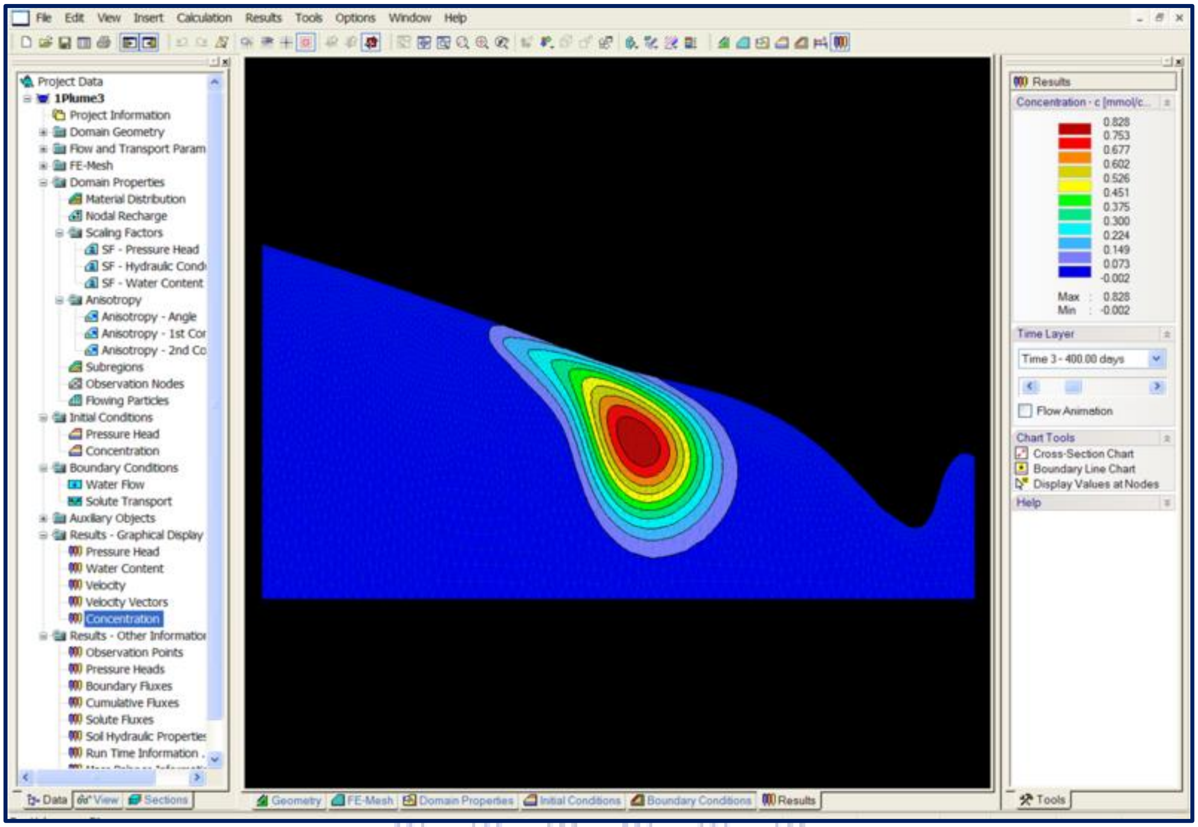


Figure 4.8: Screen printout of the HYDRUS-2D model user interface

4.6.4 Governing equation and parameters

The HYDRUS-2D code numerically solves Richard's equation for variably saturated water flow, which is a widely accepted appropriate equation for describing physical processes of water movement in variably saturated soils. The water flow equation considers root uptake through the inclusion of sink term. In a general form, the modified Richard's equation with air phase assumed to be insignificant and it can be written as:

$$\frac{\partial\theta}{\partial x} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + Cos\alpha\right)\right] - S \qquad (4.11)$$

Where *h* is the water pressure head (L), θ is the volumetric water content (L^3L^3), t is the time (T), *x* is the spatial coordinate (L), *S* is the sink term ($L^3L^{-3}LT^{-1}$) and *K* is the unsaturated hydraulic conductivity (LT^{-1}) given by

$$K\ (h, x) = Ks\ (x) Kr\ (h, x) \qquad (4.12)$$

Where *Kr* is the relative hydraulic conductivity (-), *Ks* is the saturated hydraulic conductivity (LT^{-1}).

4.6.5 Partition of root water uptake and soil evaporation

The HYDRUS code runs with potential evaporation (PE) and potential transpiration (PT) as separate components. The availability of vegetation water use (transpiration) data and ETo data allowed for the calculation of PE and PT as follows:

$$PE = (Kc - Kcb) \times ETo \tag{4.13}$$

$$PT = Kcb \times ETo \tag{4.14}$$

Where Kc and Kcb represent the crop and basal crop factor respectively, and ETo is the reference evapotranspiration which is calculated from data recorded at the automatic Weather System. For the *Pinus elliotii* compartment Kcb was calculated as follows:

$$K_{cb} = T/ET_o \tag{4.15}$$

Where T is the transpiration. A simple upscaling approach was used to calculate Kc:

$$K_c = (T + 0.1 \times T)/\,ET_o \tag{4.16}$$

Kc and Kcb were determined for the Pinus radiata compartment and the Groenkop indigenous forest at monthly intervals during previous studies by Gush (2011) and Gush et al. (2015).

4.6.6 Model domain set up and boundary conditions

B16A model compartment

For the B16A compartment, a slope length and angle were set at 287 m and 5.7° respectively, which corresponded to the observed distance from Heat Pulse Velocity (HPV1) system to the soil moisture sensor ECHO2 in the compartment. Using the observed sediment samples collected during borehole drilling three soil profile layers namely sandy loam (0–40 cm), clay (40 – 50 cm) and sandy loam (50 –100 cm) were assigned in the model domain. The default soil hydraulic properties from Carsel and Parrish, 1988 associated with these soil textural classes were maintained, while a van Genuchten-Mualem single porosity was assigned with water flow without hysteresis effect. The boundary conditions were set to atmospheric (top), variable head/no flow/constant head (upslope), seepage face (downslope) and free drainage (bottom). The variable head and constant head boundary conditions were selected to represent water flow into the model domain from upslope contributing areas. Variable head boundary data were obtained from a soil moisture sensor installed at this boundary.

A free drainage condition was assigned to the bottom boundary as the groundwater level occurs below at 43 mbgl the model domain and does not influence the root zone soil water fluxes. Soil moisture data were converted to pressure heads (cm) through the use of soil moisture retention curves. A constant head of -939 cm was assigned to the upslope boundary of the sandy clay sub-region as observed soil moisture data were not available for this soil horizon. An absolute value of minimum allowed pressure head at the surface was set at -15000 cm. Root water uptake was restricted to the Sandy Loam sub-region, and the process was parameterized to represent root water uptake by the *Pinus elliottii* occurring in the study compartment. Four observation nodes were specified at depth of 20 cm and 40 cm at both upslope and at the bottom (seepage face), this was in correspondence to the soil moisture sensor installed at the compartment. The numerical simulation was performed from 1 October 2016 to 30 September 2017, the initial condition -939 cm assigned for the numerical simulation was based on a pressure head (cm) established from the retention data. A schematic model set up for the B16A compartment is presented in Figure 4.9.

B18B model compartment

For the B18b compartment, a slope length and angle were set at 150 m and 5.3° respectively, which corresponds to that observed in the study plantation compartment. The soil material distribution, observed from sediment samples collected during borehole drilling, was assigned to be sandy loam (0 – 45 cm), clay (45 – 55 cm) and sandy clay (55 – 100 cm). The default soil hydraulic properties (hydraulic conductivity, saturated water content, residual water content, air entry parameter, pore size distribution and pore connectivity parameter) associated with these soil textural classes were maintained. The boundary conditions were set to atmospheric (top), variable head/no flow/constant head (upslope), seepage face (downslope) and free drainage ($\partial h/\partial x = 0$) at the bottom. The variable head and constant head boundary conditions were selected to represent water flow into the model domain from upslope contributing areas.

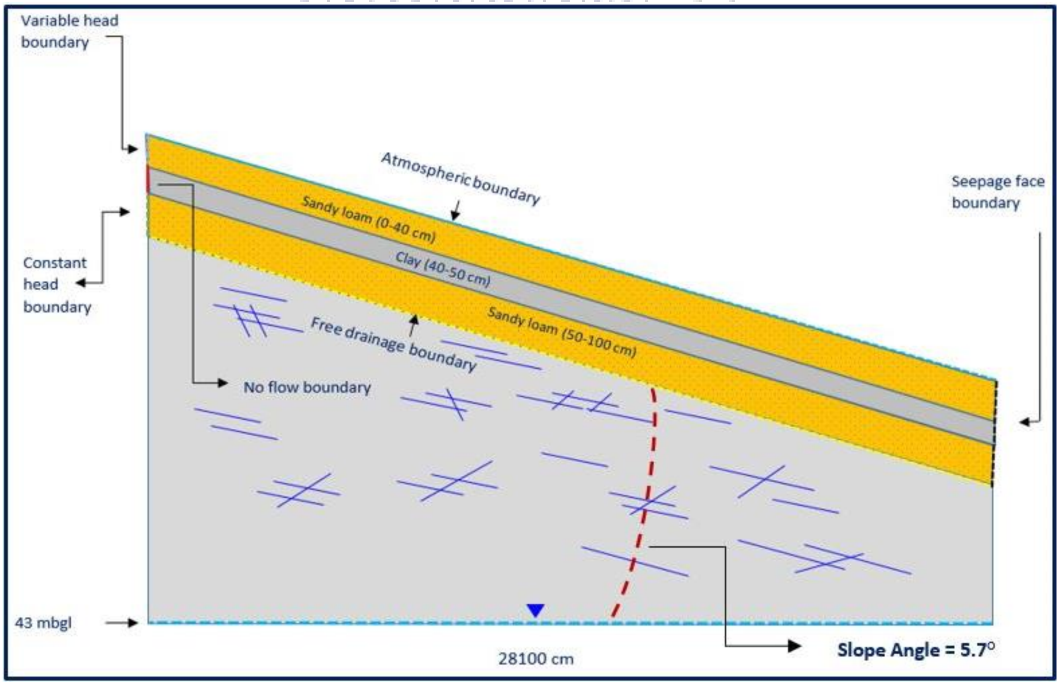
Variable head boundary data were obtained from a soil moisture sensor installed at this boundary. Soil moisture data were converted to pressure heads (cm) through the use of soil moisture retention curves. A constant head of -490 cm was assigned to the upslope boundary of the sandy clay sub-region as observed soil moisture data were not available for this soil horizon. The boundary conditions at the upslope end of the model domain aim to account for augmentation of lower lying plantation forest soil water reserves, from the upslope regions where there was fynbos vegetation. A free drainage condition was assigned to the bottom boundary as the groundwater level occurs below the model domain. Initial conditions were set to -490 cm which corresponds to the observed soil moisture on 30 September 2016, i.e. Day of Simulation (DOS) 0. Root water uptake was restricted to the sandy loam sub-region and the process was parameterized to represent root water uptake by the *Pinus radiata* occurring in the study compartment. A schematic model set up for the transect being studied is presented in Figure 4.9.

Groenkop model set up

The model domain was also designed based on collected field data, i.e. boundary conditions, soil depth, soil textural class, slope length, slope angle, rooting depth and root distribution. The slope length and angle were set at 250 m and 4.1° respectively, which corresponds to that observed in the forest from Heat Pulse Velocity (HPV3) system to the soil moisture sensor (VWC3). The boundary conditions were set to atmospheric (top), variable head/no flow/constant head (upslope), seepage face (downslope) and free drainage (bottom). The default soil hydraulic properties (hydraulic conductivity, saturated water content, residual water content, air entry parameter, pore size distribution and pore connectivity parameter) associated with these soil textural classes were maintained. The model was run for the period 1 October 2016 (Day of Simulation/DOS 1) to 30 September 2017 (DOS 365). Additional data relevant to the model set-up is presented in Table 4.1. A schematic model set up for the Groenkop transect being studied is presented in Figure 4.10

Table 4.1: Information relevant to the HYDRUS-2D set-up

Parameter		Transect		
		Pinus elliottii	*Pinus radiata*	Groenkop Forest
Slope length (m)		287	150	250
Slope angle (º)		5.7	5.3	4.1
Soil profile discretization		Sandy loam (0 – 40 cm), Clay (40 – 50 cm) and Sandy loam (50 – 100 cm)	Sandy loam (0 – 45 cm), Clay (45 – 55 cm) and Sandy clay (55 – 100 cm)	Sandy loam (0 – 40 cm), Clay (40 – 50 cm) and Clay loam (50 – 100 cm)
Water flow model		van Genuchten-Mualem (single porosity)	van Genuchten-Mualem (single porosity)	van Genuchten-Mualem (single porosity)
Hysteresis		No	No	No
Boundary Conditions	Top	Atmospheric	Atmospheric	Atmospheric
	Bottom	Free drainage	Free drainage	Free drainage
	Upslope	variable head/no flow/constant head	variable head/no flow/constant head	variable head/no flow/constant head
	Downslope	Seepage face	Seepage face	Seepage face
Root water uptake		Restricted to Sandy loam (0 – 40 cm) sub-region	Restricted to Sandy loam (0 – 45 cm) sub-region	Restricted to Sandy loam (0 – 40 cm) sub-region
Observation nodes (upslope and downslope end of the domain)		20 cm and 40 cm	20 cm and 40 cm	20 cm and 40 cm
Initial head (DOS 0) and constant head boundary value		-939.45 cm	-490.52 cm	-405.26 cm



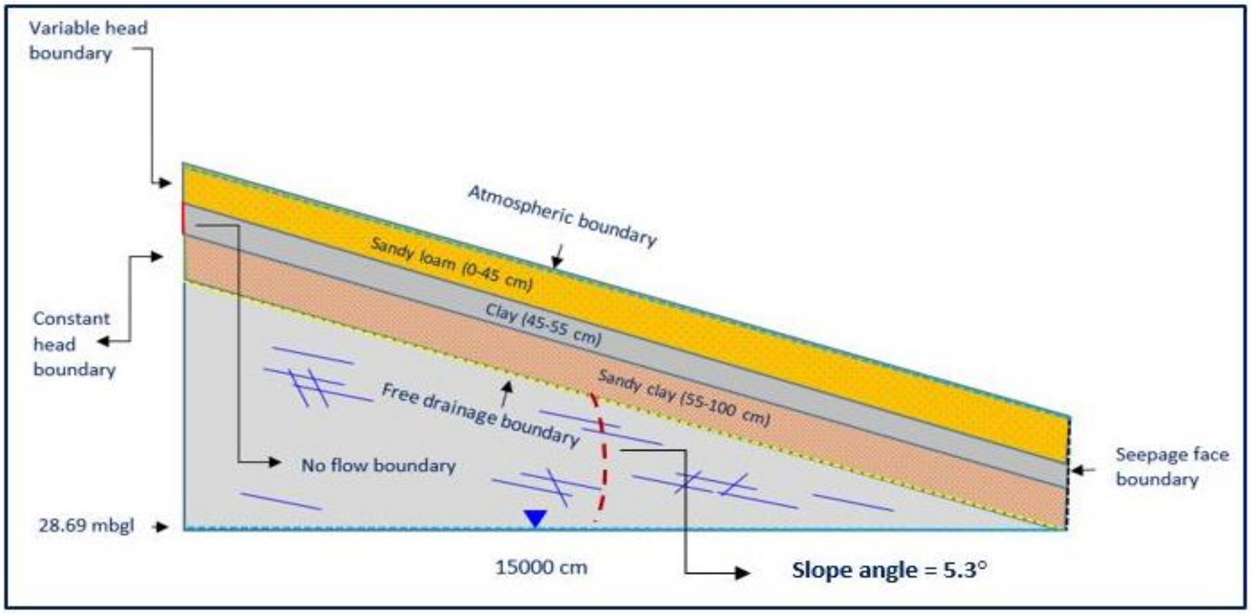


Figure 4.9: A schematic of the HYDRUS-2D set-up in the *Pinus elliottii* compartment (top) and *Pinus radiata* compartment (bottom)

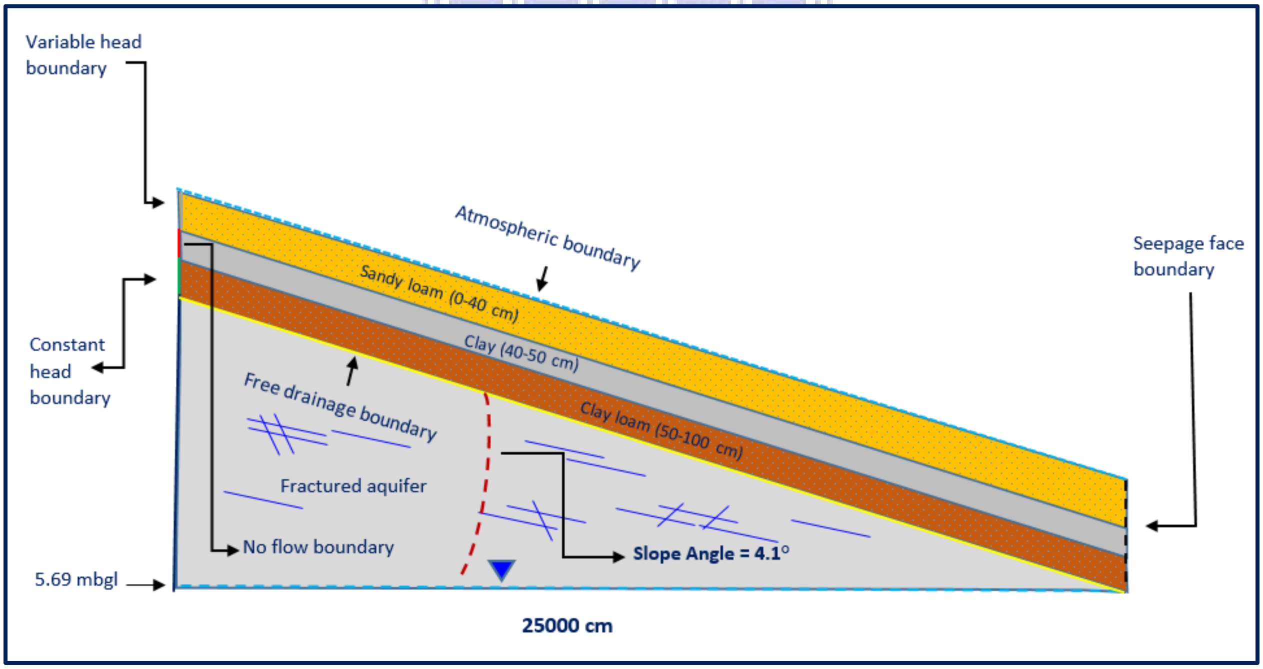


Figure 4.10: A schematic of the HYDRUS-2D set-up in the Groenkop forest

4.6.7 Model performance evaluation

To evaluate the performance of the model a parameter optimization (inverse solution), incorporated in the HYDRUS-2D software package, was applied to compare the observed (measured) and simulated soil water content. Soil hydraulic properties were changed within a justifiable range and the fit between the observed and simulated VWC studied. The root mean square error (RMSE) and mean absolute error (MAE) were used to assess the error of the simulation. RMSE and MAE are among the widely used useful parameters to evaluate the performance of models (Chai and Draxler, 2014). Although there is no acceptable limits for RMSE and MAE, values close or equal to zero indicate a perfect fit between the observed and simulated (Moriasi et al., 2007). Since the two parameters represent various magnitude of error applying them in conjunction is mostly recommended (Shamuyarira, 2017). RMSE and MAE values were calculated as follows:

$$\text{RMSE} = \sqrt{\frac{\sum(S_I - O_I)^2}{n}} \qquad (4.17)$$

$$\text{MAE} = \frac{1}{n}\sum \left| S_i - O_i \right| \qquad (4.18)$$

Where *O* is the observed volumetric water content, *S* is the simulated volumetric water content and *n* is the total number of observations of volumetric water content.

4.6.8 Assessment of the significance of the variation of recharge estimates

To test whether the variation in recharge estimates derived from the plantation forest and the indigenous forest was significantly different, a statistical method i.e. two-tailed t-test analysis at 5% significant interval (α) was applied. The t-test values were calculated as follows:

$$t = \frac{\bar{X}_1 + \bar{X}_2}{Sp\sqrt{\frac{1}{n_1} + \frac{2}{n_2}}} \, Sp = \sqrt{\frac{n_1 S_1^2 + n_2 S_2^2}{n_1 + n_2 - 2}} \qquad (4.19)$$

Where $\bar{x}_1$ and $\bar{x}_2$ represent the first and the second sample mean respectively, s stand for standard deviation, n represent the number of samples and Sp represent pool standard deviation

4.6.9 Infilling of volumetric water content data

Although the model simulation was carried out over a complete hydrological year (1 October 2016 - 30 September 2017) on some occasions, the soil moisture sensors were pulled out by baboons in the plantation forest resulting into hourly and sometimes even daily data missing. To infill the missing data, a linear regression equation was applied using VWC datasets from other sensors at the site. Linear regression equation can be written as:

$$Y = a + bX \tag{4.20}$$

Where *Y* is the independent variable, *a* is the intercept, *b* is the slope or regression coefficient and *X* represents the dependable variable.

4.7 Data quality assurance and quality control

The current section provides the steps followed during the data collection and data analysis in order to produce representative and reliable data for each objective of the study. For objective one which was (i) to characterize groundwater recharge mechanism, the following data quality assurance steps were followed: New clean and sterile sampling bottles were used to collect the isotope and chemistry samples from the field. Boreholes were firstly purged to obtain the representative isotope and chemistry samples of groundwater drawn from the aquifer. To check the credibility of the inorganic chemistry data a cation-anion balance (CAB) method was applied. The method is based on the principle of electroneutrality which states that a water cannot carry a net electrical charge (positive or negative) but must always be electrically neutral (Younger, 2007). The CAB formula can be written as follows:

$$CAB\ (\%) = 100 \times \frac{\sum cation\,[] - \sum anion\,[]}{\sum cation\,[] + \sum anion\,[]} \tag{4.11}$$

Where all concentrations are expressed in meq/L

If CAM value is less than 5% analysis can be considered as adequate accurate for all uses, while if CAB is within the range of 10 - 15%, the quality of analysis is questionable and should be used with caution, whereas value exceeding 15% cannot be considered as being adequately reliable to justify using them for serious scientific purpose (Younger, 2007).

For objective two which was (ii) to estimation of groundwater recharge, the following data quality assurance steps were taken: Every time after finishing downloading the water level data from the logger manually measurements were taken with a water level meter to validate or check any error measurement by the logger or any discrepancies between the electronic and manual measured values. All groundwater level measurements were measured to the reference datum point. The data used for CMB was also firstly subjected to the cation-anion balance error before used.

For objective three which was (iii) to assess the effect of plantation forest on groundwater recharge, the following data quality assurance steps were taken: A linear regression equation was applied to infill the missing data in order to run the model with complete data. To validate the HYDRUS model results an inverse solution method which has statistical analysis output was applied (as discussed in chapter 4 section 4.6.7).

4.8 Research integrity

Since the study sample sites are within the Groenkop Forest and Saasveld plantation therefore, permission to conduct the study was requested from South African National Parks (SANParks) and Cape Pine. This was done through a formal application and verbal explaining the purpose of the study and its significance in reserve determination. A review process was done by SANParks and Environmental Management Method Statement was further request from the research team. Activities such as borehole drilling, excavating land for soil samples and installing soil moisture sensors and Eddy Covariance instrumentation during the period of the study were explained and clarified to both organizations in advance before the study commenced. Enough time was given to SANParks to read the application form and give feedback. After finishing drilling the boreholes the site was cleaned and the pits were closed to avoid any harm from the animals. Every time after finishing measuring water levels the borehole caps were put back and locked to avoid any injuries to animals such as baboon the area. Artificial feeding the animals in the forest was avoided at all times.

4.9 Study limitation

There was no chloride dry deposition monitoring network in the area, therefore a first approximation of dry deposition of Cl was determined using an approximation equation (after Van Tonder and Xu, 2000) which could have resulted into underestimation of groundwater recharge estimation using CMB method. On some occasions, the soil moisture sensors were pulled out by baboons in the plantation forest resulting in missing data for some days. Therefore, a linear regression analysis had to be done to patch the missing datasets using other sensors in the site which could have resulted in the inaccuracy of the input VWC data on the model. The LMWL of George is not yet established and therefore the nearest LMWL of Cape Town, which was located about 429 km west of the study area, was used for a regional indication. The study site was located approximately 412 km from the research institute (University of the Western Cape) this controlled the number of visits to the site which subsequently controlled the amount of data to be collected for the study.

Chapter 5: Characterization of Groundwater Recharge Mechanism

5.1 Introduction

This chapter presents and discusses the results of objective one which aimed to characterize the dominantly occurring groundwater recharge mechanism in the area. The characterization of the recharge represents an initial step towards improving recharge estimates for the study area. Prior to characterizing the recharge mechanism in the area, the study firstly delineated potential recharge zones and developed a conceptual groundwater recharge model for the study area. The central argument in this chapter was that, if a conceptual recharge model of the area is developed and the dominantly occurring recharge mechanism are understood before quantifying recharge, it would facilitate an improved understanding of recharge estimates. The isotopic compositions of rainwater and groundwater were used to infer the dominant mode of recharge in the area. The study assumed that in a case where recharge occurs immediately (rapidly) after a rainfall event the water would reflect minimal evaporation prior to infiltration, hence a preferential recharge mechanism is inferred. Alternatively, water reflecting high evaporation after a rainfall event would infer the dominance of delayed or slow recharge mechanism. The analysis of hydrochemical data was used to supplement the isotope results.

5.2 Results and Discussion

5.2.1 The occurrence of lineaments and the spatial distribution of rainfall as a proxy for the delineation of groundwater recharge zones

The rugged mountain ranges north of the catchment serves as an important source of recharge in the area (Roberts et al., 2008). This is due to the presence of lineaments which may represent deep-seated faults, fractures and joints (Figure 5.1). Lineaments are important features in groundwater recharge assessments as they may represent pathways for groundwater movement, promoting infiltration and preferential recharge. In addition, these rugged mountains receive > 1000 mm rainfall annually because of the orographic effect while the coastal plain receives approximately 800 mm annually (Roberts et al., 2008). It is important to note that it is often observed that the high rainfall occurring in mountainous regions is usually available for recharge further down the topographic profile where favorable conditions exist (Adams, 2004). However, in this catchment, the higher lying areas that receive the higher annual rainfall correspond with the areas that are characterized by a dense presence of lineaments (favorable infiltrating conditions) therefore suggesting these areas as potential recharge zones. This is in agreement with the recharge study by Wu (2007) who reported that recharge areas of the TMG are located primarily in the rugged mountainous areas with elevations ranging from 200 – 2250 mamsl. The weakness associated with using lineaments to delineate recharge zones is the fact that fractures or joints may not always be hydraulically connected, and therefore they may not always serve as pathways to the aquifer. However, when a high density of fractures intersects each other there is a high possibility of them being hydraulically interconnected, and therefore they can be used in combination with the rainfall distribution as a proxy for the delineation of recharge zones. The results of the study have demonstrated that a spatial variation of recharge exists between the upper part of the catchment and the lower coastal plain. Any groundwater management strategy should consider such recharge variation for effective management of groundwater resources in the area.

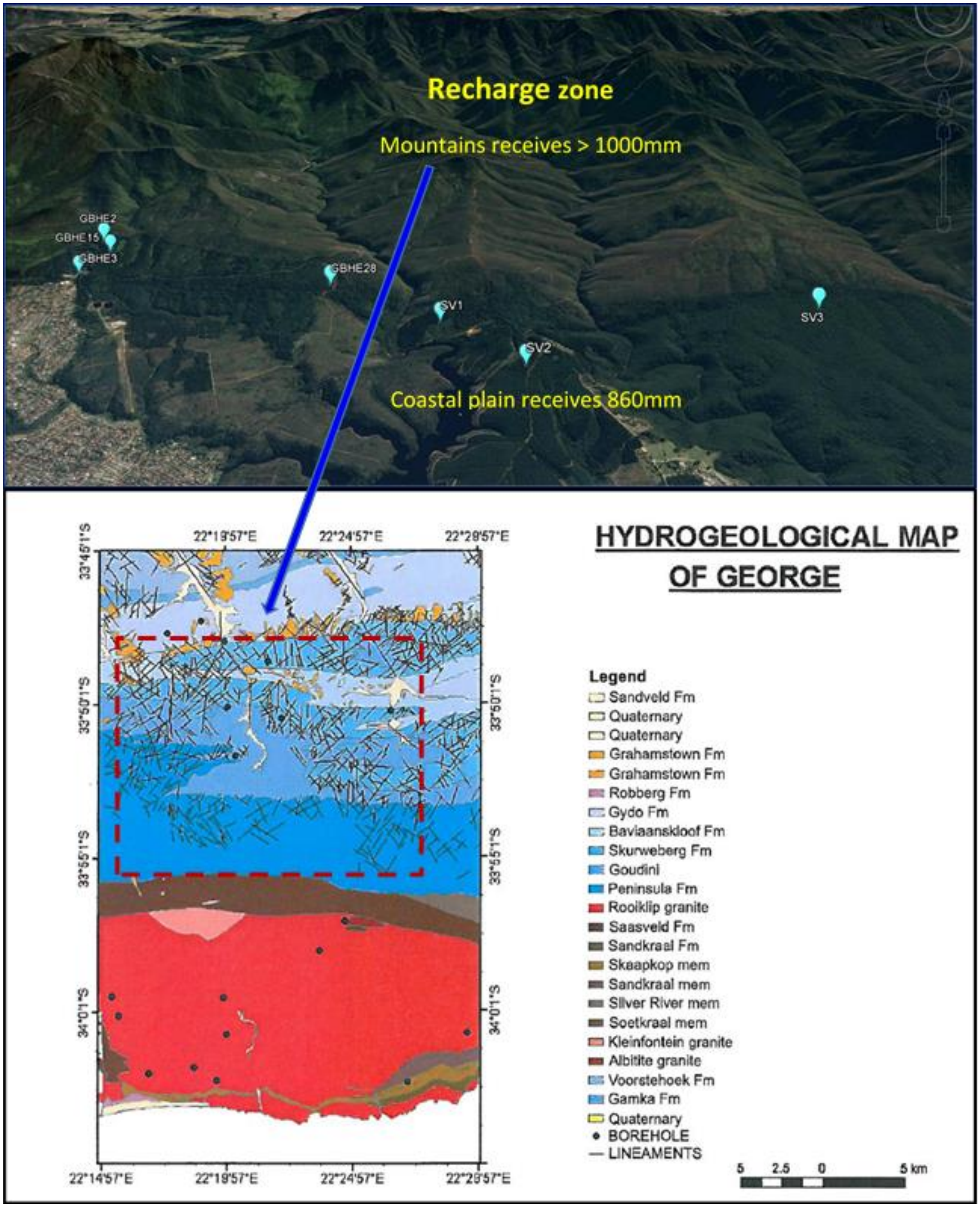


Figure 5.1: Simplified hydrogeology map of the study area showing major lineaments and the stratigraphy (Roberts et al., 2008)

5.2.2 Conceptualization of groundwater recharge processes in the area

The conceptual model of the study area was informed by previous investigations conducted in the study area (Roberts et al., 2008, Gush et al., 2015) and by other studies conducted in similar hydrogeological settings (Kotze, 2002; Wu, 2005 and Xu et al., 2007). Regionally, the study area is bounded by a watershed in the north, by a coastline boundary in the south, a drainage boundary to the west and the Outeniqua fault zone to the east (Wu, 2005). The study area consists of two major water-bearing formations, namely the sandstone rock of the Peninsula and Skurweberg Formations and the fractured shale rock aquifer of the Saasveld Formation. Transmissivity values in the sandstone are approximately 100 m^2/day while in the shale rock they are approximately 25 m^2/day (see Chapter 2, section 2.7). The higher rainfall occurring in the rugged mountain ranges north of the catchment serve as an important source of recharge. Due to the absence of snowmelt, rainfall is the only source of groundwater recharge in the area. Fractures are either open or filled (totally or partially) by soil and vegetation. Infiltration is often rapid along open fractures and reduced in filled fractures due to the reduced aperture and evapotranspiration losses. Often, high infiltration rates are observed near the surface, however the fractures tend to close at depths resulting in the generation of interflow. Thus, recharge is commonly constrained by the characteristics of fractures at depth.

Middleton and Bailey (2011) estimated the Potential Evapotranspiration (PET) in the area to be 1400 mm/yr. Vegetation affects groundwater recharge through interception and transpiration (see Chapter 7). The vegetation distribution in the study area is generally characterized by the occurrence of shrubby fynbos type vegetation at the crest of the slope, which merges into indigenous forest lower down the slope. Plantation forests occurs in mid to low elevation parts and indigenous vegetation in the riparian zone. Gush et al. (2015) measured that the plantation forests consume more water than the indigenous vegetation. Due to the soil conditions evident in the study area, it is interpreted that root water uptake is restricted to the soil zone. However, vegetation may still influence recharge by extracting soil water in the vadose zone, thereby limiting percolation and subsequently groundwater recharge (see Chapter 3, section 3.9). Due to the dense vegetation and soil properties, minimal overland flow occurs in the area. Infiltration occurs into the soil zone which is generally 0.5 – 1 m thick. The infiltration depth is slightly deeper along the roots of vegetation and along macropores.

The intensity of rainfall influences infiltration rates as infiltration may be reduced due to surface sealing caused by high rainfall intensities and rain splash. The slope of the landscape, as well as the low hydraulic conductivity of underlying strata promotes lateral flow/throughflow in the soil zone (Figure 5.2). Gush et al. (2015) dug several soil pits in the area, and these were observed to be filled with water throughout the year. Throughflow from the soil zone is thus interpreted to be a dominant streamflow generation component. Water moves laterally along the low permeability layers until preferential flow paths (fractures and faults) are encountered in the underlying strata (Figure 5.2). This downward flow is a function of the characteristics of these features, and if the flow is restricted, interflow may occur (Figure 5.2). The processes of vertical and horizontal flow occurs until the percolating water reaches the saturated zone or a watercourse.

The conceptual model is in agreement with the recharge study by Wu (2007), who reported on the influence of slope, fractures, topography and vegetation among others on groundwater recharge in TMG aquifers. The presence of these physiographic features was expected to influence groundwater recharge in the area, hence these factors were reviewed and linked to the concept of the study (see Chapter 2). The conceptual model reveals that groundwater recharge in the area occurs both vertically and laterally depending on the connectivity of fractures within the area. However, it is important to acknowledge that this lateral movement is barely incorporated in many definitions of groundwater recharge. This is because recharge by the downward flow of water through the vadose zone is usually considered the most important mode of recharge (Xu and Beekman, 2003 and Obuobie, 2008).

The presented conceptual model of the area may serve as an important tool that attempts to answer the questions of where, when and how recharge occurs within the George area. It further explains the main factors and processes that influence recharge in the area. Such information may be used to effectively manage groundwater in the area. This is further supported by a study by Bean (2003) who reported that an understanding of site recharge behavior is far more important than hydrogeologist realize, it goes beyond estimating recharge to a given aquifer. The weakness associated with using a conceptual model is that the accuracy of the model is usually based on the information that was collected at that particular time. However, as additional data become available and provide new insights the model can always be revised and improved.

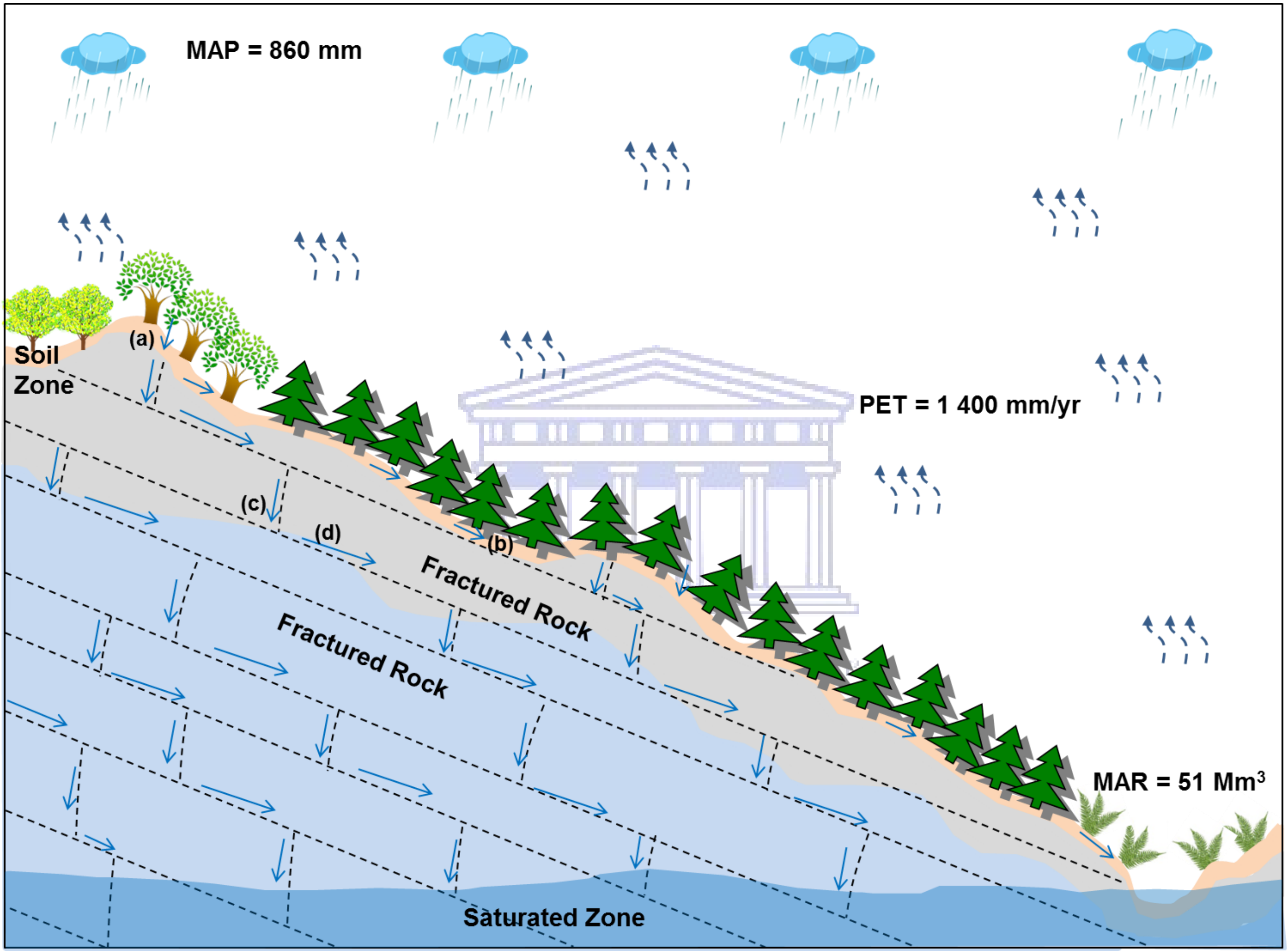


Figure 5.2: A conceptual model of groundwater recharge processes in the study area (modified from Wu, 2005 and Xu *et al*., 2007)

5.2.3 Isotopic evidence of groundwater recharge mechanism

The statistical summary of $\delta^{18}O$ and $\delta^{2}H$ signatures in the rainwater and groundwater samples collected during the study period is presented in Table 5.1 and 5.2. Rainfall samples display a wide range variation in $\delta^{2}H$ composition, ranging from -15.06 to 18.01‰ with a mean value of -3.69‰ and a standard deviation of 9.82‰, while $\delta^{18}O$ falls in a narrow range of -4.33 to 4.70‰ with a mean value of -1.43‰ and a standard deviation of 2.78. The widespread in $\delta^{2}H$ was due to enriched samples collected during the sampling period of October 2016. Although a $\delta^{2}H$ value of 18.01‰ may be interpreted as elevated or as an outlier from the rainwater samples, the same maximum value was also observed from the isotope rainfall series data from 1995 to 2008 (Harris et al., 2010). Groundwater samples show less wide variation in $\delta^{2}H$ composition as compared to rainfall, ranging from -16.64 to -9.40‰ with a mean value of -12.37‰ and a standard deviation of 2.15‰, while $\delta^{18}O$ falls in a narrow range of -3.98 to -2.26‰ with a mean value -3.47‰ and standard deviation of 0.49‰. The similar average isotopic signatures of groundwater ($\delta^{18}O$: -3.47) to that of a Local Meteoric Water Line (LMWL) ($\delta^{18}O$: -2.67, see appendix B) suggest that groundwater in the area is recharged by local rainfall.

The $\delta^{18}O$ and $\delta^{2}H$ concentrations in rainwater, surface water and groundwater samples collected during September – November 2016 are presented in Figure 5.3. These delta values are expressed as per mil deviation relative to a known standard, in this case the Standard Mean Ocean Water (SMOW) for $\delta^{18}O$ and $\delta^{2}H$. The data in Figures 5.3 – 5.5 are presented relative to the Global Meteoric Water Line (GMWL; Craig, 1961). A LMWL for George has not yet been established and therefore the nearest LMWL of Cape Town, which is located about 429 km west of the study area, is used for a regional indication. The results indicate that all rainfall samples collected in September – November 2016 have been subjected to evaporation displaying enrichment in both $\delta^{18}O$ and $\delta^{2}H$, resulting in a divergence from the GMWL. This grouping produce an evaporation line which has a slope of less than 8 (commonly 4 to 6; Weaver et al., 2007). In this case, the slope of the line is 4.5. The concentration of stable isotopes in precipitation depends on the average temperature of the region, as well as the intensity and duration of the rainfall and its altitude of occurrence (Bredenkamp et al., 1995). In this case, the enrichment is attributed to high average temperatures during this period.

For groundwater samples, it can be observed that although the samples plot close to the GMWL, they plot below the nearest LMWL and along the evaporation line, indicating an evaporation effect. It can therefore, be inferred that during these month's groundwater in the aquifer was also exposed to evaporation prior to or during the recharge process. Samples collected from the Groenkop stream are also isotopically enriched and closely related to the Saasveld groundwater (Figure 5.3). This suggests that the stream might be recharged by groundwater (a gaining stream). This is further supported by the shallow depth to groundwater, i.e. 5 mbgl, at borehole SV3. It is important to note that no spatial analysis was done along the stream, therefore the mixing only refers to the point where the sample was collected.

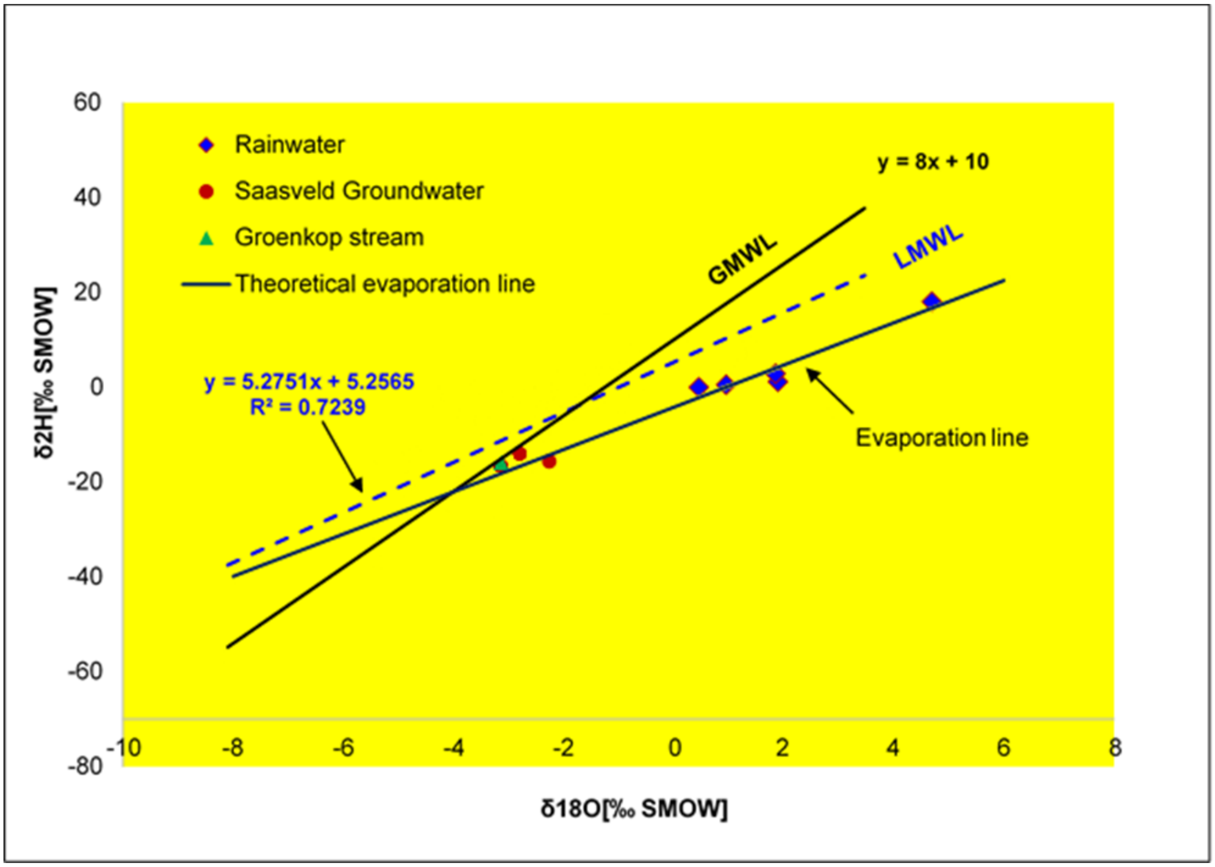


Figure 5.3: Plot of δ^{18}O and δ^{2}H concentrations in groundwater, rainfall and surface water collected from September - November 2016

Figure 5.4 presents δ^{18}O and δ^{2}H concentrations from groundwater, rainfall and surface water collected from November 2016 - February 2017. From Figure 5.4 it can be observed that all water sample sources i.e. rainwater, surface water and groundwater displays depleted isotopic signatures suggesting that groundwater and surface water is recharged by rainfall which occurred under similar climatic conditions. It can also be seen that all groundwater points plot close to the GMWL and LMWL. This further suggests that groundwater from the site is from a local rainfall that has not been subjected to significant evaporation before or during recharge. It is therefore inferred that during these month's groundwater recharge occurred via direct rapid infiltration processes.

From the clustering of samples, a distinction appears to be present between the upper catchment groundwater samples (George Municipality boreholes) and Saasveld groundwater samples (SV boreholes). Samples from the Saasveld are isotopically more depleted than those of the upper catchment. This suggests the presence of different groundwater flow systems in the catchment. The upper catchment groundwater samples appears to reflect a more local groundwater flow system, as they were less depleted and situated close to the recharge zone. Further evidence of this is reflected by lower electric conductivity values, i.e. 13 - 14 mS/m, from upper catchment samples when compared to 36 -114 mS/m from the Saasveld groundwater samples. Saasveld groundwater samples appear to be older groundwater and indicative of deeper groundwater flow systems. This was further supported by minimal to no response of the groundwater level to rainfall, including the 153 mm and 106 mm of rainfall which occurred in September 2016 and September 2017 respectively. However, due to the limited number of isotope samples collected no definite conclusions is drawn about the two systems in the area. The isotopic signature of the Groenkop stream again reflected a similar depleted isotopic signature to that of the surrounding groundwater, particularly the upper groundwater samples. This again provides more evidence of the interaction between groundwater and the stream in the area.

Table 5.1: Statistical summary of environmental stable isotopes for rainwater samples

	δ^{2}H[‰ SMOW]	δ^{18}O[‰ SMOW]
Minimum	-15.06	-4.33
Maximum	18.01	4.70
Mean	-3.69	-1.43
Standard deviation	9.82	2.78

Table 5.2: Statistical summary of environmental stable isotopes for groundwater

	δ^{2}H[‰ SMOW]	δ^{18}O[‰ SMOW]
Minimum	-16.64	-3.98
Maximum	-9.40	-2.26
Mean	-12.37	-3.47
Standard deviation	2.15	0.49

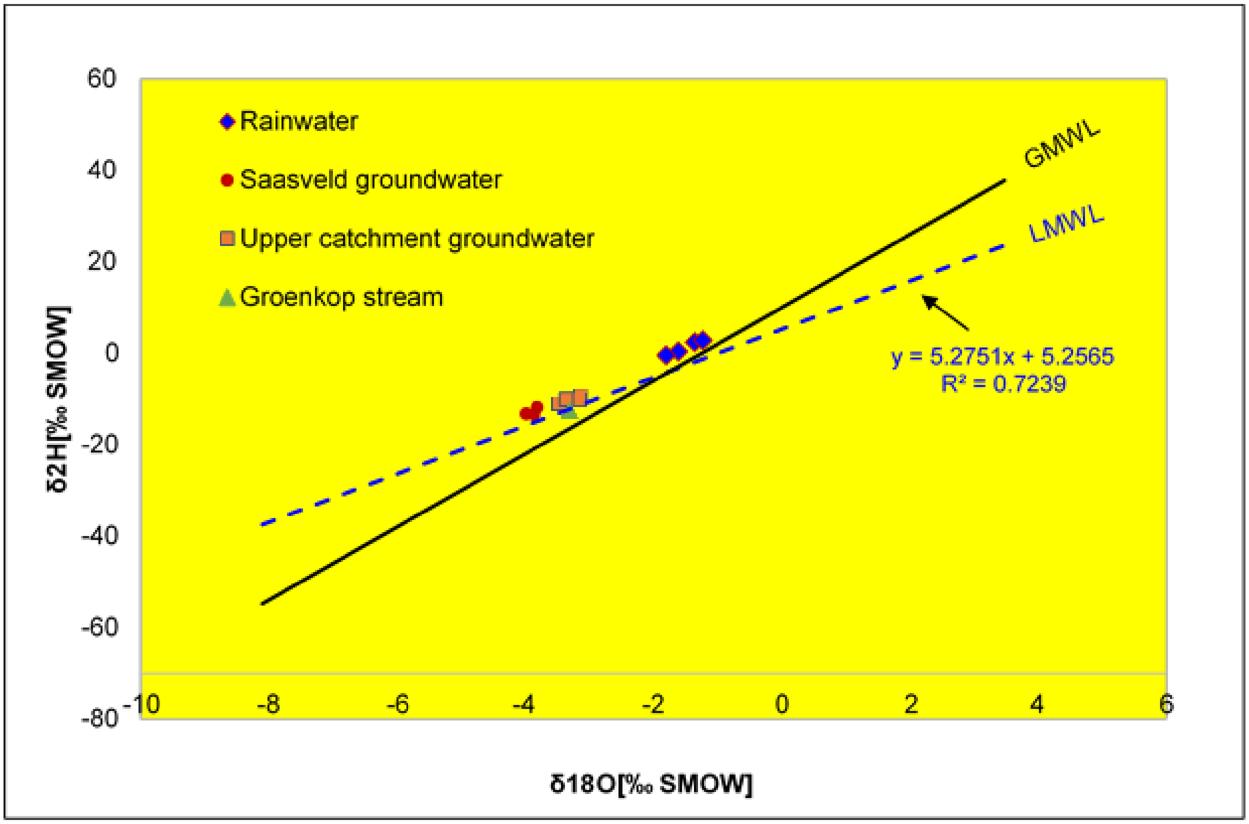


Figure 5.4: Plot of δ^{18}O and δ^{2}H concentrations in groundwater, rainfall and surface water collected from November 2016 – February 2017

Results of environmental stable isotopes analysis (δ^{18}O and δ^{2}H) for groundwater, rainfall and surface water collected between August and October 2017 are presented in Figure 5.5. All groundwater samples plot close to the GMWL and LMWL which indicates that groundwater from the site is from a local rainfall that has not been subjected to significant evaporation before or during recharge. All water sample sources i.e. rainfall, surface water and groundwater exhibit depleted isotopic signatures suggesting that groundwater and surface water were recharged by rainfall which has occurred under similar climatic conditions. Of interest, however, is that one rainfall sample is enriched possibly as a result of fractionation due to evaporation. It can be inferred that during these months groundwater was again recently recharged or groundwater recharge was through a rapid process. A similar depleted isotopic signature was again evident in the Groenkop stream sample and groundwater samples suggesting mixing between the two.

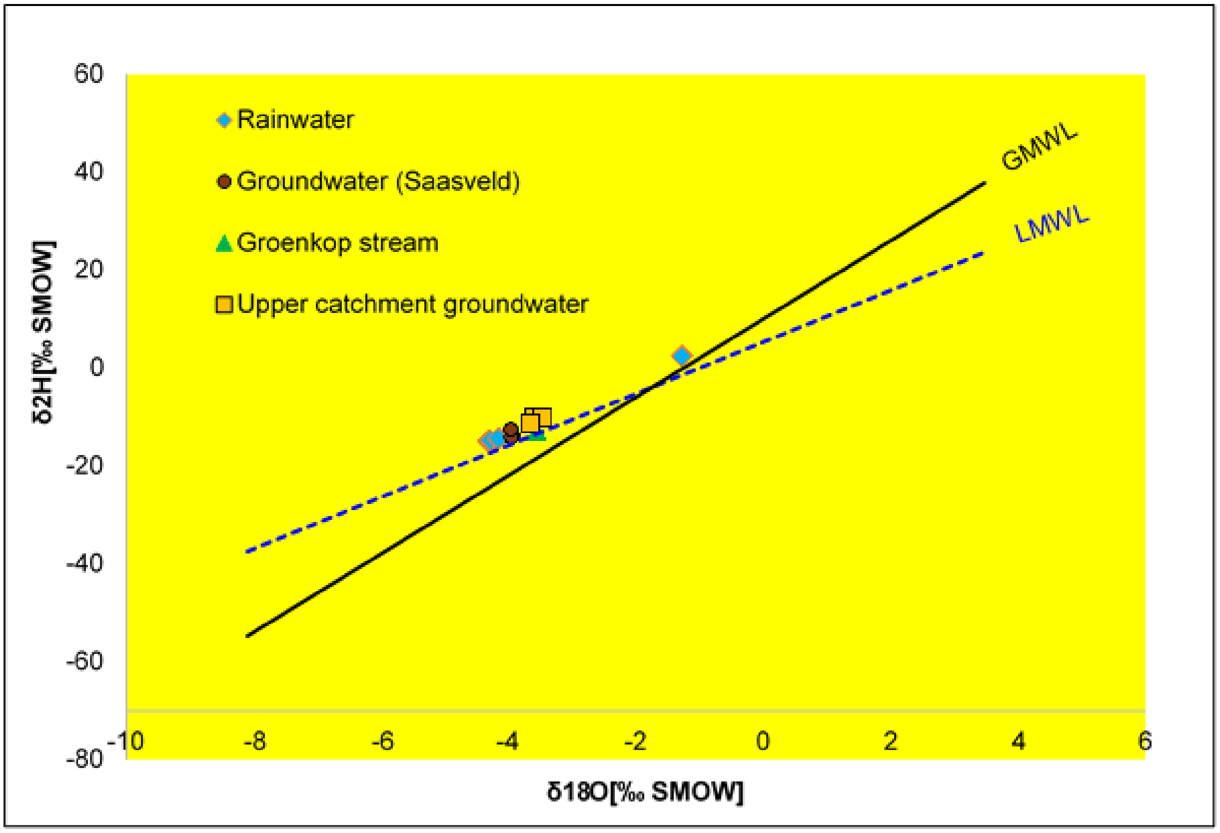


Figure 5.5: Plot of δ^{18}O and δ δ^{2}H concentrations in groundwater, rainfall and surface water collected from August – October 2017

The stable isotopes findings were in agreement with results of the conceptual model, i.e. that recharge occurred rapidly via direct infiltration. Geologically, preferential recharge mechanism was expected to be the dominantly occurring mechanism in the area due to the presence of fractures which served as preferential conduits for groundwater to move in the area. In addition the area is a vegetated environment therefore, existence of macropores which also served as preferential pathways were expected to be occurring in some parts the area. The isotope results provided scientific evidence that groundwater in the George area is recharged by local rainfall through preferential flow mechanism. Although the isotope technique proved to be successful to characterize recharge mechanism in the area, the weakness associated with the method is that the isotope interpretation is usually inferred information hence multiple tools or methods should be used to support the interpretation.

5.2.4 Hydrogeochemical evidence of groundwater recharge mechanism

Hydrochemical analysis was conducted in support of the isotope results to identify the hydrochemical facies governing the groundwater evolution and its implication to groundwater flow and circulation in the area. The summary of average measured physiochemical parameters in groundwater and surface water samples at the high lying area and at low lying area is presented in Table 5.3.The groundwater and surface water samples were plotted on a Piper trilinear plot (Figure 5.6). Groundwater chemistry analysis suggests that the water is dominated by hydrochemical facies of sodium chloride (Na-Cl) which implies that Na and Cl are the dominant major cation and anion in the aquifer respectively. This is in agreement with the recharge study done by Wu (2007) in TMG aquifers. Of relevance to the site, enrichment of Na and Cl is attributed to the dissolution of the host rock i.e. shale rock material. This implies that water-rock interaction is among the predominant geochemical processes influencing the groundwater chemistry in the area. Generally, elevated concentrations of Na and Cl were detected in the relatively deeper SV2 borehole (depth to water 43.20 mbgl) and increases with groundwater flow direction from recharge zones towards the lower coastal plain. However, as pointed out by Xu and Beekman (2003) that in an environmental setting as the study area where runoff is barely generated or limited and recharge rapidly occurs through the fractures addition of Cl could be attributed to the dissolution of airborne dust derived chloride that has been deposited on site surfaces as well. The dominance of the major cations in groundwater are in order of Na^+ > Mg^{2+} > Ca^{2+}> K^+, while anions shows abundance in order of Cl^- > HCO_3^- > SO_4^{2-}. While the dominance of the major cations in surface water are in order of Na^+ > Mg^{2+} > Ca^{2+}> K^+, whereas anions shows abundance in order of Cl^- > SO_4^{2-} > HCO_3^-. Recharge zone in the upper catchment is reflected by relative low electric conductivity (EC) values, i.e. 13 - 14 mS/m, when compared to the lower coastal lying area, i.e. 36 -114 mS/m. The measured pH at the Groenkop stream as well as at GBHE28, GBHE3, GBHE2 and GBHE15 is acidic. The pH values of the stream falls in a narrow range of 4.5 to 4.7 while groundwater samples in the upper catchment varies from 5 to 5.4. The low measured pH from groundwater samples is characteristic for groundwater occurring in TMG dominated environments. However, groundwater samples in the lower coastal lying area in Saasveld shows pH values that ranges from 6.3 to 7.1 indicating a near-neutral to weakly alkaline condition of the study area. Although it is not distinct from the piper plot, from Table 5.3 it can be observed that groundwater in the low lying area is enriched in Na-Ca- HCO_3-Cl as compared to the groundwater in the high lying area that is generally of Na-Cl facies. This again is in support of the possible existence of local groundwater flow system and deep old groundwater system in the area. These results are in accordance with the studies done by Bjørkenes et al. (2004), Bjørkenes et al. (2006) and Weitz (2016) where a slight distinction between shallow groundwater (Na-Cl) and deeper groundwater system (Na-Ca- HCO_3-Cl) was reported. Furthermore, it can be observed that the low lying area has high groundwater chloride concentration (Table 5.3) as compared to the upper area, which according to Adams et al., (2004) elevated groundwater chloride concentration are usually indicative of low recharge rates (old water which is not frequently replenished).

Given the wide range of geochemical processes that can influence groundwater chemistry such as evaporation, mineral dissolution/precipitation among others it was important for the study to identify the main process resulting in elevated groundwater chloride. Figure 5.7 presents the relationship between chloride and oxygen-18 which was used to investigate the source of groundwater Cl at the site. If the elevated chloride concentration is related to evaporation then a proportional increase in chloride and $\delta^{18}O$ in groundwater should be evident, which is not the case for the study area. This implies that the dissolution of shale rock could indeed be the source of additional chloride in the area. This is very critical for recharge estimation using the CMB method as it means that recharge estimations from CMB should be regarded as a lower limit of recharge estimates in the area (Xu and Beekman, 2003). Groundwater and surface water (Groenkop Stream) exhibit the same chemical character, which suggests that the stream might be recharged by groundwater (Figure 5.7). Evaporation normally results in an increase in the concentration of the TDS but the Na/Cl ratio remains constant (Kumar and James, 2016). Therefore to provide more evidence of the dominant geochemical process controlling the groundwater chemistry between evaporation and rock-water interaction a scatter plot of Na/Cl ratio against EC was done. According to a study by Jankowski and Acworth (1997), a scatter plot that shows constant Na/Cl ratio as EC of groundwater increases determines the dominance of evaporation processes. Figure 5.8 illustrated a decrease in Na/Cl ratio with an increase in EC at Saasveld. This trend indicates that evaporation is not a dominant process compared to the rock-water interaction process at the site.

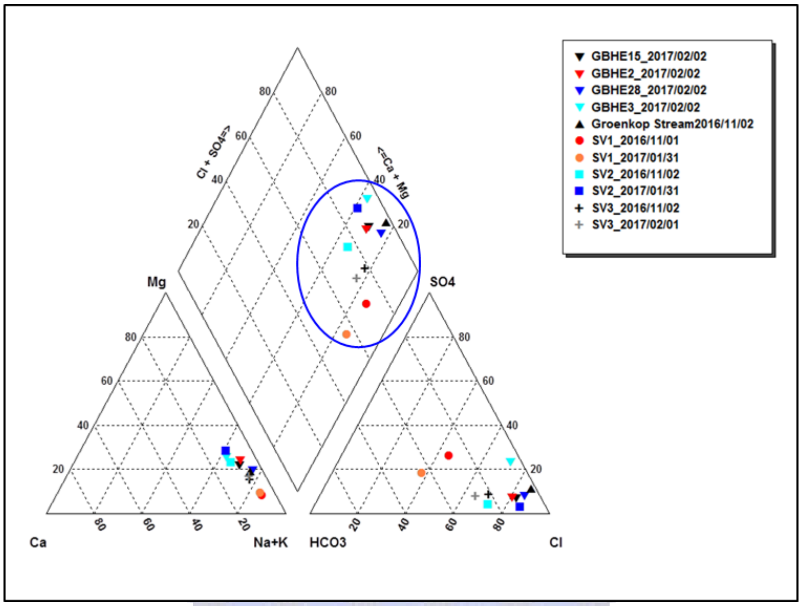


Figure 5.6: Trilinear piper diagram for samples collected at SV1, SV2, SV3, the Groenkop Stream and the George Municipality boreholes

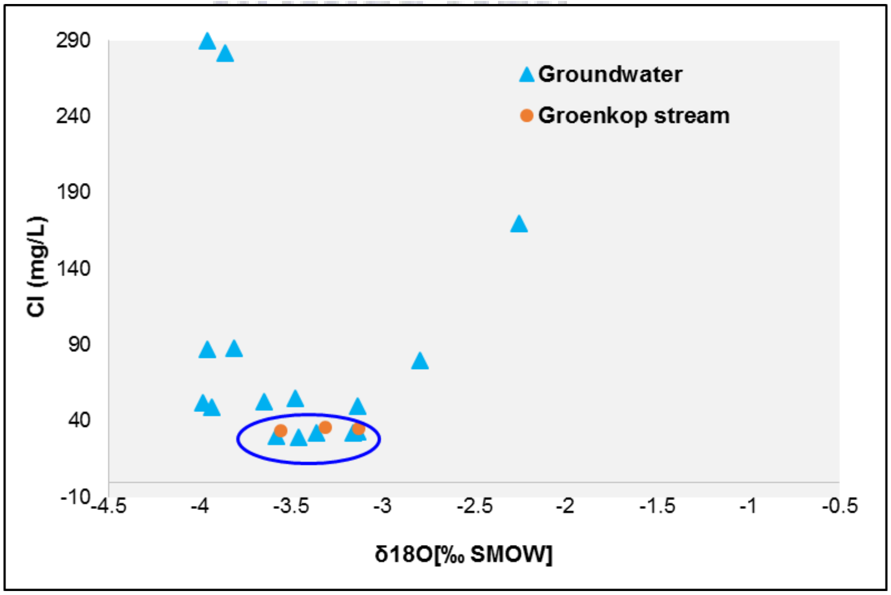


Figure 5.7: $\delta^{18}O$ against chloride depicting the relationship between chloride and Oxygen-18 from surface water and groundwater

Table 5.3: Summary of average measured physiochemical parameters of groundwater and surface water samples at the high lying area and at low lying area

		High lying area	Low lying area	
Parameters	Units	Groundwater samples	Groundwater samples	Surface water samples
pH	pH units	5.27	6.66	4.57
EC	mS/m	16.43	57.78	15.00
TDS	Mg/L	105.00	369.78	96.00
Ca^{2+}	Mg/L	1.93	9.24	0.80
Mg^{2+}	Mg/L	3.27	13.30	2.47
Na^{+}	Mg/L	19.00	80.69	18.00
K^{+}	Mg/L	0.37	2.22	0.20
HCO_3^{-}	Mg/L	6.31	71.20	1.68
Cl^{-}	Mg/L	37.71	127.56	35.00
SO_4^{2-}	Mg/L	7.89	20.33	5.70

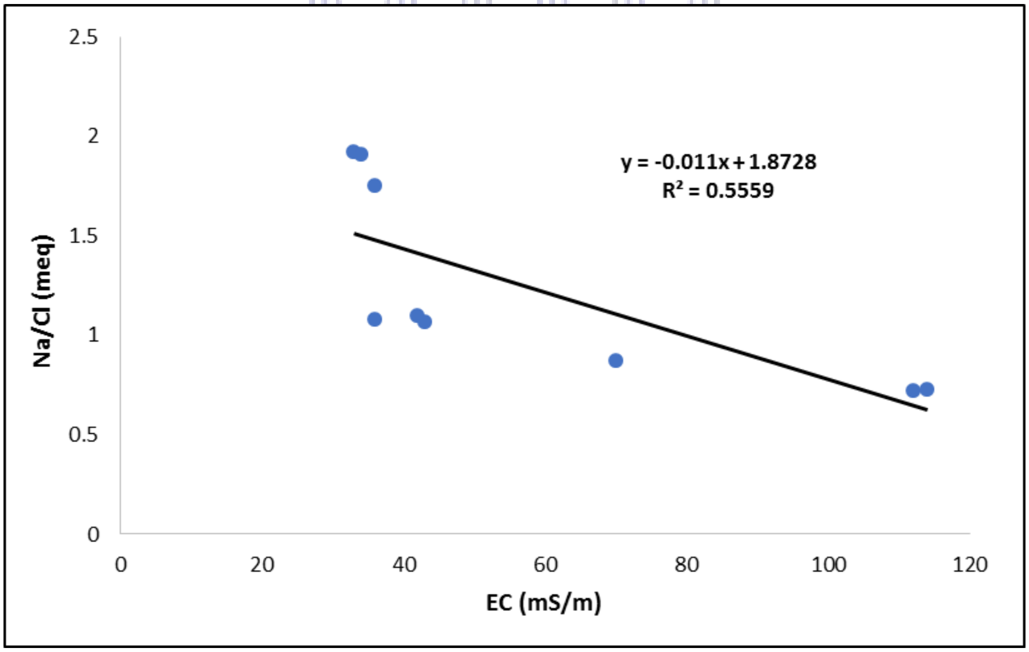


Figure 5.8: Relationship between Na/Cl and EC at Saasveld site

5.3 Chapter summary

The stable environmental isotopes and hydrochemistry were used to gain qualitative information on the mode and type of groundwater recharge mechanism in a fractured rock aquifer within the George area. This study has demonstrated how stable isotopes may successfully be used to provide useful information about the source and type of groundwater recharge mechanism in fractured rock aquifers. The isotope results revealed that groundwater at the site was recharged from modern local rainfall. The dominant recharge mechanism was inferred to be a preferential recharge mechanism which occurred through fractures and macropores. This was in agreement with the conceptual understanding of groundwater recharge processes evident in the study area. The hydrochemistry and isotope results further suggested interconnectivity between groundwater and the stream at the Groenkop site. The groundwater hydrochemical facies was of Na-Cl type, with the dominance of the major cations in order of $Na^+ > Mg^{2+} > Ca^{2+} > K^+$, while the anions showed abundance in the order $Cl^- > HCO_3^- > SO_4^{2-}$. Regionally, the major recharge zone of the catchment corresponded with the higher elevation areas (> 1000 mamsl) which were characterized by a dense presence of lineaments and increased annual rainfall (> 1000 mm/yr). Conceptually, recharge occurred both vertically and laterally depending on the connectivity of fractures within the area.

Chapter 6: Estimation of Groundwater Recharge

6.2 Introduction

The current chapter presents and discusses the findings of objective two which aimed to estimate groundwater recharge in the area. This chapter generally argues that in order to obtain robust recharge estimates in a fractured rock aquifer a physical-based method such as the RIB technique must be used conjunctively with a method that works independently of storativity (tracer methods i.e. CMB). This is based on the notion that getting representative storativity in fractured heterogeneous rock aquifer as TMG can be challenging. The value is always hampered by spatial variation of geological features such as dykes and faults that control storativity within a short distance in an aquifer. The recharge estimates derived from the RIB and CMB technique were verified against the published map or qualified guess estimation by Vegter (1995). In this current study, it is important to acknowledge that although recharge was expressed in terms of millimeters per annum, it does not imply that a recharge event is an annual event in the area.

6.2.1 Results and Discussion

6.2.2 Recharge estimation using the Rainfall Infiltration Breakthrough method

The total annual recharge estimates for the year 2011 up to 2017 are presented in Table 6.1. The results indicate that recharge rate for the study area ranges between 88 mm/yr (10% of annual rainfall) and 24 mm/yr (5% of annual rainfall) in 2011 to 2017. This suggests that over 90% of annual rainfall is lost through evapotranspiration, converted to streamflow and/or lost through other hydrological mechanisms in the area (Table 6.1). From Figure 6.1 it can be observed that a sporadic recharge pattern is evident in the area. There are extended periods where despite the occurrence of high rainfall groundwater levels within the aquifer were steadily declining, and no recharge is evident. As a result, a poor correlation is observed between the groundwater fluctuations and rainfall. Such weak correlation was also documented in a study by Jyrkama et al. (2002) which concluded that on a monthly basis, rainfall and recharge rates tend to exhibit little correlation due to the delay caused by water percolating through the unsaturated zone. This could also be partially related to anthropogenic influences of pumping that occurs in the area. This makes the estimation more complicated and challenging, especially when the abstraction occurs after a recharge event as this results in the breakthrough recharge pulse not being represented in the water level data. There are also periods of increase in groundwater levels but yet no recharge occurs, such field observation illustrates the limitations of the theoretical assumed simple relationships between mean annual rainfall and recharge.This suggests that there are other controlling factors on groundwater recharge such as rainfall intensity and total rainfall. However, when groundwater level departures (Δh_i) are calculated from an average of the entire series 2011-2017 (October), lag times starts to appear (Figure 6.2). Lag times suggests delayed recharge, which is typical in thick weathered (regolith) - fractured rock aquifers. According to Bean (2003), lag times are influenced by the geology, geomorphology and climate of the area. The maximum observed monthly recharge in the area is 78 mm which was recorded in June 2011, in response to 178 mm of rainfall that occurred in June 2011. Few peaks in recharge corresponds with peaks in rainfall (Figure 6.1), which suggests that most recharge events are initiated by antecedent conditions. Although there are disparities in curve match, the recharge values produced with the RIB method are in agreement with the estimates from the qualified guess method (Figure 6.3), i.e. 95 mm/yr (11.01% of MAP) and from values previously estimated by Fortuin (2005) and Wu (2007), i.e. 86.2 mm/yr (9.4% of MAP) and 42.5 mm/yr respectively.

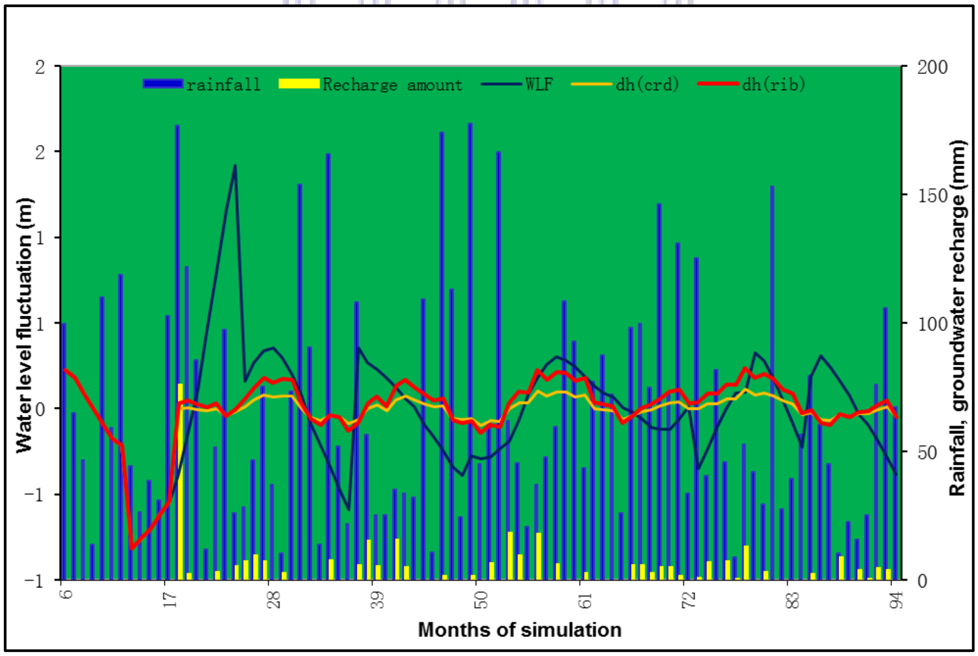


Figure 6.1: Monthly rainfall events, observed groundwater levels (WLF), simulated groundwater levels (CRD and RIB) and groundwater recharge from 2011 to 2017(October) at GBHE27

Table 6.1: Groundwater recharge from 2011-2017 (October) at Sy of 0.2 at GBHE27

Year	Rainfall (mm/yr)	Recharge (mm/yr)	Recharge (% of annual rainfall)
2011	814	88	10
2012	768	34	4.4
2013	748	49	6.5
2014	923	60	6.3
2015	962	28	3
2016	703	30	4.2
2017 (Jan - Oct)	507	24	5

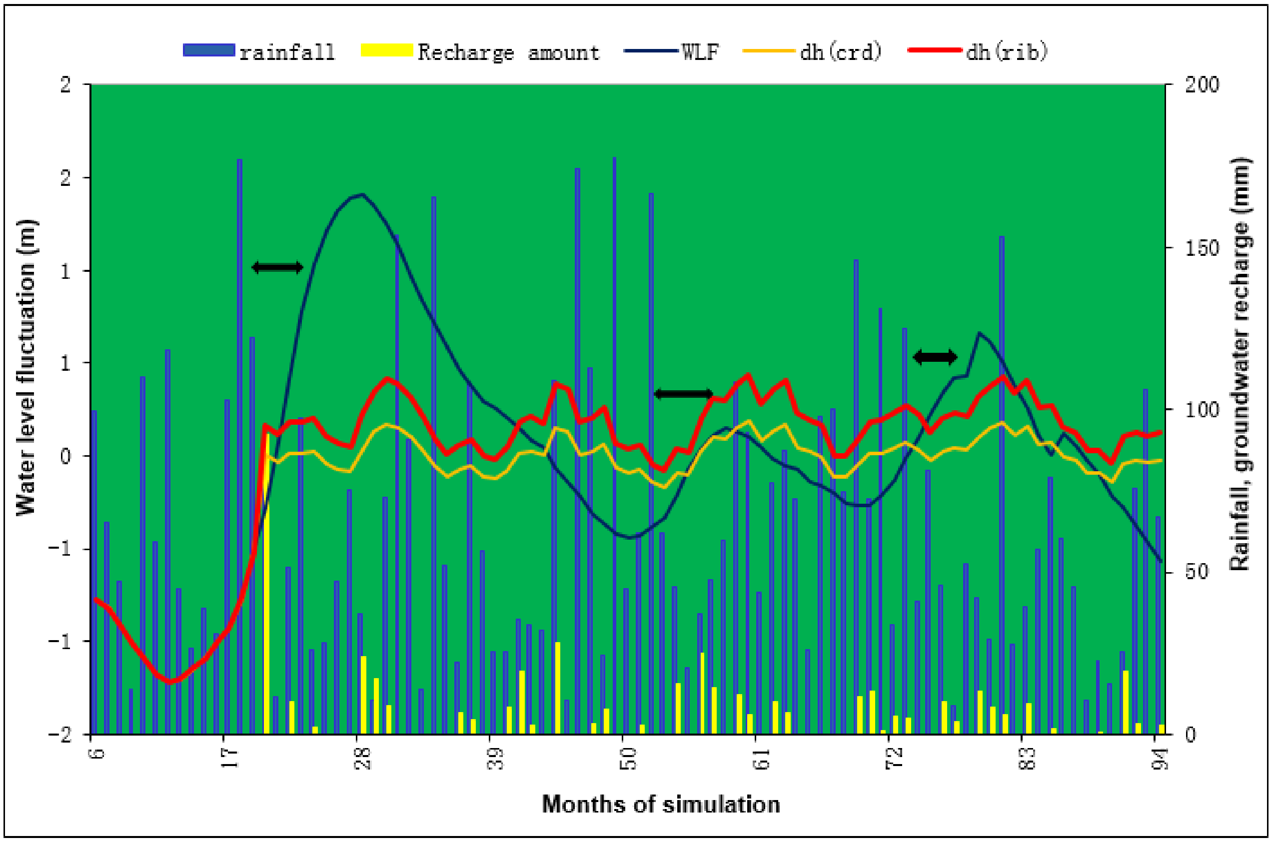
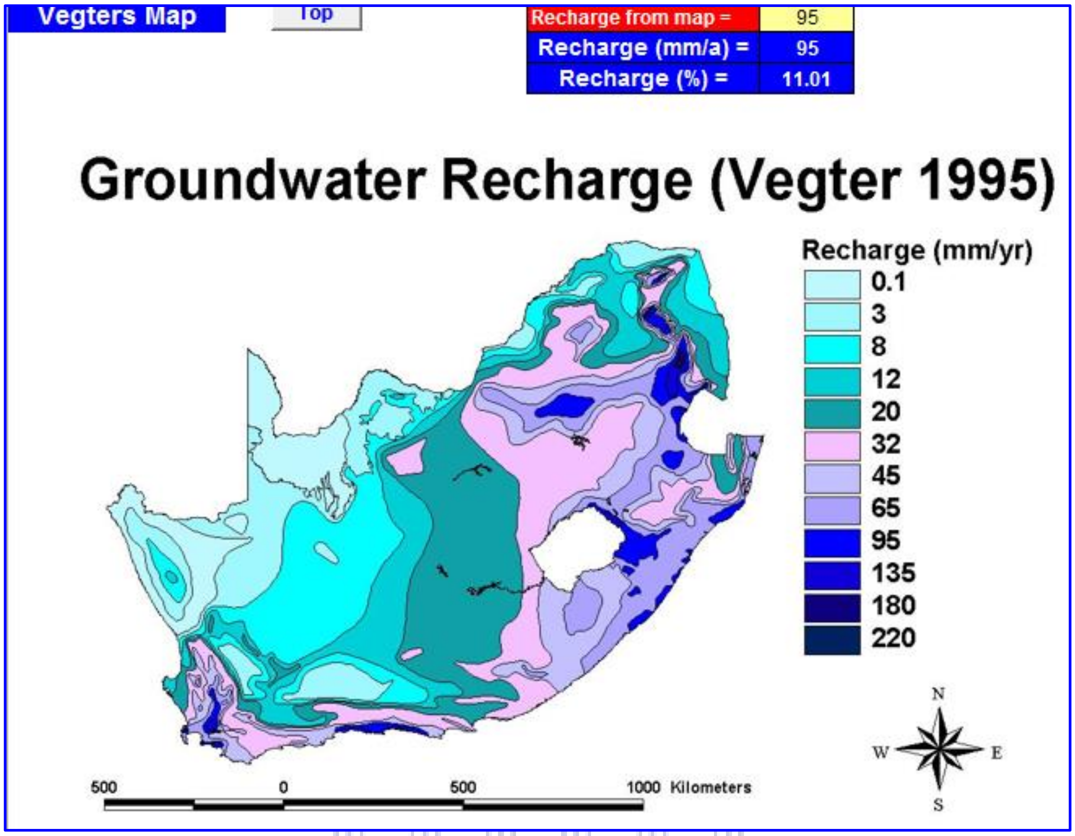


Figure 6.2: Evidence of lag times when average fluctuations are used from 2011 to 2017(October) at GBHE27



Recharge from map = 95
Recharge (mm/a) = 95
Recharge (%) = 11.01

Figure 6.3: Groundwater recharge map (Vegter, 1995) illustrating the estimated recharge amount for lower coastal region of George

6.2.3 Reliability of Recharge results

To test the reliability of the results of the RIB model a Pearson correlation coefficient was calculated between observed and simulated (produced with the RIB and CRD methods) groundwater levels (Table 6.2). Coefficient values of close to +1 implies a strong positive correlation between the observed water level and the two simulated datasets, and where the coefficient was close to -1 it implies a strong negative correlation. Values close to 0 indicates a weak correlation between the datasets. From the results, it can be observed that an average to a strong positive correlation of 0.6 is evident between the observed water levels and simulated water levels. Therefore the recharge estimations with these methods can be interpreted with a certain degree of confidence.

Table 6.2: Pearson's correlation and Root Mean Square Error between observed and simulated (RIB and CRD methods)

Criteria	CRD	RIB
Pearson Coefficient (r)	0.6	0.6
Root Mean Square Error	0.3	0.3

6.2.4 Recharge estimation using the CMB method

A Cation-Anion Balance error (CAB) of > 5% was achieved for the chemistry data collected in 2017 (see appendix C, Table 8.3), therefore the chemical data used in this study is within the acceptable range (less than 5%) and can be regarded as credible for scientific purpose. Groundwater recharge results from the CMB method are presented in Table 6.3. In 2017, the annual average Cl concentration in rainfall was observed to be 5.49 mg/L and 86.3 mg/L in groundwater samples collected from boreholes SV1, SV2 and SV3. The annual recharge is estimated to be 40 mm/yr which translates into 6.4% of the annual rainfall in 2017. This suggests that over 90% of annual rainfall is lost through evapotranspiration, converted to streamflow and/or lost through other hydrological mechanisms in the area. The recharge values estimated by the CMB method are within the range of values previously estimated by Fortuin (2005) and Wu (2007), i.e. 86.2 mm/yr (9.4% of MAP) and 42.5 mm/yr respectively.

Recharge estimates when the dry deposition from sea spray and forest canopies are incorporated are presented in Table 6.3. When mist/dust from the coast is considered a chloride dry deposition of 10 mg/m^2/yr is approximated (see equation 4.7), while when the forest canopies is considered a chloride dry deposition of 19 mg/m^2/yr is approximated (see equation 4.8). Recharge estimates when dry chloride deposition from both the sea spray and the forests were considered recharge increased to an average of 108 mm/year (17% of annual rainfall). These recharge estimates are also within the range of the values previously estimated by Fortuin (2005) and Wu (2007), i.e. 86.2 mm/yr (9.4% of MAP) i.e. 42.5 mm/yr and the published map from Vegter (1997) i.e. 95 mm/yr (11.01% of MAP) respectively. Due to dissimilarities in principles, assumptions and time scale which the RIB and CMB methods are based on the two techniques gave different recharge values as expected. The CMB method provides long-term recharge that integrates large areas, as opposed to the RIB method that estimates recharge over shorter period on a local scale.

Table 6.3: Groundwater recharge estimates for 2017 produced with the CMB method under different conditions.

Scenarios	Rainfall (mm/yr)	Average TD concentration in rainwater (mg/L)	Harmonic Cl_{gr}(mg/L)	Recharge (mm/yr)	Recharge (% of annual rainfall)
Using CMB method only	639.6	5.49	86	40	6.4
Using CMB (ocean mist/ dust considered)	639.6	10	86	73	11.5
Using CMB (TD from forest canopies considered)	639.6	19	86	143	22

6.3 Chapter summary

Two independent methods, i.e. the Rainfall Infiltration Breakthrough and Chloride Mass Balance methods, were applied in a fractured rock aquifer to estimate groundwater recharge in the Southern Cape, George. The recharge estimates derived from the RIB and CMB technique were verified against the published map or qualified guess estimation by Vegter (1995). Recharge with the RIB technique ranged between 88 mm/yr (10% of annual rainfall) to 24 mm/yr (5% of annual rainfall) in 2011 and 2017 respectively. While recharge estimated with the CMB in 2017 amounted to 40 mm/year (6.4% of annual rainfall). When dry chloride deposition from the sea spray and the forests were considered recharge increased to an average of 108 mm/year (17% of annual rainfall). The estimates from both techniques were in close agreement with the regional estimates from published maps by Vegter (1995) and from previous researchers. Due to dissimilarities in principles, assumptions and time scale which the two methods are based on the techniques gave different recharge values as expected. However, estimating recharge using two independent methods was found to be useful as it gave the range of plausible recharge rates in the study area. The lack of a strong correlation between rainfall and groundwater level fluctuations in the RIB model illustrated the complexity of dynamic fluxes in a fractured rock aquifer and limitations of the theoretical assumed simple relationships between mean annual rainfall and recharge. As expected and referenced by other authors the RIB technique was sensitive to storativity in the fractured rock aquifer in the area. Uncertainties with regards to the accurate determination of storativity for recharge estimation in fractured hard rock is still of concern for most hydrogeologists. The recharge estimates from the CMB method were regarded as minimum recharge amounts in the study area due to possible additional chloride from the dissolution of the host rock. Nevertheless, the method proved to be a promising and useful technique to estimate recharge in fractured rock aquifers as it works independently from storativity which can be problematic to estimate in fractured rock aquifers. The method can accurately estimate recharge when its assumptions are fully appreciated.

Chapter 7: Assessing the effect of pine plantation forests on groundwater recharge

7.1Introduction

The current chapter presents and discusses the findings of objective three which aimed to assess the effect of the pine plantations on groundwater recharge using a coupled atmospheric-unsaturated zone model, i.e. HYDRUS-2D numerical model. To assess this effect, the study compared the groundwater recharge estimates derived from an area occupied by the plantation forests to recharge estimates derived from an area occupied by indigenous forest (reference conditions). The central argument of the chapter was that, for the trees to affect recharge they don't necessarily need to tap directly from the saturated zone, vegetation may affect groundwater recharge indirectly by rainfall interception losses as well as the abstraction of the infiltrating water in the vadose zone before reaching the water table.

7.2 Results and Discussion

7.2.1 Atmospheric Boundary Fluxes

Fluxes simulated at the atmospheric boundary of the model domain are presented in Table 7.1. Rainfall recorded at the Saasveld AWS (Figure 4.2) during the simulation period amounted to 564 mm. Evaporation and transpiration rates were the largest components of the soil water balance, i.e. a large proportion of the rainfall infiltration was returned to the atmosphere through ET, with the balance producing potential recharge in the area. Of particular interest was that although the absolute transpiration rates where considerable higher at the plantation forest than at the indigenous forest, evaporation was in contrast. Higher evaporation rates in the indigenous forest were attributed to the higher leaf area from denser canopy which resulted in higher interception rates. No overland flow was simulated in the area, which was attributed to the dense vegetation occurring along the transects.

Table 7.1: Atmospheric boundary fluxes simulated by HYDRUS-2D

Parameter (mm)	Transect		
	Pinus elliottii	*Pinus radiata*	Groenkop Forest
Rainfall Infiltration	551	545	536
Evaporation	49	62	106
Overland Flow	0	0	0
Transpiration	435	488	250

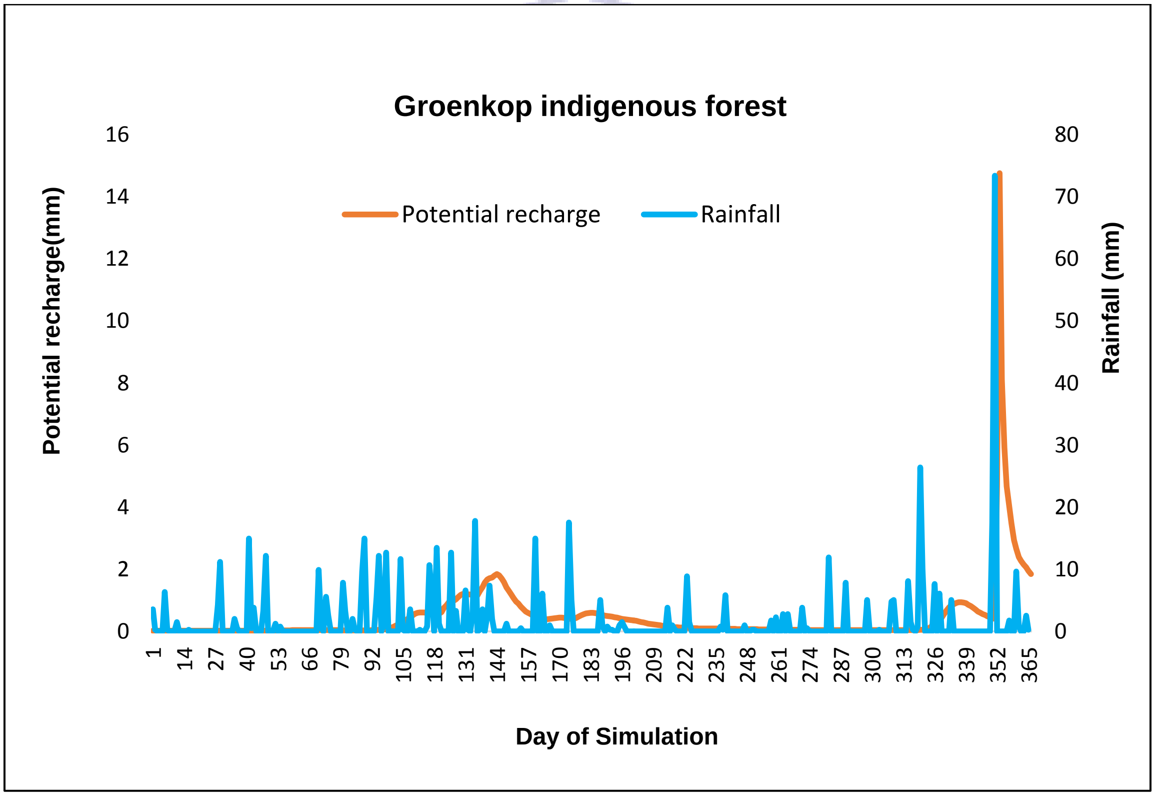
7.2.2 Potential Groundwater Recharge estimations

Potential recharge simulated at the free drainage boundary of the model domains are presented in Figure 7.1. Over the entire simulation period, potential recharge generated at the Groenkop forest, *Pinus elliottii* and *Pinus radiata* model domains via the free drainage boundary amounted to 169 mm, 36 mm and 14 mm respectively. The potential groundwater recharge was significantly higher in the indigenous forest when compared to the pine plantation forests. This was in was agreement with the study done by Adane et al., (2018) in Nebraska Sand Hills (USA) which reported an overall reduction of groundwater recharge by nearly 17% due to the introduction of a pine plantation forest. The recharge values obtained from the HYDRUS-2D model were within the same order of magnitude of estimates from previous studies, the RIB model and the CMB method. The groundwater recharge dynamics conformed to the notion that groundwater recharge was generally driven by single or multiple events and not annual averages (Parsons, 2002).

As per Table 7.1, the observed recharge at the three transects was a function of the total ET losses. The increased transpiration rates associated with plantation forests when compared to the indigenous forests was in agreement with the studies by Scott et al., 2000; Scott and Prinsloo, 2008. One distinct recharge event was evident at the *Pinus elliottii* and *Pinus radiata* sites, while two major and several minor potential recharge events were evident at the Groenkop forest site. The major potential recharge event observed at all transects was during DOS 350 (15 September

2017) and 351 (16 September 2017) in response to significant rainfall events of 17.5 mm and 73 mm respectively. It was therefore apparent that potential recharge was a function of rainfall intensity and frequency in the area. The rainfall intensity required to initiate recharge was higher at the *Pinus radiata* and *Pinus elliottii* sites than at the Groenkop forest sites.

In accordance with the conceptual model (see Figure 5.2), subsequent to the water exiting the model domain via the free drainage boundary, flow occurred sub-vertically/laterally along low permeability/impermeable layers until preferential flow paths (fractures) were encountered in the underlying strata. Downward flow along these preferential paths was a function of the characteristics of these features, and if the flow is restricted, interflow may occur again. The processes of vertical and horizontal flow occurred until the percolating water reached the saturated zone or a watercourse.



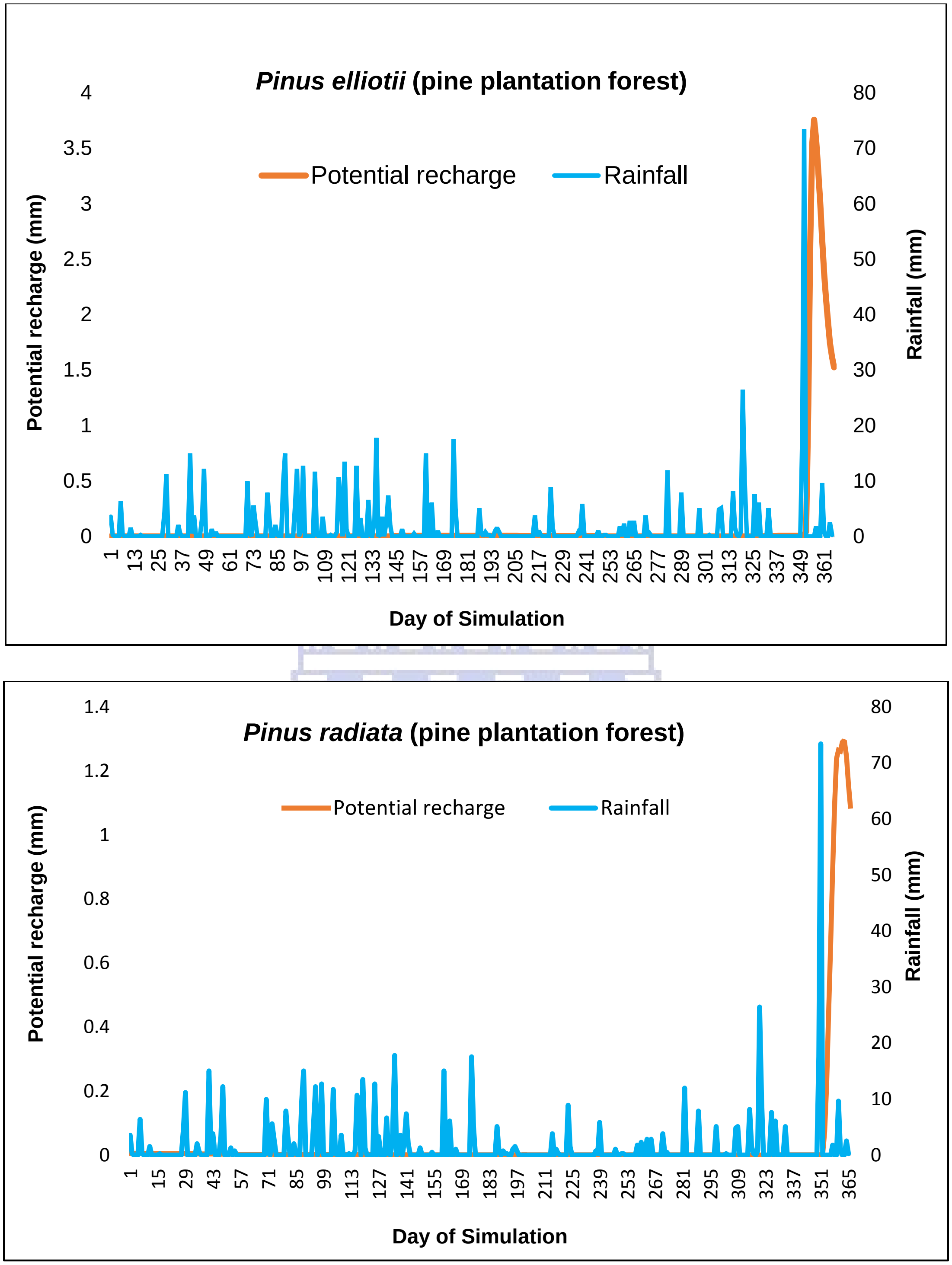
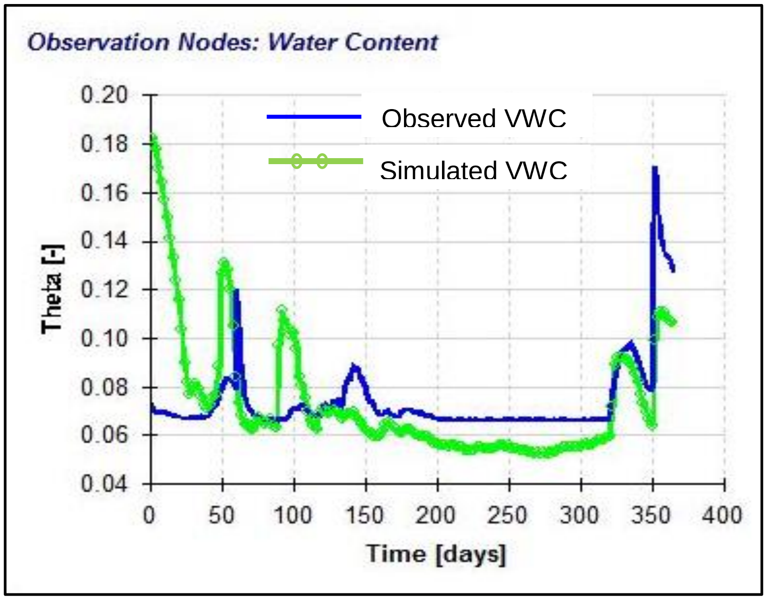


Figure 7.1: HYDRUS-2D simulation outputs: Potential recharge in the Groenkop forest (top), *Pinus elliotii* compartment (middle) and *Pinus radiata* compartment (bottom)

No fluxes were simulated at the seepage face boundary for all transects. This is was in disagreement with observations by Gush *et al*. (2015), who dug several soil pits in the area, which were observed to be filled with water throughout the year as a result of through-flow from upslope contributing areas. However, the relatively low simulated and observed VWC (Figure 7.2) at the downslope ends of the model domains, suggested that conditions were not conducive for the generation of throughflow during the simulation period, i.e. the VWC was significantly below soil saturation levels. Additionally, it was noted that the soil pits dug by Gush *et al*. (2015) were dry during frequent field observations conducted during the study period.

7.2.3 Model Performance

A comparison between observed and simulated soil water content is often used to assess the performance of a HYDRUS-2D simulation. Figure 7.2 presents the volumetric water content observed and simulated at the downslope end of the model domain at a depth of 20 cm for all the transects simulated. A good agreement was generally evident between the observed and simulated datasets in terms of the absolute values and the temporal trends. The simulated VWC was however not able to represent the peaks in VWC observed between DOS 0 - 200 in the Groenkop forest. Model performance evaluation criteria, based on the relationship between the simulated and observed VWC, are presented in Table 7.2. The comparison between the observed and simulated datasets was interpreted to be acceptable in terms of all the performance evaluation criteria.



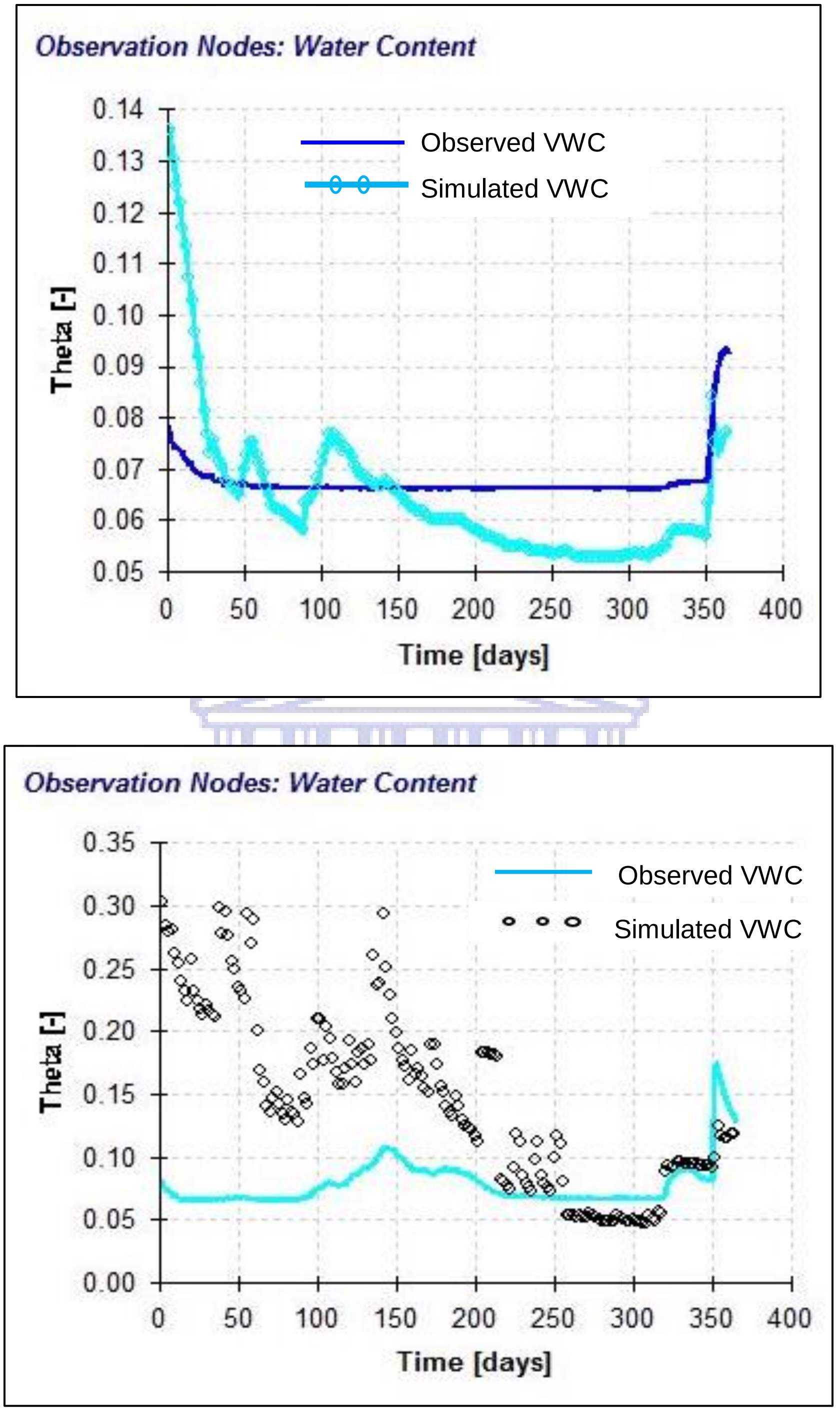


Figure 7.2: HYDRUS-2D simulation outputs: observed (solid line) and simulated (open circles) volumetric water content at the seepage face boundary in the *Pinus elliottii* compartment (top), *Pinus radiata* compartment (middle) and in the Groenkop forest (bottom)

Table 7.2: Model performance evaluation criteria derived through a comparison between simulated and observed VWC

Criteria	Transect		
	Pinus elliottii	*Pinus radiata*	Groenkop Forest
Mean Absolute Error (m^3/m^3)	0.3	0.3	0.5
Root Mean Square Error (m^3/m^3)	0.5	0.4	0.7

As an additional measure to evaluate model performance, measured transpiration estimates for the *Pinus elliottii* compartment and for the *Pinus radiata* compartment during the period 1 October 2016 – 30 September 2017, were compared to root water uptake simulated during the same period by the model (Figure 7.3). The results from HPV1 suggest that transpiration in the *Pinus elliottii* compartment during this period was 519 mm. The root water uptake simulated by the model during this period amounted to 435 mm. The results from HPV2 suggest that transpiration in the *Pinus radiata* compartment during this period was 398 mm. The root water uptake simulated by the model during this period amounted to 488 mm. The total values are within the same order of magnitude, however discrepancies exist when the data are analysed at a monthly scale (Figure 7.3). This good correlation between the observed and simulated soil water content and root water uptake allows for the model results to be interpreted with a degree of confidence.

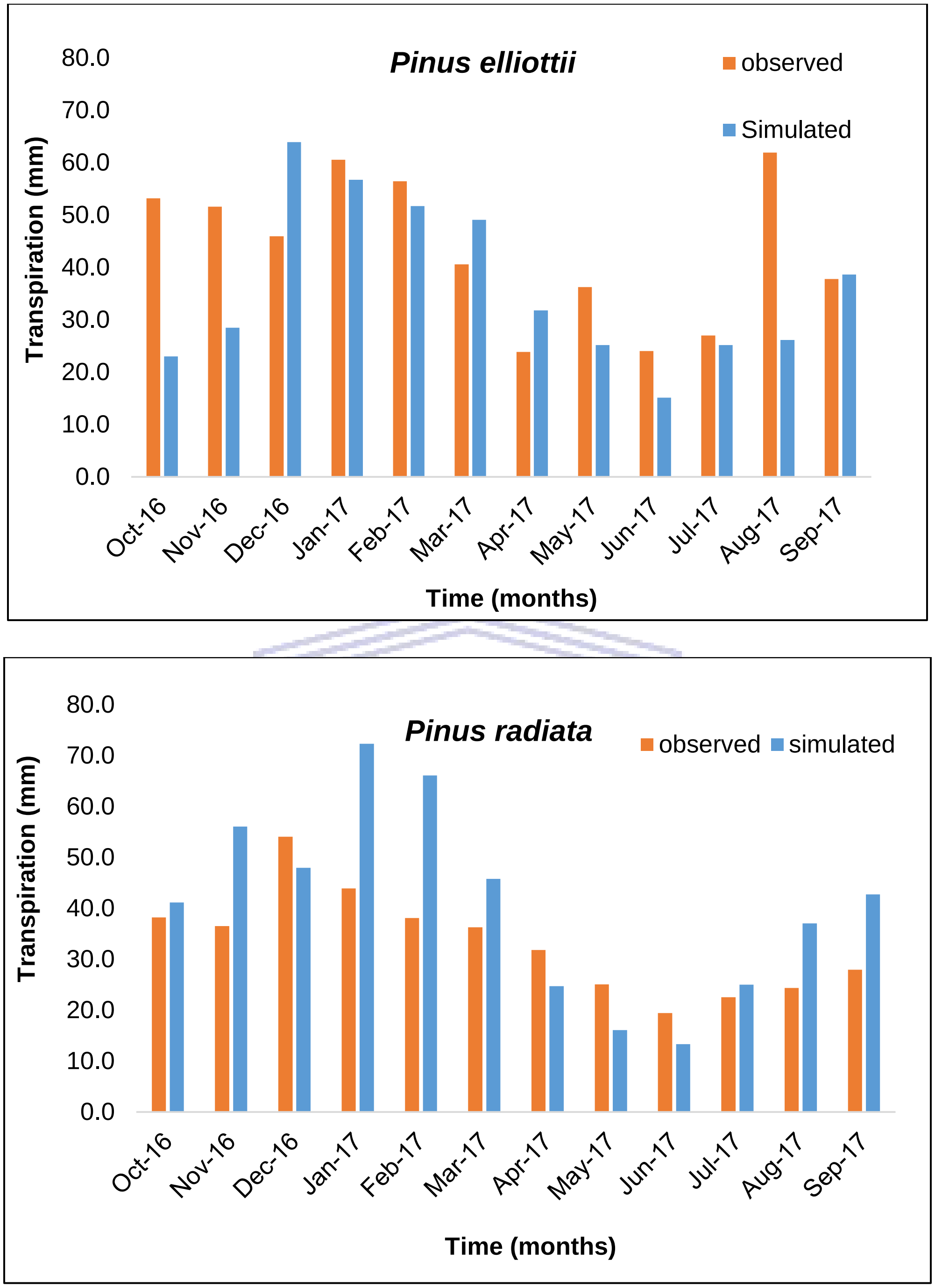


Figure 7.3: HYDRUS-2D simulation outputs: observed and simulated root water uptake in the *Pinus elliottii* compartment (top) and the *Pinus radiata* compartment (bottom)

The root water uptake simulated in the Groenkop forest and that measured at each of the sample trees is presented in Figure 7.4. The root water uptake simulated by the model during the simulation period amounted to 250 mm, while the measured root water uptake from *Podorcapus latifolius, Ilex mitis* and *Ocotea bullata* was 220 mm, 310 mm and 327 mm respectively. It is evident from Figure 7.4 that although there are differences between monthly simulated root water uptake and measured root water uptake, the total simulated value for the year 2016-2017 is within the same range of what was measured. The root water uptake simulated in the Groenkop forest is significantly less than that simulated in the plantation compartments.

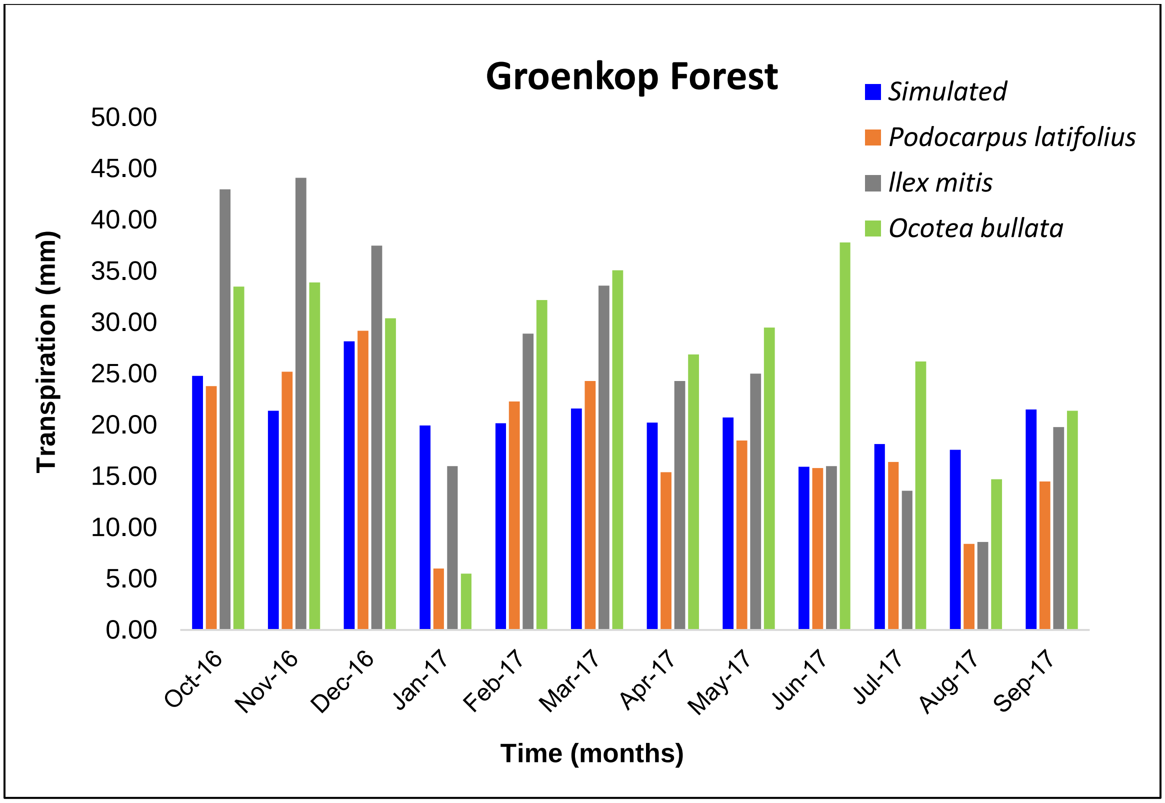


Figure 7.4: HYDRUS-2D simulation outputs: observed and simulated root water uptake in the Groenkop forest

7.2.4 Statistical analysis of Recharge

A statistical two tailed T-test analysis at 5% significant interval (α) was applied to assess whether there was a significant difference between the recharge estimates at the Groenkop indigenous forest against the recharge from the Saasveld pine plantations.

The null hypothesis tested on this analysis state that there was no significant difference between recharge values at the Groenkop forest (recharge = 169 mm) and at Saasveld pine plantations (*Pinus elliottii* and the *Pinus radiata,* recharge = 36 mm and 14 mm respectively). While the alternative hypothesis state that there was a significant difference between these recharge estimates. From table 7.3 and 7.4 it can be observed that the T-test analysis revealed that probability (p) value was less than 0.05, therefore rejecting the null hypothesis and supporting the alternative hypothesis that there was a statistically significant difference between the recharge estimates from the Groenkop forest and pine plantations at 5% (0.05) significant level.

Table 7.3: T-test analysis for recharge from Groenkop forest against recharge at *Pinus radiata* compartment

Period	Sample no	P value	t Critical value
Oct 2016- Sep 2017	365	1.62E-12	1.96

Table 7.4: T-test analysis for recharge from Groenkop forest against recharge at *Pinus elliottii* compartment

Period	Sample no	P value	t Critical value
Oct 2016- Sep 2017	365	1.45219E-08	1.96

7.3 Chapter Summary

The HYDRUS-2D numerical model was applied to assess the effect of pine plantations on groundwater recharge on a hillslope fractured rock aquifer. The results of the modelling provided clear evidence of the effect of pine plantation forests on potential groundwater recharge. Potential groundwater recharge was significantly higher in the indigenous forest when compared to the pine plantation forests. Over the entire simulation period, the potential recharge at the Groenkop indigenous forest, *Pinus elliottii* and *Pinus radiata* amounted to 169 mm, 36 mm and 14 mm respectively. The recharge values obtained from the HYDRUS-2D model were within the same order of magnitude of estimates from previous studies, the RIB model and the CMB method. Rainfall intensity and frequency were observed to be a driving variable of the recharge in the area. The dynamics of the recharge events were also in line with that presented in the conceptual model, i.e. that recharge occurs rapidly via direct infiltration. This study demonstrated how a process-based atmospheric-unsaturated-saturated zone model, i.e. HYDRUS-2D, may successfully be used to quantify potential groundwater recharge. The model provided the ability to study the dynamics of groundwater recharge at short time scales, as opposed to annual average responses which are derived from commonly applied techniques. These results highlighted the importance of accurately accounting for ET losses in groundwater recharge assessments and estimation techniques.

Chapter 8: Conclusion and Recommendations

8.1 Conclusion

The main aim of the study was to assess the effect of plantation forests on groundwater recharge by comparing groundwater recharge estimates derived from an area occupied by indigenous vegetation. The argument for this study was that for the trees to affect recharge they do not necessarily need to tap directly from the saturated zone. This means that the vegetation may affect groundwater recharge indirectly by rainfall interception losses as well as the abstraction of the infiltrating water in the vadose zone before reaching the water table. To achieve the aim of the study, firstly, the dominantly occurring recharge mechanism was characterised, secondly, long-term groundwater recharge estimates were determined, and thirdly, the effect of plantation forests on groundwater recharge were assessed. Prior to characterizing the dominant recharge mechanism in the area, delineation of potential recharge zones was conducted and a recharge conceptual model of the area was developed to explain the recharge mechanism.

The analysis on objective one showed that preferential flow was a dominant recharge mechanism in the study area. The conceptual model supported such finding by revealing that the recharge in the area occurred preferentially both vertically and laterally depending on the connectivity of fractures within the area. Such evidence from the model was further supported by the isotope results which showed minimum evaporation occurring prior to recharge implying preferential flow paths exist. The major recharge zone of the catchment corresponded with the higher elevation areas (> 1000 mamsl) which were characterized by a dense presence of lineaments and increased annual rainfall (> 1000 mm/year). The findings from the hydrochemistry and isotope analyses further suggested that groundwater was recharging the surface water at Groenkop site. From the findings in objective one, which focused on charactering recharge mechanism, it can be concluded that recharge in the area preferentially occurs through fractures particular in areas characterized by a dense presence of lineaments and increased annual rainfall. Therefore, the first objective of this study on characterization of dominantly occurring recharge mechanism was fulfilled.

The analysis on objective two showed that recharge estimates with the RIB model ranged between 88 mm/yr (10% of annual rainfall) in 2011 and 24 mm/yr (5% of annual rainfall) in 2017. While recharge estimated with the CMB in 2017 amounted to 40 mm/year (6.4% of annual rainfall). When dry chloride deposition from the sea spray and the forests were considered recharge increased to an average of 108 mm/year (17% of annual rainfall). From the findings in objective two, which focused on groundwater recharge estimation, it can be concluded that minimal recharge occurs in the area as over 83-90% of rainfall is lost through evapotranspiration, converted to streamflow and/or lost through other hydrological mechanisms in the area. Further on it can be concluded that the RIB and CMB methods can be applied fractured rock environment where pine plantations are practiced characteristics similar to the current study area. Therefore, the second objective of this study on the estimation of groundwater recharge was fulfilled.

The third objective was to assess the effect of plantation forests on groundwater recharge using HYDRUS-2D numerical model. The analysis on objective three showed the potential recharge at the *Pinus elliottii*, *Pinus radiata* and Groenkop forest amounted to 36 mm, 14 mm and 169 mm respectively. The analysis provided evidence that the recharge in the pine plantation forests was lower than at the Groenkop indigenous forest due to high evapotranspiration rates. The analysis highlighted the importance of accurately accounting for ET losses in groundwater recharge assessments. The model proved to be the most successful technique to estimate recharge due to the fact it considered most of the parameters that were found to be controlling recharge in the study area. From the findings in objective three, which focused on assessing the effect of plantation forests on groundwater recharge, it can be concluded that the presence of pine plantation forest in the area reduces groundwater recharge due to high evapotranspiration rates.

The three objectives were fulfilled and the aim of the study was addressed. The study provided evidence that although vegetation root systems in the area were restricted to the soil zone, pine plantation forests reduced groundwater recharge as compared to the Groenkop indigenous forest.

8.2 Recommendations

Results for the first objective provided evidence that the dominant recharge mechanism in the area was a preferential recharge mechanism. Despite the study being site specific where few points (8 sampling sites) were studied which could not be representative of the entire catchment, such findings provided reliable evidence about the groundwater recharge mechanism occurring in the study area. Based on such result and its evidence which provide an insight about the recharge mechanism occurring in the study area, this study recommends increasing the number of sampling sites to cover either the entire catchment or number of sampling sites that can be representative of the entire catchment for which would provide results that would be used by various practitioners in the different fields of groundwater resource.

Results for objective two illustrated that recharge estimates from the RIB model ranged between 88 mm/year (10% of annual rainfall) in 2011 and 24 mm/year (5% of annual rainfall) in 2017. While recharge estimates with CMB method in 2017 amounted to be 40 mm/year (6.4% of annual rainfall) and increased to an average recharge of 108 mm/year (17% of annual rainfall) when dry deposition from sea spray and the forest where considered. Despite the influence of shale dissolution in the computation of recharge when using the CMB method, the technique gave estimates that were in close agreement with other studies. And the methods works independently of storativity which can be challenging to accurately estimate in fractured heterogeneous rock aquifer as TMG. Therefore, this study recommends monitoring network for chloride in rainwater and chloride dry deposition from sea spray and aerosols in order to improve recharge estimates in the area (i.e. a coastal region) when using the CMB method.

Lastly, for objective three, results provided evidence that recharge in the pine plantation forests was lower than at the Groenkop indigenous forest, with recharge at the Groenkop indigenous forest, *Pinus elliottii* and *Pinus radiata* amounting to 169 mm, 36 mm and 14 mm respectively. Since the HYDRUS-2D numerical model simulation period was restricted by the availability of the soil water content data (1 October 2016 – September 2017), this study recommends further monitoring of the soil water content data in order to improve the model performance and recharge results and to model different recharge scenarios.

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Appendices

Appendix A: Water retention curves for parametrization of HYDRUS-2D numerical model

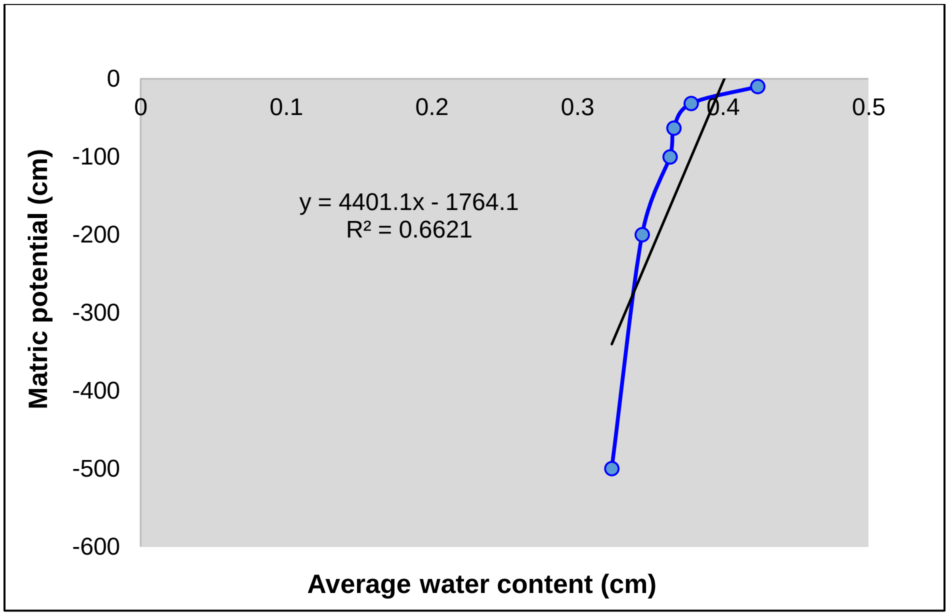

Figure A.1: Water retention curve for Groenkop indigenous forest soils

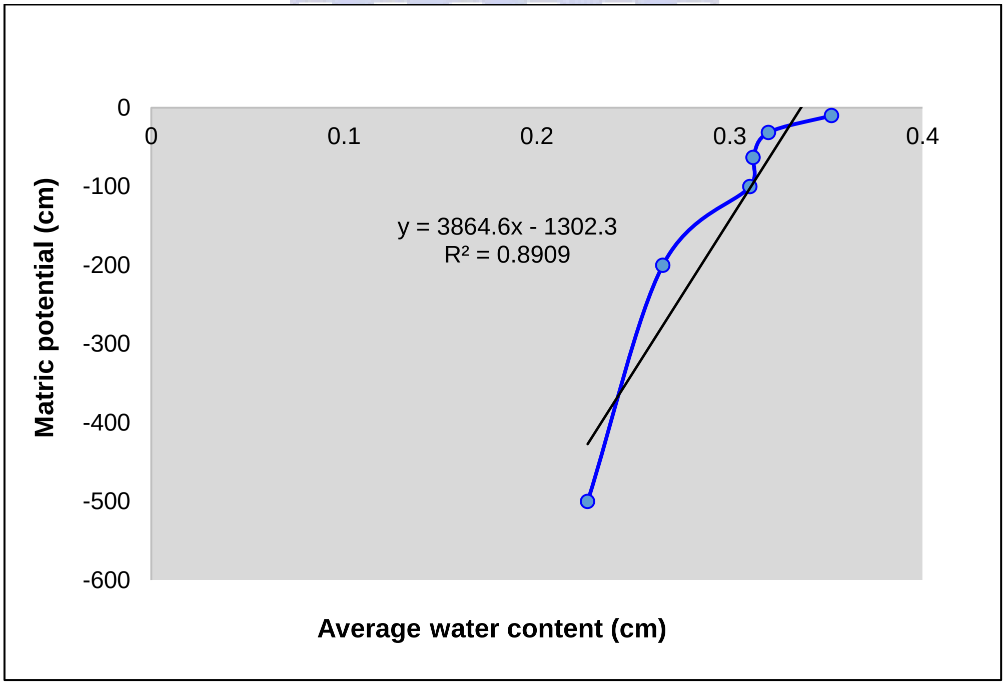

Figure A.2: Water retention curve B16A pine compartment soils

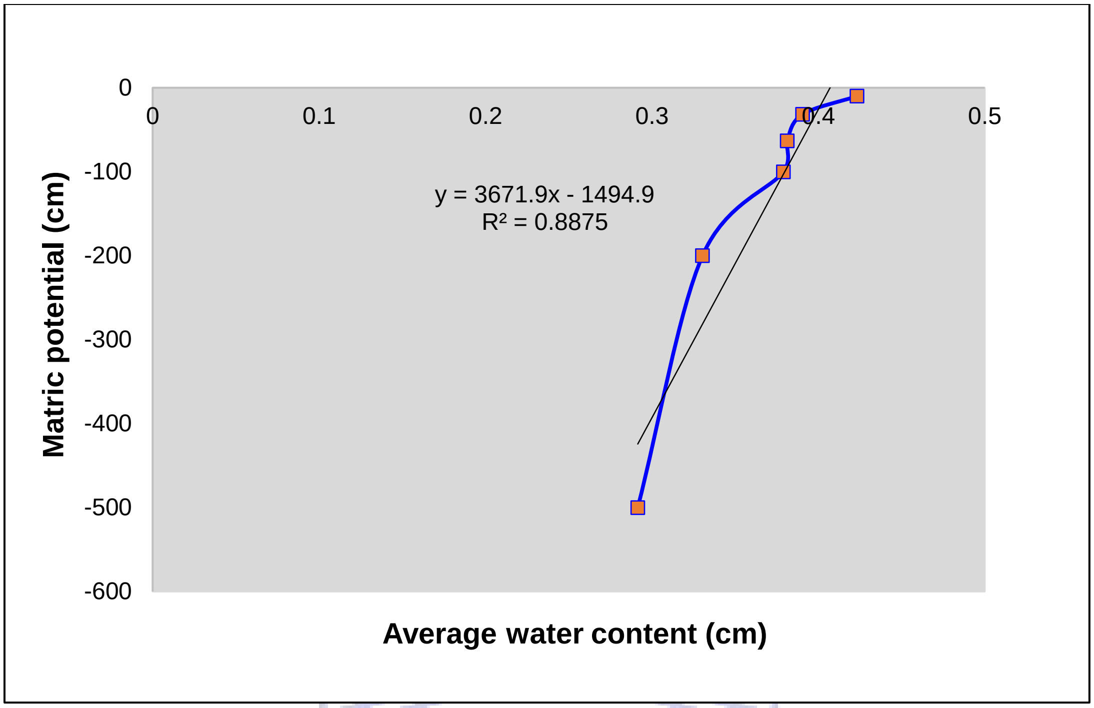

Figure A.3: Water retention curve for B18B pine compartment soils

Appendix B: Environmental stable isotope data

Table A.1: Stable environmental isotope concentrations in rainfall, surface water and groundwater

Sample ID	Description	Deuterium	Oxygen-18
		δ^{2}H‰ SMOW	δ^{18}O‰ SMOW
16/9/2016	Rain	+1.1	+1.90
6/10/2016	Rain	+0.5	+0.96
11/10/2016	Rain	+18.0	+4.70
29/10/2016	Rain	+2.8	+1.85
30/10/2016	Rain	+0.0	+0.46
SV1 (1/11/2016)	Groundwater	-16.6	-3.14
SV2 (2/11/2016)	Groundwater	-14.0	-2.80
SV3 (2/11/2016)	Groundwater	-15.7	-2.26
Groenkop Stream (2/11/2016)	Surface Water	-15.8	-3.13
18/11/2016	Rain	+0.4	-1.61
10/12/2016	Rain	+2.4	-1.36
13/01/2017	Rain	-0.5	-1.80
24/01/2017	Rain	+2.8	-1.23
SV1 (31/01/2017)	Groundwater	-13.2	-3.98
SV2 (31/01/2017)	Groundwater	-13.4	-3.86
SV3 (1/02/2017)	Groundwater	-11.9	-3.81
GBHE28 (2/02/2017)	Groundwater	-11.1	-3.48
GBHE3 (2/02/2017)	Groundwater	-10.1	-3.36
GBHE2 (2/02/2017)	Groundwater	-9.4	-3.14
GBHE15 - 02/02/2017	Groundwater	-10.2	-3.16
Groenkop Stream (1/02/2017)	Surface Water	-12.6	-3.31
11/08/2017	Rain	-15.1	-4.21
16/08/2017	Rain	+2.4	-1.28
16/09/2017	Rain	-14.7	-4.29
26/09/2017	Rain	-15.0	-4.33
29/09/2017	Rain	-14.9	-4.29

Groenkop Stream (4/10/2017)	Surface Water	-13.0	-3.56
SV1 (4/10/2017)	Groundwater	-13.8	-3.93
SV2 (4/10/2017)	Groundwater	-14.2	-3.96
SV3 (4/10/2017)	Groundwater	-12.6	-3.96
GBHE3 (5/10/2017)	Groundwater	-10.2	-3.58
GBHE15 (5/10/2017)	Groundwater	-10.3	-3.46
GBHE28 (5/10/2017)	Groundwater	-11.3	-3.65
17/10/2017	Rain	-14.4	-4.14
16/10/2017	Rain	-14.5	-4.16

Appendix C: Cation-Anion Balance Error

Table A.2: Cation-Anion Balance error for the samples used in the study

Site name	Ca (meq/L)	Mg (meq/L)	Na (meq/L)	K (meq/L)	HCO3 (meq/L)	Cl (meq/L)	SO4 (meq/L)	CAB
SV1	0.1896	0.2551	2.6968	0.0409	0.9047	1.4103	0.8120	0.0088
SV1	0.1896	0.2798	2.5663	0.0384	1.7110	1.4667	0.7079	-0.1166
SV1	0.1297	0.2551	2.6533	0.0281	0.9637	1.3821	0.6662	0.0089
SV2	0.7485	1.4812	4.1757	0.0767	1.5537	4.7951	0.2498	-0.0089
SV2	1.0480	2.7155	5.7851	0.0639	0.9833	7.9542	0.2707	0.0215
SV2	1.0979	3.1269	5.9156	0.0614	1.7110	8.1798	0.3123	-0.0001
SV3	0.2345	0.4855	2.4358	0.0844	0.6687	2.2565	0.2707	0.0069
SV3	0.2395	0.5925	2.6533	0.0614	1.0030	2.4822	0.2915	-0.0314
SV3	0.2745	0.6583	2.6968	0.0563	1.0030	2.4540	0.2290	0.0000
GBHE28	0.0699	0.3374	1.3049	0.0102	0.1141	1.5513	0.1457	-0.0251
GBHE28	0.0699	0.3456	1.3484	0.0102	0.0924	1.4949	0.1520	0.0099
GBHE3	0.1248	0.2715	0.6525	0.0102	0.0570	0.9026	0.2915	-0.0832
GBHE3	0.1697	0.2798	0.6090	0.0102	0.1023	0.8462	0.2915	-0.0742
GBHE15	0.0798	0.2057	0.6525	0.0077	0.1101	0.9026	0.0770	-0.0708
GBHE15	0.0998	0.2304	0.6090	0.0077	0.1141	0.8180	0.1103	-0.0480
GBHE2	0.0599	0.2139	0.6090	0.0102	0.1337	0.9308	0.0812	-0.1240
Groenkop Stream	0.0599	0.2057	0.8264	0.0051	0.0236	0.9872	0.1228	-0.0164
Groenkop Stream	0.0250	0.1893	0.7395	0.0051	0.0098	1.0154	0.1103	-0.0844
Groenkop Stream	0.0349	0.2139	0.7829	0.0026	0.0492	0.9590	0.1228	-0.0446

Appendix D: Data for Recharge estimation using the RIB method

Table A.3: Data for Recharge estimation using the Rainfall Infiltration Breakthrough method

Months	Rainfall	Observed water level fluctuations (m)	Simulated water level fluctuations (CRD)	Simulated water levels fluctuations (RIB)
6	99.554	0.23	0.23	0.23
7	65.083	0.18	0.18	0.18
8	46.723	0.09	0.09	0.09
9	13.812	-0.01	-0.01	-0.01
10	110.078	-0.09	-0.09	-0.09
11	59.257	-0.18	-0.18	-0.18
12	118.584	-0.22	-0.22	-0.22
13	44.485	-0.82	-0.82	-0.82
14	26.345	-0.76	-0.76	-0.76
15	38.438	-0.70	-0.70	-0.70
16	31.052	-0.61	-0.61	-0.61
17	102.692	-0.54	-0.54	-0.54
18	176.792	-0.38	-0.38	-0.38
19	121.942	-0.14	-0.14	-0.14
20	85.672	0.11	0.11	0.11
21	11.793	0.45	0.45	0.45
22	51.421	0.80	0.80	0.80
23	97.545	1.16	1.16	1.16
24	26.125	1.42	1.42	1.42
25	28.364	0.16	0.16	0.16
26	46.723	0.27	0.27	0.27
27	75.157	0.34	0.34	0.34
28	36.869	0.35	0.35	0.35
29	10.454	0.30	0.30	0.30
30	73.139	0.20	0.20	0.20
31	153.734	0.08	0.08	0.08
32	90.599	-0.09	-0.09	-0.09
33	13.591	-0.21	-0.21	-0.21
34	165.598	-0.34	-0.34	-0.34
35	51.871	-0.46	-0.46	-0.46
36	21.868	-0.59	-0.59	-0.59
37	108.060	0.35	0.35	0.35
38	56.569	0.27	0.27	0.27
39	25.226	0.23	0.23	0.23
40	25.402	0.18	0.18	0.18
41	35.304	0.12	0.12	0.12
42	33.526	0.06	0.06	0.06
43	32.258	0.01	0.01	0.01
44	109.212	-0.09	-0.09	-0.09

45	10.668	-0.16	-0.16	-0.16
46	174.238	-0.24	-0.24	-0.24
47	113.034	-0.34	-0.34	-0.34
48	24.384	-0.39	-0.39	-0.39
49	177.544	-0.28	-0.28	-0.28
50	44.954	-0.29	-0.29	-0.29
51	61.718	-0.28	-0.28	-0.28
52	166.37	-0.24	-0.24	-0.24
53	61.726	-0.19	-0.19	-0.19
54	45.462	-0.07	-0.07	-0.07
55	20.574	0.08	0.08	0.08
56	37.082	0.18	0.18	0.18
57	47.748	0.26	0.26	0.26
58	59.438	0.30	0.30	0.30
59	108.454	0.28	0.28	0.28
60	92.718	0.25	0.25	0.25
61	43.692	0.19	0.19	0.19
62	77.212	0.13	0.13	0.13
63	87.382	0.09	0.09	0.09
64	72.144	0.07	0.07	0.07
65	25.91	0.01	0.01	0.01
66	98.05	-0.02	-0.02	-0.02
67	99.822	-0.06	-0.06	-0.06
68	74.684	-0.11	-0.11	-0.11
69	146.056	-0.12	-0.12	-0.12
70	72.644	-0.12	-0.12	-0.12
71	131.064	-0.06	-0.06	-0.06
72	33.78	0.01	0.01	0.01
73	125.224	-0.35	-0.35	-0.35
74	40.634	-0.24	-0.24	-0.24
75	81.536	-0.11	-0.11	-0.11
76	45.972	0.01	0.01	0.01
77	8.636	0.09	0.09	0.09
78	52.578	0.10	0.10	0.10
79	41.91	0.32	0.32	0.32
80	29.462	0.28	0.28	0.28
81	153.16	0.17	0.17	0.17
82	27.69	0.04	0.04	0.04
83	39.372	-0.08	-0.08	-0.08
84	56.648	-0.22	-0.22	-0.22
85	79.242	0.19	0.19	0.19
86	60.452	0.31	0.31	0.31
87	45.22	0.24	0.24	0.24
88	10.414	0.16	0.16	0.16
89	22.352	0.08	0.08	0.08
90	15.494	-0.03	-0.03	-0.03
91	25.148	-0.09	-0.09	-0.09
92	75.952	-0.18	-0.18	-0.18
93	105.924	-0.29	-0.29	-0.29
94	67.05	-0.38	-0.38	-0.38

Appendix E: Photographs during fieldwork

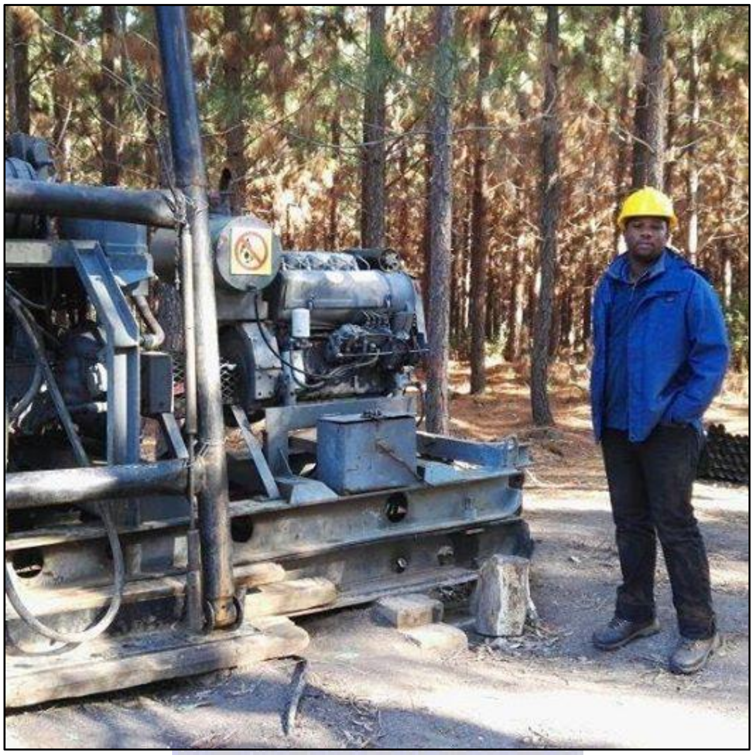

Figure A.4: Photo captured during the drilling of SV2 at Saasveld

Figure A.5: A Photo captured during analysis of drilling logs

Figure A.6: Photo captured during calculation of the purging rate at SV1

Figure A.7: Purging process at SV3 at the Groenkop indigenous forest