Estimating groundwater recharge using chloride mass balance in the upper Berg River catchment, South Africa

By

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A thesis submitted in the fulfillment of the requirements for the degree of

Masters of Science (MSc) in Environmental and Water Sciences

in the Faculty of Sciences,
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May 2015

Declaration

I declare that *Estimating groundwater recharge using chloride mass balance in the upper Berg River catchment* 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... Date.................................

Signed..

Dedicated to my son

Ompha Mutoti

Acknowledgements

I would like to thank my supervisors, Dr T.O.B Kanyerere and Prof Y. Xu for their supervision, encouragement and guidance they have provided me throughout the research period. They devoted much time and effort in not only making my research work came through, but also to make sure that I develop the skills and insights to become a better researcher. God bless them.

I would like to thank all organization and individuals who made it possible for me to complete my study. I am very grateful to the Department of Water Affairs for sharing their data with me. I would like to give deep gratitude also to the African Union (AU) project for funding me during my period of study. I give thanks for the experience and exposure they gave during my research study. I give thanks to Mrs. Caroline Barnard for always being there when I need her assistance with my research work.

I would like to give thanks to my colleagues and technical staff at the University of the Western Cape Department of Earth Sciences for their encouragement and support. God bless all of them.

My acknowledgement will not complete without mentioning my family. I am especially grateful for the bondless love and support they gave me during my entire period of study. Thanks to my parents for encouraging and motivating me to aim high while also being supportive through all my decisions.

Lastly, I would love to thank God almighty for making it possible for me to complete this work.

Abstract

Previous studies have shown that the use of chloride mass balance (CMB) method is a suitable and practical approach to estimate groundwater recharge. This enables the prediction of groundwater availability to inform practical strategies for managing groundwater resources. However, such studies have largely applied the chloride mass balance method on national and catchment scales with limited focus on quaternary catchment level (QCL). Neglecting the chloride mass balance method at quaternary catchment level limits practical management and utilization of water resources at quaternary catchment level. The goal of the current study was to prove that 1) the chloride mass balance method should be applied at quaternary catchment level to ensure practical assessment of groundwater availability and that 2) chloride mass balance assessment should be accompanied with supplementary methods for its application in quaternary catchments of similar physiographic and hydrogeologic conditions. To achieve these goals, the present study assessed the application of chloride mass balance method on a pilot scale used alongside rainwater infiltration breakthrough (RIB) and water table fluctuation (WTF) methods to estimate the groundwater recharge as an indicator of groundwater availability. The pilot area (PA) was in the upper Berg River catchment in Western Cape in South Africa. Chloride concentrations were determined in groundwater samples collected from boreholes and rain water in rain gauges in the pilot area. Rainfall and borehole water levels in the pilot area were used in water table fluctuation and rainwater infiltration breakthrough analyses. As quality assurance, the specific yield data obtained from the pumping test were compared to those determined with the linear regression model. This established the reliability of the analysis i.e. the relationship between groundwater level and rainfall. Mean groundwater recharge values calculated using the chloride mass balance, rainwater infiltration breakthrough and water table fluctuation methods were 27.6 %, 23.67 %, and 22.7 % of the total precipitation received in the catchment, respectively. These results indicate that the use of these three methods have potential to estimate groundwater recharge at quaternary level which is the basic unit of water management in South Africa. These findings agree with previous studies conducted in the same catchment that indicate that mean groundwater recharge ranges between 18.6 % and 28 % of the total precipitation. In the future, these methods could be tested in catchments which have physiographic and hydrogeologic conditions similar to those of the current pilot area.

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Abbreviation

AU	African Union
BH	Borehole
Cl^-	Chloride
Cl_{gw}	Chloride concentration in Groundwater
Cl_p	Chloride concentration in Precipitation
CMB	Chloride Mass Balance
CRD	Cumulative Rainfall Departure
DWA	Department of Water Affairs
GW	Groundwater
GWR	Groundwater Recharge
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
IWRM	Integrated Water Resource Management
KGA	Klipheuwel Group Aquifer
MAP	Mean Annual Precipitation
MAPE	Mean Annual Potential Evaporation
MGA	Malmesbury Group Aquifer
P	Precipitation
PA	Primary Aquifer
QCL	Quaternary Catchment Level
RIB	Rainfall Infiltration Breakthrough
S_y	Specific yield
SADC	Southern African Development Countries
SVF	Saturated Volume Fluctuation
SWAT	Soil and Water Assessment Tool
SWB	Soil Water Balance
TMG	Table Mountain Group

TMGA	Table Mountain Group Aquifer
uBRc	upper Berg River catchment
WB	Water Balance
WRCSA	Water Resource commission of South Africa
WTF	Water Table Fluctuation

Chapter 1: General introduction

1.1 Introduction

The present study argues that a) using chloride mass balance (CMB) alongside rainfall infiltration breakthrough (RIB) and water table fluctuation (WTF) methods remains a reliable and practical approach of estimating groundwater recharge; b) executing these three methods at quaternary catchment level provides insights on how feasible and adaptive these methods are to conventional methods. The study uses a groundwater recharge conceptual model as descriptive framework and quaternary catchment scale in upper Berg River catchment as a case study. The research seeks to generate information on the applicability of the chloride mass balance at quaternary scale alongside rainfall infiltration breakthrough and water table fluctuation. Groundwater recharge was estimated using chloride mass balance, rainfall infiltration breakthrough and water table fluctuation to provide basis for feasible but reliable estimates as proxy for groundwater availability so that management and utilisation strategies are developed based on quantified information. As a case study, the thesis shows how recharge estimates at quaternary scale of the catchment can be estimated to indicate potential of the methods so that wider replication of such an approach can be considered in other catchments of similar hydrogeologic and physiographic conditions.

Groundwater is a significant part of the total water resources in many areas; it plays a role in socio-economic development in many countries and groundwater is considered one of the scarcest natural resources in many semi-arid areas. As population increases and socio-economic activity development expand within semi-arid basins and on adjacent mountain fronts, local surface and ground water resources are increasingly utilized. Though recharge estimation in mountain environments is hindered by the difficulty in measuring or modelling evapotranspiration affected by variable soil depth, slope, vegetation and elevation, accurate recharge estimation is needed for groundwater management for population water supply, food production, and aquifer storage (Boerner and weaver, 2012). Therefore, estimating the available water in aquifers remains fundamental.

Groundwater is more vital in both arid and semi-arid than in humid areas because such areas receive less rainfall. Though estimating groundwater is significant for groundwater balance assessment, acquiring field measurements to practice such estimation remains a challenge (Subyani and Sen, 2006; Sophocleous, 1991). During dry season climate, the component of recharge is the most important element after the occurrence of rainfall. However, it cannot be measured directly. Due to the difficulties of measuring groundwater recharge, it has led many researchers (Allison and Hughes, 19787; Bazuhair and Wood, 1996; Xu and Beekman, 2003; Eriksson, 1960; Wood and Sanford, 1995) to use chloride mass balance approach to estimate groundwater recharge. Therefore, it is important to practice recharge measurements more carefully and accurately in arid and semi-arid regions where recharge rates are low (Subyani and Sen, 2006).

Determining recharge is the most important part of hydrological system, and is also the most difficult activity. Accurate recharge estimation helps to plan important human activities, domestic and agricultural activities as they depend on short and long term assessment of storage volume. Spatial and temporal variation factors such as climate, geology, and land cover complicates determination of recharge. The upper Berg River catchment is a semi-arid region experiencing a Mediterranean climate with warm dry summer and cool wet winters. The area is dominated by sandy loam soil and the aquifer consists of fractured sandstones of the Table Mountain Group. Fynbos mostly dominate this area. Boerner and Weaver (2012) reported that these factors can significantly affect estimation of recharge. However, previous studies have managed to estimate groundwater recharge in the area.

It has been demonstrated by wood and Sanford (1995) that chloride mass balance approach can yield regional rates of recharge under certain conditions and assumption in arid and semi-arid area compared to other physically based methods. And again, it has been reported by Subyani and Sen (2006) that the chloride mass balance approach yields groundwater recharge rates that are integrated spatially over the watershed and over time of tens to thousand years. The chloride mass balance only utilise parameters that can be measured directly, including, annual precipitation, chloride concentration on that precipitation, and chloride concentration of the groundwater of the aquifer of interest. Therefore, to report cost effective, reliable methods for estimating groundwater recharge, the present study utilises the chloride mass balance method in the upper Berg River catchment.

1.2 Previous studies

The Department of Water Affairs has conducted a baseline monitoring programme focusing on the groundwater atlas of the Berg River catchment. This study was conducted in 2003. They conducted another same study in 2007 focusing on the groundwater and hydrology of the Berg River catchment. They estimated groundwater recharge in all the Berg River quaternary catchments including the upper Berg catchment using the GRID-based GIS modelling techniques. Of the total annual rainfall of 1603 mm received in the upper Berg River catchment, groundwater recharge estimates obtained in these studies was 18.6 and 21% in 2003 and 2007, respectively. However, these studies did not utilize the chloride mass balance, water table fluctuation and rainfall infiltration breakthrough model to estimate groundwater recharge, but the study was done in a quaternary catchment level.

Another study was conducted by Albhaisi et al., (2008) in the upper Berg River catchment aiming to predict the impacts of land use change on groundwater recharge of the upper Berg. The GRID-based distributed hydrologic model was used to estimate recharge from the rainfall in the area. The estimated groundwater recharge was 28.8% of the total rainfall. In this study they also predicted a systematic increase groundwater recharge of about 8% per year for the 21 year period, due to the change in land use from the different years to that of 2008, which confirms that the clearing of the non-native hill slope vegetation is of considerable importance for the increase in groundwater recharge. Their study also did not use the chloride mass balance, water table fluctuation and rainfall infiltration breakthrough model to estimate recharge but the GRID-based distributed hydrologic model was used instead.

In the late 2003, the Department of Water Affairs and Forestry (DWAF) quantified the groundwater resources of the South Africa on a national scale. Annual groundwater recharge from rainfall was estimated using the chloride mass balance and a GIS based modelling approach using various empirical rainfalls versus recharge relationship (SRK, 2003). Estimation of recharge to groundwater was done during this project in the upper Berg River catchment. The groundwater recharge from rainfall was estimated to 28% of the total rainfall. However, this study had focused more on a national scale than on a quaternary catchment level. Results and recommendations from this study were based and focused on national scale. Therefore, there is a need to focus on quaternary catchment level for better understanding on how much groundwater is available in the area and for effective assessment of such groundwater resource.

A number of methods have been formulated for estimating groundwater recharge, such as direct measurement, Darcian approaches, tracer techniques, isotope dating, chloride mass-balance equations, analysis of baseflow hydrographs and spring discharges, water-table fluctuations, numerical modelling, water budgeting (Gee and Hillel, (1988); Simmers, (1997); Sharma, (1989); Lerner et al., (1990); Allison et al., (1994); Stephens, (1996); Bredenkamp et al., (1995); Lerner, (1997); De Vries and Simmers, (2002); and Scanlon et al., (2002). Many studies have been done with a focus on estimating groundwater recharge at regional scales (Adar et al., (1988); Gieske and De Vries, (1990); Athavale et al., (1992); Edmunds and Gaye, (1994); Kennett-Smith et al., (1994); Leaney and Herczeg, (1995); Sukhija et al., (1996); Birkley et al., (1998); and Rangarajan and Athavale, (2000)). However, Love et al, 2003 indicated that it is important to use the chloride mass balance at quaternary catchment level since such studies have been done seldom at quaternary catchment level.

A study was conducted by Ping et al. (2014) on a local scale using chloride mass balance to estimate groundwater recharge in a semi-arid mountainous terrain in Southern Interior British Columbia. The findings indicates that at the valley bottom recharge estimates was 1.1-1.9% of precipitation and 1.8-2.7% of precipitation on mountain areas appear useful. They concluded that the chloride mass-balance method applied at a watershed scale appears to offer a useful method to rapidly estimate groundwater recharge. However, these findings were not compared and validated using other methods. Boerner and Weaver, 2012 indicated that it would be useful to compare chloride mass balance estimations with recharge estimations from soil water balance, or other methods.

In study conducted by Hagedorn et al. (2011) water table fluctuations, chloride mass balance, apparent groundwater chlorofluorocarbon (CFC-12) ages and tritium (3H) mean residence times were used to assess recharge rates on Jeju Island (with 16 catchments) in Korea, where groundwater is the main source of potable water. All methods yield highest recharge rates in the southern and eastern districts of Jeju implying a strong control of rainfall on the spatial recharge distribution. Recharge rates from water table fluctuations, chloride mass balance, apparent groundwater chlorofluorocarbon (CFC-12) ages and tritium (3H) were 34.8%, 22.5%, 25.8% and 22.3% of rainfall, respectively. This study was conducted in a catchment level with 16 quaternary catchments. However it was not conducted on a quaternary catchment level.

1.3 Description of research problem

There is lack of using chloride mass balance method to estimate groundwater recharge in the upper Berg River catchment. Studies have shown that the use of chloride mass balance method is suitable and practical approach to estimate groundwater recharge that enables the prediction of groundwater availability to inform practical strategies for managing groundwater resources. However, such studies have largely applied the chloride mass balance method on national and catchment scales with limited focus on quaternary catchment level.

In area with regular water stress and large aquifer system groundwater is often utilised as an extra water source. Chloride mass balance has been applied during recharge investigation world-wide in recent time to estimate groundwater recharge. The chloride mass balance uses the same concepts as the water budget method which considers a soil column as a closed system in which all outputs and inputs to the system are accounted for and quantified or assumed negligible.

Lack of using chloride mass balance is a problem because its application needs to be conducted in order to enhance understanding on application of such method. Application of chloride mass balance approach is an extension of the method shown to be suitable for estimation of groundwater recharge in local aquifers. Many studies have been conducted in local catchment using the chloride mass balance to estimate groundwater recharge (Subyani and Sen, 2006; Buzurhair and Wood, 1995; Simmons et al., 2010; Nyagwambo, 2006). However, the chloride mass balance method has seldom been applied in the upper Berg River catchment. This method requires knowledge of annual precipitation, chloride concentration in that precipitation and chloride concentration of groundwater of the aquifer of interest. Wood et al. (1995) indicated that no sophisticated instrumentation or dependence on catching specific runoff event is required and the method is independence of whether recharge is focused or diffuse. Therefore, there is also a need to conduct such studies in the upper Berg River catchment.

Bazuhair and Wood, 1995 indicated that chloride mass balance needs to be applied at small catchment scale because this application is an extension of the method shown to be suitable for estimating recharge in regional aquifers in semi-arid areas. They showed that this method integrates recharge in time and space and it appears to be, with certain assumptions, particularly well-suited for areas with large temporal and spatial variation in recharge. Love et al, 2003 and Ping et al, 2014 indicated that the chloride mass balance method must therefore be re-written to reflect a basin scale chloride mass balance because estimates of recharge at the local scale are important. Chloride mass balance method applied at a watershed scale appears to offer a useful method to rapidly estimate groundwater recharge.

Lack of knowledge on the application of chloride mass balance method to estimate recharge is the main cause of the problem and this problem may cause lack of effective assessment, planning and management of groundwater resources that can result not only in poor service delivery to water users, but also to significant detrimental impacts on the aquifer systems themselves (Boerner and Weaver, 2012; DWAE, 2010). Data unavailability also limits the application of the chloride mass balance method. There is non-existence of data on dry atmospheric deposition of chloride as well as long-term data on total chloride deposition in the upper Berg River catchment and that limits the application of the this method in groundwater recharge estimation.

1.4 Rational of the study

The role of groundwater, with recharge as a critical parameter for determining its sustainable use is becoming increasingly important in the emerging integrated water resource management (IWRM). A proper understanding of computing recharge is crucial to assessing groundwater availability efficiently. Utilizing methods such as chloride mass balance, water table fluctuation and rainfall infiltration breakthrough model is crucial since these methods are suitable and practical approaches to estimate groundwater recharge that enables the prediction of groundwater availability to inform practical strategies for managing such resource. However, good estimates of groundwater recharge is not an end in itself but must be viewed on the usefulness of its value, skills to compute it and methods and application when its required to assess, plan and use of groundwater resource.

Participatory approach to management of groundwater resource is required in countries such as South Africa, where optimal management of all water resources is essential. The present study provides a better understanding of groundwater recharge in the upper Berg River catchment and also provides details on how much groundwater is available in the area. The study provides the insights, the feasibility of using chloride mass balance, water table fluctuation and rainfall infiltration breakthrough model to estimate groundwater recharge which is a step forward for groundwater availability assessment and such estimates of groundwater recharge can be used as indicators of groundwater availability and therefore can be used during water resource assessment and planning.

1.5 Study objectives

1.5.1 Main objective

The main objective of this study is to assess the application of chloride mass balance method at a local scale (upper Berg River catchment in Western Cape in South Africa) alongside rainwater infiltration breakthrough and water table fluctuation methods to estimate the groundwater recharge as indicator of groundwater availability.

1.5.2 Specific objectives

To estimate groundwater recharge using chloride mass balance method.

To estimate groundwater recharge using rainfall infiltration breakthrough model.

To estimate groundwater recharge using water table fluctuation method.

1.6 Thesis statement and recharge question

1.6.1 Thesis statement

The present study argues that 1) CMB method should be applied at quaternary catchment level to ensure practical assessment of groundwater availability and that 2) its assessment should be accompanied with supplementary methods for its application in quaternary catchments of similar physiographic and hydrogeologic conditions.

1.6.2 Research questions

Using chloride mass balance, rainfall infiltration breakthrough and water table fluctuation how much of the annual precipitation that is received in the upper Berg River catchment is recharged to groundwater?

To what extent can the use of chloride mass balance, rainfall infiltration breakthrough and water table fluctuation be relied upon as appropriate practical methods for estimating groundwater recharge as indictor of groundwater availability in the area?

How well are the use of chloride mass balance, rainfall infiltration breakthrough and water table fluctuation compare with other methods in estimating groundwater recharge?

1.7 Thesis outline

This thesis is divided into seven chapters. Chapter one outlines the framework of the study, it gives the general introduction and defines the context within which the study was conducted. It also gives out the objectives that guided the study. Chapter two describes the literature review to provide gap analysis. This literature covers research in the study area and research elsewhere. Chapter three outlines the research design and discuss the methods that were used in the present study to collect and analyse data. Chapter four presents and discusses results from the chloride mass balance. Chapter five presents and discusses results from the rainfall infiltration breakthrough model. Chapter six presents and discusses results from the water table fluctuation method. Chapter seven provides the conclusion of the study and also outline the recommendations for further studies.

Chapter 2: Analysis of literature review

2.1 Introduction

The objective of this chapter is to present a review on previous work on recharge estimation for groundwater management with a focus on the use of chloride mass balance, water table fluctuation and rainfall infiltration breakthrough methods. In order to fulfil the objective, this chapter starts with the conceptual and theoretical framework on groundwater recharge estimation that guides this study. Within this framework, the operation definition of groundwater recharge is provided. This framework informs the methods for generating and analysing data for the study. The reviewed literature has been presented following the specific objectives of the study to provide a systematic review on various methods that are used to estimating groundwater recharge. Such a review has been presented in an analytical way to highlight the gaps in knowledge and practice.

2.2 Definition of recharge and influencing factors

Recharge is one of the most significant aspects of the hydrological system, though it is also the most difficult to determine. Groundwater recharge can be defined as water that moves downward through the water table and replenishes to the groundwater stock (Boerner and Weaver, 2012; Nyagwambo, 2006). Downward flow of water through the unsaturated zone is the most significant mode of recharge in arid and semi-arid regions such as upper Berg River catchment (Xu and Beekman, 2003). Therefore, this study refers groundwater recharge to the downward flow of water from the unsaturated zone reaching the water table (Freeze and Cherry, 1979; Lerner et al, 1990). Lerner et al, 1990, reported that groundwater recharge occurs naturally from sources such as precipitation, rivers, canals, lakes, as well as irrigation and urbanisation as man induced activities. The present study focuses only on quantifying natural sources of recharge, therefore, artificial recharge such as irrigation, canals, and urban water-delivery system are not considered.

There are three mechanisms of natural groundwater recharge, such are, direct indirect, and localized (Boerner and Weaver, 2012). Figure 1, illustrates these three types of groundwater recharge. Direct recharge refers to direct infiltration of precipitation and subsequent percolation through the unsaturated zone and replenishes the groundwater reservoir after subtracting interception, runoff and transpiration. Localized recharge is the accumulation of surface water bodies, and subsequently concentrated infiltration and percolation through the unsaturated zone to a groundwater whilst indirect recharge refers to percolation to the water table from surface watercourses. Each type of mechanism is more prevalent in some climatic conditions than others (Lloyd, 1986).

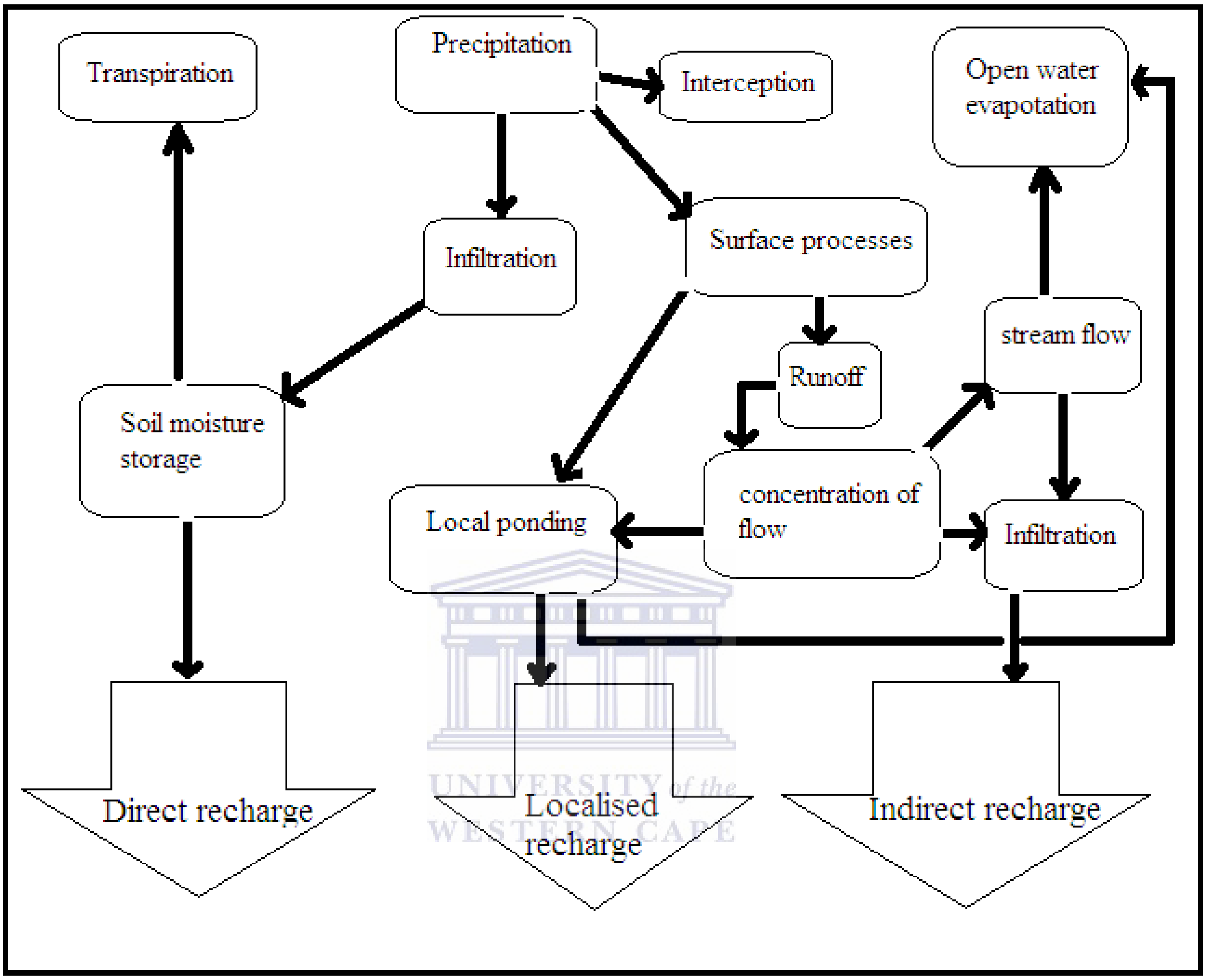


Figure 1: Elements of recharge in a semi-arid area (modified from Nyagwambo, 2006)

The accuracy of groundwater recharge estimation depends to a great extent on the correct identification of the recharge mechanism. However, no actual recharge process is precisely discussed in figure 1. Actual recharge is likely to be a combination of any of the above processes (Lerner et al., 1990; Nyagwambo, 2006). In arid and semi-arid areas, assessment of groundwater recharge is one of the key challenges in determining the sustainable yield of the aquifer as recharge rates are generally low in comparison with average annual rainfall and thus difficult to determine precisely (Xu and Beekman, 2003). The problem is that when the basic recharge mechanism are reasonably defined, deficiencies still remain in quantifying the elements particularly in areas of data scarcity (Lloyd, 1986). Methods applied in this study will require quantification of total annual precipitation that the upper Berg River catchment receives.

There are several factors that control groundwater recharge, such as, rate and duration of rainfall, the antecedent moisture condition of the soil profile, geology, soil properties, the depth of water table and aquifer properties, vegetation and land use, topography and landform. The amount of recharge or infiltration at a specific site depends on the amount of precipitation evaporated back into the atmosphere, the amount of water transmitted from natural vegetation to the air, site topography, type of vegetation and surficial soil type. Surficial geology influences recharge rates. Area of hummocky topography exhibit higher recharge rates since soil run-off collects in depressions where it can then infiltrate through the surficial soil (Toronto and Region Conservation Authority, 2009).

Vegetation cover influences the recharge processes. For example, Albhaisi et al, (2012), observed that recharge has increased systematically with years after deforestation in the Berg River catchment of South Africa. This was after being hypothesized that evapotranspiration will decline and recharge will increase due to this change in land use. In the soil, its nature, depth, cohesion, homogeneity and hydraulic properties determine recharge whilst the aquifer-porosity determines the magnitude of recharge. It can be concluded that the hydro climate, soil texture, and slope play a role in determining the baseflow from a catchment (Nyagwambo. 2006).

2.3 Methods for groundwater recharge estimation

Most authors agree that recharge estimation is best calculated as an iterative process, because data is always limited and circumstances vary both in time and space (Simmer, 1997; Lerner et al, 1990; Lewis and Walker, 2002). Nyagwambo (2006) shows three steps that should be considered when selecting a method for estimating groundwater recharge. The first step is to define the groundwater system in terms of the geological structures and the resultant flow mechanisms. Second, the complete water balance must account for all water that ‘does not become recharge’ and the underlying groundwater recharge processes clear. Third, the estimate must consider the time scale for the recharge process. Lerner et al, (1990), state that estimates that are based on the summation of shorter-time steps are better than those based on longer term steps for the same duration. However, the present study choses to use estimates based on longer term steps because of limited data availability. They then identified five methods used for estimation of groundwater recharge and such methods are described and dicsusssed in chapter three of this thesis.

2.4 Method Applicability of for difference recharge mechanisms

Many methods are available for quantifying groundwater recharge as there are different sources and processes of recharge. Each of the methods has its own limitations in terms of applicability and reliability. The objective of the recharge study should be known prior to selection of the appropriate method for quantifying groundwater recharge as this may dictate the required space and time scales of the recharge estimates (Scanlon et al., 2002).

Three recharge mechanism (direct, indirect, localised) estimate groundwater recharge from different sources. Localized recharge refers to water that infiltrate and percolate through the unsaturated zone from surface water bodies after being accumulated. Indirect recharge refers to surface watercourses percolation to the water table and direct recharge refers to direct infiltration and percolation of precipitation through the unsaturated zone and replenishes the groundwater reservoir. The chloride mass balance, water table fluctuation method and the rainfall infiltration breakthrough model estimates groundwater recharge from precipitation, therefore, these methods are applicable and suitable for direct recharge mechanism.

2.5 Recharge - Spatial and temporal variability

The various techniques for quantifying recharge differ in the range of recharge rates that they estimate and the space and time scales they represent. The range of recharge rates estimated with a particular technique should be evaluated on a site-specific basis by conducting detailed uncertainty analyses that include uncertainties in the conceptual model and in the input and output parameters. Use of environmental tracers, such as Cl, is one of the few techniques that can estimate very low recharge rates and is generally more accurate in this range. Analytical uncertainties in Cl measurements and uncertainties in Cl inputs restrict the upper range of recharge rates that can be estimated with the CMB technique.

The time scales represented by recharge rates are variable. Unsaturated zone methods, such as applied tracers, and saturated zone methods, such as water table fluctuations and rainfall infiltration breakthrough model, provide recharge estimates on event time scales. These methods are restricted to providing recharge estimates for the length of the monitoring record. The time scales represented by recharge rates estimated using water table fluctuations and rainfall infiltration breakthrough model range between 0.1 – 5 years and 0.1 – 20 years, respectively. Recharge estimation based on climatic data is generally restricted to about 100 years. Cl is one of the only methods that can provide integrated, long-term estimates of recharge. The time scales represented by recharge rates estimated using chloride mass balance range between 5 – 10 000 years. Tracers are very useful for estimating net recharge over long time periods but generally do not provide detailed time series information on variations in recharge.

The surface areas represented by the recharge estimates vary markedly among the different techniques. In general, many techniques based on unsaturated zone data provide point estimates or represent relatively small areas. Spatial scales represented by chloride mass balance, water table fluctuation method and the rainfall infiltration breakthrough model for estimating recharge range between 1- 1000 km^2 , 5 x 10^{-5} – 5 x 10^{-2} km^2 and 2 x 10^{-6} – 2 x10^{-2} km^2, respectively. These spatial scales consent the application of these methods at a national, regional, and local scales. Therefore, these methods are applicable at quaternary catchment scale.

2.6 Trends in groundwater recharge estimation methods

The response of water table to recharge method consists of calculating the ratio of water table rise to total rainfall (Risser et al., 2005) for all the registered events in the analysed area. The height of water table rise measured after a rainfall event provides an estimates of the amount of open pore space available in the unsaturated zone i.e. $S_{y.}$ The method is valid for a shallow water table (Varni et al., 2013); Croie et al., (2005) stated different methods to estimates S_y at two sites, determining the water retention curve in the laboratory through the analysis of the response of the water table and by pumping tests. The results after testing several methods show that the rainfall water table response seems to provide the best estimates.

Xu and Beekeman, (2013), indicated that the absence of unsaturated zone storage could also explain the high recharge (50%) calculated using the chloride mass balance method for the fractured TMG group aquifer near Cape Town. Visual inspection of the out cropping mountain peaks in the area confirms that there is little, and in many places no unsaturated zone. Thus, given that, a) recharge water is only resident in the unsaturated zone for a limited time due to the lack of storage; b) transpiration cannot take place because vegetation has difficulty becoming established at such site; c) vegetation cannot take place because rapid recharge occurs via preferred pathways, then recharge can be defined as that component of rainfall that does not leave the recharge area as run-off.

The chloride mass balance underestimates recharge rates in non-irrigated areas compared with other method. It agrees with this method, however, in irrigated area (Grismer et al., 2000; Flint et al., 2002; Russo et al., 2003). It has been showed by Wood and Sanford, (1995) and Wood and Imes (1995), that the chlorine mass balance method can yield regional rates of recharge under certain condition and assumption. On the other hand, Buzuhair and Wood (1996) stated that the chloride mass balance method yields groundwater recharge rates that are integrated spatially over the watershed over tens of thousands of years. Various applications of chloride mass balance methods has been presented for different parts of the world (Ericson and Khuna Kasem, 1969; Ericson, 1976; Allison and Hughes, 1978; Grismer et al., 2002; Edmunds et al, 2002; Hanington et al., 2002; Scanlon et al., 2002). However, it has not been applied in the small scale upper Berg River catchment.

Subyani and Sen (2005), showed that although evaluating recharge component is an essential part of groundwater balance assessment, acquiring field measurements to perform such an evaluation remain a challenge. In dry climates, the recharge component of the hydrologic cycle becomes the most significant element after rainfall occurrences. Its direct calculation is not possible, however, the recharge rates in arid and semi-arid region are low and must therefore, be carefully and accurately estimated. Consideration of these difficulties, such as exploitation and use of groundwater resources in arid and semi-arid areas has led many researchers to use the simple method of the chloride mass balance approach during the last decades.

2.7 Previous studies on groundwater recharge estimation

2.7.1 Groundwater recharge studies in South Africa

In South Africa, study on groundwater recharge was conducted by Sami and Hughes (1995) with a focus on using an integrated surface-subsurface modelling approach to estimate recharge in a semi-arid Karoo aquifer and compared such results with a chloride mass balance on a sub-area scale. Chloride mass balance suggests a mean annual recharge of 4.5 mm/year based on a mean annual rainfall of 460 mm. The model predicts 5.8 mm/year from a mean annual rainfall of 483 mm during the simulation period. Both methods suggest that recharge is considerably less than the mean of 9.9 mm/year estimated from the currently prescribed rainfall- recharge relationship for Karoo aquifers. Three methods have been used to estimate groundwater recharge in a small catchment (180 km^2), the chloride mass balance

(CMB), the daily catchment water balance (WB) and the water table fluctuation (WTF) methods.

In South Africa, studies in groundwater recharge estimation have been done using various direct and indirect techniques and methodologies in the unsaturated and the saturated zones. Over 80% of South Africa is underlained by relative low-yielding, shallow, weathered and fractured-rocks aquifer systems. In the late 2003, the department of water affairs and forestry (DWAF) initiated the groundwater phase two project which is aimed at the quantification of the groundwater resources of the South Africa on a national scale. Annual groundwater recharge from rainfall was estimated using the chloride mass balance and a GIS based modeling approach using various empirical rainfall versus recharge relationship (SRK, 2003).

Assessment of groundwater in the unsaturated zone has been done using lysemeter studies, tritium profiling, soil moisture balance, and chloride profiling techniques. Resulted from lysemeter indicate an apparent annual threshold value of rainfall below which no recharge takes place (Bredenkamp et al., 1995). Bredekamp et al., 1978, indicated that tritium profiling yielded estimates that were generally less than those derived from water balance methods. Recharge estimates of 5% and 18% of average annual rainfall were obtained. The soil moisture balance method was found to be too dependent on the assumed equivalent soil moisture available to the vegetation (Bredekamp et al., 1995). The recharge rates estimated using the chloride mass balance was found to correspond well with values obtained using other techniques. The value ranged between 0.9% and 37% of annual rainfall.

In the saturated zone of South Africa, there are two main methods that are utilized in the estimation of groundwater recharge. Such are, saturated volume fluctuation (SVF) and cumulative rainfall departure (CRD). The saturated volume fluctuation method was used to estimate groundwater recharge in a dolomite aquifer covering $70Mm^2$. Recharge rates estimated was between 10 and 14% of average annual rainfall using recorded water levels, rainfall and spring flow data for the period 1960 to 1993 and computer simulated groundwater level data for the same period (Botha, 1994). Such values agreed closely with those obtained from chloride profiling approach.

Xu and Beekman, (2003), reported that in South Africa, the need for reliable recharge estimation originated from a desire to sustainably manage limited water resources. The Water Research Commission of South Africa (WRCSA) therefore initiated the project based on preparation of a manual on quantitative estimation of groundwater recharge and aquifer storativity. This manual was published in 1995 by Bredenkamp et al., (1995), present a great variety of well-tested method (semi-imperial) that are widely employed in South Africa .

2.7.2 Groundwater recharge studies in Southern African Development Countries

In the Southern African Development Countries (SADC), most regional and local recharge studies have been carried out intensively in semi-arid Namibia, South Africa, Botswana, and sporadically in Malawi and Zimbabwe (Xu and Beekman, 2003; Nyagwambo, 2006). Xu and Beekman, (2003), reported that in Southern Africa, experience in recharge estimation cover a time span of at least three decades. This experience formed the basis for this review of recharge estimation. They then concluded that there are several methods that can be applied with greater certainty in the arid and semi-arid parts of the region. Various methods and techniques ranging from tracer and stable isotope, profiling techniques to groundwater balance methods and pore soil moisture profiling has been used in the study of groundwater in the Southern Africa.

The semi-arid Botswana is situated on the Southern African platen. It is taken as a sand province of the Kalahari sediments underlained by Karoo strata. Rainfall ranges between 200 and 600 mm/year. During the 1970 and 1980, studies were also carried out in the Kalahari (Verhagen et al., 1974; Mazor et al., 1977; foster et al., 1982; De vries and Von Hoyer, 1988). Methods used included analysis of hydrographic records and groundwater dating with tritium (^{3}H), carbon (^{14}C) and carbon-13 (^{13}C). Selaolo et al., (2000), use the helium isotopes and abundances, chloride mass balance, groundwater flow and hydrochemical isotope modeling. Recharge rates of 10 to 50 mm/year takes place under favorable condition in the Eastern part of Botswana. A decreasing recharge trend was observed from 5 mm/year in the fringe of the Kalahari to less than 1 mm/year towards the central part. Some conclusions were that lower recharge rates or even hardly any recharge at all, may be expected where rainfall drops below 400 mm/year, which is 66% of the total rainfall.

The study was conducted in a tropical crystalline basement aquifer Zimbabwe by Nyagwambo in 2006. The study concluded that though the methods yielded the same range of recharge, between 8% and 15% of annual rainfall. The study also showed that all recharge estimation methods used in the study had the weakness of over reliance on one critical parameter such as the chloride deposition for the CMB method and specific yield for the WTF method. These studies use an integrated surface-subsurface modelling and the water table fluctuation methods in comparison with the results obtained by chlorine mass balance in the Karoo and tropical crystalline basement aquifer, respectively. The present study aims to compare the results obtained from the chloride mass balance with the results obtained from the water table fluctuation and the rainfall infiltration breakthrough model. The expectation is that the results should be in a similar range since all these methods are estimating groundwater recharge from rainfall.

2.7.3 Groundwater recharge studies beyond SADC

Kaba et al., (2012) investigated groundwater recharge in the Thiaroye sandy aquifer Dakar in Senegal. Combined use of water table fluctuation, chloride mass balance and environmental isotopes were used in this study. Their results indicated that recharge obtained by water table fluctuation method ranged between 18 and 144 mm/year during the rainy season (June to October), whereas the recharge given by chloride mass balance method ranged between 8.7 and 73 mm/year. The Thiaroye aquifer recharge obtained from these different methods also showed relatively similar range values. In this study, the water table fluctuation method applied computes both infiltration from rainwater and domestic waste water, while the chloride mass balance method estimates potential recharge from rainwater.

In Saudi Arabia, a study was conducted by Bazuhair and Wood in 1995. The area is dominated by crystalline and high metamorphic rocks. The aim of the study was to extend the chloride mass balance method to small local valley-filled aquifers in arid areas and to test applicability of chloride mass balance for local basins in arid areas. Chloride mass balance approach was utilised in this study to estimate recharge. Recharge was found to be between 3 to 4% of precipitation and their conclusion was that chloride mass balance method appears to offer a useful method to rapidly estimate groundwater recharge. The chloride mass balance was applied in three types of aquifers in these two studies i.e. the sandy aquifers, the crystalline and metamorphic rocks aquifers. The present study aims to estimate the groundwater recharge in the Table Mountain Group aquifer. All these aquifers are related in the fact that they are all fractured rock aquifers. The study expect the recharge rate to be very high since the aquifer is foulded and faulted giving them their secondary water bearing features.

The chloride mass balance was used to estimate groundwater recharge in Nebraska in 2012. The area is a Sandhills dominated by well sorted, coarse sand. This study was conducted by Boerner and Weaver using the chloride mass balance as the same concept as the water budget method to estimate annual recharge across Nebraska. The chloride mass balance method indicates the majority of this area experiences less than 30 mm/year of recharge. They then concluded that chloride mass balance provides a reasonable estimation of recharge across the state of Nebraska and also recommended that it is useful to compare the chloride mass balance estimations with recharge estimation from other methods. Therefore, the present study aim to compare the chloride mass balance groundwater recharge estimations with groundwater recharge estimation from water table fluctuation and rainfall infiltration breakthrough and the present study expects groundwater estimates from these methods to be on the same range.

Groundwater recharge study was conducted in Dry Creek Experimental Watershed which is located 6.5 km north of Boise, Idaho within the Boise Front Range in semi-arid south-western Idaho. The main objective of this study was to estimate how much of the annual precipitation received is partitioned to net groundwater recharge. The estimate of annual precipitation partitioned to net groundwater recharge for the entire catchment, water year July 2004 through June 2005, is zero to 11%. The contrasting results for water year 2004-2005 versus 2005-2006 emphasize caution necessary in addressing assumptions underlying application of chloride mass balance to recharge estimation. Following conclusions made from these two studies, the present study aims to estimate the annual groundwater recharge from precipitation taking caution on the assumptions that need to be considered when applying the chloride mass balance. The study expects the chloride mass balance to give out reasonable estimates of groundwater recharge across the upper Berg River catchment.

Study was done in Makutupora basin in Dodoma Tanzania by Rwebugisa in 2008. The study aims to assess groundwater in the Precambrian metasediments and fractured crystalline granitic rocks in the Dodoma region, central of Tanzania. The area is characterized by a semi-arid climate with average annual rainfall of about 550 mm/a and evapotranspiration of about 2000 mm/a. chloride mass balance was used along with Earth model and hydrograph analysis to estimate groundwater recharge flux within the basin. Recharge flux was estimated to be 5-12 mm/a equal to 1-2 % of annual rainfall. They concluded that the annual groundwater recharge in the basin is fluctuating depending on the amount of rainfall received in a particular year. The study area of the present study falls under the semi-arid climate area, but this catchment receives an annual precipitation of 1603 mm/a and mean annual evaporation of 1475 mm/a. the present study aims to estimate groundwater recharge from precipitation expecting such recharge to be slightly high since evaporation rate is lower than the amount of rainfall received.

Aurand conducted a study in 2013 in the lower Tertiary and upper Cretaceous Aquifers in the Williston and Powder River Structural Basins. The study aim was to estimate groundwater recharge. A numerical soil-water-balance (SWB) model was used to estimate groundwater recharge in the Williston and Powder River structural basins. Recharge was estimated for glacial deposits and exposed areas of the Lower Tertiary and upper Cretaceous aquifer systems in the Dakotas, Montana, Wyoming, Saskatchewan, and Manitoba. The water-table fluctuation (WTF) and chloride mass-balance (CMB) methods were applied to local areas with available groundwater-level and chloride data. SWB model results were compared to the WTF and CMB results. Recharge was calculated to be about 1.1 percent of precipitation in the Williston basin. Recharge was about 0.8 percent of precipitation in the Powder River basin. The study concluded that diffuse recharge estimates from the SWB models are reasonable and compare reasonably well with local recharge estimation results, and previous investigations. The present study need to estimate recharge using the chloride mass balance and compare the results to the WTF and RIB model results. However, the present study expects results from all these three methods to be on the same range.

Estimation of groundwater recharge in the context of future climate change in the White Volta River Basin, in West Africa was done by Obuobie in 2008. The study estimates the total amount and spatial distribution of the groundwater recharge at different scales in the White Volta Basin using the chloride mass balance, water table fluctuation, and hydrological modeling with the Soil and Water Assessment Tool (SWAT). The mean annual recharge estimated using chloride mass balance represents 8 % of the long-term mean annual rainfall of 990 mm upper East Region of Ghana. Water table fluctuation method was used in the south of the basin called the White Volta Basin of Ghana, representing 8 % of the annual rainfall (870 mm). About 7 % of the mean annual rainfall (824 mm) was obtained using SWAT-simulated water balance. They concluded that water balance in the White Volta Basin shows important increases in the mean annual discharge, surface runoff and shallow groundwater recharge as a result of future climate change in the basin. The shallow groundwater recharge is expected to increase by about 29 %. The present study estimates groundwater water recharge in the upper part of the Berg River catchment using three different methods and in comparison of these methods, the present study expects reliable and accurate recharge estimates.

2.8 Limitation and errors in GW recharge estimation

Since it is difficult to measure groundwater recharge directly, indirect methods have been used to estimate recharge to groundwater. Using indirect methods to estimates recharge is associated with various limitation which leads to large errors and uncertainties of recharge rates. The unsaturated-zone methods are founded on the principle of mass balance, for example, the chloride mass balance. When using physical or chemical mass balance to obtain an estimate, an important underlying assumption made when using unsaturated zone methods is that recharge occurs through a diffuse process or piston flow of water and, thus, at sites were recharge occurs through preferred pathways is often not accounted for. Reliability of resulting estimate is questionable in sites where preferred pathways influence the recharge flux, i.e., in many arid and semi-arid areas such as Sub-Saharan Africa (Xu and Beekman, 2003; Obuobie, 2008). Groundwater recharge at the study area of the present study occurs as diffuse or direct recharge i.e. direct infiltration of precipitation and subsequent percolation through the unsaturated zone to groundwater. Therefore, reliability of resulting groundwater recharge estimates is not questionable.

Four types of errors associated with indirect estimation of the recharge have been identified by Obuobie, 2008 after Lerner, 1990. The types of errors identified are (i) incorrect conceptual model, (ii) neglect of spatial and temporal variability, (iii) measurement errors, and (iv) calculation errors. The most common error type that arises when the recharge process is over-simplified or not properly understood is the use of incorrect conceptual model Other errors associated with saturated zone methods such as the chloride mass balance. There are other parameters that are difficult to measure when using the chloride mass balance method (i.e. rain). Such input parameters are highly variable (i.e. seasonal effects), prone to pollution, and poorly understood. While at sites where diffuse recharge is occurring unsaturated and saturated zone processes can be measured and understood. The correct conceptual model of the study area is used in the present study as this model attempts to answer the question of how, where, when, and why recharge occurs. So this model identifies the prominent recharge mechanisms and provides initial estimates of recharge rates. Rainfall measurements as required by methods to be used in the presents study, it is being measured daily in the catchment site. To reduce calculation or measurement errors, the present study will undertake data quality assurance i.e. data validity, data cleansing, and data reliability in order to make groundwater recharge estimates reliable, accurate and valid.

Chapter 3: Research design and methodology

3.1 Introduction

This chapter describes the research design which refers to the overall strategy that was chosen to integrate different components of the present study, thereby, ensuring that the research problem is addressed. The chapter explains the methods used for data collection and also methods used for data analysis. The chapter describes the upper Berg River catchment with a focus on its physical environment i.e. hydrology, topography, climate, vegetation and geology of the area to provide a context for the research problem.

3.2 Research design

The research design provides the context of the study and also describes aspects that provide such context. This section indicated data gathering methods that fit with the research purpose, conceptual and theoretical framework and methods for data analysis. This section is needed to make the working of the current research operation possible and it carries an important influence on the reliability of the results attained. Therefore, this section indicated full description of the study area and also gives the map indicating all the sampling sites.

3.2.1 Description of study area

The Berg River catchment (figure 2) is the largest catchment in the Western Cape Province of South Africa and has an area of about 9,000 km2. The catchment has 8 major towns (Saldanha, Vredenburg, Hopefield, Piketberg, Porterville, Paarl, Wellington and Franschhoek) and has a population in the order of 200 000 most of whom live in the urban areas.

The catchment is sub divided into 12 Quaternary catchments of which they vary in sizes. Quaternary catchments G10L and G10M are the largest of these, covering 1750 km^2 and 2000 km2 respectively. These two catchments are located in the western and drier parts of the Berg catchment. The smallest quaternary catchments are G10A and G10B. These are located near the headwaters of the Berg River and are with areas comprising 170 km^2 and 125 km^2 respectively (DWAF, 2007). Catchment G10A is the one that is of interest in this study. The upper part of G10A is the study area.

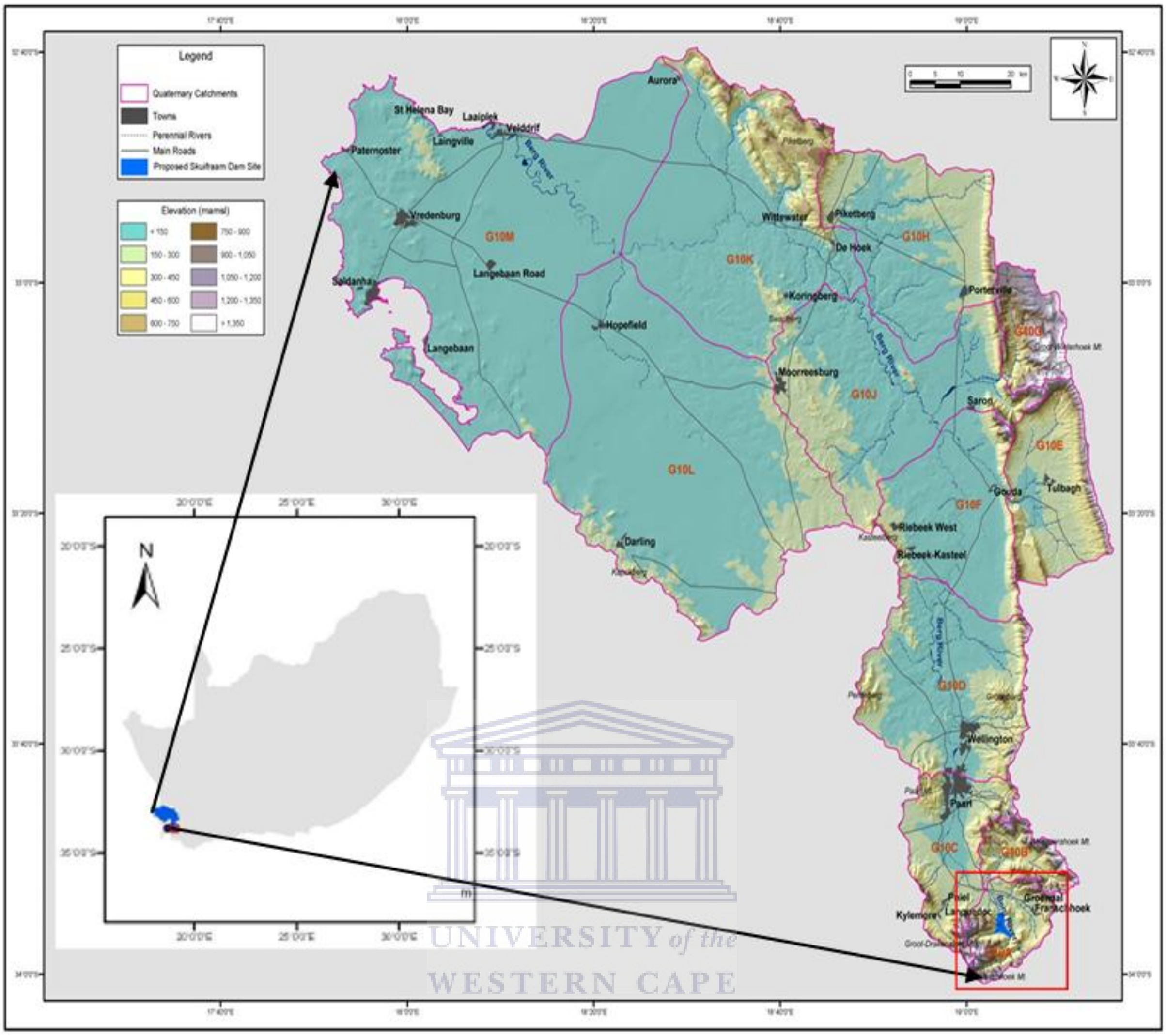


Figure 2: Berg river catchment with the upper part of 10GA indicated in red box (DWAF, 2007)

The upper Berg River catchment consist of the Berg River Dam that was constructed to capture and store winter runoff from mountainous upper reaches of the Berg River catchment and transfer it to the existing Western Cape Water Supply system. Its strong economic and population growth is projected to continue and these might have impacts on the future requirements of water. Significant quantities of groundwater are also abstracted in the area with small-scale artificial recharge of groundwater being practiced. Nevertheless, there was an on-going need to continue augmenting water resources, and options identified to meet future requirements including the exploration of deep groundwater from the Table Mountain Group aquifers. A stronger reliance is likely to be placed on groundwater in to the virtue by the fact that the surface water yield potential is reaching its exploitable limit and options such as desalination remain relatively more expensive. So estimating recharge in this area is important as it will indicate the volume of groundwater that can be abstracted sustainably.

3.2.1.1 Influence of climate on groundwater recharge

The upper Berg River catchment experiences a Mediterranean climate with warm dry summers and cool wet winters. Rainfall is of a cyclonic nature, extending normally over a few days with significant periods of clear weather in between. During summer there is little rain falls with low groundwater recharge. Rainy season extends from April through to October with high groundwater recharge. Precipitation is generally in the form of frontal rain approaching from the northwest.

Mountainous areas of the study area experience mean annual precipitation (MAP) in excess of 1603 mm/a. The mean annual potential evaporation (MAPE) in the upper Berg River catchment exceeds 1375 mm/a. Like rainfall, MAPE exhibits marked seasonal differences. During summer monthly evaporation losses amount to about 250 mm, but during winter monthly evaporation losses are in the order of 50 mm (Schulze, 1997) and therefore, groundwater recharge is expected to be very high during winter seasons.

3.2.1.2 Influence of vegetation and land use on groundwater recharge

The upper Berg river catchment has a lot of agricultural activities and its economy is predominantly agriculture based. The industries in the area include wineries, canneries and other food processing factories and textile factories. However, in the higher lying areas and areas with low agricultural potential, natural vegetation still exists. The higher lying parts of G10A are still largely natural. However, non-native hill slope vegetation was cut down after being hypothesised that groundwater recharge has been increased due to this change in vegetation. Studies have shown that the spatial distribution and variation of vegetation in the catchment has a much stronger correlation with the geology than with the rainfall distribution and other climatic variables (Schloms et al., 1983; Cowling and Holmes, 1992; Rebelo, 1996). The outcrops of rocks belonging to the TMG are characterized by fynbos vegetation and little soil cover and constitute the few remaining remnants of natural vegetation in the catchment (DWAF, 2007). Land use change is a major factor influencing catchment hydrology and groundwater resources. Land use such as urbanisation causes delay in the water table response or groundwater recharge (Albhaisi et al., 2013).

The upper parts of the Berg River catchment have been intensively developed with vineyards and, to a lesser extent, for fruit and vegetable farming. Much of the area south and west of the Berg River Dam site remains in a natural state and comprises mountain fynbos. Approximately 17 km^2 or 22% of the dam catchment area supports *Pinus* species (McDonald et al., 1996) and 14 km^2 or 18% of the dam catchment is infested with alien vegetation with a density of greater than 25%. The alien vegetation are non-native plants mainly shrubs that have been planted during the second half of the 19th century as a result of a decision made by the colonial authorities to stabilize the sand with plants native to the British colonies (Stirton, 1978). The area directly east of the dam site has been developed with vineyards, vegetables and other crops (DWAF, 2007). Dense vegetation cover reduces the amount of water available for recharge of groundwater by interception and transpiration due to high suction capacity and root length of many plants adapted to drought (Simmers, 1987). However, the slow movement of water through the vegetation prevents runoff and facilitates the infiltration.

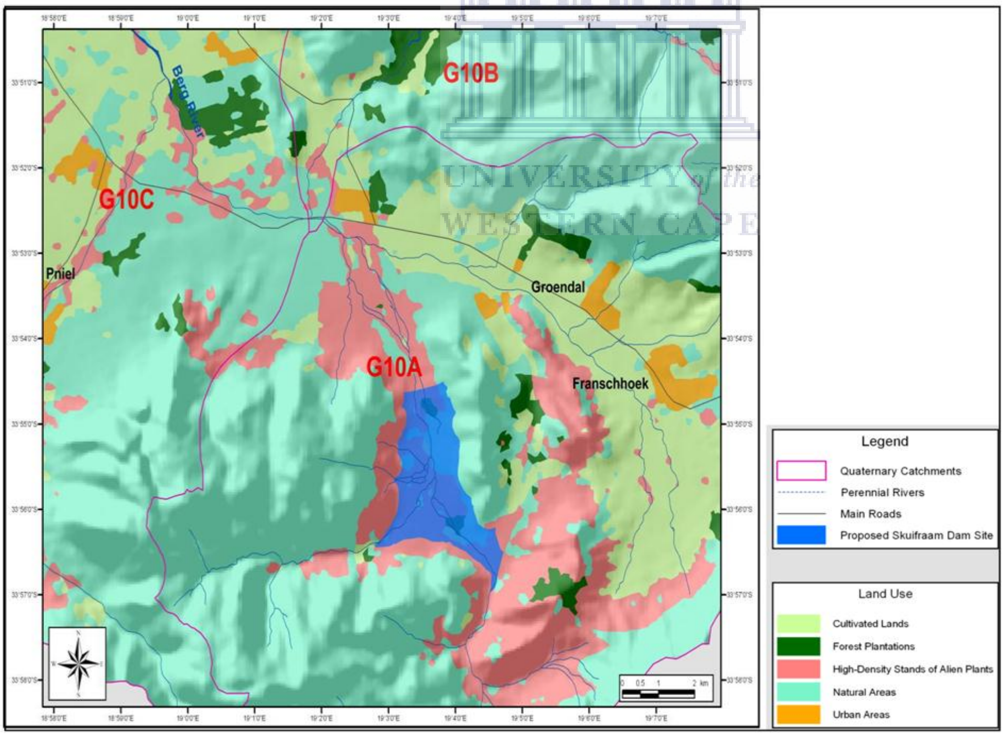


Figure 3: Vegetation in the upper Berg River (DWAF, 2007)

3.2.1.3 Topography and groundwater recharge

The upper Berg River catchment generally has mountaneous topography. Part of the upper Berg River is mountains of the Table Mountain Group situated, which range in excess of 1000 m elevation. The Table Mountain Group (TMG) extends from Western Cape to Eastern

Cape in South Africa and comprises of hard sedimentary rocks dominated by fractured sandstones with a thickness estimated to range from 900 m to 5000 m (Jia, 2007). It has been suggested, from numerous groundwater aquifer practices in the TMG and studies on the lithology of the area, that the TMG is a regional aquifer system that extends to deeper depths making it potentially a huge groundwater reservoir (Jia, 2007).

Quaternary catchment G10A forms the headwaters of the Berg River and is characterised by steep slopes. Grinevskii, (2013) indicated that the main feature of the relief is slope exposure and the greatest differences in groundwater recharge in comparison with flat surface are manifested at the foot of a hill. Groundwater recharge areas are at a topographical high spot, where there is high precipitation that falls and recharges groundwater.

3.2.1.4 Geology, hydrology and groundwater recharge

The upper Berg River catchment comprises Table Mountain Group Aquifer (TMGA). The TMGA predominantly occurs in the upper catchment the Table Mountain Group (TMG) aquifer system that has a potential for bulk water supply in the Western and Eastern Cape provinces. As an important basis for the hydrogeological settings, aquifer properties, groundwater storage, and circulation, it is necessary to understand the geological background of TMG. The Table Mountain Group comprises hard resistant quartzitic sandstones that form the mountain ranges that flank the north-trending river valley in the east. The rocks have been folded and faulted, giving them their secondary water-bearing features i.e. groundwater recharge occurs via fractures and faults.

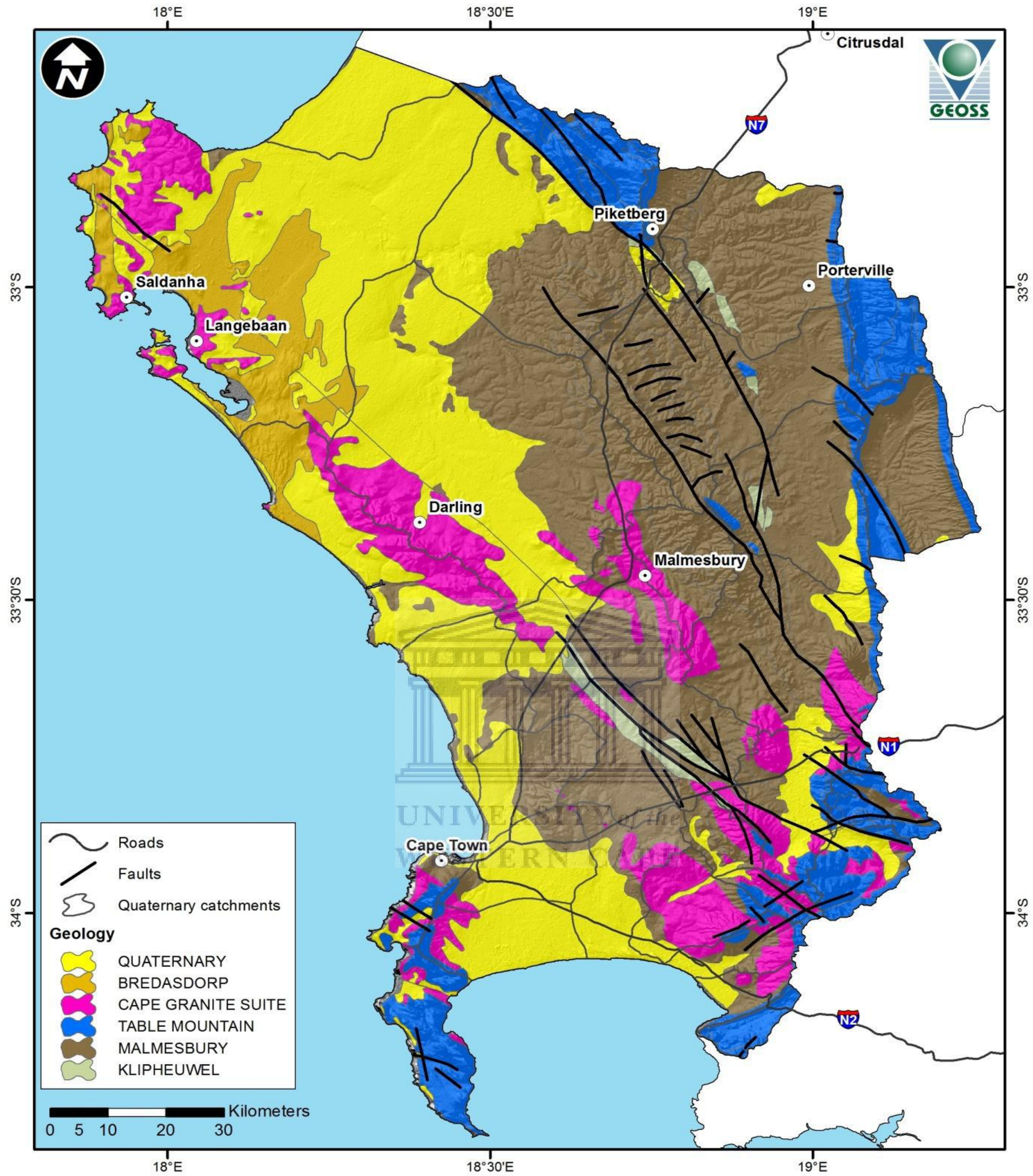


Figure 4: Geological setting of the Berg River catchment (DWA, 2007)

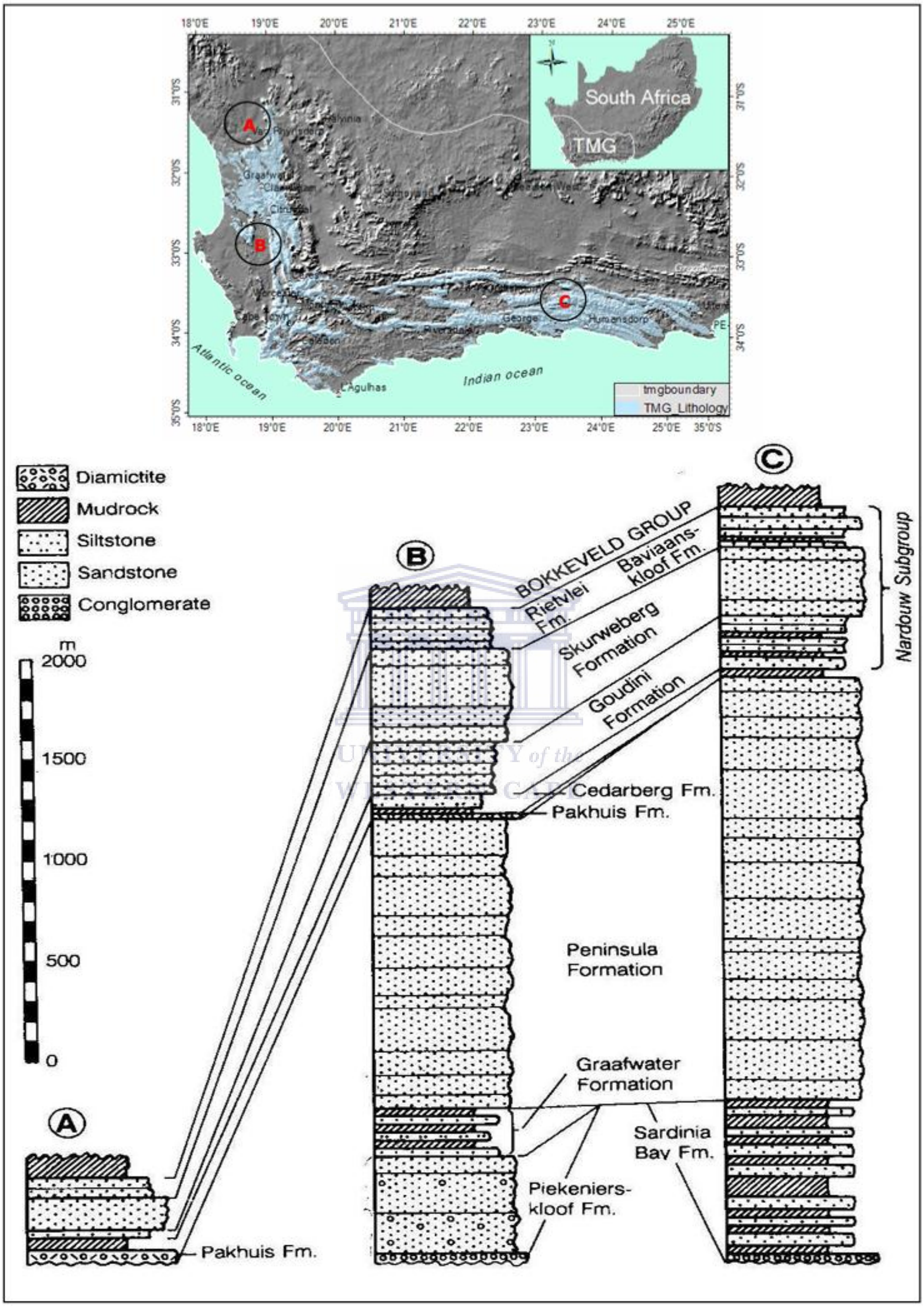


Figure 5: Stratigraphic subdivision and its location of the Table Mountain Group (From Albhaisi, 2013)

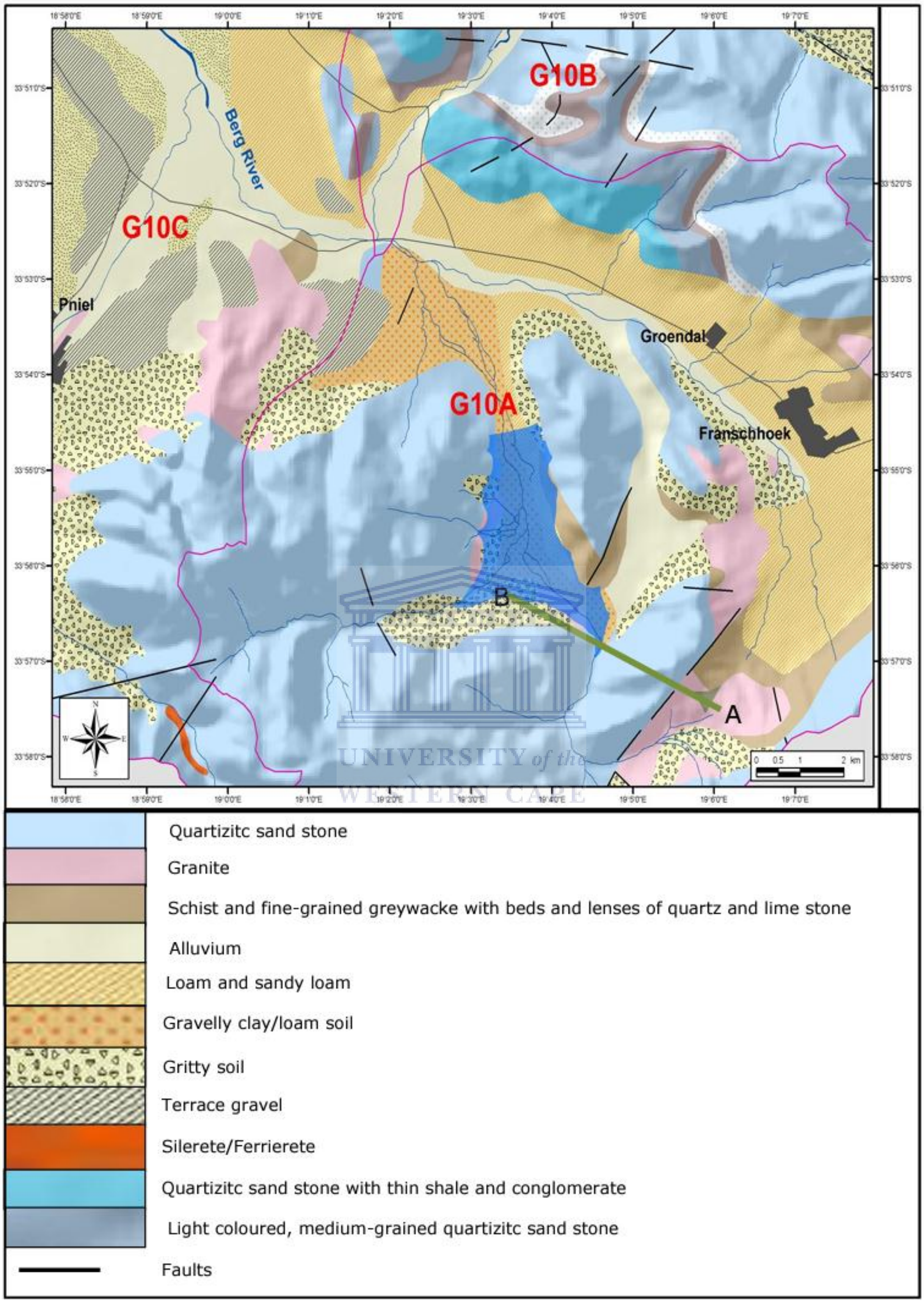


Figure 6: Local geology of the upper Berg River catchment (From DWAF, 2007)

The total mean annual runoff (MAR) generated in the upper Berg River catchment amounts to 137 MCM/a which constitutes about 20% of the total runoff in the Berg River catchment of 913 MCM/a. High runoff reduces recharge to groundwater.

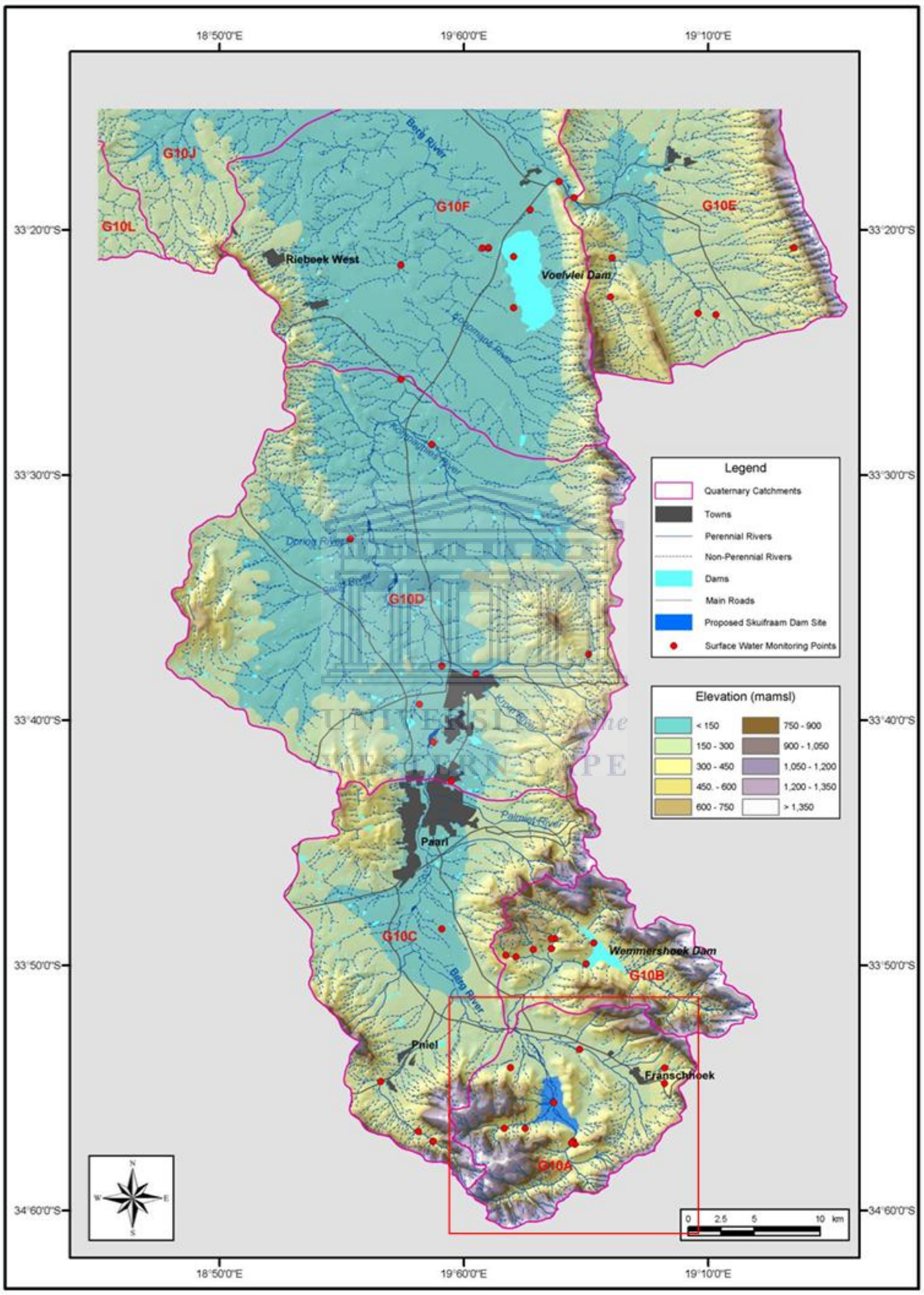


Figure 7: Hydrology of the Berg River catchment (DWAF, 2007)

2.2.2 The conceptual understanding of recharge processes

It has been stipulated that before a quantitative evaluation of recharge can be made in a specific area, a conceptual model has to be built. A conceptual model of recharge process attempts to answer the questions of how, where, when, and why recharge occurs (Healy, 2010). The model identifies the prominent recharge mechanisms and provides initial estimates of recharge rates, and serves as a guide for the selection of methods and decides on the location and time frames for data collection (Healy, 2010). The accuracy of groundwater recharge depends on the correlation of the conceptual model to the actual physical model. The conceptual model of area of interest is characterized on the basis of climate, geology and soil type. The present study is focused in mountainous area dominated by sandy loam soils with fractured sandstone aquifer. The sandstones form the Table Mountain Group that comprises hard resistant quartzitic sandstone that forms the mountain ranges. The hydrological processes that influence recharge in typical mountainous catchments are illustrated on the diagram below.

Groundwater recharge can be classified as (i) direct or indirect recharge on the basis of the origin of the recharging water, (ii) piston or preferential flow on the basis of the flow process through the unsaturated zone, (iii) point, line or areal recharge on the basis of the area on which it acts, and (iv) present-day, short-term or long-term recharge on the basis of the time scale during which it occurs (Beekman et al., 1999; Lerner et al., 1999; Lerner et al., 1990).

The conceptual model of the upper Berg River is illustrated below. Key components of this conceptual model include multiple water flux pathways. Flux pathways featured are: 1. infiltration of water to fractured rocks, 2. groundwater discharge to surface runoff via springs and/or base flow, 3. shallow subsurface flow toward stream channels, 4. Fractured rock-interface flow to stream channels, 5. stream channel loss to fractured rock, and 6. loss of water via evapotranspiration.

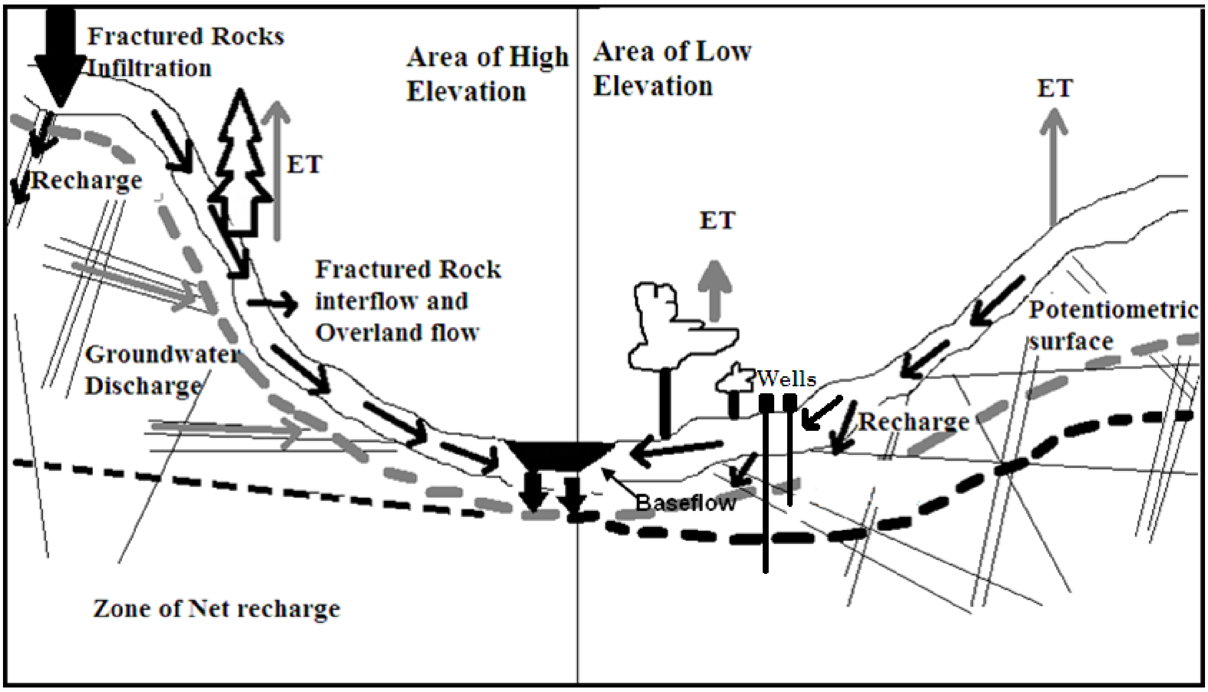


Figure 8: Conceptual model of the upper Berg River catchment showing groundwater recharge mechanism

In mountain region, in addition to the stochastic nature of rainfall, the precipitation pattern may be influenced by the irregular topography. The large variability in altitude; slope and aspect may increase variability by means of processes such as rain shading and strong winds. The mountain rages cause the air to be forced upward resulting in reliable mountain rainfall compared with the frontal plains (Bath, 1993). As a result of the orographisical influence of the mountain, a large spatial variability in the mean annual precipitation is experiences. Mountainous areas of the study area receive more rainfall than lowlands areas causing mountainous areas to be area of high groundwater recharge.

Based on the above observation at the upper Berg River catchment, the conceptual model for uBRc includes infiltration of precipitation thin sandy loam soil to fractured bedrock (sandstone), which is predicted to occurs primary in the catchment during cold wet winters. Steep slopes, however, are considered to facilitate development of lateral through flow and soil-bedrock interface flow towards stream channels when hydraulic connection develops within hill slopes, while groundwater may occurs within stream channels, particularly at higher elevations. The role of evapotranspiration in upper Berg River catchment is dominated by transpiration throughout vegetation growing season, with the greater amount of actual evapotranspiration occurring in the lower elevation where vegetation is denser. However, the percentage of precipitation being partitioned to evapotranspiration may be greater in lower elevation facilitated by less precipitation and warmer temperature.

The availability of recharge as a function of precipitation depends on many factors, but topography that focuses and concentrates runoff and storm duration and intensity are the major consideration (Wood and Bazuhair, 1995). It is generally accepted that the interaction of climate, geology, soil condition and vegetation determine to varying degrees of the process (Simmers, 1997; De Vries and Simmers. 2002). Determination of groundwater recharge in arid and semi-arid area is neither straight forward nor easy. This is a consequence of the time variability of precipitation in arid and semi-arid climate and spatial variability in soil characteristics, topography, vegetation, and land use (Lerner et al., 1990). The greater the aridity of the climate, smaller and potentially more variable in the recharge flux (Allison et al., 1994).

Groundwater recharge can be described in a broad sense as an additional of water to groundwater storage. Xu and Beekman, (2003), distinguished four main modes of recharge, such are: (1) downward flow of water through the unsaturated zone reaching the water table, (2) lateral and vertical inter-aquifer flow, (3) induced recharge from nearby surface water bodies resulting from groundwater abstraction and (4) artificial recharge such as from boreholes injection or man-made infiltration ponds. However, the study focuses on the first mode of natural recharge by downward flow of water through the unsaturated zone, which is generally the most important mode of recharge in arid and semi-arid areas.

Just as the net rainfall reaching the ground is reduced by interception (De Groen, 2002), not all percolating water necessarily reaches the water table. Nyagwambo, (2006), indicated that percolation may be hampered by low vertical conductivity horizons resulting in lateral flow to nearby depressions, similarly in shallow aquifer system local seepage may result in net recharge being lower than the total addition to the water table. Direct evaporation and transport from the saturated zone has a similar effect (De Vriesand Simmers, 2002).

Capillary rise is a mechanism that causes water to ascend from considerably deep water tables especially in arid and semi-arid. This capillary rise induced by deep rooted vegetation has been reported to cause upward fluxes of up to 1mm/year from depths ranging between 15m and 50m (Nyagwambo, 2006). Recently, vapour transport has been observed to produce considerable vertical fluxes in area where a temperature graduate exists. It has been reported by De Vriesand Simmers, (2002), that if a winter upward and a summer downward vapor transport flux of 0.2 to 0.3 mm per season due to a temperature gradient of $4C^0$ between the lower limit of the root zone at 3m depth and the 7m depth level. Since direct groundwater recharge is defined as the downward flow of water to the saturated zone, the capillary rise and vapour transport are some of the subtle considerations that may affect groundwater recharge processes.

3.2.3 Study sampling sites

The map bellow (figure 9) indicates all the sampling sites that were used in the present study in order to generate data. The map indicates all boreholes in light green dots, meteorological station with red dot and also rain gauges in yellow triangles.

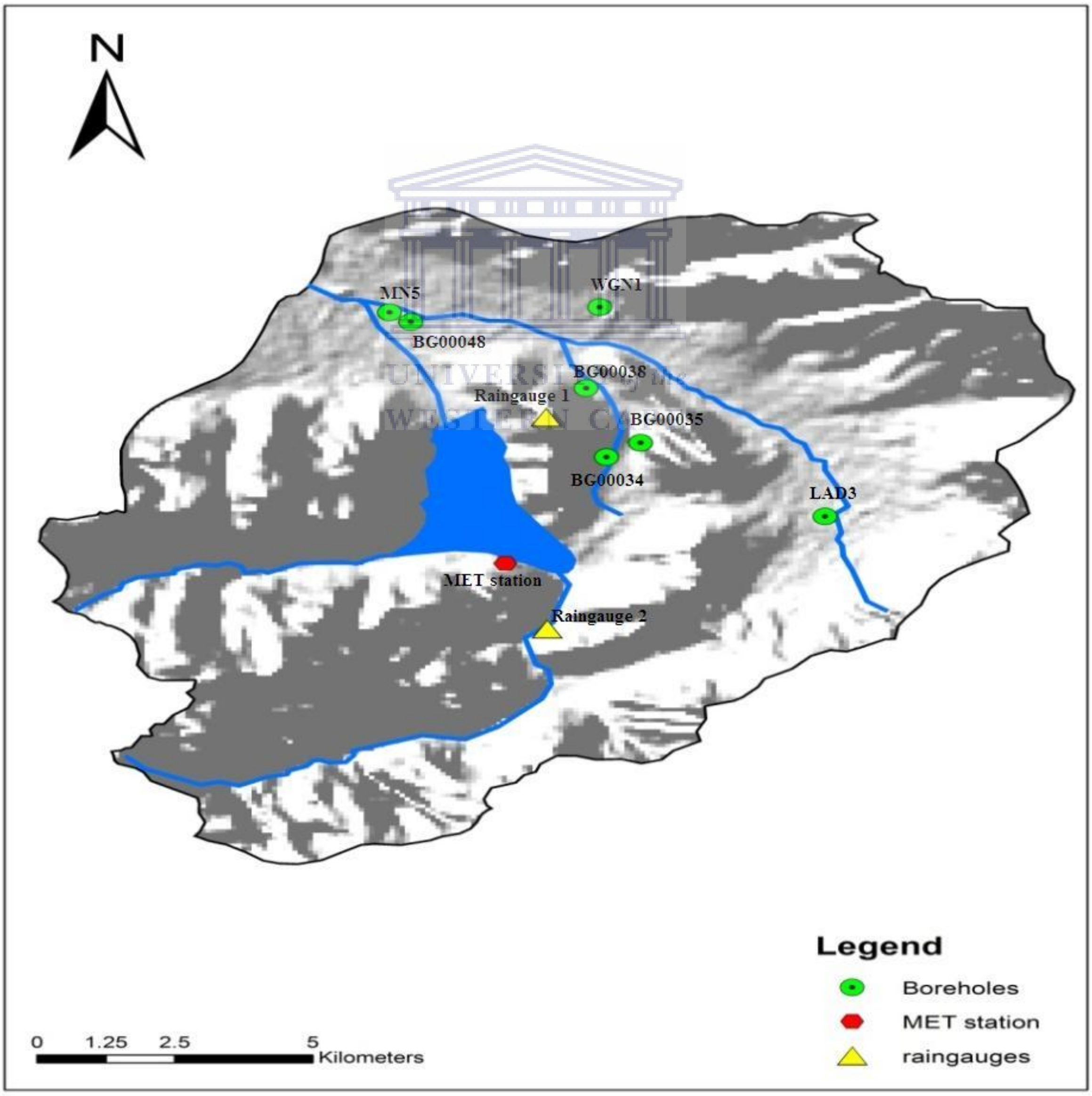


Figure 9: Location of sampling sites (boreholes and rain gauges) in the G10A catchment

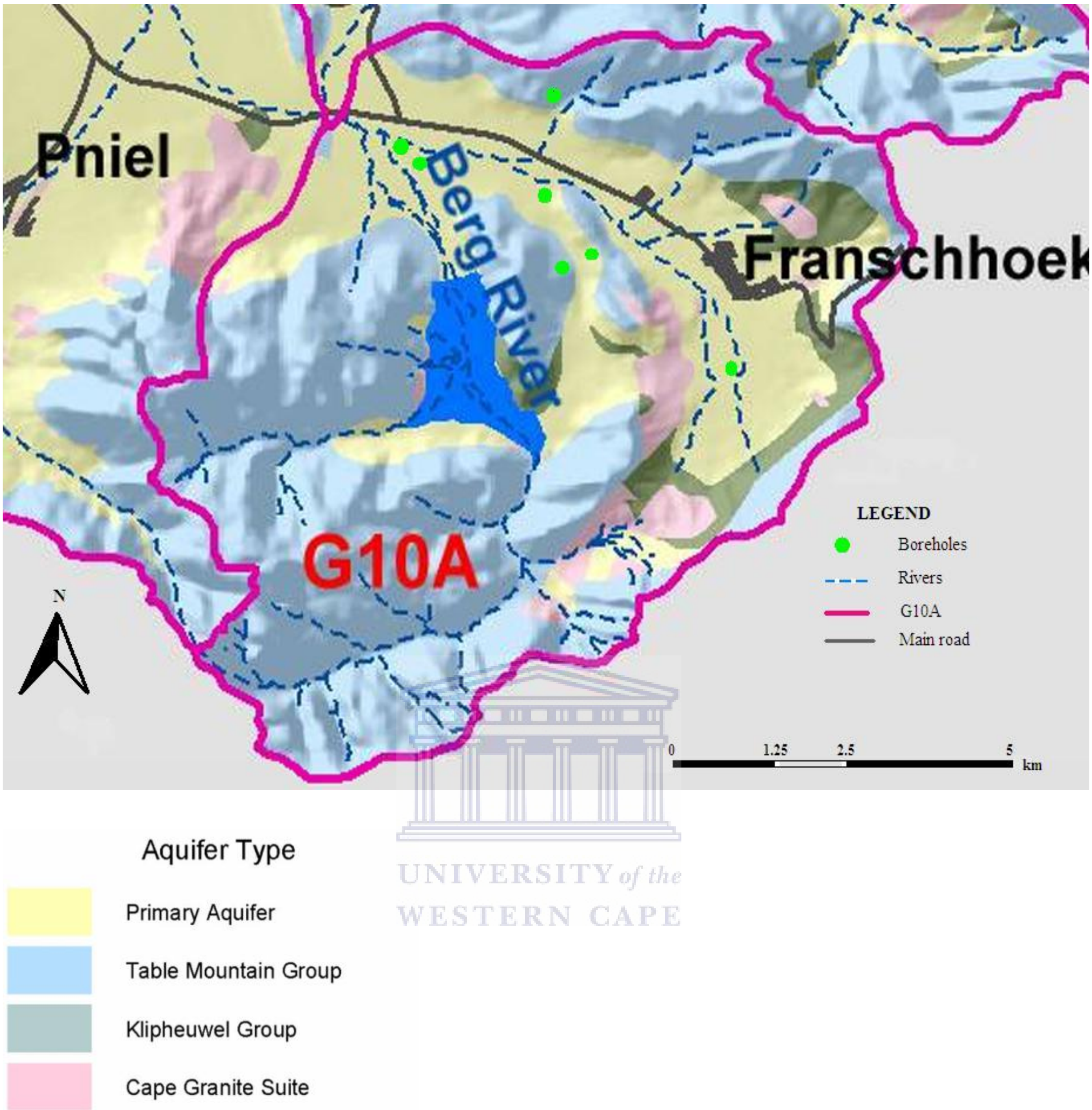


Figure 10: Locations of boreholes and intersecting aquifers

Figure 10 shows the locations of monitoring boreholes and their intersecting aquifers. Intersecting aquifers are the primary aquifer within the alluvium of the Franschhoek River valley and the Table Mountain Group Aquifer (TMG).

3.2.4 Study parameters and unit of analysis

The present study aims to quantify groundwater recharge using three methods i.e. the chloride mass balance, water table fluctuation as well as the rainwater infiltration breakthrough model. Therefore, recharge is the unit of analysis of the present study. In order to estimate this unit of analysis using these three methods, there are parameters that need to be measured. The chloride mass balance method requires three variables to be measured; such are annual precipitation, chloride concentration in rain water and chloride precipitation in groundwater. The second method which is the water table fluctuation requires data of the groundwater level in the unit area and also the specific yield of aquifer in that area. The third method is rainfall infiltration breakthrough, where groundwater level and rainfall data is required to run this model.

3.2.5 Sampling design

Because of data unavailability from boreholes a network of seven (7) monitoring boreholes that are representative of the study area were selected randomly among other boreholes located in the whole catchment (table 1). The upper Berg River catchment consist of two major aquifer system, the primary aquifer in the lower parts of the catchment and the Table Mountain Group Aquifer in the upper parts of the catchment. The selected monitoring boreholes are widely distributed in the catchment and all of them intersect with the major aquifer system of the catchment. These monitoring boreholes were sampled for groundwater physicochemical determination during the dry and the wet season. Six (6) monitoring boreholes (BH 34, BH 35, BH 38, BH LAD3, BH MN3, and BH WGN1) were sampled for groundwater chloride concentration and the seventh borehole was inaccessible for groundwater sampling and had no previous chloride concentration data, so this borehole was not considered for chloride mass balance estimations. Of the total of seven boreholes, three (3) monitoring boreholes (BH 34, BH 38, and BH 47) were selected for groundwater levels monitoring as required by the RIB model and the WTF methods. These boreholes were selected because they are equipped with automatic data loggers that measure the daily time series data; therefore, secondary data (daily time series) from previous years was available for these boreholes. These three monitoring boreholes are located away from the water bodies as required by the rainwater infiltration breakthrough model that the water level fluctuation from the monitoring boreholes should not be close to surface water bodies unless these sources and sinks can be quantified accurately.

There are three rain gauges installed in the upper Berg River catchment by the Department of Water Affairs (Table 2). These rain gauges were utilized to provide consistency with the upper Berg River catchment site. Only two rain gauges among the three were selected and used for precipitation chloride concentration data collection because of data availability and another rain gauge was used for rainfall data collection of the study area. Selection of the boreholes and rain gauges was done depending on the data availability.

Table 1: Sampled boreholes and their coordinates

Borehole No.	Monitoring Point Name	Coordinates	Intersection aquifer	Borehole depth (m)	Static water level (m)	Elevation (m)
BH 34	Roberts valley PTN Glenwood BG00034	-33.91694 S 19.0825 E	Table Mountain Group	39	2.5	258
BH 35	Roberts valley PTN Dassenberg BG00035	-33.91361 S 19.08806 E	Primary	36	10.0	264
BH 38	Keysersdrift PTN LA Motte forest station BG00038	-33.90083 S 19.07917 E	Primary	25	5.6	232
BH 47	Franschhoek forest reserve BG00047	-33.8832 S 19.0471 E	Primary	34	2.9	174
BH LAD3	Roberts valley PTN LA Dauphine LAD3	-33.9308 S 19.1182 E	Primary	_	22.0	280
BH MN3	LA Motte annex PTN Moreson MN3	-33.88541 S 19.05058 E	Primary	_	10.0	200
BH WGN1	LA Motte PTN Welgelegen WGN1	-33.88194 S 19.08139 E	Table Mountain Group	_	5.2	200

Table 2: Raingauges used and their coordinates

Raingauge No.	Coordinates
RB Vlei_RF Robertsvlei G1N0510_RF	-33.95705 S
	19.07288 E
Matoppi_RF Matoppi hill at BergRiver Dam GINP0006	-33.90761 S
	19.07268 E
Meteological station G1E006	-33.56302 S
	19.35768 E

3.3 Data collection methods

The use of chloride mass balance to determine annual groundwater recharge for a catchment requires a minimum of one year of data collection (Pamella, 2006). The present study involved one year of data collection in both dry and wet season of water year 2012-2013. The study year start or end date was selected to correspond with the start of the dry season or end of spring rain to assure the necessary zero chloride storage in the unsaturated zone.

3.3.1 Data type and data source

The data-base creation involved collection of existing data from archives and generation of new data from field campaign. Data was collected from the Department of Water Affairs and the South Africa Weather Station data base. Data collection was conducted as dictated by the parameter required by the chloride mass balance approach i.e. the annual precipitation volume (P), chloride concentration in precipitation (Cl_p), and chloride concentration in groundwater (Cl_{gw}). Types of data involve groundwater levels data, rainfall data, precipitation chloride concentration data and groundwater chloride concentration data.

3.3.2 Sampling methods, tools and procedures

All boreholes were pumped and let water run for about 20 minutes before water was collected into sample bottles and this is done to make sure that water collected for analysis is from the aquifer but not water that has stayed inside the boreholes for long time. Depth to water level was measured at a specific time before the pump was started. Sample bottles were rinsed three times before collecting groundwater samples and was then stored in a cooler-box. All groundwater sample bottles were labelled with borehole number and sampling time. Secondary groundwater levels time series data was obtained from the Department of Water

Affairs geoscience site. Groundwater levels were recorded using the time series data loggers that are installed in boreholes.

Rain water sampling was performed during the dry and wet season. Secondary data on precipitation chloride concentration was obtained from the Department of Water Affairs database. Rainfall data was recorded and downloaded every six (6) month by the DWA in one of the rain gauges installed in the catchment. Therefore, the secondary data of rainfall was also obtained from the Department of Water Affairs data base, and then the average annual precipitation volume was estimated.

Figure 11: Sampling techniques and tools

3.3.3 Samples analysis for groundwater chloride concentration

3.3.3.1 Instrumentation

The Inductively Coupled Plasma (ICP) system consisted of the Liberty 200 with the SPS-5 Auto sampler and Diluter, controlled by a Compaq 386/20e Computer. A V-groove nebulizer was used.

3.3.3.2 Technique used

The elemental analysis of solutions was undertaken by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The samples were nebulized then transferred to an argon plasma. It was decomposed, atomized and ionized to excite atoms and ions. The intensity of the light emitted when the atoms or ions return to lower levels of energy was measured. The element emits light at characteristic wavelengths and these lines can be used for quantitative analysis after a calibration.

3.3.3.3 Sample preparation

To analyse chloride in water samples, standard was prepared by dilution of 1000µg/ml single-element solutions with deionized water. The standard was made from NaCl. For chloride analysis, a calibration curve was made with four points, with the concentrations of standards 0, 5, 10, and 50mg/L. The operating conditions are listed in table below

Table 3: Operating conditions

Parameter	Condition
RF generator power	1000 W
Plasma gas flow rate	12 L/min
Auxiliary gas flow rate	0 L/min
Sheath gas flow rate	0.2 L/min
Nebulizer gas flow rate	1.2 L/min
Nebulizer flow rate	3 bars (45 psi)
Sample uptake	1 mL/min
Type of nebulizer	Concentric
Type of spray chamber	Cyclonic
Argon humidifier	Yes
Injector tube diameter	3.0 mm

3.4 Data analysis methods

A number of methods have been formulated for estimating groundwater recharge, such as direct measurement, Darcian approaches, tracer techniques, isotope dating, chloride mass-balance equations, analysis of baseflow hydrographs and spring discharges, water-table fluctuations, numerical modelling, Rainfall infiltration breakthrough, water budgeting (Gee and Hillel, (1988); Simmers, (1997); Sharma, (1989); Lerner et al., (1990); Allison et al., (1994); Stephens, (1996); Bredenkamp et al., (1995); Lerner, (1997); De Vries and Simmers, (2002); Xu and Van Tonder, (2001); and Scanlon et al., (2002). From all these methods, the present study chooses to utilize three methods i.e. chloride mass balance, water table fluctuation, and rainwater infiltration breakthrough. These methods were chosen because of their strengths regardless of their limitations regarding groundwater recharge estimation. These methods are briefly discussed below with their strengths and weakness.

3.4.1 Chloride mass balance (CMB)

Comparison of recharge estimation methods has shown that methods utilizing environmental tracers have been more successful for recharge estimation in arid regions than physical parameter methods (Allison et al., 1994; Phillips, 1994). Natural tracers used for recharge estimation include deuterium, tritium, oxygen-18, bromide, chloride and chloride-36 (Tyler and Walker, 1994; Gee and Hillel, 1988). Of these tracers, chloride has been utilized for mass balance estimation of recharge as simplest, least expensive and most universal (Allison et al., 1994). The use of chloride as a natural tracer in hydrologic investigations arises from its conservative behaviour and containment in water moving through a hydrogeologic system under average concentrations. Chloride is applicable to water balance investigations when concentration in system water occurs solely from exclusion during evapotranspiration processes.

Among notable outcomes in environmental chloride tracer studies, Wood (1924) hypothesized a relationship between increase in stream chloride and destruction of native vegetation in Australia, Anderson (1945), also in Australia, observed relationships between catchment ratios of stream discharge to precipitation relative to chloride concentrations, and Eriksson (1960) conducted analyses of stream chloride concentrations relative to atmospheric chloride, from which he hypothesized chloride impingement by vegetation. Also, in his 1960 study, Eriksson presented application of chloride to water budget analyses utilizing relative concentrations of precipitation and groundwater chloride concentrations and proposed the use of chloride concentrations for recharge estimation. This was followed by calculation of recharge rate on the coastal plain of Israel using CMB by Eriksson and Khunakasem (1969).

In arid and semi-arid regions, to determine the mean annual recharge using CMB, it is assumed that the only source of chloride input is from the rainwater and contribution from other sources such as human activities and weathering are neglected (Dettinger, 1989; Wood and Sanford, 1995; Gaye and Edmunds, 1996; Zagana et al., 2007).

The method is built on the conservative (non-reactive) and stable state of the ion chloride (Bromley et al., 1997) which is not uptaken by plants but its concentration in soil water can increase due to evapotranspiration. The recharge is then calculated in equation 3.1 as the product of annual rainfall depth to the ratio of the chloride concentration in rainwater and that in groundwater. The assumptions are related to the chloride origin considered solely from rainfall with no significant run-on or run-off occurring in the basin and the recharge flow process mainly vertical rather than lateral bypass flow (Bromley et al., 1997).

$$R = P. \ \frac{\mathrm{Clp}}{\mathrm{Clgw}} \quad \text{..} \quad (3.1)$$

Where R is the groundwater recharge flux (LT^{-1}); P, the average annual precipitation (LT^{-1}), Cl_p is the average precipitation-weighted chloride concentration (ML^{-3}) and Cl_{gw}, the average weighted chloride concentration in the basin groundwater (ML^{-3}). M is representing mass, T is time and L, length; all in consistent units.

The method cannot be applied in area underlained by evaporates or in areas where upcoming or mixing of saline water occurs. Its application is complicated in fractured rocks system because: additional chloride is produced through weathering of the rock matrix, time is needed to develop new equilibrium between rock matrix and fractures, if additional chloride is produced then recharge rates from CMB is considered minimum. Recycling of dried salt by wind, unaccounted runoff and uptake by harvested plants may also distort the results. The present study chooses to utilize this method on the virtue of the fact that its application is simple. It is based or requires the knowledge of annual precipitation and chloride concentration in precipitation and in groundwater. During evaporation the concentration increases, and the increase is a measure of the evaporation. Together with rainfall data, and under the assumption of negligible runoff, recharge can be computed. The method can be carried out in less sophisticated laboratories. It follows the chloride profile in the unsaturated zone, but can also be applied more readily to concentrations in the top layer of the saturated zone.

The assumptions necessary for successful application of the method are that:

1. There is no source of chloride in the groundwater other than that from precipitation,
2. Chloride is conservative in the system,
3. steady-state conditions are maintained with respect to long term precipitation and chloride concentration in that precipitation,
4. Precipitation is evaporated and/or recharged to groundwater with no surface runoff leaving the aquifer area,
5. No recycling of chloride occurs within the basin, and
6. No evaporation of groundwater occur upgradient from the ground water sampling points.

3.4.2 Water table fluctuation (WTF)

According to Sophocleous (1991), the main techniques used to estimate groundwater recharge rates can be divided into physical methods and chemical methods (Allison, 1988; Foster, 1988). Among the physical methods, the water table fluctuation technique (WTF) links the change in groundwater storage with resulting water table fluctuations through the storage parameter (specific yield in unconfined aquifer). This method is considered to be one of the most promising and attractive due to its accuracy, ease of use and low cost of application in semiarid areas (Xu and Beekman, 2003). The WTF method was first used to estimate ground water recharge and has since been used in numerous studies for the same purpose (Leduc et al., 1997; Moon et al., 2004) or groundwater storage changes estimation (Ruud et al., 2004).

The method may involve large errors, since the variation of groundwater storage is estimated from the calculation of the difference of other terms of the water budget involving much larger water volumes. However, this approach allows an average value for a large area rather than a local value to be obtained. The water table fluctuation method consists of calculating the ratio of water table rise to total rainfall (Risser et al. 2005) for all the registered events in

the analysed area. The height of water table rise measured after a rainfall event provides an estimate of the amount of open pore space available in the unsaturated zone (i.e. S_y).
The water table fluctuation method is based on the premises that the rise in the groundwater levels are due to recharge water arriving at the water table (Varni et al., 2013), with the assumption that the amount of available water in a column of unit area is equal to specific yield times the height of water in the column. Healy and Cook, 2002, showed the equation for calculating recharge which is given by:

$$R = \Delta S_{gw} = S_y \frac{dh}{dt} = S_y \frac{\Delta h}{\Delta t} \qquad (3.2)$$

Where R is the recharge; S_y is the specific yield of the aquifer; Δh, the water table rise and Δt, the time period within which the rise occurred. S_y is a dimensionless parameter while Δh, and Δt are respectively in consistent units of (L) and (T). Δh is expressed as the difference between the peak of the water level rise and the extrapolated antecedent recession curve at the time of the peak.

Recharge rates may vary substantially within a watershed because of deference in elevation, geology, vegetation and other factors. Data from multiple wells is used to ensure that recharge estimations are representative of the whole catchment. This method cannot be applied in regions where outflows and inflows in the system are equal, recharge is equal to zero. Difficulties in estimating specific yield contribute to overall uncertainty of the method. The present study uses this method because it is a straightforward and simple method, especially when a full cycle of water table variation is considered. No assumption are made on the mechanisms of water flow through the unsaturated zone, preferential flow path does not restrict the application of this method. Recharge estimates are representative of an area of thousands of square kilometre (km^2).

3.4.3 Rainfall infiltration breakthrough (RIB)

The RIB model simulates groundwater levels and it accounts for the manner in which recharge occurs (Ahmadi et al., 2012). This method was developed and applied by (Xu and Van Tonder, 2001; Sun et al., 2013). The RIB model uses the relationship between water level fluctuation and the departure of rainfall from mean rainfall of a preceding time.

If records of rainfall events are expressed as a time series: P_1, P_2, P_3…… P_n, a RIB (cumulative recharge from rainfall event *m* to *n*) can be defined as:

$$RIB(i)\,_{m}^{n} = r\left\{\sum_{i=m}^{n} Pi - \left(2 - \frac{1}{Pav(n-m)}\sum_{i=m}^{n} Pi\right)\sum_{i=m}^{n} Pt\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.5)$$

(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 rainfall event of m to n; I is the total length of rainfall series, while parameters m and n, introduced as memory markers, represent the start and end of a time series length, during which period rainfall events contribute to the breakthrough RIB(i); r is a fraction of cumulative rainfall departure; Pi 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 a threshold value representing the boundary conditions (P_t ranges from 0 to P_{av}).

Value of 0 represents a closed aquifer system, which means that the recharge at i_{th} time scale only depends on preceding rainfall events from P_m to P_n; while value of Pav represents an open system, which means that the recharge at the i_{th} time scale depends on the difference between the average rainfall of preceding rainfall events from P_m to P_n and the average rainfall of the whole time series). Both r and P_t values are determined during the simulation process.

The equation below describes a linear relationship between RIB and water level fluctuation under natural conditions. The relationship between rainfall and water level fluctuation can be described as:

$$\Delta h_{i} = \left(\frac{1}{S}\right) * \left(RIB(i)_{m}^{n}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.5)$$

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 is the storativity of the aquifer.

Assumptions and rules for applying the RIB method

The water level fluctuations from the monitoring borehole should be representative of the study area; the term groundwater abstraction (Q_p), flow (Q_{out}) and volume changes (Q_{oth}) could be ignored if the impact of pumping and/or outflow on WTF is not evident; the specific yield should be representative of the aquifer system; it is usually applicable where transmissivity is relatively small, and where the water level responds clearly to rainfall and where suitable time series of rainfall and groundwater level are available.

The method is user friendly and requires only few spatial data for groundwater recharge estimation. The RIB method can be used to estimate either groundwater recharge or aquifer storage. The method provides a better opportunity for explaining the occurrence of recharge under different conditions. The RIB method fails to explain the condition where the continuous departures are negative and yet the observed water levels may still rise, and the physical meaning of parameter *r* representing the recharge percentage and previous RIB method is problematic. However, the present study choose to use this method because different scenarios can be simulated to estimate the water level fluctuation and calculate groundwater recharge with different rainfall and abstraction inputs, which could provide valuable information to water manager.

3.4.4 Estimation of specific yield

To apply the WTF and RIB method, an estimation of the specific yield (S_y) at the depth of water table fluctuation is required. Methods commonly used to determine S_y are laboratory methods, aquifer tests, water-budget methods, water table response to recharge and linear regression. The present study uses the aquifer tests and linear regression methods to estimate S_y and also compare the value with values obtained from previous studies.

Aquifer test provide measurements of Sy integrated over relatively large area, depending on the distance between observation wells and pumping well therefore the specific yield is given by:

$S_y = V_w/V_c$………………………………………….. (3.4)

Where V_w is the volume of water pumped out of the system at some point in time and V_c is the volume of the cone of depression at that time (Clark, 1917; Wenzel. 1942).

To estimate Sy, a graphical procedure was proposed: a graph of rainfall values is plotted against water table fluctuations. The inverse of the slope of a line drawn through the origin to just above all of the measured points gives the maximum value of the specific yield. This Sy estimation method was chosen because it provides a robust Sy value due to the long data record. This method is equivalent to calculating the precipitation–groundwater rise ratios of all measured events and selecting the smallest value, but the graphical method has the advantage of clearly displaying whether there are several points near the minimum value of Sy, or if there is one point far from the rest that needs to be revised. Methodologies such as Sophocleous's (1991), that combine a Darcian soil water balance with the WTF method, could have improved the estimation, but unfortunately there is no historical information (neutron probe and tensiometer data) to do so. The total annual declines in groundwater level were calculated and the relationship between these and the mean annual groundwater level were analysed. Relationships between recharge and other basin budget variables were also analysed (Varni et al., 2013).

3.5 Data quality assurance

All necessary procedures were undertaken during samples and data collection. To improve the data quality, data quality assurance was undertaken as the process of profiling the data to discover inconsistencies and other anomalies in the data after samples analysis, as well as performing data cleansing i.e. removing outliers and also missing data interpolation using the Microsoft Excel software. This was done to verify the reliability and efficiency of the data. The aspects of data quality include accuracy, completeness, relevance, reliability and appropriate presentation. Above all, data quality assurance was done to avoid groundwater recharge estimates errors.

3.6 Statement of ethical consideration

Some of the boreholes that were sampled during this study are located in the farms where I need to have consent for access. Therefore, in order to sample I must first get the permission from the owner of a specific farm where the boreholes are located. There are other boreholes that are located behind the Berg River dam wall and the area is fenced and sometimes the gate is locked so we must first go get the keys from the Department of Water Affairs.

3.7 Study limitations

Study time was limited because data collection and data analysis require more time. The main limitation of the study was the challenge that was faced when estimating the specific yield of an aquifer at the depth of the zone of the water table fluctuation when applying the WTF and RIB methods of estimating groundwater recharge. The pumping test method of estimating specific yield is the most used method, but due to limited resources (unavailability of resources needed for conducting pumping test and inaccessibility of other boreholes in the catchment) pumping test was conducted in one borehole located in the area of study and this limits data availability and might affect groundwater recharge estimates. Unavailability of advanced laboratory instruments for analysing chemical parameters in the department had limitation for the present study. Some of rainwater and groundwater samples had to be taken to private laboratory for analysis. This took time needed for writing up and for data interpretation because samples took time before they are brought back from the laboratory. More data on groundwater chloride is significant in studies like this one. I had to collect groundwater samples following the sampling time table from the Department of Water Affairs because I did not have access to other boreholes and I also did not have other resources needed for pumping test. As a result data from groundwater was limited.

Chapter 4: Recharge estimation using chloride mass balance

4.1 Introduction

The current chapter presents and discusses results on the estimation of natural groundwater recharge using the chloride mass balance method. This method was used to estimate the amount of precipitation partitioned to groundwater recharge during dry and wet season. The argument in the present chapter is that the chloride mass balance method can be used to estimates recharge to groundwater at quaternary catchment level and such estimates can be used as indicator of groundwater availability and therefore can be used during water resource assessment and planning. Chloride mass balance can therefore be used in quaternary catchment of similar physiographic and hydrologic conditions as that of upper Berg River catchment where it was tested.

Recharge estimation using the chloride mass balance method is based on the premise that a known fraction of chloride in precipitation and dry-atmospheric deposition is transported to the water table by the downward flow of water (Sumioka and Bauer, 2004). Recharge estimates are obtained from measurement of the concentration of chloride directly associated with the recharging waters. The method is based on the assumption that precipitation is the only source of chloride concentration in groundwater and also based on other assumptions necessary for successful application of the method (as indicated in chapter 3.5.1). Therefore, this chapter highlights all the groundwater recharge estimates obtained using chloride mass balance method in the upper Berg River catchment and discusses the results in comparison with results from previous studies or other methods.

4.2 Recharge estimation using chloride mass balance

In arid and semi-arid regions, to determine the mean annual recharge using CMB, it is assumed that the only source of chloride input in groundwater is from the rainwater. It is based on or requires the knowledge of annual precipitation received and chloride concentration in that precipitation as well as chloride concentration in groundwater in area where that precipitation is received. Therefore, groundwater recharge in the area of interest can be estimated.

4.2.1 Precipitation for upper Berg River catchment

Precipitation refers to any form of water, liquid or solid falling from the atmosphere and reach the ground. It includes rain, sleet, snow, hail and drizzle plus a few less common occurrences such as ice pellets, diamond dust and freezing rain. In the present study area the only data available is of rainfall. Therefore, in the present study precipitation refers to rainfall. The figure below shows the monthly rainfall received in the upper Berg River catchment.

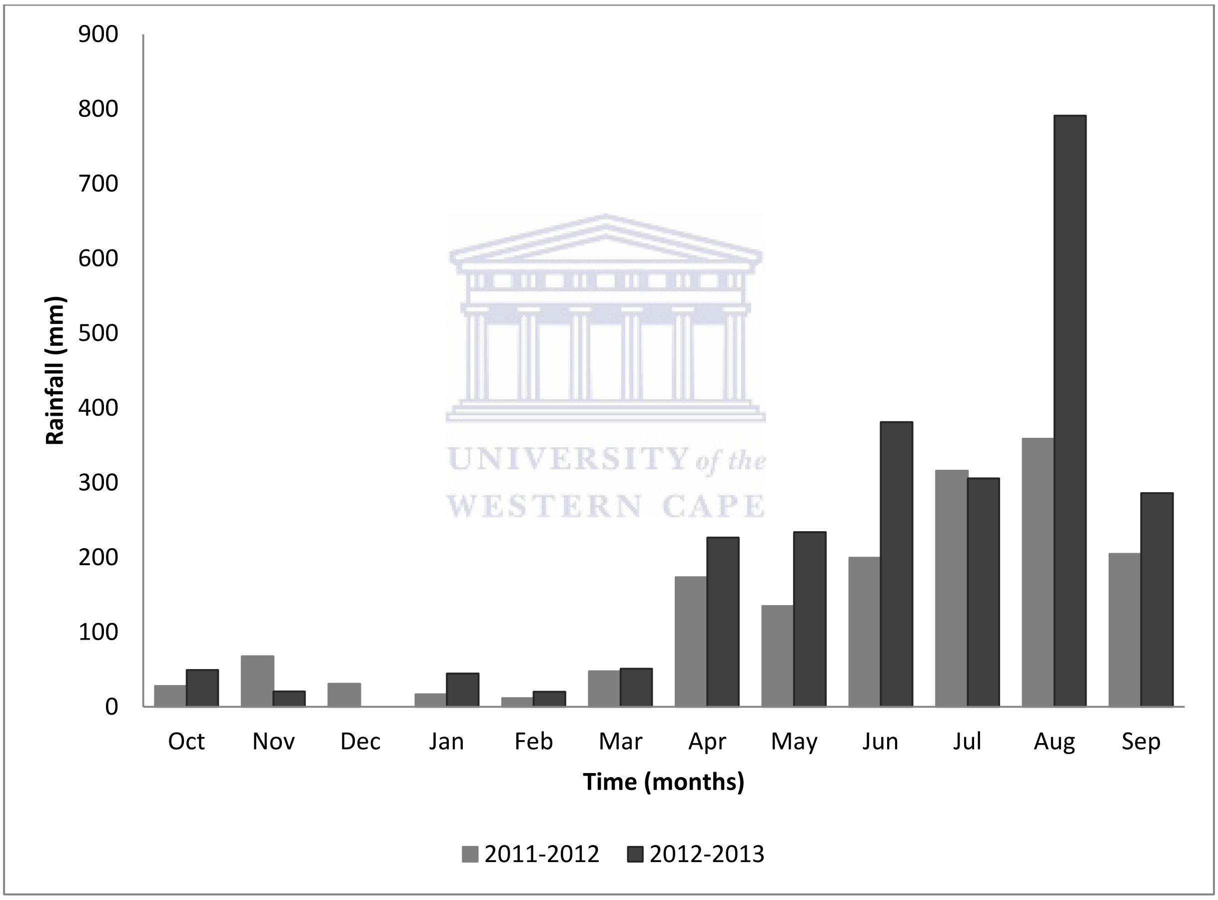


Figure 12: Trend of monthly precipitation received in the upper Berg River catchment for water years 2011-2012 and 2012-2013

Figure 12 shows the monthly precipitation received in the study catchment. The figure indicates significant differences occurred in quantity and timing of precipitation received during water year 2011-2012 versus water year 2012-2013. Precipitation received is 65% less during the first water year (2011-2012) compared to the second study year (2012-2013). Maximum monthly precipitation occurred in August for both water years, whereas the minimum monthly precipitation occurred in December for study year 2012-2013 and in February for study year 2011-2012. The study year 2012-2013 value represents a greater depth of annual precipitation received during the year on record.

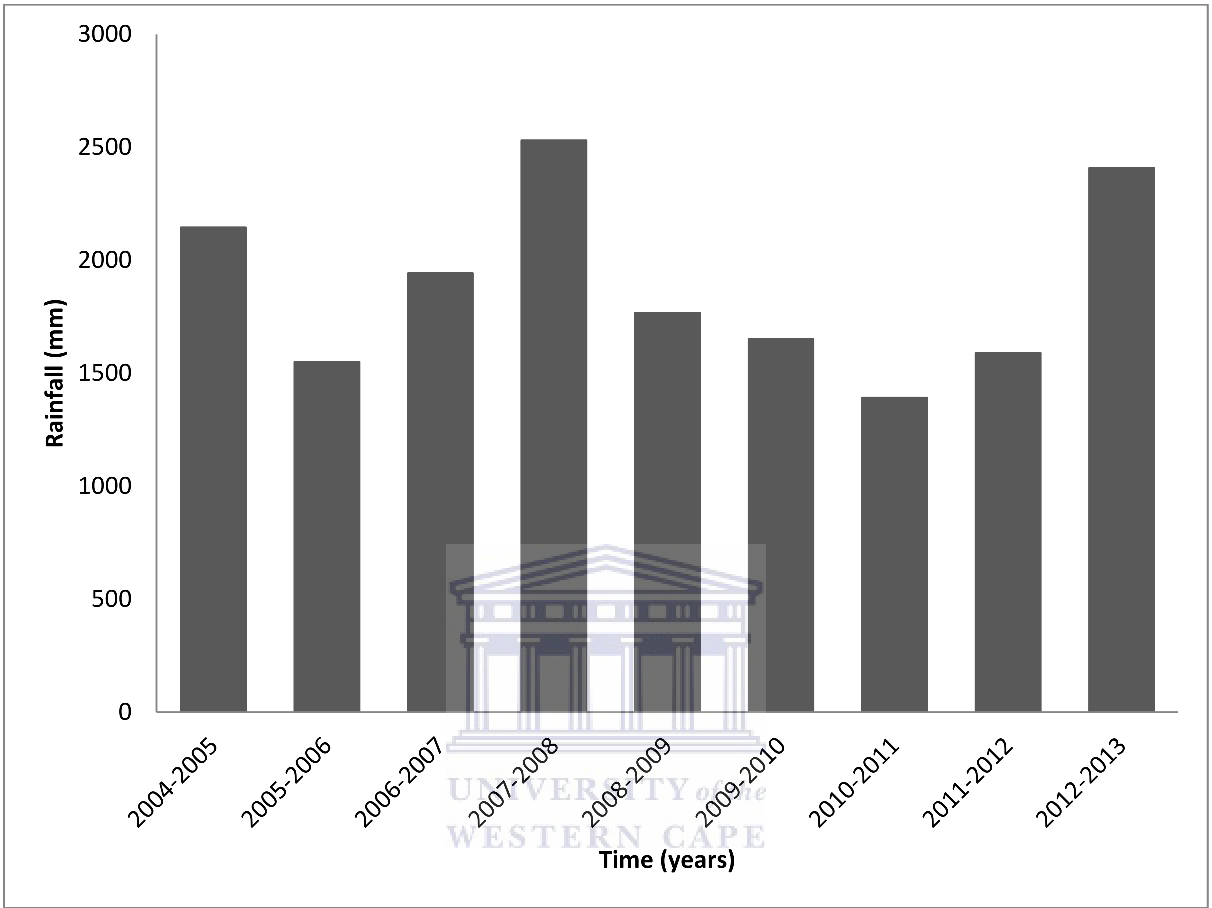


Figure 13: Trend of annual precipitation received in the upper Berg River catchment from 2004 to 2013

Figure 13 shows the water years variation of rainfall received in the catchment. The water years rainfall in this area does not change significantly over the years and in most occasions, rainfall ranges between 1500 and 2500 mm/year (DWA, 2007). The maximum rainfall intensity recorded in the catchment amounts to 2530.1 mm/year recorded in water year 2007-2008 and the minimum rainfall intensity recorded was 1391.6 mm/year recorded in water year 2010-2011. The annual rainfall received in water year 2012-2013 was 2409 mm/year.

4.2.2 Groundwater chloride concentration in upper Berg River catchment

Concentration of groundwater chloride as one of the parameters required by the chloride mass balance in the present study was measured in groundwater for the six (6) randomly selected monitoring wells. The graph below indicates the chloride concentration in groundwater during wet and dry season in the upper Berg River catchment. However, the average chloride concentration per borehole was calculated without considering the possibility of outliers or other impacts on chloride estimation. Although the assumption states that precipitation is the only source of chloride in groundwater, there are other sources that can influence concentration of chloride in groundwater such as irrigation water, pesticides and fertilizers.

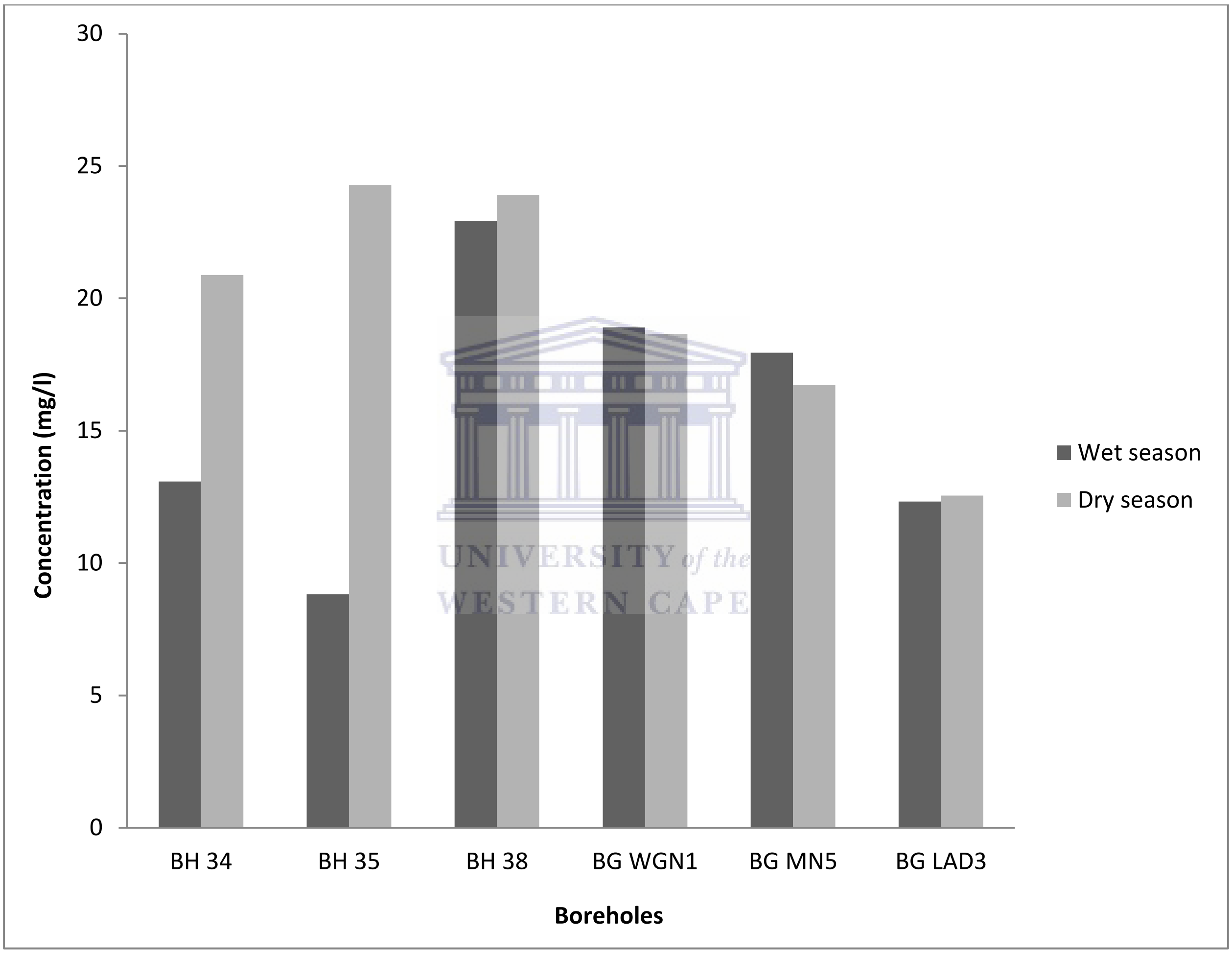


Figure 14: Chloride concentration in groundwater during wet and dry season

Previous studies (Nyagwambo, 2006; Obuobie, 2008; Boerner and Weaver, 2012) indicated that low chloride concentration suggests higher recharge and higher chloride concentration indicates low recharge. This is depicted in the inverse relationship of recharge rate and chloride concentration in groundwater in equation 3.1 (page 54). Figure 14 shows the variability of groundwater chloride concentration in the present study area. The graph shows the concentration of chloride being higher in boreholes located in mountainous area during the dry season with the highest amount of 24.276 mg/l and the lowest in this area being 12.553 mg/l. Monitoring boreholes located in areas of high elevation found to have low levels of chloride concentration during wet season. This suggests that the highest rates of recharge to groundwater in the study area in water year 2012-2013 occurred in areas represented by these boreholes. The highest groundwater chloride concentrations were measured in water samples taken from monitoring boreholes located in lower elevation areas.

The figure 14 shows that concentration is lower during wet season and higher during dry season. There are samples collected from irrigation wells (BG WGN1, BG MN5 and BG LAD3). These wells indicate an elevated groundwater chloride concentration because of the land use taking place. Several studies have also shown elevated concentrations of chloride in aquifers related to urban land use (Grady and Mullaney, 1998; Fong, 2000; Thomas, 2000; Savoca and others, 2000). During wet season, the highest chloride concentration is 22.914 mg/l and the lowest is 8.818 mg/l. This graph shows high concentration of groundwater chloride in areas of high elevation than in areas of low elevation during dry season and the concentration is lower during wet season in mountainous areas (BG 38 with values of 22.914 mg/l in wet season and 23.905 mg/l in dry season; BG 34 with values of 13.079 mg/l in wet season and 20.876 mg/l in dry season; and BG 35 with values of 8.818 mg/l in wet season and 24.276 mg/l in dry season).

This suggests that the highest rates of recharge to groundwater in the study area in water year 2012-2013 occurred in areas indicated by boreholes located in mountainous area where the concentration of chloride in groundwater is low and such recharge occurs during wet season. Rise and Crilley (2014) and Ping et al, (2014) obtained similarly low values from wells located in mountainous area in the East Mountain Area, Eastern Bernalillo County and in a semi-arid mountain terrain, South Interior British Columbia, Canada. This is also supported by records of groundwater level and recharge estimated by Obuobie (2008) in the White Volta River Basin, West Africa. High chloride concentrations in groundwater are generally associated with lower rates of recharge and vice versa.

4.2.3 Rainfall chloride concentration in upper Berg River catchment

Concentration of rainfall chloride is also one of the parameters required by the chloride mass balance in the present study and was measured from rainwater collected in two rain gauges that were selected randomly. The graph below indicates the concentration of chloride in precipitation for those two rain gauges.

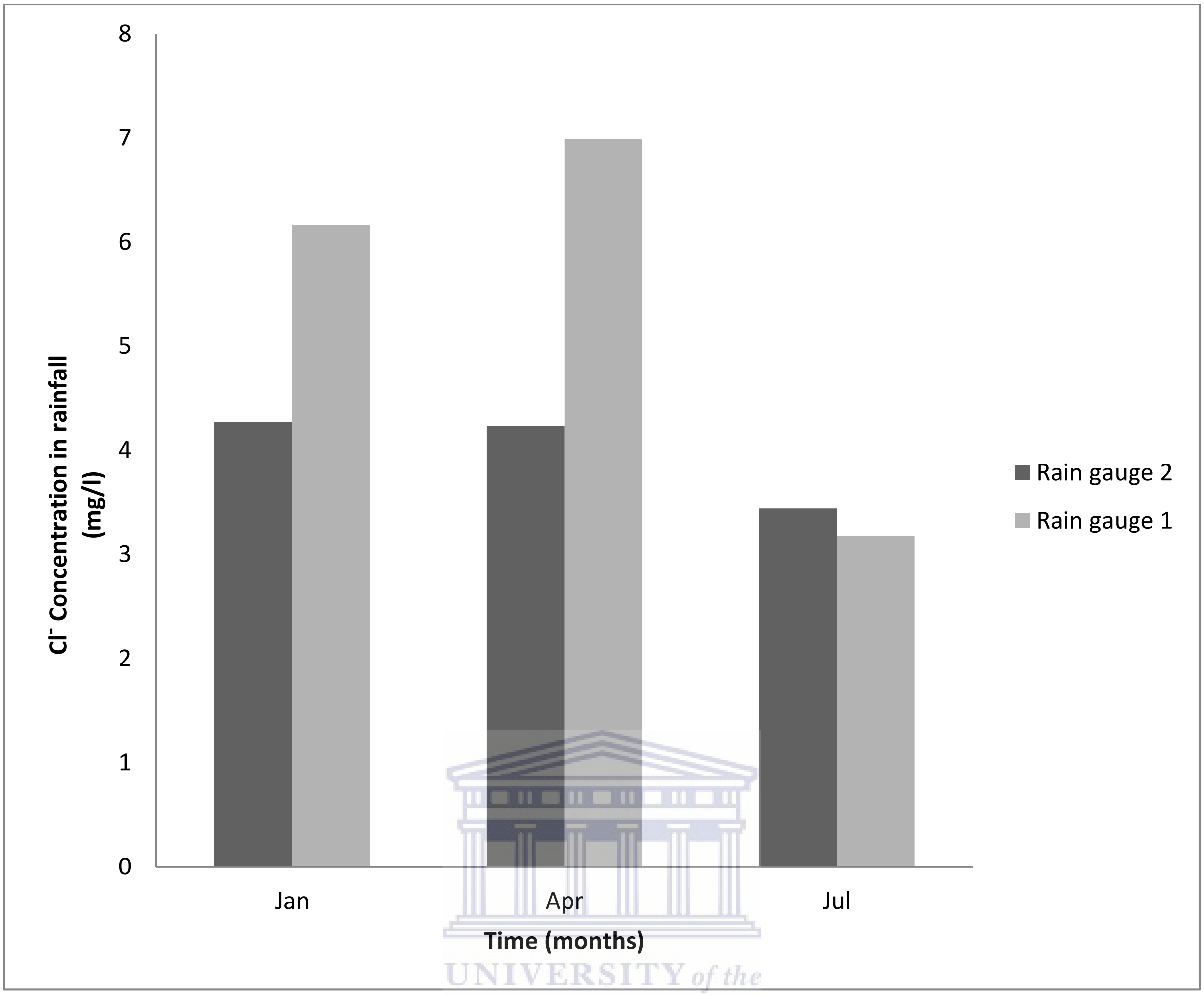


Figure 15: Concentration of chloride in precipitation from two rain gauges in the catchment

The concentration of chloride in precipitation is shown in figure 15, with the highest concentration amount of 6.99 mg/l and the lowest amount of 3.179 mg/l in rain gauge number 1 with an average chloride concentration of 5.445 mg/l. It showed the highest concentration amount of 4.273 mg/l and the lowest being 3.44 mg/l in rain gauge number 2, with an average chloride concentration of 3.984 mg/l. The total average of 4.7145 mg/l chloride concentration was estimated from these two rain gauges representing the total chloride concentration of precipitation received in the area of study. These results shows that the concentration of chloride for the rainwater collected in rain gauge located in high elevation is lower than the concentration of chloride for the rainwater collected in rain gauges located at the lower elevation. Ping et al, (2014) also obtained the same results that the chloride concentration in precipitation in mountainous areas is typically lower than at the valley bottom.

High chloride concentrations were measured in dry season in the month of January and April. At all the rainwater sampling locations, the lowest concentrations were measured in July. Generally, monthly chloride concentrations in rainfall decreased with increasing rainfall amounts. This agrees with the inverse relationship between rainfall amount and chloride concentration in rainfall as depicted in equation 3.1. When comparing these measurements with measurements obtained in areas with similar climate, chloride depositions in the study area are reasonable and acceptable. Generally, figure 15 indicates that chloride deposition is high during dry season and lower during wet season. Obuobie (2008) also obtained the same results that the lowest concentrations at all sampling locations were measured during rainy season (winter). Obuobie (2008) study concluded that the monthly chloride concentrations in rainfall decreased with increasing rainfall amounts.

4.3 Recharge estimates of upper Berg River catchment

Using the parameters estimated in the above section recharge rates were calculated using equation 3.1 ($R = P.\ \frac{Clp}{Clgw}$). The overall groundwater recharge for the study area was calculated based on the recharge values of the individual wells and the area weight of the wells. The recharge value of each of the six (6) wells sampled for chloride analysis was estimated using the area-weighted mean chloride concentration in rainwater (4.7145 mg/l), the long-term mean annual rainfall in the study area (2409 mm) and the mean chloride concentrations in groundwater (Table 4, page 68).

Table 4 indicates the recharge estimates from all the study boreholes of study water year 2012-2013. The chloride mass balance method indicates that the upper Berg River catchment experienced recharge ranging between 484.68 to 912.41 mm, representing 20.1 % to 37.8 % of the total precipitation received in the catchment, with mountainous areas receiving high recharge estimates.

Table 4: Average groundwater recharge estimates from chloride mass balance

Site	Annual precipitation (mm/year)	Groundwater cl^{-1} concentration (mg/l)	Precipitation cl^{-1} concentration (mg/l)	Groundwater recharge (mm/year)	Groundwater recharge (%)
BH 34	2409	16.9775	4.71	668.31	27.7
BH 35	2409	16.547	4.71	685.70	28.4
BG LAD3	2409	12.4355	4.71	912.41	37.8
BH 38	2409	23.41	4.71	484.68	20.1
BG MN 5	2409	17.3345	4.71	654.55	27.1
BG WGN1	2409	18.779	4.71	604.20	25

4.4 Discussion of results from chloride mass balance method

The overall mean groundwater recharge was estimated to be 668.31 mm, representing 27.73 % of the total mean annual rainfall. The recharge estimate obtained in this study is similar to estimates from groundwater recharge studies done elsewhere in the catchment and the whole of the Western Cape, using the chloride mass balance method. For example, Adelana (2010) used multiple recharge estimation methods, including the WTF and CMB method to the Cape Flats of Western Cape, in 2005 and estimated the recharge to be from 17.3 to 47.5 % of the annual rainfall. Similarly, Department of Water Affairs (2003, 2004) applied the chloride mass balance method in the upper Berg River catchment and estimated the recharge to be 18 % of the annual rainfall in 2003 and 28 % of the annual rainfall in 2004. However, the reliability of the values can be improved if long-term data on chloride deposition are used instead of the one-year mean values used in the present study. Data on long-term mean chloride deposition in the study area do not exist. Nevertheless, findings from the present study provide insight on the recharge pattern and align with the previous studies.

A number of groundwater recharge values have been calculated on studies carried out on the South African west coast in the primary aquifers. Vandoolaeghe and Bertram (1982) calculate a groundwater recharge rate of 26% of the total rainfall (380mm/a) for the Atlantis using the water balance method. Bredenkamp and Vandoolaeghe (1982) calculated a recharge rate of 25% (rainfall of 380mm pa) also using a water balance method. These results agree with results of the present study from the virtue of the fact that the aquifers of interest are high yielding aquifers (Atlantis and Table Mountain Group aquifers). The Atlantis aquifers consist of the sedimentary deposits, especially of Quaternary age, that vary greatly in composition and grain size from peaty deposits (with a high clay and mud component), through to course, well rounded sand and gravel deposits. Where these coarse-grained deposits occur, and especially where they have been deposited in eroded valleys and large, saturated thicknesses, they have resulted in the occurrence of high yielding aquifers with high groundwater recharge potential. The Table Mountain Group also hosts fractured aquifers systems that are well developed resulting in high groundwater recharge potential.

Groundwater recharge estimate of the present study are higher than groundwater recharge estimates obtained in a study that was conducted by Sun et al, (2013) in the Table Mountain Group aquifer in the West coast, in Western Cape of South Africa. They obtained groundwater recharge estimate of 183.7 mm/a, representing 17.46 % of the mean annual precipitation. However, they have used water level data recorded from only one borehole in the area to calculate recharge to groundwater. Nyagwambo (2006) indicated that no single point measurement of recharge is a good indicator of regional recharge. Therefore, their groundwater recharge estimate is not a good representative of their area of interest. Their results need to be re-evaluated using more boreholes. The present study has used data from at least six boreholes located in the study area to make recharge estimates realistic.

The present study was weak compared to the study done by Ping et al, (2014) in terms of the study design. In the present study, data from only six (6) monitoring boreholes were used for groundwater chloride concentration and only two rain gauges were used for annual precipitation data and precipitation chloride concentration data that have been recorded in the Department of Water Affairs data base. No data on dry deposition was used in the present study during recharge estimation. However, in the study done by Ping eat al, (2014) both dry and wet deposition were collected from the total of eight (8) of the 74 location consisted of measures of both wet and dry deposition in the area. Moreover, the totals of 42 groundwater samples were collected for geochemical analyses and an additional of 34 historical groundwater chemical analyses from other from the area of interest. In their study they have used both primary and secondary data in order to strengthen their groundwater recharge estimates. Therefore, their groundwater recharge estimates are more realistic compared to groundwater recharge estimates of the present study.

The use of multiple boreholes for groundwater samples collection in recharge study is more significant. Boreholes must be selected in numbers in order to represent the whole area of interest. Because of limited data availability for boreholes located in the study area, groundwater chloride concentration data from only six monitoring well were used and only two rain gauges were used for annual precipitation data and precipitation chloride concentration data. This limits the reliability and reality of the groundwater recharge estimates.

The locations of six borehole sites for the chloride mass balance analysis were not optimally chosen. It is uncertain that they were absolutely not influenced by nearby irrigation works. Where irrigation was applied on the site, the amount and exact chloride content of irrigation water was unknown. This approach requires a careful determination of irrigation application and monitoring of chloride inputs from other sources. Not all the chloride in precipitation percolate and reach the groundwater table, other chloride is lost via runoff. Therefore, if the value of chloride concentration in runoff water is known it can therefore subtracted from the total rainfall. Rofe and Raffety (1965) estimated the West bank recharge by subtracting the average annual runoff value from the total rainfall.

4.5 Chapter summary

A proper understanding of computing recharge value is crucial to assessing groundwater availability efficiently. In this chapter, we have showed calculation of average groundwater recharge value which is the estimate but which provides a basis or insight on groundwater recharge for the study area. Such results have been compared with other scholars who obtained similar estimates. Good estimates of groundwater recharge is not an end in itself but must be viewed on the usefulness of its value, skills to compute it and methods and application when its required to assess, plan and use groundwater resources.

Chapter 5: Using RIB model to estimate recharge

5.1 Introduction

The present chapter presents and discusses natural groundwater recharge estimates obtained using the rainfall infiltration breakthrough (RIB) model. The aim is to compare groundwater recharge estimates from rainfall infiltration breakthrough model and chloride mass balance method for validation purpose. The argument is that groundwater recharge estimates calculated using the rainfall infiltration breakthrough model are in close range with estimates from the chloride mass balance method. To achieve this aim groundwater level from boreholes and rainfall data from raingauges were obtained and groundwater recharge were estimated.

The rainfall infiltration breakthrough model requires spatial data for groundwater recharge estimation. This method can be used to estimate either groundwater recharge or aquifer storage and it provides a better opportunity for explaining the occurrence of recharge under different conditions. However, the rainfall infiltration breakthrough model fails to explain the condition where the continuous departures are negative and yet the observed water levels may still rise. This chapter provides groundwater recharge estimates calculated using rainfall infiltration breakthrough model and presents the estimates of specific yield as required by this method for estimation of groundwater recharge.

5.2 Estimation of specific yield

To apply the rainfall infiltration breakthrough model, an estimation of the specific yield (S_y) at the depth of water table fluctuation is required. The specific yield value obtained from pumping test data was compared to the specific yield obtained from the method based on the relationship between groundwater rise and rainfall. This relationship was verified by available data and then the specific yield could be estimated by a simple linear regression model. This technique has been tested by the Azul university campus and also by Varni et al., (2013) using the 2-year-long series of data. The relationship between rainfall and groundwater level increase for individual recharge event is indicated in the figure below.

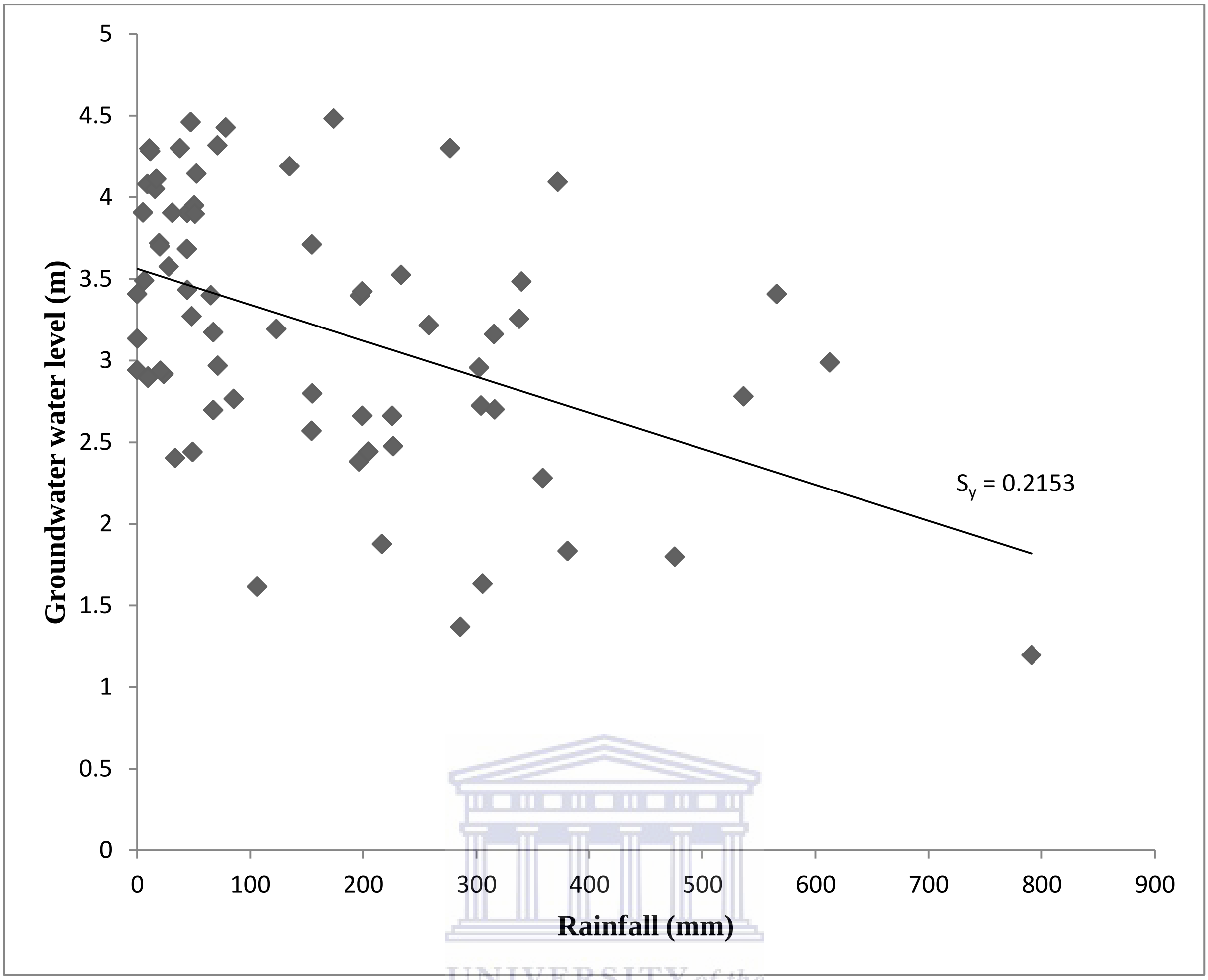


Figure 16: Graphical determination of specific yield using the envelope straight line of the precipitation–groundwater rise points of each registered rainfall–recharge event

The relationship between rainfall and groundwater level increase for individual recharge event is indicated in figure 16. The line drawn corresponds to S_y=0.2153. Varni et al., (2013) mentioned that this number is a maximum value because if all the rainfall recharge events occurred when the soil and vadose zone profile were not at field capacity this value could be less. Saayman et al., (2007) obtained specific yield value of 0.21 in the Table Mountain Group aquifer while assessing aquifer vulnerability in South Africa. The same specific yield value was obtained by Sun et al. 2013, in the Table Mountain Group aquifers in Oudebosch (West coastal).

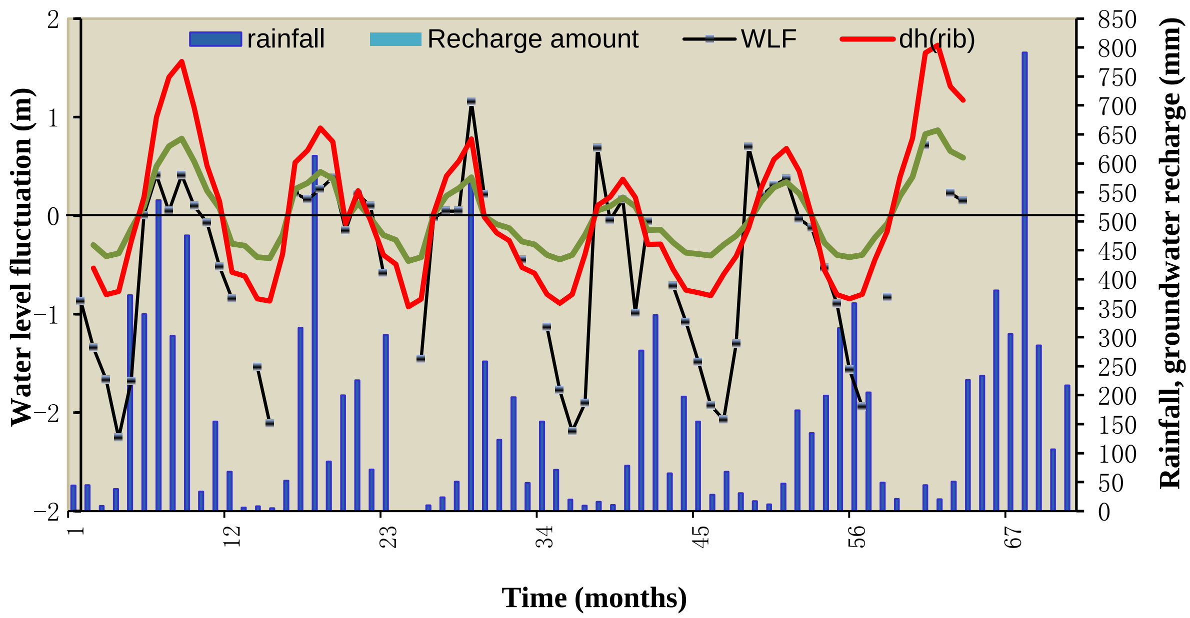
5.3 Recharge estimation using RIB model

Based on hydrogeological information, the rainfall infiltration breakthrough model was selected to estimate the groundwater recharge. This model is based on the water balance principle (rainfall-groundwater level relationship) and requires non-deterministic data such as groundwater level measurements, rainfall, and aquifer properties (S_y).

Figure 17, 18 and 19 show the plotted graphs of rainfall inputs and calculated groundwater recharge in mm as bars. The simulated groundwater level fluctuation calculated from the RIB method closely fit the observed values after calibration of the time lag (lag-month) and also the length of related rainfall events (length-month) on a monthly basis. For all the boreholes the term lag- month was 0 month, meaning that it took less than a day for percolating rainwater to reach the water table and the term length-month was 4 for all the boreholes monitored. Using the rainfall infiltration breakthrough model (Eq. 3.5), the predicted annual groundwater recharge was 13.3% in borehole BG00034 with specific yield of 0.21. In borehole BG00038 the predicted annual groundwater recharge was 44.3% with specific yield of 0.21 and the predicted annual groundwater recharge was 13.4% in borehole BG00047 with specific yield of 0.21.

The monthly time series of rainfall and groundwater levels was used during simulation. The length of this simulation was 72 months for all the boreholes monitored. Simulation started from 24/01/2008 to 28/11/2013. There are some gaps occurred in groundwater level data in borehole 34 and borehole 38. There is a gap from 28/01/2010 to 22/04/2010, which is 2 month gap and there is another 2 months groundwater level data gap occurred from 30/05/2013 to 22/08/2013. There was no groundwater level data for the 8^{th} month of 2010, 10th month of 2010, 1st month of 2011 and the 11^{th} month of 2011. The monthly and yearly groundwater recharge estimates for the TMG aquifers are shown in figure 17, 18 and 19, as well as the observed groundwater level fluctuation calculated with the RIB method.

A



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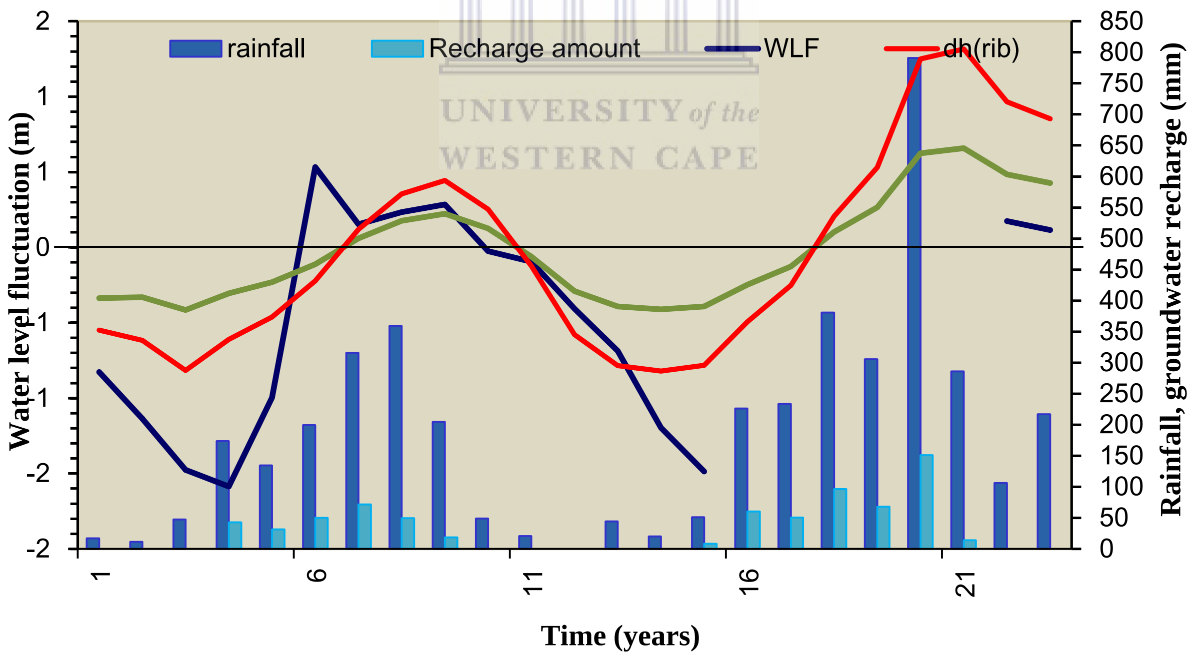
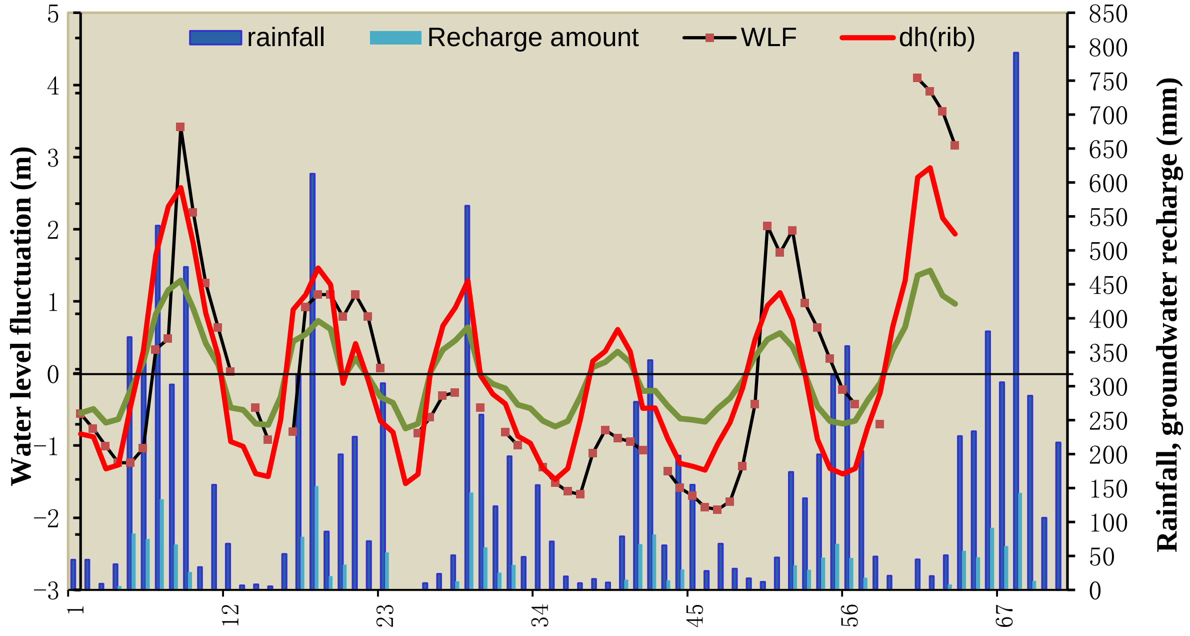


Figure 17: Monthly and yearly rainfall observed WLF and calculated WLF and groundwater recharge in BG00034

A



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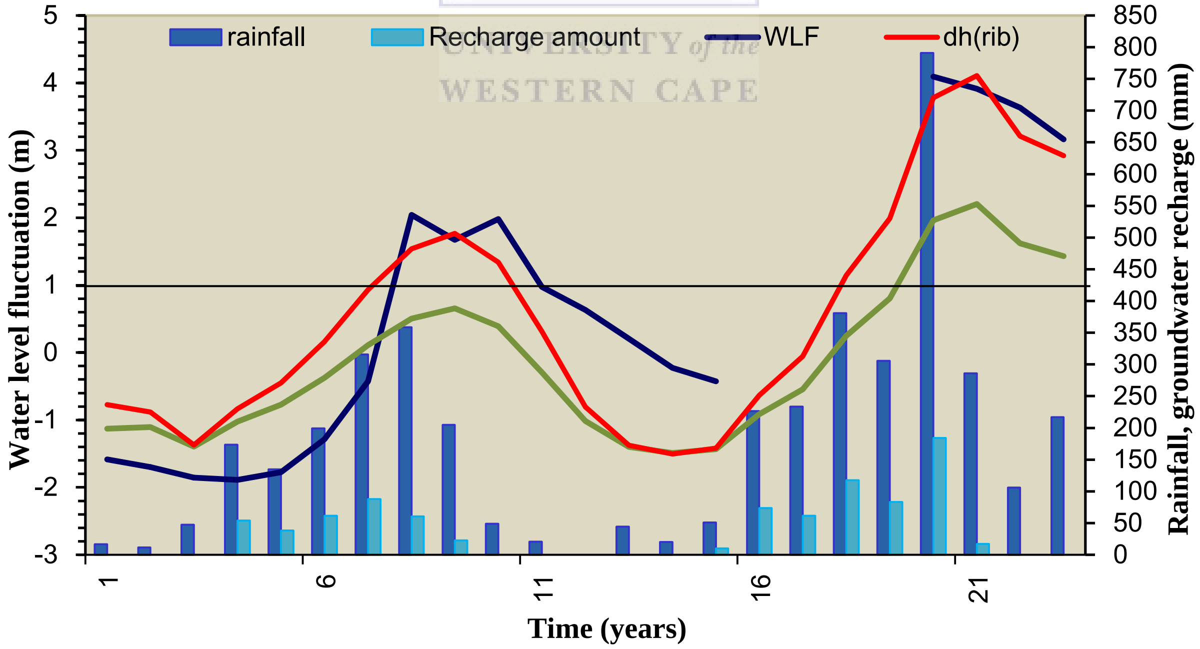
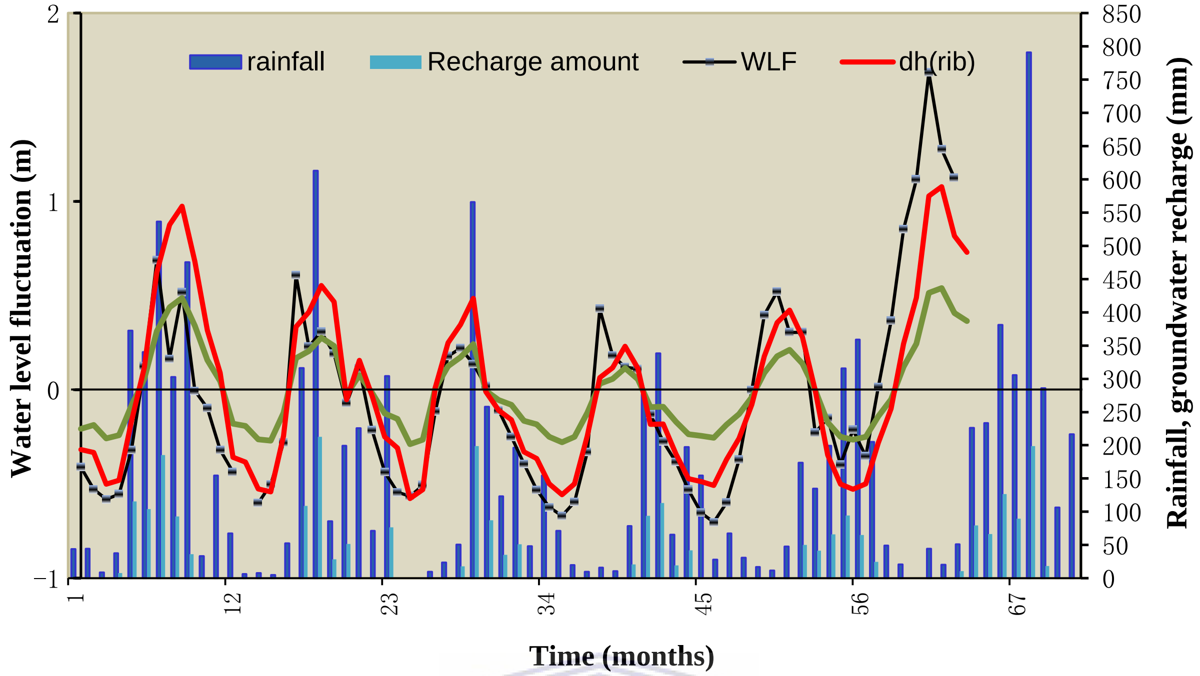


Figure 18: Monthly and yearly rainfall observed WLF and calculated WLF and groundwater recharge in BG00038

A



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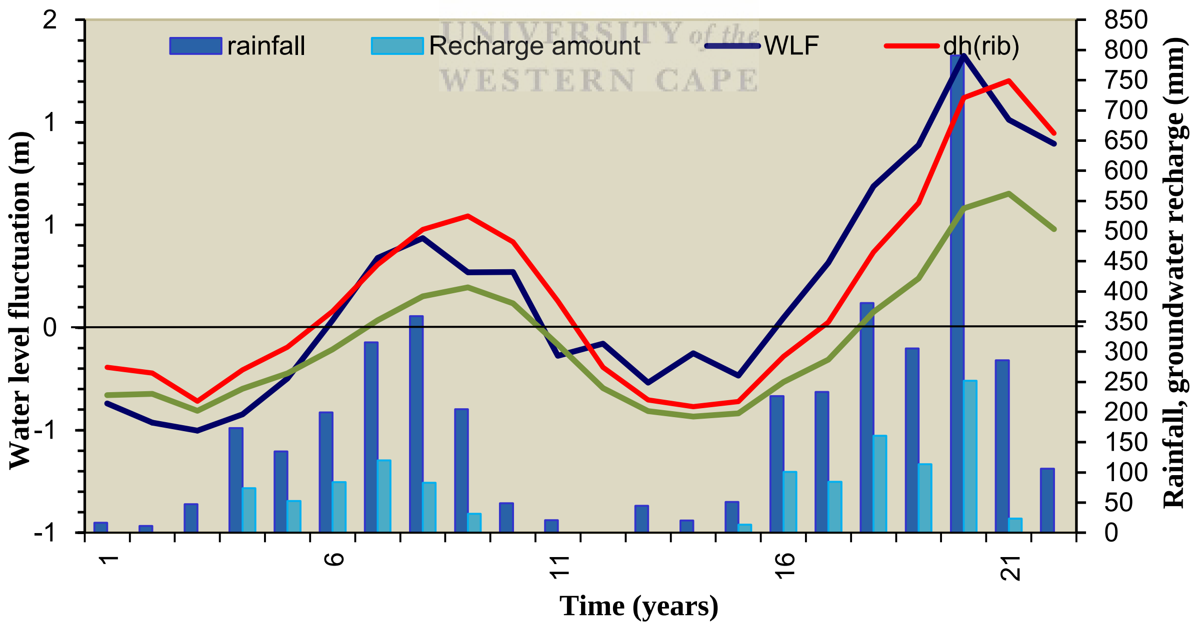

Figure 19: Monthly and yearly rainfall observed WLF and calculated WLF and groundwater recharge in BG00047

5.4 Recharge results from rainfall infiltration breakthrough model

Results on a monthly and yearly basis for the time lag and length of related rainfall events are shown in table 5. The table indicates that the recharge estimates on a monthly is less than the recharge estimated on a yearly basis. The Spearman correlation coefficient was applied and indicated that the relationship between rainfall and observed water level fluctuation was significant. Therefore, the recharge values estimated in a yearly are more realistic than recharge estimates on a monthly basis. This agrees with the groundwater flow mechanisms which state that precipitation which is stored in the unsaturated zone, is displaced downwards by the next infiltration/percolation event without disturbance of the moisture distribution and preferential flow in the unsaturated zone with a relatively high infiltration and/ or percolation capacity. The accuracy of the RIB model is indicated by the fact that the simulated groundwater level fluctuation calculated from the RIB method closely fit with the observed values after calibration. The table shows the yearly predicted recharge of 13.3% in borehole BG00034 with specific yield of 0.21. In borehole BG00038, the predicted yearly recharge was 44.3% with specific yield of 0.21 and the predicted yearly recharge was 13.4% in borehole BG00047 with specific yield of 0.21. This shows that the model is sensitive to specific yield, particularly when applied to the TMG aquifer system the estimated recharge rate may become unrealistic with a high specific yield value.

Table 5: Groundwater recharge estimates from RIB model

Borehole	Time lag		Length of rainfall events		Specific yield	Groundwater recharge (monthly)	Groundwater recharge (yearly)
	Monthly scale (month)	Yearly scale (year)	Monthly scale (month)	Yearly scale (year)			
BG00034	0	0	4	4	0.21	12.3%	13.3%
BG00038	0	0	4	4	0.21	26.5%	44.3%
BG00047	0	0	4	4	0.21	7.6%	13.4%

5.5 Results discussion from rainfall infiltration breakthrough model

The RIB model was applied in three existing observation wells. The monthly groundwater recharge as a percentage of monthly rainfall and the yearly groundwater recharge as a percentage of annual rainfall were estimated for each of the three observation wells. Using the RIB model, with the specific yield of 0.21, monthly groundwater recharge was estimated ranging between 7.6 % and 26.5 % of the mean monthly rainfall and annual groundwater recharge was estimated ranging between 13.3 % and 44.3 % of the mean annual rainfall as shown above (table 2).

The local groundwater recharge estimates from the rainfall infiltration breakthrough model analysis fell within the range of the groundwater recharge estimates calculated using the chloride mass balance. Recharge estimates calculated were 20.1 % to 37.8 % and 13.4 % and 44.3 % using the chloride mass balance method and rainwater infiltration breakthrough model, respectively. The slight difference in the estimates obtained using chloride mass balance and estimates obtained using rainfall infiltration breakthrough might be due to the different timeframes between the chloride mass balance and the rainfall infiltration breakthrough model (Crosbie et al., 2010). That means that the chloride mass balance method provides an estimate of recharge over the residence time of the water in the aquifer, which can be many thousands of years, while the rainfall infiltration breakthrough model provides an estimate of recharge over the length of time that measurements of water levels were recorded; this can be days, months, or decades.

The recharge estimates obtained using the RIB model in this study are in a same range with estimates from groundwater study conducted in a coastal plain in Riverlands Nature Reserve (Western Cape, South Africa) and in Oudebosch catchment in the Kogelberg Nature Reserve (Western Cape, South Africa), representing the Table Mountain Group aquifer (TMG). The study was done by Sun et al., (2013). The estimated groundwater recharge obtained range between 9.3 to 27.8 % of the total mean annual rainfall. Based on these similar findings, it can be said that the RIB model is capable of recharge estimation if specific yield is known and the critical assumptions listed in the previous section are met. However, groundwater recharge estimates of the rainfall infiltration breakthurgh model are higher than the groundwater recharge estimate of 29.74 mm/a obtained by Wu (2005). The specific yield differs significantly from place to place (10^{-6}–10^{-2} of specific yield is appropriate; Lin, 2007;

Jia, 2007), this is because of the heterogeneous geology in the Table Mountain Group (TMG), and therefore, it is reasonable to expect high variability in recharge (Sun et al., 2013).

Regardless of the evidence provided in the paragraph above, results of the present chapter were weak in terms of the study design compared with the study design that was used in the previous study conducted by Ahmadi et al, (2014). Data from only six (6) monitoring boreholes were used for groundwater level data and only two rain gauges were used for annual precipitation data that have been recorded in the Department of Water Affairs data base. Comparatively, in the study conducted by Ahmadi et al, (2014) non-deterministic data such as groundwater level measurements, rainfall, and aquifer properties (specific yield) were required to implement the rainfall infiltration breakthrough model. In their study, the study area was subdivided based on observation wells. The total of 35 observation wells were used in their study with the help of ARCGIS products and Thiessen method, then, specific yied, monthly records of rainfall and groundwater levels data were provided for each subzone and groundwater recharge was calculated based on such data. Their study used primary and secondary data in order to strengthen estimates of groundwater recharge. Therefore, their groundwater recharge estimates are more realistic compared to groundwater recharge estimates of the present study. Despite such difference in quantity of data, the current study has provided the insights, the feasibility of using rainfall infiltration breakthrough and chloride mass balance methods to estimate groundwater recharge which is step forward for groundwater availability assessment.

For accurate and reliable estimates of groundwater recharge using the rainfall infiltration breakthrough, the specific yield should be representative of the aquifer system of the catchment of interest. For determining the effect of long-term pumping of an aquifer, laboratory values of specific yield are appropriate, but for estimation of groundwater recharge with the RIB model, laboratory values of S_y are probably too large (Sun et al,. 2014). The specific yield of the present study was estimated from the data from the pumping test that was done in only one borehole that is in the catchment and then it was compared with the specific yield from the envelope straight line of the precipitation–groundwater rise points of each registered rainfall–recharge event and also compared with the specific yield obtained from other studies (Sun et al., 2014; Saayman et al., 2007) conducted in Table Mountain Group aquifers. For the present study, representative value of specific yield could have been much accurate if the specific yield was measured for the whole upper Berg catchment, but not in one point. The specific yield that is not representative of the whole area limits the strength of groundwater recharge estimates.

Sun et al, (2013) stated that the rainfall infiltration breakthrough model is best suited for shallow unconfined aquifers with relatively lower transmissivity. Rainfall infiltration breakthrough (RIB) is of water balance approaches which depend on investigating groundwater level fluctuations in shallow unconfined aquifers as a result of rainfall (Ahmadi et al, 2014). Therefore, rainfall infiltration breakthrough model was applied in the present study to estimate groundwater recharge in unconfined aquifer of the Table Mountain Group. This method can give out accurate estimates of groundwater recharge when applied in areas where the aquifers are unconfined and are shallow aquifers where groundwater levels respond distinctly to rainfall. In the present study the model was used to test and compare groundwater recharge estimates with estimates from chloride mass balance method.

5.6 Chapter summary

In this chapter, we have demonstrated the feasibility of using the rainfall infiltration breakthrough model despite having few borehole and raingauges to provide large data. The chapter has shown that results from rainfall infiltration breakthrough model supplement results from chloride mass balance thereby improving the reliability of using such estimates for groundwater availability assessment.

Chapter 6: Recharge estimation using water table fluctuation

6.1 Introduction

The present chapter addresses the third objective of the present study, which is to assess groundwater table response to precipitation and test the method by computing groundwater recharge from rainfall using the water table fluctuation method. The method is based on the principle that groundwater table/level rises in respond to rainfall infiltration, which indicates that there is replenishment of groundwater in the aquifer. Therefore, the present chapter assumes that any increase in groundwater level is recharge. To fulfill the objective of the present chapter, WTF was applied whereby groundwater level and rainfall data were used to estimate groundwater recharge in the study area.

The water table fluctuation technique (WTF) is one of the physical methods that links the change in groundwater storage with resulting water table fluctuations through the storage parameter (specific yield in unconfined aquifer). This method is considered to be one of the most suitable methods due to its accuracy and is best applicable in semiarid areas (Xu and Beekman, 2003). The approach used in the study allows an average value for a large area rather than a local value to be obtained. The water table fluctuation method consists of calculating the ratio of water table rise to total rainfall (Risser et al. 2005) for all the registered events in the analyzed area. This chapter presents results obtained by WTF and discusses such results. Finally, this chapter summarizes the key aspects of the water table fluctuation method regarding its usefulness in estimating groundwater recharge as a proxy of groundwater availability in the study area.

6.2 Estimating recharge using water table fluctuation method

The water table fluctuation method is based on the premises that the rise in the groundwater levels are due to recharge water arriving at the water table (Varni et al., 2013), with the assumption that the amount of available water in a column of unit area is equal to specific yield times the height of water in the column. The graphs below (figure 20, 21 and 22) indicate groundwater level fluctuation in response to rainfall from all the boreholes that were analysed for the period of 2008 to 2013.

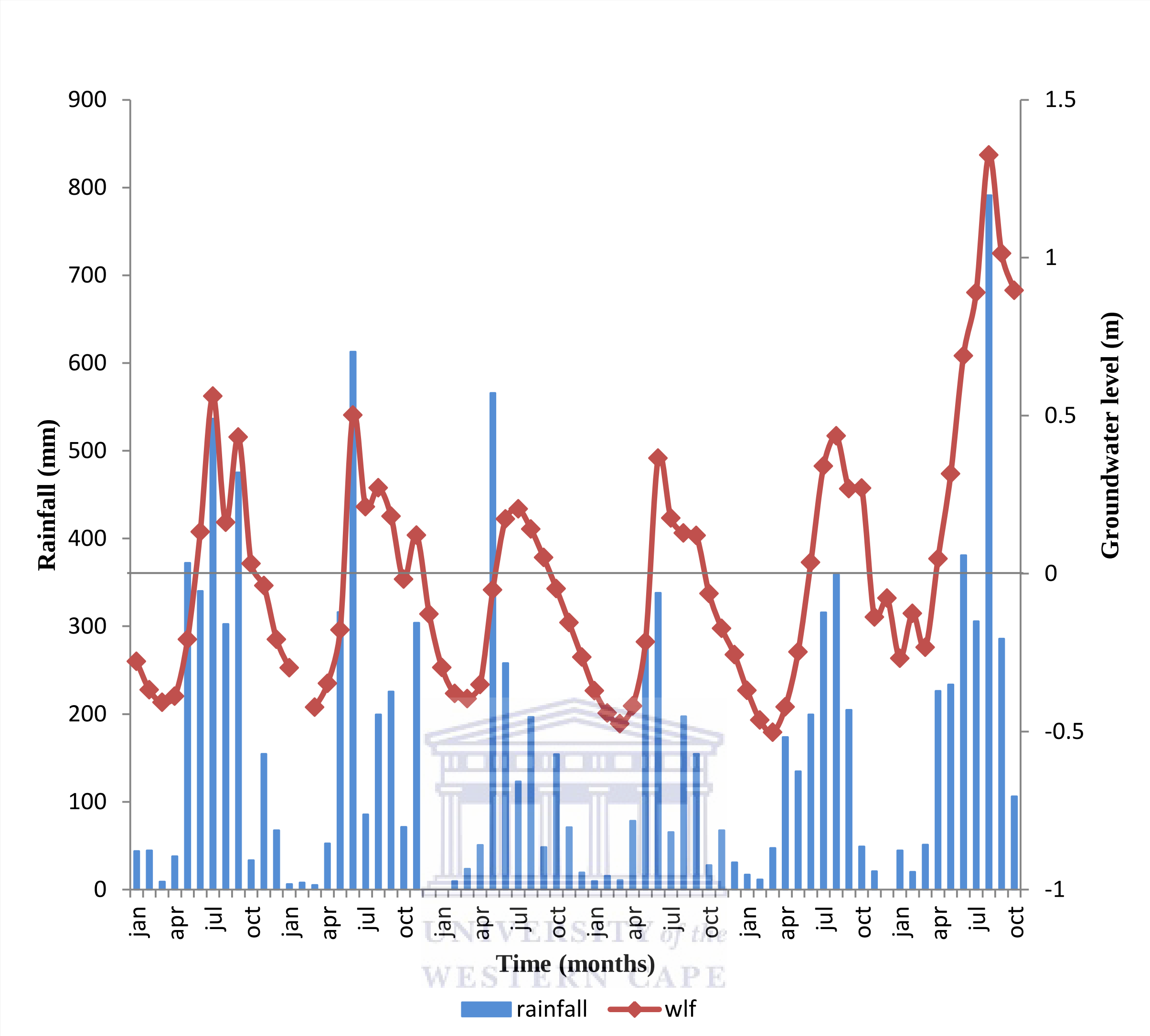

Figure 20: Water table fluctuation in response to rainfall in BG00047 from 2008 to 2013

The graph in figure 20 shows that the only time when groundwater levels rises is when rainfall event has occurred. The graph shows that the area receives high rainfall in winter season (between April and September). The highest rainfall was received in in August of the year 2013 with the volume of 791.1 mm and during that event groundwater level increased to 1.32 m in borehole BG00047. This increase indicates that high percentage of rainfall has been recharged to the groundwater. The graphs also indicate less rainfall occurred in 2011 and also in 2012 with the highest rainfall of 338.1 mm which occurred in June 2011 and the highest rainfall of 358.8 mm which occurred in August of 2012 and during these years groundwater level increased to 0.36 m and 0.43 m, respectively.

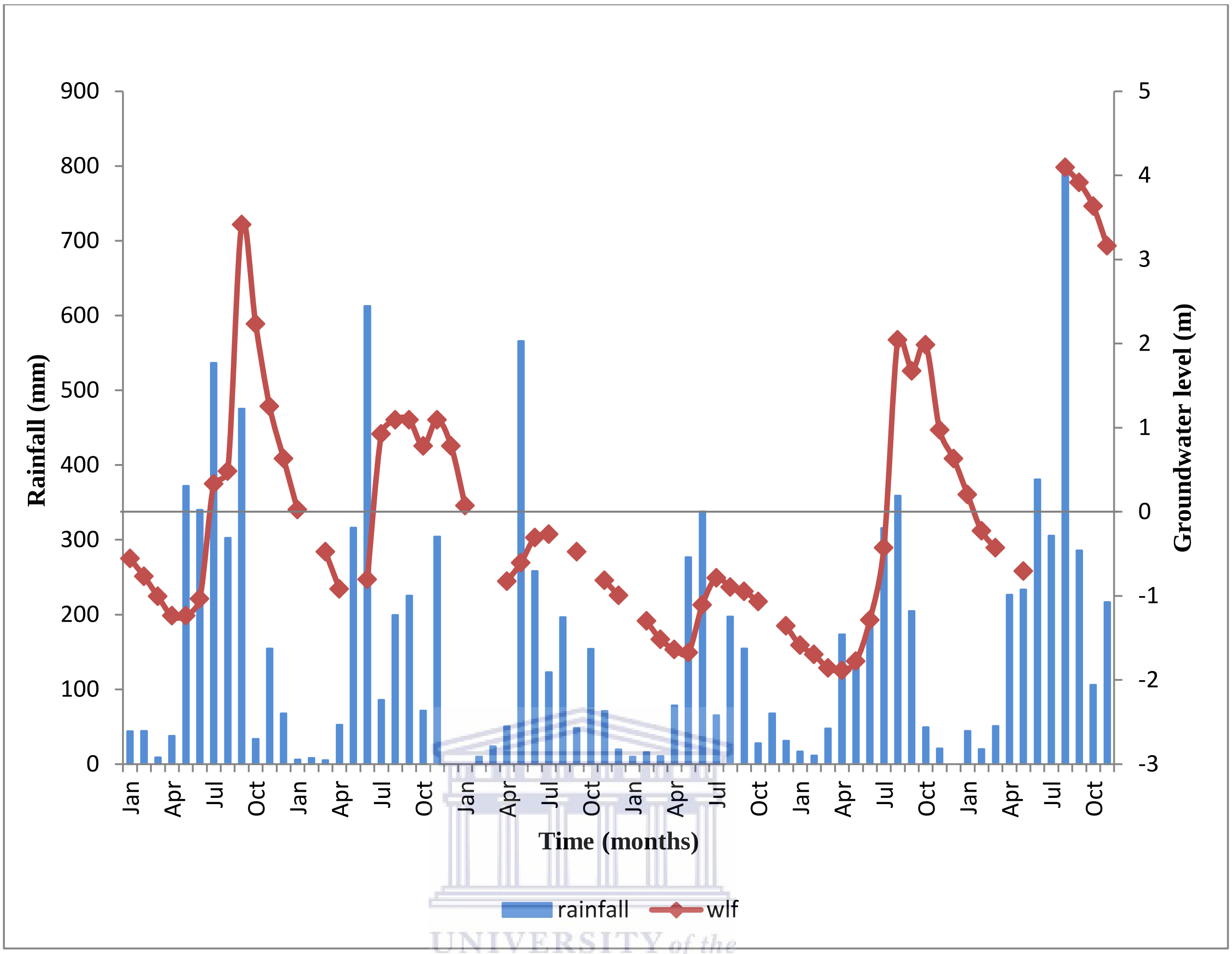

Figure 21: Water table fluctuation in response to rainfall in BG00038 from 2008 to 2013

The graph in figure 21 indicates that the only time when groundwater levels rises is when rainfall event has occurred. The graph shows that the area receives high rainfall in winter season (between April and September). The highest rainfall was received in August of the year 2013 with the volume of 791.1 mm and during that event groundwater level increased to 4.09 m in borehole BG00038. This increase indicates that high percentage of rainfall has been recharged to the groundwater. The graph also indicate less rainfall occurred in 2011 and also in 2012 with the highest rainfall of 338.1 mm which occurred in June 2011 and the highest rainfall of 358.8 mm which occurred in August of 2012 and during these years groundwater level increased to -0.78 m and 2.04 m, respectively.

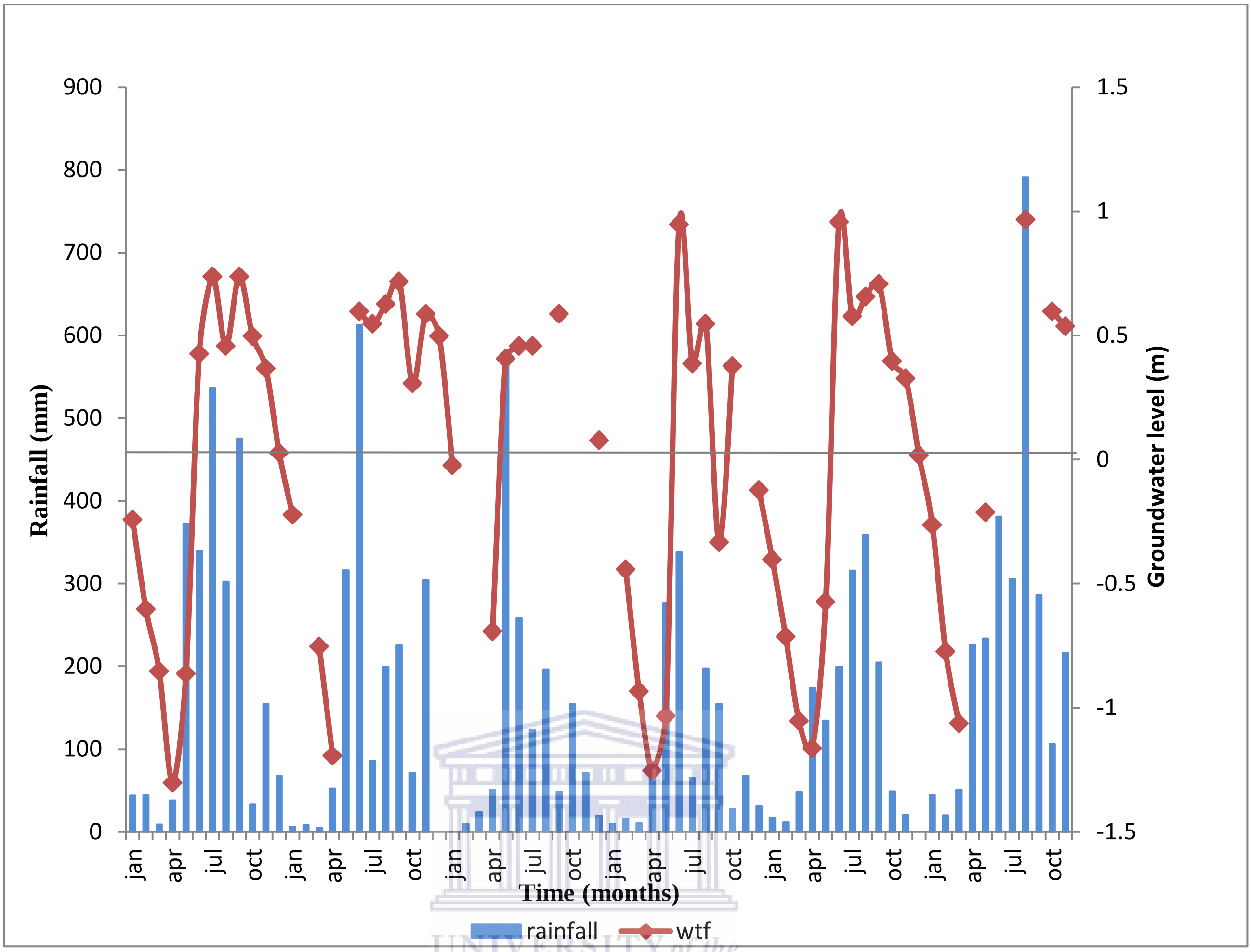

Figure 22: Water table fluctuation in response to rainfall in BG00034 from 2008 to 2013

The graph in figure 22 indicates that the only time when groundwater levels rises is when rainfall event has occurred. The graph shows that the area receives high rainfall in winter season (between April and September). The highest rainfall was received in in August of the year 2013 with the volume of 791.1 mm and during that event groundwater level increased to 0.96 m in borehole BG00034. This increase indicates that high percentage of rainfall has been recharged to the groundwater. The graphs also indicate less rainfall occurred in 2011 and also in 2012 with the highest rainfall of 338.1 mm which occurred in June 2011 and the highest rainfall of 358.8 mm which occurred in August of 2012 and during these years groundwater level increased to 0.94 m and 0.95 m, respectively.

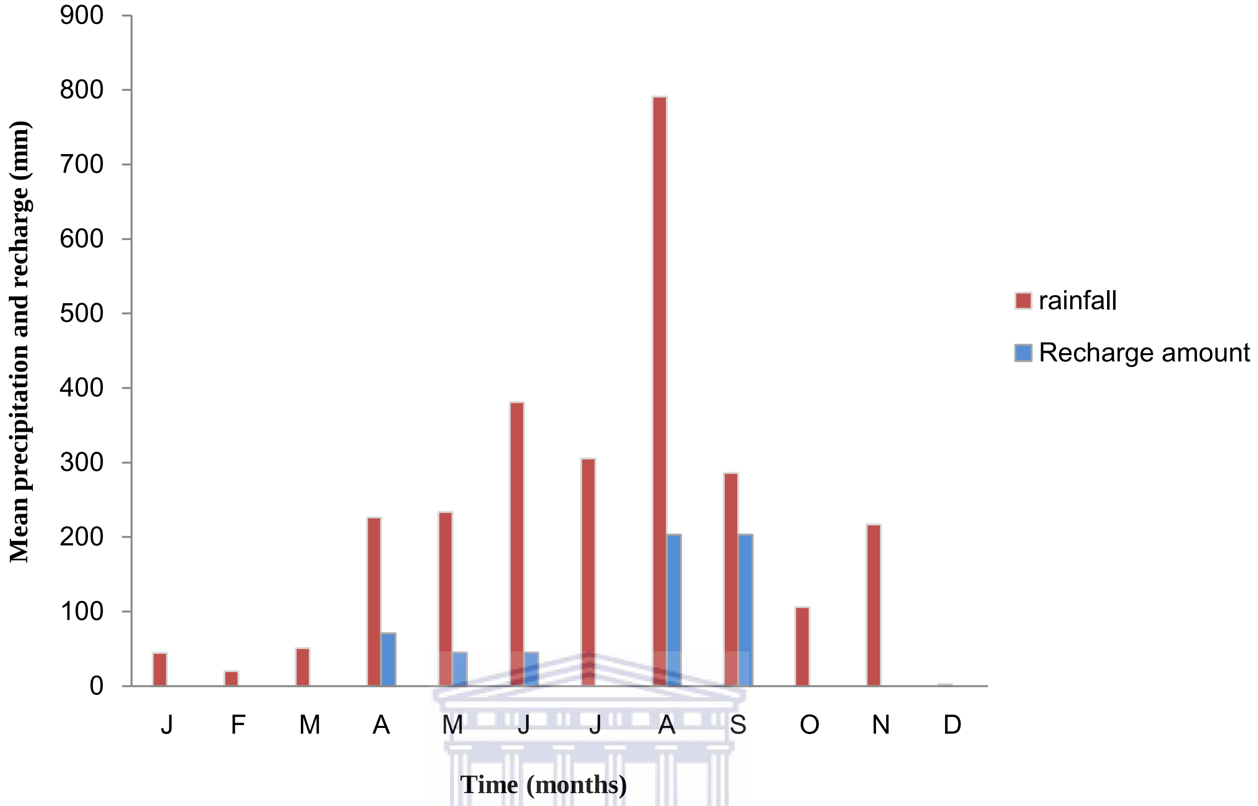

Figure 23: Mean monthly rainfall and recharge in borehole BG00034

Distribution of the mean monthly rainfall and recharge for borehole BG00034 monitored for the period of 2013 is shown in figure 23. Distribution of recharge is similar to that of rainfall, with September and August having the highest amounts of rainfall and recharge, except for the warmest months of the year (December, January, February and March), during which the greater influence of evapotranspiration reduces groundwater recharge values. In boreholes BG00034, high percentage of recharge values were obtained in April, August and September (31.1%, 28.6% and 70.6% of precipitation, respectively), but the actual amounts of recharge (in mm) during this month differ greatly. The graph indicates no groundwater recharge during the dry season, that is, in December, January, February and March where rainfall is very low.

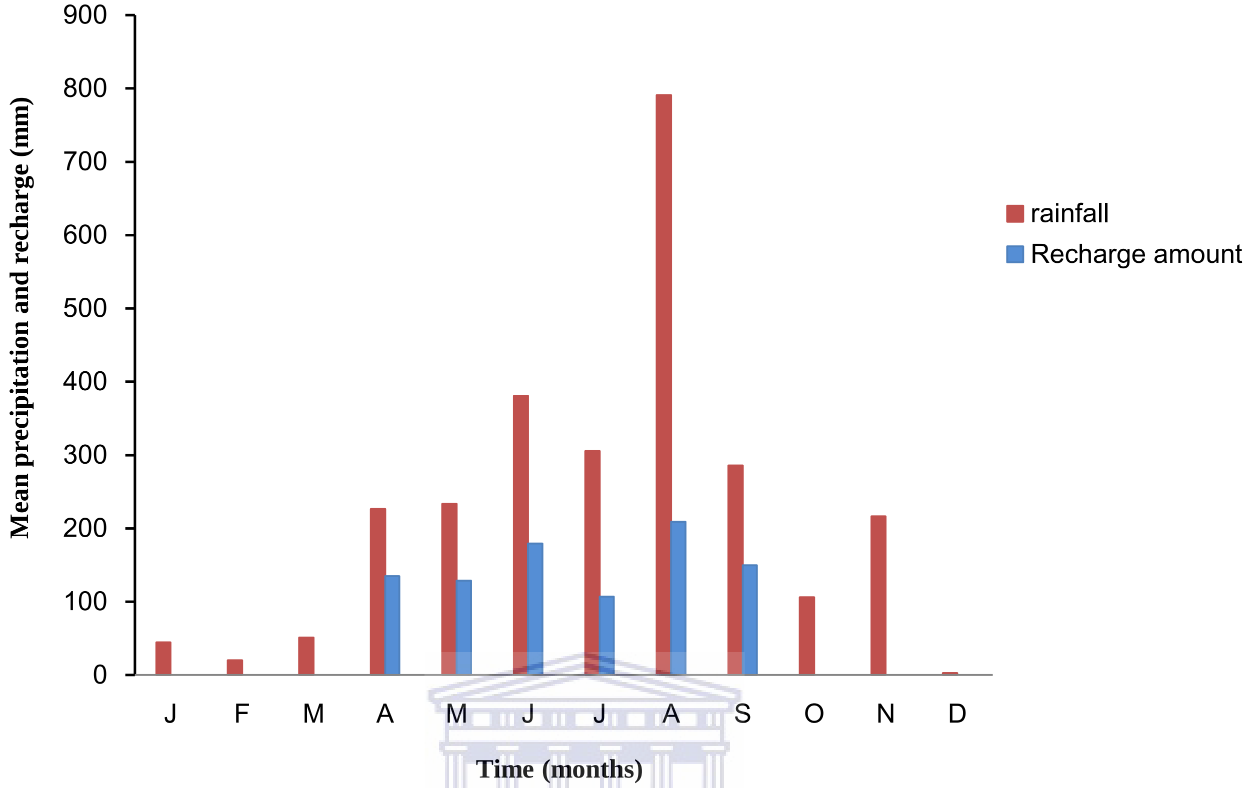

Figure 24: Mean monthly rainfall and recharge in borehole BG00047

Distribution of the mean monthly rainfall and recharge for borehole BG00047 monitored for the period of 2013 is shown in figure 24. It indicates that distribution of recharge is similar to that of rainfall, with April and September having high amounts of rainfall and recharge, except for the warmest months of the year (December, January, February and March), during which the greater influence of evapotranspiration reduces groundwater recharge values. However, in boreholes BG00047, high percentage of recharge values were obtained in April, September and June (59.5%, 52.3% and 47% of precipitation, respectively), although the actual amounts of recharge (in mm) differ greatly. Thus, although the mean values of annual recharge reached 20.5 % of precipitation, the monthly recharge distribution shows significant variation. The magnitude of the percentage recharge in winter and early spring is due to the usually greater water storage in the soil resulting from the combination of autumn rainfall and low winter evapotranspiration; with high soil moisture contents, even small rainfall amounts can produce groundwater recharge.

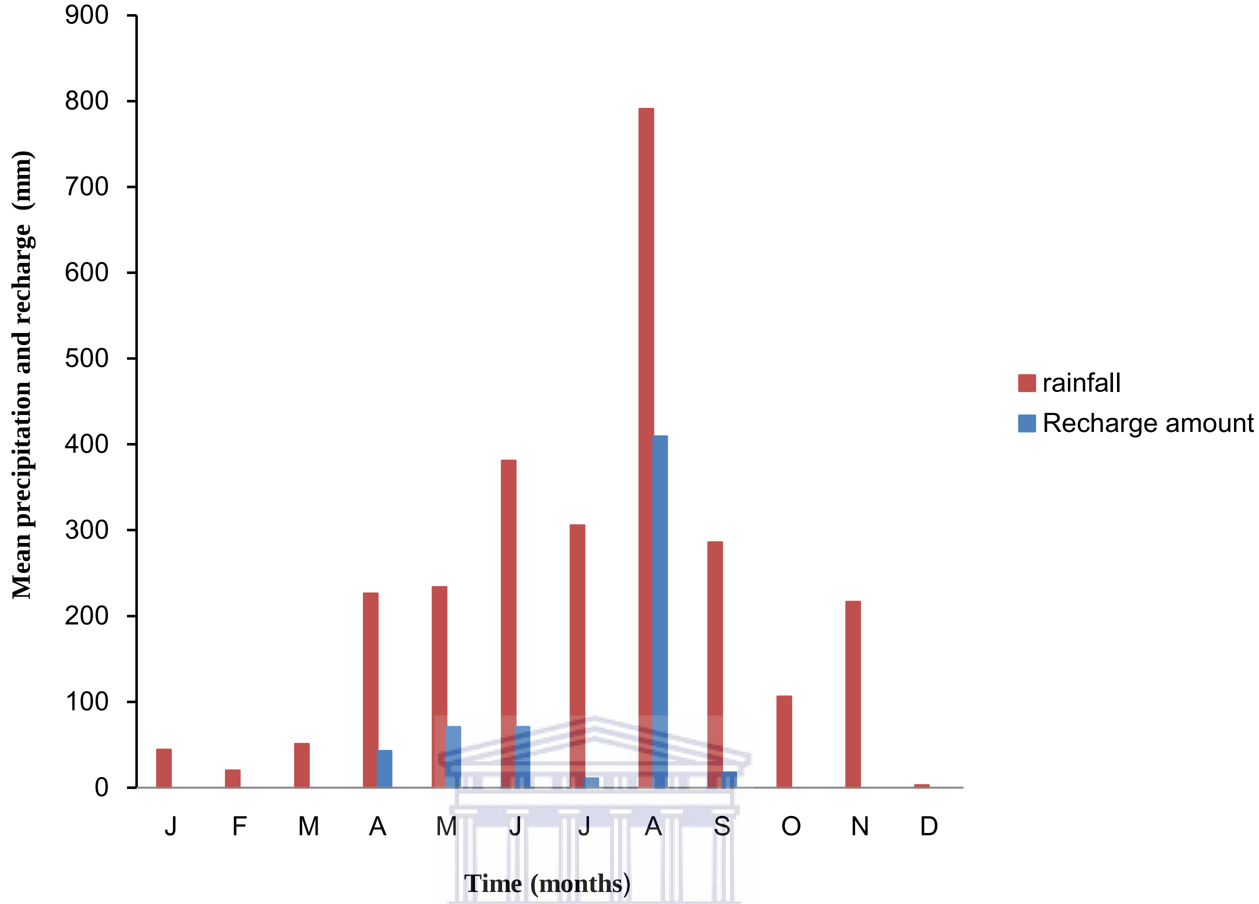

Figure 25: Mean monthly rainfall and recharge in borehole BH00038

Distribution of the mean monthly rainfall and recharge for borehole BG00038 monitored for the period of 2013 is shown in figure 25. The graph also indicates distribution of recharge being similar to that of rainfall, with May and August having the highest amounts of rainfall and recharge, excluding the warmest months of the year (December, January, February and March), during which the greater influence of evapotranspiration reduces groundwater recharge values. In boreholes BG00038 (figure 25), high percentage of recharge values were obtained in August, May and April (57.7%, 30.2% and 18.8% of precipitation, respectively), although the actual amounts (in mm) differ greatly. The magnitude of the percentage recharge in winter and early spring is due to the usually greater water storage in the soil resulting from the combination of autumn rainfall and low winter evapotranspiration; with high soil moisture contents, even small rainfall amounts can produce groundwater recharge.

6.3 Recharge estimates from water table fluctuation method

Table 6 shows results of groundwater recharge from WTF method. Groundwater recharge estimates was 344 mm in borehole BG00034, representing 18.4% of the total rainfall received. In borehole BG00038 groundwater recharge estimated was 721 mm, representing 27% of the total rainfall, and in borehole BG00047 groundwater recharge estimates was 434 mm, representing 16.2% of the total rainfall.

Table 6: Groundwater recharge from WTF method

Boreholes	Specific yield	$\Delta h/\Delta t$ (m/year)	Groundwater recharge (mm/year)	Groundwater recharge (%)
BG00034	0.21	2.337	490	20.3
BG00038	0.21	3.437	721	29.9
BG00047	0.21	2.066	434	18.01

Table 7: Previous groundwater recharge studies done in the similar area

Author (s)	Year of study	Method used	Results
Department of Water Affairs	2003	GRID-based GIS modelling technique	18.6%
Department of Water Affairs	2004	CMB	28%
M Albhaisi, L Brendonck, O Batelaan	2008	GRID-BASED distributed hydrologic model	27.8%

Groundwater recharge estimates from the water table fluctuation method are in a similar range with some of the studies done in the similar upper Berg catchment as shown in table 7. The Department of Water Affairs conducted Berg River monitoring project study in 2003. During this project, they estimated groundwater recharge using the GRID-based GIS modelling technique. They estimated recharge from each quaternary catchment in the Berg including the upper catchment of the Berg. They estimated recharge and find out that only 18.6% of total rainfall is recharged to groundwater. They conducted another groundwater recharge study in 2004. They were using the chloride mass balance to estimate recharge in the upper Berg. They find out that only 28% of total rainfall is recharged to groundwater. The table also shows the study done by Albhaisi et al, 2008; the study used the GRID-BASED distributed hydrologic model to quantify groundwater recharge in the same area. Recharge was quantified and found to be only 27.8% of the total rainfall received in the catchment.

Despite using different methods when estimating groundwater recharge in the upper Berg River catchment the recharge estimates tend to be in the same range. However these methods should always be applied with caution and following all the assumptions necessary for successful application of each method in order to produce representative and reasonable estimates of recharge. Estimated recharge rates obtained using the CMB are close to rates determined by Grid-Based distributed hydrologic model in similar environments as shown in table 7 and also close to the recharge estimates obtained by methods used in the present study.

6.4 Discussion of results from water table fluctuation method

The water-table fluctuation method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge arriving at the water table. Recharge is calculated as the change in water level over time multiplied by specific yield. This approach is a gross simplification of a very complex phenomenon, namely, movement of water to and from the water table. Favourable aspects of the WTF method include its simplicity and ease of use: it can be applied for any well that taps the water table, and an abundance of available water-level data exists (Healy and Cook, 2002). Wu et al, (2005) and Sun et al, (2013) indicated that the water table fluctuation method cannot be applied in areas that has no groundwater level fluctuation or water levels not responding well to rainfall. It was also indicated that the method is best suited for shallow unconfined aquifers. In the present study, the water table fluctuation was utilized because the study area has the groundwater level fluctuation data and the water level responds well to rainfall. Therefore, the aquifers are unconfined aquifers. The groundwater recharge estimates obtained in the present study using the water level fluctuation method agrees with the groundwater recharge estimates obtained in the study done by Kaba et al, (2012) in the shallow unconfined Thiaroye sandy aquifer using the same water table fluctuation method. The study was done in Dakar, Senegal.

The groundwater recharge for each of the observed wells was calculated by multiplying the water level rise with the specific yield values of the aquifer material in which the wells are situated. The calculated mean recharge for the study area ranged from 434 mm to 721 mm in water year 2012-2013, representing 18.01 to 29,9 % of the mean annual rainfall (table 6). The recharge value calculated using the water table fluctuation (WTF) method is close to what was obtained with the chloride mass balance (CMB) method in the present study. A comparison of spatial interpolated groundwater recharge estimates obtained with the CMB and the water table fluctuation methods for the upper Berg River catchment (G10A), show that the two methods are generally in agreement regarding potentially high and low recharge areas. These results indicate that the use of the two methods have potential to estimate groundwater recharge at quaternary level which is the basic unit of water management in South Africa.

The WTF method relates changes in measured water-level elevation to changes in the amount of water stored in the aquifer. Recharge is assumed to be equal to the product of water-table rise and specific yield. Specific yield is the amount of water a unit volume of saturated permeable material will yield when drained by gravity. The groundwater-level fluctuation method, when applied in isolation, is not reliable unless accurate values of aquifer effective storativity are available from a reliable method, which is rarely the case. It is well known, especially in aquifers with a shallow water table, that significant errors are introduced in recharge estimations by the use of a constant specific yield.

For accurate and reliable estimates of groundwater recharge using the water table fluctuation method, the specific yield should be representative of the aquifer system of the catchment of interest. For determining the effect of long-term pumping of an aquifer, laboratory values of specific yield are appropriate, but for estimation of groundwater recharge with the water table fluctuation method, laboratory values of S_y are probably too large (Sun et al,. 2014). The specific yield of the present study was estimated from the data from the pumping test that was done in only one borehole that is in the upper Berg catchment and then it was compared with the specific yield from the envelope straight line of the precipitation–groundwater rise points of each registered rainfall–recharge event and also compared with the specific yield obtained from other studies (Sun et al., 2014; Saayman et al., 2007) conducted in Table Mountain Group aquifers. For the present study, representative value of specific yield could have been much accurate if the specific yield was measured for the whole catchment, not in one point. The specific yield that is not representative of the whole area limits the strength of groundwater recharge estimates. However, the results obtained provide the insight on how to apply the method and produce results that inform further analysis.

Selecting boreholes that are representative of the whole catchment of study is one of the requirements for successful application of the water table fluctuation method. Therefore, the use of more boreholes for groundwater samples collection in recharge study is more significant. Boreholes selected must be representative of the whole area of interest. In the study done by Kaba et al, (2012) 30 dug wells, boreholes and piezometers were used for groundwater level data collection. Using data from boreholes that are representative of the whole area strengthen the groundwater recharge estimates. Using few boreholes limits the reliability and reality of the groundwater recharge estimates. The present study suggests that future studies should be carried with more boreholes selected for groundwater level data.

The WTF method is capable of estimating recharge when water is arriving at the water table at a greater rate than it is leaving, a condition that produces a water level rise. Recharge can still be occurring even when a well hydrograph shows that water levels are declining. Such an occurrence simply indicates that the rate of recharge is less than the rate of water movement away from the water table. If water movement away from the water table were equal to the steady recharge rate, no change in water level would occur, and the WTF method would predict no recharge (Healy and Cook, 2002). Hydrographs (figure 20, 21 and 22), show that the rainfall amount and groundwater levels graphs closely fit to each other and this indicates perfect relationship between rainfall amount and groundwater levels. Therefore, this suggests that the amount of water recharged to groundwater is from rainfall amount received during that rainfall event.

6.5 Chapter Summary

The water table fluctuation method was tested in the present study to estimate recharge and compare results with chloride mass balance results. Results values obtained by water table fluctuation were found being close to groundwater recharge values obtained by chloride mass balance. The water table fluctuation method was tested for its applicability in unconfined aquifers and the outcomes indicated similarities of recharge values from both methods (CMB and WTF) and such similarities suggested that the water table fluctuation method is applicable in unconfined aquifers where the groundwater level responds well to rainfall.

Chapter 7: Conclusion and recommendations

7.1 Introduction

In the present study, the chloride mass balance, water table fluctuation and the rainfall infiltration breakthrough were used to estimate the amount of groundwater recharge. The study was conducted in the Berg River catchment which is the largest catchment in the Western Cape Province of South Africa and has an area of about 9,000 km2. Catchment G10A is one of the 12 quaternary catchments that the Berg River catchment consist of and that G10A was of interest in the present study. The upper part of G10A is the study area. The present study was done to enhance knowledge on applying chloride mass balance approach to estimate groundwater recharge as decision making tool for water resource management using upper Berg River catchment as a case study. This was done because studies in groundwater recharge estimation have been conducted in the upper Berg River catchment using other methods such as water balance method, but groundwater recharge estimation have seldom been done using the chloride mass balance in this catchment.

To achieve the main objective of the study three methods were used. The chloride mass balance method was used as the main method in the present study and was used to estimate annual groundwater recharge partitioned from rainfall (precipitation) with the assumption that if this method is applicable for estimating groundwater recharge in the upper Berg River catchment, therefore it can be applied in other quaternary catchment of similar physiographic and hydrologic conditions. The other two methods (WTF and RIB) were used in the present study to compare and validate chloride mass balance recharge estimates. The Table Mountain Group aquifer recharge estimates obtained from these different methods (CMB, WTF, and RIB) show relative similar range values. Analysis of long term groundwater levels records suggest that the water levels rising in the upper Berg River catchment are due to infiltration of rainfall. The RIB model, CMB and WTF method applied in the present study estimates infiltration from the rainfall, and therefore compute groundwater recharge.

7.2 Recharge estimation using CMB

A proper understanding of computing recharge value is crucial to assessing groundwater availability efficiently. In this chapter, we have showed calculation of average groundwater recharge value which is the estimate but which provides a basis or insight on groundwater recharge for the study area. Overall mean groundwater recharge was estimated to be 668.3 mm, representing 27.6 % of the long-term mean annual rainfall. Such results have been compared with other scholars who obtained similar estimates. Good estimates of groundwater recharge is not an end in itself but must be viewed on the usefulness of its value, skills to compute it and methods and application when its required to assess, plan and use groundwater resources. Weaknesses of the chloride mass balance method as applied in the present study include the non-existence of data on dry atmospheric deposition of chloride as well as long-term data on total chloride deposition. However, the present study concludes that the chloride mass balance can be used as an indicator of groundwater availability in the area.

The chloride mass balance method can be used as tool and as first-hand information on the groundwater recharge for water resources planning and management. There is a need to conduct more studies in areas that are not close to the monitoring wells that were sampled for more reliable estimates of groundwater recharge. Accurate groundwater recharge estimation is important for sustainable planning and management of the groundwater resource. Therefore, further research is required in the upper Berg River catchment in order to improve the accuracy of groundwater recharge estimation and it would be useful to still compare the chloride mass balance estimations with recharge estimations from other methods. The chloride mass balance is a relatively an appropriate method for estimating groundwater recharge and provides long-term recharge information of the area of interest. However, the CMB method requires long-term data of wet and dry atmospheric deposition, rainfall, and chloride concentration in groundwater. Presently, there is no history of data on dry atmospheric deposition and long-term data on wet deposition in the upper Berg River catchment. Therefore, a continuous monitoring of chloride deposition is required in order to provide long-term data for a more reliable estimation of the long-term recharge.

Only few monitoring wells were sampled for use with the CMB method. However, the number of wells from which groundwater samples were taken and analysed can greatly influence the recharge estimate. It is, therefore, recommended that samples should be sampled from more representative number of monitoring wells for chloride analysis in order to have recharge estimates that are more representative and reliable.

7.3 Recharge estimation using RIB

In this chapter, we have demonstrated the feasibility of using the rainfall infiltration breakthrough model despite having few borehole and raingauges to provide large data. The estimated groundwater recharge values were averaged to 23.67 % of the total precipitation. The chapter has shown that results from rainfall infiltration breakthrough model supplement results from chloride mass balance thereby improving the reliability of using such estimates for groundwater availability assessment.

The rainfall infiltration breakthrough model was used to estimate groundwater recharge in order to test, supplement and validate the chloride mass balance recharge estimates by comparing such groundwater recharge estimates. The objective was achieved because groundwater recharge estimates were compared and found to be in the same range. The chapter also answers the questions of whether the method can be used as indicator of groundwater availability in the area and how much of the annual precipitation that is received in the catchment is partitioned to groundwater recharge.

Recharge estimates from the rainfall infiltration model depend on the values of the specific yield used in calculating them. Currently, there is no data on the exact specific yield of the aquifer materials in the study area. The specific yield values of the present study were estimated from the pumping test data and the rainfall groundwater level relationship and were then compared to the specific yield values from literature. However, selecting specific yield values from literature can result in wide ranges of estimated groundwater recharge, which may not be good for management of the groundwater resource. Therefore, further research is required to determine the exact specific yield values of aquifer materials in the entire upper Berg River catchment. It is therefore recommended that specific yield becomes one of the mandatory aquifer parameters that must be estimated during pumping tests on wells constructed in the catchment.

7.4 Recharge estimation using WTF

The water table fluctuation method was tested in the present study to estimate recharge and compare results with chloride mass balance results. Results values obtained by water table fluctuation were found being close to groundwater recharge values obtained by chloride mass balance. The estimated groundwater recharge values were averaged to 22.7 % of the total precipitation. The water table fluctuation method was tested for its applicability in unconfined aquifers and the outcomes indicated similarities of recharge values from both methods (CMB and WTF)

The water table fluctuation method was applied with the same aim and same questions with that of rainfall infiltration breakthrough model of which the objective was achieved and the questions were answered. The main limitation of this method is the difficulty in obtaining specific yield values that are representative of the aquifer materials in the study area. Besides the specific yield limitation, there are few wells for monitoring water table data, which affects the reliability of the recharge estimates. Despite these limitations the present study concludes that water table fluctuation method under few assumptions appears to offer reasonable estimates of groundwater recharge in arid and semi-arid areas and can be used as indicators of groundwater availability in the catchment.

Similar to the rainfall infiltration breakthrough model recharge estimates from the water table fluctuation method depend on the values of the specific yield used in calculating them of which further research is required to determine the exact specific yield values of aquifer materials in the entire catchment. For accurate estimates of groundwater recharge this method needs to be applied in areas where the aquifers are unconfined and are shallow aquifers where groundwater levels respond distinctly to rainfall. Therefore, for accurate estimates of groundwater recharge, it is recommended that these methods are being applied with great caution in areas where these conditions are not met.

7.5 Final conclusion

Three methods were used to estimate groundwater recharge in upper Berg River catchment, the chloride mass balance, the rainfall infiltration breakthrough and the water table fluctuation methods. When comparing results from all the three methods, recharge estimates obtained using CBM, RIB and WTF ranged between 20.1 % to 37.8 %, 13.3 % to 44.3 % and 18.01 % to 29.9 %, respectively. The study concluded that though the methods yielded the same range of recharge, between 13.3 % and 44.3 % of annual rainfall. All methods are indicating that no single point measurement of recharge is a good indicator of regional recharge. The study also showed that all recharge estimation methods used in the study had the weakness of over reliance on one critical parameter such as the chloride deposition when applying the CBM method and specific yield when applying the WTF method and the RIB model. Therefore, groundwater recharge estimates obtained using these three methods are in a similar range and they also agrees with the groundwater recharge estimates obtained from previous studies (table 5) conducted in the same area. Results from these methods indicate that these methods are applicable when all assumptions necessary for their successful application are been followed.

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APPENDICES

Appendices

Chloride mass balance

- Annual precipitation was measured (table 10)
- Concentration of chloride in precipitation was analysed (table 8)
- Concentration of chloride in groundwater was analysed (table 9)

	Month	Rain gauge 2	Rain gauge 1	
	JAN	4.273	6.166	
	APR	4.235	6.99	
	JUL	3.444	3.179	
Average		5.445	3.984	
Tot. Ave				**4.7145**

Table 8: Average concentration of chloride in precipitation

	Apr	Oct	Average
BH 34	13.079	20.876	**16.9775**
BH 35	8.818	24.276	**16.547**
BH 38	22.914	23.906	**23.41**
BG WGN1	18.904	18.654	**18.779**
BG MN5	17.939	16.73	**17.3345**
BG LAD3	12.318	12.553	**12.4355**

Table 9: Concentration of chloride in groundwater

	Time	**Rainfall**
	Oct	**49.1**
	Nov	**20.7**
	Dec	
	Jan	**44.5**
	Feb	**20.2**
	Mar	**51**
	Apr	**226.4**
	May	**233.6**
	Jun	**380.9**
	Jul	**305.6**
	Aug	**791.1**
	Sep	**285.9**
Total rainfall		**2409**

Table 10: Annual precipitation

Therefore, groundwater recharge values were estimated using the CMB equation below:

$$R = P. \frac{Clp}{Clgw}$$

Rainfall infiltration breakthrough and water table fluctuation methods

- Water level time series data (last page of appendices) was obtained or measured. Data quality assurance was done to insure data reliability. Outliers were removed from data.
- Annual rainfall data was measured.
- Estimated specific yield was used during recharge estimation using these two methods.
- Area size was measure as required by the RIB model.

WTF

- Average annual rainfall was measured
- Average water level was measured for each borehole and was multiplied by the value of specific yield. The value obtained was in meters m/yr, it was then multiplied by 1000 to convert the value into mm/yr.
- To convert the value of recharge into percentage (%), it was multiplied by 100% and then divided by the total average annual rainfall.

The equation below was used to estimate recharge using the WTF:

$$R = \Delta S_{gw} = S_y\frac{dh}{dt} = S_y\frac{\Delta h}{\Delta t}$$

RIB

- The RIB programme that is written on Excel Spread sheet 2007 was used to estimate recharge (figure…)

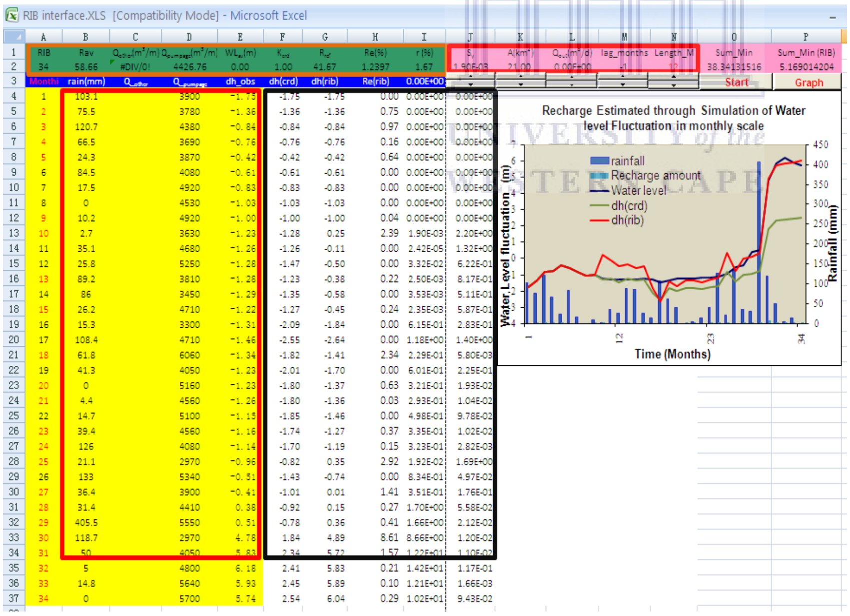


Figure 25. The user interface of RIB programme

- Water level time series data from 2008 to 2013 was used. Average water level was calculated and each monthly value from 2008 to 2013 was subtracted from the average value to obtain the water level fluctuation from 2008 to 2013.
- Specific yield, catchment area, water level fluctuation and rainfall data was then inserted in the RIB programme and was simulated and the recharge values was obtained for each boreholes.
- The time lag value was adjusted manually until the measured and modelled water levels are close to each other.

Specific yield

Linear regression

Water level fluctuation data and rain fall data was used for linear regression method for estimating data. Below is the data that was used; the water level fluctuation data was obtained from one of the boreholes selected for the use of the RIB and WTF method:

rainfall	wlf
44	2.55
44.4	2.91
9	3.16
37.8	3.61
372.3	3.17
340.1	1.88
536.5	1.57
302.5	1.85
475.5	1.57
33.5	1.81
154.7	1.94
67.6	2.28
6.3	2.53
8	
5.1	3.06
52.5	3.5
316.2	
612.8	1.71
85.7	1.76
199.5	1.68
225.5	1.59
71.5	2
304.1	1.72
0	1.81
0	2.33
9.7	
23.6	
50.7	3
565.8	1.9
258.1	1.85
123.1	1.85
196.6	
48.4	1.72
154.3	
71.1	
19.6	2.23
9.6	
15.8	2.75
10.7	3.24
78.5	3.56
276.7	3.34
338.1	1.36
65.3	1.92
197.4	1.76
154.5	2.64
27.9	1.93
67.6	
31	2.43
16.9	2.71
11.5	3.02
47.5	3.36
173.6	3.47
134.7	2.88
199.4	1.35
315.8	1.73
358.9	1.65
204.8	1.6
49.1	1.91
20.7	1.98
0	2.29
44.5	2.57
20.2	3.08
51	3.37
226.4	
233.6	2.52
380.9	
305.6	
791.1	1.34
285.9	
106.2	1.71
216.7	1.77

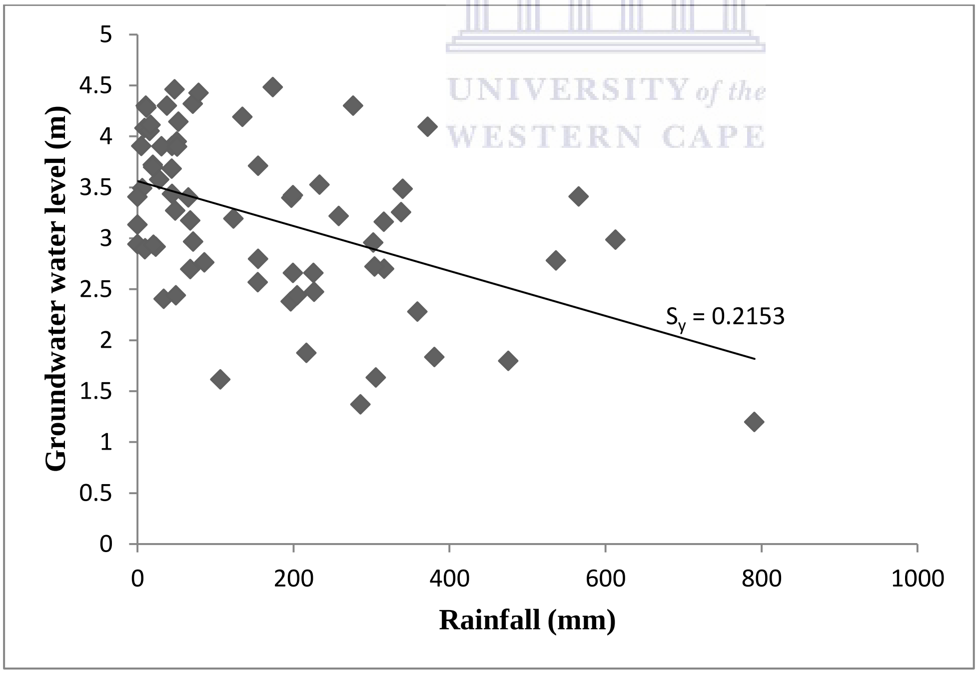
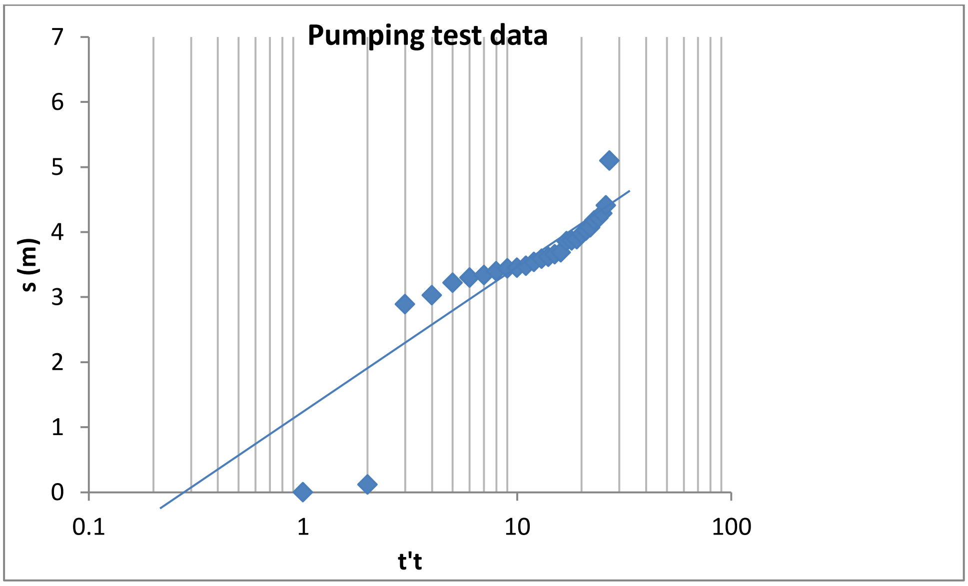


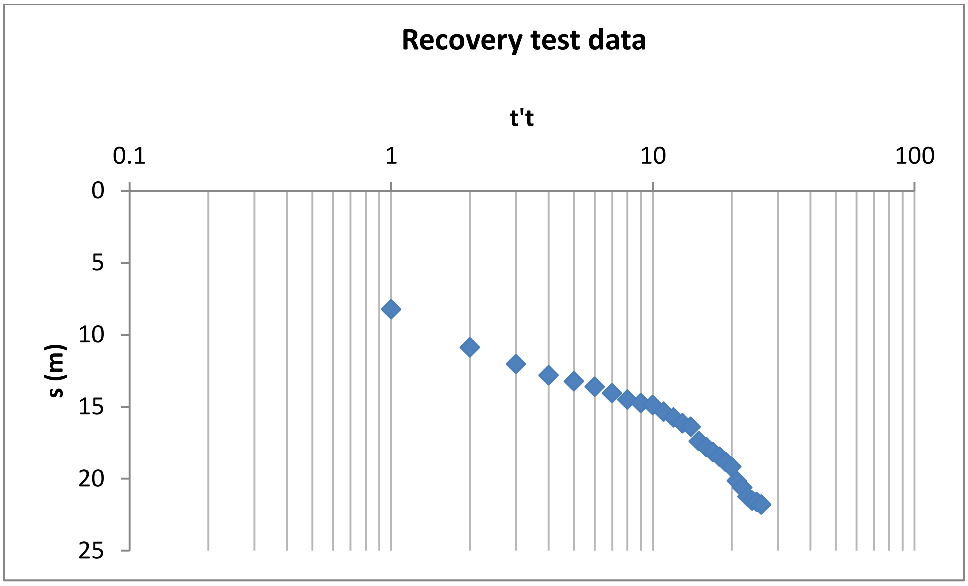
Figure 16: Determination of specific yield using the envelope straight line of the precipitation–groundwater rise points of each registered rainfall–recharge event

Pumping test data

SITE NAME: BERG UPPER CATCHMENT			
PUMPING BOREHOLE No. 1			
DEPTH OF BOREHOLE: 162m			
DATE: 01 AUGUST 2014			
TIME THE TEST STARTED: 10:30 am			
TIME THE TEST ENDED: 12:30			
WEATHER: VERY SUNNY (27^{0}C)			
STATIC WATER LEVEL: 5.80m			
TIME	**WATER LEVEL**	**DRAWDOWN (s)**	**PUMP RATE**
10:30	**5.8**	**0**	
10:31	**5.92**	**0.12**	
10:32	**8.69**	**2.89**	
10:33	**8.83**	**3.03**	
10:34	**9.02**	**3.22**	
10:35	**9.1**	**3.3**	
10:36	**9.14**	**3.34**	
10:37	**9.2**	**3.4**	
10:38	**9.24**	**3.44**	
10:39	**9.25**	**3.45**	
10:40	**9.28**	**3.48**	
10:42	**9.34**	**3.54**	
10:44	**9.39**	**3.59**	
10:46	**9.42**	**3.62**	
10:48	**9.46**	**3.66**	
10:50	**9.49**	**3.69**	
10:55	**9.66**	**3.86**	
11:00	**9.67**	**3.87**	
11:05	**9.69**	**3.89**	
11:10	**9.77**	**3.97**	
11:15	**9.82**	**4.02**	
11:25	**9.87**	**4.07**	
11:35	**9.98**	**4.18**	
11:45	**10.02**	**4.22**	
12:00	**10.09**	**4.29**	
12:15	**10.21**	**4.41**	
12:30	**10.9**	**5.1**	

TIME'	WATER LEVEL	RESIDUAL DRAWDOWN (s')	(s')
12:30	10.9	0	0
12:31	8.03	-2.87	8.2369
12:32	7.6	-3.3	10.89
12:33	7.43	-3.47	12.0409
12:34	7.32	-3.58	12.8164
12:35	7.26	-3.64	13.2496
12:36	7.21	-3.69	13.6161
12:37	7.15	-3.75	14.0625
12:38	7.09	-3.81	14.5161
12:39	7.06	-3.84	14.7456
12:40	7.04	-3.86	14.8996
12:42	6.98	-3.92	15.3664
12:44	6.93	-3.97	15.7609
12:46	6.88	-4.02	16.1604
12:48	6.85	-4.05	16.4025
12:50	6.73	-4.17	17.3889
12:55	6.68	-4.22	17.8084
13:00	6.64	-4.26	18.1476
13:05	6.6	-4.3	18.49
13:10	6.56	-4.34	18.8356
13:15	6.52	-4.38	19.1844
13:25	6.41	-4.49	20.1601
13:35	6.36	-4.54	20.6116
13:45	6.29	-4.61	21.2521
14:00	6.26	-4.64	21.5296
14:15	6.25	-4.65	21.6225
14:30	6.23	-4.67	21.8089





Calculations

1. Average flow rate Q = 2,01 l/s

   1 l/s = 86,4 m^3/d

   $Q = \frac{2{,}01\ l/s\ x\ 86{,}4\ m^3/d}{1\ l/s}$

   Q= 2,01 l/s x 86,4 m^3/d

   Q= 173,66 m^3/d

2. $\Delta s\ (3{,}79\ m - 3{,}01\ m)$

   $\Delta s\ (0{,}78\ m)$

3. Transmissivity (T) = $\frac{2.3Q}{4\pi\Delta s} = \frac{2.3(173{,}66\ m^3/d)}{4\pi(0{,}78\ m)}$

   (T)= 40,7 m^2/d

4. $t_\circ$ = 0,45/1440 $t_\circ$ = 0,003125

5. Storativity (S) = $\frac{2.25Tt_\circ}{r^2} = \frac{2{,}25(40{,}7)(0{,}003125)}{(22)^2}$

   (S) = $5{,}9132 \times 10^{-3}$

6. $\Delta s\ (1{,}70\ m - 1{,}12\ m)$

   $\Delta s\ (0{,}58\ m)$

7. Theis recovery equation (T) = $\frac{2.3Q}{4\pi\Delta s} = \frac{2.3(173{,}66\ m^3/d)}{4\pi(0{,}58\ m)}$

   (T) = 54,8 m^2/d

date	wtf	rainfall
20080124	-0.24345	44
20080225	-0.60345	44.4
20080326	-0.85345	9
20080429	-1.30345	37.8
20080528	-0.86345	372.3
20080624	0.426552	340.1
20080729	0.736552	536.5
20080827	0.456552	302.5
20080928	0.736552	475.5
20081030	0.496552	33.5
20081126	0.366552	154.7
20081222	0.026552	67.6
20090129	-0.22345	6.3
		8
20090330	-0.75345	5.1
20090430	-1.19345	52.5
		316.2
20090601	0.596552	612.8
20090728	0.546552	85.7
20090827	0.626552	199.5
20090929	0.716552	225.5
20091029	0.306552	71.5
20091126	0.586552	304.1
20091222	0.496552	0
20100128	-0.02345	0
		9.7
		23.6
20100422	-0.69345	50.7
20100526	0.406552	565.8
20100629	0.456552	258.1
20100729	0.456552	123.1
	2.306552	196.6
20100901	0.586552	48.4
		154.3
		71.1
20101223	0.076552	19.6
		9.6
20110216	-0.44345	15.8
20110330	-0.93345	10.7
20110428	-1.25345	78.5
20110526	-1.03345	276.7
20110623	0.946552	338.1
20110728	0.386552	65.3
20110830	0.546552	197.4
20110927	-0.33345	154.5
20111027	0.376552	27.9
		67.6
20111222	-0.12345	31
20120126	-0.40345	16.9
20120223	-0.71345	11.5
20120328	-1.05345	47.5
20120420	-1.16345	173.6
20120524	-0.57345	134.7
20120627	0.956552	199.4
20120720	0.576552	315.8
20120829	0.656552	358.9
20120925	0.706552	204.8
20121018	0.396552	49.1
20121128	0.326552	20.7
20121219	0.016552	
20130117	-0.26345	44.5
20130228	-0.77345	20.2
20130326	-1.06345	51
		226.4
20130530	-0.21345	233.6
		380.9
		305.6
20130822	0.966552	791.1
		285.9
20131010	0.596552	106.2
20131128	0.536552	216.7

BH00034

date	wlf	rainfall
20080124	-0.55717	44
20080225	-0.76717	44.4
20080326	-1.00717	9
20080429	-1.23717	37.8
20080528	-1.23717	372.3
20080624	-1.03717	340.1
20080729	0.332833	536.5
20080827	0.482833	302.5
20080929	3.412833	475.5
20081030	2.232833	33.5
20081126	1.252833	154.7
20081222	0.632833	67.6
20090129	0.022833	6.3
		8
20090312	-0.47717	5.1
20090430	-0.91717	52.5
		316.2
20090601	-0.80717	612.8
20090728	0.922833	85.7
20090827	1.092833	199.5
20090929	1.092833	225.5
20091029	0.782833	71.5
20091126	1.092833	304.1
20091222	0.782833	0
20100128	0.072833	0
		9.7
		23.6
20100422	-0.82717	50.7
20100526	-0.60717	565.8
20100629	-0.30717	258.1
20100729	-0.26717	123.1
		196.6
20100901	-0.47717	48.4
		154.3
20101124	-0.81717	71.1
20101223	-0.99717	19.6
		9.6
20110216	-1.29717	15.8
20110330	-1.51717	10.7
20110428	-1.63717	78.5
20110526	-1.67717	276.7
20110623	-1.10717	338.1
20110728	-0.78717	65.3
20110830	-0.89717	197.4
20110927	-0.94717	154.5
20111027	-1.06717	27.9
		67.6
20111222	-1.35717	31
20120126	-1.58717	16.9
20120223	-1.69717	11.5
20120328	-1.85717	47.5
20120420	-1.88717	173.6
20120524	-1.77717	134.7
20120627	-1.28717	199.4
20120720	-0.42717	315.8
20120829	2.042833	358.9
20120925	1.672833	204.8
20121018	1.982833	49.1
20121128	0.972833	20.7
20121219	0.632833	0
20130117	0.202833	44.5
20130228	-0.22717	20.2
20130326	-0.42717	51
		226.4
20130530	-0.70717	233.6
		380.9
		305.6
20130822	4.092833	791.1
20130918	3.912833	285.9
20131011	3.632833	106.2
20131128	3.162833	216.7

BH00038

date	wlf	rainfall
20080124	-0.27804	44
20080225	-0.36804	44.4
20080326	-0.40804	9
20080429	-0.38804	37.8
20080528	-0.20804	372.3
20080624	0.131958	340.1
20080729	0.561958	536.5
20080827	0.161958	302.5
20080929	0.431958	475.5
20081030	0.031958	33.5
20081126	-0.03804	154.7
20081222	-0.20804	67.6
20090129	-0.29804	6.3
		8
20090312	-0.42304	5.1
20090430	-0.34804	52.5
	-0.17804	316.2
20090601	0.501958	612.8
20090728	0.211958	85.7
20090827	0.271958	199.5
20090929	0.181958	225.5
20091029	-0.01804	71.5
20091126	0.121958	304.1
20091222	-0.12804	0
20100128	-0.29765	0
	-0.37969	9.7
	-0.39566	23.6
20100422	-0.35179	50.7
20100526	-0.05137	565.8
20100629	0.172652	258.1
20100729	0.20521	123.1
	0.141156	196.6
20100901	0.050652	48.4
	-0.04739	154.3
20101124	-0.15522	71.1
20101223	-0.26409	19.6
	-0.37042	9.6
20110216	-0.44095	15.8
20110330	-0.47552	10.7
20110428	-0.41913	78.5
20110526	-0.21647	276.7
20110623	0.365231	338.1
20110728	0.175466	65.3
20110830	0.128759	197.4
20110927	0.120263	154.5
20111027	-0.06273	27.9
	-0.17395	67.6
20111222	-0.25666	31
20120126	-0.36969	16.9
20120223	-0.46357	11.5
20120328	-0.50214	47.5
20120420	-0.42194	173.6
20120524	-0.24772	134.7
20120627	0.035527	199.4
20120720	0.33977	315.8
20120829	0.435681	358.9
20120925	0.269041	204.8
20121018	0.270587	49.1
20121128	-0.13804	20.7
20121219	-0.07804	0
20130117	-0.26804	44.5
20130228	-0.12569	20.2
20130326	-0.23369	51
	0.047305	226.4
20130530	0.315775	233.6
	0.689097	380.9
	0.890024	305.6
20130822	1.325237	791.1
20130918	1.013277	285.9
20131011	0.896535	106.2
20131128		216.7

BH00047