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ASSESSING GROUNDWATER-SURFACE WATER INTERACTION AS A DECISION-MAKING TOOL LICENSING WATER USE SOUTH AFRICA: CASE STUDY AREA OF GEVONDEN FARM

By

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A thesis submitted in fulfillment of the requirements for the degree of Master of Science (MSc) in Environmental and Water Sciences, Department of Earth Sciences, Faculty of Natural Sciences, University of the Western Cape, South Africa

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Declaration

I declare that "*Assessing groundwater-surface water interaction as a decision-making tool licensing water use South Africa: Case study area of Gevonden Farm*" 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.

NAME: **Mfundi Cyril Biyela**

SIGNED: ……………………………….

Dedication

I would like to dedicate this work to the heavenly God, for His omnipresence in my life and work. Without Him I would not have reached this far. My mother and father I whole heartedly dedicate this work to you too for the spirit you have to understand your son and accepting who I am with appreciation but not trying to alter me to be another person.

My parents King and Khulile Biyela I may not have any thing tangible and material to put before you as thanks giving. I may not be able to stand before you and utter the utterances that would make you happy forever. I may not be walking a walk you would wish for your child to walk. I may be different from all of my siblings. However one thing for sure you need to know from inside me, is that I love both of you with all my heart and you mean a lot to me.

I wholeheartedly dedicate this work to you as one of the ways to demonstrate the love I have for you. I would have loved, if you were able to comprehend each and every word written in this thesis and whishing if you could be able to conceptualize all the geohydrologic concepts and understand the theories presented in this work. I would have the immeasurable happiness to share ideas with you and get corrected by you as we discuss. However, you have supervised me since I was born and you have guided me from my entire walk until today, I salute you. Therefore let us leave this field for its experts to supervise and nurture me.

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Abstract

Assessing groundwater-surface water interaction as a decision-making tool licensing water use South Africa: Case study area of Gevonden Farm is the title of the current study with the context that arises from the use of GRAII methodology which uses quaternary catchment boundaries for groundwater abstraction water use licence application assessment during decision making. The problem is that the quaternary catchment scale approach does not provide the scientific bases for site specific scale. The current study argues that such approach provides realistic, practical information at site specific scale and therefore informs the issuing of licences more accurately.

The aim of the current study is to improve understanding of how the assessment of groundwater abstraction water use licence should be carried out at a site specific scale to improve decision making during licence issuance. The objective of the study is to outline the scientific study and demonstrate how the investigation that leads to the decision making can be conducted. The study was carried out using hydraulic methods such as pumping test and geochemical analysis method. Hydraulic properties were determined and chemical elements were analysed for and compared with the SANS 241 water quality standards for domestic and agricultural use. Hydraulic properties such as hydraulic conductivity (K), transmissivity (T), yield and storativity (S) were determined. Major and minor ions that are required to be analysed for domestic and agricultural water use were analysed. Piper diagrams and FC method were used to analyse data.

The piper diagrams plotted indicated that surface water is mixing with groundwater and that means there is connection between groundwater and surface water. The chemical elements analysed for were compared with SANS 241 water quality standards for domestic and agricultural use. The water quality on the investigated site can be categorized as having good water quality. A sustainable yield estimated from the two boreholes (BH03 and BH05) which was 1.02 l/s. The available drawdown estimated with reference to the boreholes water strikes that were determined by EC profiling were 135 mbgl from both boreholes. The study recommends the issuance of water use licence with conditions that chemistry of water should be analysed for once a quarter and boreholes water levels should be analysed for once a month.

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1 Chapter 1: General Introduction

1.1 Overview/Synopsis of the study

The present study shows i) why it is important to conduct a pumping test to estimate hydraulic parameters from the borehole in support of a water use licence ii) how the geochemical analysis used to support the issuance of water use licence, and iii) how improved understanding of how groundwater-surface water (GW-SW) interaction is used to facilitate decision-making process for licensing groundwater abstraction at a local scale. The study also shows that there are feasible and adaptive conventional methods or approaches that could be implemented at local scale such as farm scale level. The research assessed the groundwater abstraction water use licence using Gevonden Farm as case study area and then generated a model for licensing groundwater abstraction at a local scale with the goal of replicating such an approach in other catchments of similar environment. As a showcase, the thesis i) demonstrates how local based methods function at farm level for licensing groundwater abstraction and ii) provides the basis to recognize the potential of such a local method for wider replication of such an approach.

1.2 Background of the study

In the Department of Water and Sanitation (DWS), sub-directorate: Water Use is responsible for assessing and processing of water use licence applications. For the past years until present there has been an increase in a number of groundwater abstraction water use licences received from different clients such as agricultural sector and local governments. The increase of groundwater abstraction water use licence is due to various reasons, first being the surface water resources abstraction not allowed to be abstracted in some areas because of the identified deficit in terms of the Reserve and the second reason being the surface water resource too far from the area in need of water.

For groundwater abstraction water use licence to be issued, DWS geohydrologist must give comments recommending the issuance or none issuance of a licence. Generally, the geohydrological report submitted by the client as a supporting document must be estimating the following: 1) Available groundwater for abstraction in the area, 2) Sustainable yield (safe aquifer yield), 3) Hydraulic properties to do risk analysis by uncertainty propagation, 4) Available drawdown, and lastly, 5) Resource Directed Measures (RDM) should provide the Reserve which is calculated at quaternary catchment scale. However, most of the reports submitted with the groundwater abstraction water use licence application do not respond to these issues and therefore it becomes difficult to recommend most of the licences for issuance. If the recommendation is issuance of groundwater abstraction water use licence it becomes a baseless recommendation as it lacks science base and management recommendations for groundwater abstraction are also baseless and may be misleading.

The Reserve by definition is the quantity and quality of water required to satisfy basic human needs and protect aquatic ecosystems in order to secure ecologically sustainable development and use of water resources. It was understood that the Ecological Reserve specifically excludes water required to maintain terrestrial ecosystems (including terrestrial vegetation). However, the bucket analogy used to determine the Reserve is inappropriate for groundwater (Steward et al., 2006). This is due to the monitoring data which are often not diagnostic. This compounded difficulties in assessing current processes and making reasonable prediction. Water levels alone are ambiguous and cannot be relied upon to determine whether a system is sustainable or not. For example declining water levels may indicate that a resource is being over-abstracted and will eventually be depleted. Or they may indicate that water is being taken from storage in the short term, as a precursor to equilibrium conditions being established. These examples and issues clearly suggest that our groundwater, and groundwater-related, knowledge base is imperfect, and our ability to predict outcomes is highly uncertain. Thus the conditions have been identified where the application of adaptive management would be either beneficial or even necessary.

Other uncertainties exist that hinder making the correct decision and assemble the correct and feasible conditions to a licence. Those uncertainties are as mentioned by Steward et al (2006): 1) Lack of knowledge of groundwater use, 2) Lack of knowledge on regional status of groundwater resources, 3) lack of knowledge to determine groundwater parameters, 4) lack of ability to predict the impacts of groundwater abstraction on surface water and ecological systems and 5) Lack of ability to predict future outcomes. Because of the above mentioned uncertainties the current study seeks to demonstrate what kind of a geohydrological report that can be compiled in support of a groundwater abstraction water use licence and give a guide how the decision can be made from such geohydrological report.

In South Africa, the previous studies on groundwater-surface water interaction which focuses on groundwater licensing indicate that investigations have been conducted at a quaternary catchment scale using international methods of quantifying groundwater (DWAF, 2004). With an intention of accounting for the issuance of groundwater abstraction licence, DWS embarked on a series of studies (DWA report 3bA, 3bB, 3bC, 3bD and 3bE). The final product of the studies was to develop methodology to quantify groundwater without double accounting for baseflow in the quaternary catchment using the Pitman model (Pitman, 1973)with some additions from Hughes (1997). The excel-based tool (known as GRAII) developed from Pitman model with some additions from Hughes was also produced. Using the data from WR90 (Midgley, et al., 1994) it calculates the total of groundwater available in the quaternary catchment, what has been allocated, how much is required by the ecosystem and how much is left from which an applicant can abstract.

The recent study by Water Research Commission indicated the possibility of determining the groundwater-surface water interaction at a local scale (Matthews, 2013). The project uses Mixing Cell Model (MCM) to assess groundwater resource and its interaction with surface water at a local scale. It reviews the methodology used by DWS to determine the groundwater resource and its interaction with surface water resource at a quaternary catchment scale. It quantifies the groundwater availability at a sit specific scale using MCM and compares it with the quantified amount of water by DWS methodology at a quaternary catchment scale. The quaternary catchment which according to DWS methodology, its groundwater has all been allocated is found to be having a significant amount of water at a site specific scale.

Beside conduction of groundwater-surface water interaction at local scale, in 2014 Nelson identified the legislation and policy loophole in the report about the impact of groundwater abstraction to rivers. Legislation and policies only covers the surface water and ignore groundwater component and its interaction with surface water resources. The loophole in the legislation and policies hinders a correct and informed decision-making during licence issuance (Nelson, 2014)

The groundwater assessment for different countries is controlled by the groundwater situation in a specific country. Other countries such as Canada have groundwater quality issues, so their groundwater management strategies focus on groundwater quality management. Other countries, mostly arid to semi-arid focus on groundwater allocation management, while others such as South Africa and Australia, focus on both water quality and groundwater allocation management. South Africa is one of the countries that are affected by both groundwater contamination because of industries and intensive commercial farming and groundwater scarcity because it is an arid country whilst the water demand is high, so it manages both. Most of the countries such as Australia and South Africa are conducting their groundwater assessment studies at a quaternary catchment scale for decision making during groundwater abstraction licence issuance. There is little literature that has been done at a site specific scale for groundwater assessment.

In Australia, the assessment of groundwater resource for human consumption before issuance of water use licence requires Department of Water in Australia to know the suitability of groundwater quality, and the yield that can be provided by a borehole. The assessment of any resource (Groundwater or surface water resource) includes the determination of groundwater and surface water interaction using methods such as integrated surface water-groundwater models, hydrograph separation techniques, and environmental tracer methods. However, the disadvantages with most of these methods are that they have been applied at quaternary catchment scale, the second disadvantage is that they do not account for double accounting in water resources assessment, which has drawn the attention of many researchers globally and hinder the correct decision making during the groundwater and surface water licence issuance.

The focus in Canada is more on the groundwater quality then groundwater allocation. The Environmental Canada, 2004b refers to Canada as the fortunate country with enormous resources of freshwater. Almost 900 000 km^2 or 80 percent of the nation's total area is covered with fresh surface water. The groundwater abstraction is takes place to dewater the mining area and some residential areas so that they do not get disturbed by enormous ground and surface water. Their groundwater-surface water interaction studies are not giving much of a focus in terms of a yield but they are focused more on groundwater pollution. Hence, the Canadian government has taken groundwater management initiative for the betterment of deeper understanding in groundwater quality, and protection of groundwater dependent ecosystem (Council of Canadian Academies, 2009). In Canada the law that governs water is Canada Water Act (Canadian Ministry, of Justice, 1985) and it focuses more on the management of water resources, Research, planning and implementation of programs relating to the conservation, development and utilization of water resources and meeting the present and future water demands. Provinces are responsible for water use licence applications. The administrative procedure to issue the water use licence may differ from province to province as the Water Acts differ from Province to province.

In the United Kingdom the United Kingdom Water Act (United Kingdom, 2003) is used to regulate water resources. The main focus of their water act is on abstraction and impounding of water, applications for a licence, modification of licences, claims and compensation, water resources management schemes, miscellaneous, supplementary, regulations, orders and schedules. Environment agency is responsible for processing water licence application in the United Kingdom. The form for application for a water resource abstraction (WR330) requires the applicant to provide groundwater investigation as part of the required documents. However, the form does not specify the content of groundwater investigation but it mentions the submission of pumping test results to the Agency. The Environment Agency on its environmental management guide gives the conditions of the variables that need to be monitored; however, it does not specify the frequency.

The Southern African Development Communities (SADC) is impacted by climate change, which makes it to be between semi-arid to arid region (Abiye, 2012), therefore the focus of the studies is more on climatic change and drought. The groundwater levels data from boreholes is monitored with a purpose of predicting the impact of drought; therefore, their groundwater assessment is expected to be regional (large scale). This limits the availability of a literature for groundwater-surface water interaction and for groundwater assessment at local scale. The climate change causes a shift of water use from surface water resource to groundwater resource as the water demand increases due to development and population increase. It is not taken into consideration that when surface water resources dry up the groundwater resource will also dry up because of the continuous interaction between the two resources and the study does not address groundwater use licencing.

The determination of groundwater-surface water interaction requires the intensified groundwater monitoring network and other programmes to determine various parameters at a quaternary catchment scale. The conduction of groundwater assessment study at local scale is more expensive for the individuals to afford and it is not a requirement before the licence is issued in most of the SADC countries. Some of the countries such as Lesotho, Botswana, Zimbabwe, Swaziland and Namibia in the SADC region do not have the well established groundwater monitoring systems. To these countries the states of water resources management is low and still not prioritized because of lack of capital to fund their water resources management. Initiatives by some of the countries in the SADC region (South Africa, Angola, Botswana, Namibia, Mozambique, Zambia, Tanzania and Zimbabwe) have been taken to monitor and intensify groundwater monitoring networks for the betterment of groundwater management in the region (International Groundwater Resources Assessment Centre, 2013). Nothing much in the SADC literature indicates the initiatives towards quantification of GW-SW interaction in most of the countries in the SADC region except South Africa.

The groundwater management in South Africa is compromised by the trans-boundary groundwater systems because the way South Africa is monitoring and managing the groundwater resource in that trans-boundary aquifer is not applicable in another neighboring country with which the aquifer is shared. Currently, monitoring of trans-boundary groundwater systems in the SADC region is nonexistent (Abiye, 2012). The currently targeted trans-boundary aquifer shared by Namibia, Botswana and South Africa has been given the priority (SADC (Southern African Development, Community);, 2010). However, capacity building in different fields of groundwater management such as groundwater quality and quantity and GW-SW interaction is required (Abiye, 2012).

1.3 Problem statement of the study

The lack of scientific based approach for decision making at site specific scale for the issuance of groundwater abstraction water use licence is a reason for conducting the current study. The study argues that the quaternary catchment scale method used by DWS for making a decision during the groundwater abstraction licence issuance cannot be used as the scientific base at site specific scale. Many licences have been issued based on the quaternary catchment method; hence, those licenses do not have scientific conditions and recommendations with which the groundwater resource can be managed.

DWS regional offices have indicated the dissatisfactory views about the use of method based on a quaternary catchment scale (Groundwater Technical forum (GTF), 2013, Limpopo Regional Office). The problem started to be noticed because of the increase in a number of water users complaining that their boreholes are drying up because of the neighboring water users who are over pumping their boreholes. The DWS had to review their conditions and recommendations that were put in their water use licences backed up by geohydrologic principles. However, it became clear that there is a lack of scientific reasoning behind the conditions and recommendations in most of the water use licences.

Lack of methodology for assessing groundwater at site specific scale have negative implications on the groundwater management because of the lack of scientific based decision making at site specific scale. The management recommendations and conditions given in water use licence should be manageable and speak to the groundwater management problems with which DWS is faced. It also leads to non compliance (over pumping of boreholes by water users). The problem is caused by the lack of qualified personnel in a field of geohydrology within the Department and the lack of trained personnel that will monitor groundwater pumping on site.

Lack of the staff from Head Office pioneering the application of geohydrology in Water Use sub-directorate is another cause of the problem. The drivers of the problem are political and also economical. The political interference during the processing of water use licence by municipal officials and other stakeholders puts pressure to DWS officials to take a decision based on the commonly used quaternary catchment scale methodology as the local methodology is time consuming and unaffordable. Some of the clients cannot afford the costs to hire a geohydrological consultant to carry the site specific scale geohydrological report.

1.4 Research question

The main research question of the current study is that, what can be the scientific basis for the decision making during assessment of groundwater abstraction water use licence for recommending or not recommending the issuance at a site specific scale. The current study provides better scientific basis of conditions and recommendations that can be used to support the issuance or none issuance of the water use licence for groundwater abstraction. The other three sub-questions that needed to be asked for each objective are: i) How can the establishment of groundwater-surface water interaction be used to support the issuance or none issuance of water use licence for groundwater abstraction? ii) How can the pumping test be used to support the issuance or none issuance of the water use licence for groundwater abstraction? iii) How can the water quality assessment be used to support the issuance or none issuance of water use licence for groundwater abstraction?

1.5 Research Hypothesis

The assumption is that the proposed approach for decision making during assessment of water use licence for groundwater abstraction at a site specific scale provides scientific basis of conditions and recommendations for groundwater management using the following methods:

- The methodology of stream flow gauging is appropriate to establish if there is interaction between groundwater and surface water at a site specific scale.
- The method of conducting a pumping test is appropriate for determination of the sustainable yield and putting the borehole management recommendation.
- The method that is used to ascertain if groundwater is fit for irrigation use by comparing the chemical concentrations of water with South African water quality guidelines for agricultural use: irrigation is appropriate.

1.6 Aim and objectives of the study

1.6.1 Study aim

The aim is to improve understanding of how the assessment of groundwater abstraction water use licence should be carried out at a site specific scale to improve decision making during licence issuance and site specific based groundwater management.

1.6.2 Study objectives

The specific objectives of this study are to:

1. Determine hydraulic properties of the aquifer at the local scale in the case study area.
2. Assess groundwater and surface water quality for irrigation in the case study area.
3. Evaluate groundwater contribution to surface water in the case study area.

1.7 Scope, nature and rationale of the study

The scope and rationale of the current study is aimed at giving brief overview of the component of geohydrology under which the study is conducted and to give the reason why the study of this nature needed to be conducted.

1.7.1 The scope of the current study

Within the whole scope of geohydrology that includes groundwater recharge, groundwater flow patterns and discharge, the current study is on the groundwater discharge component. The discharge component of geohydrology includes natural discharge which is springs and baseflow and artificial discharge which is groundwater abstraction through boreholes. The scope of the current study is focused on groundwater abstraction at a site specific scale, strictly focusing at groundwater abstraction licencing, groundwater quality and spatial and temporal variations of groundwater-surface water interaction.

1.7.2 Nature of the current study

Groundwater abstraction licensing requires an applicant to fill in a form (DW784) that requires pump information then it requires aquifer and the surrounding information. The only geohydrologic information requested from an application form is about maximum pumping hours in section 2 and coordinates, yield and depth of a borehole are also requested in section 6 of an application form. The additional information that would be requested by DWS officials does not have details on what is required under each section of a geohydrological report. DWS personnel are not trained to evaluate the submitted additional information and to take an informed decision based on the submitted information. If an official happen to be professional geohydrologist most of the geohydrological reports are not clear to assist in decision making.

If the decision taken after review of a licence is that licence should be issued, the licence issued will have inter alia geohydrological conditions. The geohydrological conditions are derived from a geohydrological report submitted. Part of those geohydrological conditions are 1) how much water should be pumped from a borehole, 2) where the pump should be installed, 3) fitness of water for human consumption or agricultural purpose, 4) how far it should be from other water resources including neighboring boreholes, 5) what is the sustainable yield for the borehole.

1.7.3 The rationale of the current study

The current study is important because it will enhance groundwater management both at site specific and quaternary catchment scales. It will also improve knowledge of geohydrologist and water use licences assessors on additional required information on groundwater abstraction licencing and they will know what to ask for and what to expect from the water use applicants. The information in the current study is needed by DWS and other water institutions, Municipalities, Department of Rural Development and Land Reform, Farmers and Mines

The current study teaches geohydrologist and other DWS officials what is expected from the geohydrological report that is always requested by them as additional information that will assist in groundwater use licence processing. Geohydrological consulting firms will learn what kind of a study that is required to be conducted when DWS request the geohydrological report for groundwater abstraction licence application. Other stakeholders such as Department of Rural Development and Land Reform, Municipalities and Mines will learn what kind of a study is expected to come with groundwater abstraction water use licence and they will be able to do correct cost estimates how much it will be spent for water use licence application.

1.8 Brief overview of the study area (Case study area)

The selected case study area of Gevonden Farm is located at Rawsonville Town towards the south western part of Worcester in the Western Cape Province. Western Cape Province is in a Mediterranean region at the southern tip of South Africa. University of the Western Cape Groundwater Research Site is situated near the stream known as Watervalskloof stream. The case study area is part of Breede River catchment and situated in the upper reaches of Breede River (within Molenaars River, quaternary catchment H10J) in the intermountain region of Western Cape Province (Figure 1-3).

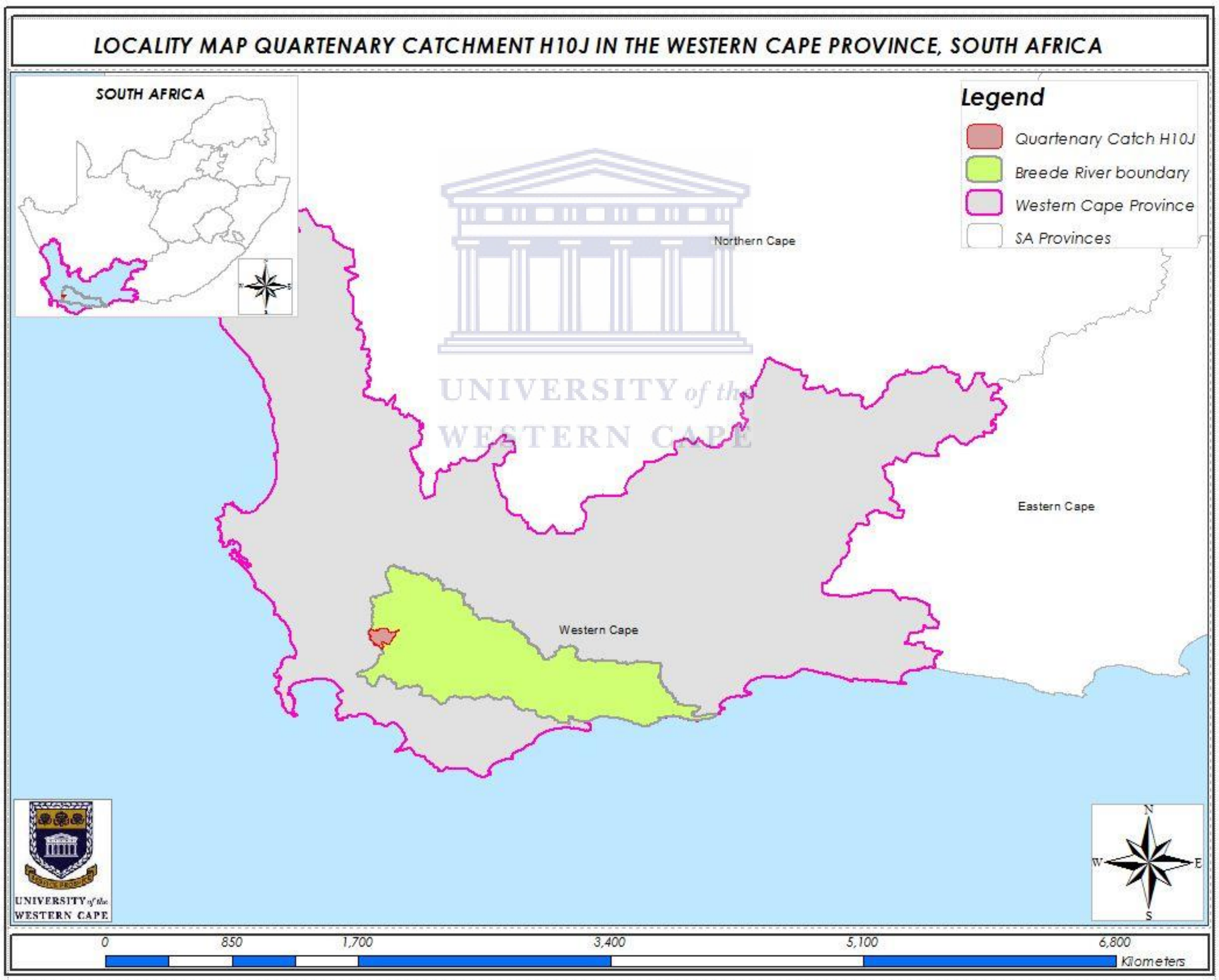

Figure 1-1: Locality map for Molenaars river catchment in Breede river catchment

1.9 Structure of the thesis

Chapter one introduces and gives the background of the current study and the aim and primary objectives of the project. Theoretical and conceptual framework is also introduced in this chapter. Chapter two presents the gap in the theories that inform the current practice of assessing the groundwater resource. Chapter three gives the physiographic of the case study area where by the position of the area of interest is shown. The chapter includes description of site specific and quaternary catchment geohydrology, geology and climatic conditions. It further entails the technical and the desktop based methods that were used during the investigation. Some of the methods that were used are chemical, hydrogeological and computer software based tools. Chapter four presents the hydraulic properties estimated from the pumping test conducted from BH03 and the observation boreholes (BH01, BH02, BH04 and BH05) in the case study area. The chapter further interprets and discusses the presented results and gives a summery to a chapter. In the chapter the sustainable yield, available drawdown, pump depth installation and the pumping cycle is recommended. Chapter five presents the results of chemical analysis data obtained from a laboratory. The chapter further interprets and discusses the presented results and gives a summary at the end of the chapter. In the chapter the concentration of chemical elements is compared with the South African water quality guidelines for irrigation and the recommendation whether water is suitable for irrigation is made. Chapter six presents the results generated from the streamflow measurements on site. The chapter further interprets and discusses the presented results and gives a summary to a chapter. In this chapter the interaction between groundwater and surface water is evaluated and recommended for further research as future hypothesis. Chapter seven concludes, recommends and suggests the further research hypothesis on a subject of decision making during the recommendation of issuance or none issuance of the groundwater abstraction water use licence. The chapter further recommends adaptive management and capture principle as the other approaches to be used for groundwater management.

2 Chapter 2: literature review

2.1 Introduction

This chapter presents the review from peer-reviewed journals and some reports with the purpose of showing what is known and unknown about the available approaches for the assessment of groundwater abstraction water use licence issuance. In order to achieve such a purpose, the review has been presented systematically following specific objectives set in chapter one and also analytically to highlight the gap in literature about the use of quaternary catchment scale methodology to make a decision at site specific scale. Finally, conceptual and theoretical frameworks which inform the current study have been provided.

This study argues that currently, decision-making processes to issue groundwater abstraction water use licenses are based on quaternary catchment scale methods which do not consider site specific issues or local context. Therefore, there is a need to develop site specific approach that would focus on the local scale issues. Based on this argument, the literature review justifies the need for developing site specific approach for practical decision making. The review also shows how theoretical catchment scale methods fail to work in reality.

Quaternary catchment scale methods fail to inform decision that is practical to issue water use licence. The current practice of issuing water use licence is informed by results from assessments that use quaternary catchment scale methods. These methods are designed to capture information at a large scale, thereby ignoring to capture information at local scale where water users live and need water. The result is that, what practically exists at local scale is not reflected in the assessments that use large scale methods. Therefore, decisions based on such information do not reflect reality on the ground. It can be said that such methods misinform decision makers on issuing water use license. This motivates the need to seek for site specific approach which seems to have potential to inform a practical decision for issuing groundwater abstraction water use licence. For the site specific approach to provide information for practical decision making, data should be obtained from both groundwater and surface water resources at site specific scale.

2.2 The current practice of issuing water use licence

The currently used groundwater-surface water interaction methodology (DWAF, 2006) that assists in the assessment of groundwater use licence application at a cut off scale from a country scale (GRAI) to quaternary catchment scale is known as Groundwater Resource Assessment Phase II. The tool was developed under the study known as GRA II under project 3b, and is currently used country wide to inform a decision making during groundwater abstraction water use issuance. The main objective of project 3b was to develop methodologies and databases to support groundwater resource quantification per defined management unit (DWAF, 2006).

Out of five studies that were conducted under GRA II project; the third one addresses the issues of GW-SW interaction and proposes the methodology to be used to quantify GW-SW interaction to better the decision making during licence issuance (DWAF, 2006). The project presented the MS-EXEL environment methodology that can quantify recharge, groundwater baseflow, interflow, transmission losses, groundwater evapotranspiration and outflow and the impact of groundwater abstraction on these processes at a monthly time scale.

The methodology from Report 3bC comprises the following steps: i) performing a hydrograph separation to separate groundwater baseflow (baseflow from the regional aquifer) and interflow (baseflow from perched aquifers) from storm runoff on a monthly time scale using simulated WR90 or other monthly flow data, ii) back calculating subsurface storage to calculate a monthly time series of recharge, iii) incrementing groundwater storage from recharge to a maximum aquifer capacity level, iv) depleting groundwater storage by evapotranspiration and groundwater outflow as a function of dynamic groundwater storage and rest water level conditions, v) calculating groundwater baseflow or transmission losses in a non-linear manner as a function of groundwater storage and volume, vi) depleting groundwater and groundwater baseflow due to abstraction, and vii) calculating modified groundwater baseflow and interflow conditions resulting from abstraction.

The source of data used in the methodology is Surface Water Resources of South Africa 1990 (known as WR90) which is a study conducted by consortium of consulting Engineers appointed by Water Research Commission in March 1990. The WR90 study was conducted to update and improve the 1981 survey of the Surface Water Resources of South Africa by the Hydrological Research Unit of the University of Witwatersrand. Another source of data used is the Water use Authorization Registration Management System. WARMS is the database managed and owned by DWS under Water Use: Sub-directorate. It registers Water Use Licence (WUL), General Authorizations (GA) and Existing Lawful water Use (ELU). The volume of water already licensed and the volume of water required by the ecosystem are calculated at a quaternary catchment scale. These totals are subtracted from the total amount of groundwater calculated using GRAII.

The administrative part of groundwater abstraction licensing requires an applicant to fill in the forms DW756, DW757, DW758 and DW759 for details on personal information and the property where the borehole is located. For abstracting water from a water resource the form DW773 is filled. The supplementary form DW784 for pump technical data is required. The only geohydrologic information required by a form DW784 is on pumping hours and coordinates in section 2 and yield and depth of a borehole in section 6 of the form. The additional information that is normally requested does not have details on what is required under each section of a required geohydrological report.

The other tool used is a reserve defined as the quantity and quality of water required for basic human needs and protecting aquatic ecosystems in order to secure ecologically sustainable development and use of water resources. However, the Ecological Reserve excludes water required to maintain terrestrial ecosystems (including terrestrial vegetation). The "*bucket analogy"* used to determine the Reserve is inappropriate for groundwater. This is due to monitoring data which are often not diagnostic. This compounded difficulties in assessing current processes and making reasonable prediction. Water levels alone are indistinct and cannot be relied upon to determine whether a system is sustainable or not. For example declining water levels may indicate that a resource is being over abstracted and will eventually be depleted. Or they may indicate that water is being taken from storage in the short term, as a precursor to equilibrium conditions being established. These examples and issues clearly suggest that groundwater, and groundwater-related, knowledge base is inaccurate, and our ability to predict outcomes is highly uncertain (Seward et al., 2006). Thus, the conditions have been identified where the application of adaptive management would be either beneficial or even necessary.

2.3 Previous studies on water use licences issuance

A number of studies that have been conducted for the past years show that there has always been a problem when it comes to science based decision making on groundwater abstraction water use licence. Tools have been developed to facilitate the decision making but until recent all the developed tools challenges with their application have been identified. Harvest potential is at a country scale and Groundwater Resource Assessment II is at quaternary catchment scale. These two tools proved to be having a number of inaccuracies in terms of their scientific methodologies.

2.3.1 Groundwater harvest potential (GRAI)

A number of studies have been conducted by Department of Water and Sanitation (3bA, 3bB, 3bC, and 3bD and 3bE DWA report, 2003) to assist in decision making during groundwater use licence assessment. The first well known tool produced and used by the Department is Groundwater Harvest Potential Map (GRAI) with its methodology explanatory report. The Harvest Potential Map is a map published by the DWAF (currently known as DWS) in 1996 (Baron et al., 1996). It is one map covering the whole of South Africa and was the first attempt to provide quantitative information on sustainable rates of groundwater abstraction in South Africa on a country-wide basis.

The shortcoming of the groundwater harvest potential is that it could not be applicable for the decision making at a local or site specific scale for the issuance of groundwater abstraction water use licence but it could only give the general overview of quantitative information. The second pitfall was that it considered groundwater resources in terms of recharge, a large portion of which generates baseflow, hence the simple addition of surface water runoff volumes and groundwater resources based on recharge double accounts for baseflow. The groundwater harvest potential map was not rendering the required confidence results during groundwater use assessment for the issuance of groundwater abstraction water use licence application and for decision makers and planners.

2.3.2 Groundwater Resource Assessment II (GRAII)

There was a need for the development of GW-SW interaction based methodology that will assist in the assessment of groundwater use licence at a cut off scale from a country scale to quaternary catchment scale. The tool was developed under the study known as Groundwater Resource Assessment Phase II (GRA II) under project 3b, and is currently used country wide to inform a decision making during groundwater abstraction water use issuance. The main objective of project 3b was to develop methodologies and databases to support groundwater resource quantification per defined management unit (DWAF, 2004).

Out of five studies that were conducted under GRA II project; the third one addresses the issues of GW-SW interaction and proposes the methodology to be used to quantify GW-SW interaction to better the decision making during licence issuance (DWAF, 2004). The project presented the MS-EXEL environment methodology that can quantify recharge, groundwater baseflow, interflow, transmission losses, groundwater evapotranspiration and outflow and the impact of groundwater abstraction on these processes at a monthly time scale.

The methodology from Report 3bC comprises the following steps: i) performing a hydrograph separation to separate groundwater baseflow (baseflow from the regional aquifer) and interflow (baseflow from perched aquifers) from storm runoff on a monthly time scale using simulated WR90 or other monthly flow data, ii) back calculating subsurface storage to calculate a monthly time series of recharge, iii) incrementing groundwater storage from recharge to a maximum aquifer capacity level, vi) depleting groundwater storage by evapotranspiration and groundwater outflow as a function of dynamic groundwater storage and rest water level conditions, v) calculating groundwater baseflow or transmission losses in a non-linear manner as a function of groundwater storage and volume, vi) depleting groundwater and groundwater baseflow due to abstraction, and vii) calculating modified groundwater baseflow and interflow conditions resulting from abstraction.

However, the literature show that the confidence level of the results rendered by this tool for the rapid assessment of GW-SW interaction is low as it does not account for the site specific situations. Beside its shortcomings to account for site specific issues, it is found to be having number of shortcomings (DWAF, 2006) such as: i) Uncertainty as to actual baseflow figures against which to calibrate hydrograph separations, ii) Uncertainty and lack of recharge figures to calibrate GW and GPOW, iii) Arbitrary nature of K2 and K3 parameters controlling the relationship between abstraction and baseflow depletion due to lack of data regarding impacts of abstraction against which to calibrate these parameters. In general, the impacts of abstraction on baseflow depletion may take a long time to occur; hence it is difficult to estimate.

2.3.3 Groundwater Resource Assessment III (GRAIII)

In 2009, Department of Water Affairs reviewed GRAI, GRAII and international assessment methodologies under strategy and guideline development national groundwater planning requirements. The GRAIII proposes the adoption of more sophisticated methods for groundwater management at a local scale and it also questions the algorithms used in GRA II. In this study it is further stressed that since aquifers often vary in their hydraulic properties over short distances, the variability in local scale can make the regional average meaningless. Because of the challenges encountered from GRAI and II the report proposes the intensification of monitoring at both local and regional scale and intensified operation and maintenance of monitoring systems.

2.4 Suggested methodologies during issuance of groundwater abstraction water use licence

Seeing the difficulties in decision making when it comes to groundwater abstraction water use licence over the past years methods to be used to deal with this kind of water use licence have always been suggested. Capture method and adaptive management are some of the methods that were suggested (Seward et al., 2006). In general terms, capture method is continuation of monitoring or capturing some variables before the activity of groundwater abstraction commences and during and even after the abstraction. It is believed that out of the captured data the researchers will be able to manipulate the captured data and have the scientifically reasonable recommendations over that groundwater abstraction water use. Adaptive management on the other hand is a management meant to bring about effective capturing of required data for decision making.

2.4.1 Pumping a borehole in a confined aquifer

De Smedt (2009) explained the scenario of pumped borehole in the confined aquifer. In the scenario the confined aquifer is completely closed and no input or output is possible in the vicinity of the well. However, the aquifer must receive water from somewhere further away where it is no longer confined. The area from which the aquifer receives water is referred to as recharge area. Assuming that this area is at a distance L from the pumped well and estimate the recharge by a well that injects water into the aquifer with the same rate Q as the pumped well. Using the principle of superposition it follows that:

$$s = \frac{Q}{2\pi T} In\left(\frac{r_0}{r_1}\right) - \frac{Q}{2\pi T} In\left(\frac{r_0}{r_2}\right) = \frac{Q}{2\pi T} In\left(\frac{r_2}{r_1}\right) \qquad 2\text{-}1$$

Where, s is the drawdown, T the aquifer transmissivity, r_1 the distance to the pumped well, and r_2 the distance to the recharge well. Close around the well, r_2 can be approximated as L

$$s = \frac{Q}{2\pi T} In\left(\frac{L}{r_1}\right) \qquad 2\text{-}2$$

Comparing this equation with the steady state well flow equation follows that the radius of influence equals L, hence

$$r_0 = L$$

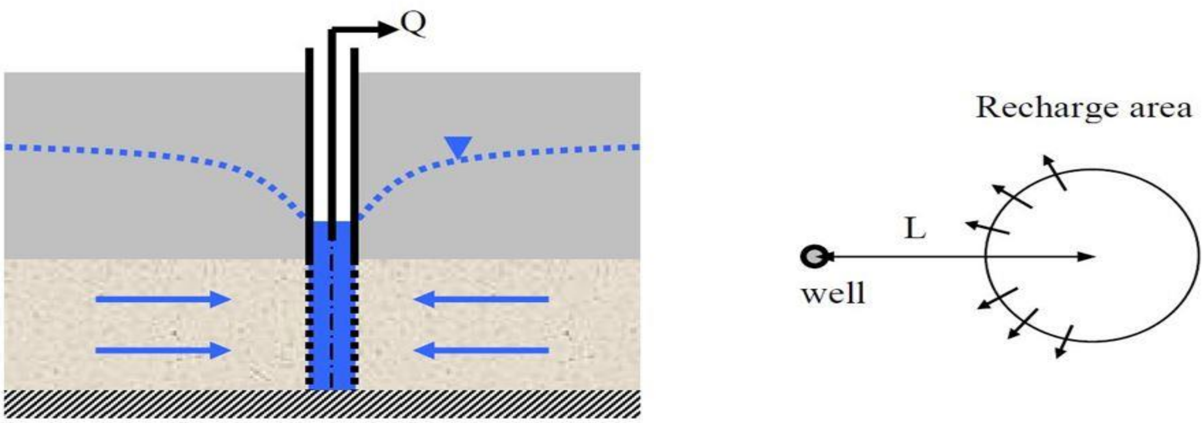

Figure 2-1: Groundwater flow towards a pumping well in confined aquifer

2.4.2 Relationship between the pumped borehole and the neighboring borehole

In a case whereby the pumped borehole is not next to any sensitive hydrological feature such as a river, wetland and estuaries but next to another borehole the effect of pumping can be measured and conceptualized by taking the nearby boreholes into consideration. The most important hydraulic properties needed to measure the period it will take before the pumped borehole has an effect to the nearby borehole are transmissivity (T) and hydraulic conductivity. Transmissivity is a measure of how much water can be transmitted horizontally in an aquifer and is defined as hydraulic conductivity multiplied with the saturated thickness of the aquifer. Hydraulic conductivity (K) is a physical property which measures the ability of the material to transmit fluid through pore spaces and fractures in the presence of an applied hydraulic gradient. For the estimation of transmissivity and hydraulic conductivity from the confined aquifer the following assumptions should be made: 1) The aquifer has infinite aerial extent, 2) The aquifer is homogeneous, isotropic and of uniform thickness, 3) The piezometric surface is horizontal prior to pumping, 4) The aquifer is pumped at a constant discharge rate, 5) The well penetrates the full thickness of the aquifer and thus receives water by horizontal flow. Consider a borehole that is pumping continuously with a constant rate (Q) in a confined or semi-confined aquifer with constant thickness b and homogeneous hydraulic conductivity (K). The situation can be represented as follows in Figure 2-2:

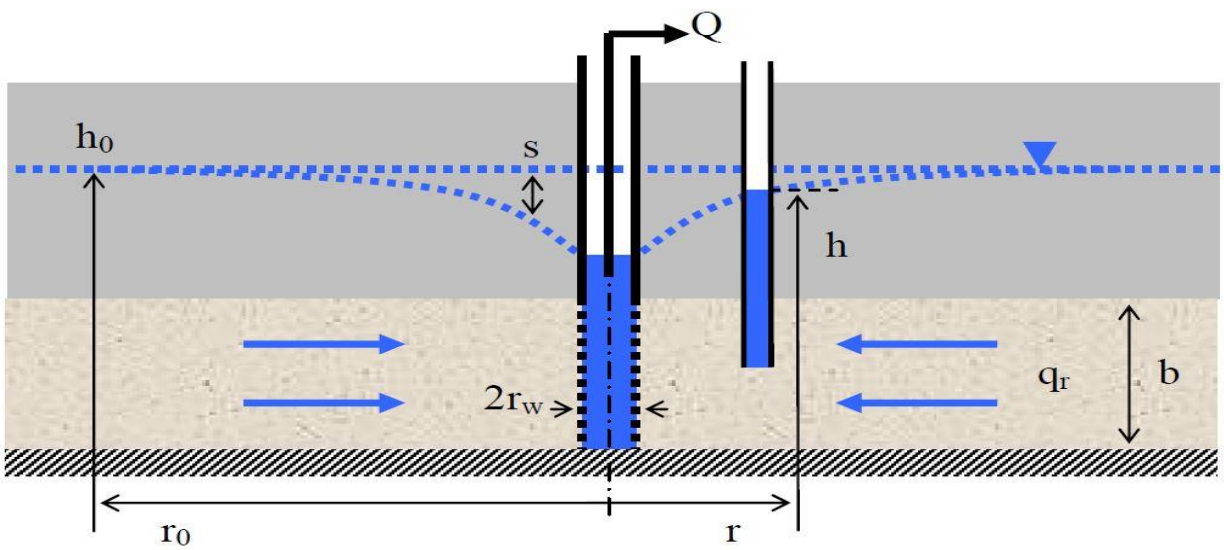

Figure 2-2: Pumped borehole and the nearby borehole (De Smedt, 2009).

Originally, when the well was not pumping the groundwater head was at a level h_0, which can be assumed more or less constant in the vicinity of the well. When the well is pumping a cone of depression is formed that enables groundwater flow towards the well. The flow can be considered completely radial towards the well if the well is screened throughout the entire thickness of the aquifer. If q_r is the radial groundwater flux at a distance r from the well, it follows from the mass balance equation that the total radial flow towards the well should be equal to the pumping rate:

$$Q = -2\pi r b q_r \qquad \text{2-3}$$

Where, the minus sign expresses the fact that q_r is negative as it is directed against the positive sense of the radial axis r. Using Darcy's law to express the groundwater flux this becomes

$$Q = 2\pi r b\left(-K\frac{dh}{dr}\right) = 2\pi r T\frac{dh}{dr} \qquad \text{2-4}$$

Where, T is the transmissivity of the aquifer. From this equation it follows:

$$dh = \frac{Q}{2\pi T}\frac{dr}{r} \qquad \text{2-5}$$

This equation can be integrated to obtain an expression for the groundwater head, h:

$$h = \frac{Q}{2\pi T} Inr + c \qquad \text{2-6}$$

Where, c is an integration constant, whose value can be obtained by stating that at a distance r_0 from the well the groundwater head is equal to its original natural level h_0, Equation 2-6 becomes:

$$h = h_0 - \frac{Q}{2\pi T} In\left(\frac{r_0}{r}\right) \qquad \text{2-7}$$

This radius r_0 is called the radius of influence; it determines the zone in which the pumping well creates a cone of depression and influences the groundwater flow and head. Outside this zone for $r > r_0$ there is no influence and h equals h_0 (The Thiem Analysis).

2.4.3 Borehole near the stream

Hunt (2003) investigated a special case of an aquifer that is hydraulically connected with a stream by an aquitard. All of these approaches predict that after extended pumping, 100% of pumping rate originates from the depletion of the adjacent stream. However, Hantush (1965) and Zlotnik (2004) showed that, under common realistic hydrostratigraphic conditions in leaky aquifers, an adjacent stream might supply only a fraction of the pumping rate, which might vary from 0 to 100% depending on the aquifer, aquitard, and well properties. The diagram below (Figure 2-3) illustrates the interaction between the stream and a pumped borehole.

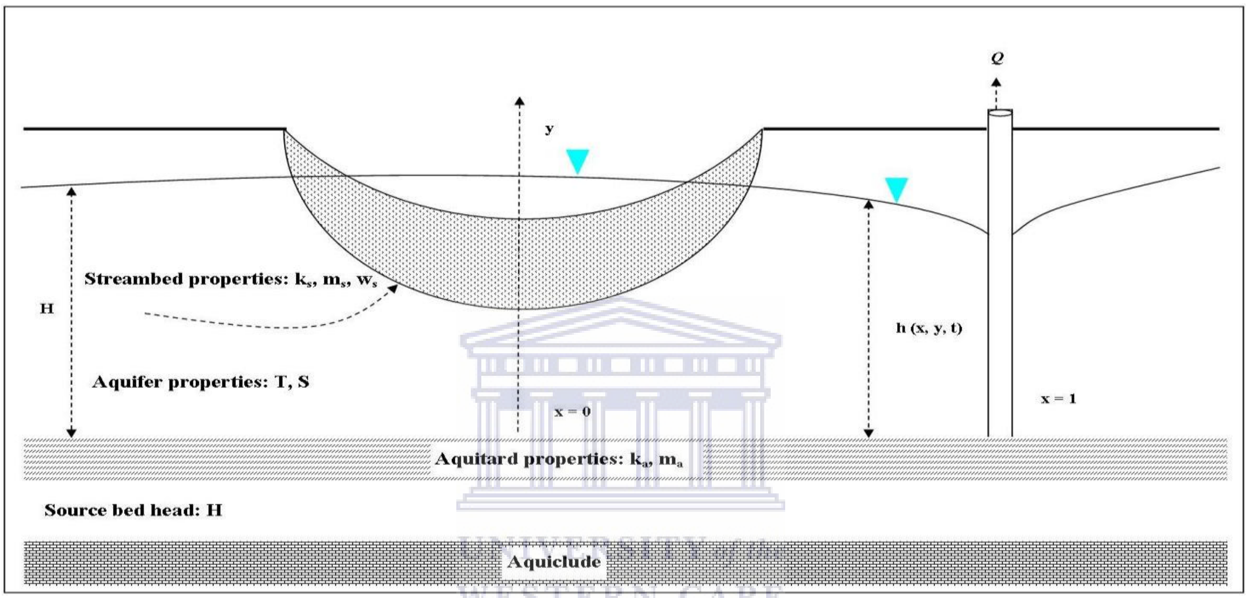

Figure 2-3: A schematic representation of a stream-aquifer interaction

Consider a well operating with a constant pumping rate *Q* in a leaky aquifer at a distance *l* from a shallow stream (Figure 2-3). Our assumptions for problem formulation are as follows: 1) The Dupuit assumptions are valid, and hydraulic head $h(x, y, t)$ is a function of Cartesian coordinates *x* and *y* and time *t*. 2) An alluvial aquifer with hydraulic conductivity *K*, transmissivity *T*, and storativity *S* is homogeneous and isotropic, and has infinite extent. 3) Relative to the thickness of an unsaturated aquifer, drawdowns are small enough to warrant the use of linearized flow equations. 4) Drawdowns are small enough to provide a permanent stream aquifer hydraulic connection. 5) Both the horizontal and vertical dimensions of a streambed's cross section are smaller than the thickness of the aquifer. 6) A stream is located along the *y* axis and is of infinite extent ($-\infty < y < \infty$), 7) Seepage flow rates between the stream and the aquifer are proportional to the difference in piezometric head across the streambed. 8) The alluvial aquifer is separated from the source bed with constant head by an incompressible aquitard whose hydraulic conductivity is k_a ($k_a \ll k$) and thickness is m_a. 9) Changes in both hydraulic head in the source bed and stream stage are negligible. 10) The hydrologic system (i.e., the aquifer, the stream, and the source) is in the state of equilibrium before the commencement of pumping.

Under these assumptions, the flow problem can be described by (Hantush 1964; Zlotnik et al. 1999; Hunt 1999; Butler et al. 2001; Zlotnik 2004).

$$T\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial x^2}\right) = S\frac{\partial h}{\partial t} + w \qquad \text{2-8}$$

Where

$$w = Q\delta(x-l)\delta(y) - \lambda(H-h)\delta(x) - \frac{k_a}{m_a}(H-h) - R \qquad \text{2-9}$$

In equation 2-9, the four terms represent ground water pumping, streambed seepage, aquitard leakage, and aquifer recharge R, respectively; $\delta(x)$ = Dirac delta function, H = hydraulic head in the aquifer, stream, and source bed at time t = 0; and λ = streambed characteristic. For streambeds with small horizontal and vertical dimensions, the latter can be approximated by $\lambda = k_s w_s / m_s$, where k_s, w_s, and m_s represents hydraulic conductivity, width, and thickness of the streambed, respectively (Hunt, et al., 2001).

Pumping from a well beside the stream lowers groundwater levels and reduces surface water flow within the stream. In smaller streams this decrease in flow can be large enough to create harmful effects upon the stream and its wildlife. An understanding of the interaction between the surface water and groundwater in this problem will allow engineers to specify well locations and pumping schedules that would minimize these harmful effects. The first unsteady solution for this problem was obtained by Theis (1941). As shown in Figure 2-3, the river edge was modeled as infinitely long straight line with zero drawdown, the stream was assumed to completely penetrate a homogeneous aquifer, and changes in free surface elevation were assumed to be small enough to allow use of the linearized form of the equations that are derived from the Dupuit approximation. Theis (1941) obtained the solution in the form of an integral, which he evaluated with an infinite series. Thirteen years later this solution was rewritten by Glover and Balmer (1954) in terms of the complementary error function, erfc, as follows:

$$\frac{\Delta Q}{Q_w} = erfc\left(\sqrt{\frac{Sl^2}{4Tt}}\right) \qquad 2\text{-}10$$

Where $\Delta Q$is the stream depletion flow rate, $Q_w$is the constant flow rate abstracted at the well from$t = 0 \; to \; t = \infty$; S is the aquifer storage coefficient, specific yield of effective porosity; T is the aquifer transmissivity; t is time, $l$is the shortest distance between the well and short edge. A second problem was solved by Huntush (1965) for a streambed lined with semi pervious material. This problem differed from the problem considered by Theis (1941) only by the inclusion of vertical layer of semi pervious material along the stream edge, as shown in Figure 2-3. The Huntush solution is given by:

$$\frac{\Delta Q}{Q_w} = erfc\left(\sqrt{\frac{Sl^2}{4Tt}}\right) - \exp\left(\frac{Tt}{SL^2} + \frac{l}{L}\&\right) erfc\left(\sqrt{\frac{Tt}{SL^2}} + \sqrt{\frac{SL^2}{4Tt}}\right) \qquad 2\text{-}11$$

Where L is the stream leakance that has dimensions of length and is defined as a combination of the aquifer permeability, K, the permeability, K´, and thickness b´ of the semi pervious layer

$$L = \frac{K}{K'} b' \qquad 2\text{-}12$$

2.5 Groundwater-surface water interaction and groundwater use licence

If the interaction between the two components of groundwater and surface water is not well established it is difficult to take an informed decision of issuing or not issuing the groundwater abstraction water use licence. Groundwater-surface water interaction is the most important component to be considered during the decision making on issuance or none issuance of the groundwater abstraction water use licence. It is however deemed to be a challenge to have a clear methodology that will make it easy for DWS to take a decision. The ability to predict the impacts of groundwater abstraction on surface water and ecological systems are highly imperfect (Seward et al., 2006). Large uncertainties exist with respect to the nature of groundwater-surface water interactions (Sophocleous, 2002). The link between groundwater and ecology is poorly understood, making it very difficult to make even educated guesses as to the likely impacts of groundwater use (Hunt et al., 2003). The knowledge of the environmental impacts of groundwater use is lacking. Nationwide ecological monitoring is at a very embryonic stage.

2.5.1 South African Development Community (SADC)

A number of studies on GW-SW interaction in Botswana have been conducted. However there is a lack of literature on groundwater abstraction water and the licencing required to keep the groundwater resource healthy. The study in the Okavango Delta whereby the impact of groundwater and surface water abstraction and reservoir taking place in the upstream countries were expected to reduce and redistribute the available flows for the Okavango Delta ecosystem (Bauer et al., 2006). Out of the study the coupled GW-SW model was developed. However, the study does not provide the management measures which involve management of groundwater and surface water abstraction upstream of Okavango Delta.

A numerical groundwater model study of the regional groundwater movement in the Swakop River basin, Namibia was conducted (Winker, 2010). The basin was a target of intensive economic development and associated migration. Both had strong impacts on the availability of groundwater. The aim was to develop an initial understanding of the groundwater flow system, to determine recharge and discharge areas as well as possible direct recharge rates consistent with the basin geology. Furthermore, potential interactions between alluvial aquifers and the basement were investigated. However, the scale on which the study was conducted is large and the nature of a study does not help an individual to take a decision whether the licence should be issued at a local scale.

A study on GW-SW interactions and scale relationships in small alluvial aquifers has been conducted (Love et al., 2007). In the study, three small alluvial aquifers in the Limpopo Basin of Zimbabwe were selected: (i) upper Bengu catchment, 8 km^2 catchment area on a tributary of the Thuli River, (ii) Mnyabeze catchment, 22 km^2 catchment area on a tributary of the Thuli River, and (iii) upper Mushawe catchment, 350 km^2 catchment area on a tributary of the Mwenezi River. The study concludes by comparing the Bengu and Mnyabezi aquifers. The shallowness of the Bengu aquifer (0.3 m) means it has effectively no storage potential. The deeper Mnyabezi aquifer (0.9 m) can store water for slightly over two weeks.

The study further, shows that the much higher storage of the Mushawe aquifer, as well as the longer period of storage after a flow event, can be assigned partially to scale and partially to the geological setting. (i) With a depth of over 2 m, the Mushawe aquifer has over half of its depth below the evaporation line, decreasing losses substantially when compared to the shallower aquifers. (ii) The Mushawe aquifer sits on younger and less weathered rock and this reduces seepage losses. The study, however, is not straight forward when it comes to decision making at a local scale.

The study conducted in Nigeria (Bolaji, 2005) on assessment of groundwater contribution to environmental flow in Ogun River whereby the spatial and temporal interactions were assessed in line with the water quality and groundwater hydrology on the floodplain. Results of the study revealed that there are temporal variations in GW-SW interactions regarding the discharged water quantity and quality. The effects of the hydrological changes on the ecotones could not be ascertained, due to limited data. Suggestions for further research on the floodplain are made along with necessary measures that must be taken for sustainable management of the floodplain. As much as the study was conducted at a local scale, it does not specify the necessary measurements for sustainable management. The groundwater-surface water interaction studies conducted seem not to be informing a decision maker of anything and they do not suggest any form of water resources management after they have been conducted.

The study conducted by ORASECOM, 2000, shows that determination of groundwater-surface water interaction requires the intensified groundwater monitoring network to determine various parameters at a quaternary catchment scale. The conduction of groundwater assessment study at local scale is more expensive for the individuals to afford and it is not a requirement before the licence is issued in most of the SADC countries. Some of the countries such as Lesotho, Botswana, Zimbabwe, Swaziland and Namibia in the SADC region do not have the well established groundwater monitoring systems. To these countries the states of water resources management is low and still not prioritized because of lack of capital to fund their water resources management.

Initiatives by some of the countries in the SADC region (South Africa, Angola, Botswana, Namibia, Mozambique, Zambia, Tanzania and Zimbabwe) have been taken to monitor and intensify groundwater monitoring networks for the betterment of groundwater management in the region (International Groundwater Resources Assessment Centre, 2013). Nothing much in the SADC literature indicates the initiatives towards quantification of GW-SW interaction at a quaternary catchment scale in most of the countries in the SADC region except South Africa. There are GW-SW interaction studies conducted at a local scale in some of the African countries, however, the findings of a study suggests no management measures to be taken based on the findings.

2.5.2 Australia

Sinclair Knight Merz (SKM) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) conducted a study for the Australian government under the programme known as Water for the Future-Water smart Australia programme (Australian Government, 2012). The intention of the programme is to facilitate integrated water management and in quantification of double accounting in water resource assessments. The objective of a programme was to develop a practical and moderately priced methodology for assessing the different connections between groundwater and river systems. The programme compares the estimates of surface water-groundwater interaction using flow differences, hydraulic gradient analysis, hydrograph baseflow separation and geochemical comparisons in ten representative catchments.

The programme categorises the groundwater and surface water resource systems into three categories and those are: 1) low importance groundwater and surface water resources, 2) moderate importance groundwater and surface water resources, and 3) high importance groundwater and surface water resource. The intention of categorizing water resources as low, medium and high importance was to easily recommend different studies based on the level of importance of the particular catchment. However, it is important to note that the higher the accuracy of a surface water-groundwater interaction assessment is, the higher the cost will be.

The approach developed for the Australian Government has gaps that lower the level of the confidence in the results obtained. The first gap is that the approach is applied at a catchments scale with the size ranging between 1660 to 83 km^{2}which is a large scale to take a decision based on it. The second gap is that the approach uses the available data which also lowers the level of confidence in the final results if the data available is not enough or have gaps in it. The third gap is the assumption that the catchment is a closed system, meaning that groundwater throughflow into and out of the catchment is zero. The last loophole is that the results obtained from a catchment scale cannot be used in decision making during the issuance of the groundwater abstraction licence at a site specific scale.

However, in Australia, groundwater-surface water interaction has started to be taken serious during licencing of groundwater or surface water use licence. WT Norman MN Murtagh and Goulburn Murray Rural Water Corporation (2010) VCAT declined the licence on the basis that the evidence pointing to a strong hydraulic connection to the River Murray (Norman, et al., 2010). Given that connection, VCAT found that a licence to extract groundwater from the borehole would effectively result in licensing extraction from the River Murray. This would be contrary to the cap on the issue of new entitlements required by the Murray Darling Basin Cap and the ministerial policy that no new allocations should come from Murray Basin waterway.

2.5.3 Europe

Muller et al., (2008), in Denmark conducted a study on modelling to support the assessment of inter-linkages between groundwater and surface water in the context of the EU Water Framework Directive. The aim of the study was to assess the entire hydrological systems at the catchment scale, implying among others, that water abstraction may not affect dependent ecosystems such as wetlands, lakes and water courses, nor the water quality of existing drinking water resources. A procedure was developed and tested based on the application of results from a regional groundwater model for the whole country of Funen (Denmark) to investigate linkages between groundwater bodies (GWBs) and surface water, both under current and pristine conditions with respect to groundwater withdrawal. The approach used is at catchment scale and may not be used to inform the impact of groundwater abstraction to ecosystem or to surface water at a site specific scale (Muller and Mielby, 2008).

In Netherlands, Calderon and Uhlenbrook (2014) conducted an investigation on seasonal river-aquifer interactions in a tropical coastal area controlled by tidal sand ridges. Connectivity between the river and the aquifer influences water quality and water availability for humans and for the downstream estuarine ecosystem. The effect of stream stage fluctuations on river-aquifer flows and pressure propagation in the adjacent aquifer 10 was investigated analyzing high temporal resolution hydraulic head data and applying a numerical model (HYDRUS 2-D). From the study it was concluded that pressure variation observations and numerical groundwater modeling are useful to examine river-aquifer interactions and should be coupled in the future with chemical data to improve process understanding. However, it only deals with the identification of whether groundwater interacts with surface water and it does not propose how the river and the underlying aquifer would be managed (Calderon and Uhlenbrook, 2014).

2.5.4 United States of America and Canada

In Canada, Oxtobee and Novakowski (2002) conducted a study on behalf of Natural Science and Engineering Research Council of Canada to enhance the understanding of GW-SW interaction between a fractured rock aquifer and a bedrock stream. The study makes use of air-photo interpretation, detailed stream surveys, electrical conductivity, temperature and isotopic surveys, mixing calculations and point measurements from mini-piezometers, seepage meters and weirs to identify and quantify the interaction between the creek and local aquifer. Groundwater and surface water could easily be distinguished within the study area on the basis of differences in electrical conductivity, temperature and isotopic signatures (Oxtobee et al., 2002).

Oxtobee and Novakowski (2002) conclude that GW-SW interaction between the fractured bedrock and the nearby stream occurs as discrete point sources related to open fractures. The process differs from the diffusion that takes place in the porous medium such as alluvial aquifer environments where continuous seepage is observed. Techniques such as electrical conductivity, temperature and hydraulic head surveys applied to studies of groundwater-surface water interaction in the porous media were found to produce reasonable estimates of groundwater discharge to a stream in a fractured bedrock situation.

In United State of America (USA) Rosenberry et al (2008) described three of the most commonly used methods applied at the local scale for investigation of GW-SW interaction. The methods are water-level measurements and flow-net analysis, hydraulic mini-piezometer and seepage meters methods. The water level measurements and flow net analysis method involves the measurement of water levels in a network of wells in combination with measurement of the river stage to calculate gradients and then water flow. The Hydraulic mini-piezometer method makes use of multiple mini-piezometers to measure gradients. The Seepage Meters method makes use of seepage meters to directly measure flow across the sediment-water interface at the bottom of the surface-water body (Rosenberry et al., 2008).

The gaps on the reviewed studies include that they do not quantify the impact of groundwater abstraction to surface water resources and do not inform any decision making during groundwater abstraction licencing as they do not deal with groundwater abstraction directly. The methods insignificantly help in design of groundwater and surface water resources management at a site specific scale. Because of the loopholes mentioned, the current study attempts to respond to a question of how much water that will be pumped out of the borehole per day, how long will it take for a nearby stream to respond to groundwater abstraction and how does the monitoring programme need to look like or how the water resource at a point of abstraction will have to be managed.

2.6 Review of used methods selected for the current study

This section reviews the literature which is associated with the objective of the current study. The intention to include the literature is to have the knowledge of what kind of studies that have been done on establishment of GW-SW interaction using the stream gauging.

2.6.1 Establishing spatial GW-SW interaction using stream gauging method

Stream gauging method is a familiar method used to determine the groundwater-surface water interaction at a temporal and spatial scale along the streams (Lowry et al., 2007; Ivkovic, 2009;

Mayer et al., 2010; Werner et al., 2005). However, the literature shows that the method is used to complement the other methods such as heat distributed temperature sensors method, chemical hydrograph separation method, chemical tracer methods, and others. Lowry, et al. (2007) conducted a study using the distributed temperature sensors (DTS) and stream gauging to verify if the DTS results will correlate with the stream gauging results and both methods indicated that the reach is gaining groundwater.

Few studies are linking the use of a method with the groundwater and surface water management. Werner et al., (2005) conducted a study at Sandy Creek River in Australia to assess the impact of groundwater and stream abstractions on water supply reliabilities. The stream-aquifer model was developed to plan and manage the Pioneer Valley situated in the north-eastern Australia. The study was conducted at a regional scale not at site specific scale and the study cannot therefore be able to derive management recommendations and conditions for a site specific groundwater abstraction.

The current study acknowledges the use of large scale approach; however, the approach works well for the derivations of management recommendation at a broader and generic view. The intention of the first objective of the current study is to establish the spatial GW-SW interaction at a site specific scale using velocity-area method in a lower reach of Watervalskloof stream during groundwater pumping from the adjacent borehole. Once the objective is carried out, it will be concluded if the selected stream reach is a losing or gaining reach and if the pumping of the adjacent borehole affected the streamflow to give sound management recommendations and conditions to water use licence.

2.6.2 Determining sustainable yield using the pumping test method

Sustainable yield is one of the parameters that are important to be determined before groundwater abstraction water use licence. Van Tonder et al. (2000) conducted a study intending to show that fracture characteristics (FC) method can determine the sustainable yield to be recommended for pumping. The current study proposes that before the issuance of a licence estimation of the sustainable yield for the pumped borehole needs to be estimated. The sustainable yield is the ratio of drawdown, s to pumping rate Q which is a constant for a well.

This constant only depends on the aquifer properties transmissivity, T and storativity, S (Van Tonder et al., 2000). If t_{long} describes the maximum operation time in which s shall not exceed a maximum drawdown, $s_{Available}$, the extrapolation of the measured pumping test drawdown can be used to determine the sustainable yield $Q_{sustainable}$:

$$Q_{Sustainable} = Q_{Pump\ Test} \frac{s_{Available}(t=t_{long})}{s_{Pump\ Test}(t=t_{long})} \qquad \text{2-13}$$

Determination of the sustainable yield alone is not enough to give the sound recommendations before the commencement of groundwater abstraction. Available drawdown, risk analysis by uncertainty propagation and characterization of flow regime are important to be determined for better understanding of a borehole and to give the feasible recommendations.

Available drawdown is one of the parameters to be determined during pumping test in support of the groundwater abstraction water use licence. The available drawdown is from the static water level (SWL) to above the position of the main water strike in the borehole. The problem of extrapolating the drawdown measured during the pumping test from the time of the end of the pumping test to a time t_{long} of around two to five years remains. This extrapolation is traditionally done by applying the Theis solution. A more sophisticated extrapolation of the pumping test drawdown beyond the time of the end of the measurement is obtained by using a Taylor series expansion based on the extrapolation of the measured drawdown curve including drawdown derivatives, and by accounting for boundaries (Van Tonder et al., 2000).

The drawdown measured during a pumping test is the sum of the drawdowns due to the production well, s_{Well}, and the boundaries, $s_{Boundary}$:

$$s(t = t_{long}) = s_{well} + s_{boundary} \qquad \text{2-14}$$

The drawdown due to the production well (s_{well}) is extrapolated by a Taylor series expansion around the late measurement points of the drawdown at $t = t_{EOP}$ (subscript EOP denotes end of pumping test). The Taylor series expansion is performed with respect to the logarithm of time, login. A second order approximation is assumed to be sufficient:

$$s_{Well}(t = t_{long}) \approx s(t = t_{EOP}) + \frac{\partial s}{\partial logt}\Big|_{t=t_{EOP}}(logt_{long} - logt_{EOP}) + \frac{1}{2}\frac{\partial^2 s}{\partial (logt)^2}\Big|_{t=t_{EOP}}(logt_{long} - logt_{EOP})^2 \qquad 2\text{-}15$$

The time t_{EOP} has to be large enough to ensure that the drawdown has already passed the early time flow behavior that is due to well bore storage, fracture flow and double porosity effects. This can clearly be monitored by looking at the derivative plot $\partial s/\partial logt$ (Van Tonder, 1998; Bourdet et al., 1984). Usually the effect of the boundaries can only be seen at very late times of the pumping test. The extrapolation of equation (2-15) therefore does not in general include boundary information.

For simple geometries of the boundaries, image well theory is applied to analyse the effects of the boundaries on the drawdown *($s_{Boundary}$)*. The analytical expressions and the simplified boundary configurations already yield far better estimates of the sustainable yield than the traditional Theis extrapolation, which assumes an aquifer of infinite extent. The estimate can be improved further by taking into account uncertainties in the required parameters like the late time transmissivity *T*, storativity *S*, and the distances to the boundaries *a* and *b* (Van Tonder et al., 2000).

2.6.3 Groundwater-surface water interaction general conceptual model

The general conceptual model of GW-SW interaction (Winter et al., 1998) can be used to explain the scenarios involved when a borehole is developed near the stream. The first scenario involved is whereby the stream gains water from inflow of groundwater through the streambed (Figure 2-4 A): (gaining stream). For ground water to discharge into a stream channel, the altitude of the water table in the vicinity of the stream must be higher than the altitude of the stream water surface. The second scenario is whereby the stream loses water to the groundwater resource by outflow through the streambed (Figure 2-4 B): (losing stream). For surface water to seep to groundwater, the altitude of the water table in the vicinity of the stream must be lower than the altitude of the stream water surface. The third scenario is that one stream can be a gaining and losing stream in different reaches.

Losing streams can be connected to the groundwater system by a continuous saturated zone or can be disconnected from the groundwater system by an unsaturated zone. Where the stream is disconnected from the groundwater system by an unsaturated zone, the water table may have a discernible mound below the stream if the rate of recharge through the streambed and unsaturated zone is greater than the rate of lateral groundwater flow away from the water table mound. An important feature of streams that are disconnected from groundwater is that pumping of shallow groundwater near the stream does not affect the flow of the stream near the pumped wells.

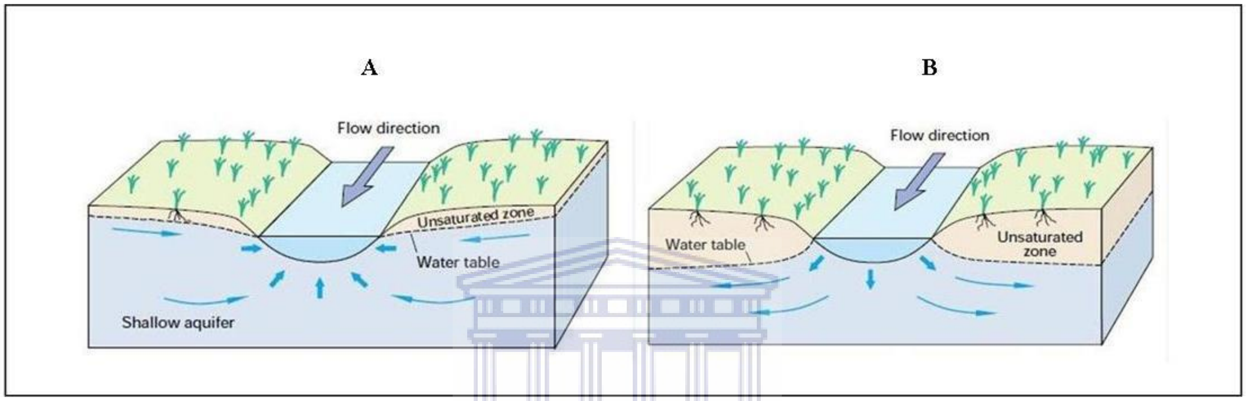

Figure 2-4: Gaining (**A**) and losing (**B**) stream (Winter et al., 1998)

Where the stream is disconnected from the groundwater system (Figure 2-5 A) by an unsaturated zone, the water table may have a discernible mound below the stream if the rate of recharge through the streambed and unsaturated zone is greater than the rate of lateral groundwater flow away from the water-table mound. In some environments, streamflow gain or loss can persist; that is, a stream might always gain water from groundwater aquifer, or it might always lose water to ground water (Figure 2-5 B). However, in other environments, flow direction can vary a great deal along a stream; some reaches receive groundwater aquifer, and other reaches lose water to groundwater. Furthermore, flow direction can change in very short timeframes as a result of individual storms causing focused recharge near the stream bank, temporary flood peaks moving down the channel, or transpiration of ground water by streamside vegetation. A type of interaction between ground water and streams that takes place in nearly all streams at one time or another is a rapid rise in stream stage that causes water to move from the stream into the stream banks.

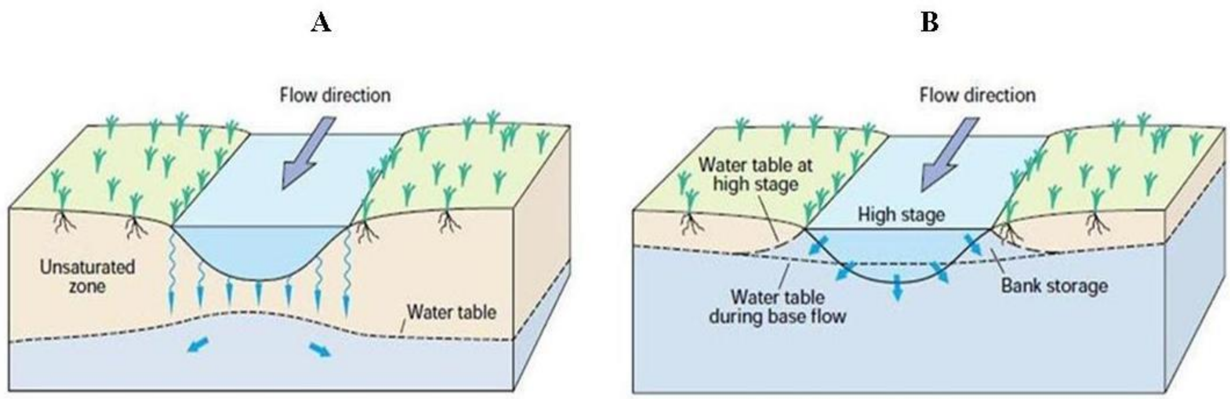

Figure 2-5: Disconnected (**A**) and connected (**B**) streams (Winter et al., 1998)

Withdrawing water from shallow aquifers that are directly connected to surface water bodies can have a significant effect on the movement of water between these two water bodies. The effects of pumping a single well or a small group of wells on the hydrologic regime are local in scale. However, the effects of many wells withdrawing water from an aquifer over large areas may be regional in scale. Withdrawing water from shallow aquifers for public and domestic water supply, irrigation, and industrial uses is widespread. Withdrawing water from shallow aquifers near surface-water bodies can diminish the available surface-water supply by capturing some of the ground-water flow that otherwise would have discharged to surface water or by inducing flow from surface water into the surrounding aquifer system. An analysis of the sources of water to a pumping well in a shallow aquifer that discharges to a stream is provided here to gain insight into how a pumping well can change the quantity and direction of flow between the shallow aquifer and the stream. Furthermore, changes in the direction of flow between the two water bodies can affect transport of contaminants associated with the moving water. Although a stream is used in the example, the results apply to all surface-water bodies, including lakes and wetlands (Winter et al., 1998).

2.6.4 Groundwater-surface water interaction between borehole and stream

A groundwater system under predevelopment conditions is in a state of dynamic equilibrium whereby recharge at the water table is equal to groundwater discharge to a stream. Winter (1998) further explains the concept of groundwater-surface water interaction between the borehole and a stream when the borehole is installed and pumped continuously. After a new state of dynamic equilibrium is achieved, inflow to the groundwater system from recharge will equal outflow to the stream plus the withdrawal from the well. In this new equilibrium, some of the groundwater that would have discharged to the stream is intercepted by the well, and a groundwater divide, which is a line separating directions of flow, is established locally between the well and the stream. If the well is pumped at a higher rate at a later time a new equilibrium is reached. Under this condition, the groundwater divide between the well and the stream is no longer present and withdrawals from the well induce movement of water from the stream into the aquifer. Thus, pumping reverses the hydrologic condition of the stream in this reach from a groundwater discharge feature to a groundwater recharge feature. The diagram below (Figure 2-6) indicates the three situations A) whereby there is no pumping next to the stream, B) whereby there is a well developed next to the stream and partly deviates groundwater to well bore storage and part of water still goes to the stream, and C) whereby the borehole is now getting water from the stream and from the groundwater resource (Winter et al., 1998).

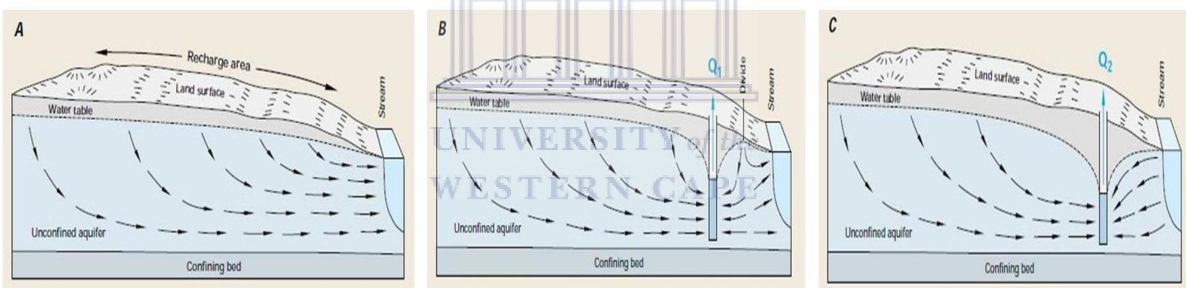

Figure 2-6: Impact of groundwater pumping in the stream (Winter et al., 1998)

In the hydrologic system depicted in Figure 2-6, the quality of the stream water generally will have little effect on the quality of the shallow ground water. However, in the case of the well pumping at the higher rate, the quality of the stream water, which locally recharges the shallow aquifer, can affect the quality of ground water between the well and the stream as well as the quality of the ground water withdrawn from the well. This hypothetical withdrawal of water from a shallow aquifer that discharges to a nearby surface water body is a simplified but compelling illustration of the concept that groundwater and surface water are one resource. In the long term, the quantity of ground water withdrawn is approximately equal to the reduction in streamflow that is potentially available to downstream users.

2.6.5 Establishing GW-SW interaction using geochemical water quality analysis

The current section intends to use Piper diagram to further establish if in a selected reach of Watervalskloof stream there is an interaction between the reach and groundwater by deriving the water types from different resources and points in the case study area. Piper diagram has always been used by other researchers and scholars such as Kumar (2012) and Rao (2006) for establishing the spatial interaction between the groundwater and surface water at a site specific scale. The method uses the cations and anions to classify if water is either as Ca-SO_4 (typical of gypsum groundwater and mine drainage), Ca-HCO_3 (typical of shallow, fresh groundwater), Na-Cl (typical of marine and deep ancient groundwater), and Na-HCO_3 (typical of deeper fresh groundwater influenced by ion exchange) water type.

The Piper diagram is often used to classify groundwater, however, due to the nature of the current study and for the comparisons of groundwater with surface water the diagram is used also to plot surface water cations and anions. Dixon-Jain (2008), combines the isotope method with the piper diagram method when studying GW-SW interaction to investigate the implications for nutrients transport to tropical Rivers of Australia. The study discovered that groundwater is the key vector for the transportation of nutrients to surface water resources in the tropical rivers (Dixon-Jain, 2008).

In the current study, the Piper diagram is used together with the other methods such as pumping test and stream gauging methods to establish the spatial interaction between groundwater and surface water resource. The reason for the use of Piper diagram in this study is to compare groundwater to surface water at a site specific scale and the chemical constituencies for which samples were analysed will be compared with South African water quality guidelines for agricultural use (DWAF, 1996). The establishment of GW-SW interaction in the current study will assist during the design of water resources management plan at a site specific scale and it will assist in taking decision as to how frequent the water resources need to be monitored.

2.7 Theoretical and Conceptual framework

The philosophical basis on which the study is taking place are that groundwater abstraction water use licence can be supported by the study that contains the following components 1) stream flow gauging, 2) borehole yield determined from pumping test data and 3) establish the fitness of groundwater and surface water quality for irrigation purposes. This is a suitable methodology to be used for groundwater abstraction licence issuance. The theoretical and conceptual framework in the current study acknowledges the currently used methodology that operates at a quaternary catchment scale (GRA II, 2006), which renders the results of low confidence for the issuance of licence at a site specific scale.

A series of the studies were conducted (DWAF report 3bA, 3bB, 3bC, 3bD and 3bE, 2003-2006) for the methodology to be used to determine GW-SW interaction prior to groundwater abstraction licence issuance. The international literature prompted DWS to come up with the methodology at a quaternary catchment scale, and the objectives the methodology are outlined below: i) performing a hydrograph separation to separate groundwater baseflow (baseflow from the regional aquifer) and interflow (baseflow from perched aquifers) from storm runoff on a monthly time scale using simulated WR90 or other monthly flow data, ii) back calculating subsurface storage to calculate a monthly time series of recharge, iii) incrementing groundwater storage from recharge to a maximum aquifer capacity level, vi) depleting groundwater storage by evapotranspiration and groundwater outflow as a function of dynamic groundwater storage and rest water level conditions, v) calculating groundwater baseflow or transmission losses in a non-linear manner as a function of groundwater storage and volume, vi) depleting groundwater and groundwater baseflow due to abstraction, and vii) calculating modified groundwater baseflow and interflow conditions resulting from abstraction.

The volume of water already licensed and the volume of water required by the ecosystem (Reserve) are calculated at a quaternary catchment scale. These totals are subtracted from the total amount of groundwater calculated using GRAII. The accuracy of data from WR2009 is questionable because it is having gaps and monitoring points not evenly distributed within the quaternary catchment scale. The status of WR2009 leads to yielding of low confidence results for decision making at a site specific scale. This prompts the current study to look for the comprehensive methodology that can be used at site specific scale without firstly trying to calculate the amount of groundwater using the surface quaternary catchment boundary.

The current study proposes the use of an approach at a local scale as applied in this study for the improvement of DWS decision-making during groundwater abstraction licence issuance. The recent study by Water Research Commission indicated the possibility of determining the GW-SW interaction at a local scale (Matthews, 2013). The study used Mixing Cell Model (MCM) to assess groundwater resource and its interaction with surface water at a site specific scale. It reviews the methodology used by DWS to determine the groundwater resource and its interaction with surface water resource at a quaternary catchment scale. It quantifies the groundwater availability at a site specific scale using MCM and compares it with the quantified amount of water by DWS methodology at a quaternary catchment scale. The quaternary catchment that is in deficit according to GRAII is found to be having a significant amount of water at a site specific scale.

The methodology proposed by the current study encompasses the establishment of GW-SW interaction. In the current study, the GW-SW interaction concepts (Winter et al., 1998) are reviewed. The concepts describe the interaction of groundwater resource with rivers, wetlands and lakes and groundwater surface water interaction in a mountainous terrain. The literature review also gives four types of interaction scenarios outlined in Resource Directed Measures by Xu et al. (2002).

The theoretical framework on which the current study follows is that between groundwater and surface water resources there is always spatial and temporary interaction (Oxtobee et al., 2002). The theoretical framework for GW-SW interaction explaining how groundwater resource interacts with surface water resources is given by Winter et al (1998) and for the holistic approach in water resources management, the groundwater and surface water as a single resource is presented. The concept describes the interaction of groundwater resource with rivers, wetlands and lakes and groundwater surface water interaction in a mountainous terrain. To explain the interaction between groundwater and streams led to the classification of rivers into gaining and losing streams. The gaining stream can generally be defined as a stream gain water from groundwater through the streambed when the elevation of the water table adjacent to the streambed is greater that the water level in the stream. On the other hand the losing stream loses water to groundwater resource by outflow through the streambed when the elevation of the groundwater table is lower than the water level in the stream.

FC method is the method used to determine the maintainable aquifer yield and EC profiling method to determine available yield. The 24 hour constant discharge pumping test was conducted to estimate the maintainable aquifer yield (Safe aquifer yield) using Fracture Characteristics (FC) method. To assess the quality of groundwater and surface water hydrochemical methods were used. Groundwater samples were obtained using purging method and surface water using grab sampling technique (Tracer/Isotope). The water types of both waters were characterized using graphical method (Piper diagram). For the establishment of GW-SW interaction process the stream gauging method was used simultaneously with 24 hour constant discharge pumping test to ascertain connectivity by observing the response in a stream.

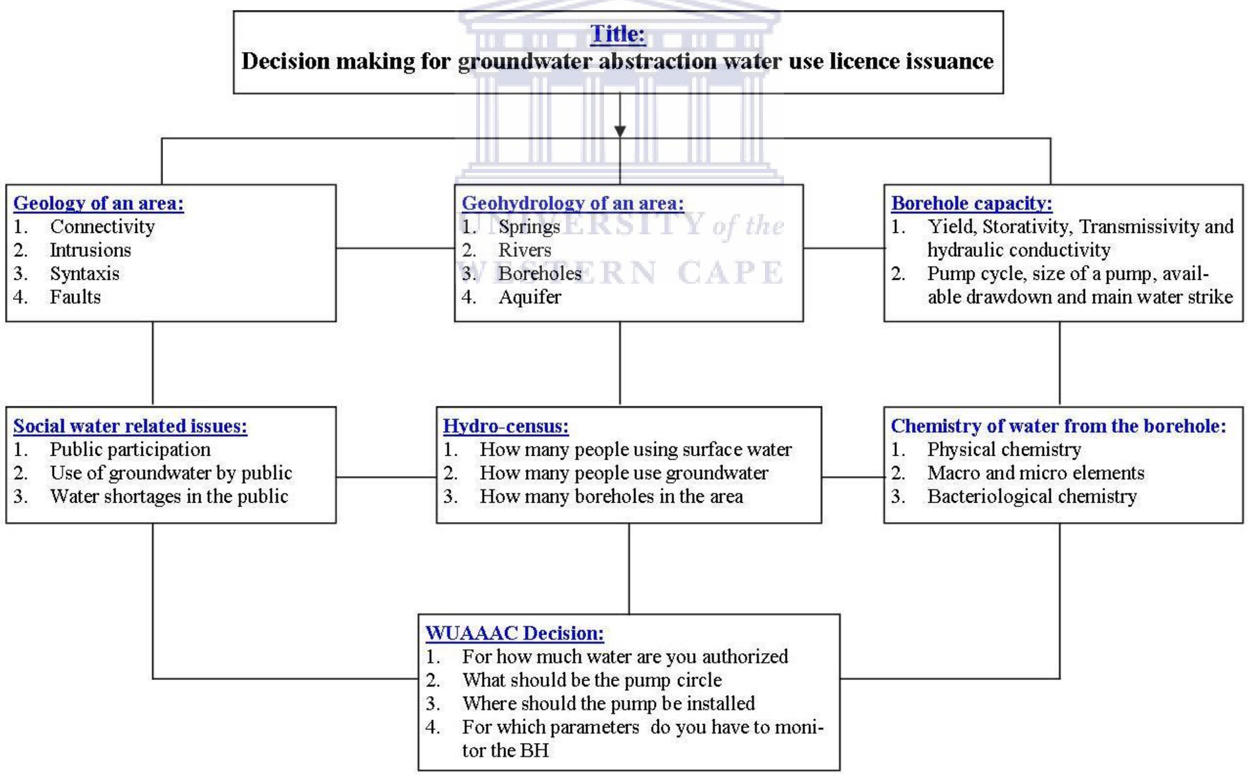

Figure 2-7: Schematic diagram for the current study

The flow diagram (Figure 2-7) simplifies how the study will be conducted and how the decision recommending or not recommending the issuance will be reached. For the current study to respond to the aim of the investigation the certain variables and parameters need to be estimated. Figure 2-7 indicates the sections that need to be covered for a complete and holistic decision making. The decision making process comprises sections such as geology of an area, geohydrology of an area, borehole capacity, social water related issues, hydro-census, chemistry of water from the borehole and surrounding area and WUAAAC decision. With the information gathered from pumping test, stream discharge and water quality the decision of recommendation for issuance or none issuance can be taken, therefore monitoring programmes will be put for both groundwater and surface water resources not for only one that is abstracted.

3 Chapter 3: Research Design and Methodology

3.1 Introduction

Chapter three is aimed at presenting the research design, data collection methods, data analysis methods, data quality assurance, ethical consideration and limitation of the current study. Under research design the study area, sampling size, parameters and unit of analysis and sampling design and sample size are described. On the data collection methods available methods, chosen data collection methods, data collection tools that were used and procedure that was followed in the current study were presented. On the data analysis methods available methods, the chosen data analysis methods, data analysis tools that were used and procedure that was followed were presented.

3.2 Research design

The intention of the research design is to give a description of the study area, description of sampling sites, study parameters and unit of analysis, sampling design and sample size. The description of the study area and sampling sites, study parameters, unit of analysis, sampling design and sample size are explained objective by objective. The type of a research design used is the case study design whereby an experimental technique is used to assess at site specific scale, the groundwater-surface water interaction for groundwater abstraction licence in South Africa.

3.2.1 Description of the study area

The research area is located along a small tributary of the Molenaars River called Watervalkloof. It lies on the Gevonden farm which is about 8.5km away from town of Rawsonville, a small town along the main road (N1) from Cape Town to Worcester (Figure 3-1). The project area is on Portion 4 of Gevonden farm number 522, district Worcester with the coordinates 19^{o}14’44.1”South, 33^{o}43’06.7”East and the area size of the portion is 571.5198 hectors. The total area of the catchment of Watervalkloof tributary is about 8.6 km^2 and its total stream length is 8.2km. The Molenaars River is part of Breede River primary catchment which has its exit to the ocean as Witsand near Swellendam. The northern part of the study area is bounded by the Slanghoek Mountains and Dutoits Mountain to the Southern part.

The investigation is taking place only in the lower reach of the stream of Watervalkloof. The lower reach of Watervalkloof in dominated by alluvial material, the middle reach is dominated by Nadouw subgroup, whilst the upper reach of the stream is dominated by the peninsula formation outcrops. The gentle slope in the lower reach of the stream allowed the deposits of alluvial material to settle and created the shallow porous or primary aquifer of 8 meters thickness. After the depth of 8 meters the weathered and fractured material from Nadouw subgroup follows. The main water strike is hit between weathered and fractured deep aquifer, however, there is a significant seepage from the porous shallow aquifer. The setup in the lower reach is suitable for the current investigation as it contains shallow and deep borehole and the stream nearby and the scenario as explained above fits to the conceptual framework given under the literature review, section of theoretical and conceptual framework.

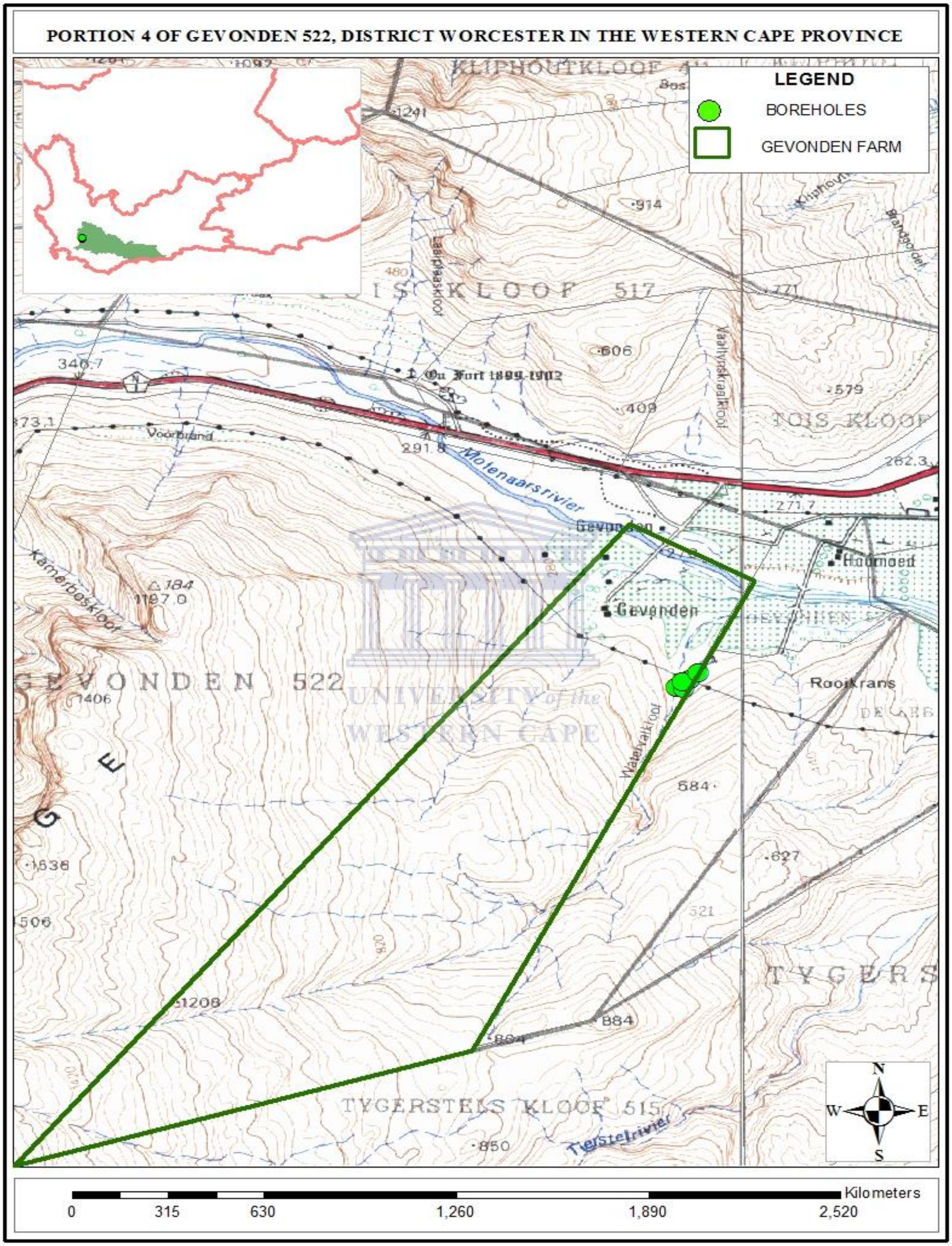

Figure 3-1: Locality map the for portion 4 of Gevonden 522, District Worcester

In the project area, water is diverted from the perennial Watervalkloof tributary by means of the above ground pipeline to a nearby dam in the nearby property for irrigation and drinking purpose. In winter-wet season, the river flows throughout the season and in summer-dry season when there is less water available for irrigation the stream water is diverted to a farmer’s dam for irrigation of vine yards. The latter mentioned activity causes stream flow reduction on the lower reaches of the river. The upper reaches of the stream retains its stream flow at a normal rate even during summer-dry season.

Regardless of GW-SW water interaction process that may lead to the stream gaining or losing water, the activities taking place in the stream contribute to the stream flow depreciation. The first point from which the stream discharge is measured is after the river diversion has taken place to find out if in a targeted lower reach the stream is gaining or losing. The point from which the water sample for chemical analysis is obtained is within the two points where the stream discharges were measured. The borehole from which the pumping test was conducted is also in between the two points from the stream from which the stream discharge was measured.

The project area lays largely in the Cape Fold Belt (CFB), which is composed of the rocks of the basement and the Cape Supergroup. These rocks include Malmersbury, Cape Granites, Bokkeveld, Witteberg and Table Mountain Groups. The geology of the case study area represents the general stratigraphy of the TMG. The geological map (Figure 3.2) shows the extent of TMG with its various geological formations extending from the Western Cape to the Eastern Cape Provinces. The Peninsula Formation is described as light-grey quartzitic sandstone and is between 1800 ~ 2150 m thick (Geological Survey of South Africa (GSSA), 1988). It outcrops mainly to the west of the study area and builds the higher mountains (Figure 3-2).

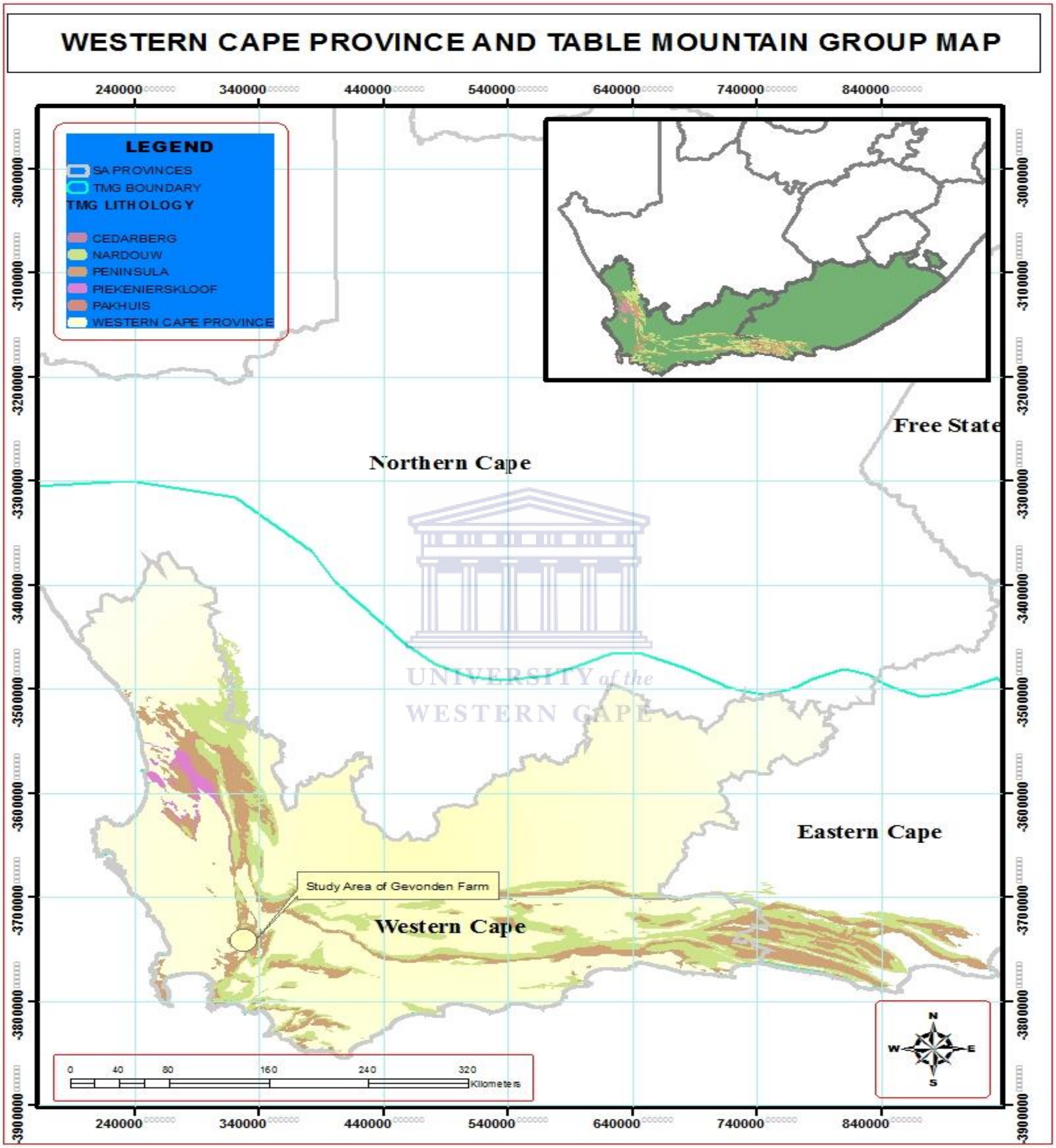

Figure 3-2: TMG aquifer extending from Western Cape to the Eastern Cape

Table 3-1: TMG formations its description and maximum thicknesses (De Beer, 2002)

SUBGROUP	FORMATIONS	DESCRIPTION	AVERAGE THICKNESS (m)
Nardouw	Rietvlei	Light-grey, well-bedded quartzitic/ feldspathic sandstone, subordinate siltstone and shale	280
	Skurweberg	Light-grey, thick-bedded, coarser grained quartzitic sandstone, cross-bedded with grit and pebble stringers and lenticles	200 ~ 400
	Goudin	Brown-weathering, quartzitic sandstone thinner bedded than skurweberg, subordinate siltstone	230
	Cedarberg	Dark-grey, thinly laminated to massive shale, siltstone, lenticular sandstone	50 ~ 120
TMG	Pakhuis	Grayish blue, massive diamictite, sandstone	40 ~ 70
	Peninsula	Light grey quartzitic sandstone, minor siltstone and shale	1800 ~ 2150
	Graafwater	Reddish thin-bedded sandstone, siltstone and mudstone	440
	Piekenierskloof	Sandstone, minor conglomerate, gritstone and shale	±800

The table (Table 3-1) and the local geological map (Figure 3-4) show the geological groups, subgroups and formations dominating in the case study area of Gevonden Farm. The area immediately alongside the lower reaches of the Watervalkloof is dominated by the Gaudini and Skurweberg Formations of the Nardow Subgroup. The Goudini Formation is on average 230m thick and is described as brown weathered quartzitic sandstone and thinner-bedded subordinate siltstone. The Skurweberg formation is 200 ~ 400m thick and consists of light-grey, thicklybedded, coarse grained quartzitic sandstone, cross-bedded with grit and pebble strings and lenticles (GSSA (Geological Survey of South Africa), 1988). The chemical composition of quartzitic sandstone is SiO_2, Fe_2O_3, Al_2O_3, Na_2O, CaO and MgO among others. Since the deep borehole penetrates through the Nadouw subgroup groundwater from the deep aquifer is therefore expected to be rich in Si, Fe, Al, Na, and Mg among others when compared with surface water (stream) and water coming from the shallow aquifer.

Overlying the peninsula formation is the grayish-blue, massive diamictite and sandstone of the Pakhuis formation which is on average 40 ~ 70 m thick. It shows up as a narrow band on the western side of the watervalkloof. Stratigraphically above the latter formation is the 50 ~ 120m thick Cedarberg formation. This formation is a dark-grey, thinly laminated to massive shale and siltstone with lanticular sandstones. The Cedarberg formation outcrops mainly on the eastern bank of the Watervalkloof (Figure 3-2).

The dip and strike of strata in the study area indicate some displacement of the strata on the eastern side of the Watervalskloof compared to those on the western side. Figure 3-3 shows the change in vegetation density between the lower reaches of the stream and the upper parts of the catchment dominated by the Peninsula Formation seem to confirm this. Vegetation changes may however also be related to changing lithology. Figure 3-4 shows the repetition of the Cedarberg and Pakhuis Formations on either side of the Watervalskloof indicates normal faulting during earlier tectonism. An Explanation of the 1: 500 000 General Hydrogeological Map, Cape Town 3317 shows that the case study area of Gevonden is sitting in the Table Mountain Group (TMG) which is divided into six units as have mentioned above (Theron et al, 1992).

The TMG, extending from the Western Cape to the Eastern Cape Provinces (Figure 3-5), notably the often fractured arenaceous components, is largely anisotropic, and thus does not display uniform aquifer characteristics. An intricate network of the fissures, joints, fractures, and even cavities govern the infiltration, storage and transmission of groundwater in the largely component and brittle natured arenaceous units of the TMG (Meyer, 2001). Due to the fractured nature of the sandstones in generally high rainfall regions, groundwater recharge is favourable and an infiltration rate of 15% of precipitation in certain areas is not unrealistic. It would appear that the TMG thus offers by far the most favourable opportunities for groundwater development from fractured aquifers in the south-western Cape region.

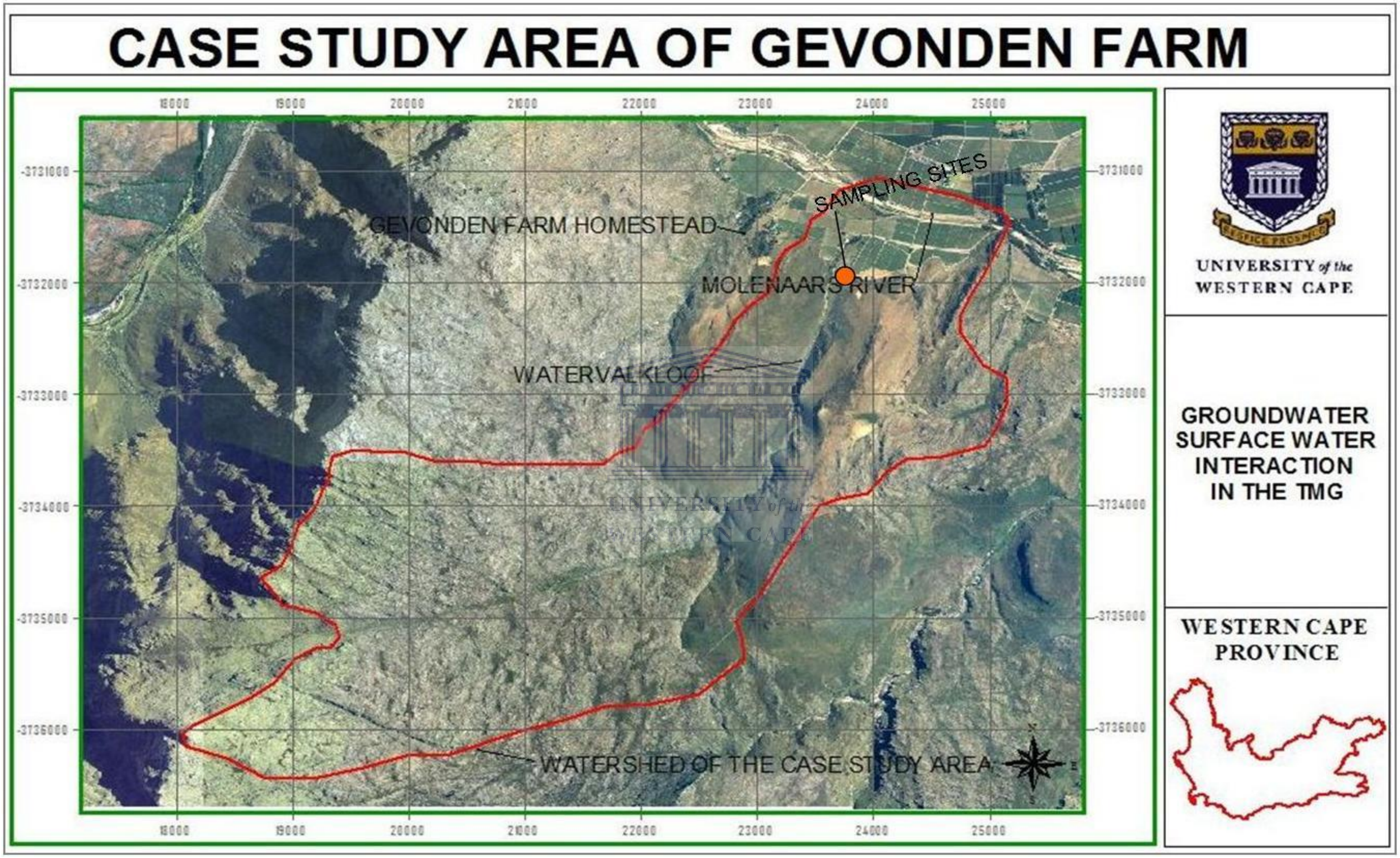

Figure 3-3: Watershed for the case study area of Watervalskloof at the Gevonden Farm

Figure 3-4: Local geology of the case study area of Gevonden Farm

An Explanation of the 1: 500 000 General Hydrogeological Map, Cape Town 3317 discusses an abundance of springs as a further characteristic of the TMG (Figure 3-5). Three kinds of springs can be notable: 1) Fault and major structure controlled, generally deep circulating springs, often with large constant supplies. The Brandvlei Hot spring, with a constant yield of 127 l/s is an example; 2) Lithologically controlled, relatively shallow circulating springs. These springs discharge due to the presence of impeding shale layers such as the Cedarberg Shale Formation. Yields from these springs are less constant and seasonal yield fluctuations are a distinctive feature. The bulk of the perennial springs discharging from the TMG are likely to be lithologically controlled; 3) Springs seeping from numerous small fractures and joints. They are very evident during and shortly following rainy periods and are responsible for the myriad of springs in the TMG. They are however highly seasonal and cease to exist with the onset of dry weather conditions.

The quality of groundwater from the TMG is generally within the South African water quality standards (SANS 241-1:2011) for drinking water with electrical conductivity values generally ranging between 5 and 70 mS/m. However, groundwater with EC values of up to 180 mS/m can occasionally found from boreholes drilled into inter-bedded shaly layers. Groundwater is generally of a sodium chloride nature (Meyer, 2001). Groundwater associated with the TMG is characterized as being amongst the purest occurring in South Africa in terms of EC (ranging between 5 and 70 mS/m) and low Total Dissolved Solids (TDS). The quality of water has been related to its source, namely the frontal systems which bring rain-bearing clouds from the Atlantic and Indian Oceans. However, the pH is as low as 5 particularly during summer, which is acidic and therefore corrosive. This pH range is common, however, since streams fed from fynbos-dominated catchments in the Western Cape Mountains typically have their pH between 4.5 and 6.5.

Borehole blow-yields of up to 120 ℓ/s have been recorded and hot-spring flows of 127 ℓ/s (Rosewarne, 2002). The Peninsula Aquifer generally constitutes the mountainous areas, which in turn influence precipitation to a significant extent. The fractured nature of the sandstones in these areas tends to favour groundwater recharge. Taking the orographic rainfall pattern, the elevation of the outcrop areas of the Peninsula Aquifer and its weathered and highly fractured surface into account, it is evident that the Peninsula Aquifer receives the higher amount of recharge.

Despite the favorable groundwater potential in the TMG, provided proper scientific methods of borehole siting are applied, some adverse groundwater exploitation aspects should be cited: 1) Permeability inhibiting material derived from microbreccia, mylonite, iron and manganese oxides and silica were formed and deposited in many of the fractures and joints, rendering some of them less effective groundwater conduits; 2) Due to the rough, mountainous terrain, large areas of the TMG are almost inaccessible. Groundwater development is thus generally limited to the foothills of mountains; 3) The TMG sandstones are hard, brittle and cross-jointed and are difficult to drill into. Due to the abrasiveness of these rocks, drilling bits tend to lose gauge, resulting in a gradual narrowing of a borehole diameter with depth. If this is not heeded, considerable problems of delivering a borehole of uniform diameter can result.

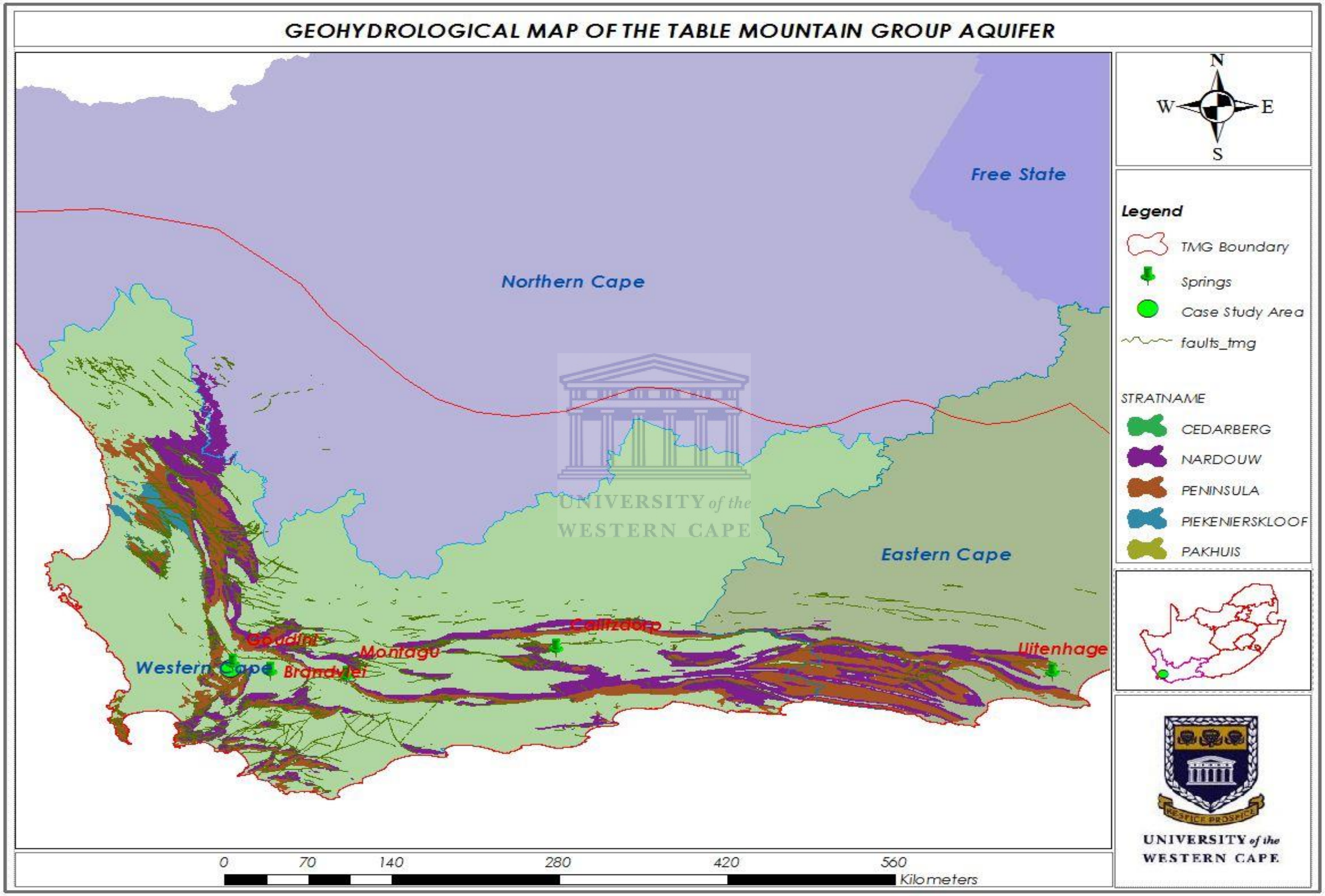

Figure 3-5: Geohydrological map of the TMG showing the springs and the faults

Rosewarne (2002) reported transmissivity and storativity of 10 to 200 m^2/d and 10^{-4} to 10^{-2} for the Peninsula Formation and Nardouw Subgroup, respectively, in the Klein Karoo area. These values were estimated using the FC Method. In the Hex River valley Transmissivity was estimated at 55 m^2/d for the Rietvlei and Gydo Formations using Gringarten and Witherspoon Method. The bulk Storativity of 0.01 or 1 x 10^{-3} is a fair estimate for the Peninsula and Nardouw Formations.

The Nardouw Aquifer has a scale effect introduced by lower fracture frequency and more ductile nature of the formation due to the presence of thicker shale layers. The scale effect refers to the different scale of heterogeneity introduced by micro-fractures in the matrix blocks themselves subdividing the matrix blocks. Alternatively, the rock is also referred to as fractured porous rocks (Kotze, 2002). According to Weaver et al. (1999), the boreholes drilled in the TMG are located entirely within this aquifer. The Skurweberg Formation was targeted for drilling during the Koo Valley Groundwater Scheme (De Beer, 2002). Rosewarne and Weaver (2002) regard the Skurweberg Formation as a sub-aquifer with sufficient overall thickness and massive thick-bedded zones to support large-scale groundwater abstraction. As opposed to Peninsula Aquifer, the Nardouw Aquifer outcrops are generally at lower elevations and receives much less direct recharge. Considerable amounts of indirect recharge are possible via fractures connecting Peninsula and Nardouw Aquifers. The Cedarberg Formation, which acts as an aquitard, and the Pakhuis Formation separate the Peninsula and Nardouw Aquifers from each other.

Generally the semi-arid climate of the Western Cape Province has the dry warm summer and the wet cold winter. The climate of the region is largely influenced by the topography. The annual rainfall varies greatly within the region, from between 500 mm and 1700 mm on the Cape Peninsula, to between 500 mm and 800 mm on the Cape Flats, and ranges from 800 to over 2600 mm in the mountains. The Western Cape receives 80% of its annual rainfall during winter (May to September) and in the summer months (December to March) it could be as low as about 10 – 20mm and about 50mm in the mountains (Diamond and Harris, 2000). The Worcester and Ceres areas receive precipitation of > 2000 mm/a in the mountainous areas where the elevation also reaches >2000m. The average daily maximum temperatures vary from minimum of about 28° C in mid-summer and 17° C in mid winter. Little snow is experienced during winter time. In the Koo Valley area, the overall precipitation is minimal.

3.2.2 Description of sampling sites

To determine hydraulic properties from the pump test data four boreholes were drilled along the river bank to various depths. All boreholes that were not pumped were used as observation boreholes including borehole BH05 used as abstraction borehole situated in the nearby property. To establish quality of groundwater and surface water using Piper diagram and sodium adsorption ratio (SAR) groundwater and surface water samples were taken from the boreholes and stream respectively. The surface water sample was obtained from the stream of Watervalskloof. The water quality results were compared with the South African water quality guidelines for agricultural use: irrigation.

To establish GW-SW interaction process by measuring the stream flow from the upper and lower point with reference to the stream in a reach of the stream parallel to the point of abstraction. Two points were located before and after the point of abstraction, from the two points in the stream, stream gauging was conducted using the area-velocity method. The velocity of the stream flow across the stream was measured and the cross-sectional area was calculated. From the mentioned variables the stream discharge was calculated. The logical thinking used during the selection of the two points was that the discharge should be measured before pumping takes place and before and after the abstraction point and after pumping has taken place after the point of abstraction.

3.2.3 Study population/parameter and unit of analysis

To recommend the sustainable yield (safe aquifer yield) hydraulic properties such as hydraulic conductivity, borehole water levels, drawdown, recovery and distance between the stream and pumped borehole, boreholes depths, water table, pumping rate, pumping cycle and the main water strikes is the data that was collected. Calculations involved in the determination of the sustainable yield needs the parameters mentioned in the latter sentence. To respond to the second objective of assessing if groundwater and surface water quality is fit for irrigation purpose, parameters such as major and minor ions were analysed including chloride, calcium, sulphate, magnesium, sodium, potassium, carbonates and hydrocarbonate ions. The categorization of groundwater as deep fresh, shallow, deep ancient and gypsum and mining groundwater in the piper diagram requires the parameters mentioned in the latter sentence. To establish GW-SW interaction process the stream discharge from two points was calculated. The parameters required to calculate stream discharge are stream flow velocity (m/s), stream cross-sectional area (m^2), width of a stream (m) and depth of a stream (m). The velocity-area method of calculating the stream discharge requires the parameters as mentioned above. Groundwater and surface water resources are the units of analysis where the water samples were obtained and hydrological procedures were conducted.

3.2.4 Sampling design and sample size

To determine hydraulic properties as the means to estimate sustainable yield deep (200 meters) borehole BH03 was selected as a borehole from which the pumping test had to be conducted. The reason for the selection of BH03 is that it has a diameter of 216 mm which is large enough for the pump used to fit in. BH02 has a small (165 mm) diameter as it was drilled for core samples and borehole one (BH01) was also drilled for core samples and it is a borehole drilled at an angle. The pumped borehole, BH03, is 54 m away from the stream. The remaining four boreholes were used as observation boreholes during the conduction of the pumping test. The 24 hour pumping test was conducted only on borehole three (BH03) and from this borehole drawdown and recovery data was obtained per minute using water level loggers. The position from which the pumped borehole was drilled was randomly selected using a knowledge that the area is in the fault zone.

To deduce if groundwater and surface water quality is fit for irrigation purpose, five groundwater samples were obtained from five boreholes available on site and one sample was obtained from the stream of Watervalkloof during wet season and fourteen samples (nine from surface water resource and five from groundwater resource) obtained during dry season. The plastic bottle size used to obtain the samples was 500ml in size and the samples were preserved with ice in a cooler box. All four boreholes were purged before sampling, only borehole one was not purged making use of pump; however the water was allowed to run out of the borehole for thirty minutes before sampling. Groundwater and surface water samples were obtained twice per year in different seasons.

To evaluate GW-SW interaction process the stream gauging was conducted from two points in the Watervalkloof stream. The first point is before the point of the borehole where pumping took place and the next point is further down the stream after the point where the pumping is taking place. The two points were selected in this sequence to be able to compare the discharge before and after pumping and to compare the stream discharge of the first to the second point.

3.3 Data collection methods

The current section of data collection methods describes and explains 1) the methods that were chosen for data collection in the case study area under each objective, 2) the data collection tools that were used to obtain the required data for each objective, 3) and procedures that were followed for data collection for each objective. Different methods such as pumping test, area-velocity stream measurement for discharge and hydrogeochemical methods were used to collect the required data.

3.3.1 Available data collection methods

Besides using the current meter for stream discharge measurements discharge in small streams can be conveniently measured using a weir. A weir is a small dam with a spillway, usually made of erosion-resistant material such as concrete, of a specific shape. Two common weir shapes are a 90° V-notch or a simple rectangular cutout. This method for measuring discharge involves creating a dam just downstream of the weir. This dam impounds in the weir, resulting in a more or less consistent stage height. The method is costly when compared to the use of current meter.

Besides the use of pumping test for determination of hydraulic properties the slug test method is one of a number of different methods that are used to determine hydraulic properties of an aquifer. The procedure involves either adding or removing a measured quantity of water from a well rapidly, followed by making a rapid series of water level measurements to assess the rate of water level recovery (either rising-head or falling-head). These evaluations have advantages and disadvantages when compared with other methods. Advantages of the slug test method include: 1) Relatively low cost, 2) Requires little time to conduct slug test, 3) Involves removal of little or no water from the aquifer. Disadvantages of the slug test method include: 1) Only evaluates a small portion of the aquifer adjacent to the well bore, 2) Does not provide an evaluation of portions of the aquifer not screened by the well being tested and, 3) May be profoundly influenced by gravel or sand pack material in the bore hole adjacent to the well screen. The type of procedure that is used to evaluate a well is often determined by aquifer conditions. A bail down evaluation may be conducted in aquifers that have poor transmissivity and require many minutes to recover after they have been bailed. However, it is difficult or impossible to test a high transmissivity aquifer by bail down methods because water level recovery is so rapid. Assessments using transducer measurements and a data logger may be used to evaluate hydraulic conductivity in situations where water-level recovery is either slow or rapid. In either situation, more accurate results are generally obtained when using an in-well transducer to collect periodic water level versus time measurements.

3.3.2 The chosen data collection methods

To collect data of drawdown and recovery from the pumped borehole and from the observation boreholes water level loggers were used during pumping test. The water level meter that obtains water levels from the borehole was used to obtain static water levels from all the boreholes before the commencement of pumping test. Geographic positioning system (GPS) was used to obtain the coordinates from the boreholes on site and also from the two points in the stream where stream gauging was conducted. The pipe to which the pump is connected was manually calibrated so as to get the depth at which the pump was submerged.

To obtain the samples for chemical analysis so as to establish the relationship between groundwater and surface water and to deduce if groundwater and surface water quality is fit for human consumption grab method of sampling from the surface water and purging method from the boreholes were used. All four boreholes were purged before sampling, only borehole one was not purged making use of pump; however the water was allowed to run out of the borehole for thirty minutes before sampling. The method of purging used is that one recommended by (Weaver et al., 2007). The volume of water in well bore storage was calculated using the formula for calculating the volume of a cylinder. From each borehole the volume of water was pumped out three times the volume of water available in the well bore storage.

To establish GW-SW interaction process the data collection method used to obtain the stream discharge was velocity-area method. The method requires the calculation of the stream area across the stream using the simple formula length multiply by breath and it also needs the measurement of stream velocity across the stream in the very same cross section where the area was calculated. The current meter is a tool that was used which measures velocity from the stream and to also measure the depth of the stream across the stream. The width of the stream was manually measured using the tape measure. The measurements obtained from this exercise were used to calculate the stream discharge.

3.3.3 Data collection tools that were used

To determine the extent of impact of groundwater abstraction on surface water resource the borehole pump of capacity 11*l/s* was used during conduction of the pumping test and the EC, temperature and pH meter was used to obtain these three parameters on the field. The water level meter of 100 meter length was used to measure the static water levels from the boreholes on site and the Geographic Positioning System was used to obtain the GPS coordinates of the boreholes and where the surface water sample was obtained and the points where the cross-sections for measuring the streamflow were selected. Electronic data loggers were used to obtain the drawdown and recovery data at a time interval of one minute during pump testing.

To establish the relationship between groundwater and surface water and to deduce if groundwater and surface water quality is fit for human and agricultural consumption the data collection tools that were used are 1 liter plastic bottles for groundwater and surface water sampling. To establish GW-SW interaction process the current flow meter for the measurement of the streamflow in the two selected points. The tape measure was used to measure the width of the stream.

3.3.4 Procedure that was followed

The CTD Diver that measures temperature, electrical conductivity and water level was installed at a depth of 30 meters and set to take readings at a minute interval in a pumped borehole. The water level change values from the observation boreholes, BH02 and BH05 were obtained making use of the CTD Divers. The shallow borehole, BH4, which is eight meters deep, was also used as observation hole and its water level change was obtained manually by dip meter. The initial water levels from boreholes in the field were manually recorded, in order to calibrate the reading taken by the Diver devices. The discharge in liters per second was manually recorded during pumping process for several times as the pumping continues. All divers from observation boreholes were set to take readings every minute. The data generated from the diver devices was imported to the Personal Computer for interpretation. The time versus drawdown and recovery graphs were plotted to derive the hydraulic properties such as hydraulic conductivity, transmissivity and storage coefficient.

To deduce if groundwater and surface water is fit for human consumption the procedure that was followed during the study was convenience procedures hence convenience sampling was carried out. The once off groundwater and surface water samples were obtained and taken to BEM Lab for analysis. The water quality samples were obtained twice in one year but different seasons. Groundwater sampling methods were derived from Weaver et al., 2007 Groundwater Sampling. Special care was taken not to contaminate samples. This includes storing samples in a secure location to preclude conditions which could alter the properties of the sample. Samples were well closed during long-term storage or shipment.

Sampling was carried out from the anticipated cleanest to the most contaminated location as guided by the previous analytical results to minimize the opportunity for cross-contamination to occur during sampling. Sampling took place from 60º inclined borehole (BH01), 200m core drilled borehole (BH02), and 200m air percussion drilled borehole (BH03), 8m shallow borehole (BH04) and lastly farmers' borehole (BH05). Samples were labeled as BH01, BH02, BH03, BH04 and BH05. Before sampling, boreholes were purged using the plastic bailer, Efforts were made to reduce the flow from the bailer during sample collection to minimize sample agitation. It was made sure that the bailer does not contact the sample container. The samples were placed into appropriate, labeled containers and the ice bags were used as the preservative for samples to keep the temperature as low as possible in a cooler box immediately at the time of sample collection.

To establish GW-SW interaction process the points where stream flow was measured were selected based on the positioning of the boreholes that were already drilled. Discharge is the volume of water moving down a stream or river per unit of time, commonly expressed in cubic meters per second. In general, river discharge is computed by multiplying the area of water in a channel cross section by the average velocity of the water in that cross section:

$$Discharge = area \times velocity$$

The current meter water used to measure the velocity of water and passing the cross-sectional area and the cross-sectional area. The stream channel cross section was divided into numerous vertical subsections, in each subsection, the area was obtained by measuring the width and depth of the subsection, and the water velocity was determined using a current meter. The discharge in each subsection was computed by multiplying the subsection area by the measured velocity. The total discharge was then computed by summing the discharge of each subsection. Subsection width was measured using a steel tape. Subsection depth was measured using a wading rod.

Sodium chloride was also used as it can behave both non-reactive, i.e. as ideal tracers, and also reactive. Non-reactive, ideal tracers are used if the transport of solutes is investigated, which are not subject to degradation or interaction with the subsurface material. The main aim of this tracer test was to establish the relationship between the shallow aquifer and deep aquifer. The shallow aquifer was represented by shallow borehole (BH04) which is 8m deep and the deep aquifer was represented by the deep borehole (BH03) which is 200m deep. The two boreholes are 48m apart and were all drilled using air percussion drilling method. A 1*l* solution of 500g of sodium chloride was prepared and dispensed into the shallow borehole; the water sample was obtained the same day from both shallow and deep boreholes. After two weeks the second set of samples were taken and the two chemical analyses were compared.

To determine the extent of impact of groundwater abstraction on surface water resource the sites where boreholes were drilled were selected without geophysics conducted to facilitate borehole sitting and the points from the river where surface water sample was obtained. The pumping test was conducted in the Gevonden Farm, Rawsonville University of the Western Cape Groundwater Research Site at Watervalskloof. The test carried out was a twenty four hour constant discharge test and the recover values were recorded for twelve hours. The pumping was conducted in a 200m percussion hole (BH3) with a submersible pump set at the depth of 70 meters. Other boreholes such as BH02, BH04 and BH05 were used as observation boreholes.

3.4 Data analysis methods

The data analysis for this section is quantitative, meaning it measures the quantity, deals with the numbers, conducted short time span, more objective, it is restricted to limited variables, and last but not the list, sample is selected randomly. The data analysis methods section of the current study describes the data analysis method under the sub-topics such as 1) the chosen data analysis methods, 2) and data analysis tools that were used.

3.4.1 Available analytical methods

Besides Aqua-Chem that was used for hydrochemical data analysis Hydrogeochemical Analytical Model (HAM) is a tool known for converting basic hydrochemical data from analytical results (mg/l) to equivalent concentrations for identification of major processes and influences. The programme is excel spreadsheet based visualisation tool using common hydrochemical diagrams such as Piper plots, Durov and Expanded Durov diagrams, Schoeller or Fingerprinting plots. Built-in equations to assist in "patching" hydrochemical data, to input missing data or correct suspect values.

Sodium Adsorption Ratio (SAR) was used to evaluate the suitability of irrigation water. Sodium Adsorption Ratio focuses on three ions and those are Sodium (Na), Calcium (Ca) and Magnesium (Mg). The potential for irrigation water to have poor infiltration properties is assessed by determining the sodium adsorption ratio (SAR) of the water. The sodium adsorption ratio relates the concentration of Na to the concentration of Ca and Mg. The ratio is calculated using the equation below:

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}} \qquad 3\text{-}1$$

3.4.2 The chosen data analysis methods for determining the GW-SW interaction

To establish the interaction between groundwater and surface water from the geochemical data obtained the analysis method selected was piper diagram and laboratory analytical method for the groundwater and surface water analysis for the parameters selected. To determine hydraulic properties in order to estimate sustainable yield the analysis method for the pumping test data analysis was the statistical data analysis using Theis (1935), Cooper and Jacob (1946), Chow (1952), Neuman (1975) statistical analytical methods. To establish interaction between groundwater and surface water the analysis method selected to analyse the streamflow data was algorithmic analysis method to calculate discharge from the two chosen cross-sectional areas from the stream.

3.4.3 Data analysis tools that were used for determining GW-SW interaction

To determine the hydraulic properties in the local area of Gevonden pumping test data was analysed using Theis (1935), Cooper and Jacob (1946), Chow (1952), Neuman (1975) statistical analytical methods. To deduce if groundwater and surface water resources are fit for irrigation piper diagram was used for the water type comparisons of groundwater and surface water and sodium adsorption ratio and comparisons of the results with South African water quality standards were used to evaluate the fitness for irrigation use. Chemical analysis was conducted from BEM laboratories for parameters that were chosen for this study. For the establishment of GW-SW interaction stream flow was measured using current flow meter to obtain velocity of a stream in a cross-sectional area.

3.4.4 Procedure that was followed for determining GW-SW interaction

The 24 hour constant discharge and recovery pumping test was conducted in BH03 which is 200m deep. BH4 (8m deep), BH02 (201.06m deep), BH05 (175m deep) and BH01 (270.55 inclined borehole) were used as observation boreholes. The procedure that was followed for the analysis of data generated during the pumping test was FC data analysis method which contains Theis (1935), Cooper and Jacob (1946) pumping test data analysis methods. The drawdown and recovery data was pasted into the FC spreadsheet and plotted and the log-log and semi-log graphs were plotted and the diagnostic graphs were also plotted. The sustainable yield and other hydraulic properties such as hydraulic conductivity, transmissivity and storativity were determined.

From five samples obtained from the boreholes and one obtained from the river, the procedure used for chemical analysis was hydrogeochemical analysis model well known as Piper diagram which is excel based software used to differentiate types of waters from different resources. The chemical data for Cl, SO_4, Mg, CO_3, HCO_3, Na and K is plotted into Piper diagram and it categorises water according to four water types. The four types of water presented into the diagram are Ca-SO_4 water, Ca-HCO_3 water, Na-Cl water and Na-HCO_3 water. The comparison of water from groundwater and surface water with South African water quality guidelines for irrigation water is one of the procedures followed to analyse water chemistry data.

The procedure followed to analyse incremental streamflow data was mathematical. The velocity of the stream was gauged using current meter and the cross-sectional area from which the velocity was measured was calculated manually. The product of the streamflow velocity and cross-sectional area is equals to the discharge. The data obtained from the two cross-sectional areas (before and after the borehole that was pumped) was compared. Sodium chloride was used as a tracer to perform tracer test as it can behave both non-reactive, i.e. as ideal tracers, and also reactive. Non-reactive, ideal tracers are used if the transport of solutes is investigated, which are not subject to degradation or interaction with the subsurface material. The main aim of this tracer test was to establish the relationship between the shallow aquifer and deep aquifer. The shallow aquifer was represented by shallow borehole (BH04) which is 8 m deep and the deep aquifer was represented by the deep borehole (BH03) which is 200 m deep. The two boreholes are 48 m apart and were all drilled using air percussion drilling method. A 1 *l* solution of 500 g of sodium chloride was prepared and dispensed into the shallow borehole; the water sample was obtained the same day from both shallow and deep boreholes. After two weeks the second set of samples were taken and the two chemical analyses were compared.

The TLC water level meter which measures the electrical conductivity, temperature and borehole water level, was used to conduct EC profiling. The EC readings were recorded with depth going an interval of 5 meters down in each borehole with an exception of borehole one (BH01) which is an inclined borehole. The water level meter was 100 meters long so the electrical conductivity that was taken with depth was only up to 100 meters. The intention of conducting the sodium chloride tracer test was to determine the relationship between four (BH02, BH03, BH04 and BH05) boreholes with relation to surface water in terms of electrical conductivity with depth. In general, the flowing fractures contain fluids with different chemical compositions and ion content from each other and hence different electrical conductivities.

Electrical conductivity and pH of the Watervalkloof stream was measured from the lower to the upper reaches of the stream, making use of the EC and pH meter. The purpose of this exercise was to compare the pH and EC values of the stream from the different reaches of the stream;

hence, with a hope to see which reaches of the stream are gaining water from the groundwater by being characterized by the low pH values. This exercise was performed during the surface water sampling which took place in nine selected point in the Watervalkloof stream.

3.5 Data quality assurance

Data quality assurance was carried out and it included the following steps: 1) data cleaning, 2) reliability, and 3) validity. During the application of stream gauging method to have a laminar flow the cross section where the measurements were to be obtained was cleared of holders that might have caused turbulent flow and give noisy results. It was further made sure that a data collector does not interfere with the stream flow as the current flow meter might produce the noisy results. Before the day when the pumping test was conducted the short test to ensure the well functioning of water level loggers that were to be used on site was conducted. During the sampling of groundwater and surface water for chemical analysis, because one plastic bailer was used to all the boreholes, the continuous cleaning of a bailer was carried out using distilled water before its use to another borehole to avoid cross contamination. The surface water sample that was obtained from the stream during its sampling it was made sure that the sampler does not interfere with the stream in a manner that would cause cross contamination from the sampler to the sample.

3.6 Ethical consideration

Ethical consideration for the current study to improve and maintain good and healthy relations with the organisations, government departments and individuals from whom the support and cooperation was required included the following ethics: 1) application of the principle of fairness (justice, 2) application of the principle of autonomous of subjects, 3) application of the principle of doing good, and 4) application of the principle of avoiding doing harm. Before the commencement of the drilling project the Owner of the farm Mr. Boonzaaier Cornelius was engaged in talks of drilling the boreholes in his farm and it was explained that it is for research purpose. There was a verbal agreement that before the researches come to site they will make him aware that they are coming. The property owner was given an opportunity to agree or not to agree for the University of the Western Cape researchers to establish the research site in his property. He further agreed that he will not disturb them by installing his own pumps and pump water to furnish his own water needs. It was agreed that after drilling and pump testing, the site will be cleaned and he was given a full access to the site and promised to report to the institution if there is something rare from the research site. The owner of the property was promised that there would be not sensitive reports published about the status of water from the boreholes in his property without him being informed and given a chance to agree or disagree with the publication. Any chemical results that can cause harm to people will not be put at the community disposal.

3.7 Study limitation

The current study was technically involving from field visits, pumping test, tracer test, EC profiling and stream gauging. It would be preferred for the data of the study to be obtained both during winter and summer season to investigate the variation of the variable obtained during dry and wet season. However because of the limitations in the time allocated for the study that was not done. The preferred method of measuring stream flow during the study to check the impact of groundwater abstraction to a nearby stream is to have two weirs from the stream. Weirs give better results than using a current meter to measure the stream flow. However, in the current study due to the lack of financial resources there is no weir that was constructed and current meter was used, therefore a high level of error was expected. The instrument to measure the streamflow proved to be difficult to deal with the errors brought by the fact that one could not be able to standardize the state (Laminar or turbulent flow) at which the stream is flowing. Another study limitation was that the geophysical survey was not conducted to site boreholes and to have a clear concept of the geohydrological structures underground. The identification of groundwater surface water interaction through pumping is difficult as the stream may not respond during pumping due to the size of a pump and purchasing the bigger pump has financial implications.

The components of the current study are 1) geohydrology expertise which was required more in chapter five that deals with objective two of the current study. The objective is to determine the extent of impact of groundwater abstraction on surface water resource by measuring the stream flow before and after borehole pumping and by conducting a pumping test and determining the hydraulic properties from the pump test data. The second expertise is 2) hydrology expertise as the stream flow measurements were measured and needing to be analysed to respond to objective one that deals with establishing GW-SW interaction process by measuring the stream flow from the upper and lower point with reference to the stream in a reach of the stream parallel to the point of abstraction.

The last expertise required was 3) geophysics expertise as has been proposed earlier on that if financial limitations were not an issue, geophysics for carrying out the borehole siting before they were drilled and to locate all the geohydrological structures in the case study area would be embarked on. This exercise would have helped at understanding stratigraphy so as to design the sound geological conceptual model. Due to the limitations in the involvement of the individuals having the expertise mentioned above some of the sections that are supposed to appear in the study, do not appear.

4 Chapter 4: Determining hydraulic properties

4.1 Introduction

The current chapter presents and discusses the results on determining the aquifer maintainable yield, estimating the borehole pumping rate, and available drawdown and recommend management measures for the production boreholes in the Wellfield of Gevonden Farm. Its aim is to demonstrate the feasible method with high confidence level results that can be used to estimate maintainable aquifer yield before the issuance of groundwater abstraction water use licence. The chapter argues that to make a decision on a groundwater abstraction water use licence application, maintainable aquifer yield and management recommendations of a borehole must be established. A wrong maintainable aquifer yield may lead to the wrong management recommendations of a resource. To achieve the study objective, a 24 hour constant discharge pumping test was conducted in a borehole (BH03) to determine sustainable yield and pumping rate of both a borehole and aquifer. The chapter addresses the first objective of the current study, which is to estimate the maintainable aquifer yield for the Wellfield of Gevonden Farm. The licence application assessor should know the following before the licence issuance: 1) How much water (Sustainable yield, Sy) can be supplied per time from the aquifer before licence issuance? 2) How much water does the aquifer have (Storativity, S) that needs to be licenced? In this chapter the available drawdown is also estimated and flow characteristic regime is identified using Flow Characteristics (FC) method.

4.2 Hydraulic properties a basis for water use licence

A 24 hour constant discharge pumping test was conducted to collect drawdown and recovery readings which were plotted in the Fracture Characteristics (FC) programme to estimate hydraulic parameters such as transmissivity (T), storativity (S) and maintainable yield (Sy) of the Table Mountain Group aquifer (TMG). The focus of the current study was to estimate the storativity (S) which is the volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head in unconfined aquifers where such saturation of aquifer varies and storativity varies too which depend on gravity drainage from the pore spaces. The other parameter that the current chapter is meant to estimate is the maintainable yield (safe yield) which is the attainment and maintenance of a long-term balance between the annual amount of groundwater withdrawn and the annual amount of recharge. The last parameter determined in this chapter is transmissivity which is the amount of water that can be transmitted horizontally through a unit width by the full saturated thickness of the aquifer under a hydraulic gradient of one (1).

At an initial stage before the pumping was started, the water level from each borehole and the general parameters such as EC, pH, temperature and TDS were recorded. Table 4.1 shows how general parameters and water level in each well looked like. From an artesian BH01 the yield was recorded as 0.21*l*/s.

Table 4-1: Showing the physical parameters from four boreholes

Stations	SWL (m)	pH	EC (uS/m)	Temp (^{0}C)
BH2	2.05	5.53	35.0	20.0
BH3	3.28	5.76	120	18.5
BH4	2.89	6.42	130	18.9
BH5	5.25	6.00	55.4	20.4

The pump test commenced at 16:54 from BH03 (Figure 4-1) and stopped at 16:54 the following day. To obtain the accurate values of drawdown and recovery, electronic water level data loggers were installed to boreholes BH02, BH03 and BH05. The 24 hour pumping test was conducted from BH3 and the static water level (SWL) was 3.28 mbgl. The last water level recorded from the water level logger after 24 hour pumping was 9.97 mbgl, which gives the total drawdown of 6.69 m. A SWL of 5.25 mbgl was recorded from borehole number five (BH05) used as an observation borehole and located 65.22 m away from the pumped BH03 (Figure 4-1). After 24 hour pumping the last water level recorded from the water level logger was 8.69 mbgl which gives the total drawdown of 3.44m. The interaction between BH03 which was the pumped hole and BH05 which was one of the observation holes is dynamic. The distance from BH03 to the fault is 18 m and that of the BH05 is 30 m. The data logger installed in BH2 which is 48 m away from the pumped BH03 (Figure 4-1), the water level for BH2 was not affected by the pumped BH3 according to diver readings. However the water level for BH2 was also manually recorded, the very minor water level changes were observed ranging from 1.48 m to 2.08 m, which roughly gives the drawdown of 0.6m before the pumping was stopped.

Only BH05 had a sharp response to the pumped borehole (BH03). The first drawdown observed at BH05 was 3 minutes after the pumping started, whereas it was 5 minutes at BH02 before drawdowns were observed. The maximum drawdown in BH02 is merely 0.6 m which seems to be on the boundary of the depression cone. Monitoring data also show that there is no noticeable response at BH01 and BH04 to pumping at BH03.

Figure 4-1: Showing five boreholes and distance from BH03

The discharge from pumped BH03 was manually measured continuously as the pumping continued and it was 1.8 *l*/s soon after pumping was started. After the pump was switched off the boreholes were given sixteen (16) hours to recover and after sixteen hours data loggers were taken out. The time versus drawdown and recovery graph for pumped BH03 were plotted (Figure 4-2).

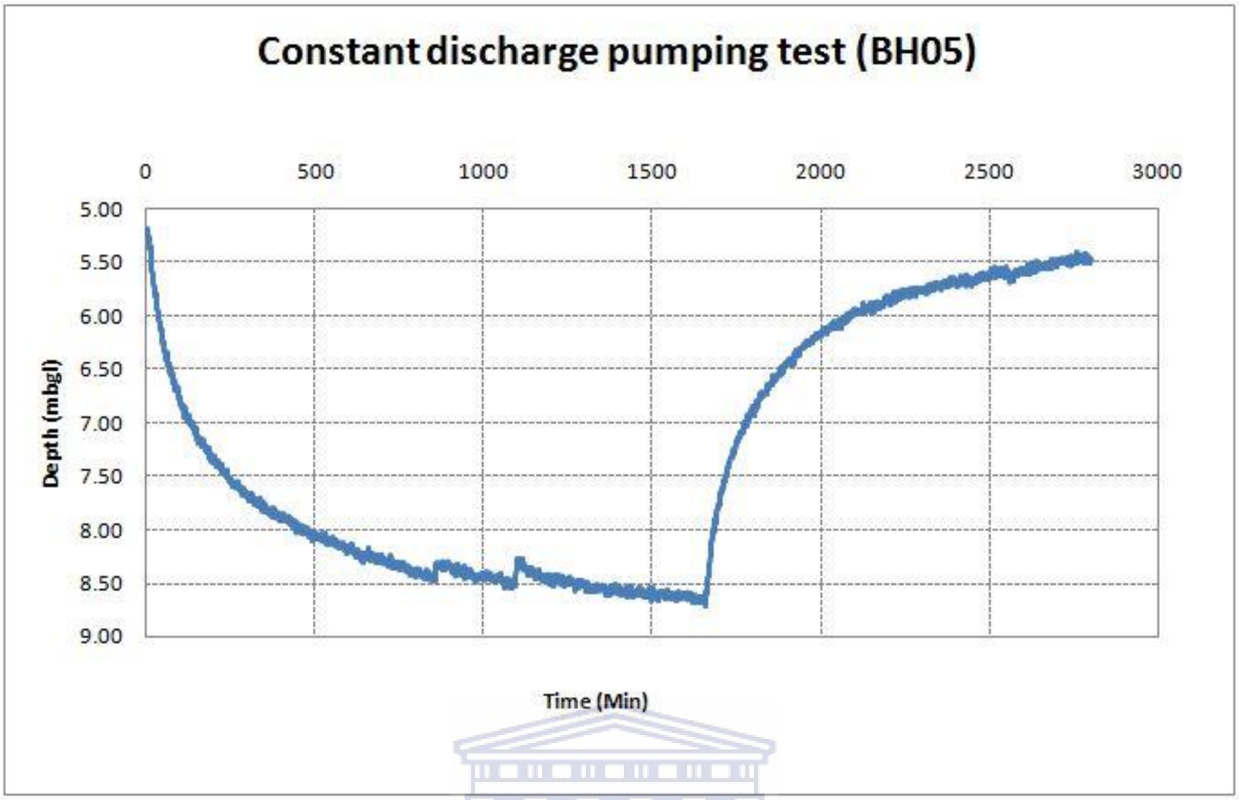

Figure 4-2: Drawdown-recovery graph for BH05

Determination of hydraulic properties is required for groundwater abstraction water use licence application to identify characteristics of flow regime in support of the groundwater abstraction water use licence issuance. The drawdown and recovery data obtained from borehole number five (BH05) which is an observation borehole was used to estimate the hydraulic properties in the case study area of Gevonden Farm. The drawdown made during conduction of a pumping test was 3.64 m as the static water level (SWL) is 5.18 mbgl and the final recorded water level before the pump was switched off after 24 hours was 8.64 m. The borehole recovered up to 5.47 mbgl while the initial SWL was 5.18mbgl. The borehole (BH05) recovered 91.6% of water lost during pumping of BH03 (pumped borehole).

The drawdown made in the pumped BH03 was 5.11 m as the SWL was 3.58 mbgl and the final recorded depth to water before the pump was switched off after 24 hours was 8.69 mbgl. The borehole recovered up to 3.43 mbgl while the initial SWL is 3.58 mbgl. The borehole recovered 102% of water that is pumped out during the test. The constant discharge pumping test data for drawdown and recovery was plotted in Figure 4-3 below. From BH01 which is an artisan inclined borehole the yield measured manually remained the same.

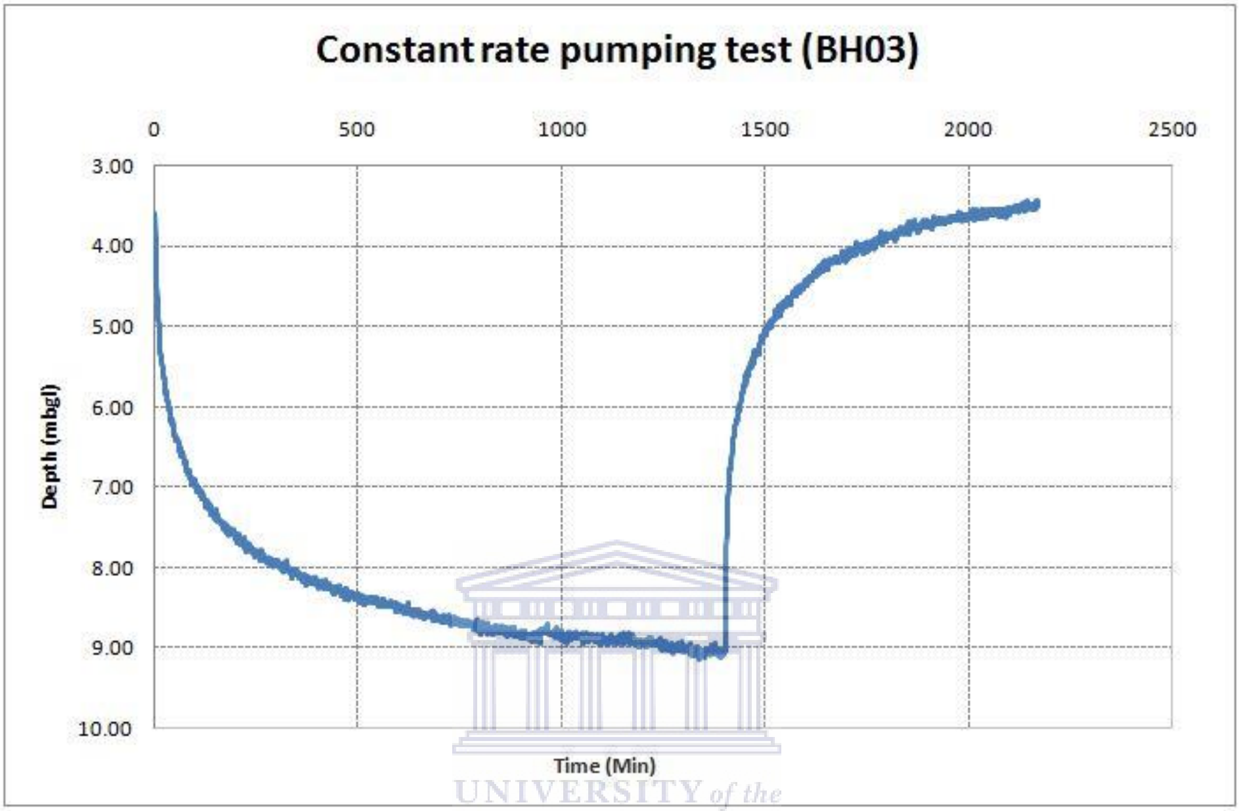

Figure 4-3: Drawdown-recovery graph for BH03

Table 4-2: SWL, drawdown and recovery from BH03 and observation boreholes

Boreholes	Latitudes	Longitudes	SWL (mbgl)	Drawdown (m)	Recovery (m)
BH01	19.24558	-33.71852	Artesian	Artesian	Artesian
BH02	19.24659	-33.71853	2.05	0	0
BH03	19.24635	-33.71803	3.58	5.11	3.43
BH04	19.24590	-33.71818	2.89	0	0
BH05	19.24686	-33.71763	5.18	3.64	5.47

Hydraulic properties were estimated from the borehole that was pumped (BH03) and the borehole that was used as the main observation borehole and responded sharply to pumping (BH05). The hydraulic conductivity and transmissivity for BH05 were estimated as 0.0817 m/d and 14.3 m^2/d; respectively; and the hydraulic conductivity and transmissivity for BH03 were 0.0715m/d and 14.3m^2/d; respectively using Cooper-Jacob method encompassed in the FC method. The discharge was measured by observing the time taken to fill a 10 liter bucket. This is a practical way of measuring discharge at low pumping rates (Driscoll, 1995).

Table 4-3: Hydraulic properties estimated using Cooper Jacob method 1946.

Points	**Instrument**	**Instrument depth (mbgl)**	**Hydraulic conductivity (m/d)**	**Transmissivity (m^2/d)**
BH1	Pressure gauge	On top of borehole	Not estimated	Not estimated
BH2	CTD diver	30	Not estimated	Not estimated
BH3	CTD diver & submersible pump	CTD at 90 & pump at 70	0.0715	14.3
BH4	Water level meter	Operated from the surface	No response	No response
BH5	CTD diver	30	0.0817	14.3

Estimation of the sustainable yield for the pumped borehole needs the ratio of drawdown s to pumping rate Q which is a constant for a well. This constant only depends on the aquifer properties transmissivity T and storativity S. If t_{long} describes the maximum operation time in which the drawdown s shall not exceed a maximum drawdown $s_{available}$, the extrapolation of the measured pumping test drawdown was used to determine the sustainable yield $Q_{sustainable}$:

$$Q_{Sustainable} = Q_{Pump\ Test} \frac{s_{Available}(t = t_{long})}{s_{Pump\ Test}(t = t_{long})}$$

The estimated sustainable yield (from Fracture characterization (FC) method) for BH03 and BH05 production boreholes was 1.02l/s which is 57 percent (%) of the pumping rate estimated during pumping. The table below presents the recommended pump installation depth, sustainable yield, hydraulic conductivity, transmissivity and storativity.

Table 4-4: Sustainable yields and recommended pump installation depth

Points	Water strike (mbgl)	Recommended pump installation depth (mbgl)	Sustainable Yield (l/s)	Hydraulic conductivity (m/d)	Transmissivity (m^2/d)	Storativity
BH3	45	140	1.02	0.0715	14.3	8.02×10^{-4}
BH5	20	140	1.02	0.0817	14.3	8.02×10^{-4}

From the FC method the storativity was estimated to be 8.02×10^{-4}. This storativity is within the storativity values recommended by Jia, 2007 for TMG aquifers. The storativity estimated using Cooper-Jacob method in the case study area of Gevonden Farm was ranging between 6.9×10^{-3} to 2.8×10^{-5}. The table below shows the recommended storativity for Peninsula and Nardouw aquifer types.

Table 4-5: Recommended storativity values for TMG aquifers (Jia, 2007)

Aquifer Type	Range	Storativity	
		Specific yield (Unconfined)	Storage coefficient (Confined)
Nardouw	Low	7.0×10^{-5}	7×10^{-6}
	Medium	3.5×10^{-4}	7×10^{-5}
	High	3.5×10^{-3}	7×10^{-4}
Peninsula	Low	1×10^{-4}	1×10^{-5}
	Medium	5×10^{-4}	1×10^{-4}
	High	5×10^{-3}	1×10^{-3}

The range of storativity values from TMG (Jia, 2007) sourced from different reports where different methods were used to estimate storativity for Peninsula and Nardouw formations indicated that while different methods are applied a variety of are produced. These results show that storativity of the TMG fractured aquifers falls in a wide range from 10^{-2} to 10^{-5}, according to the interpretation of data through various methods based on the Theis theory for confined aquifer. Improbability in the results from the testing data is frequent in the fractured rock aquifers because of, inter alia, the diversity of observed drawdown curves, and difference in the interpretive methods. Because of this it would make more sense to express storativity as a range of values, rather than single value, for regional studies. For the estimation of storage and the characterization of flow, an *S* value of less than 10^{-3} has been applied to groundwater resource evaluation for the TMG aquifers at a national scale (Vegter et al., 1995). Based on the study of Jia (2007), the recommended storativity range for regional studies of the Peninsula Aquifer and Nardouw Aquifer respectively is listed in Table 4-5.

4.3 Characteristics of flow regime

Identification of flow regime characteristics using FC method is important as part of motivation for groundwater abstraction water use licence. It shows if there is continuation on fracture connectivity which is an important characteristic to sustain the borehole to have water for a long time. This section is intended to show if the boreholes on site are gaining water from the main fracture or from both the fracture and matrix that exists along side with the fracture (Figure 4-4). Figure 4-4 shows the diagnostic plots for BH03 and BH05 on log-log graph (Theis Plot). The graphs were plotted to establish the flow mechanisms involved between linear and bi-linear flows during borehole recharge and the graphs below were derived. The graph labeled as A represents the log-log graph plotted for borehole three (BH03) and one labeled as B represents the log-log graph plotted for borehole five (BH05). In a standard graph there are three line graphs siting at three different gradients, the first one with a gradient of 1 represents the well bore storage (WBS) at an early stage, the other one with the gradient of 0.5 represents linear flow at an early stage while the last one with a gradient of 0.25 represents the bi-linear flow at a medium stage.

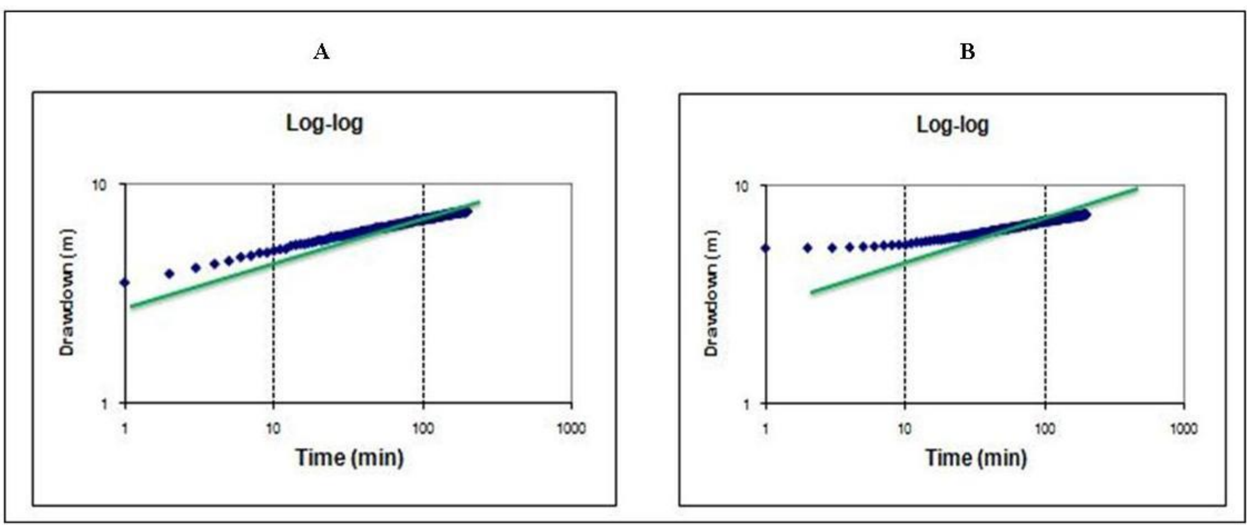

Figure 4-4: Diagnostic graphs for BH03 (A) and BH05 (B)

The diagnostic plot of the two boreholes (BH03 and BH05) indicates that the boreholes are bi-linear, meaning that they gain water from both the fracture at 45 mbgl and matrixes around the fracture. The interaction existing between the stream and groundwater may be taking place through fracture matrixes. Given the fact that the fracture is at 45mbgl the recharge of groundwater by stream may be very difficult and take time to notice. The generic illustration of bi-linear flow can diagrammatically be shown in Figure 4-5.

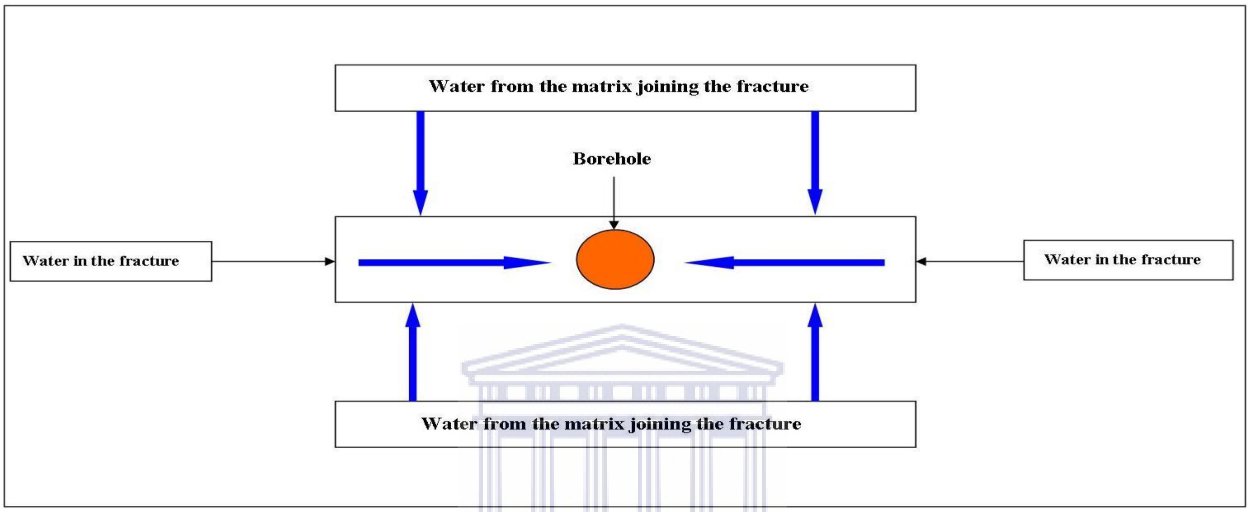

Figure 4-5: Diagram showing the radial flow (Van Tonder et al., 2000)

4.4 Determination of available drawdown

Determination of the available drawdown is important for the support of the groundwater abstraction water use licence issuance. This section argues that the licence cannot be issued if this parameter is unknown and not presented correctly in a geohydrological report submitted to the Department for a support of groundwater abstraction water use licence application. The determination of available drawdown is important because once a borehole is pumped until its water level is below the main water strike the borehole is prone to getting dry or the drastic decrease in yield will be experienced.

The EC profiling was used to confirm the water strikes given by a driller (BH02 and BH03) and also for BH05 which belongs to a farmer. The results from BH02 shows the first EC reading as low as 34 *u*S/cm which is associated with the stagnated well bore storage on top of the water column. The stagnated water on top of the borehole water column allows for the chemical precipitation to the bottom of the borehole living the top part of water column with a low electrical conductivity. The EC rose between 48 and 40 uS/cm between the depth of 4.4 and 60.4 mbgl. At the depth between 62.4 and 94.4 mbgl the EC readings increase between 69 and 73 uS/cm and the increase in associated with the water strike at 62.4 mbgl. The last increase in EC is also witnessed at the depth between 96.4 and 100.4 mbgl.

The EC rises between 92 and 94 mbgl and this increase is also associated with the second water strike that brings water with different chemical constituency. The similar trend observed in BH03 and BH05 whereby the EC is high at the top of the borehole and gradually decreases towards the bottom of the boreholes. The high readings of EC in BH04 which is a shallow borehole are observed; such readings indicated that the shallow aquifer interacts with the deep aquifer as the bottom part of the borehole has the high reading of EC that is associated with deep groundwater coming from below the shallow aquifer. The graph presented below (Figure 4-2) indicates the EC measured with depth from four boreholes on site.

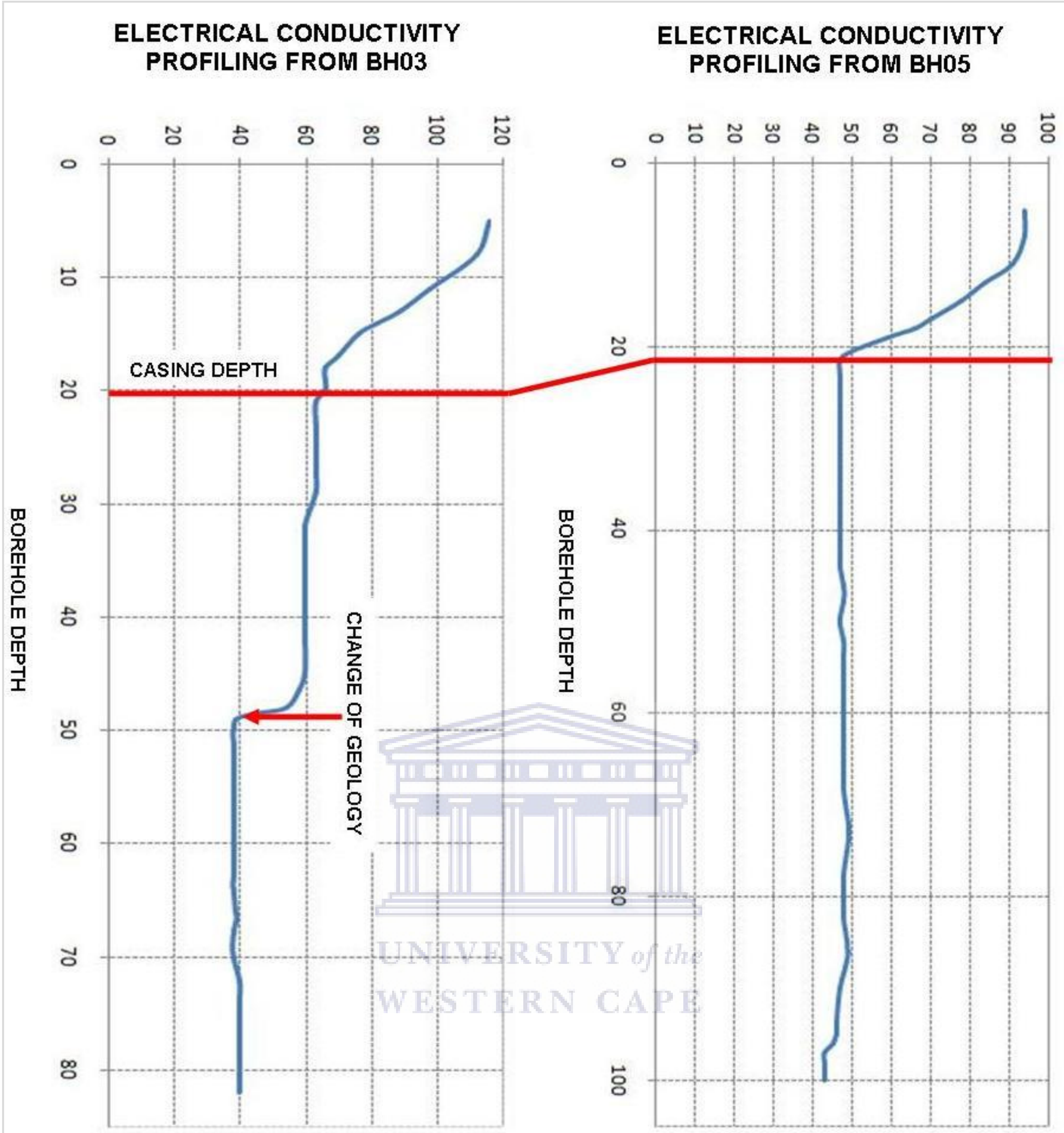

Figure 4-6: EC profiling graphs for boreholes in the Gevonden Farm

According to the EC profiling exercise conducted the water strike is 48mbgl for BH03 and the EC profiling for BH05 did not show any change with which the water strike can be located. It is recommended that the pump for BH03 is installed above the identified water strikes because if the pump is installed below the water strikes the borehole will dry up quickly. The recommended daily pump cycle per hour is 10 hours per day; this is based on a response of a borehole during pumping test and drawdown it made in 10 hours. The determination of available drawdown with relation to main water strikes for BH03 and BH05 was hindered by the instrument used (100 m LTC water level meter) which profiled EC from SWL to 100m whilst BH03 is 200 m and BH5 is 175 m. The literature indicates that if the instrument to conduct EC profiling can go down to

200m the results are likely to be different from the initial ones. Lasher (2011) conducted a study in the very same site; the study uses the fluid electrical conductivity logging for fractured rock aquifer characterization. Using three methods for profiling 1) Natural water quality logging, 2) Ambient fluid electrical conductivity (AFEC) and, 3) Flowing fluid electrical conductivity (FFEC) in BH03. The graphs presented below show the natural water quality logging which indicates that the main water strike is at 140mbgl.

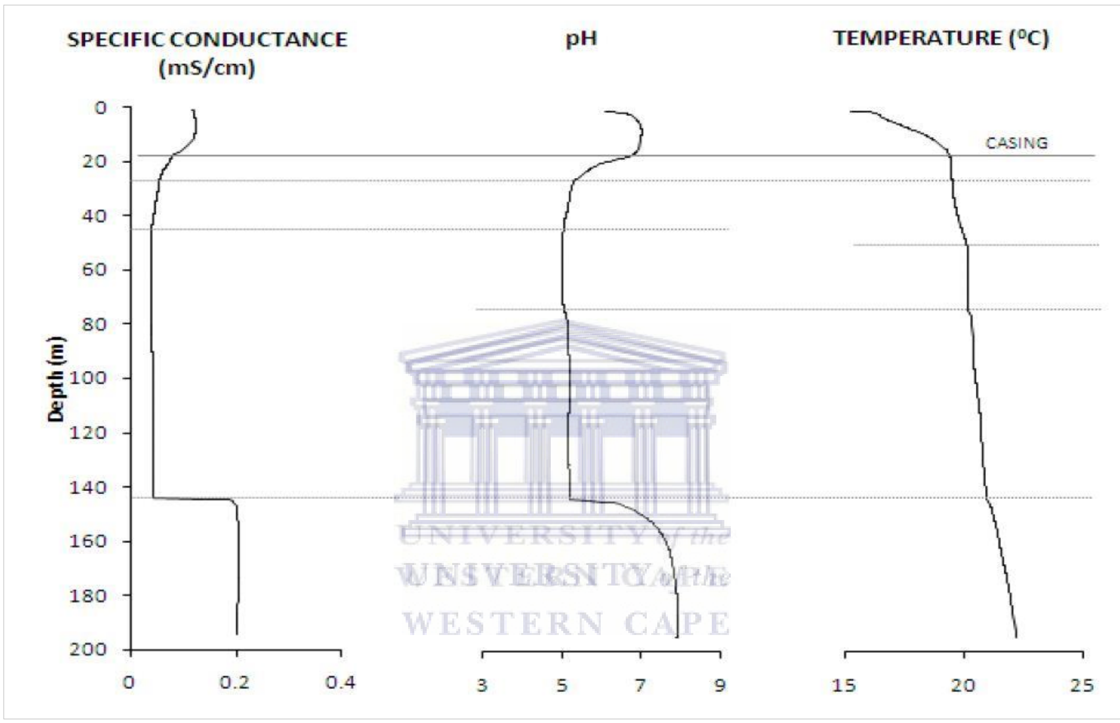

Figure 4-7: Possible main water strike for BH03 (Lasher, 2011)

4.5 Summary of a chapter

The aim of this chapter was to determine the maintainable yield, storativity, transmissivity and hydraulic conductivity and available drawdown in support of the groundwater abstraction water use licence issuance. The recommended sustainable yield for both BH03 and BH05 was 1.02 l/s and the pumping cycle is 10 hours per day. According to the study conducted in the case study area of Rawsonville (Lasher, 2011) it can be concluded that the pump installation depth for BH03 and BH05 can be anywhere above the depth of 150 mbgl, the estimated hydraulic conductivities for the BH03 and BH05 are 0.0715 and 0.0817 m/d respectively and the transmissivity for BH03 and BH05 is 14.3 m^2/d.

5 Chapter 5: Assessing GW and SW suitability for irrigation

5.1 Introduction

The current chapter presents and discusses the results on the establishment of characteristics of groundwater and surface water by comparing water-types in the same area using Aqua-Chem programme which enables assessment of water quality for appropriate use. It aims to demonstrate the methodology of water quality comparisons from different water resources with South African water quality guidelines for agricultural use: Irrigation (DWAF, 1996) and to ensure if the water type for groundwater and surface water are suitable for water use licencing. The chapter argues that to make a decision on a groundwater abstraction licence, the water quality for the borehole in question must be known and must be suitable for use that the applicant is asking for or applying for.

The present study does not support the current practice in South Africa where a water quality aspect is not considered when making decision regarding water use licence. The norm that is followed in DWS when assessing the groundwater and surface water abstraction licence does not consider water quality as it is said that the sub-directorate: Water Use considers which ever water as raw water. The application forms from Water use Authorization and Management System (WARMS) also do not cater for water quality; therefore this makes the applicants to be reluctant to provide water quality results from the accredited laboratory. With the groundwater and surface water type it is aimed at establishing if the water resources may be connected.

This chapter addresses the second objective of the study, which was to establish the quality of groundwater and surface water using hydrogeochemical analysis model. The improvement of knowledge on water quality analysis and interpretation helps in the issuance of water use licence for groundwater as a scientific basis. This approach aligns the management recommendations of the water use licence in terms of the National Water Act (Act 36 of 1998). To fulfill the third objective of the study one research question was: Is the quality of water that needs to be licensed for use suitable for the intended use by the applicant?

Assessing the quality of groundwater and surface water for suitable utilization is one important component before the issuance of water use licence. For section 21(a) water use licence the assessment of water quality suitability for utilization is always ignored as it does not appear even to the application form for water use licence. This study suggests the methods that can be used to carry out the assessment of water quality suitability before the licence issuance. Assessing the water suitability for utilization five groundwater samples and one surface water sample were obtained for chemical analysis. Table 5-1 presents the cations and anions concentrations from both boreholes and stream. The analytical results were compared with the South African water quality guidelines for agricultural use: Irrigation (DWAF, 1996). The comparisons were established using Piper diagrams to see if the borehole water and surface water samples are typical of gypsum groundwater and mine drainage or shallow fresh groundwater or marine and deep ancient groundwater or deep fresh groundwater influenced by ion exchange or mixture of groundwater and surface water. This was going to be indicated by where the cations and anion plot when plotted on Piper diagram on the diamond shape.

Table 5-1: Chemical elements for which groundwater sample were analysed

Elements	BH01	BH02	BH03	BH04	BH05	Stream
General parameters						
T(°C)	21.400	21.000	21.300	21.500	21.500	21.800
pH	6.300	6.000	5.700	6.400	5.800	5.400
EC(μS/m)	115.200	30.800	59.100	108.600	53.300	21.200
TDS(ppt)	87.400	22.730	43.900	80.200	39.600	15.940
TAL (mg/l)	44.600	10.020	6.510	40.580	5.012	7.520
Major ions (mg/l)						
Na	9.550	2.700	5.360	3.780	5.370	2.240
K	1.520	0.730	0.520	0.530	0.340	0.020
Ca	7.570	1.370	2.440	17.550	1.510	0.300
Mg	4.000	0.690	1.380	0.600	1.220	0.270
HCO_3	71.960	32.150	21.440	76.560	16.840	13.510
CO_3	0.000	0.000	0.000	0.000	0.000	0.000
SO_4	1.580	0.200	5.880	0.260	1.550	0.450
Cl	8.830	7.060	11.480	6.180	9.710	5.300
NO_3	0.590	0.590	0.700	0.490	0.000	0.000
NO_2	0.020	0.010	0.010	0.020	0.000	0.000
NH_4	1.710	1.140	1.260	1.240	1.310	1.260
PO_4	0.240	0.069	0.330	0.237	0.100	0.162
Minor ions (mg/l)						
B	0.010	0.010	0.020	0.010	0.010	0.001
Si	5.618	1.239	2.658	3.326	2.660	1.779
As	0.029	0.030	0.000	0.000	0.000	0.000
F^-	0.050	0.000	0.000	0.000	0.000	0.000
Br^-	0.010	0.000	0.000	0.000	0.000	0.000
Traces (mg/l)						
P	0.080	0.023	0.105	0.079	0.034	0.054
Li	0.000	0.000	0.000	0.000	0.000	0.000
Rb	0.000	0.000	0.000	0.000	0.000	0.000
Sr	0.122	0.122	0.008	0.019	0.010	0.003
Ba	0.000	0.000	0.002	0.000	0.001	0.002
Al	0.014	0.600	0.150	0.631	0.022	0.070
V	0.000	0.000	0.001	0.000	0.001	0.000
Cr	0.006	0.006	0.009	0.010	0.011	0.010
Mo	0.003	0.009	0.000	0.001	0.005	0.000
Mn	0.421	0.441	0.119	0.296	0.285	0.001
Fe	3.810	8.450	27.010	10.680	20.240	0.190
Ni	0.000	0.000	0.008	0.002	0.006	0.012
Cu	0.000	0.016	0.000	0.000	0.000	0.002
Zn	0.000	0.015	0.015	0.002	0.008	0.002
Cd	0.000	0.000	0.000	0.000	0.000	0.000
Hg	0.000	0.000	0.000	0.000	0.000	0.000
Pb	0.000	0.000	0.000	0.000	0.000	0.000

5.2 Physical chemistry

The readings of EC, pH and Total alkalinity (TAL) were presented (Figure 5-1) and discussed for the purpose of establishing if groundwater in the local area is fit for irrigation. The pH from groundwater ranged between 6.5 to 8.4. The pH should range between 5.5 and 9.5 for irrigation water. The low pH values of water may cause accelerated irrigation system corrosion where they occur. High pH values above 8.5 are often caused by high bicarbonate (HCO_3) and carbonate

(CO_3) concentrations, known as alkalinity. High carbonates cause calcium and magnesium ions to form insoluble minerals leaving sodium as the dominant ion in solution. The common method for evaluating the total salts content in water is by measuring the EC at 25°C. EC is expressed in MilliSiemens per meter (mS/m). There is a relation between the electrical conductivity and the concentration of salts in milligrams per liter when the EC_w is in the range of 1 to 5 mS/m. The sum of cations should equal the sum of anions. The accuracy of the chemical water analyses should be checked on the basis of the above relationships.

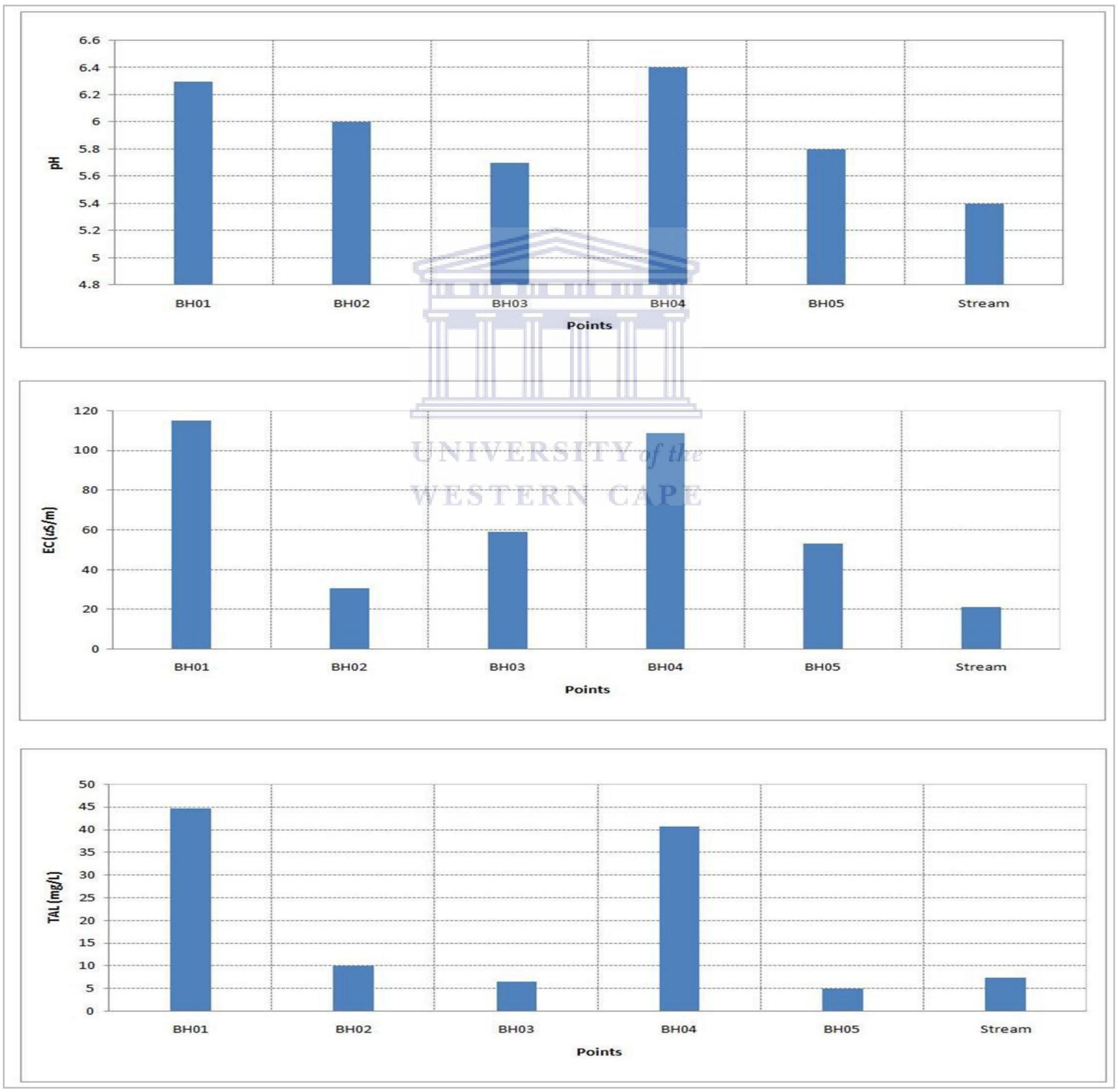

Figure 5-1: Graph for pH, TAL and EC

The pH, EC and TAL of the streamwater remained low whilst the ones for BH01 and BH04 were high. The high values of pH, EC and TAL for BH04 can be associated with the shallow aquifer from which the borehole is getting water as it is only 6mbgl. The high values of pH, EC and TAL for BH01 can be associated with the geological formations that the borehole penetrates through. The borehole penetrates through Nardouw, Cedarberg and Peninsula formations. Unlike the other boreholes that penetrates through Peninsula alone.

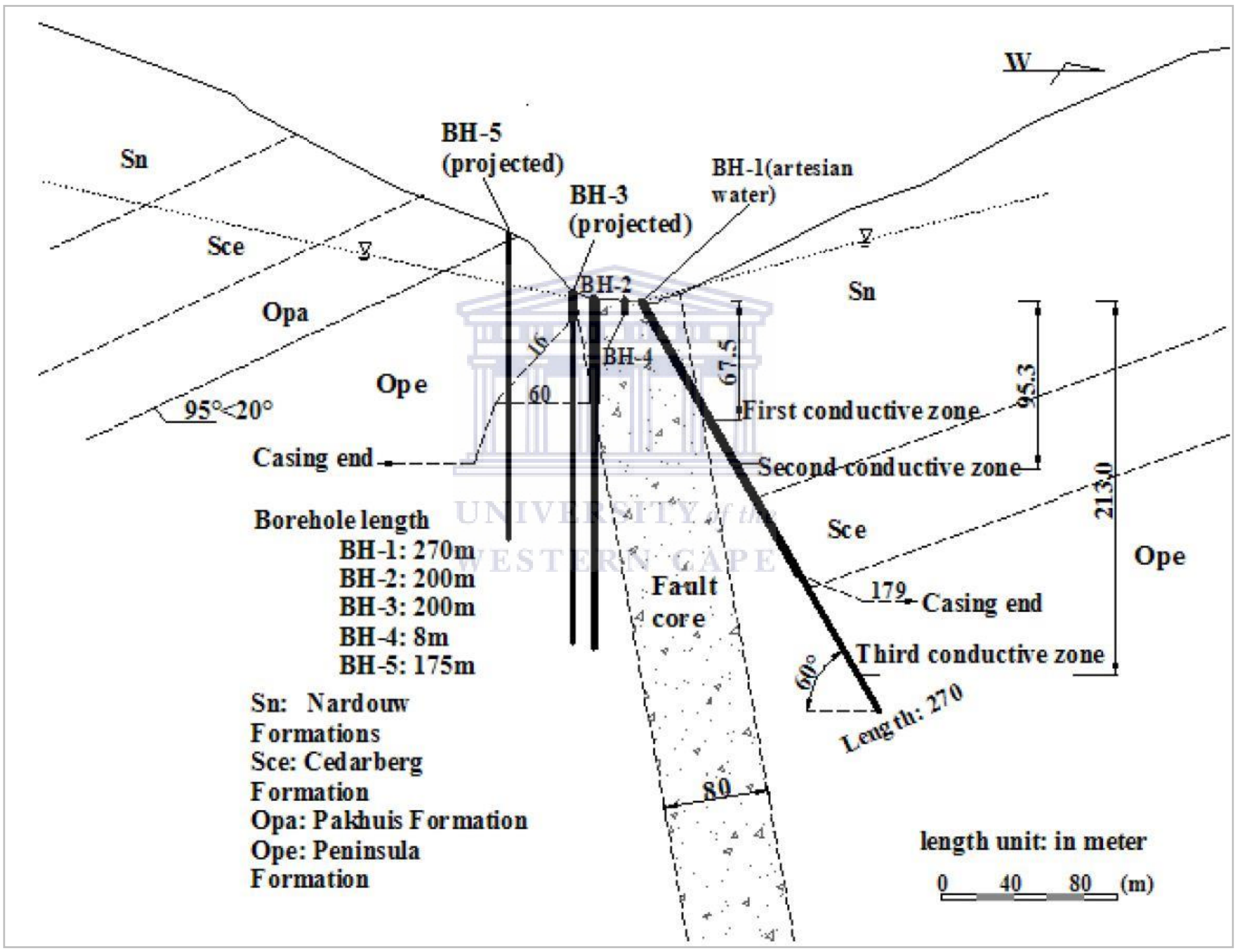

Figure 5-2: Schematic hydrogeological cross section for Gevonden site (Xu et al., 2009)

5.3 Composition and concentration of soluble salts

Six water samples were obtained from five boreholes and one sample from the stream in the case study area of Gevonden Farm. Water samples were analysed for cations and anions or salts and these salts include substances such as gypsum or calcium sulphate ($CaSO_4.2H_2O$), sodium chloride (NaCl) and sodium bicarbonate ($NaHCO_3$). When dissolved in water, salts separate into ions; e.g. sodium chloride breaks down into sodium and chloride ions. Thus, it is customary to refer to ions rather than salts. Water for irrigation from arid climates contains soluble salts which are likely to give problems to the crops given their concentration is high. Water from all kinds of water resources, springs, streams and wells, contains the certain quantities of chemical substances in solution. The quantities of chemical substances are contributed by geology through which water has always been passing. Waters with a high salt content may have moved from a saline water table. In areas with intensive agriculture, fertilization is a major cause of aquifer salinization. The composition of salts in water varies according to the source and properties of the constituent chemical compounds. The principal ions in irrigation water and their characteristics are listed in Table 5-1.

Table 5-2: Principal ions present in irrigation water

Ion	Chemical symbol	Equivalent weight
Anions (Acidic ions)		
Chloride	Cl^-	35.5
Sulphate	SO_4^{--}	48
Carbonate	CO_3^{--}	30
Bicarbonate	HCO_3^-	61
Nitrate	NO_3	62
Cations (basic ions)		
Sodium	Na^+	23
Potassium	K^+	39.1
Calcium	Ca^{++}	20
Magnesium	Mg^{++}	12.2

Table 5-3: Concentrations of cations and anions in mg/L

Elements	BH01	BH02	BH03	BH04	BH05	Stream
Na	9.55	2.70	5.36	3.78	5.37	2.24
K	1.52	0.73	0.52	0.53	0.34	0.02
Ca	7.57	1.37	2.44	17.55	1.51	0.30
Mg	4.00	0.69	1.38	0.60	1.22	0.27
HCO_3	71.96	32.15	21.44	76.56	16.84	13.51
CO_3	0.00	0.00	0.00	0.00	0.00	0.00
SO_4	1.58	0.20	5.88	0.26	1.55	0.45
Cl	8.83	7.06	11.48	6.18	9.71	5.30
NO_3	0.59	0.59	0.70	0.49	0.00	0.00

The samples obtained were analysed and their concentrations were plotted and the graph below (Figure 5-3) indicates that water from all five sampled points can be categorized as hydrocarbonate water type. BH04 and BH01 have a high concentration of hydrocarbons than the other boreholes and stream water. This behavior can be associated with BH04 being a shallow borehole and BH01 penetrating through different formation compared to other boreholes.

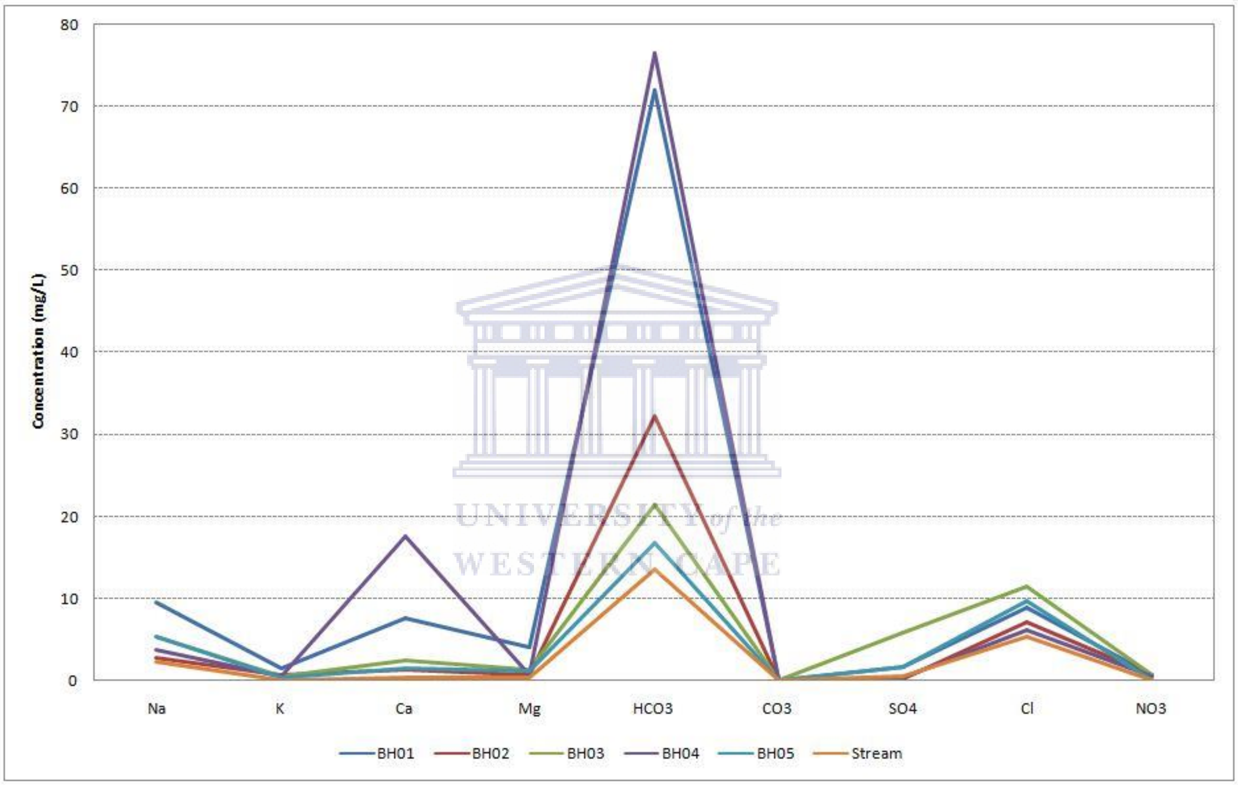

Figure 5-3: Anions and cations for five sampled points

5.4 Sodium Adsorption Ratio (SAR)

Irrigation sources high in sodium (Na) may lead to the deterioration of soil structure. High soil Na causes soil clays and organic matter to disperse. The clays and organic matter clog soil pores, reducing water infiltration and soil ventilation. These problems are greater on fine textured soils such as clays and loams than on sandy soils. Calcium (Ca) and magnesium (Mg) cause the soil to flocculate, and therefore counteract the negative effects of Na.

From all of the elements the sodium adsorption ration was less than 10 milliequivalents per liter, meaning the water from five boreholes and nearby stream is fit for irrigation. The use of water with a high SAR value and low to moderate salinity may be hazardous and reduce the soil infiltration rate. The effects of high SAR on irrigation water infiltration are dependent on the electrical conductivity of the water. For a given SAR, lower EC_w leads to poorer infiltration properties and higher EC_w leads to better infiltration properties. Irrigation water with SAR of 15 milliequivalents per liter (meq/L) has poor infiltration properties if the EC_w is equals to 0.5 deci Siemens per meter (dS/m) but good infiltration properties if the EC_w is equals 2.0 deci Siemens per meter (dS/m). A good rule of thumb is that SAR should be ten times greater than the EC_w, then poor water infiltration is likely to occur.

5.5 Use of Piper Diagram to establish GW-SW Interaction

The piper plot for both groundwater and surface water during dry and rainy season were plotted using Aqua-Chem programme. Figure 5-4 indicates the positions from which the surface water samples were obtained from the stream. The piper diagram presents the results obtained during dry season. The anions and cations plotted towards the center of the diamond shape part of the piper diagram. The piper diagram indicated that water from BH03 which is deep borehole has the same characteristics as surface water from eight surface water points except one surface water point (P4). The piper diagram indicates that other boreholes (BH01, BH02 and BH04) are calcium carbonate (Ca-HCO_3) water type which is typical of shallow, fresh groundwater. The piper diagram indicated that the rest of surface water points are sodium carbonate (Na-HCO_3) water type which is typical of deeper fresh groundwater influenced by ion exchange.

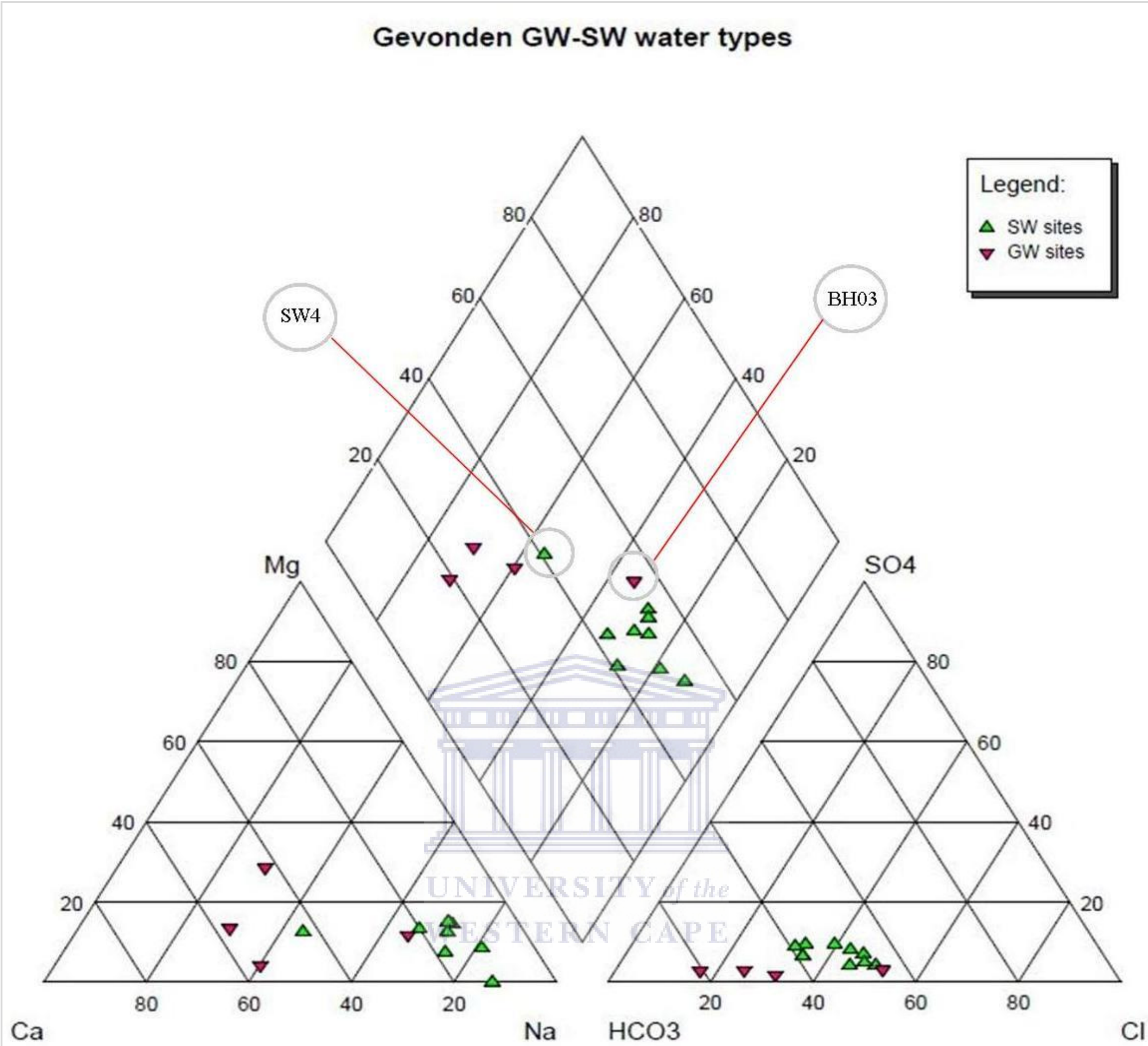

Figure 5-4: Piper diagram for GW and SW during dry season

Borehole four (BH04) which is a shallow borehole and expected to be containing Ca-HCO_3 water typical of shallow, fresh groundwater, set at a center of the diamond shape of the Piper diagram indicating that its water is mixing with deep groundwater as the bottom of the casing was not capped to prevent deep groundwater to be pressured up to join shallow aquifer. The results for BH04 (shallow borehole) suggest that the shallow aquifer interacts with deep aquifer and that the deep aquifer feeds its water to the shallow aquifer. This information can be used for decision making during groundwater abstraction licencing and putting the monitoring plan for groundwater abstraction in place.

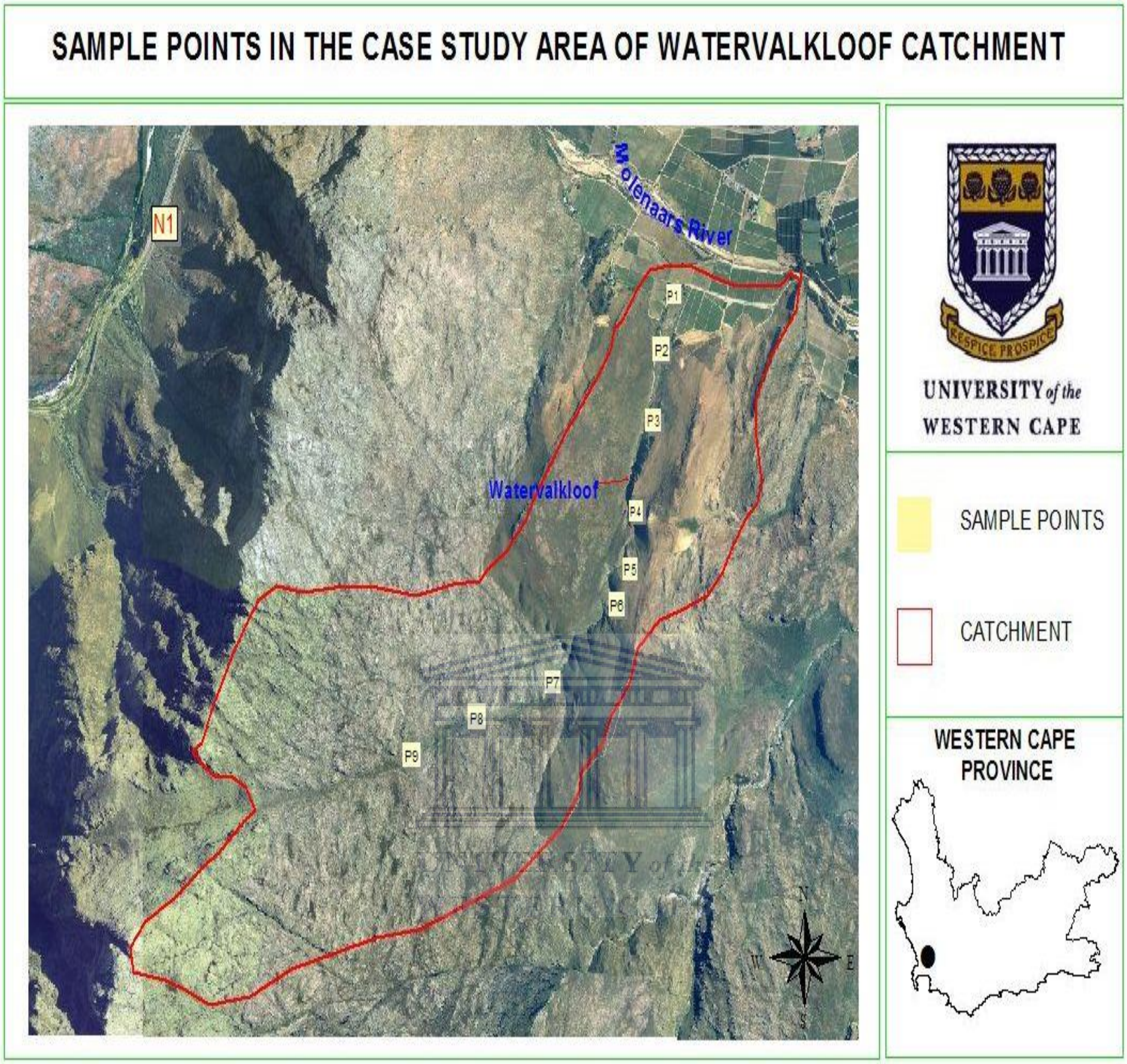

Figure 5-5: Photo map indicating nine surface water points sampled

The second piper diagram presented for the rainy season (Figure 5-6) where five samples were obtained from the boreholes and one sample from the stream of Watervalskloof. The piper diagram indicated that surface water in the area is sodium carbonate (Na-HCO3) water type which is typical of deeper fresh groundwater influenced by ion exchange.

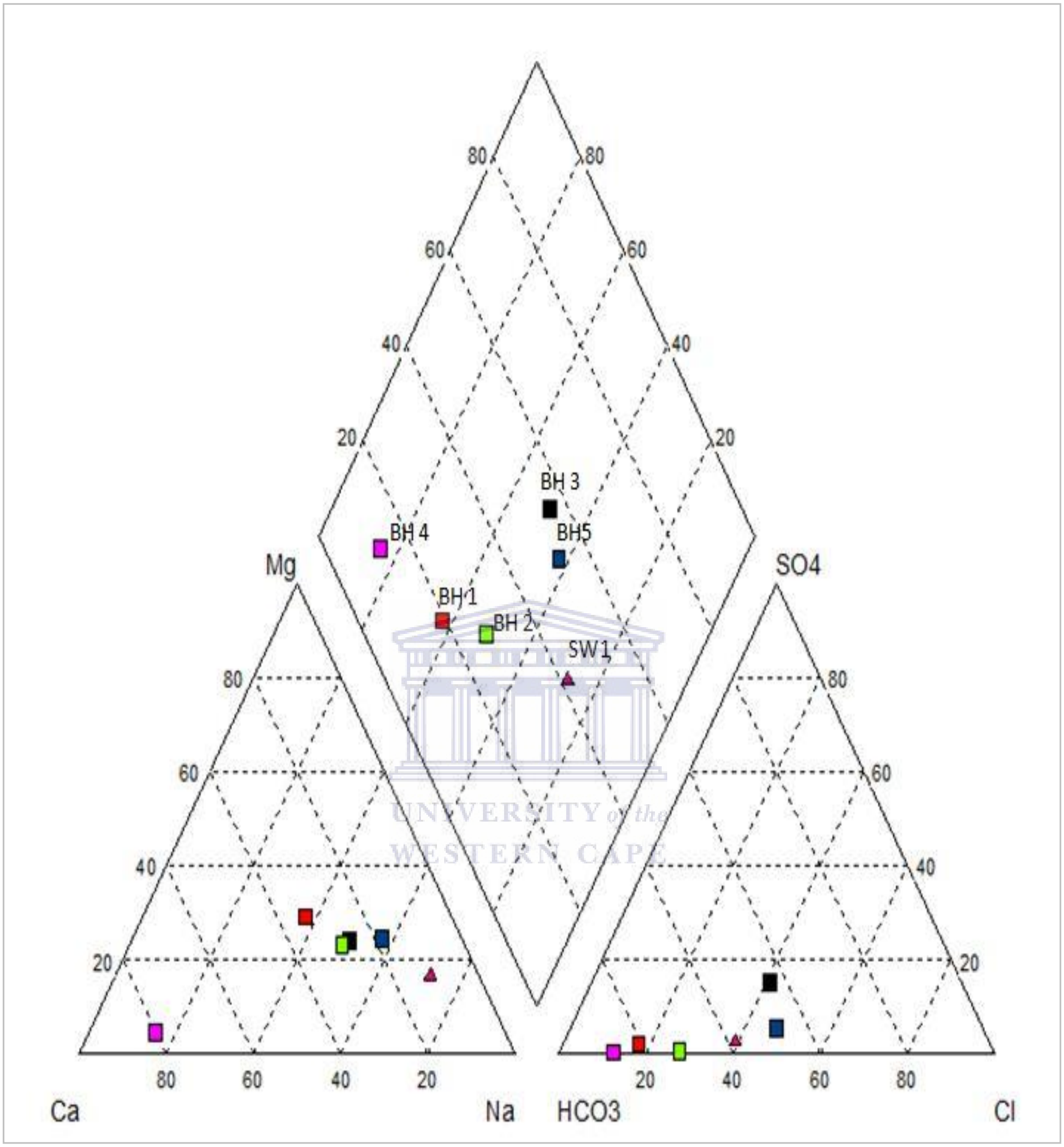

Figure 5-6: Piper diagram for GW and SW during rainy season

5.6 Summary of a chapter

The physical chemistry (pH and EC) were below the limit when compared with South African water quality guidelines for agricultural use: Irrigation (DWAF, 1996). The pH ranging from 5.4 to 6.4 from all the sampled points was measured and EC ranging between 21 and 115.2 uS/m. Cations and anions were also within the limit when compared with the South African water quality guidelines for agricultural use: irrigation. However, bicarbonate, calcium and sodium ions were high. The plotted piper diagrams for rainy and dry seasons and the piper diagram during rainy season indicated that surface water in the area is sodium carbonate (Na-HCO_3) water type which is typical of deeper fresh groundwater influenced by ion exchange. The piper diagram indicates that other boreholes (BH01, BH02 and BH04) are calcium carbonate (Ca-HCO_3) water type which is typical of shallow, fresh groundwater. The piper diagram indicated that the rest of surface water points are sodium carbonate (Na-HCO_3) water type which is typical of deeper fresh groundwater influenced by ion exchange. In general

6 Chapter 6: Groundwater contribution to surface water

6.1 Introduction

The current chapter presents and discusses the results on the establishment of spatial interaction of groundwater-surface water (GW-SW) interaction process by measuring the stream flow from the upper and lower point in a lower reach of Watervalskloof River with reference to a pumped well (BH03) alongside the stream. The method used aims to demonstrate the methodology of obtaining discharge measurements during borehole pumping as one of the methodologies that can be used to establish the relationship between groundwater and surface water resources. The establishment of an interaction will assist in groundwater and surface water management during the continuous use of groundwater resource in the Farm of Gevonden.

The chapter argues that to make a decision on a groundwater abstraction licence in a scenario where a borehole is near the stream, the interaction between surface water and groundwater resource needs to be established using the feasible methods. The methods should be based on scientific principles and they should be clear to non-hydrologists. To achieve the study objective, discharge from two points in the stream was quantified from upper and lower points before and soon before the borehole pumping was stopped to establish if the pumping of water from underground can reduce the stream from Watervalskloof River.

This chapter addresses the third objective of the study, which was to establish spatial interaction of GW-SW interaction process by measuring the stream flow from the upper and lower point with reference to the point of abstraction (BH03). The improvement of knowledge on groundwater and surface water interaction helps in the issuance of water use licence for groundwater or surface water abstraction as a scientific basis that bring about the correct terms and conditions of the water use licence in terms of the National Water Act (Act 36 of 1998). To fulfill the first objective of the study, this chapter answers a question: i) what method that can be used to establish the spatial interaction of GW-SW interaction process?

The groundwater contribution to surface water was evaluated using the current flow meter to measure the streamflow from the two selected cross-sectional areas in the stream of Watervalskloof before and after the point of abstraction. The current flow meter has the capability of automatically calculating the velocity of the stream flow in a particular depth and automatically records it to its memory. The depth of the stream in that particular point across the stream was measured using the calibrated current flow meter steel rod and manually recorded. The width of the stream was measured manually using the tape measure. Five measurements were taken across the stream to improve accuracy.

6.2 The use of stream flow gauging for determining GW-SW interaction

Two points with laminar flow were selected as lower and upper points in the stream of Watervalskloof with relation to a position of a pumped borehole. The streamflow measurements were obtained across the stream from the two selected points before the 24 hour constant pumping started. The second cycle of streamflow readings was carried out soon before the pumping was stopped. The purpose of obtaining the streamflow readings was to calculate the stream discharge so as to establish if there is response from the river due to pumping. The purpose for this exercise was to put conditions that would address the impact that may be caused by groundwater abstraction to the nearby stream. The results are presented in Table 6.1 below:

Table 6-1: Calculated discharge upstream before pumping

Points	Velocity (m/s)	Depth (cm)	Depth (m)	Width (cm)	Width (m)	Area (m^2)	Discharge (m^3/s)
1	0.85	36.5	0.365	22.0	0.20	0.080	0.07
2	1.22	42.0	0.420	22.0	0.20	0.092	0.11
3	1.59	44.0	0.440	22.0	0.20	0.097	0.15
4	1.41	51.0	0.510	22.0	0.20	0.112	0.16
5	0.90	31.0	0.310	22.0	0.20	0.068	0.06
Mean	**1.19**	**40.9**	**0.409**	**22.0**	**0.20**		
Total						**0.45**	**0.55**

For the upper point the width of a chosen cross sectional area was 0.22 meters and the mean depth out of five recorded values is 0.31 meters while the maximum depth is 0.51 meters. The total cross sectional area calculated as the product of length and breadth was 0.45 square meters. The average velocity in meters per second was 1.19 m/s and the average depth of the cross-section is 0.409 meters. The stream discharge (Q) was manually calculated as cross-sectional area and measured velocity of water and the total discharge was $0.55 m^3/s$ (Table 6-1).

For the lower point the measured width of a chosen cross sectional area was 0.273 meters and the mean depth out of five recorded values is 0.301 meters while the maximum depth was 0.446 meters. The total cross sectional area was calculated as the product of length and breadth and was found to be 1.151 square meters. The average velocity was calculated as 0.33 m/s and the average depth was calculated as 0.3 meters. The stream discharge (Q) was manually calculated using the cross sectional area and the average velocity of the stream flow measured and the total discharge was calculated as 0.348 m^3/s.

Table 6-2: Calculated discharge in the lower point before pumping

Points	Velocity (m/s)	Depth (cm)	Depth (m)	Width (cm)	Width (m)	Area (m^2)	Discharge (m^3/s)
1	0.27	19.5	0.19	140.0	1.400	0.273	0.07
2	0.34	30.1	0.30	93.0	0.930	0.279	0.09
3	0.31	44.5	0.45	67.0	0.670	0.298	0.09
4	0.29	44.6	0.45	23.0	0.230	0.103	0.03
5	0.29	38.0	0.38	52.0	0.520	0.198	0.05
Total	**0.33**	**35.3**	**0.35**	**375.0**	**3.750**	**1.151**	**0.35**

The same procedure used for stream discharge measurement before the commencement of pumping was used towards the end of pumping and the results are tabulated in the table below: The second measurements for the upper point were obtained towards the end of 24 hour constant discharge. The width, cross-sectional area and average depth remained the same. The average velocity in meters per second remained 1.19m/s and the stream discharge (Q) calculated as a ratio of total cross-sectional area and measured velocity of water flow was 0.55m^3/s. The table below (Table 4.3) tabulates the measurements obtained in the upper point soon before the pumping process took place.

Table 6-3: Calculated discharge in the upper point soon before the pumping was stopped

Points	Velocity (m/s)	Depth (cm)	Depth (m)	Width (cm)	Width (m)	Area (m^2)	Discharge (m^3/s)
1	0.78	34	0.34	22	0.22	0.07	0.05
2	0.99	44.5	0.45	22	0.22	0.09	0.09
3	1.57	42	0.42	22	0.22	0.09	0.14
4	1.52	43	0.43	22	0.22	0.09	0.14
5	1.12	35	0.35	22	0.22	0.08	0.08
Total	**1.19**	**39.7**	**0.39**	**110**	**1.1**	**0.4367**	**0.53**

The velocity of water flow decreased from 0.33 m/s before the pumping commenced to 0.31m/s soon before the pumping could be stopped. The total stream discharge from the lower point soon before the pumping has taken place was 0.35 m^3/s. The total stream discharge from the point after the pumping point after the pumping has taken place was 0.34 m^3/s (Table 6-2). Table 6-4 shows the measurements obtained in the lower point soon before the pumping was stopped.

Table 6-4: Calculated discharge in the lower point soon before the pumping stops

Points	Velocity (m/s)	Depth (cm)	Depth (m)	Width (cm)	Width (m)	Area (m^2)	Discharge (m^3/s)
1	0.34	17.52	0.18	135	1.4	0.25	0.08
2	0.28	31.67	0.32	92	0.93	0.29	0.08
3	0.29	41.9	0.42	74	0.67	0.28	0.08
4	0.32	46.1	0.46	25	0.23	0.10	0.03
5	0.29	35.69	0.36	49	0.52	0.19	0.05
Mean	**0.31**	**34.57**	**0.35**	**375**	**3.75**		
Totals						**1.11**	**0.34**

6.2.1 Implication of using stream flow gauging to establish GW-SW interaction

Streamflow gauging method was aimed at finding out if the stream lost its water to groundwater during 24 hour constant discharge pumping. The perception was that if the stream is connected to the groundwater resource there would be a decrease in stream discharge in a lower point towards the end of pumping. Secondly it was aimed at showing if the reach from which the discharge was calculated is a gaining or losing reach by comparing the two calculated discharges from the upper and lower point. The understanding was that if a reach is gaining water from the groundwater component, the upstream discharge will be lower than the downstream discharge and if the reach is losing water to the groundwater the upstream discharge will be higher than the downstream discharge.

The results presented in this chapter indicated that there is interaction between groundwater and surface water resource in the lower stream reach and that the stream is a losing stream in this reach as the stream discharge before the pumping point is greater than the stream discharge further downward (See table 6.5 below).The results obtained even after pumping still indicates that the stream is a losing stream.

Table 6-5: Discharge values before and after the pumping

	Discharge (m^3/s) (Before pumping commenced)	*Discharge (m^3/s) (After pumping commenced)*	*Difference*
Upper point	0.5548	0.531	0.0238
Lower point	0.3480	0.338	0.01

The decrease in the stream discharge values obtained after the borehole pumping indicates that the pumping impacted to streamflow reduction. The difference in streamflow discharge before and after pumping indicates the amount of stream water that is lost to groundwater component. However with the velocity gauging method, the net exchange of groundwater with stream water is captured, but it is not possible to identify inflow and outflow components of surface water exchange. The response of a stream from the 24 hour groundwater abstraction indicated that there is interaction between groundwater and surface water resource, the identification of GW-SW interaction substantiates the decision making during groundwater abstraction licence.

6.3 The use of sodium chloride for determining GW-SW interaction

Sodium chloride (NaCl) solution as a tracer method was used to establish if groundwater interacts with surface water in the lower reach of Watervalkloof stream. The first water sample was obtained from a shallow borehole (BH04) and from the upstream point of the river. NaCl solution was dosed into the borehole. Before the dosing of NaCl solution the Na concentration was 1.8 mg/L and the Cl ions concentration was 8.8 mg/L upstream. Downstream the Na concentration was 1.9 mg/L and the Cl concentration was 5.3 mg/L. The samples obtained two weeks after the dosing the NaCl solution had concentrations and the Na concentration of 1.6 mg/L and Cl ions concentration was 7.95 mg/L upstream. Downstream the Na concentration was 2.24 mg/L and the Cl ions concentration was 5.3 mg/L. From BH04 where the NaCl solution was dosed the Na concentration was 1.7 mg/L and the Cl ions concentration was 3.24 mg/L before dosing NaCl solution. Two weeks after the solution was dosed the Na concentration was 3.7 mg/L and Cl ions concentration was 6.18 mg/L.

6.3.1 Implication of using NaCl solution to establish GW-SW interaction

The intention of the use of sodium chloride (NaCl) solution was to further establish if there is interaction between groundwater and surface water resource. The establishment of GW-SW interaction would also help in terms of decision making during the issuance of water use licence and also help in formulation of conditions that should be stipulated into the licence if issued. With the dispensation of sodium chloride solution into BH04 the expectation was that the Na and Cl ions concentration will increase on the next sample cycle. The concentration of Na ions increased from 1.9 mg/L to 2.24 mg/L, but the one of Cl ions did not as it remains to 5.3 mg/L. The resistance in increase can be associated with the geological formation through which Cl ions had to percolate towards the stream which reacted with Cl ions and eliminated it from the process. The dispensation of NaCl solution into the borehole however; proved that the water from the shallow aquifer recharges the stream of Watervalkloof.

The NaCl as the tracer has been used successfully in a study conducted by Winfield et al. (2003), whereby tracer-injection technique (using NaCl solution) was used to demonstrate surface-water and ground-water interactions between an Alpine stream and the North Star Mine, Upper Animas River Watershed, Southwestern Colorado. In this study the NaCl solution was injected from the upper reaches of the stream and samples were taken from the mining tunnels. The high concentrations of sodium and chloride detected in the mining tunnels indicated that there is interaction between groundwater and surface water in the Animas watershed. However the method is vice versa as compared to the method used in the current study as the NaCl solution was injected in the borehole (BH04) hoping to detect the high concentrations of Na and Cl ions further downstream.

Determination of discharge through tracer-dilution (tracer-injection and dilution) methods includes hyporheic-zone flow and can provide needed precision when the goal of a seepage run is to quantify inflows to the stream that may be only a few percent of the total streamflow. Continuous and instantaneous (slug) tracer-dilution methods were applied and combined during the study to assessment of GW-SW interaction and simulation of potential streamflow depletion induced by groundwater withdrawal, Uinta River near Roosevelt, Utah to enable the quantification of gain and loss of water in the West Channel of the Uinta River (Lambert, et al., 2011) as described in the following sections.

In a study by González-Pinzón, (2015), NaCl and resazurin tracers suggested different surface-subsurface exchange patterns in the upper and lower of the reaches. The study mentioned of that the (GW-SW) interactions in streams are difficult to quantify because of heterogeneity in hydraulic and reactive processes across a range of spatial and temporal scales. The challenge of quantifying these interactions has led to the development of several techniques, from centimeter-scale probes to whole-system tracers, including chemical, thermal, and electrical methods.

6.4 Implications of pumping next to the stream and other boreholes

The implication of pumping a borehole which is next to the other boreholes and stream is perceived as illustrated in (Figure 6-1). When BH03 was pumped at a rate of 1.8 l/s BH05 responded within three minutes and BH02 had an insignificant response to pumping whilst BH04 and BH01 did not respond at all. BH04 is only 6m deep and it goes through the shallow aquifer which is disconnected to the deep aquifer hence that is the reason why it did not respond. On BH01 (inclined borehole) the reason for none response to pumping is the depth of the casing which is 179m deep, the casing deprived the response of a borehole during pumping. The insignificant response on BH02 was also due to the depth of casing which is 60m deep (Biyela et al., 2006). It is unlikely that the stream can be affected by immediate pumping of a nearby borehole because the current experiment indicated that there is no connection between the groundwater and surface water, however, geohydrologically, when the alluvial aquifer on which the stream exists gets unsaturated the water from the stream will easily infiltrate through the shallow aquifer towards the deep aquifer.

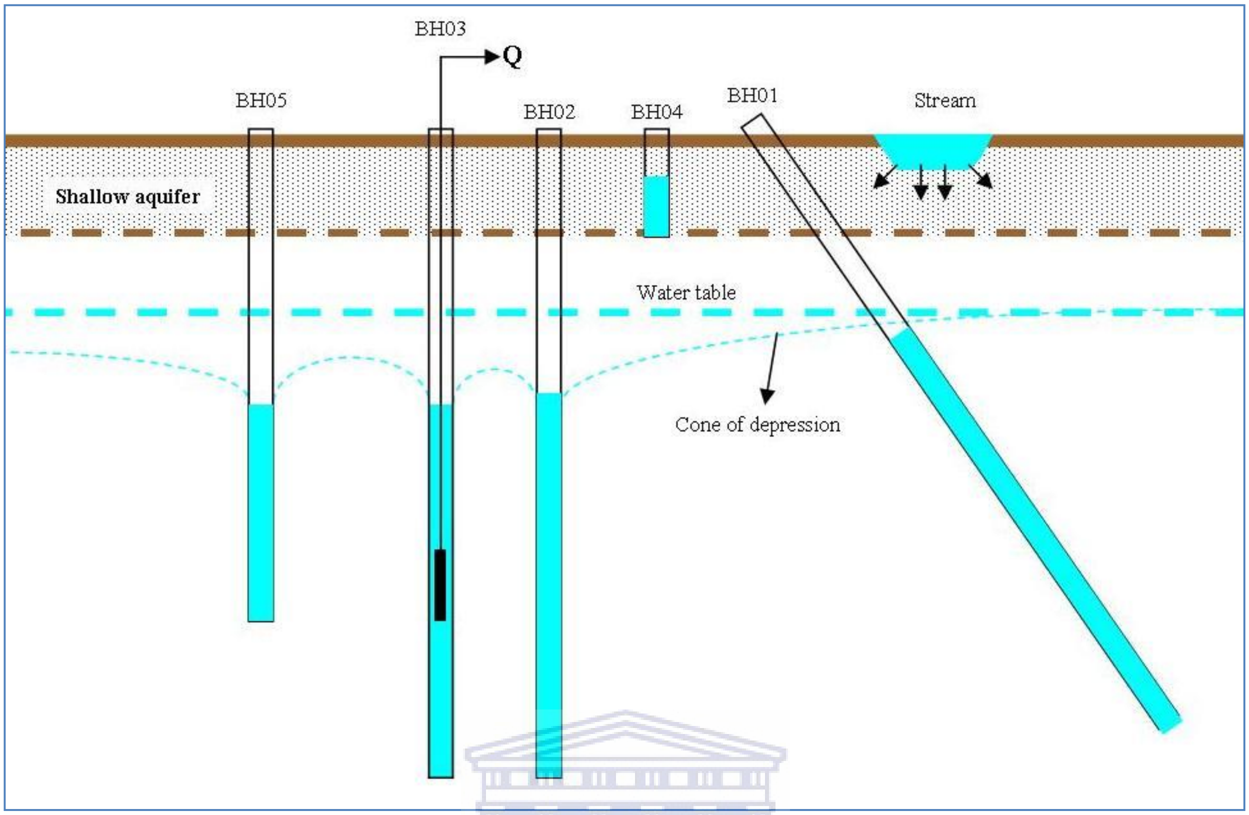

Figure 6-1: Conceptual model of connections between boreholes and stream

6.5 Summary chapter

This chapter was aimed at establishing the spatial interaction of GW-SW process by measuring the stream flow from the upper and lower point with reference to the stream in a reach of the stream parallel to the point of abstraction and by dispensing the NaCl solution to the borehole. The objective was aimed at identifying the spatial interaction between groundwater and surface water. The methods can be used for substantiating the decision of issuing the groundwater abstraction water use licence and intensifying or relaxing the monitoring programme for the groundwater abstraction in the given area.

The use of streamflow measurements has its own strength in identifying the GW-SW interaction. In a scenario where the method is used to reveal if the stream in a particular reach is a losing or gaining stream the method is quick, cost effective and gives reliable results and correct conclusion. This scenario simply needs the measurements of the streamflow from two point from the stream and compare them. If discharge at the upstream point is less than the downstream point that means the stream is a gaining stream. If the discharge at the upstream point is higher than the downstream point therefore the stream is a losing stream. However, in a situation whereby the interaction between the borehole and stream is determined the results obtained from the current meter are unreliable.

The literature reviewed for the current study indicated that the reliable streamflow measurement can be obtained when making use of a weir. The use of a current meter can however be applied in the circumstances where there are no financial means to construct a weir. It can also be used to confirm the streamflow measurements obtained from a weir for quality assurance. The current meter used in the current study needs the laminar flow from the stream, therefore in the next study the cross section where the measurements are taken should be cleaned and prepared so as to give a laminar flow before the measurements are taken. The recommendation from this chapter is that the streamflow should be monitored at least three times during rainy season and three times during dry season.

7 Chapter 7: Proposed Approach

7.1 Introduction

To respond to the topic of the current study which is *"Assessing groundwater-surface water interaction as a decision-making tool licensing water use South Africa: Case study area of Gevonden Farm"* three objectives were outlined, and those are 1) Determine hydraulic properties of the aquifer in the local area of Gevonden Farm, 2) Assess groundwater and surface water quality for irrigation in the case study area and, 3) Evaluate groundwater contribution to surface water in the case study area. The three last chapters (chapters four, five and six) responded to the objectives with an attempt to have a scientific backing for water use licence issuance for groundwater abstraction. Results and analysis were presented and discussed in the three latter mentioned chapters. This chapter concludes and recommends the depiction made from the three chapters and a literature review.

7.2 Proposed approach

The aim of the current chapter is to outline the proposed approach for groundwater use licence as the procedure used to take a decision is currently based on the reserve determination and geohydrological report. However, the current study argues that the groundwater reserve cannot be used to take decision at site specific scale as determined at a quaternary catchment scale. The geohydrological report remains unclear what is required from it and how it should be used as a motivation for groundwater abstraction water use licence. The study recommends decision making based on the standard geohydrological report only. The steps below outlines the important sections of a recommended geohydrological report:

7.2.1 Local geology as motivation for the issuance of water use licence

Understanding the local geology of an area where the borehole water needs to be licence is important during the decision making by WUAAAC. The geohydrologist involved during should comprehend the structural geology at local scale. The structural geology should entail about connectivity, intrusions, syntaxis, faults, joints, fractures and fissures of geology where the groundwater resource will be developed. For the borehole to be referred to as sustainable there should be an intensive connectivity on the fractures and it should be able to draw water from far

7.2.2 Local geohydrology as motivation for the issuance of water use licence

Local geohydrology gives a picture how much connected the surface water resource to groundwater resource and how possible it is for the groundwater resource to be developed in an area. The availability of springs in the area means groundwater is abundant and the level of fracture connectivity is high and that the groundwater levels are few meters below ground levels. There is always the perceived interaction between the rivers and groundwater, the presence of intensive river network and their tributaries can be associated with sustainable groundwater availability. The number of boreholes at a local scale (within 2 kilometers radius) is important as it gives a clear picture how intensive the groundwater is used and for what it is used. It is also crucial to delineate the conditional boundaries of the aquifer at local or site specific scale. Under hydro-census, questions such as how many people using surface water, how many people use groundwater and how many boreholes in the area are important questions. The hydraulic properties such as yield, storativity, transmissivity and hydraulic conductivity help the DWS geohydrologist to confirm the sustainability of the boreholes. Pump cycle, size of a pump, available drawdown and main water strike help during compilation the borehole management recommendations.

Groundwater and surface water quality as a section in the geohydrology report need to be analyzed for. The chemistry that should be taken into consideration is physical chemistry, micro and macro elements and bacteriology. Elements that need to be analysed under macro and micro elements differ based on what the water will be used for between agriculture, domestic and industrial. The chemistry should be compared with SANS 241standards to make sure if they are all under the required limits. If there are some of the elements that are above the limits they should be discussed and solutions how to purify water should be suggested by a geohydrologist or water quality specialist.

7.2.3 Social water related issues

The public should be informed about the activity that is going to take and how much water it will need. The public participation specialist should compile a questionnaire with relevant questions which are related to the issues surrounding water to which the members of the community will respond will respond by yes or no. The questions should talk to the scarcity of water, water resource that the community uses, water quality problems they have observed and how they feel about the amount of water they their neighboring developer is applying for. The function of conducting public participation should be assigned within the relevant sub-directorate in DWS. Currently this function is carried out by the clients themselves and that opens a loophole on an issue of handling public participation.

7.2.4 WUAAAC decision

WUAAAC is a committee that is established from DWS and it is given a mandate to take decisions when any of the water uses is authorized. For groundwater abstraction water used authorization the qualified geohydrologist should be part of the committee to help with the review of geohydrology report from the client or client's consultant. The geohydrologist should look at issues such as the capacity of the borehole, water quality and if the content of a report was covered correctly including borehole siting, borehole drilling and geological logging, identification of the main water strike and if the available drawdown was determined correctly. The positioning of the pump and its capacity is also important to look at together with the pumping cycle if it was determined correctly. Lastly the geohydrologist should advice the committee for which parameters should the client monitor and for how long should the client be authorized to pump water from the borehole.

7.3 Conclusion

From this investigation it is concluded that the three main objectives were responded to and the main aim of the investigation was addressed. The local approach to make an informed decision when issuing the groundwater abstraction water use licence was addressed. However, there are hypothesis that were not responded to such as the one of GW-SW interaction.

7.4 Decision making on the current study

Figure 7.1 shows the components of the current geohydrological study and how the decision was made. The diagram outlines the objectives of the study which are 1) Determine hydraulic properties of the aquifer at the local scale in the case study area, 2) assess groundwater and surface water quality for irrigation in the case study area, 3) evaluate groundwater contribution to surface water in the case study area. It further gives the methods that enabled the current study to respond to the objectives and those were 1) analysis of geochemistry and surface water chemistry, 2) conducting a pumping test, and 3) comparing surface water with groundwater do determine the interaction. The diagram also outlines the results and recommendations from the geohydrological report.

7.5 Recommendation

For groundwater management purpose on site, it is recommended that production boreholes be pumped at a recommended rate of 1.02 l/s in BH03 and BH05 which is equivalent to 32188.06 m^3/a, the pump should be installed at a depth of 135 mbgl for both BH03 and BH05 based on the water strikes determined by Lasher, 2011, the continuous monitoring of water quality once in six months should be carried out, the continuous monitoring of water levels from all the boreholes in the surrounding takes place at least once a month or the installation of water level loggers to all the monitoring wells or nearby well from the pumped wells, and the continuous monitoring of stream discharge using current meter takes place at least once in six months or a proper weir should be installed. The records for data collected from site should safely be kept by a client for in case the Department of Water and Sanitation (DWS) requests the data. The chemical analysis using piper diagram and using stream flow measurements suggested that BH03 and BH05 are connected hydraulically. The recommendation for a licence condition is to investigate further if there is connection between groundwater and surface water in the local area and how the groundwater abstraction will affect the surface water resource in the surrounding area.

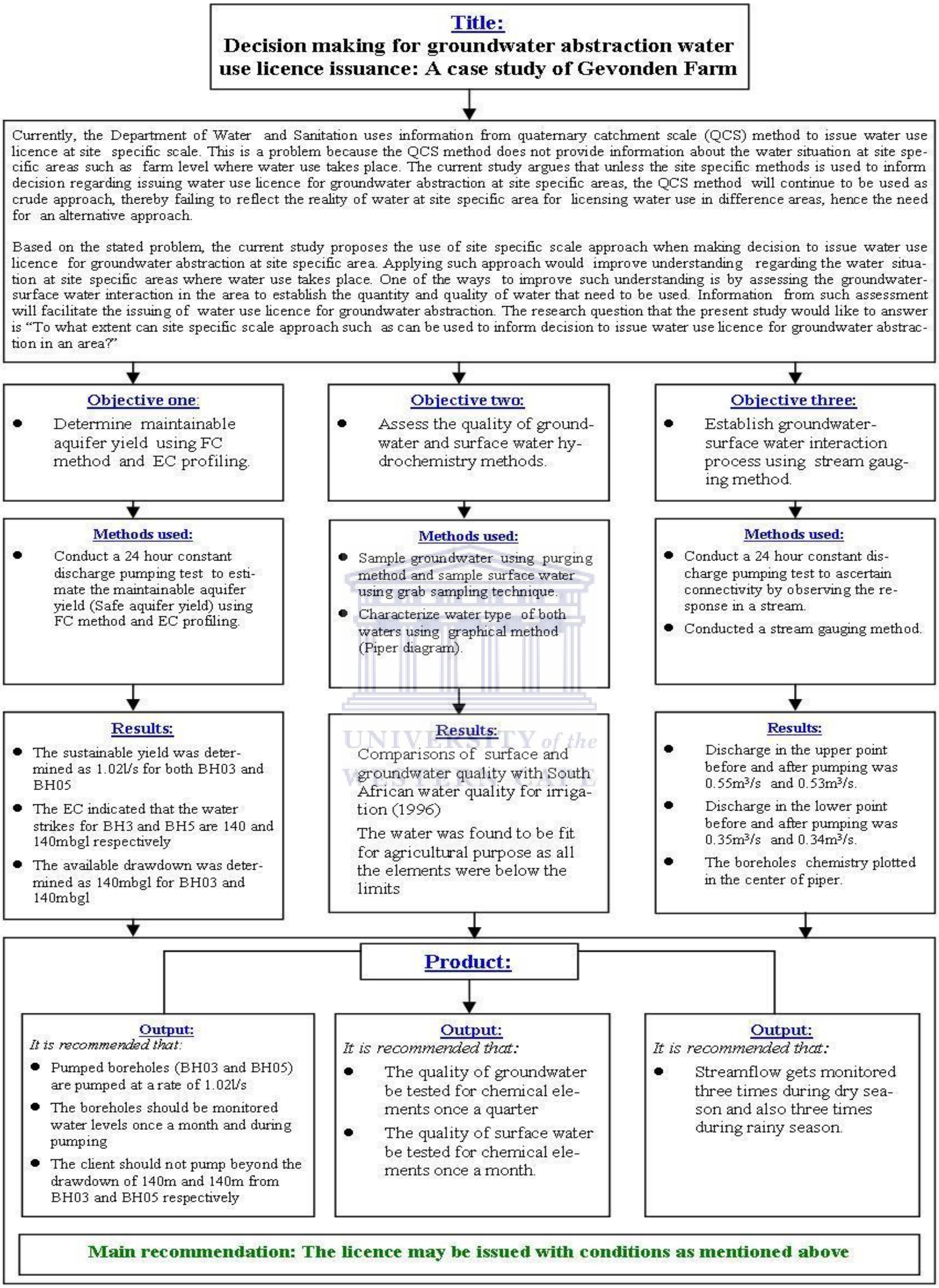

Figure 7-1: The diagram outlines the conduction of the study until decision making

7.6 Adaptive management

The process used to take a decision for the issuance of groundwater abstraction water use licence leaves behind a number of questions unanswered. Those questions are; can the water use licence be confidently issued based on the recommendations of a Reserve? Can we not issue the groundwater abstraction water use licence because the Reserve indicates the deficit in groundwater resource within a particular quaternary catchment? If the Reserve indicates that there is enough water, is the Department sure of the calculation used to determine the available water? Can a decision to issue be supported with only the site specific geohydrological report prepared by a client? The questions trigger the suggested adaptive groundwater management.

The adaptive management is generally explained as learning from implementation (Allan, 2007). There are four fundamental steps to understand in adaptive management and those are 1) Planning, 2) implementation, 3) Monitor and, 4) learning. There three types of adaptive management and those are 1) Evolutionary, 2) Passive and, 3) Active adaptive management. Evolutionary adaptive management is undirected learning from random experience, or trial and error learning. Passive adaptive management has a strong focus on implementation, in particular the implementation of a historically informed best practice or policy, followed by review of that implementation. Active adaptive management, like passive adaptive management, is about implementation, but there is a stronger emphasis on learning.

The adaptive management suggested in the current study is active adaptive management as it emphasizes more on learning. However active adaptive management does not mean all the water use applications for groundwater abstraction need to be issued and after that get closely managed. There should still be a criteria used to evaluate the water use licence application for groundwater abstraction. The suggested steps to appear in the criteria are 1) geohydrological report that responds to the potential of the borehole to give the amount of water applied for, 2) fitness of water quality for agricultural or human consumption depending on what are was an application about and 3) If the there is a surface water resource or even groundwater resource situated nearby there should be a study conducted to evaluate the interaction between these resources.

However, the first steps of the criteria to be followed are 1) is the borehole 100m away from any water resource? 2) Was the public participation conducted to ensure that the neighbors do not object the groundwater abstraction applied for? And 3) is the borehole not next to any source of pollution that might cause threat to groundwater quality? The issues that make the Reserve to be unable to stand litigation should be addressed because either than that the use of Reserve for decision making becomes irrelevant if the client appeal the decision of not issuing the licence because deficit realized from the catchment.

In a case of the current situation created in the case study area of Gevonden Farm with relation to adaptive management the following condition need to be specified to a client, 1) The water meter should be installed to measure the amount of water abstracted per day, 2) The groundwater levels should be measured from the borehole pumped borehole and monitoring boreholes once a month, 3) The water quality samples should be obtained from the river and five boreholes on site and sent to the accredited laboratory for analysis seasonally, 4) All records for the information collected should be stored safely for in case DWS request to have them.

7.7 Capture principle

Other studies have suggested that capture method (Alley et al., 1999 and Seward et al., 2006) is a method that can be used to determine sustainable yield within a quaternary catchment to substantiate decision making when the groundwater abstraction water use licence is issued. Capture is defined as the sum of the increase in recharge and decrease in discharge (Lohman, 1972). For the current study capture principle is not an alternative as it still does not consider the parameters to be considered at local scale for the licence issuance.

7.8 Groundwater resource assessment at local scale

The assessment of a production borehole requires the preparation of geohydrology report that entails the sitting, drilling, pump testing and water quality testing. Information that needs to be depicted in each and every section of this nature of a geohydrological report has not been dealt with in details to make an informed decision during the licence processing. The main suggestion going forward is that this nature of a report should serve a training to capacitate young geohydrologist so that they can understand what they are doing during geohydrological report review.

Further suggestions are that GW-SW interaction investigation needs suitable borehole construction. Understanding of the types of aquifers that exist in the area is important. The categorization of aquifer into primary and secondary aquifer is required. In the case study area the shallow aquifer is regolith or primary aquifer and the deep aquifer is hard fractured rock or secondary aquifer. The construction of a shallow borehole was supposed to be such that it allows recharge from the shallow aquifer only. The borehole should be capped at the bottom so that it does not allow water from the deep aquifer to vertically get into the shallow borehole.

The borehole representing the deep aquifer should also be constructed such that it allows no water from the shallow aquifer to get to the deep aquifer. This can be achieved by using two different drilling rigs diameters normally through the shallow regolith aquifer the 203mm diameter should be used and from the hard rock or deep aquifer the 165mm diameter should be used. In the 203mm drilling rig diameter (shallow aquifer), the plain steel or PVC casing larger than the pipe to go through the deep aquifer. The small diameter pipe going through the deep aquifer should be perforated to the depth where water strikes were identified. The bottom of the shallow aquifer in the deep aquifer should be sealed with bentonite seal in the laminar space between the steel and PVC casing. Such shallow and deep boreholes construction will render the two different waters from two different aquifers.

7.8.1 Borehole purging before sampling

Purging of each borehole before taking some field measurements and samples is important. The recommended method of purging is the calculation of a column of water in the borehole and purge three times the calculated volume Weaver et al., 2007. The prescription of a pump size that will pump water required from a borehole is prescribed by conducting a step test. In the current study the step test was not conducted due to financial constrains. Geological logging for the development of a conceptual model of an aquifer was not done and geophysics for borehole siting was not carried out before borehole drilling. The three components of the study are important as they contribute to management recommendations for sustainable use of a borehole. It is therefore suggested that step test, geological logging and geophysics are included in the next study.

There are some field measurements that could be obtained for stream-aquifer interaction, but may give misleading results due to incorrect assumptions. The first one is inaccurate gauging survey. It is conceptually appealing to assess stream depletion effects by simply pumping a well for a period of time and monitoring the flow in a nearby stream to see the change that occurs. Float methods and current meters can be used to measure the water flow rate and when this information is combined with the cross-sectional area of the flow channel, the flow rate can be estimated. However, this is not a reliable method of assessment due to measurement inaccuracies coupled with background fluctuations in stream flow compared to the relatively small effect from a pumping well, particularly over short pumping periods (i.e. less than 48 hours).

Water chemistry analyses: consideration may also be given to measuring the change in water quality characteristics that occurs between the surface water body and the groundwater. If such a parameter could be found then monitoring of the water quality in the pumped well could detect a change in the proportion of surface water being pumped from the well. For instance, a common example of the change in water chemistry between surface water and groundwater occurs in the pH value of the water.

One difficulty that exists with such chemical indicators of surface water is that many of the chemical parameters will typically undergo chemical transformation as they move through the streambed and into the subsurface environment. Consequently, by the time any water that originated from the surface water body reaches a well, its chemical composition will have been modified so that it can no longer be directly compared with the chemical composition of surface water.

Stream depletion effects can occur without any stream water reaching the well. The stream depletion effect is caused by a pumping well creating a change in hydraulic gradient adjacent to the streambed which results in a loss in streamflow, or an equivalent reduction in groundwater seepage that would otherwise enter the stream. This effect can occur without any surface water actually was drawn into the well. As a result, sampling the water quality of the pumping well for surface water indicators cannot be used as a reliable measure of stream depletion effects.

Pumping test results near streams: pumping test is a common hydrogeological field technique to determine aquifer transmissivity and storage characteristics. They involve the pumping of an individual well at a constant rate for a period of several hours whilst the drawdown in water levels is measured both in the pumped well and in surrounding "observation wells. These tests are typically analysed using methods that assume the aquifer is of infinite extent. However, if such tests have taken place in aquifers where stream depletion effects are expected to occur then it may be inappropriate to use aquifer parameters that have been analysed using the assumption of an infinite aquifer. In such circumstances it will be more appropriate to re-analyse the test data using the approach described in Hunt (1999). It has also sometimes been misleadingly reported that because pumping tests have created very small drawdowns, there must be no stream depletion effect occurring. However, it is often the recharge from a stream that causes the small drawdown effects during pumping.

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