Determination of groundwater-surface water interaction, upper Berg River catchment, South Africa

Tebogo Eugene Madlala

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Department of Earth Sciences, Faculty of Sciences, University of the Western Cape

Supervisor: Dr. T.O.B Kanyerere

Co-Supervisors: Prof. Y. Xu and Dr. P. Oberholster

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Declaration

I, Tebogo Eugene Madlala declare that *Determination of groundwater-surface water interaction, upper Berg River catchment, South Africa* is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name: Tebogo Eugene Madlala

Date…..............................

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

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Abstract

The present study investigated the application of a multi-method approach to determine groundwater-surface water (GW-SW) interactions to quantify and characterize the quality of water resources in a fractured rock aquifer system in upper catchment of the Berg River (G10A). Demonstrating methods for improved understanding of groundwater and surface water interactions is important for informing development of strategies that ensure effective utilization and management of water resources. Applying a single method to inform innovative strategies for water resources has proved futile. The current study shows how the use of several methods can provide the basis for devising practical strategies for water resource utilization and management.

The three methods were applied as follows: First, the base flow separation was used whereby the Chapman and Lynne & Hollick digital filter algorithms were applied to time-series streamflow data from four stream gauging stations in the catchment. The computation from algorithms on three sites (gauging stations) showed that the mean Base Flow Index (BFI) value ranged between 7%-8% for the 2012-2014 periods. This means that discharges from subsurface water storages dominate stream flows throughout the study period. Secondly, the quality of groundwater and surface water was sampled using standard methods. Piper Diagrams generated on Aquachem™ software and radial charts were used to identify the predominant hydrochemical facies. Results showed that Na-Cl was the predominant GW and SW water-type. This means that both GW and SW are mainly influenced by recharging surface water as well as interaction occurring between the rock matrices and infiltrating water. Multivariate statistical analyses were used to evaluate the factors controlling GW and SW chemistry in the upper Berg River catchment and the results showed that GW and SW are influenced by natural processes. Two main factors (a. & b.) were extracted which explained 71.8% of the variation in both GW and SW physicochemical parameters. These factors include water-rock interactions and the recharge of surface water. Cluster Analysis extracted four major clusters that grouped sites with similar physicochemical characteristics together. Finally, differential stream gauging was applied to a 600m reach above the Berg River Dam. Three 200m sub-reaches were used to compute differences in flows between sub-reaches. Stream flow at each sub-reach was estimated using mass balance equations with electrical conductivity measurements during instant salt tracer injection tests. Results indicated that during both the wet season (high flow) dry season (low flow), the river continuously lost water to the subsurface. This was demonstrated by the 0.91m^3/s and 2.24m^3/s decrease in stream flow along the 600m reach. Dry season flow decreases were less than wet season flow decreases, indicated by markedly lower flow loss in respect to the wet season. This confirms results of the analysis of base flow separation, which indicated that discharges from subsurface storages dominate stream flows during low flow periods. The differential stream gauging approach did not provide distinct points along the selected stream reach where GW-SW interaction occurred; rather it provided a holistic representation of seasonal flow variations along the selected reach.

This study showed that upper Berg River catchment is dependent on discharges from subsurface water storages to maintain dry season flows. Furthermore, this study showed that infiltration of surface water and discharge of subsurface water transfers the respective chemical signature of the contributor, meaning that the transfer of water of suitable quality will reduce contamination in the receiving water body (i.e. surface water). Transfer of water between subsurface and surface water contributed an average of 8% of the gauged flows in the catchment between 2012 and 2014, suggesting that the groundwater recharge process dominates this catchment.

Keyword: Groundwater-surface water interactions, hydrochemistry, base flow, multivariate statistics, spatiotemporal, contamination.

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Chapter 1: General introduction

1.1.Introduction

Chapter 1 aims to introduce the study and the various methodological approaches used to infer groundwater-surface water interactions in varying physiographical environments. Interactions between groundwater and surface water are known to comprise a single water resource. Additionally, the available methods were developed for porous media and applying them in fractured rock environments is challenging. Furthermore, a lack of integration between groundwater and surface water is lacking, most particularly in South Africa due to the old water act that saw groundwater and surface water as separate entities, their use, and allocation would happen separately. The New Water Act 36 of 1998 requires for integrated water resources management that takes into account the impacts of development on interactions between groundwater and overlaying surface water bodies, such as lakes, dams, rivers, wetlands and estuaries. Additionally, the requirement for the utilization of a multi-methodological approach to determine and assess groundwater-surface water interactions is widely noted. Thus, this study aims to use a multi-method approach to determine groundwater-surface water interactions and establish their suitability in fracture rock environments such as the upper Berg River catchment.

Groundwater and surface water have historically been isolated in research and management, despite the fact that they constantly interact over a variety of physiographical environments (Sophocleous, 2002; Winter, 2001). Additionally, studies on groundwater and surface water interaction are often complex and difficult tasks to undertake, especially in complex fractured rock environments (Levy & Xu, 2011; Parsons, 2004). The source of such complexities arises mainly from the widespread occurrence of secondary porosity aquifers and differences in opinions between hydrogeologists and hydrologists on the selection of methodological approaches to investigate interactions between groundwater and surface water. This separation is complicated further by scientific uncertainty about hydrogeological settings, the variations in physiographical characteristics between and within catchments, as well as the appropriate method selection within the wide range of available appropriate methods aimed at attaining consistent groundwater-surface water and solute exchange fluxes. These differences are mainly caused by variations in catchment physiographical characteristics such as variations in topography, geology, climate, stream geomorphology, as well as the positioning of surface water features relative to subsurface water flow paths in catchments, and availability of sampling locations that influence the choice of study method to be used.

1.2.Previous studies

Exchange fluxes between groundwater and surface water have been successfully investigated in many catchments globally. Many different methods of estimating the rates and directions of exchange have been established and also been replicated globally, indicating the varying water resources implications of these interactions in varying physiographical environments (Banks, et al., 2011; Cey, et al., 1998; Ellis, et al., 2001; Kalbus, et al., 2006; Welderufael & Woyessa, 2010; Yang, et al., 2014).

However, because of the variations in catchment physiographical characteristics that influence the rate and direction of exchange, some approaches are favored over others based mainly on their scale of representation and their ability to be implemented in similar physiographical environments (Levy & Xu, 2011). Within the wide range of available methodologies, careful selection of suitable methods must be taken to ensure representative estimations of groundwater-surface water interaction fluxes and directions. Consideration of the applicability of such methods under different catchments and physiographical characteristics has played the most crucial role in ensuring representative estimation of groundwater-surface water exchange fluxes. This knowledge is crucial for the holistic and sustainable utilization and management of water resources at catchment scales and in catchments with conflicting water user requirements.

To characterize the interactions between groundwater and surface water, there have been many methods developed and applied in many catchments globally. Most of these methods are scale dependant (Kalbus, et al., 2006), although others enable upscaling of these measurements for use over larger scale catchments (Cey, et al., 1998). Kakuchi et al., (2012) suggest a requirement for a spatially telescoping approach to the characterization of these interactions for the resulting estimates to be compared over varying spatial resolutions allowing for realistic estimate computation. This approach should comprise various methods for the quantification and characterization of groundwater-surface water interactions.Such an approach allows the triangulation of the areas where natural or atificially induced groundwater-surface water interactions play the most significant role in the water budget of that area. Furtermore, for groundwater-surface water interaction assessments at quaternary catchment scale, the use of the telescoping methods depends mainly upon the physiographic environment with consideration of the spatiotemporal hetrogenieties that may affect interaction rates and directions.

Globally, the increase in studies appliying grouped methods for the quantification of groundwater-surface water interactions has significantly improved knowledge on hydrologic and hydrogeologic processes that drive these interactions (Ladouche, et al., 2001; Yang, et al., 2014). Interactions between groundwater and surface water have frequently been assessed by analyzing continuous stream hydrographs to derive major sources of water to the stream flow during and after storm events (Brodie & Hostetler, 2005; Hughes, et al., 2003; Smakhtin, 2001). These methods have enabled the quantification of the various components that contribute to stream discharge, such as the contributions from direct rainfall (quick flow), groundwater discharge to streams (base flow) and the shallow delayed lateral flow of water through the unsaturated soil layer (interflow). In addition, this approach has enabled the delineation of different stream types based on the type of major streamflow contributor (Welderufael & Woyessa, 2010).

The differences in environmental tracers, such as major ions dissolved in the water, environmental isotopes and ecological water quality indicators between groundwater, surface water, and interflow have been used to assess groundwater-surface water interactions. These environmental tracers have enabled the determination of groundwater dependent ecosystems; determination of the major contributors to stream flow and also the demarcation of areas of sensitive groundwater-surface water interactions (Al-Charideh & Hasan, 2012; Burns, et al., 2001; Burns, et al., 2001; Craig, 2005; Krause, et al., 2007).

The use of differences in stream discharge over consecutive flow gauging stations has helped infer net gains or losses to streams, although this approach remains useful at reach scales rather than catchment scales (Becker, et al., 2004; McCallum, et al., 2012). The latter approach allows for the determination of areas sensitive to groundwater outflows or surface water inflows. In addition, such areas also present possible areas of cross contamination or purification between groundwater and surface water. Thus, this reach scale method coupled with the physicochemical approach can aid in the establishment of contamination or purification of either ground or surface water depending on the gain/loss regime of that reach.

Measurements of aquifer properties from aquifer tests are also used by hydrogeologists to infer estimates of groundwater-surface water exchange fluxes over an entire catchment, although some of these methods remain scale dependent (Kakuchi, et al., 2012). This approach commonly generates low-resolution exchange flux estimates that reflect the interaction direction and rates at small scales (i.e. discrete points). Other methods used to investigate these interactions include the use of seepage measurements, field observations, ecological indicators (aquatic flora and fauna), hydrological mapping, geophysical and remote sensing methods, temperature surveys and water budgets (Brodie, et al., 2007). In most cases, the application of a combination of methods may be useful in yielding valid estimates of exchange fluxes, irrespective of the variations in physiographical aspects of the catchments (Banks, et al., 2011; Becker, et al., 2004; Craig, 2005; Kalbus, et al., 2006; Yang, et al., 2014).

The current study employed a combination of methods (i.e. hydrograph, hydrochemical, and differential stream gauging analyses) in the upper Berg River catchment to assess their suitability in fractured rock environments and assessed potential to improve our understanding on the groundwater-surface water interactions.

1.3.Statement of research problem

Until recently, the use of a multi-method approach to characterize groundwater-surface water interactions has been underutilized in South Africa. The major underlying issues impeding the use of such an approach have been the fact that most of South Africa’s groundwater resources are found in widespread fractured rock environments and the problem of appropriate method selection for the investigation of groundwater-surface water interactions in fractured rock environments persists (Parsons, 2004).

Environments of this nature exhibit great variability in groundwater-surface water interaction rates, directions and, nutrient and pollution transport between groundwater and surface water (Oxtobee & Novakowski, 2002). Therefore, in order to acquire an understanding of the interactions between groundwater and surface water and their influence on water quantity and quality, it is important to study these interactions with the use of a multi methodological approach.

Furthermore, considering that South Africa is classified as a water-stressed country (Gassert, et al., 2013, Figure 1), it becomes considerably important to understand how groundwater and surface water interact in the various physiographical environments and what implications they have on the suitability of the water by the various water users. Estimates derived from a single groundwater-surface water interaction method become unreliable, thus enforcing the requirement for collective estimates from composite methods.

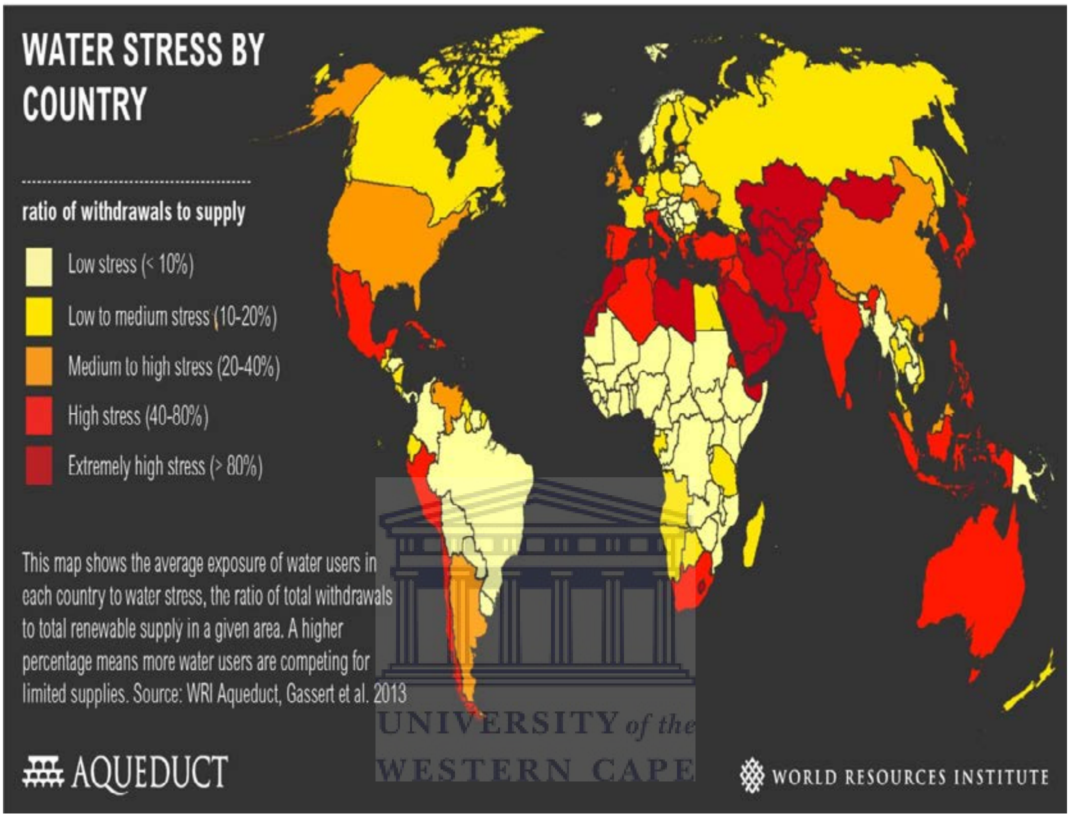


Figure 1: Water stress by country map (Source: Gassert, et al., 2013)

1.4. Thesis statement and research question

The current study assumes that the use of a combination of various complementary methodological approaches (i.e. hydrograph, hydrochemical and differential stream gauging analyses) to quantify and characterize groundwater-surface water interactions can yield reliable groundwater-surface water characterization and exchange flux estimates in fractured rock environments. Such estimates are required for sound and holistic utilization and management of water resources, more especially in water stressed regions of the world which are typically underlain by dynamically fractured rock.

The main research question intended to be addressed by the current study was, whether the use of a combination of complementary methodological approaches can yield reliable estimates of groundwater-surface water and identify the dominant processes that control the quality of groundwater and surface water in a fractured rock?

The specific research questions chosen to answer the main research question were:

a) In the upper Berg River catchment, what is the proportional contribution of groundwater to surface water flows during the dry and wet seasons?

b) What are dominant process that control the quality of groundwater and surface water in the upper Berg River catchment

c) In what direction does water exchange between groundwater and surface water occur in the upper Berg River catchment, during the wet and dry seasons?

1.5.Research objectives

The main aim of this study was to apply a multi-methodological approach to determine groundwater-surface water interactions and establish their suitability in fractured rock environments such as the upper Berg River catchment.

Specific objectives of this study were to

1. Determine the proportional contribution to stream flows by subsurface water storages during the dry and rainy seasons using automated techniques of base flow separation.
2. Characterize the quality of groundwater and surface water to identify the major factors controlling it, using *in situ* and hydrochemical analyses methods.
3. Determine seasonal flow trends (decreased/increased) along 600m selected reach using differential stream gauging in order to deduce spatiotemporal variations (seasonal and spatial)groundwater-surface water interactions.

1.6.Significance of the study

Recently, the current water quality status of the Berg River has been reported to exhibit a decline along its length, with varying effects on its suitability. Interactions between groundwater and surface water can aid in combating the decline in water quality. Therefore, understanding such interactions is important to manage water resources in this catchment holistically. The issues concerning the provision of sufficient amounts of water for development and the ecological reserve of the Berg River have also been escalating. The disproportionate dependency on surface water as opposed to groundwater and the inappropriate disposal of waste negatively affects the water resources management in this catchment, with surface water manifesting these negative affects first(de Villiers, 2007; Jackson, et al., 2013; Ractliffe, 2007). Therefore, the requirement for conjunctive management of groundwater and surface water has also received its share of interest, with considerations of the potential of such interactions to play important role in maintaining dry season flows as well as a consistent water quality status of these water resources. Thus, the implications of mismanaged wastewater treatment works, inter-basin water transfers and growing urbanization require the holistic investigation of hydrologic system to assess their impacts on water resources at quaternary catchment scale.

Inadequate uses of multi-methodological approaches to assess groundwater-surface water interactions have also been followed in South Africa, although this method has been shown to provide reasonable estimates in fractured rock environments located in other regions of the world (Anderson & Acworth, 2009; Becker, et al., 2004; Oxtobee & Novakowski, 2002). Therefore, it is essential to evaluate such interactions using a combination of various complementary methods to ensure representative estimation of exchange fluxes at quaternary catchment scales. This study also draws on previous knowledge about the state of the Berg River's water resources and examines the use of this approach to assess groundwater-surface water interactions with a focus on:

a) Characterization of the quality of groundwater and surface water,
b) Identifying the major factors controlling the quality of groundwater and surface water,
c) Determining the proportional contribution to stream flows made by discharges form subsurface water storages and,
d) Determination of groundwater-surface water flow direction during the wet and dry seasons.

1.7.Scope and nature of the study

The present study focused on combining complementary methods to determine groundwater-surface water interactions in mountainous fractured rock environments. Thus, literature on the appropriate methodological approaches used in such areas was reviewed and a selection of applicable methods sought. Figure 2 shows the research framework followed in the current study. The present study investigated the relationships between rivers and underlying groundwater in terms of the quantity and quality of exchanges. These exchanges were inferred with methods that firstly identify the direction of flow and secondly, compute the quantities of exchanges. In addition, main factors affecting the quality of groundwater and surface water were identified and sampling sites of groundwater and surface water were grouped together based on dissimilarities in physicochemical characteristics.

1.8.Framework of the study

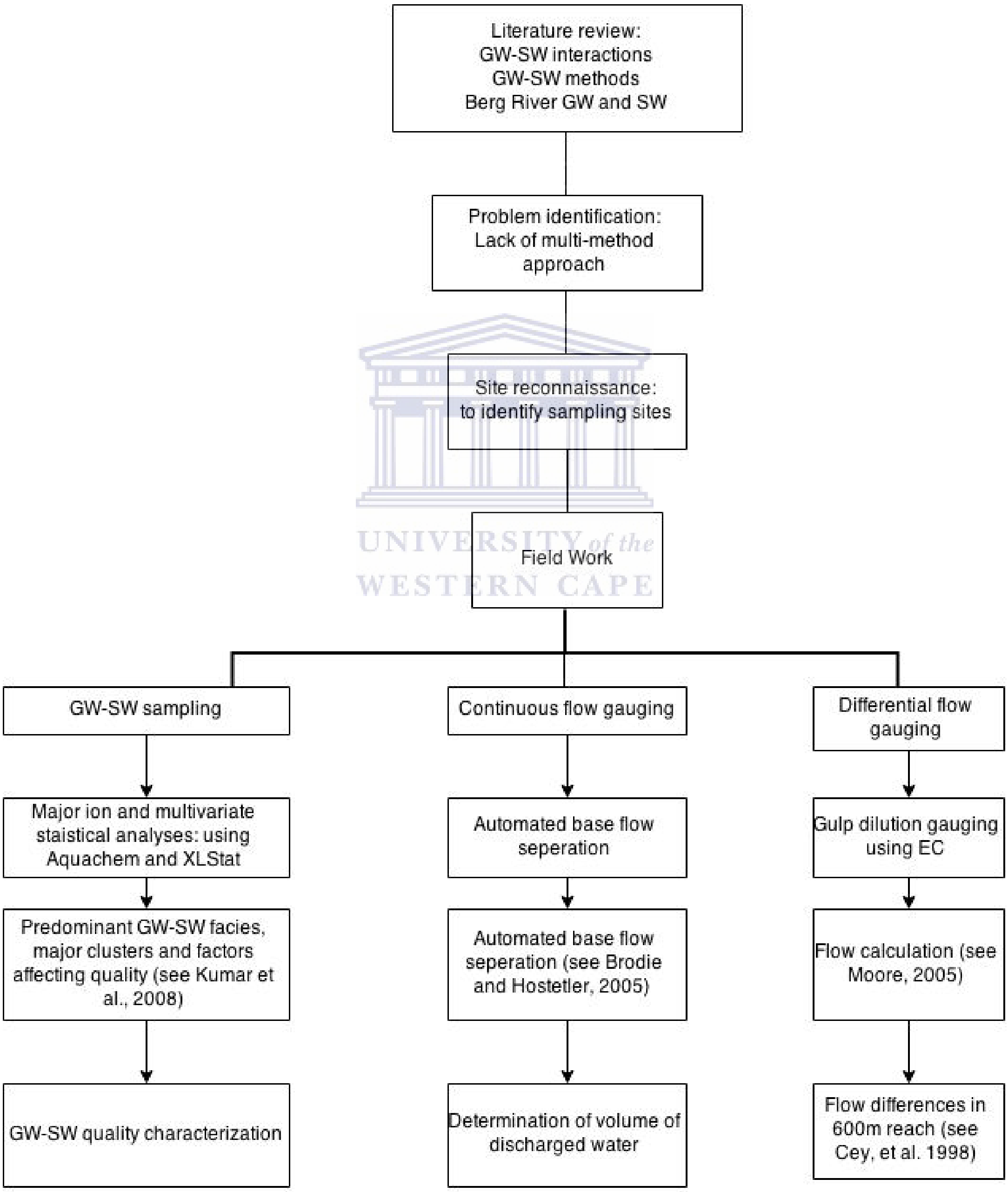


Figure 2: Research framework of the project

1.9. Outline of thesis

The present study consists of seven chapters. This section of the present study presents the general structure of the thesis. Chapter 1 provides the general introduction of the study, while contextualizing the study with reference to its main aim. The background, statement of the research problem, research objectives, research questions, assumption as well the significance of the study are outline in this chapter. In addition, the scope and nature of the study, the framework of the study and the outline of the thesis are provided. Chapter 2 provides the theoretical framework and conceptual understanding that guides the study. Chapter 2 also provides a review of studies conducted globally that pertain to groundwater-surface water interaction using a multi-method approach, with careful consideration of studies which have emphasized the use of a multi-methodological approach to groundwater-surface water interactions in fractured rock environments. Chapter 3 outlines the research design and methodology used in the present study. In this chapter, commonly used methods are highlighted, while also indicating their advantages and disadvantages. The chapter also provides a description of the study area, the experimental study site, study variables, sampling design, study approach as well as study perspective. Chapter 4 provides the conceptual model for the upper Berg River catchment. This chapter discusses the general flow directions groundwater and surface water in the upper Berg River catchment. The chapter further provides the conceptual basis for the choice of methods, based on the study catchment physiographical conditions and surficial activities. Mention on the implications of groundwater-surface water interactions and the above-mentioned physiographical conditions and surficial activities are provided in the context of studies conducted globally indicating the conceptualized interaction pathways and implications.

Chapter 4 presents a hydrogeological conceptual model for the upper Berg River catchment depicting local and regional groundwater flow paths in the catchment. The chapter emphasizes the role of groundwater levels in the interactions between groundwater and surface water in this catchment. The three chapters following the hydrogeological conceptual understanding of the upper Berg River catchment (Chapters 5, 6, and 7), provide the results attained from the use of the three chosen methods, i.e. hydrograph, hydrochemistry and differential stream gauging analyses. In these chapters, the main research findings are discussed and explanations of the results are provided. The final chapter of this study (Chapter 8) provides a conclusion based on the obtained results and suggests some recommendations on conducting further studies on the interactions between groundwater and surface water in the upper Berg River catchment.

Chapter 2: Literature Review

2.1. Introduction

Interactions between groundwater and surface water are widely influenced by a variety of natural physiographical conditions existing in a catchment. In addition to these natural physiographical factors, the quantity and quality of groundwater and surface water in a catchment area also affected by the various land use activities occurring in the catchment. Consequently, the interaction of groundwater and surface water along with the abovementioned activities can increase or reduce the quantity and deteriorate or improve the quality of receiving water bodies. Thus, understanding how these two hydrological zones interact over time and space provides insight on the relative vulnerability of such water resources to deterioration and decrease. A lot of work has been done to understand groundwater-surface water interactions over varying physiographical environments globally (Anderson & Acworth, 2009; Banks, et al., 2011; Braaten & Gates, 2003). Findings of such studies have indicated the requirement of the use of a multi-methodological approach to assess groundwater-surface water interactions, irrespective of the physiographical environment.

Additionally, the importance of the interactions between various aspects of the hydrological cycle (i.e. groundwater and surface water) and their role as an important part in water resources management and allocation has recently, gained much attention (Becker, et al., 2004; Brodie, et al., 2007; Sophocleous, 2002; Winter, 2001). Understanding the distribution and the dynamics of groundwater-surface water interactions has been shown to be necessary for the assessment and quantification of the contribution of one component to another for sustainable water resources utilization and management in catchments with varying physiographical conditions. Another important aspect of this understanding is the provision of a realistic conceptual knowledge of the physiographic controls that oversee the exchange of water from groundwater to surface water and vice versa (Kalbus, et al., 2006; Sophocleous, 2002; Winter, 2001). This knowledge is crucial for proper method selection that is defined largely by the catchment physiographical conditions, and is considered significant for reliable groundwater-surface water interaction estimates. The chapter catalogues the range of available methods used in groundwater-surface water interactions studies. Finally, the chapter highlights the selected methods and describes them in further detail.

2.2. Types of approaches for groundwater-surface water interaction investigations

There is a range of approaches used in the quantification and characterization of groundwater-surface water interactions. Traditionally, these approaches have generally followed four principle approaches, i.e. hydrometric measurements, direct measurements of seepage, the use of tracer approaches, and direct measurements of stream flow gains/losses.

Brodie, et al., (2007) catalogue the different types of methods into 12 catagories based on the type of method. These methods are classified into 1) seepage measurements, 2) field observations, 3) ecological indicators, 4) hydrogeological mapping, 5) geophysics and remote sensing, 6) hydrographic analysis, 7) hydrometric analysis, 8) hyrdochemical and environmental tracer analysis, 9) artificial tracers, 10) temperature studies, 11) water budgets and 12) hydrogeological modelling. These approaches all involve the quantification of the water buget, determination of water level differences, or the identification of interaction areas based on differences in aquatic biota, temperatures, isotopic or physicochemical signitures. A shorter discription is provided by Kalbus, et al., (2006) where these methods are grouped by similarity. Kalbus, et al., (2006) catagorize the available methods into those that a) directly measure exchange fluxes, b) heat tracer methods, c) methods based on Darcy's law, and d) those methods that follow mass balance apporaches.

The methods that directly measure the exchange fluxes include approaches such as the use of seepage meters that directly measure the amount of water seeping into the stream through the streambed. These methods however, do not provide insights on the loss of water to underlaying groundwater storages and are therefore not ideal for detecting groundwater inflow conditions in a stream. Heat tracer flux methods involve the continious measurement of streambed, stream water and groundwater temperatures to reveal changes in temperature that may be result from interactions between groundwater and surface water. Heat sensors installed in streambed piezometers at different depths enable the measurement of temperature differences along the vertical gradient in a streambed

Anothother widely used approach involves the determination of the various parameters required for the computation of Darcy's law equation (Kalbus, et al., 2006). Such measurements are made from monitoring boreholes, and adjacent streams to determine the hydraulic gradient. This information is used to infere groundwater-surface water interactions where the groundwater level is above the surface water table. As with the two previously mentioned approaches, the monitoring of water levels provides insight on areas of groundwater discharge to streams. Although this approach can provide insight on the general trend of groundwater flow in a catchment, it does not however, provide information on the recharge of groundwater by overlaying surface water bodies. Furthermore, the measurement of direct fluxes through the streambed and changes in streambed temperature can be important in determining the dynamics of groundwater-surface water interaction at point scale, these methods can be time consuming and costly when applied at catchment scale, requiring many sampling points for representivity.

Finally, Kalbus, et al., (2006) describes the methods that follow the traditional mass balance approaches. In this suite of approaches, methods aim to compute the amount or proprtion of water exchanged by applying mass balance equations to solve for any changes in storages. Within this suite of approaches, the computation of water budgets where all inputs and outputs of water to the catchment are determined and the net change in what came into the catchment to what came out is calculated. This difference is used to infere any inputs or abstraction of water to the catchment system. Other commonly used methods in this suite of methods include the separation of base flow from total stream flow hydrographs and the computation of differences in stream flows between two or more consecutive stream cross sections. The former method provides insight on the dependancy of stream flows to discharges from subsurface water storages. This method does not descretly identify the source of water that has discharged to the stream, but provides an indication on how the relationship between the underlaying groundwater aquifers and overlaying surface water bodies. The latter approach which involves the measurement of stream flow to deduce groundwater-surface water interaction provides insight on the amount of water lost/gained and the direction of flow between the two water bodies. For catchment studies, many studies have used approaches that follow mass balance prinicpals with success.

This dissertation investigates interactions occurring between groundwater and surface water in a fractured rock environment in the upper Berg River catchment by using a multi-methodological approach. In this approach, base flow separation, hydrochemical, and differential stream gauging analyses were selected. The purpose for the selection of the chosen methods is that they:

1. Enable the computation of the proportion of stream flow derived from subsurface storages,
2. Characterize the quality of groundwater and surface water to identify the major factors controlling their quality, and
3. Determine the direction of exchange between groundwater and surface water during both the high and low flow periods.

2.2.1. Base flow separation approach

The most commonly used stream flow gauging method for estimating the contribution of groundwater to surface water (exchange fluxes) is the separation of the base flow component from a stream hydrograph. Researchers report that this indirect method has allowed the quantification of groundwater discharge without the measurement of any groundwater variable, and relies mainly on the stream discharge series over time (Hughes, et al., 2003; Ladouche, et al., 2001). However, in fractured rock regions, Levy & Xu (2012) warn that although base flow separation methods are informative and can provide estimates of total groundwater contributions to a stream, when applied to small streams with single hydrographs, they do not account for spatial heterogeneity. This limitation ignores the potential impacts associated with the placement of production wells. Despite this inadequacy of this method, it has enjoyed global recognition and recommendation for projects dealing with ascertaining the overall contributions of subsurface water to total stream flow hydrographs (Bruskova, 2007; Hughes, et al., 2003; Ladouche, et al., 2001; Welderufael & Woyessa, 2010; Yang, et al., 2014). The present study is concerned with the implications of groundwater-surface water interactions on water quantity and quality. Thus, to achieve the objective of establishing the quantity of exchange fluxes between groundwater and surface water, automated base flow separation was used.

Access to time-series stream flow data is required for achieving the computation of the various contributing factors using various filtering methods. The presence of a good network of gauging stations within a catchment strengthens the use of this method. This technique also requires access to time-series stream flow data from gauging stations located along streams and the various contributing factors to stream flow computed, using various filtering methods. The network of five active gauging stations in the upper Berg River catchment was ideal for the use of this method, while also comparing the flow conditions over differing land covers.

The analysis of a stream hydrograph to differentiate between the quick flow and base flow components provides information on the natural storages feeding into the stream as well as the number of times a certain flow exceeded or equaled. It is a general perception that groundwater discharge from shallow unconfined aquifers is the main contributor to base flow during periods of drought. However, stream flow may comprise many components of subsurface origin (not entirely from unconfined groundwater) such as deep regional groundwater flow from confined aquifers, delayed overland flow, bank storage, wetlands and other hydraulically connected surface water bodies. Smakhtin (2001) maintains that for the above-mentioned process to be of significance, sufficient recharge to the aquifer needs has to exist, must have a shallow water level, and must have adequate storage and transmission properties to maintain flow to the stream. In the case if gaining streams, where the aquifer satisfies these requirements, analysis of the stream hydrograph can demonstrate the magnitude and timing of subsurface water contributions to stream flow (Brodie & Hostetler, 2005).

The upper Berg River is one such area that conforms to the requirements of this principle. The upper Berg River catchment is a mountainous recharge zone in a fractured rock environment, where the seasonal rainfall regularly replenishes groundwater, water levels are relatively close to the surface, and extensive underground fracture networks provide sufficient water storage and transmission properties (Lasher, 2011; Ractliffe, 2007). Moreover, the prevalence and contact of fractures in the subsurface geology with the ground surface, contributes to the diffused seepage of water along valley sides into the streams during rainy periods. Thus, investigation and characterization of the quantity and quality of water derived from subsurface water storages facilitates the generation of reliable groundwater-surface water interaction estimates, particularly in fractured rock environments.

In South Africa, the most widely used method for quantifying groundwater-surface water interaction (particularly during dry seasons) has been to separate the base flow component of a stream hydrograph. With the sparse distribution of stream gauging stations along most of South Africa's rivers, an incomplete time-series data set with the prerequisite 1-day time step is lacking in most rivers. This time series data has been crucial in evaluating the components of a hydrograph, mainly a storm hydrograph. However, streams draining the upper berg River catchment generally have consistent stream flow time-series data, this enabling the computation of subsurface-surface water exchange fluxes.

Hughes, et al. (2003) applied continuous base flow separation from time series of daily and monthly stream flow data in a study conducted to affirm the work reported by Smakhtin (2001), which indicated that much of the streams in South Africa were base flow dependant during dry periods. Applying a digital filtering algorithm, Smakhtin (2001) found deficiencies relating to the development of a conceptual understanding of runoff generation processes in South African rivers to be result of the lack estimates on the contributions of base flows. Hughes, et al. (2003) argued that greater clarity is required about groundwater-surface water interactions in areas where base flows appear to contribute substantially. Such areas include those areas with perennial and intermittent streams.

To oppose this short fall, a combination of environmental tracers along with filtering algorithm, Furey & Gupta, (2001) proposed a physically based filter algorithm to help distinguish the source of water flowing in a stream at a particular time. This approach is crucial to identify the main source of water to stream flows during storm events, most particularly in fractured rock environments with extensive seepage of water along the valley sides. However, the cost implications associated with continuous sampling and the analysis of large numbers of samples constrains the use of such an approach at larger scales, and the comparison between tracers in waters derived from the various components may serve useful in identifying the most dominant source to stream flow.

Bruskova (2007) illustrated in his study a user-friendly approach to representing the separated base flow component in relation to stream flow (Base Flow Index) in the upper part of the Torysa River catchment, Slovakia. The method entailed the calculation of the index (Base Flow

Index), which gives a ratio of base flow to the total flow calculated from a hydrographic smoothing and separation procedure using daily stream discharges. In his aim to apply and assess this method, one conclusion from the study was that this method was efficient as the required data was readily available and practical as it is written in Visual Basic Application, which uses Microsoft Excel, and it could be applied to different catchments. Bruskova, (2007) places caution on the fact that the reliability of the method lies in the accuracy of the input data. Use of this approach has been rare, probably due to the inherent errors that might come from deriving the base flow component to find the ratio between the components (stream flow and base flow). However, calculation of the Base Flow Index can inform of any negative implications on water resources management during periods of extended drought. Insights raised by this index are important for the equitable allocation of water, particularly in semi-arid environments.

2.2.2. Hydrochemical characterization of groundwater and surface water

Globally, the use of environmental tracers has grown favorable among water resource researchers and managers. Environmental tracers used include naturally occurring dissolved ions in water (Ellis, et al., 2001; Orlikowski, et al., 2006; Soulsby, et al., 2007), isotopes of water (Petelet-Giraud, et al., 2007; Yang, et al., 2012), *in situ* water quality parameters(McCallum, et al., 2012), temperature (Becker, et al., 2004; Cox, et al., 2007) and radioactive isotopes(Banks, et al., 2011). These tracers coupled with flow data have also indicated the various sources of stream flow during storm events (Furey & Gupta, 2001; Krause, et al., 2007). Thus, the current study aims to use *in situ* and major dissolved ion analyses to describe the quality of these exchange fluxes in order to assess their influence on receiving water bodies.

Many studies conducted globally, which have focused on characterizing groundwater contributions to surface water flows using a variety of environmental and artificial tracers are available. For example, Chen, et al., (2002), focused on groundwater flow and geochemistry in the Yellow River, China. The authors studied the extent of mixing between groundwater and surface water using environmental tracers and groundwater flows. Results of this study indicated that, the characteristic of the groundwater had a linear relationship among the major ions in groundwater and this was a result of mixing of groundwater and surface water. This mixing was confirmed by the groundwater isotopic analysis, indicating contributions from three main sources, i.e. rainfall, old water, and diverted water. Chen, et al., (2002) found that water from the Yellow River proved to be dominant in mixing in the aquifer in terms of groundwater flow and geochemistry. In addition, groundwater showed elevated nitrate levels, derived from infiltrating surface water transporting such contamination. Thus, understanding the dominant groundwater flow pattern and chemical contributors to the different waters allows for the investigation of the water quantity and quality implications of interactions between groundwater and surface water in varying physiographical environments including fractured rock environments.

More recently, in a study conducted in the Jailu River Basin, China, evidence indicated continuous recharge of surface water by groundwater throughout the year (Yang, et al., 2012). Yang, et al. (2012) argued that contaminated aquifer water discharging to rivers potentially results in a long-term contamination of surface water. This has been the case in many contaminated aquifers such as the Chalk aquifer, U.K, where contaminated groundwater discharges to surface water did transfer the contaminants. Thus, a comparative assessment of groundwater and surface water chemistry is important to investigating the potential impacts of exchange fluxes on the usability of the water.

The use of environmnetal tracers to track water movement through a catchment can indicate the impacts of land use activities on the land surface. Petelet-Giraud, et al. (2007) studied the contributions of groundwater to surface water quality in the Mulde catchment in Germany, to provide a new view on the relationships between groundwater and surface water. The study found that in half the sampled rivers, groundwater discharges to surface water and in the other half, that surface water recharges groundwater. The data identified two main end-member groups, i.e. natural and anthropogenic end-members (Petelet-Giraud, et al., 2007). Similarly, studies using multivariate statistical methods also were able to abstract the main factors that contribute to the chemistry of both groundwater and surface water (Kumar, et al., 2009; Kura, et al., 2013; Rajesh, et al., 2002). Furthermore, these studies have also enabled the collective grouping of sites with similar chemical characteristic, which indicates the interaction between groundwater and surface water where they are in the same group. Krause, et al., (2007), agrues that there is a need for a combination of numerical and experimental studies of the water balance and groundwater dynamics for yielding valid results of exchanges between groundwater and surface water. Thus in the present study, the combined use of an experimental and statistical study approach is tested.

Moreover, these studies have all succeeded in using multiple tracers, discharge measurements, and base flow separation techniques to ascertain the extent and implications of groundwater-surface water interactions on water quality. However, the main findings of such works have focused on the implications on contamination of either hydrological zone by the other. Therefore, the present study aims to identify the major contributors to groundwater-surface water chemistry to establish any contamination or dilution of existing contamination of either resource.

2.2.3. Differential stream gauging

Another method that has gained global interest is the measurement of stream discharge between consecutive cross sections along a stream reach. These differences in stream flow help to compute any inflows/outflows to the stream over the chosen reach. In many catchments, the application of this method has been successfully achieved (Becker, et al., 2004; Cey, et al., 1998; McCallum, et al., 2012; Ryan, et al., 2010, Zellweger 1994). However, all the authors that have applied this approach emphasize that the combination of this and other methods can yield better results. Therefore, the use of this method is explored in a fractured rock environment to assess its ability to estimate gains/losses to an un-impacted reach of a mountain stream, in the Upper Berg River Catchment.

Differences in stream flow are achieved by using current meter readings, dilution gauging, or permanent stream gauges to calculate differences in flows occurring along a reach at different cross section. Commonly, this method has been applied in streams flowing in low-lying flat areas, where stream geometry is uniform and the velocity of the stream is such that a practitioner can enter the water and conduct measurements. For example, Becker, et al., (2004) used a combination of differential stream gauging, stream temperatur survays combined with stream flow and heat transport modelling of measured temperature gradienst below the streambed in the Ischua Creek, New York, USA. In this study, the authers report that the first and second methods allowed for the lumped discharge value over the entire reach to be computed, while the last method only provided point indication of interactions between the underlaying groundwater and stream. These indications are resultant from the termal gradient approaches inability to quantify actual fluxes through the streambed, while the mesurement of stream flow over consecutive cross sections provided a larger scale estimate of groundwater-surface water inflows/outflows.

In another study in Ontario, Canada Cey, et al., (1998) applied a combination of four techniques to estimate the contributions of groundwater discharge to stream flow. The methods applied included the use of stream measurements, hydrometric measurements of stream hydraulic gardient and conductivity, seepage meters and hydrograph seperation. In the study it was stated that the first three method were applied during base flow periods, while the fourth was applicable during high flow periods. Among the methods applied during base flow period, stream measuremets indicated a net groundwater flux to the stream suring the summer months, net streambed groundwater fluxe estimates and the use of seepage meters yieled no result on the inflows/outflows to the stream. During high flow periods (particularly during two large rainfall events), hydrograph seperation combined with electrical conductivity and envrionmental isotopes of water were used to infer any interaction between ground and surface water. Results of this approach indicate that pre-event water (groundwater) comprised 60%-80% of stream flow. This indicates that the stream gauging methods combined with tracer and hydrograph seperation methods can prove useful to the estimation of groundwater-surface water interaction at catchment scale, as these methods provide lareger scale estimates of exchange fluxes.

McCallum, et al., (2012) indicated that while the use of differential stream gauging can enable the calculation of inflows/outflows to streams, combining such an approach with tracer measurements (water chemistry and isotoptes) both inflows and outflows could be seperately quantified. The authors quantified ground and surface water exchange fluxes using differential flow gauging, sequential addition of environmetal tracer data (conductivity and chloride and radon concentrations) and finally by conducting a tracer experiment to constrain the gas transfer velocity for radon. Groundwater inflow rate were estimated by calibrating a numerical model which simulated flows and concentrations in the river. Furthermore, the authors report that the total groundwater inflow and spatial distribution of inflows was dependent on the quality of the data used for model calibration. However, this study indicates that the combined use of tracer and stream flow methodology can provide suitable estimates of ground andsurface water interactions and enables the quantification of inflows and outflows, but care must be taken in ensuring that the tracer in groundwater is well defined and that contrast between the concentration of the tracer in the respective waters is established.

Zellweger (1994) applied four different tracers to compute stream flows in order to infer stream flow losses along a 507m reach of the St Kevin Gulch in Colorado, USA. This study indicated the use of sodium, lithium, chloride and bromide as conseravtive tracers that enable the measurement of stream flows using the concentrations of these ions. Furthermore, this study, was undertaken in a mountain catchment with similar stream morphology as the present study site, indicated that in such streams exhibiting great streambed morphological heterogenity, the use of dilution gauging for stream gauging was the most appropriate method. In this study, Zellweger (1994) found that stream losses accounted for 8% of stream flows measured, thus this stream reach was influent in nature. The current study draws insight of the use of conservative NaCl as a tracer to measure stream flows to infer groundwater-surface water interactions along the selected 600m reach of the upper Berg River catchment.

The abovementioned studies indicate that the use of differential stream gauging is a good tool to identify ground andsurface water exchange fluxes in streams. Furthermore, the combination of this tool and others such as tracers and hydrometrics has enabled identification of point and diffused larger scale exchange fluxes. In fractured bedrock stream environments, (Oxtobee & Novakowski, 2002) found that groundwater discharge mainly appears to be point source associated with open fractures, as compared to more diffuse, or continuous seepage zones often observed in a porous media environment. In the study area, (Oxtobee & Novakowski, 2002) conclude that measurements of stream discharge to determine areas of large-scale loss or gain proved to be inconclusive due to the relatively small volume of groundwater discharge occurring. However, the use of this method in such environmnets has potential to identify and quantify the nature and direction of exchange flux, particularly for issues pertaining to supply of adequate quantity of water of good quality.

Kalbus et al., (2006) and others note that the use of a multi-scale approach combining multiple methods can significantly influence the reliability and validity of estimates of interactions between groundwater and surface water. The current study thus utilizes a combination of base flow separation, hydrochemical, and differential stream gauging analyses to facilitate an improved understanding of stream-aquifer interactions in a fractured hard-rock environment, situated in the upper Berg River catchment. In addition, the study also aims to assess whether the amount and quality of exchange fluxes is sufficient to maintaining water quality and quantity within usable levels in the Berg River catchment.

2.3. Chapter summary

In this chapter, a brief review of the commonly utilized approaches in studying the interactions between groundwater and surface water is provided. The chapter examines the scale representations of these methods with emphasis on those methods that allow for greater scale studying of groundwater-surface water interactions. In addition, emphasis on the suitability of these methods in fractured rock environments is placed on the selected methods.

The main underlying issue among the methods is scale representation. However, the methods selected for use in the present study have been shown to work over varying spatial scales, which was the basis for their selection in the current study. Furthermore, the availability and access to information of the required parameters for these methods is readily available, thus allowing for rapid assessment of the dynamics between groundwater and surface water on a catchment scale.

Combining methods that operate over multiple scales can improve estimates through comparative assessment of the results of the respective methodology. The integration of multi-scale estimates poses the greatest concern on estimate validity and reliability. However, using a multi scale multi-method approach allows the comparison of exchange estimates of the different methods to triangulate the most realistic representation without distorting the estimates and scales that they represent. The present study used this approach through the selection of methods that have been showed to provide catchment scale information on the characteristics of groundwater and surface water, identifying the proportion of stream flows derived from subsurface water storages and, determines the direction of flow between groundwater and surface water during different seasons.

Chapter 3: Research design and methodology

3.1. Introduction

Chapter 1 of this thesis states the thesis statement and poses research questions based on this assumption. The chapter also provides the aim and specific objectives identified to answer the research questions, while chapter 2 reviews literature on groundwater-surface water interactions in fractured rock environments and highlights applicable methodologies in such areas. Furthermore, the requirement for a multi-methodological approach to determine groundwater-surface water interactions is stated based on the ability of such an approach to reliably quantify and characterize such interactions.

The present chapter describes the research design followed, data collection and analysis methods used, procedures for data quality assurance followed, ethical consideration required for the current study as well as the limitations to the study. This chapter aims to highlight the methodology and literature associated with the acquisition, preparation, interpretation, and validation of the collected data. The chapter also provides a description of the main physiographical features in the study area that can potentially influence interactions between groundwater and surface water. The main methods described in this chapter include:

1. Base flow separation
2. Hydrochemical analysis
3. Multivariate statistical analysis, and
4. Differential stream gauging

Limitations of these methods are stated with justification for their selection stated.

3.2.Research Design

3.2.1. Study area description

The upper Berg River catchment (G10A) is a mountainous sub-catchment of the Berg River catchment in the Western Cape of South Africa (Figure 3). Geographically, the area is located approximately S33.95733° and E19.07264° (WGS84). The catchment size is approximately

172km^2, with minimum, mean, and maximum elevations of 213m, 238m, and 1367m above sea level respectively. Figure 3 illustrates the catchment boundary comprising of the Franschhoek and Drakenstein mountains to the south and south-west of the catchment. The average height of these mountains is 1300m-1500m above sea level. The dominating force that drives the flow of groundwater is gravity. In this catchment, water flows from areas of high elevation to low elevation. Additionally, the presence of a hydraulic gradient along the topographical gradient also influences the flow of groundwater, indicating that groundwater discharges where the water level intercepts the topographical surface, typically at streams, wetlands and the dam site.

Groundwater recharge occurs during the Western Cape winter months, when precipitation increases the elevation of the water table, while discharge of this groundwater depends on the presence of hydraulic gradient differences between the aquifer and discharge point. This primarily occurs during periods of reduced streamflow, where groundwater levels are higher than surface water levels. Mountainous areas with steep valleys are natural groundwater recharge sites among others. In these areas, local discharge of water occurs along the valleys, mountain faces (seepages), and adjacent surface water bodies (rivers, lakes, dams or wetlands). Mountainous areas in the Western Cape are highly fractured with varying geologic heterogeneity that results in numerous seeps/flows from the mountain face (Jia, 2007). Apart from problems of groundwater quantification and understanding flow through the fracture networks, additional uncertainties arise with how groundwater and surface water interact in such environments (Jia, 2007; Lasher, 2011).

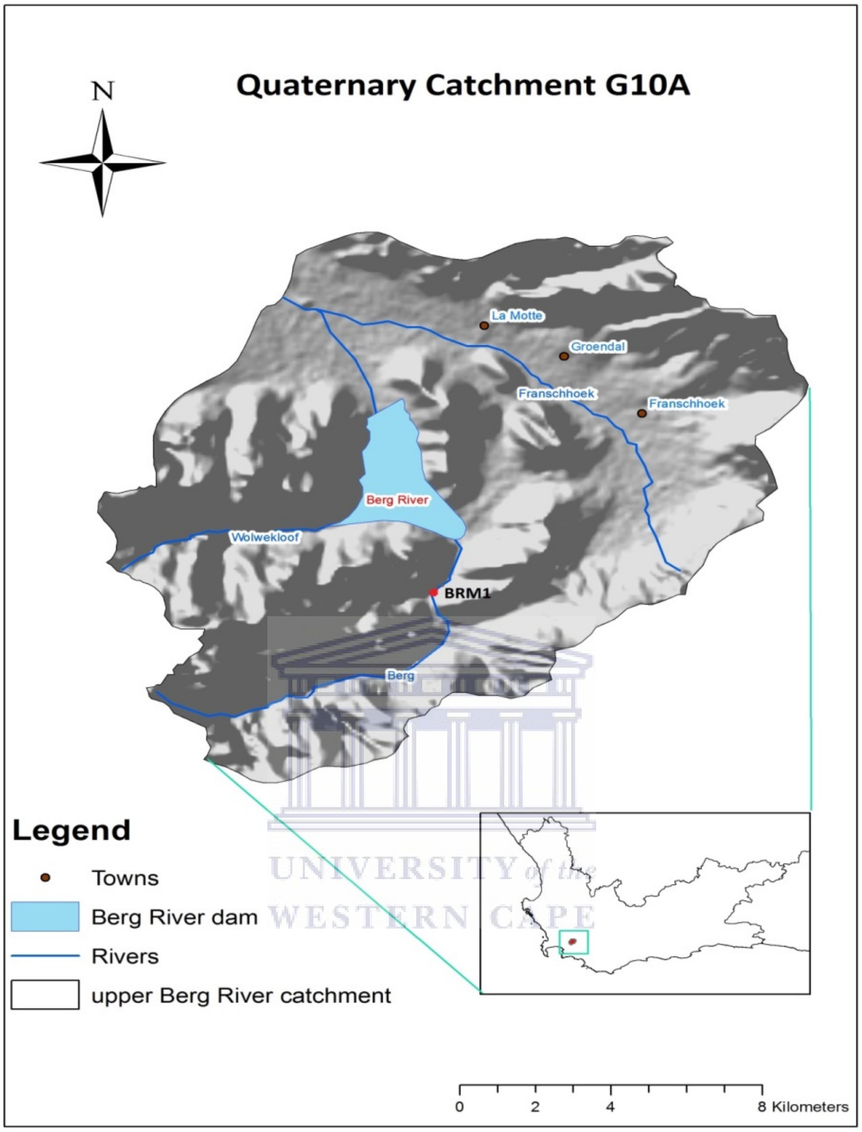


Figure 3: Topographical map of the upper Berg River catchment (G10A) in the Western Cape Province

The upper Berg River catchment experiences a Mediterranean climate, with warm, dry summers (November-March) and cool, wet winters (April-October). Temperatures are cooler near the coast than in the interior of the catchment, because of the cold ocean current flowing on the West Coast of South Africa (Ractliffe, 2007). Most rainfall occurs between the months May through to October, with few clear days occurring between many days of intense rainfall (Ractliffe, 2007). The orographic influence of the high mountain ranges in the area introduces a large spatial variability in the mean annual precipitation, indicative of a decreasing rainfall trend with movement towards the northwesterly corner of the Berg River catchment. Thus, groundwater recharge is expected to be higher in the areas with highest precipitation and least evaporative loss of water. Ractliffe (2007) reports that for the upper Berg River catchment, a mean annual precipitation (MAP) of 1603mm/a, mean annual potential evaporation (MAPE) averaging 1475mm/a. and mean annual runoff (MAR) of 1 015mm/a. With such a contrast between MAP, MAPE, and MAR, the catchment is considered one of the 21 high water yielding areas in South Africa. Nel, et al., (2013) emphasizes that a high water yielding area is strategic water sources area and that these areas are defined by the disproportionate amount of mean annual runoff to the geographical area of interest. As such, the upper Berg River catchment has a higher precipitation rate than evaporation and runoff rate, thus indicating recharge of underlying groundwater reserves.

The Berg River originates in the Franschhoek and Drakenstein mountains and flows in a northerly direction to discharge into the Atlantic Ocean at St Helena Bay. The river flows through deep incised valleys in the south (upper catchment) and through lowland valleys in the north (lower catchment). Flowing through deep valleys in the upper catchment, stream flow is governed by various factors including direct precipitation, groundwater discharge, and interflow discharges. The quantity and manifestation of the various controlling factors differs between base flow and high flow periods. Thus understanding these principle controls on stream flow is important for understanding water quantity and quality issues for both ground and surface water in order to achieve sustainable water resources utilization and management in mountain catchments like this one.

In the upper part of the greater Berg River catchment (Figure 3), the main tributary of the Berg River in this area is the Franschhoek River, which rise from the Franschhoek mountains. Two streams emerge behind the Berg River Dam and collect in the dam area. These two headwater streams are the Berg and Wolwekloof Rivers. The inlet streams drain natural areas, while the Franschhoek River drains an area primarily used for human settlements and agriculture. The Berg and Franschhoek Rivers converge in the northern part of the catchment, where they continue flowing as the Berg River (Figure 3). The amount and quality of water from these respective areas is directly linked to underground water reserves (Sophocleous, 2002; Winter, 2001) and thus deterioration of either can potentially deteriorate the other. Thus, understanding interactions between groundwater and surface water and their implications to water resources management and utilization in such a complex environment is crucial to attend to any possible water quantity or quality issues that may arise because of these interactions.

Naturally, during base flow periods (dry season), flows in the Berg River vary along the length of the river from 0.2 to 2m^3/s in the low flow period (November-March) and increase to between 4 and 15 m^3 /s in winter, April-October (Clark &Ractliffe, 2007; Parsons, 2003; Ractliffe, 2007). After construction of the Berg Water Project, flows have been altered by releases from the Inter Basin Transfer Scheme with the Theewaterskloof Dam, the building of the Berg River Dam and several other diversion pipelines that transfer water stored during high flow season to augment base flows. These alterations on the catchment have changed the rate at which subsurface water discharges to surface water and thus changed the flow regime in affected streams.

In their reports, Clark and Ractliffe (2007) and Ractliffe (2007), state that groundwater discharges to the river where the depth to groundwater level is within 2.5m of the surface. Shallow depths to water levels in this catchment that have been reported by various authors indicating a common state of groundwater discharge in the low laying fluvial plains adjacent to the Franschhoek Wetland Trust and streams in the catchment during high flow periods(Clarke & Ractliffe, 2007; Kotzee, 2010; Ractliffe, 2007). Conversely, during base flow periods, higher levels of groundwater opposed to surface water introduce the hydraulic gradient required for the movement of groundwater and discharge into surface water bodies.

Based on a developed contour map of groundwater levels, Clark and Ractliffe (2007) found the direction of groundwater flow in the catchment was identified as flowing from areas of high elevation to those of lower elevation (along GW-SW hydraulic gradient). The contour map also revealed that groundwater flows toward the center of the valley before flowing northwesterly toward the sea and therefore first discharges to the nearby rivers (Ractliffe, 2007). From such previous observations, the contour map further shows areas of constant inundation, suggesting the high dependency of surface water bodies on discharges from subsurface storages.

Figure 4 shows the primary geology in the upper Berg River catchment. The area has complex geology. A combination of granites of the Cape Granite Suite, sandstones of the Table Mountain Group (i.e. Peninsula and Nardow formations) and the Franschhoek basement formation make up the surrounding mountains, with quaternary sediments lining the valleys and flat areas of the catchment

These formations comprise primarily of chemically inert granite, quartzitic sandstones, relatively mineralized siltstones, shale, and mudstones. The most prominent geological formation is the Peninsula Formation (Lasher, 2011). The average thickness of the Peninsula formation ranges between 2000-5000m (Jia, 2007; Theron, et al., 1992). This formation and its vast depth constitute the main secondary aquifer in this catchment. The Nardow, Cape Granite Suite, and Franschhoek formations occur on the east to south east of the catchment, near Franschhoek. A layer of alluvium in the valleys covers these formations and constitutes the primary aquifer material in the catchment. Although there is great extent in the interconnectivity between the underlying fractured Peninsula Formation and alluvium, a negligible impact on groundwater levels measured in either is found. The different geological formations share a common attribute, which is the high level of fracturing within them, thus indicating the potential for large amounts of water and dissolved solutes to be transported rapidly through fracture flow.

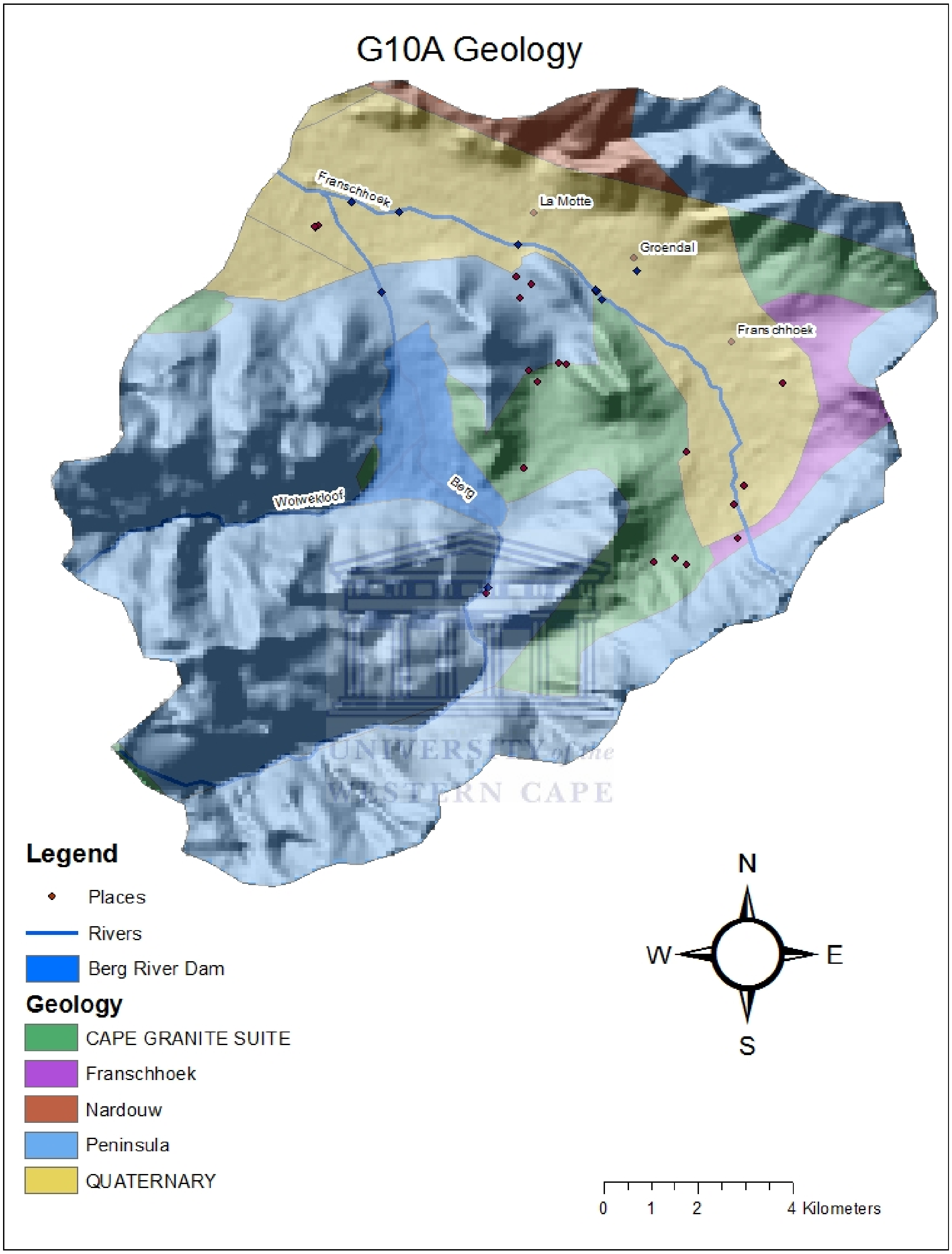


Figure 4: General geology of quaternary catchment G10A, upper Berg River catchment (Source: WR2005)

This feature increases the spatial extent upon which groundwater and surface water can interact and increases the potential of interaction. Fractures also act as conduits for water and any contamination, thus may be chiefly influential in the connectivity between ground and surface water. Large amounts of water are able to flow within connected fracture networks, while the sandstones of the TMG (Peninsula formation) are chemically inert, rendering the chemistry of water flowing through them fairly unaltered. The exceptions are noticeable were formations change from sandstone to shale-siltstone, which have decreased permeability and increase the level of mineralization of the water. River water quality is noted to decrease with distance downstream, with main negative influences from human settlements and agricultural activities (de Villiers, 2007; Jackson, et al., 2013).

Apart from mineralization problems, problems of nutrient loading and contamination from other types of land use activities can exist where possible interactions may affect the receiving water resource. This kind of impacts are currently unknown, with great fear of cross-contamination occurring. However, if the opposite occurs, where purer water discharges/recharges contaminated waters, there is a possibility for the dilution of such contamination. Therefore understanding the principle elements that influence groundwater and surface water chemistry can assist in identifying possible areas of interaction and sources of positive/negative impacts of water quality.

The TMG sandstones comprise a sequence of varying formations with varying secondary porosity that play varying roles in groundwater storage and circulation as aquifers, aquicludes, and aquitards. Thus, the occurrence of mountain face seepages and spring flows is common in this area. These mountain face seepages and springs contribute significantly to the total stream flow, as they will eventually flow into the surface water bodies, i.e. streams. Furthermore, due to the extensive fracture networks and prevalence of interflow seepages, the chemistry of this water is expected to be generally closer to that of rainwater. The main reason for this is that precipitation water has a short length of residence time in the geological formation as can be observed during high flow periods. It therefore becomes crucial to understand the complexity of the lithological and hydrogeological environments based on previous studies to evaluate interaction between groundwater and surface water resources in such environments comprehensively to facilitate informed decision making in water resources management and use.

Following a geophysical survey using electrical resistivity, Lasher,(2011) deduced that due to the occurance of a conductive layer of regolith ≈265masl, the stream and borehole network at BRM1 were in connection. However, the author noted that a study was required to ascetain the extent of this connectivity between ground and surface water in this area. The present study endeavours to answer this question of interconnectivity, not only around the BRM1 experimental site but the entire upper Berg River catchment by assessing groundwater quantity and quality contributions to stream flows. Additionally, the sudden changes in resistivity imaging results, indicated that there was high hetrogeneity in the subsurface formation, causing discrete interaction locations at the site and the prevelence of interflows during rainy seasons (Figure 5).

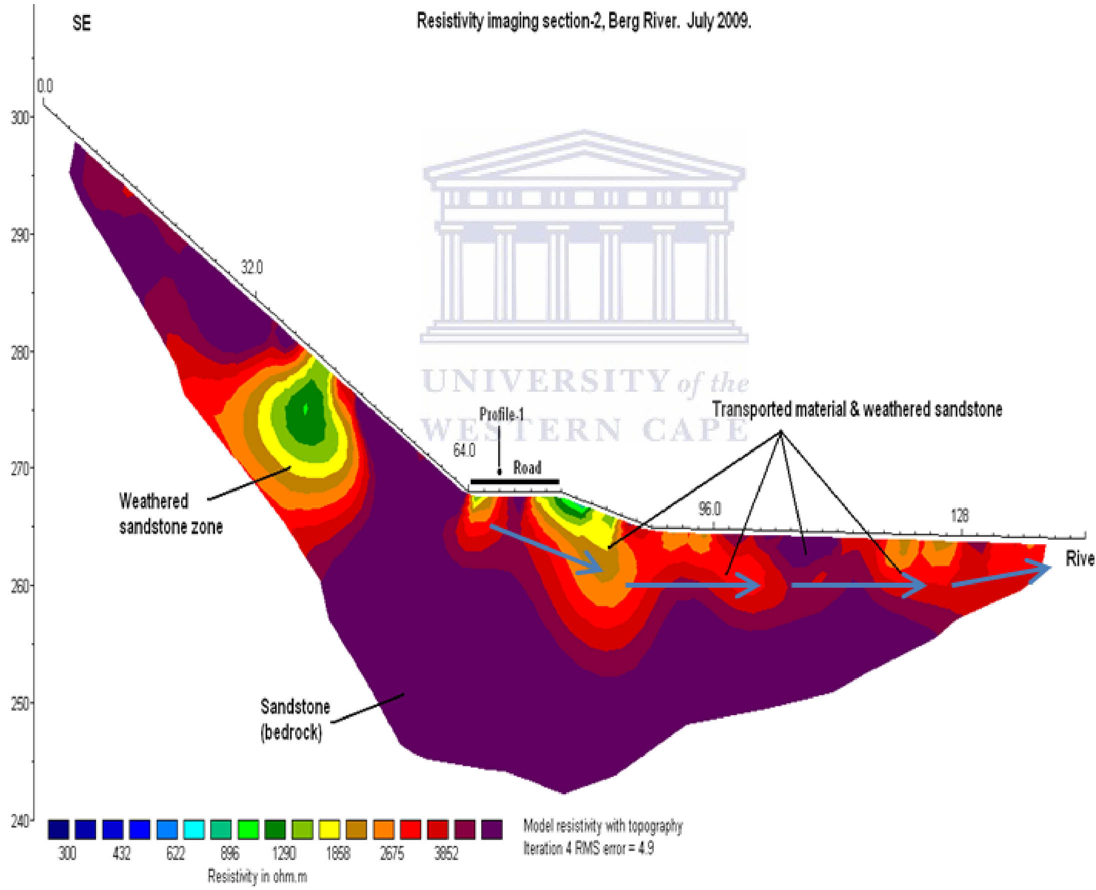


Figure 5: Electrical Resistivity logging at BRM1 Source: Lasher (2011)

The main water bearing formation of the TMG sandstones present in this quaternary catchment is the Peninsula Formation. This formation is typically highly fractured and composed of chemically inert quartzitic materials (Ractliffe, 2007). These features increase the amount of water that can possibly exchange between the two, while also indicating that goundwater and surface water are predominantly similar in chemical character where there are no external controls on water quality, such as infiltration of surficially contaminated water from human settlements or agricultural fields.

Ractliffe, (2007) reports that the TMG sequence in the upper Berg River catchment comprises major aquifer systems due to the highly permeability of these formations. These formations usually have significant secondary porosity which alters the nature of groundwater flow and interactions between groundwater and surface water by introducing additional flow paths that could be used. Aquifers in these formations are highly productive and able to support large abstractions for public water supply. For this to occur, great connectivity between the fracture conduits is required.Using Fluid Electrical Conductivity (FEC) logging, Lasher, (2011) was able to identify fracture positions, flow zones and flow directions.

Furthermore, (Ractliffe, 2007) report that in the upper Berg River catchment, groundwater quality is commonly considered good, relative to higher conductivity water found in the lower parts of the Berg River catchment (less than 70 mS/m to values in excess of 20000mS/m, respectively) (Bugan, 2008; Demlie, et al., 2011). To further emphesize the quality of the groundwater, Lasher, (2011) states that a number of farms in the Franschhoek area are also using the groundwater for bottling purposes (*Richeneau Water*). All of these studies emphasize the declining water quality from the upper parts to the lower parts of the catchment. Furthermore, emphasis on the great amounts of water able to move through the fracture networks as well as the near-pristine water quality reported, indicate that water resources in this area are important to sustaining water requirements for downstream users. Therefore, studying the interactions between groundwater and surface water can potentially help to invisage and prevent any future impacts of the growing anthopogenic activities in this area.

The main land cover in the area primarily occupies three categories, i.e. natural afro-montane forests, agriculture, and human settlements (Figure 6). Agriculture makes up the largest proportion of land cover in the catchment as a whole (Kotzee, 2010). These activities are distributed over the catchment, with the mountainous sections covered by natural vegetation, human settlements occupying the eastern side of the catchment, forestry activities found along the Roberstvlei Saddle area, and agricultural activities distributed throughout the catchment, apart from the area adjacent and behind the Berg River dam. Forestry operations ran by Cape Nature deal mainly with the non-native hill slope vegetation, such as pine trees. These land covers have varying impacts on groundwater and surface water resurces. Albhaisi, et al., (2013) points out that the removal of non-native hill slope vegetation increases the rate of groundwater recharge, while other authors have reported the negative impacts of anthopogenic activities on water quality in this area (Adams, 2011; Clark & Ractliffe, 2007; Jackson, et al., 2013; de Villiers, 2007).

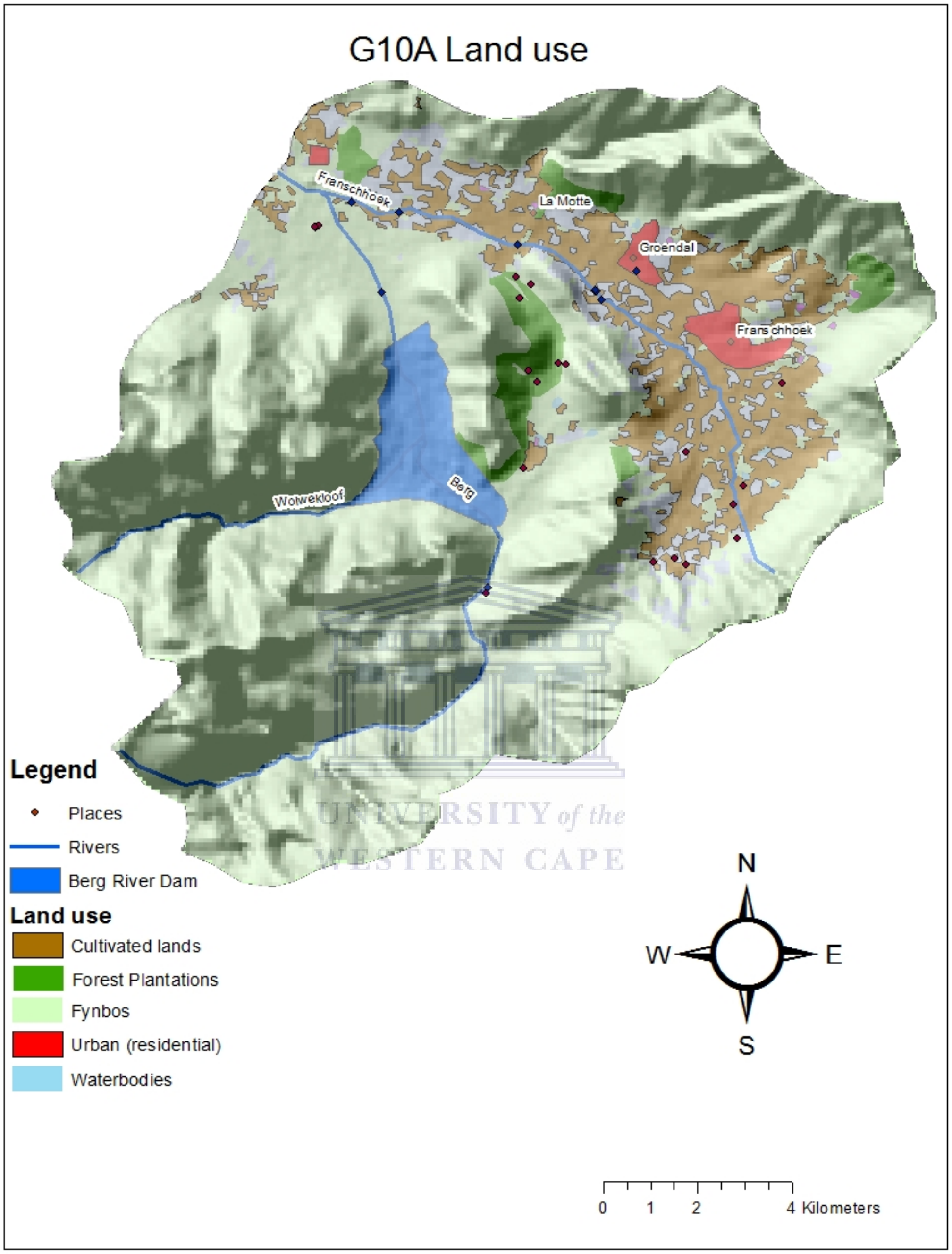


Figure 6: Land cover map of G10A

The agricultiral activities in the area are limited to deciduous fruit and vineyard cultivation. Deciduous fruit and vineyard cultivation require reliable water resource during the summer, dry period and this increases the stress on water resources during such periods. Irrigation with surface water in the Berg River catchment is confined to the areas immediately adjacent to the river and therefore increases tension concerning the distribution of water resources. Forestry is also a great water user in this catchment. Farley, et al., (2005) point out that afforestation with *Eucalyptus* and *Pine* species reduces runoff by 75% (±10) and 40% (±3) respectively. Preciptation is intercepted by these plantations and this reduces the amount of groundwater recharge along with surface runoff. The removal of such plant species in catchments is crucial to increasing the amount of runoff and groundwater recharge. As illistrated by Albhaisi, et al., (2013), after the clearing of such plant species, a systematic increase in groundwater reacharge can be realized.

During dry periods, the contribution of subsurface water discharges to the streams and other surface water bodies alleviates the pressure introduced by reduced water for allocation. Understanding the rates and directions of water and solute exchange between groundwater and surface water during both base flow and high flow periods is essential for proper allocation of water to the water users and enabling the saving of extra water for further allocation where necessary.

3.2.2. Study sampling sites

This section presents the sites selected for groundwater and surface water chemistry, stream gauging and time series flow data generation during the study. The selection of the sites was random, with information on the location of sites gathered during prior reconnaissance field excursions during 2013. Figure 7 shows the stream gauging stations located around the catchment. This image also indicates the type of dominant land cover in the areas drained by the relative streams. The groundwater and surface water sampling sites used for the investigation of water quality are shown on Figure 7, 8 and 9. Figure 10 illustrates the reach of the Berg River selected for quantifying inflows/outflows using dilution gauging. This site was selected based on the requirements of the method, which include that the selected reach should be straight, with no input or abstraction of water from external sources. Considering the catchment is rapidly developing and the growth of human settlements expanding, the other streams that drain this catchment were not ideal for the use of this method, due to any possible inputs/outputs to stream flows.

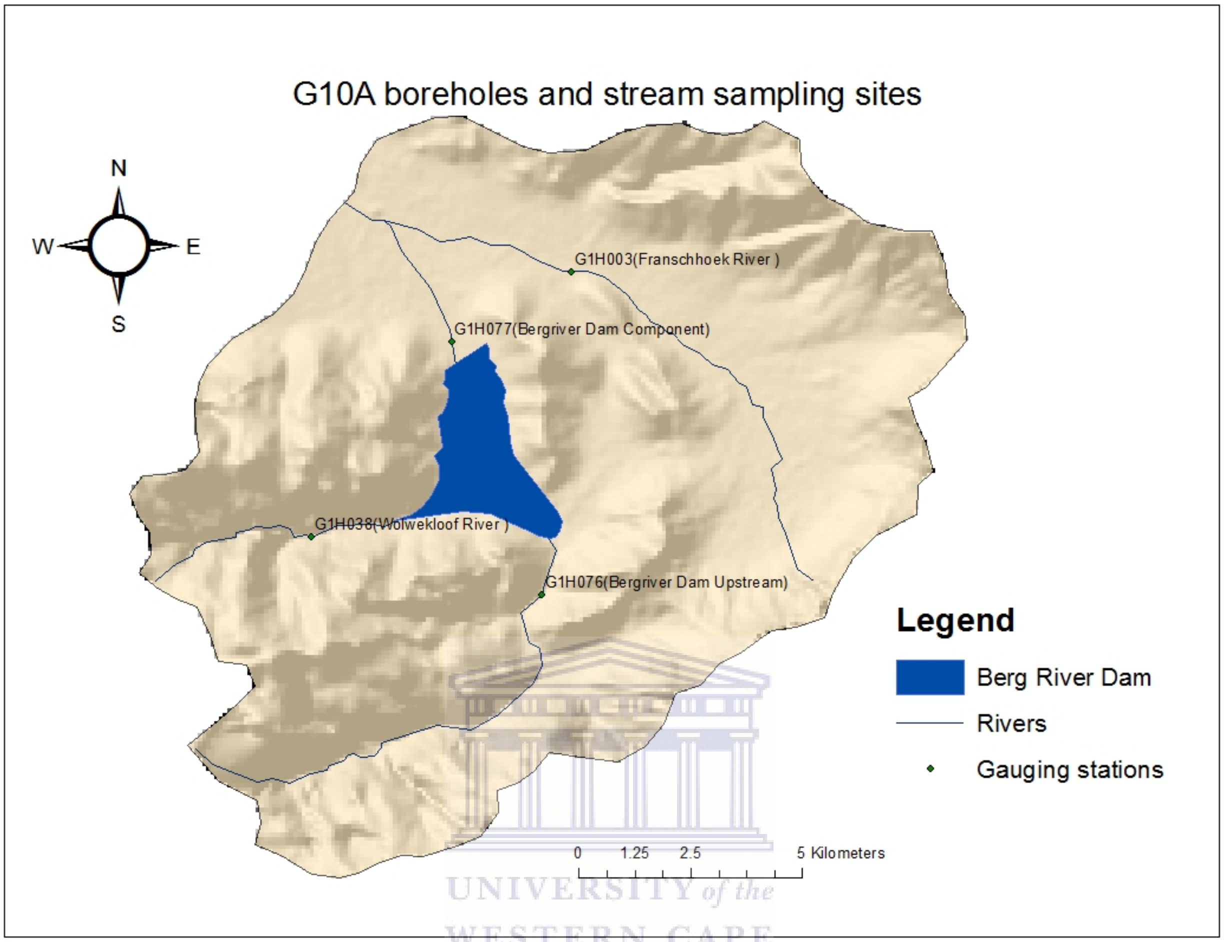


Figure 7: Stream gauging station around upper Berg River catchment

Figure 7 shows the locations of the selected stream gauging stations around the upper Berg River catchment. Five selected gauging stations consist of stations that drain all the small streams surrounding the Berg River Dam. These include the following sites: below the dam outlet (G1H077) and the one situated along the Franschhoek River (G1H003).The three stations located at Wolwekloof (G1H038), below the Berg River dam, and along the Franschhoek River are all influenced by abstractions and discharges of water from agriculture, human settlements, and inter-basin water transfers (Adams, 2011; Ractliffe, 2007). Thus, the only site devoid of any artificial input /output of water was the site located at the BRM1 site (G1H076), above the Berg River Dam. This site was selected for the comprehensive separation of stream flow hydrographs into the components it is comprised.

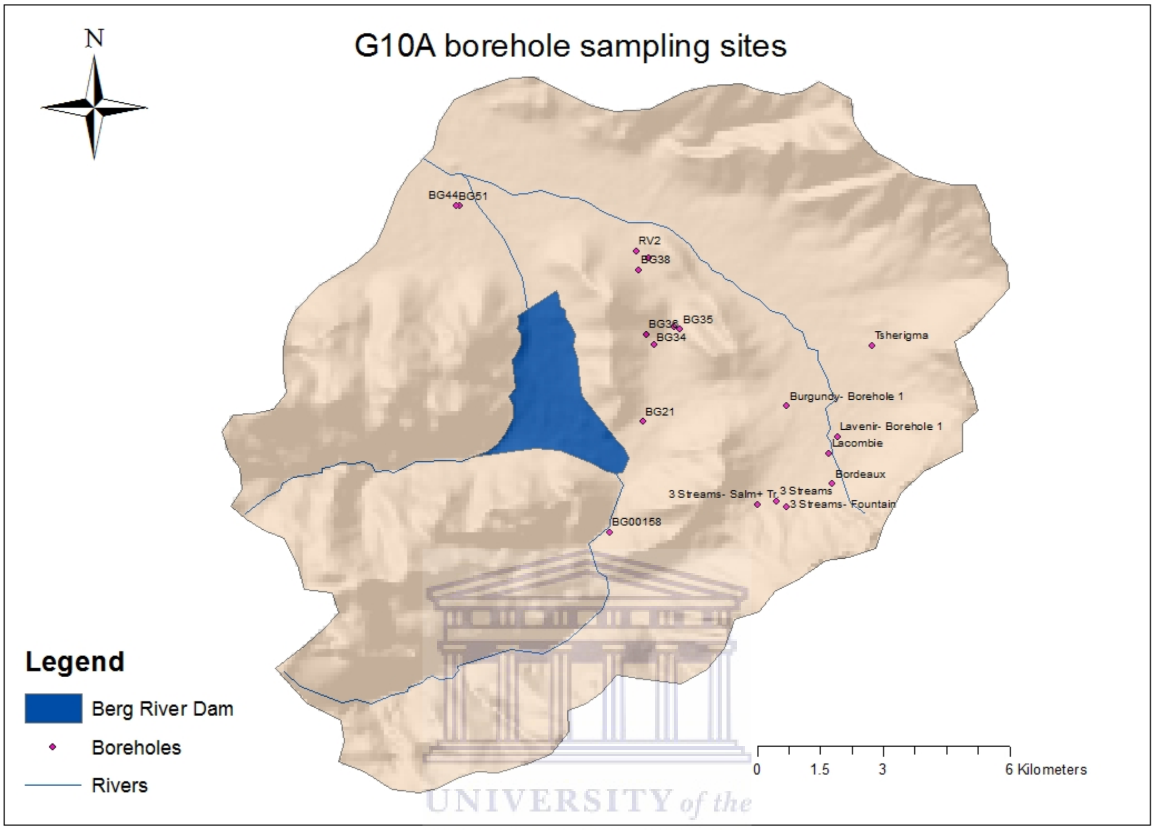


Figure 8: Groundwater sampling sites in upper Berg River catchment

Figure 8 illustrates the groundwater sampling sites within the studied catchment. Some of the abovementioned sites were located on private land; however, as part of an Honors research project in collaboration with Department of Water and Sanitation, Bellville office, borehole sites could be visited to collect groundwater samples for characterizing groundwater quality in the upper Berg River catchment.

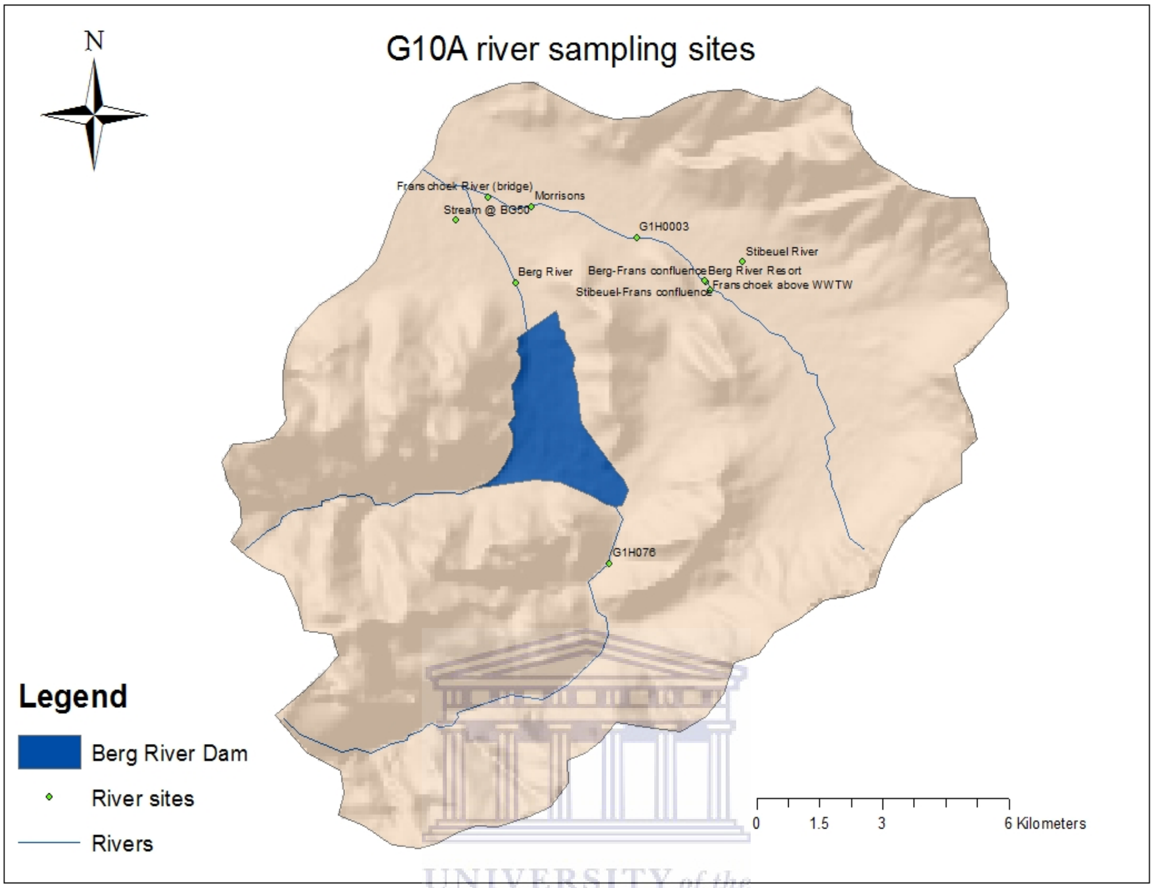


Figure 9: Surface water sampling sites in upper Berg River catchment

Figure 9 shows the locations of the surface water sampling sites located along the Berg and Franschhoek Rivers in the upper Berg River catchment. Additional sites included during the 2014 summer period, included sites located along a small, but influential tributary of the Franschhoek River (i.e. Stibeuel River). This stream traverses through informal and formal settlements, which have been noted to directly impact the water quality of the Berg River through the contribution of point and diffused sources of heavy metals and nutrients from land use activities (de Villiers, 2007; Jackson, et al., 2013)

Figure 10: Selected 600m reach upstream Berg River Dam at BRM1

Figure 10 shows the 600m reach chosen for the differential stream gauging by a dilution gauging exercise. This reach is located above the G1H076 stream gauging station near BRM1. The exercise included inputting a diluted river water saline solution and measuring the conductivity of the water at a downstream end of the measured reach (i.e. 200m intervals). As previously mentioned, the reach conforms to the requirements of the method, which require a relatively straight reach, devoid of any abstraction or discharge of water. The selected reach was found most suitable for the exercise.

3.2.3. Study population and unit of analysis

In the investigation of groundwater-surface water interactions in the upper Berg River catchment, various parameters were measured. These parameters included data on time-series stream flow, physical and chemical measurements of groundwater, stream water, and interflow water during wet and dry periods as well as stream flows measured at various cross sections along a selected reach of the study stream. These data were obtained using passive and grab sampling techniques, which entailed continuously measuring stream flows and collecting water samples upon fieldwork excursions.

The present study examined the use of a multi-methodological approach to investigate the interactions between groundwater and surface water. The study focused on information retrieved from time series flow data, groundwater and surface water physicochemical parameters as well as measurements of stream flows at different cross sections along a 600m reach of the Berg River. Using the information on groundwater-surface water interactions, the study aimed to assess the potential for these interactions to play a role in water purification in a fractured rock mountain catchment. The study used base flow separation, hydrochemical, and differential gauging analyses to infer interactions and consider the purification aspect of these interactions.

3.2.4. Sampling design

The present study followed a combination of purposeful and random sampling design approaches. Firstly, a site reconnaissance visit was undertaken in 2013. The main purpose of the field reconnaissance visit was to identify possible sampling sites for the present study. During this period, initial sites for groundwater quality characterization and stream gauging stations located around the upper Berg River catchment were identified. These sites included boreholes located below and above the Berg River Dam outlet and inlet as well as stream gauging stations located along the Franschhoek, Berg, and Wemmershoek Rivers. Thereafter, with the help of officials from the Council for Scientific and Industrial Research (CSIR), five surface water-sampling sites were identified during 2013 as part of the joint UWC-CSIR Appropriate Capacity and Training for the benefit of Sub-Saharan Africa Water Security (ACT4SAWS) project. A further seven river sampling sites and two more stream gauging stations were identified during the sampling 2014 low flow campaign. At the BRM1 experimental site located at the inlet to the

Berg River Dam, a 600m reach was selected for differential stream gauging. The site was devoid of abstractions or discharges of water into the river, rendering it suitable for this activity.

In 2014, in a co-operative groundwater sampling campaign with officials from the Department of Water and Sanitation (DWS) Bellville office, borehole sites located on private land and those that were inaccessible were accessed. These boreholes included those located in the restricted Berg River Dam area, private vineyards and estates around the upper Berg River catchment as well as those initially identified, but could not be accessed, because they were locked. Therefore, sampling occurred on different days and times of day during both the 2014 low and high flows.

3.2.5. Study design, approach and perspective

The current study was both observational and experimental and it focused on two main aspects of water resources management. Firstly, the use of base flow separation and comparison of flows along consecutive reaches along a stream aimed to provide the quantity of water derived from subsurface storages and inflows/outflows along the stream, respectively. Secondly, hydrochemical analysis of water sampled from aquifers, streams and seepage faces along the valley was used to infer interactions in terms of water quality, while also enabling the determination of areas of cross contamination or purification in the upper Berg River catchment.

The approach followed for this part of the study was to collect water samples for the quality of groundwater and surface water (i.e. streams) to infer interaction between ground and surface water. Continuous recordings of stream flows were collected at the gauging station to conduct base flow separation. The data was collected at various sites around the upper Berg River catchment and after rigorous mathematical (mass balance) and statistical (multivariate) expressions were applied to quantify and illustrate the interaction between groundwater and surface water as well as the main direction during a hydrological year, and the possibility of cross-contamination or purification resulting from such interactions.

To understand how groundwater and surface water interact in a fractured rock environment, a suit of complementary and commonly used methodology were applied in the upper Berg River catchment. The aim was to test the applicability of the selected methods, while also assessing the potential for interactions between groundwater and surface water. The present study quantifies groundwater-surface water interactions by assessing the base flow contribution to streamflow's as well as by assessing the net gains/losses of water along a reach of the river. The potential for dilution of polluted surface water by ground water as well as further evidence of interaction is presented by statistical interpretation of hydrochemical data from samples collected in the upper Berg River catchment.

3.3. Data collection methods

The collection and generation of field data on groundwater and surface water is a crucial step for holistically evaluating the upper Berg River water resources and improving the understanding of the interconnectivity between groundwater and surface water. To this end, many methods are available for the generation of data required to conceptualize the hydrologic system in its entirety. Methods vary between the two water sciences fraternities (hydrology and hydrogeology).

The available methods for addressing the first objective include the measurement of direct seepages through the streambed, hydrographic analysis of base flow contribution to stream flows, stream recession curves and flow duration cures, and the computation of water budgets for the selected catchment. Although these methods all provide the quantities of exchange fluxes between groundwater and surface water, differences in the spatial application vary. Thus, the most spatially favorable method (i.e. base flow separation) was selected.

In addressing the second objective of this study, available methods include field observations, evaluation of ecological indicators (e.g. SASS system), environmental and artificial tracers, and the evaluation of temporal variations in groundwater and surface water temperatures. Field observations are generally an appropriate point of beginning the research process, with relevant sites identified during field reconnaissance visits. The current study used field observations, environmental and artificial tracers to characterize and quantify groundwater-surface water interactions. These approaches enabled a spatially representative indication of influences of groundwater-surface water interactions on water quality.

The third objective of this study entailed determining the seasonal flow trends between groundwater and surface water. To achieve this, many methods are available and include geophysical and remote sensing analysis, analysis of hydrometric potential between groundwater and surface water, mapping the hydrogeological environment and conducting water budgets. These methods provide the direction and rate at which water is exchanged between subsurface and surface water. The present study combined hydrographic, water budget and artificial tracer analysis to infer the spatiotemporal flow trends along the selected 600m reach of the Berg River.

The application of an integrated approach using methods from both respects has proven very useful recently (Anderson & Acworth, 2009; Bamuza & Abiye, 2012; Levy & Xu, 2011; Moseki, 2013; Yang, et al., 2014). This study aimed at applying a group of complementary methods selected from both disciplines to assess the importance of understanding groundwater-surface water interactions with respect to the temporal and spatial extent in an important mountain quaternary catchment for improving water resources management and utilization in the future.

3.3.1. Data type and collection source

Firstly, to describe the catchment physiographical characteristics and land use activities, topographical, land use and geological maps were used. Additional information was sourced from previous theses and reports on the study catchment. Thereafter, time series rainfall and stream flow data measured at the selected gauging stations were retrieved from the Department of Water and Sanitation's climate and stream-gauging database. To characterize groundwater-surface water interactions, water samples and physical parameters were collected from both groundwater and surface water during fieldwork excursions. Finally, to identify the flow trends, input of artificial tracer (i.e. NaCl) into the stream was done in field and continuous measurements of changes in the streams EC were used to compute the discharge along the selected reach. NaCl as a tracer for the dilution gauging was chosen because of its non-toxic nature at relatively low concentrations to aquatic ecosystems and organisms.

3.3.2. Methods that were used and parameters measured

Stream flow data was measuredautomatically in a stilling well (located at the gauging station), where stream stage is related to the amount of water flowing through that section of the stream. These flows are recorded every hour over a period of 24 hours. These flow readings are collected monthly to compile the DWS hydrological data repository. End users can access the data on www.dwa.gov.za/hydrology. Data are frequently validated with measurements from the stream-stage relationships at the stilling wells

Field measurements of Electrical Condcuctivity (EC), Total Dissolved Solids (TDS) and pH of both groundwater and surface water were measured onsite with a multi parameter probe. Therafter, surface water samples were collected for major ion analysis using agrab sampling approach. Prior to sample collection, field variables would first be monitored untill they stabilized, indicating equilibrium in the instruments measurements. When these parameters had stabilized, a sample was collected and stored in polyethylene bottles (250 ml) that had been pre-rinsed with dilute sulfuric acid (to pH 2.0) for chemical analysis. Samples was kept on ice during transport to the laboratory. Failure to promptly transport sample to analysis laboratories, was avoided to prevent degradation of water samples prior to analysis.

Stream gauging by dilution gauging utilized a grab sampling approach as well. Firstly, weather conditions were checked on https://www.accuweather.com to ascertain the ideal days (preferably without rainfall) on which this exercise would be done. Therafter, equipemt required fro the excersize (including multi parameter probe, waders, GPS, etc) was examined and calibraed if required. At the field, the tacer solution was input into the stream and a change in EC measured 200m below the point of insertion. Continuous (every 5 sec) measurements were logged with multiparameter probe. Data generated onsite and input to Microsoft Excel spreadsheets for analysis. the calibration of the equipment prevented discrepencies associated with faulty machinary.

3.3.3. Tool/equipment used

Secondary continuous stream flow data was electronically downloaded from the DWS website. Thereafter, data were sorted on Microsoft Excel to check for zero or error measurements. Tools that was required for the collection of water samples included an YSI Professional Plus 20™ Multi-parameter sonde, a submersible pump, 250ml Polyethylene bottles, surgical gloves, ice bucket with ice and permeant marker for sample labeling. To quantify stream gains/losses using dilution gauging, a 100L drum, 10kg salt, YSI Professional Plus 20™ Multi-parameter sonde, and waders were required. The requirement for a stopwatch was countered by the ability of the sonde to continuously measure physical water quality parameters at stipulated intervals

3.3.4. Procedure followed

Firstly, secondary stream flow data from the abovementioned gauging stations was retrieved. However, as indicated, the station located in an area unaffected by anthropogenic activities which can potentially alter the groundwater-surface water flow regime, was selected for the separation of direct runoff and base flow signals of total flow. Time series stream flow data, spanning from 2012-2014, collected at the DWS gauging station (G10A) was retrieved from the www.dwa.gov.za/hydrology website. The process entailed entering the exact station number or searching for the required station within all the stations in that particular quaternary catchment. The retrieved data was sorted on Microsoft Excel to arrive to the data from which the hydrographs would be constructed and separated into the flow components.

Secondly, the collection of groundwater and surface water samples for chemical analysis as well the measurement of field water quality was done in accordance to standard sampling procedure (Weight, 2008). Before collecting water samples from both ground and surface water, physical water quality parameters were measured onsite using an YSI Professional Plus 20™ Multi-parameter sonde. This process entailed dropping the sonde into the water and waiting for measurements to auto-stabilize, thereafter recording the measured values. Recorded values were inserted and stored on Microsoft Excel spreadsheets.

Prior to the collection of groundwater samples, a submersible pump was inserted into the borehole. The pump served as a means of removing at least three well volumes (purging) and retrieving a representative sample. Groundwater was pumped for a minimum of 15 minutes to achieve sufficient purging. To ensure that the sample was representative of groundwater, physical water quality parameters (EC, TDS, and pH) were measured until they stabilized. Thereafter the samples were collected. Using 250ml Polyethylene bottles (rinsed at least three times prior to collection with the water to be sampled) samples were collected and placed in a dark cooler box prior to refrigeration at 4°C. A similar approach to sampling surface water was applied, whereby the polyethylene bottles would be rinsed three times, then a sample collected. Furthermore, no specific sample preservation was required as the analysis would be for the general chemistry of the water, however, storage at low temperatures and analysis was to be done as soon as possible (within one month) so as to retain the representative sample concentrations without disturbance. The collected samples were then sent to Bemlabs for chemical analysis.

To ascertain the occurrence of groundwater outflows to surface water along the experimental research site at BRM1, the differential stream gauging method was applied. With this method, volumetric discharge quantity was derived from the flow measurements. Measurements of stream flow in consecutive cross sections enabled the determination of groundwater –surface water exchange by computing the differences in stream flow between the cross sections and inferring groundwater-surface water interactions from the resulting inflows or outflows (McCallum, et al., 2012). Differential stream gauging is a commonly used method for determining the difference in the volume of water flowing through two or more cross sections of a stream per unit time. Various techniques for achieving this task exist, however, due to stream geomorphological constraints, the available utilizable methods were observed to the dilution gauging method.

Finally, differences in stream flow over two consecutive cross-sections were estimated by conducting instantaneous discharge tracer test to deduce the rate of flow in the river. For this activity, a 100L drum filled with a dilute solution of 10kg table salt, a pump with constant pumping rate, the YSI Professional Plus 20™ Multi-parameter sonde were all used to achieve this objective. The dilute solution was pumped into the stream water at a constant rate, while the concentration (as Electric conductivity (EC) and Total Dissolved Solids (TDS)) was measured 250m downstream of the injection point. The natural EC and TDS profiles of the stream were measured for at least an hour prior to injection to ascertain the background values. After the injection, the test would continue until the dilute solution had completely passed the measuring point, where after this was estimated to represent the stream returning to this natural values. The main idea of this method is that any changes in stream EC while there is a tracer injected, would be indicative of a discharge of subsurface water of lower EC, and therefore be indicative of a gaining reach of the river. The YSI Professional Plus 20™ Multi-parameter sonde served the purpose of continuous measurement of EC and TDS very well as the device has a logging application that can be set to log to a minimum of every 5 seconds, enabling the clear distinction between any changes in stream EC because of discharging subsurface water

3.4. Data analysis methods

The analysis of collected data first required sorting and labelling of the data, to prevent misinterpretation of data. The first step was to process the collected water level, field parameter, chemistry, and flow data on Microsoft Excel™. Once processed, data were subjected to various analysis methods to determine the interactions between ground and surface water. Analysis approaches used included, the use of separation algorithms for the base flow separation analysis, the use of descriptive statistics to represent field water quality data and hydrochemical data (major ions i.e. Cl^-, NO_2^-, SO_4^-, HCO_3^-, Na^+, Mg^{2+}, K^+ and Ca^{2+}) and the application of a mass balance approach to determine stream flow loss/gains over the 600m reach investigated.

Firstly, stream flow, field water quality, and hydrochemistry data were inserted onto a Microsoft Excel spreadsheet and the descriptive statistics generated. Statistical tests for normality in the distribution of stream flow and physicochemical data were conducted to determine the statistical approach to be followed when describing results of base flow and hydrochemical analysis. Thereafter, data were graphed on various types of graphs including bar graphs, Piper diagrams, and line graphs. These graph types indicated stream flow, the proportion of dissolved ions in sampled water over the 2012-2013 hydrological year, which distinguished the major ionic character of the water and illustrated differences in flows and concentrations levels between sampling sites. Histograms and Q-Q plots of computed base flow indices and pH and EC were computed and presented in the appendices.

3.4.1. Determining subsurface water discharge/recharge using automated base flow separation

To achieve base flow separation, collected stream flow data was processed on Microsoft Excel. Thereafter, selected one-parameter separation algorithms adopted from Chapman and Maxwell and Lyne and Hollick separation algorithms (Chapman & Maxwell, 1996; Lyne & Hollick, 1979) were applied to obtain estimates of discharges from the subsurface. Developed for signal analysis, these separation algorithms have been noted not to have any hydrological basis (Brodie, et al., 2006). However, this approach has been illustrated to produce repeatable results, using time series data, and has allowed the computation of the ratio between the quick flow component and the base flow component of a total stream flow hydrograph. As proposed by Hughes, et al., (2003) and Welderufael & Woyessa, (2010) the most appropriate alpha and beta parameters to be input into the filtering algorithm were 0.925 and 0.5 respectively. The current study utilized the commonly applied and recommended filter parameter of 0.925.

Recursive digital filters proposed by Chapman and Maxwell (Equation a) and Lynne and Hollick (Equation b)were used for the stream flow filtering procedure to determine the base flow component (Equations c and d) of total flow (Brodie & Hostetler, 2005; Chapman, 1991; Chapman & Maxwell, 1996; Nathan & McMahon, 1990; Smakhtin, 2001).

These algorithms are as follows:

a) Chapman & Maxwell algorithm:

$$\text{a)} \quad qf(i) = \frac{3\propto -1}{3-\propto} qf(i-1) + \frac{2}{3-\propto}\left(q(i) - \propto q(i-1)\right)$$

b) Lyne & Hollick algorithm:

$$\text{b)} \quad qf(i) = \propto qf(i-1) + \left((q(i) - q(i-1)\right)\frac{1+\propto}{2}$$

Where qf(*i*) is the filtered quikflow component for the *i*th sampling instant, qf(*i*-1) is the filtered quikflow for the previous sampling instant to *i*, q(*i*-1) is the original stream flow for the previous sampling instant to *i* and α is the filter parameter. These digital filters, as mentioned, have no hydrologic basis and have been borrowed from signal analysis to separate the high frequency quikflow signal to derive the low frequency base flow signal as prescribed by Nathan & McMahon (1990). It should be noted that these separation algorithms provide only the component of stream flow directly derived from direct runoff (precipitation) and to get the base flow contribution, it is important to find the difference between the filtered stream flow and the total recorded stream flow, using the proposed filter parameter (0.925 for α). Following the determination of the base flow component, the ratio between base flow and total gauged stream flow (BFI) was computed to indicate the proportion of total flow derived from base flow.

The equations for base flow (Equation c) and the BFI (Equation d) are:

Base flow:

$$\text{c)} \quad QB(i) = Q(i) - qf(i)$$

d) Base Flow Index:

$$\text{d)} \quad BFI\% = Qb(i)/qf(i)$$

The resultant index (Equation d) indicates the streams dependence of discharges from subsurface storages. However, this index or the separated base flow do not indicate what the exact source of water discharged to the stream during base flow periods is, thus further sampling and analysis accompanied by a mass balance approach documented by Freeze & Cherry, (1979) is required to identify the true source of water.

Student's T tests were applied to test the significance in the differences the mean base flows computed using both filter algorithms. Two-sample sample T tests, assuming equal variances between the two means were applied to test the significance in the differences between these means (Ramsey 2000). The p value ranged between 0 and 1, indicating the percentage significance between the means. A score close to zero indicated low levels of significance, indicating a marked difference in the two means. A score closer to 1, indicated high significance, suggesting that there was less difference within the means at a 95% confidence interval. Based on the interpretations of the Q-Q plots for the resultant BFI% , the computed BFI% did not follow normal distribution, thus the use of non-parametric statistical methods was sought to differentiate between the computed BFI% values for the stream gauging stations in the upper Berg River catchment. Because the stream flow and resultant separated base flow component data did not follow the normal Gaussian distribution, the non-parametric Kruskal-Wallis test was applied (Ramsey 2000). The hypothesis tested in this study was whether the stream flows measured at the different gauging stations and resultant BFI% values were identical in their distribution. Thus to conduct a multiple sample analysis, the Dunn (1963) approach was used to show the differences in the means of the means of the ranks computed by the Kruskal-Wallis test (Dinno, 2015). This method is used as an alternative to ANOVA and is used to test if k-number of samples is derived from the sample population or the populations have identical properties (Ramsey 2000). In this study, the similarities in the stream flow data collected from the four gauging stations around the upper Berg River catchment were tested. If the computed p-value is such that the null hypothesis should be rejected, the method assumes that at least one sample in the population is responsible for the rejection of the null hypothesis (Ramsey 2000).

3.4.2. Hydrochemical and multivariate statistical characterization of groundwater-surface water quality

3.4.2.1. Hydrochemical analysis of groundwater and surface water

Water samples were analyzed at Bemlabs in Strand, Western Cape. All analyses were done according to ISO/IEC 17025 standards and the testing laboratories are South African National Accreditation System (SANAS) accredited. Samples using SANS accredited methodology (SANS 11885:2008). Cation analysis was done with Inductive Coupled Plasma Optic Emission Spectroscopy, while anions were analyzed using Ion Chromatography. As indicated in the Bemlabs Methods description document, the uncertainty of measurement among all elements analyzed ranged between 0.000% and 8.55 %, which is lower than the 10% recommended limit for uncertainty (Weight, 2008). To measure the suitability of groundwater and surface water in the upper Berg River catchment for irrigation use in agricultural activities, the Sodium Absorption Ratio was computed. This ratio indicates the suitability of the water for irrigation as a high SAR can cause a decrease in the ability of the soil to form stable aggregates and cause loss of soil structure and tilth. This condition ultimately results in a decrease in infiltration and permeability capabilities of the soil to water, which affect crop production (Weight, 2008). The SAR (Equation e) was computed using the following equation:

$$\text{e)} \quad SAR = \frac{Na}{\sqrt{0.5(Ca+Mg)}}$$

3.4.2.2. Multivariate statistical analysis of groundwater and surface water

Understanding how the interactions between groundwater and surface water affect water quality is another crucial aspect of such research. Many analysis techniques have been developed for varying analysis requirements. Kumar, et al., (2008) give a brief outline of the most common statistical methods applied to understand the hydrochemical implications of water exchanges between ground and surface water. Multivariate statistics, such as principle component analysis and cluster analysis can be used to manage large hydrochemical datasets as well as identify the dominant factors controlling the chemistry of ground and surface water (Dalton & Upchurch, 1978; Kumar, et al., 2009; Kura, et al., 2013; Rajesh, et al., 2002).

Principal Component analysis (PCA) is the most widely used statistical method among the families of multivariate statistics. This method identifies patterns in the data and presents them based on the similarities or dissimilarities in the dataset. Indicating patterns in extensive datasets with complex relations is a difficult task to undertake. Thus using PCA can provide reliable results on the dominant components. The main aim of PCA is to summarize the multivariate dataset by reducing the statistical noise in the data, exposing the outliers, and then arranging components in descending order. The first few PCA’s interpret the variables with the largest variance and contribute equally when the correlation matrix is used. In the present study, a Pearson correlation matrix was used to determine the relationship between variables. Classification of the correlation matrix is based on the Guilford’s rule of thumb for Pearson product moment correlation. Table 1 shows Guilford’s rule of thumb for interpreting correlation coefficients.

Table 1: Guilford's rule of thumb for interpreting correlation coefficients

***r*-value**	**Interpretation**
0.0-0.29	Negligible or little correlation
0.3-0.49	Low correlation
0.5-0.69	Moderate or marked
0.7-0.89	High correlation
0.9-1.0	Very high correlation

The Kaiser-Mayer-Olkin (KMO) measure was applied first prior to the execution of the PCA. This was done to evaluate the suitability of the PCA and to test the adequacy of samples. According to Kura et al (2013), it is advisable only to proceed to the next level of PCA if the KMO value is 0.5 and above. In this study, the computed KMO was found to be 0.636.

Cluster analysis is a method used to classify variables into groups called clusters based on their similarities or dissimilarities. This classification is done objectively without prior assumptions regarding the data to uncover the patterns in the original dataset. Cluster analysis can be achieved mainly in three ways, i.e. hierarchical, k-means and two-step clustering. In the first group, Agglomerative hierarchical clustering begins with every case being a cluster unto itself. At successive steps, similar clusters are merged until; finally, few clusters are used to represent the data based on the similarities or differences in variables.

In this study, principal component and hierarchical cluster analysis were used to understand the factors that dominate the control of groundwater and surface water chemistry in the upper Berg River catchment. Furthermore, cluster analysis groups' similar data together and is expected to indicate sampling sites that are similar to each other and therefore indicate interactions.

3.4.3. Differential stream gauging by dilution gauging

3.4.3.1. Calculation of stream flow using gulp dilution gauging

Using the gulp injection approach for dilution gauging, a known volume (V) of salt solution was injected into the stream as an instantaneous gulp at a location in the stream. Thereafter, the salt solution mixed rapidly throughout the depth of the stream reach and less rapidly across the stream cross section. Due to stream morphological heterogeneities, some portions of the salt wave stretched downstream in a process described by (Moore, 2005) as "longitudinal dispersion". This longitudinal dispersion resulted in the salt cloud having a leading edge with low conductivity, a central peak zone, with high conductivity and a trailing limb with decreasing conductivity with the passage of the salt cloud until it reached the conductivity recorded prior to any input of salt solution into the stream. A Moore (2005) state that the time required for the passage of the salt wave peak at the measurement location inversely depends on the mean velocity of the stream.

At any time (t) during the salt wave passage, the discharge of the salt tracer solution (q(t)) past the measurement point can be approximated by:

$$\text{f)} \quad Q(t) = Q.RC(t)$$

Where Q is the stream discharge and RC is the relative salt concentration in the flow at time (t). The equation assumes that the salt solution is less than the volume of water flowing in the stream

(Q). Thus, for a conservative tracer, such as table salt (NaCl), if the tracer discharge is integrated over the duration of the salt wave, the following equation can be used to approximate discharge:

g) $$Q = \frac{V}{\int RC\ (t)dt}$$

Moore, (2005) notes that, “in practice, RC(t) is determined at the downstream measurement point at discrete time intervals. In the present study, a time interval of 5 seconds was chosen between conductivity measurements. Additionally, the integral in the previous equation (Eq. g) can be approximated as a summation as follows:

h) $$\int RC\ (t)dt = k\sum_n [EC(t) - EC(bg)]$$

Where n is the number of measurements during the passage of the salt wave and k is the calibration constant that is dependent mainly on the salt concentration and the chemical characteristics of the stream water. The calibration constant is determined following the procedure described in (Moore, 2004). The relative concentration (RC) can be determined using stream conductivity (EC) as:

i) $$RC\ (t) = k\sum_n [EC(t) - EC(bg)]$$

Where EC(t) is the stream conductivity measured at the time (t), while EC(bg) is the stream conductivity measured prior to the input of salt solution into the stream. By combining the three equations explained above, a practical equation for determining stream discharge can be derived as:

j) $$Q = \frac{V}{k\Delta t\sum_n [EC(t) - EC(bg)]}$$

To apply this equation, the volume of salt solution (V) has to be known, changes in EC must be measured, and a calibration constant (k) determined. In the present study K was computed to 0.0000011, the salt solution volume was 20L and the time between EC measurements was set to 5 seconds on the YSI Professional Plus 20™ Multi-parameter sonde.

3.4.3.2. Computing stream-aquifer inflows/outflows by dilution differential stream gauging

Differential stream gauging was achieved through dilution gauging method. Using this approach, areas of groundwater-surface water inflows/outflows could be identified along a 600m reach of the upper Berg River. To obtain the differences in stream flow over consecutive stream reaches, a mass balance approach was applied to calculate the gain or loss in mass between the reaches (Brodie, et al., 2007). This method is theoretically bound by the laws of mass and energy conservation, which stipulate that in a closed system, input should equal the output, if all other inflows/outflows are accounted for. This approach was applied to discern zones of water inflow and/or out flow. The following equation was adapted:

Total inflow/outflow quantity:

$$\text{k)} \quad Qgw = Qdn - Qup + \sum Qout - \sum Qin$$

Where Q*dn* is the flow at the downstream end of the cross section, Q*up* is the flow at the upstream end of the reach, Q*out*& in are the external inputs abstractions of water into stream flow (such as diversions, irrigation return flows or rainfall onto the stream surface). Following the computation of these differences in flow, a negative Q*gw* indicates a net loss of water from the stream to the underlying aquifer, while a positive Q*gw* indicates a net gain to stream flow from subsurface sources of water (Brodie, et al., 2007). However, it should be noted that the sums of both inflows and outflows were considered zero, firstly due to the lack of abstraction infrastructure, and secondly, due to the fact that the proportion of water contributed by the inflows along the valley sides as interflow were not accounted for at this time, therefore:

Stream inflow/outflows

$$\text{l)} \quad Qgw = Qdn - Qup$$

The approaches used in this study were documented as being the most cost and labor efficient methods of determining groundwater-surface water interactions. However, as indicated by Kakuchi, et al., (2012), a crucial requirement to apply methods is that the chosen methods should enable spatial telescoping of the computed estimates, in order to scale the estimates up to catchment scale, from reach scale. Additionally, the use of methods that derive from the different discipline within hydrology enables the surface and groundwater component to be clearly differentiated, instead of lumping equally values under the assumption of them indicating a particular hydrological zone (i.e. groundwater or surface water)

3.5. Tools/software used

For managing the data retrieved via the various methods, data were incorporated into Microsoft Excel Spreadsheets. Data were correctly labeled according to the varying objective it pertained. Missing data were in filled using the Microsoft Excel logical test method in order to be able to apply the filter algorithms, statistical analysis, and computations of inflow/outflows.

Firstly, stream flow hydrographs were subjected to two one-parameter filter algorithms. Nathan & McMahon, (1990) explain the evolution of automated digital filtering techniques for base flow separation and indicate that the most commonly used algorithms include the ones proposed in works by Chapman, (1991) and Lyne & Hollick, (1979). Although many computer software programs are available for this analysis, the simplest approach is to insert the calculations into the Microsoft Excel Spreadsheet to derive the base flow contribution to total stream flow.

Secondly, water quality data consisting physical and chemical water quality indicators was input onto Microsoft Excel Spreadsheets. Descriptive statistics of groundwater, surface water, interflow and rainwater samples were generated using this application. Further statistical investigation of the principle components and various dominant clusters within the water quality data was done using a Microsoft Excel Add-on application, XLSTAT 2014. Using this software, a variety of statistical analysis could be conducted; however, the present study chose only the principle component and cluster analysis techniques.

Lastly, Microsoft Excel was used to manage and label the data generated on the differential stream gauging objective. Computations described by Moore, (2005) for calculating stream discharge from measurements of stream conductivity during dilution gauging were applied to the measured conductivities over the different stream reaches. Using these computations, stream discharge over the three 200m reaches was calculated and differences between the three sub reaches were established.

3.6. Data quality assurance

Once data were generated for the respective objectives, it had to be sorted out (cleaned). This process involved the checking for any blanks, removal of duplicates and backing up of data. To check the reliability of the data, time series data is crosschecked with the stream stage-discharge relationship at the stilling well, while the data on physical water quality parameters was checked by calibrating the multi-parameter sonde every sampling day. Calibrations were confirmed with previous calibration information, because the device stores previous calibration information and produces a flag should the calibration be unsuccessful. Water chemistry data was checked by evaluating the Charge-Balance Error of the samples. According to the Principle of Electroneutriality, water cannot carry a net electrical charge (positive or negative), but must always be electrically neutral (Weight, 2008; Younger, 2007). Therefore a final test of data quality assurance must be done to check the validity of the data. This test is called the Cation-Anion Balance (CAB). Both Weight (2008) and Younger, (2007) emphasize that the CAB is a useful test of completeness and accuracy of field and laboratory data and that only samples having CAB <=15% can be used in hydrochemical data interpretation. The CAB (Equation m) is commonly calculated by the following equation:

$$\text{m)}\quad CAB\% = \frac{\sum meq\ cations - \sum meq\ anions}{0.5(\sum meq\ cations + \sum meq\ anions)} \times 100$$

Data collected from groundwater and surface water sampling sites was subjeceted to this quality check procedure and revealed that all of the sites had charge balance errors within the recommended range for use of chemiscal data for reporting

3.7. Statement on ethical consideration

Prior to doing any fieldwork on the collection of required data, it was necessary to acquire permission from the official from the Department of Water and Sanitation that deal with the management and data generation in the upper Berg River catchment. This process facilitated entry onto private land for groundwater sampling as well as entry into the restricted sites behind and adjacent to the Berg River Dam. Furthermore, permission on reporting on data retrieved from the DWS archive was sought. The chemical introduced into the stream during dilution gauging (i.e. table salt) is not harmful to the aquatic ecosystems and promptly disintegrates and is rapidly mobilized.

3.8. Limitations of the study

The main concern is from the retrieval of secondary data from DWS and the fact that methods of data generation are not included in the retrieved data. Therefore, there may be some discrepancy regarding the accuracy and reliability of these data. However, DWS regularly maintains the gauging stations and collects the data with validation of the affectivity of the machinery with a manual method of cross checking the daily flow rates with a rating curve table that relates the stage of the stream to flow through that section. The collection of field and chemical water quality data followed the standard procedure. However, data discrepancies may arise from measuring errors introduced by the person doing the measurement. Therefore, it was agreed that one person would collect water samples, while another measures the field water quality parameters, to reduce the effect of switching operators. Regarding the effectiveness of the machinery utilized, as was done with the gauging stations, manual calibration was required to reduce instrumentation malfunctions and erroneous readings.

Regarding the application of differential stream gauging, sources of error were sought to come from the inaccurate calibration of the measuring equipment. Another possible source of error was identified as being any fault that might arise because of the breakdown of the pump with which the solution would be pumped into the stream. The rate of pumping was carefully measured prior to injection to ensure that a constant rate of pumping was achieved. This would be done at both consecutive reaches to eliminate any possible fails that may arise from the transportation of equipment from site to site.

Chapter 4: Conceptualization of groundwater-surface water interactions in upper Berg River catchment

4.1.Hydrogeological conceptualization of G10A (upper Berg River catchment)

In many types of environments, groundwater and surface water show consistent seasonal interconnectivity, through the recharge of surface water and discharge of groundwater to surface water bodies. Understanding the interactions between groundwater and surface water and the factors that govern them is an important part of water resources research that encompasses assessing the quality and quantity of water resources to identify any changes that occur in the natural flow paths in catchments that are considered strategic water resource areas. The upper Berg River catchment (G10A) is one such catchment that supplies a disproportionate proportion of runoff compared to adjacent lowland areas of the greater Berg River catchment (Nel, et al., 2013). In addition, this area is considered a significant recharge area for groundwater.

Figure 11shows the hydrological conceptual model of the upper Berg River catchment. This diagram indicates that, locally, the flow of water generally follows the topography, with shallow groundwater water levels observed in the valleys that generate the source of the perennial streams in the areas. Identification for the construction of the Berg River Dam was planned to utilize this condition in the upper catchment by capturing the large runoff generated in the south-west of the catchment (Ractliffe, 2007). This area is mountainous and is protected as part of the catchment area of the Berg River Dam, therefore human activities are prohibited in this area that have the potential to change the quality and decrease the quantity of runoff from this area. Furthermore, steep slopes with rugged topography characterize the area. The town of Franschhoek and adjacent agricultural lands are located on the Eastern side of the catchment in the Franschhoek valley. Gentler slopes overlain by quaternary sediments, ideal for cultivation, characterize this area. The Franschhoek River drains this area before it converges with the Berg River lower in the catchment. The Robertsvlei Saddle that has a mixture of agricultural lands and human settlements separates the two distinct areas. The lower part of the catchment is characterized by relatively flat alluvium comprised of quaternary sediments and the Franschhoek Wetlands that further provides insight on the shallow nature of groundwater.

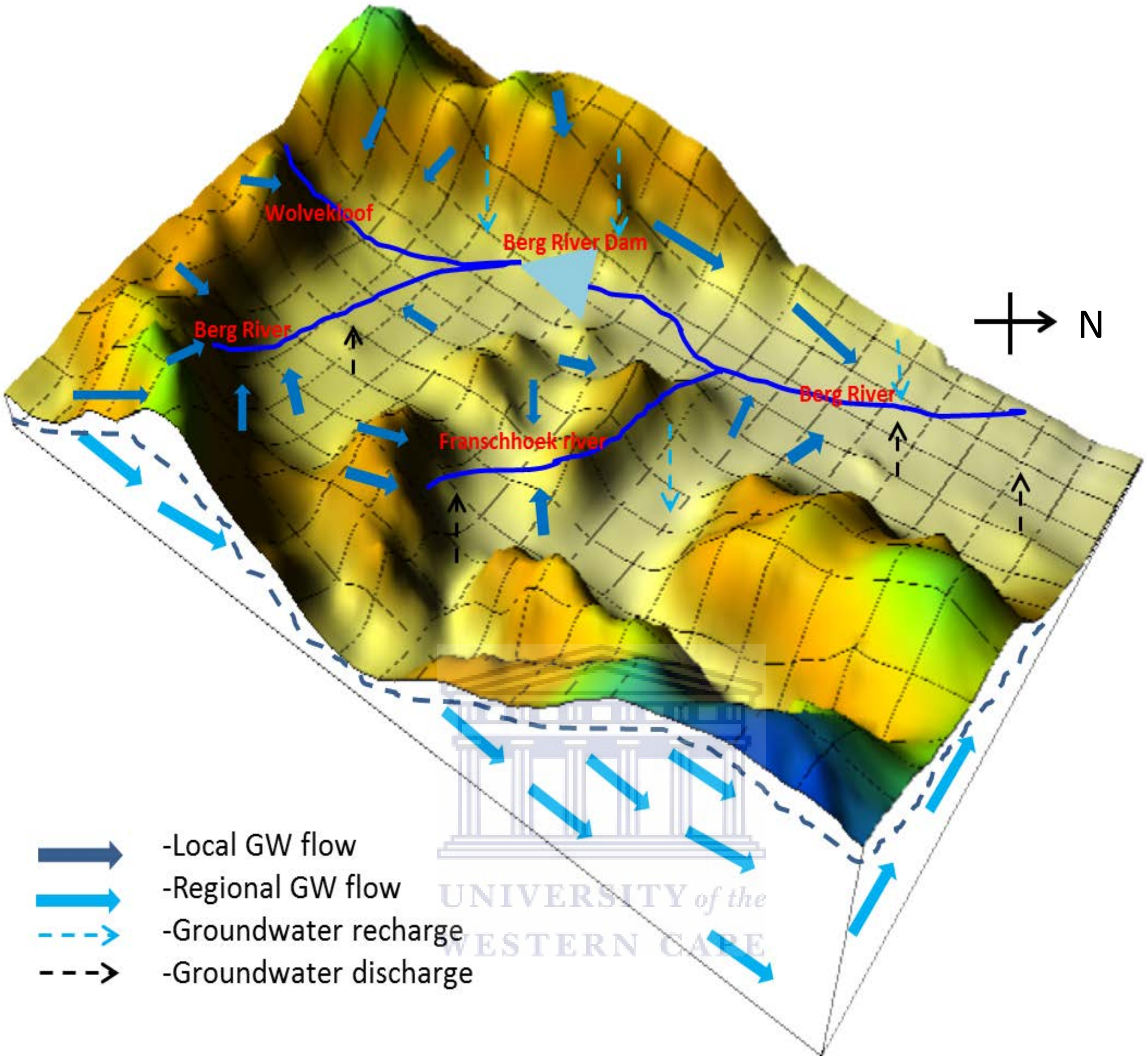


Figure 11: Hydrogeological conceptual model of G10A

Surface water bodies comprise primarily of water in the rivers, lakes, dams and overland flow, all of which are derived from precipitation. Moseki, (2013), reports that water that infiltrates the unsaturated zone component constitutes that part of the subsurface where the infiltrating water from rainfall or leakage from runoff does not completely fill the voids in between the soil grains and rocks. Furthermore, because the flow of water in the unsaturated zone is generally vertical due to gravitational pressure, the presence of relatively impermeable soils, rock layers or geological fracturing or faulting may often impede downward percolation of water into the aquifer. Consequently, these impeding layers of impermeable geological heterogeneity allow for the horizontal movement of water through the unsaturated zone, until it reaches a surface contact zone where springs and seepages occur. The area located in the mountainous southwestern part of the upper Berg River catchment is typically characterized by seepages along the fractured mountain face that substantially contribute to the amount of surface runoff measured as part of the local groundwater flow path (Ractliffe, 2007). This condition also influences the way in which groundwater is recharged, by introducing long, interconnected fissures in the geological material that enable the rapid inflow of water to the water table. Groundwater includes the water that completely fills the soil/rock pore spaces of the saturated zone and is recharged by the vertical infiltration of water from surface water bodies or the lateral migration of groundwater from adjacent aquifers (Ractliffe, 2007)

In mountainous areas, a complex variety of flow pathways exists through which precipitation travels through the catchment. It is commonly reported that between storm events and during periods of extended dry weather, discharges of subsurface water can maintain stream flows (Chapman, 1999; Furey & Gupta, 2001; Nathan & McMahon, 1990). Generally, this is what happens in mountainous perennial streams, where seasonality exists in the rainfall patterns but streams flow regardless of this contribution from rainfall. Discharges from delayed subsurface water storages (aquifers, soil moisture, etc.) help to maintain the flow required during dry seasons. This delayed discharge is known as “base flow”. On the contrary, during rainy seasons, streams in such areas are generally a source of recharge for underlying aquifers, thus replenishing the depleted subsurface water storage capacity of the catchment required to sustain flows during dry periods. The upper Berg River in the mountainous quaternary catchment of the Berg River catchment of the Western Cape is reported to indicate this state, with streams that flow throughout the year, but with a seasonal rainfall pattern (Clark & Ractliffe, 2007; Ractliffe, 2007). Furthermore, Ractliffe, (2007) reports that the contribution of groundwater to base flow is most significant during periods of low flow i.e. during summer. It is also reported that the construction of the Berg River dam could affect groundwater contributions to base flows in this catchment (Ractliffe, 2007). Thus, understanding the proportional contribution that groundwater and other sources of delayed flow have on surface water flows during dry periods is vital to attend to stressed water resources during such periods.

Many authors agree that groundwater and surface water comprise a unified part of a single water resource system and that the utilization and management of either should consider implications on the other (Kalbus, et al., 2006; Sophocleous, 2002; Winter, 2001). However, in South Africa a lack of this understanding has been reported, with difficulties ranging from previous legislative frameworks, methodology selection, and the prevalence of secondary porosity (fractured rock) aquifers (Levy & Xu, 2011; Parsons, 2004). Winter, (2001) and Sophocleous, (2002) argue that interactions between groundwater and surface water occur over a variety of physiographic environments. Therefore, understanding the catchment physiographical conditions such as topography, geology, climate and land use will enable for the selection of appropriate methodology. The selection of methods best suited for the particular physiographical environment becomes crucial for understanding the spatial and temporal variations in interactions between groundwater and surface water in varying physiographical conditions.

The interactions between groundwater and surface water differ among topographical environments. Locally in mountainous areas, the flow of groundwater is determined by the topographical conditions in the area and water level differences between groundwater and surface water. In the upper Berg River catchment, water moves downslope along the topographical gradient to the valleys where it discharges as base flow in the streams, wetlands, and dams, which sometimes flood due to the construction of the Berg River dam (Ractliffe, 2007). Figure 12 shows the groundwater level map for 2014. This map indicates that groundwater levels were highest near the Berg River dam (focused indicating groundwater recharge), while the groundwater levels gradually declined with distance downstream. The upper mountainous parts of the upper Berg River catchment constitute a significant regional groundwater recharge area. Freeze & Cherry, (1979) note that, near the ground surface in groundwater recharge areas, the flow of water is directed downward, while in a discharge area the flow of water is directed upward. This phenomenon was anticipated after the construction of the dam (Ractliffe, 2007), with some parts of the catchment exhibiting constant inundation due to differences in topographical heights and groundwater levels affected by the dam (e.g. Robertsvlei and below Berg River dam)

In mountainous areas such as the upper Berg River catchment, groundwater may indicate a gaining phenomenon from overlaying surface water bodies (recharge), while in topographically flat areas the opposite may be observed where groundwater discharges into the overlaying surface water bodies (Kalbus, et al., 2006, Ractliffe, 2007). A third extraordinary condition may occur where the surface water bodies or groundwater storages may exhibit both the gaining and losing phenomenon. These types of interactions are indicative of intermittent surface water bodies, i.e. streams (Winter, 2001; Xu, et al., 2002), where both groundwater recharge and discharged are obsereved during different seasons. The presence of such streams extends throughout catchments with the headwaters typically being groundwater recharge areas and the lower parts of the catchment being groundwater discharge areas. Locally, the upper Berg River catchment exhibits this condition, with recharge occurring during the wet seasons and groundwater discharges observed to play a significant role in stream flow generation during the dry seasons (Ractliffe, 2007).

Understanding the physiographical conditions in a catchment thus allows for the identification of local areas of groundwater discharge/recharge within the catchment. Bamuza & Abiye, (2012) and (Oxtobee & Novakowski, 2002) reaffirm the complexities linked with understanding groundwater-surface water interactions in areas underlain by secondary geological porosity formations and show the appropriate methods for identifying catchment scale groundwater-surface water interactions in mountainous and fractured rock environments. To determine groundwater-surface water interactions in a crystalline aquifer in the Johannesburg region of South Africa, a combination of hydrochemical and isotopic analysis along with a comparison of stream flows along streams, was used. Water chemistry and isotopic analysis enabled the determination of a diffused source of Acid Mine Drainage (AMD) originating from the closed mines in the area (Bamuza & Abiye, 2012). Additionally, stream gauging showed that AMD not only affected the quality of water in the area, but it also affected the volume of water in the streams. High stream flows were measured for two streams that were impacted by the discharge of contaminated groundwater namely the Rietspruit and Bloubank streams (Bamuza & Abiye, 2012). The approach followed in the above study and recommended in other studies (Oxtobee & Novakowski, 2002; Parsons, 2004) informs the choice of the most suitable methods with which groundwater-surface water interactions can be investigated in fractured rock environments that show heterogeneity in surface topography and subsurface geology, such as the upper Berg River catchment.

In topographically steep areas that are largely underlain by fractured geology, Xu, et al., (2002) recognise that two dominant types of stream classifications occur, i.e. Type a. and Type b. streams. Type a. streams reflect streams without bank storage, which are most likely to occur in mountainous areas with steep valleys. These streams are noted to have sufficient energy to incise the stream channel, resulting in steep cliffs on either side of the channel. The streams in the upper Berg River catchment that flow in the mountainous parts of the catchment flow through deeply incised valleys with steep valley sides and streambeds. It is also reported that at local scales in mountainous catchments, subsurface storm flow (interflow) seeps into the stream along its length due to flow impeding geological layers or structures, although these areas are known to be regional groundwater recharge areas. Type b. streams are controlled by streambed morphology and are associated with Type a. streams. It is also noted that although groundwater-surface water interactions may be due to bed morphology, this interaction is however localized and that interactions can be more significant at regional scales (Xu, et al., 2002). In addition to the effects of the flow though fractured geology and steep topographies, differences in rates and directions of interactions are further exacerbated by the main type of land use in these catchments (Al-Charideh & Hasan, 2012; Yang, et al., 2012). The type and extent of a certain type of land use can either enhance or hamper discharge or recharge of water from either groundwater or surface water bodies. Areas largely covered by vegetation have greater water interception and infiltration capabilities than those influenced by buildings, i.e. human settlements. As such, the rate of vertical flow of water downwards (recharge) to the aquifer is expected to be greater in well-vegetated areas with minimum surface compaction as opposed to environments comprised mainly of impermeable surfaces. Conversely, in areas with high surface compaction activity such as towns, the influence of other alternative sources of water to stream flows (i.e. storm water drainage systems) influence the rate of recharge and the proportion of stream flow derived from natural subsurface storages of water by capturing precipitation and transferring the resultant surface runoff into streams.

The upper Berg River catchment exhibits both conditions (well vegetated and artificially compacted), with the southwestern part of the catchment being natural pristine lands covered by Fynbos and the southeastern side mainly used for human settlements and agricultural activities. To derive a natural depiction of the proportions of stream flows derived from natural subsurface storages and to compute the proportion of rainfall partitioned to groundwater recharge, computing such parameters in the natural part of the catchment that is devoid of any interference from artificial sources of water that can overestimate the contributions made to groundwater recharge/discharge.

In a study conducted in the upper Berg River catchment, by Albhaisi, et al., (2013), the authors showed that the type and extent of land use had a significant influence on groundwater recharge rates. The study aimed to determine land use changes in upper Berg catchment and predict the impact of these land use changes on groundwater recharge using multi-temporal Landsat images from 1984-2008. A groundwater recharge simulation was applied with the WetSpa distributed hydrological model and results thereof showed that after significant clearing of non-native hill slope vegetation, groundwater recharge cumulatively increased at 8% of precipitation per year over a 21 year period (1984-2004). Such research clearly explains the importance of land use types and reiterates the fact that the upper Berg River catchment is a groundwater recharge area that also produces a disproportionate volume of runoff more particularly semi-arid catchments with many conflicting water users. Additionally, the Berg River Baseline Monitoring Report documents the mean annual recharge to be 7.5 % of Mean Annual Precipitation (Ractliffe, 2007), while the groundwater contribution to base flows is 4.2% of total gauged runoff (Ractliffe, 2007). Findings of this study provide insights on the influence that land use has on the groundwater recharge process in a catchment. Furthermore, varying types of land uses have varying influences on groundwater recharge and discharge rates. Such influences range from groundwater abstraction to surface compaction, which affect the recharge/discharge regime of the catchment.

As indicated above, streams may constitute a source of groundwater recharge or depend on groundwater discharge to maintain dry season flows. This losing/gaining of water from either hydrological zone occurs throughout the length of a stream, with certain areas reflecting gaining properties, whilst others indicate losing properties. Main reasons for this pattern include the type of underlying geological material, the relative position of the surface water body's water level to that of the underlying aquifers as well as the hydraulic connectivity between surface water and groundwater. Brodie, et al., (2007); Oxtobee & Novakowski, (2002) and Parsons, (2004) all report that in geologically homogeneous areas where groundwater levels are predominantly higher than water levels in surface water bodies, a hydraulic gradient from the aquifer to the surface water body will allow water to flow to the surface water body (gaining surface water bodies).

In contrast, areas with higher surface water levels than groundwater levels will indicate a situation of groundwater recharge (losing surface water bodies). This approach is very spatially limited and extrapolating information gained from such activities requires an extensive data record of all measured boreholes in the catchment for the results to be valid for larger scale studies. Therefore, to avoid time consuming and costly field work that requires extensive data, selecting methods that are able to dipict the hydrolgical zones and their interaction at larger catchment sacles is crucial to provide an indication of the proportional influence that the interaction between groundwater and surface water has on the quantity of available water as well as to identfy the predominant factors that contribute to the quality of water in a catchment. However, as an indicator of the general groundwater flow path in the catchment, the constuction of a groundwater level contour map (Figure 12) aids in identifying the predominant grondwater flow direction.

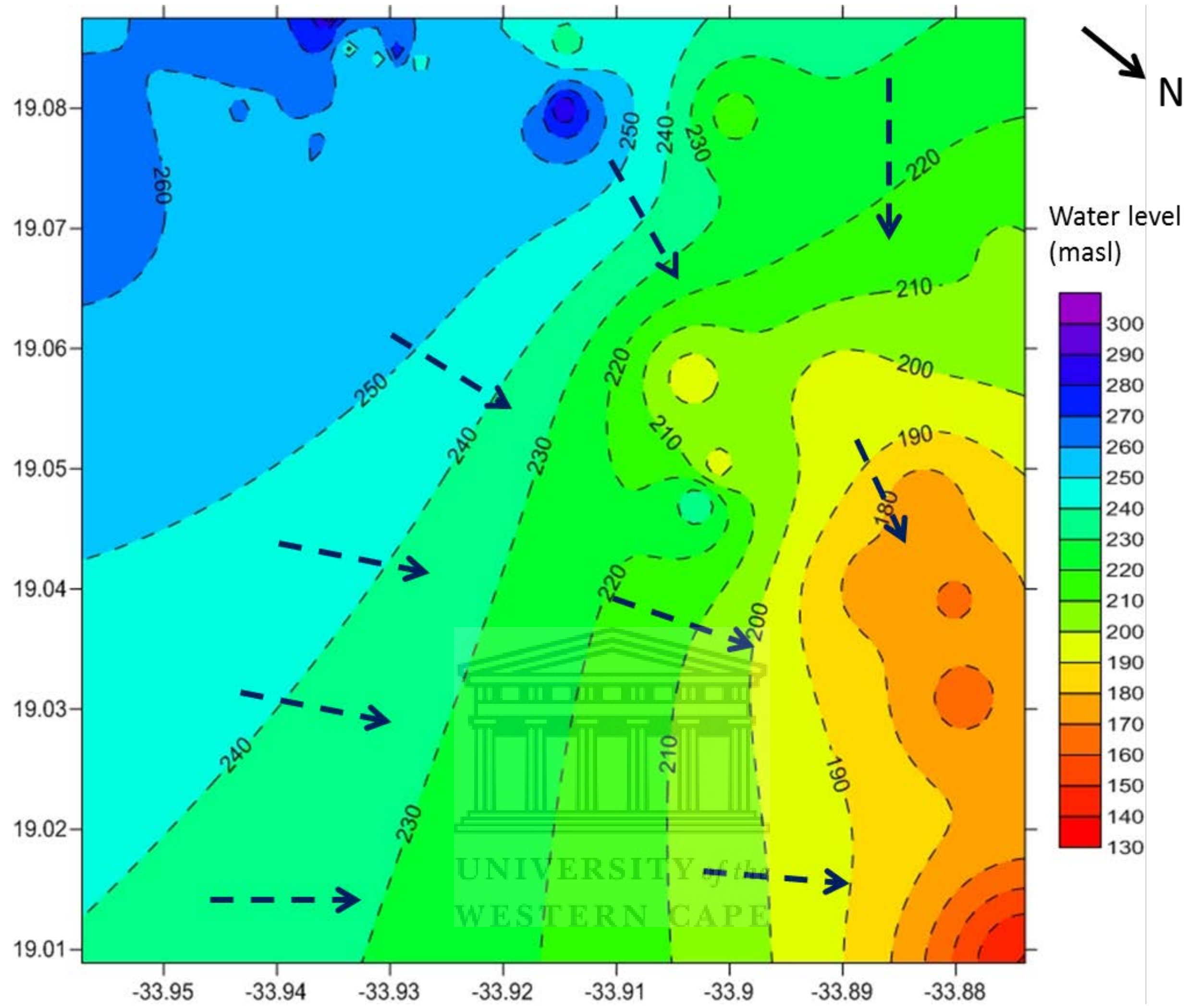


Figure 12: G10A water level contour map

Exchange discharges from one component to another can strongly influence the chemical character of the receiving water body. Levy & Xu, (2011) note that the principle role of groundwater in the protection of a rivers flow regime during dry periods and ecological state is through its contribution to stream base flow and supply of nutrients required to support aquatic biota. Furthermore, other authors agree that the exchange of contaminated water may possibly contaminate the receiving component and that understanding the type and level of contamination are required for remediation and the selection of remediation procedure (Al-Charideh & Hasan, 2012; 2002; Ellis, 2002). The present study sought to characterize the quality of groundwater and surface water, determine the proportion of stream flow derived from subsurface water storage, and establish the interaction direction between groundwater and surface water during wet and dry seasons.

For example, Cao, et al., (2012) studied the characteristics of nitrate in major rivers and aquifers of the Sanjiang Plain in China. 55 samples collected between September 2007 and September 2009 from various sources including groundwater, river, wetland, and lake sampling sites indicated that although groundwater nitrate levels were below World Health Organization (WHO) standards, they were a good indicator of local nitrate contamination derived from rural areas. Additionally, the redox analysis revealed that most of the surface water had an oxic condition and that the nitrification process was the dominating factor in surface water. Deep groundwater indicated strong anoxic conditions in comparison to surface water. The study concluded that younger groundwater (ages less than 60 years) had higher nitrate concentrations than older groundwater, which was indicative of the agricultural boom that was observed since the 1950s in the Sanjiang Plain (Cao, et al., 2012). Understanding the main chemical characteristics of both groundwater and surface water can help in identifying any possible interaction by inferring such from hydrochemical or other environmental tracer analysis. This study showed that the use of hydrochemical parameters in groundwater and surface water enables the characterization of these distinct water sources and identification of the major factors affecting their quality. The present study has utilized this approach to determine the major factors controlling groundwater and surface water quality in the upper Berg River catchment.

Al-Charideh & Hasan, (2012) conducted their study in the arid region of Rasafeh, Syria. The results of the chemical analysis indicated that indeed groundwater was highly susceptable to anthropogenic pollution through the loading of nitrate derived from N fertilizers applied in agricultural activities. Groundwater recharge for both aquifers is mainly controlled by Euphrates infiltration (Al-Charideh & Hasan, 2012), therefore, Nitrate N derived from surface activities can negatively affect the quality of recharged groundwater. The reported declining water quality status of the Berg River that is infuriated by surface activities, poses a great threat to groundwater quality through the recharge of surface water of unsuitable quality.

Both the Al-Charideh & Hasan, (2012) and Cao, et al., (2012) suggest the possibility of groundwater contamination by the seepage of contaminated surface water, however Ellis, et al., (2001) reported the opposite phenomenon in the River Thames in the United Kingdom. In their study, it was shown that the low city-scale impact of Volatile Organic Compounds (VOCs) suggested that localized point-of-plume emergence impacts on the local surface-water column, ecology and underlying benthic and hyporheic aquatic life are likely the main cause of VOC concerns in many urban rivers. These aforementioned studies all indicate that the exchange of contaminated water can contaminate the receiving water body's resource. Thus, recharge of or upwelling of contaminated water may contaminate groundwater or surface water. This complex situation is important in understanding interactions between these two resources and the implications thereof on the quantity and quality of water resources in a catchment. This complexity which further highlights the requirement for a conjunctive understanding that should be chaired by a sound selection of composite methods that represent the catchment hydrology over varying spatial and temporal scales ((Brodie, et al., 2007; Kakuchi, et al., 2012).

4.2. Summary of groundwater-surface water interaction conceptualization

The conceptual model presented and supported by literature in this chapter provides an indication of groundwater and surface water flows in the upper Berg River catchment. As documented in The Berg River Baseline Project Report (Ractliffe, 2007), both groundwater and surface water flow in a northerly direction from the headwaters in the upper Berg River catchment. The groundwater level contour map shows that indeed flow in this direction. Moreover, the conceptual model shows the variations between local and regional groundwater flow. This model also highlights the various activities occurring in the catchment that have been documented to have implications on groundwater and surface water interactions and their quality and quantity. Of great concern in this catchment is the declining water quality that is influenced by a range of activities including stream regulation, inter-basin water transfers, growing informal settlements with water related problems, and the growth of agricultural production to meet the growing demand for produce and its byproducts. Therefore, multi-method approach is applied to assess groundwater-surface water interactions to improve the understanding of these interactions and their impacts on water quantity and quality in the fractured rock environment in the upper Berg River catchment.

Chapter 5: Contribution of groundwater to stream flow

5.1 Introduction

The present chapter presents and discusses the results on the use of automated base flow seperation to determine the proportion of stream flow derived from discharges from subsurface water storages in the upper Berg River catchment. The aim was to quantify the proportion of contributions made by base flow to total gauged stream flow during 2012-2014 at the selected gauging stations in the upper Berg River catchment. The chapter addresses the first objective, which was to determine the proportion of stream flow derived from subsurface water storages by using automated base flow separation techniques. This approach does not distinguish between the exact source of water discharged to the stream (e.g. from storm water drainage, direct runoff, waste water treament works, etc.). However, it provides an indication of the dependancy of streams to discharges from delayed sources. Therfore, this chapter argues that the use of automated base flow separation to derive the proportion of stream flow derived from subsurface water storages is a practical and objective method for determining the amount of stream flow derived from base flow discharges.

To achieve the objective, the separation of stream hydrographs into their pincipal components was done using recursive digital filter algorithms adopted from Chapman, (1991) and Lyne & Hollick, (1979). These algorithms separated the high frequency quickflow component to derive the low frequency base flow component of a stream flow hydrograph. Following this seperation, the ratio between base flow and total flow was calcuated using equation (d) (as described in Chapter 3). The Base Flow Index (BFI%) provided insight on the relative dependancy of stream flows to discharges from subsurface water storages during the observed period and is presented as the evidence of the chapters argument.

Results obtained from the automated separation of stream flow hydrographs of four stream gauging stations located in the upper Berg River catchment (G1H077, G1H003, G1H038 and G1H076) are presented in this chapter. Additionally the chapter presents the BFI%, which is a ratio between the filtered base flow component to the total flow component of a streamflow hydrograph and indicates the proportional contribution to total stream flow made by discharges from subsurface water storages (base flow). The chapter further shows the statistical difference between the filtered base flows from all the obsereved stream gauges in the upper Berg Rivercatchment.

5.2 Results on using recursive base flow separation algorithms

The results presented in this section were generated by applying the two chosen filter algorithms (i.e. Chapman and Lynne & Hollick) on Microsoft Excel spreadsheets. Results are presented in composite hydrograph-hyetographs of the selected gauging station and the Assegaaibos rain gauge station for the 2012 to 2014 period.

5.2.1 Separation using Chapman filter algorithm

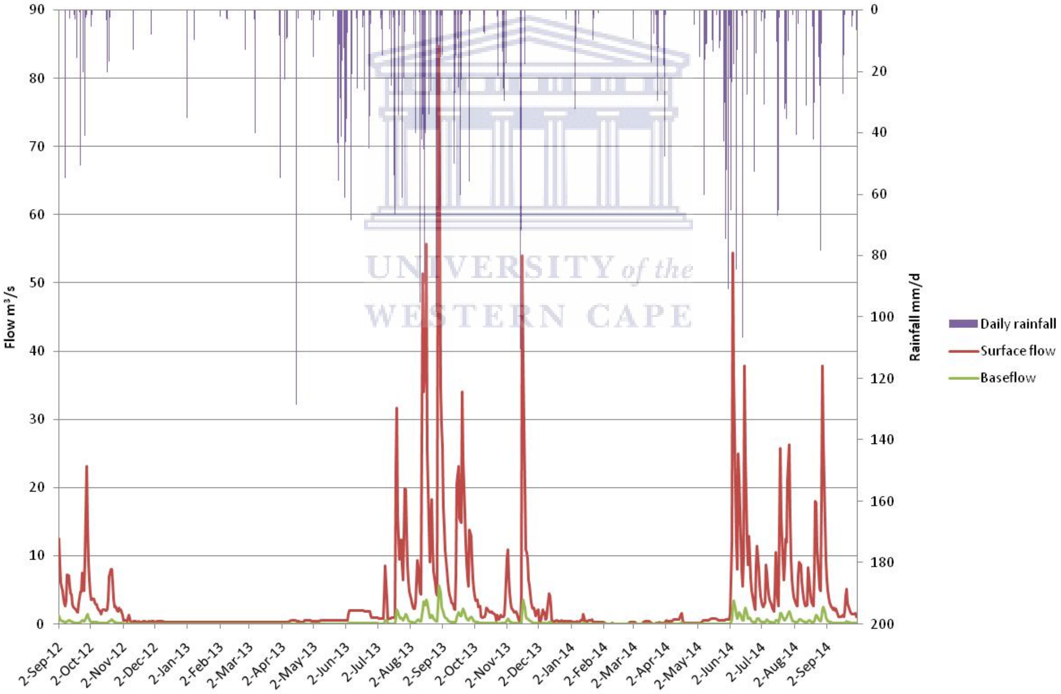


Figure 13: Chapman filtered base flow hydrograph for the Berg River Dam gauging station

Figure 13 illustrates the composite hydrograph-hyetograph for the Berg River Dam gauging station and Assegaaibos rain gauge station. The figure shows the seasonality of river flows and the base flow component from 2012-2014 in response to the seasonal variability in rainfall. The summer period between December and May shows the least flow measured at the gauging station, indicating dry conditions. Flows increase in response to the winter rainfall (May-

September), with a delayed response occurring between September and December. This delay in response to rainfall is indicative of the replenishment of depleted soil moisture in the catchment. At the Berg River Dam gauging station, minimum stream flows as well as base flows were measured during the summer period, where the dam is required to release water to sustain in-stream flow requirements as required by the Water Act (Act 36 of 1998). Flows gradually increase after May, where the winter rainfall begins to increase and stream flow was generally driven by the contribution of meteoric water as opposed to delayed water from sub-surface storages.

Table 2: Descriptive statistics for Berg River Dam gauging station

Statistic	Daily flow	Surface flow	Base flow	BFI (%)
Minimum	0.098	0.090	0.008	3.771
Maximum	90.451	84.727	5.724	29.414
1st Quartile	0.393	0.365	0.028	7.178
Median	0.849	0.797	0.071	7.247
3rd Quartile	3.989	3.680	0.291	7.838
Mean	4.234	3.927	0.307	7.499
Variance (n-1)	73.143	64.077	0.340	2.386
Standard deviation (n-1)	8.552	8.005	0.583	1.545

Table 2 shows the descriptive statistics calculated for the discharges, base flows and BFI computed with the Chapman filtering algorithm. The minimum, maximum and mean discharge obtained were as follows: 0.098m^3/s, 90.541m^3/s, and 4.234m^3/s, respectively. Minimum, maximum and mean base flow obtained were as follows: 0.008m^3/s, 5.724m^3/s, and 0.307m^3/s, respectively. Minimum discharge and base flow were recorded for the summer periods, while the maximum discharges and base flows were measured during the high flow (winter) periods.

As an indicator of the dependancy of stream flows to subsurface derived water, the minimum, maximum and mean Base Flow Index (BFI%) were calculated. Results were 3.771%, 29.414%, and 7.499%, respectively.A high BFI indicates the proportional long-term dependency of stream flows to discharges from subsurface water storages. The mean BFI % of 7.499% indicates that at this site, stream flows are generally 7.45% dependent on discharges from subsurface water storages.

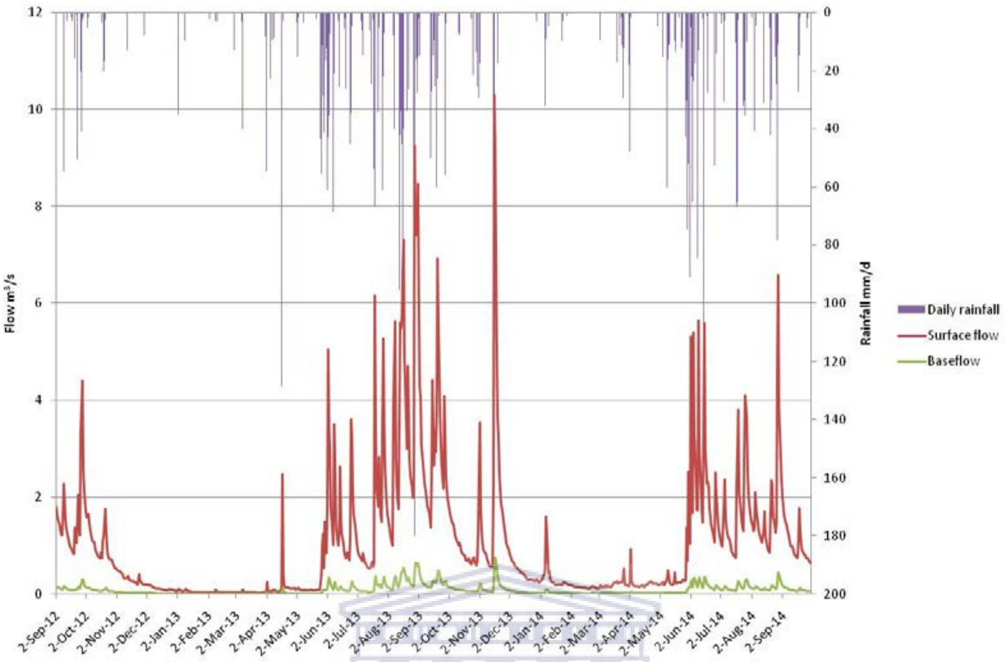


Figure 14: Chapman filtered base flow hydrograph for the Franschhoek River gauging station

The composite hydrograph and hyetograph for the Franschhoek river gauging station and the Assegaaibos rain gauge are illustrated on Figure 14. Flows in this river reflect the influence of alternative sources of water derived from numerous anthopogenic sources. Flows were the highest during the high flow season, while low flows were dominant during periods of low flow. The river flow regime follows the rainfall measured at the Assegaaibos rain gauge, where rainfall increases during the winter season.

Table 3: Descriptive statistics for the Franschhoek River dam gauging station

Statistic	Daily flow	Surface flow	Base flow	BFI (%)
Minimum	0.024	0.022	0.002	3.807
Maximum	10.765	10.293	0.748	21.116
1st Quartile	0.160	0.147	0.012	7.117
Median	0.612	0.563	0.045	7.428
3rd Quartile	1.510	1.383	0.112	7.686
Mean	1.121	1.040	0.081	7.420
Variance (n-1)	2.224	1.939	0.011	1.383
Standard deviation (n-1)	1.491	1.393	0.103	1.176

Descriptive statistics for the Franschhoek River gauging station are shown on Table 3. Minimum, maximum and mean dscharges were 0.024m^3/s, 10.765m^3/s, and 1.121m^3/s, respectively. Minimum, maximum and mean base flows filtered with the Chapman filtering algorithm were 0.0024m^3/s, 0.748m^3/s, and 0.081m^3/s, respctively. The highest measured stream flows were mesaured during August 2013, with the abnormally high flow measured during December 2013. Increase in stream flow during this period of low flow indicate the influence of an additional source of water during an otherwise dry period. The Franschhoek River passess through an area occupied human settlements and agriculture, which contribute susbstantial quantity of water from waste water treatment works and agricultural return flows, among others. The long-term average BFI% calculated for this site was 7.420%. .This stream is influenced by anthropogenic inputs of water, which could impact the response and interpretation of filtered stream flows to discharges from subsurface storages. These components that contribute to stream flow were not measured as part of this study.

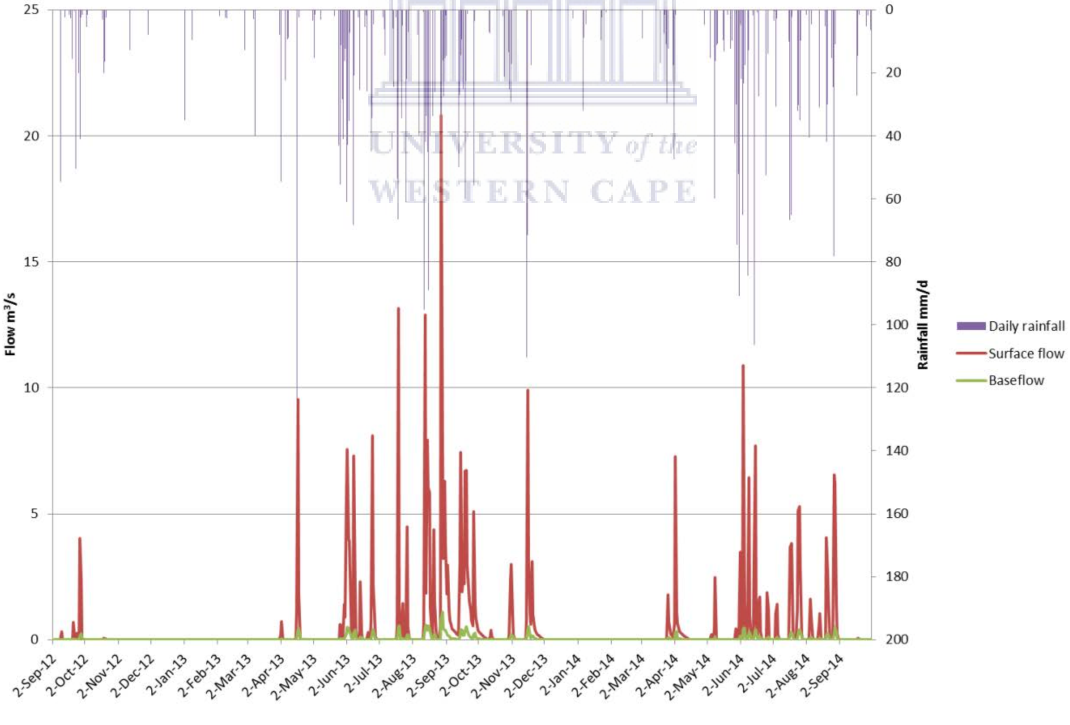


Figure 15: Chapman filtered base flow hydrograph for the Wolwekloof gauging station

The hydrograph for the gauging station situated at the Wolwekloof River is shown in Figure 15. Flows at this gauging station indicate a period where there were no flows. This period occurs during the summer months, where the little quantity of stream flow was diverted to the Inter Basin Transfer Scheme tunnel network for augmenting the water requirements of the greater City of Cape Town and its surrounding agricultural areas. Stream flow increases following rainfall events, primarily during the winter season. Consequently, due to the inability to compute the base flow for the studied period, discriptive and non-parametric statistical analysis was not done for this site. As previously stated, this gauging station only measures flow during high flow periods, as flow is consistently diverted at this station.

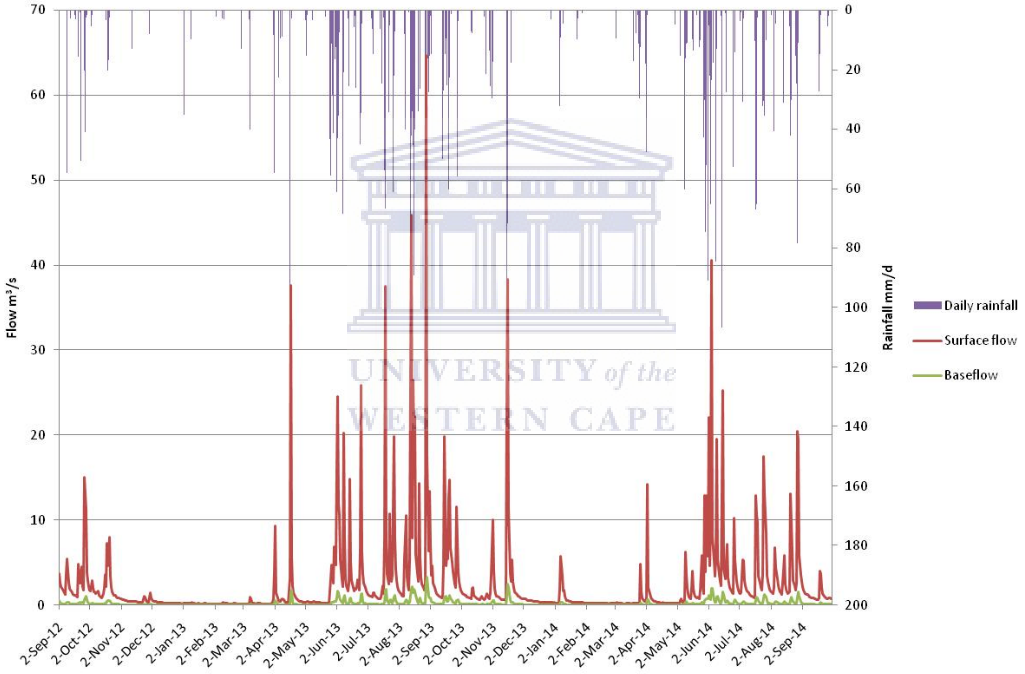


Figure 16: Chapman filtered base flow hydrograph for the Berg River inlet gauging station

Figure 16illustrates the hydrograph for the gauging station located at the inlet to the Berg River Dam. Flows measured at this site indicate a situation where there were no artificial inputs of water into the stream. The seasonality of stream flow is clear, with high flows following the rainfall pattern. Minimum, maximum, and mean flows obtained were 0.1m^3/s, 67.354m^3/s, and 2.739m^3/s, respectively (Table 4).

Table 4: Descriptive statistic for Berg River dam inlet gauging station

Statistic	Daily flow rate	Surface flow	Base flow	BFI (%)
Minimum	0.100	0.092	0.008	3.701
Maximum	67.354	64.819	3.186	23.301
1st Quartile	0.266	0.249	0.019	7.152
Median	0.886	0.823	0.067	7.527
3rd Quartile	2.387	2.169	0.197	8.084
Mean	2.730	2.532	0.198	7.798
Variance (n-1)	32.943	29.602	0.125	5.019
Standard deviation (n-1)	5.740	5.441	0.354	2.240

High flows occur during the winter, with the highest recorded flow occurring during August 2013. The Minimum, maximum, and mean flows calculated were 0.1m^3/s, 67.354m^3/s, and 2.73m^3/s, respectively. The mean BFI of this stream to discharges from subsurface water storages was 7.798%, which indicates a base flow dominant stream driven by discharges from subsurface water storages for 7.798% of the total flows during 2012-2014.

5.2.2 Separation using Lynne and Hollick filter algorithm

Filtered base flow, discharge, and rainfall for the Berg River Dam gauging station are presented on Figure 17. The graph shows that stream discharge follows the rainfall pattern, with the filtered base flow mimicking the discharge, but at a lower rate. Stream flow and discharge are relatively similar during the summer months where the contribution from direct precipitation is negligible. Thus, the proportion of base flows to total flows gauged during such periods is more significant to maintaining dry season flows as opposed to the wet season.

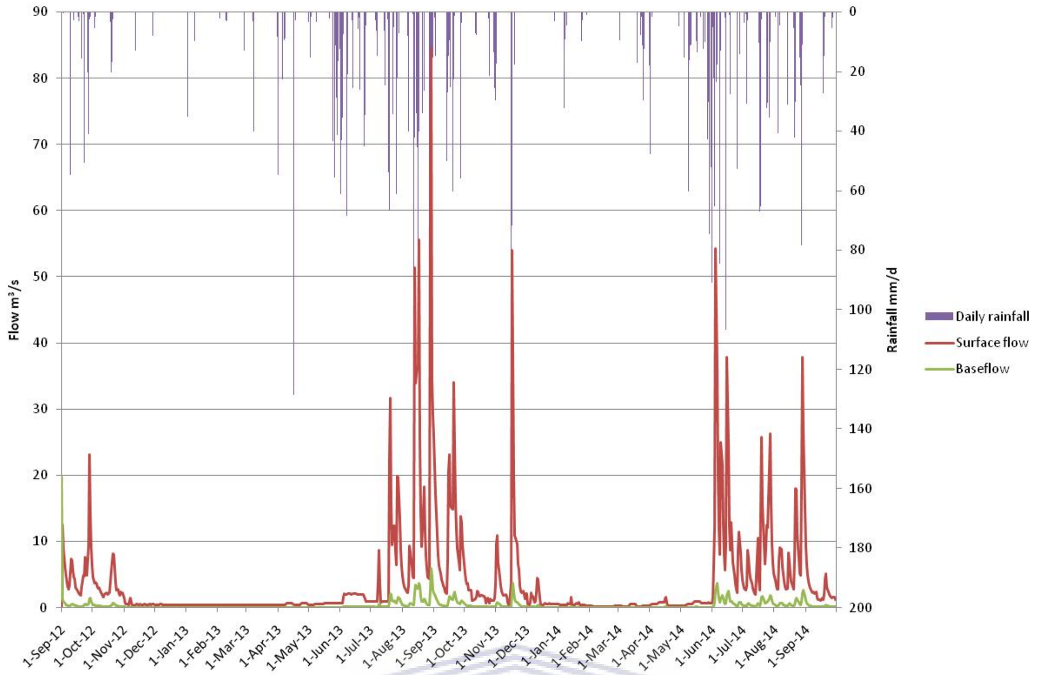


Figure 17: Lynne &Hollick filtered base flow hydrograph for the Berg River Dam gauging station

Minimum, maximum, and mean discharge measured at the Berg River Dam gauging station are presented in section 4.2.1, while the base flow filtered with the Lynne and Hollick filter algorithm is present in this section. Minimum, maximum, and mean filtered base flows are illustrated on Table 5as 0.008m^3/s, 5.939m^3/s, and 0.318m^3/s, respectively. The mean ratio of filtered base flow to total discharge (BFI) was 7.780%, indicating that a proportion of stream flow measured at this station was derived from subsurface water storages.

Table 5: Descriptive statistics for Berg River dam gauging station

Statistic	Daily flow	Surface flow	Base flow	BFI (%)
Minimum	0.098	0.090	0.008	3.913
Maximum	90.451	84.512	5.939	30.517
1st Quartile	0.393	0.364	0.029	7.448
Median	0.880	0.795	0.073	7.518
3rd Quartile	3.996	3.668	0.302	8.132
Mean	4.254	3.915	0.318	7.780
Variance (n-1)	73.366	63.750	0.366	2.568
Standard deviation (n-1)	8.565	7.984	0.605	1.603

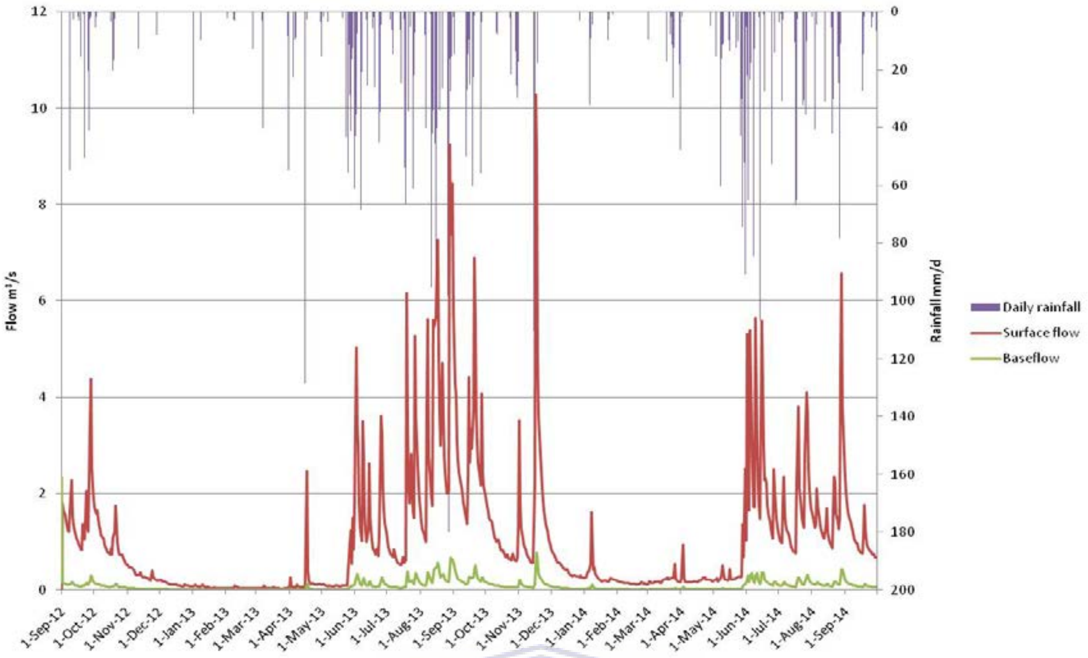


Figure 18: Lynne &Hollick filtered base flow hydrograph for the Franschhoek River gauging station

Base flow filtered using the Lynne and Hollick filter algorithm is illustrated on the Franschhoek River gauging station hydrograph (Figure 18). Base flow is shown to comprise a substantial proportion of stream flow during high flow periods, with a significant contribution during periods of low flow. Minimum, maximum, and mean filtered base flows are illustrated in Table 6 as 0.002m3/s, 0.562m3/s, and 0.063m3/s, respectively. The mean Base Flow Index was 7.708, indicating that the stream had a 7.708% dependence on discharges from subsurface water storages.

Table 6: Descriptive statistic for Franschhoek River gauging station

Statistic	Surface flow	Surface flow	Base flow	BFI (%)
Minimum	0.022	0.022	0.002	3.949
Maximum	10.275	7.273	0.562	21.908
1st Quartile	0.147	0.064	0.005	7.350
Median	0.561	0.205	0.017	7.729
3rd Quartile	1.378	1.084	0.092	8.020
Mean	1.037	0.780	0.063	7.708
Variance (n-1)	1.929	1.407	0.008	1.817
Standard deviation (n-1)	1.389	1.186	0.091	1.348

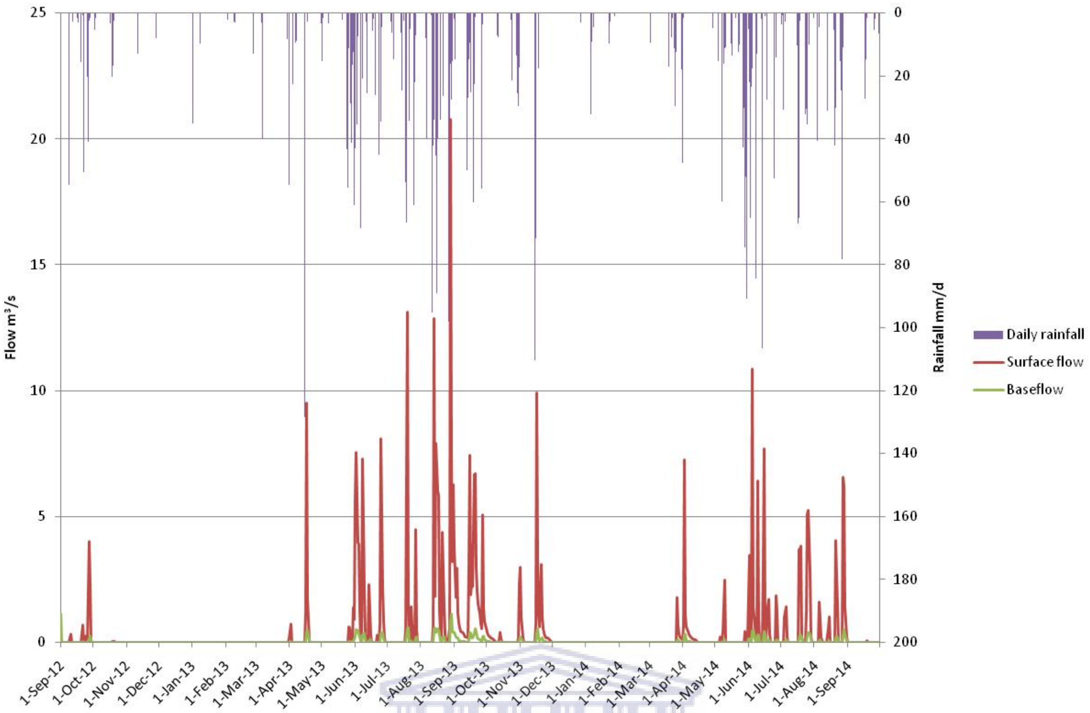


Figure 19: Lynne and Hollick filtered base flow hydrograph for the Wolwekloof gauging station

As stated in section 4.2.1, flows at the Wolwekloof gauging station have been altered by the diversion of water to augment the water supply for the City of Cape Town and its surrounding agricultural areas. Similarly, to the filtering with the Chapman algorithm, the Wolwekloof site computed values that were undefined and thus could not be used for descriptive and non-parametric statistical analysis.

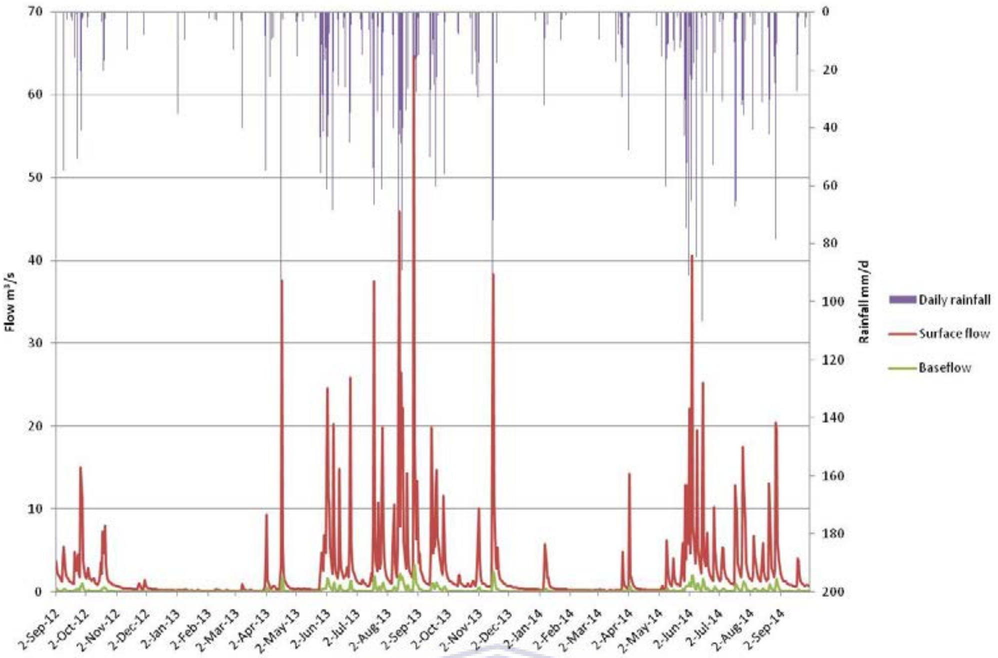


Figure 20: Lynne and Hollick filtered base flow hydrograph for the Berg River Dam inlet gauging station

The hydrograph for the gauging station situated at the inlet to the Berg River Dam is shown in Figure 20. Tables 7 illustrate the minimum, maximum, and mean filtered base flow, as 0.008m3/s, 3.306m3/s, and 0.205m3/s, respectively. The mean BFI was computed to 8.091%, indicating high natural dependence on discharges from subsurface water storages compared to the other gauging stations at which base flows were separated from total stream flows during 2012-2014.

Table 7: Descriptive statistics for Berg River Dam inlet gauging station

Statistic	Daily flow	Surface flow	Base flow	BFI (%)
Minimum	0.100	0.092	0.008	3.840
Maximum	67.354	64.724	3.306	24.175
1st Quartile	0.266	0.248	0.020	7.420
Median	0.886	0.820	0.069	7.809
3rd Quartile	2.387	2.163	0.204	8.387
Mean	2.730	2.525	0.205	8.091
Variance (n-1)	32.943	29.482	0.135	5.402
Standard deviation (n-1)	5.740	5.430	0.367	2.324

5.3 Sample characteristics of computed Base Flow Indices

Shapiro-Wilk’s normality tests were conducted in the computed BFI’s for the three gauging stations (i.e. G1H076, G1H077, and G1H003). The fourth gauging station (G1H038) was omitted from statistical analysis, due to computational errors produced by missing data and incomputable values generated. Consequently, information on the three stream gauging sites is represented below.

A Shapiro-Wilk’s tests ($p>0.05$) conducted on resultant BFI% values and visual inspection of their histograms, normal Q-Q plots and Box plots was conducted and showed that the BFI% values computed for G1H076, G1H077, and G1H003 were not normally distributed with skewness values of5.17, 2.85, and 3.15, respectively. Kurtosis values for the same sampled sites were 61.41, 14.45, and 32.35, respectively. The computed standard errors for the three sites were 0.056,0.081 and, 0.042 respectively. The above-mentioned values were used to compute the z-values for the respective sites. According to Kim, (2013) the critical values for rejecting the null hypothesis need to be different according to the sample size as follows:

1. For small samples ($n< 50$), if absolute z-scores for either skewness or kurtosis are larger than 1.96, which corresponds with an alpha level 0.05, then reject the null hypothesis and conclude the distribution of the sample is non-normal.
2. For medium-sized samples ($50 <n< 300$), reject the null hypothesis at absolute z-value over 3.29, which corresponds with an alpha level 0.05, and conclude the distribution of the sample is non-normal.
3. For sample sizes greater than 300, depend on the histograms and the absolute values of skewness and kurtosis without considering z-values. Either an absolute skew value larger than 2 or an absolute kurtosis (proper) larger than 7 may be used as reference values for determining substantial non-normality.

The data utilized and computed as BFI in this chapter all abided by the fourth stipulation as documented by Kim, (2013) and all had z-values greater than the required 2 and 7 for the skewness and kurtosis, respectively.

5.4 Non-parametric description of groundwater contribution to stream flow

The current chapter aimed to illustrate the proportionate dependence of stream flows to discharge from subsurface water storages in the upper Berg River catchment. Additionally, the proportions derived with the two distinct filter algorithms indicate that there was no difference between them. However, because the stream flow and resultant separated base flow data do not follow a normal distribution, this chapter sought to find statistical differences between sites and between the two filter algorithms. To this end, Kruskal-Wallis tests were conducted for all of the sites (except Wolwekloof) to identify the source of difference in results, if there was any (Ramsey 2000). Using the Dunn (1963) approach to identify the source of null hypothesis rejection, it was apparent that from the three compared sites, G1H076 statistically differed from the other two sites (G1H077 and G1H003). Table 8 shows the correlation of the p-values computed using the two different filter algorithms for the three gauging station in the upper Berg River catchment. The table shows that for both the Lynne & Hollick and Chapman filter algorithms, the two sites, i.e. G1H077 and G1H003 had no significant difference between them, while the site located at the inlet to the Berg River dam (G1H076) was dissimilar to the other sites in the catchment.

Table 8: P-values computed using Kruskal-Wallis tests for the three gauging stations

p-values:

	Chapman G1H077	Chapman G1H076	Chapman G1H003	LnH G1H077	LnH G1H076	LnH G1H003
Chapman G1077						
Chapman G1076	**< 0.0001**					
Chapman G1003	0.307	**< 0.0001**				
LnH G1077	**< 0.0001**	0.012	**< 0.0001**			
LnH G1076	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**		
LnH G1003	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.143	0.005	1

Table 9: Correlation (Significant differences) between sites and filter algorithms

Significant differences:	Chapman G1H077	Chapman G1H076	Chapman G1H003	LnH G1H077	LnH G1H076	LnH G1H003
Chapman G1077						
Chapman G1H076	**Yes**					
Chapman G1H003	No	**Yes**				
LnH G1077	**Yes**	No	**Yes**			
LnH G1H076	**Yes**	**Yes**	**Yes**	**Yes**		
LnH G1H003	**Yes**	**Yes**	**Yes**	No	No	

Table 9 explains the significant differences between the sites and filter algorithms. This table shows that for both the Lynne & Hollick and Chapman algorithms, the sites located along the Franschhoek River and below the Berg River Dam had no significant difference between them, even though the input data was different. The site located at the inlet of the Berg River dam was noted to have significant difference. Furthermore, comparing the results of the two filter algorithms showed that there was significant ($p<0.0001$) differences between the filtered base flows at the same sites. Significant differences between sites were not as great, however, between the two filter algorithms, they were significant ($p<0.0001$).

5.5 Seasonal differences in base flow contribution

Table 10 shows the mean BFI% computed for the different gauging stations in the upper Berg River catchment from 2012-2014. The table shows the seasonal averages of BFI% contribution to stream flow. The G1H076 site situated above the Berg River dam had the highest seasonal mean BFI% for the 2013 dry season and 2014 wet season, indicating that base flow discharges were greatest during these times in the data record. However, the mean BFI% computed for all the sites during the respective seasons had no significant differences between each other, as they all ranged between 7%-8%.

Table 10: Chapman algorithm separated mean BFI% by season

Season	BFI (%) G1H077	BFI (%)G1H076	BFI (%)G1H003
2012 D mean	7.569	7.678	7.395
2013 W mean	7.236	7.315	7.322
2013 D mean	7.468	8.090	7.488
2014 D Mean	7.659	7.660	7.409
2014 W mean	7.519	8.009	7.428

Table 11 shows the mean computed BFI% for the period 2012-2014. The table shows the BFI% according to the gauging station and respective seasons. Similar to the seasonal mean BFI% computed using the Chapman filtering algorithm, the Lynne and Hollick algorithm computed high BFI% for the 2013 dry season and 2014 wet season. However, the general differences between the different seasons was insignificant as BFI% ranged between 7%-8%, which was similar to the Chapman filtering algorithm. Thus, form the two tables above, it can be suggested that discharges from subsurface water storages contribute on average 7%-8% of the total gauged stream flows.

Table 11: Lynne and Hollick algorithm separated mean BFI% by season

Season	BFI (%) G1H077	BFI (%)G1H076	BFI (%)G1H003
2012 D mean	7.85	7.97	7.67
2013 W mean	7.51	7.59	7.60
2013 D mean	7.75	8.39	7.77
2014 D Mean	7.95	7.95	7.69
2014 W mean	7.80	8.31	7.71

5.6 Results discussion of groundwater contribution to stream flow

This chapter addressed the first objective, which was to determine the quantity of exchange fluxes between groundwater and surface water by using automated base flow separation techniques. It was argued that use of automated base flow separation to determine amount of stream flow originating from subsurface water storages is a feasible, practical and objective method for determining the contribution of discharges from subsurface water storages to total stream flows in the upper Berg River catchment. The current study found that using the Chapman filter algorithm, mean contributions from subsurface water storages to stream flows in the selected stream gauging stations in the upper Berg River catchment ranged between 7.499% and 7.798% of total stream flows gauged during 2012-2014. The Lynne and Hollick filter algorithm provided similar results with base flow contributions ranging between 7.78%-8.091% of total stream flows gauged. It should be noted from the hydrographs, the Wolwekloof gauging station had the least contribution from subsurface water storages due to the impacts of the stream flow diversion at this site to augment the Inter Basin Transfer Scheme. The greatest proportion of base flow contributions to stream flows was during the rainy season. However, due to the influence of direct precipitation, these contributions were negligible during such periods because the streams in this catchment respond quickly to precipitation inputs.

Furthermore, as indicated in the Berg River Baseline Report (Ractliffe, Geordie, 2007), the upper Berg River catchment is dependent on discharges from subsurface water storages to maintain dry season stream flows and wetland levels. In a previous study conducted in the upper Berg River catchment, Ratcliffe, (2009) found that the contribution of base flows to flood peaks were equal to an average 4.2%. This finding illustrated the dependency of the upper Berg River catchment and its streams on discharges from subsurface water storages, which is confirmed further by the results of the present study, which indicate reliance (of up to 8% of total stream flows) on these subsurface water discharges during dry periods.

Considering previous predictions that the damming of the Berg River in its upper reaches would hinder the flow regime of the river, the percentage contribution was expected to exhibit a decline from the 4.2% during low flow periods. However, the results of the present study indicate that the impact of the dam, the Inter-Basin Transfer Scheme as well as additions to stream flows from urban storm water runoff have influenced the base flow contribution at the Berg River Dam and

Franschhoek River gauging sites (BFI=7.778% and 7.708%). However, as with the Wolwekloof gauging station, discharges from artificial sources and abstractions of water from the stream affect the Berg River Dam and Franschhoek River gauging stations, thus altering the natural base flow contribution to total stream flows gauged at these sites.

In a comparative study done in the upper Modder River catchment, Welderufael & Woyessa, (2010) report that base flow contribution to stream flow computed using the Chapman and Lynne and Hollick filter algorithms was 65% and 67% for 1999, respectively. Contributions of 65% and 66% were computed for the year 2000, using the two filter algorithms. Comparing the use of the Chapman and Lynne &Hollick filter algorithms, Welderufael & Woyessa, (2010) found that both the Chapman and Lynne & Hollick algorthims provided reasonable estimates of the base flow component of stream flows in the Modder River. These two methods, along with the Flow Duration Curve analysis, provided base flow contribution values in the the same order of magnetuded (Welderufael & Woyessa, 2010). The study also concluded that it was advisable to use a calibrated physically based model which is able to differentiate between the actual sources of base flow in addition to their quantification. However, to answer the question of how exchange fluxes between groundwater and surface water affect the quantity of water in the upper Berg River catchment, the use of simple filter algorithms was sufficient to confirming the rivers depenancy of the to discharges from subsurface water storages.

Although Chapman, (1999) notes that two parameter filter algorithms provide plausable estimates of base flow discharges and that the use of one parameter and three parameter filter algorithms (such as the ones chosen in the current study) can result in over- and/or underestimation of the base flow contribution to total stream flow, Arnold & Allen, (1999) oppose that the application of digital filter algorithms gives reasonable estimates of groundwater (subsurface water) discharges to streams, when using monthly stream flow data. Thus, investigating their use for separating daily stream flows was also practical.

Using a modified one parameter algorthim, Smakhtin, (2001) evaluated its use for estimation of base flow contribution from monthly stream flow data and concluded that the groundwater (subsurface water) contribution to ecological reserve could be estimated. The present study shows that although they have no hydrological foundation (Brodie & Hostetler, 2005), the use of these filter algorithms can yield reliable estimates of subsurface water discharges to stream flow and thus quantify the depenancy of a river to such discharges. In the current study the objective was to quantify the amount of water derived from subsurface water storages and thus used the digital filter method, which is replicable and provides reasonable estimates of base flow discharges in order to assess the dependancy of streams to discharges from subsurface water storages (Hughes, et al., 2003).

Brodie & Hostetler, (2005) reviewed the techniques used for analyzing base flow from stream flow hydrographs and noted that the analysis of base flow was a valuable strategy in understanding the dynamics of groundwater discharge to streams. However, Brodie & Hostetler, (2005) emphasize that the assumption that base flow directly equates to groundwater discharge was invalid and that further tracer analysis should be done to confirm the source of water that was termed “base flow”. The present study considered base flow as the culmination of water discharged from subsurface water storages and thus did not evaluate the exact source of base flow. The current study was limited by the inability to discern the actual origin of base flow discharges in the upper Berg River catchment. However, this approach facilitated the quantification of the amount of water discharged from subsurface water storages.

The current study shows that base flow discharge play an important role in maintaining stream flows. However, further work is required to ascertain the exact source of base flow and assess the influences of the diversions, releases, and discharges from human settlements on stream flows in the catchment, through the comparative analysis of temporal and spatial tracer variations in groundwater, stream water and other surficial derived water.

5.7 Summary of chapter

In summary, the present chapter provided an indication of the dependancy of stream flows to discharges from subsurface water storages in the upper Berg River. However, this dependancy is also indicative of the influences of water derived from other sources such as storm water, stream flow diversions and irrigation return flows. This chapter illustrated the use of one parameter digital filter alogorithms as a practical tool to determine the percentage contribution to stream flows from base flows in upland catchments with a percieved natural flow regime. However, following the identification of a suit of influencial factors to stream flow in the upper Berg River catchment, it is apparent that apart from “true” base flow, artificially derived water plays an important role in mainataining flows during dry periods. Thus, it is important to understand how these artificial water sources influence the amount of water in the streams as well as the quality thereof. Furthermore, the present chapter showed how upland catchment stream flows can exhibit varying conditions, from natural to impacted. This is dependant on the level of human activity in the catchment and thus shows that such areas should be conserved and kept as natural as possible to enable the natural water systems to contribute to replenishing themselves.

Due to the cost and complexity implications of other automated physically based filter approaches, the use of one parameter seperation algorithms has been shown to be effective in defining the base flow contribution to stream flows, although it cannot differentiate between the sources of water classified as base flow. The objective of quantifying exchange fluxes using this approach was fullfilled by indicating the proprtional contribution made by subsurface water discharges to stream flows.The present study has shown that the upper Berg River catchment is moderately dependent on discharges from subsurface storages, however, the implications of such a dependancy are unknown with regards to the extent to which these discharges may dilute contaminated surface waters they discharge into.

Chapter 6: Hydrochemical characterization of groundwater and surface water

6.1 Introduction

The current chapter presents and discusses findings from the hydrochemical analysis of groundwater and surface water in the upper Berg River catchment.The chapter aims to characterize and compare the physicochemical parameters of groundwater and surface water in order to determine interactions between groundwater and surface water.The chapter argues that the interaction between groundwater and surface water can reduced concentrations of dissolved substances reported in the streams draining the upper Berg River catchment.

This chapter addresses the second objective,which was to characterize the quality of groundwater and surface water in order to identify the major factors controlling it, using *in situ* and hydrochemical analyses methods. Furthermore, the chapter assumes that by statistically assessing the physicochemical characteristics of groundwater and surface water, the dominant factors affecting the quality of groundwater and surface water can be determined.

In achieving this objective, characterization of groundwater and surface water hydrochemistry was done using a Piper Diagram and correlations between the physiochemical properties of groundwater and surface water were established using Principal Component Analysis and Hierarchical Cluster Analysis. Thereafter, the major factors governing the hydrochemistry of both groundwater and surface water were ascertained using Principal Component Analysis; and similarities in physicochemical characteristics between groundwater and surface water were used to cluster sampled sites into clusters based on their physiochemical similarities using Cluster Analysis.

6.2 General hydrochemical classification of groundwater and surface water

Table12 shows the concentrations (in mill-equivalents per liter), charge balance, and Sodium Absorption Ratio (SAR) for the major ions in groundwater (borehole) samples in the upper Berg River catchment. The physicochemical water quality indicators of groundwater and surface water determined by *in situ* and laboratory analysis are presented in the appendices. The descriptive statistical summary of the physicochemical parameters of groundwater-surface water for the upper Berg River catchment for 2014 are presented in Table 13. The distribution of the physical water quality parameters was influenced by the instrumentations detection limits and field re-calibration procedure. Because low salinity and TDS were expected from the literature survey, a low conductivity and TDS were expected to be measured at the sites in the upper Berg River catchment. However, upon measurement, unexpected rises in salinity at Lavenir BH3 and Tsherigma indicated an unusual level of salinity in the catchment, although it remained below DWS target water quality guidelines for irrigation water use (DWAF, 1996).

The Piper diagrams (Figure 21and 22), plotted using Aquachem™ software, were used to examine the predominant groundwater and surface water interaction in the study area. The Piper diagrams shows that the predominant interaction in ground and surface water in the study area are Na-Cl, with significant slight inputs of Ca and HCO_3^-, causing variation among samples. The concentration trends of major ions in both groundwater and surface water are Cl^->HCO_3^->SO_4^- >NO_3^- for anion and Na^+>Ca^{2+}>Mg^{2+}>K^+. Figure 21, shows that the dominant water type is Na-Ca-HCO_3—Cl and that there are some areas with relatively higher concentrations of HCO_3, NH_4 and NO_3. According to Younger, (2007), various possiblities for the sources of NaCl can be derived, however based on the geographical location in question, researchers should look at the catchment physiographical environment to determine the most approriate source of NaCl in natural waters. Among the various possibilities, the Na-Cl water type in this catchment still refers to saline water as possible source. However, the samples that fell in the left quadrant of the diamond on the Piper Diagram, reveal that the water is Ca-HCO_3^-type, indicating the presence of shallow fresh groundwater. The Sodium Absorption Ratios computed for the sites ranged between 0.485 and 1.923 for the 34 groundwater and surface water sampling sites in the upper Berg River catchment. Ninety-one percent of the sampling sites (31/34) were all below the of DWS target water quality guidelines of SAR<2.0 (DWAF, 1996), while 9% (3/34) sites fell above the DWS target water quality guidelines for SAR (Table 12).

Table 12: Charge Balance Error and Sodium Absorption Ratio for all upper Berg River catchment groundwater and surface water sites

Origin	Na+	K+	Ca+	Mg+	Cl-	HCO3-	SO4-	P-	NH4-N+	NO3-N-	F-	sum+-	sum+	sum-	SAR	SAR<2meq/L	charge balance error	CAB<15%
BG21	0.174	0.005	0.010	0.066	0.324	0.013	0.021	0.0003159	0.185	0.015	0	0.813	0.440	0.374	0.894	√	4.06	√
BG33	0.496	0.005	0.025	0.132	0.756	0.010	0.021	0	0.111	0	0	1.556	0.769	0.787	1.772	√	-0.57	√
BG34	0.305	0.003	0.090	0.041	0.505	0.013	0.062	0	0.081	0	0	1.100	0.519	0.581	1.190	√	-2.79	√
BG35	0.365	0.003	0.020	0.099	0.575	0.010	0.021	0	0.061	0	0	1.154	0.548	0.606	1.500	√	-2.53	√
BG35.2	0.257	0.043	0.080	0.074	0.432	0.013	0.042	0.0003159	0.058	0.00097	0	1.000	0.512	0.488	0.925	√	1.21	√
BG36	0.204	0.003	0	0.049	0.347	0.015	0.021	0	0.043	0	0	0.682	0.300	0.383	1.301	√	-6.07	√
BG44	0.226	0.005	0.030	0.082	0.313	0.015	0.021	0.0003159	0.042	0	0	0.735	0.386	0.349	0.955	√	2.50	√
BG46	0.370	0.003	0	0.082	0.564	0.018	0.021	0	0.047	0	0	1.104	0.501	0.603	1.823	√	-4.61	√
BG51	0.196	0.010	0.040	0.058	0.299	0.010	0.021	0	0.078	0	0	0.711	0.381	0.330	0.886	√	3.63	√
BG00158	0.157	0.003	0.010	0.041	0.288	0.012	0.021	0.0002106	0.031	0	0	0.562	0.241	0.321	0.979	√	-7.06	√
BG37	0.526	0.003	0.005	0.115	0.767	0	0.062	0	0.041	0	0	1.520	0.690	0.830	2.147	X	-4.59	√
BG38	0.579	0.003	0	0.148	0.852	0.008	0.042	0	0.038	0.00065	0	1.669	0.767	0.902	2.126	X	-4.05	√
BG50	0.500	0.023	0.015	0.107	0.638	0.013	0.042	0	0.070	0.0361	0	1.444	0.715	0.728	2.026	X	-0.46	√
RV2	0.278	0.008	0.060	0.074	0.457	0.013	0.021	0.0003159	0.029	0	0	0.940	0.449	0.491	1.076	√	-2.25	√
Burgundy- Borehole 1	0.661	0.020	0.489	0.173	0.815	0.642	0.042	0.0009477	0.031	0.038228	0.005264	2.918	1.375	1.544	1.149	√	-2.90	√
Burgundy- Fountain	0.278	0.013	0.145	0.107	0.375	0.284	0.021	0	0.030	0.018550	0.010528	1.282	0.573	0.709	0.785	√	-5.30	√
Holden Manz- B/H 2	0.513	0.020	0.489	0.099	0.355	0.992	0.042	0.0006318	0.032	0.002903	0.021056	2.567	1.154	1.413	0.947	√	-5.05	√
Holden Manz- B/H 3	0.374	0.015	0.369	0.107	0.355	0.698	0.042	0	0.030	0.004033	0.010528	2.006	0.896	1.110	0.767	√	-5.34	√
Holden Manz- Produc.	0.248	0.010	0.150	0.066	0.344	0.272	0.021	0.001	0.030	0.014840	0.005264	1.162	0.504	0.658	0.755	√	-6.63	√
Lacombie	0.513	0.013	0.559	0.115	0.409	0.905	0.021	0.0041067	0.029	0.005807	0.015792	2.589	1.229	1.360	0.884	√	-2.53	√
Lavenir- Borehole 1	0.696	0.015	0.644	0.132	0.731	1.046	0.021	0.0025272	0.033	0.006291	0.031584	3.358	1.520	1.838	1.118	√	-4.73	√
Lavenir- Borehole 2	0.692	0.015	0.514	0.115	0.722	0.675	0.021	0.0015795	0.026	0.014194	0.010528	2.806	1.362	1.445	1.233	√	-1.48	√
Lavenir- Borehole 3	1.079	0.018	1.078	0.296	1.473	1.123	0.042	0.0028431	0.027	0.005162	0.015792	5.158	2.497	2.661	1.302	√	-1.58	√
Stonybrook	0.548	0.013	0.818	0.140	0.513	1.069	0.083	0.0034749	0.041	0.002903	0.015792	3.248	1.560	1.688	0.792	√	-1.96	√
Tsherigma	1.118	0.020	0.639	0.272	1.402	0.774	0.104	0.0015795	0.024	0.027098	0.015792	4.397	2.073	2.324	1.657	√	-2.85	√
Bordeaux	0.2088	0.010232	0.25948	0.090519	0.344162	0.447447	0.02082	0	0.0322451	0.0003226	0.005264	1.4192917	0.6012761	0.8180156	0.499	√	-7.64	√
3 Streams	0.2436	0.01279	0.18962	0.057603	0.355446	0.358941	0.02082	0.0006318	0.0266856	0.0017743	0.010528	1.2784397	0.5302986	0.7481411	0.693	√	-8.52	√
3 Streams- Salm+ Tr.	0.19575	0.007674	0.06986	0.049374	0.344162	0.152427	0.02082	0	0.0244618	0.0027421	0.015792	0.8830629	0.3471198	0.5359431	0.802	√	-10.69	√
G1H0003	1.222	0.171	0.594	0.214	1.168	1.552	0.250	0.0322218	1.112	0.00790	0	6.323	3.313	3.010	1.923	√	2.40	√
Morrisons	0.600	0.074	0.304	0.156	0.496	0.677	0.104	0.0186381	0.318	0.01581	0	2.765	1.453	1.312	1.251	√	2.55	√
BG51 stream	0.187	0.005	0.015	0.049	0.313	0.013	0.021	0	0.063	0	0	0.667	0.320	0.347	1.043	√	-2.04	√
Franschhoe above WWTW	0.174	0.013	0.070	0.049	0.212	0	0.052	0.0015795	0.006	0.001613	0	0.578	0.312	0.267	0.713	√	3.87	√
Berg River	0.1218	0.007674	0.08483	0.041145	0.155155	0	0.029148	0.0015795	0.0055595	0.001613	0	0.448504	0.2610085	0.1874955	0.485	√	8.20	√
Franschoek River below bridge	0.6525	0.066508	0.33433	0.16458	0.64883	0	0.13533	0.009477	0.0211261	0.035486	0	2.0681671	1.2390441	0.829123	1.306	√	9.91	√
Confluence of Berg and Franschoek River	0.5655	0.05116	0.2495	0.131664	0.5642	0	0.127002	0.0123201	0.0055595	0.022582	0	1.7294876	1.0033835	0.7261041	1.295	√	8.02	√
Franschoek below WWTW	0.5655	0.046044	0.34431	0.172809	0.62062	0	0.085362	0.0044226	0.0055595	0.001613	0	1.8462401	1.1342225	0.7120176	1.112	√	11.43	√
Stibeuel river on Main road to Franshoek	0.6525	0.058834	0.38423	0.148122	0.53599	0	0.15615	0.0101088	0.133428	0.041938	0	2.1213008	1.377114	0.7441868	1.265	√	14.92	√

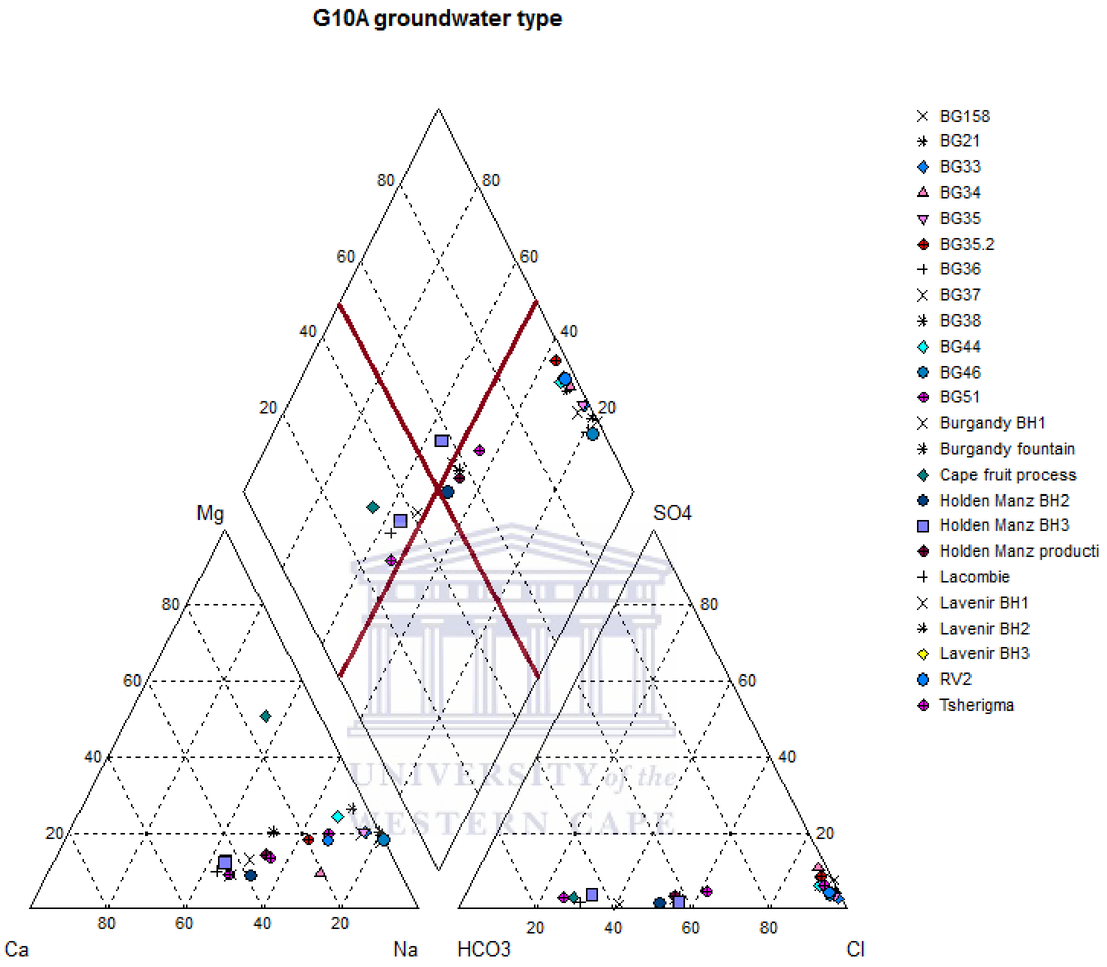


Figure 21: Typical water type of groundwater in the upper Berg River catchment

Figure 21 shows the Piper Diagram for groundwater in the upper Berg River catchment. The diagram shows that the dominant groundwater types in the upper Berg River catchment are Na-Ca-HCO_3^--Cl. This water type is reflective of mixing waters from more than one quadrant on the diamond in the Piper diagram. The plotting of groundwater sampling sites on the left-hand quadrant indicates the presence of shallow, recently recharged groundwater with a markedly higher dominance of Ca and HCO_3^- (i.e. Holden Manz BH3 and BH2, Lacombie, and Lavenir BH1). However, due to their inability to comply with the limits of the cation-anion charge balance, 3 Streams fountain, 3 Streams Salm.Tr, 3 Streams, Bordeaux, and Stonybrook were not interpreted as part of the viable groundwater hydrochemical data. In addition, the rest of the sampling sites, which were a greater number of sampling sites, plotted on the right-hand quadrant, which is indicative of Na-Cl type waters. Such waters are primarily derived from the saltwater intrusion to groundwater, weathering of geological material and anthropogenic inputs. However, the concentrations of these ions in groundwater were below DWS target water quality guidelines for irrigation (DWAF, 1996)

The dominance of the dissolution of halite (NaCl) indicates that there is an input of NaCl into groundwater from one of the abovementioned sources. Due to the locality of the upper Berg River catchment, relative to the sea and the dominant presence of chemically inert quartzitic sandstones, the inputs of NaCl from anthropogenic sources is most applicable in this catchment. However, the current study did not seek to identify the sources of NaCl in groundwater in the upper Berg River catchment, but this condition creates suspicion about the activities occurring in the catchment and their possible impact on groundwater quality.

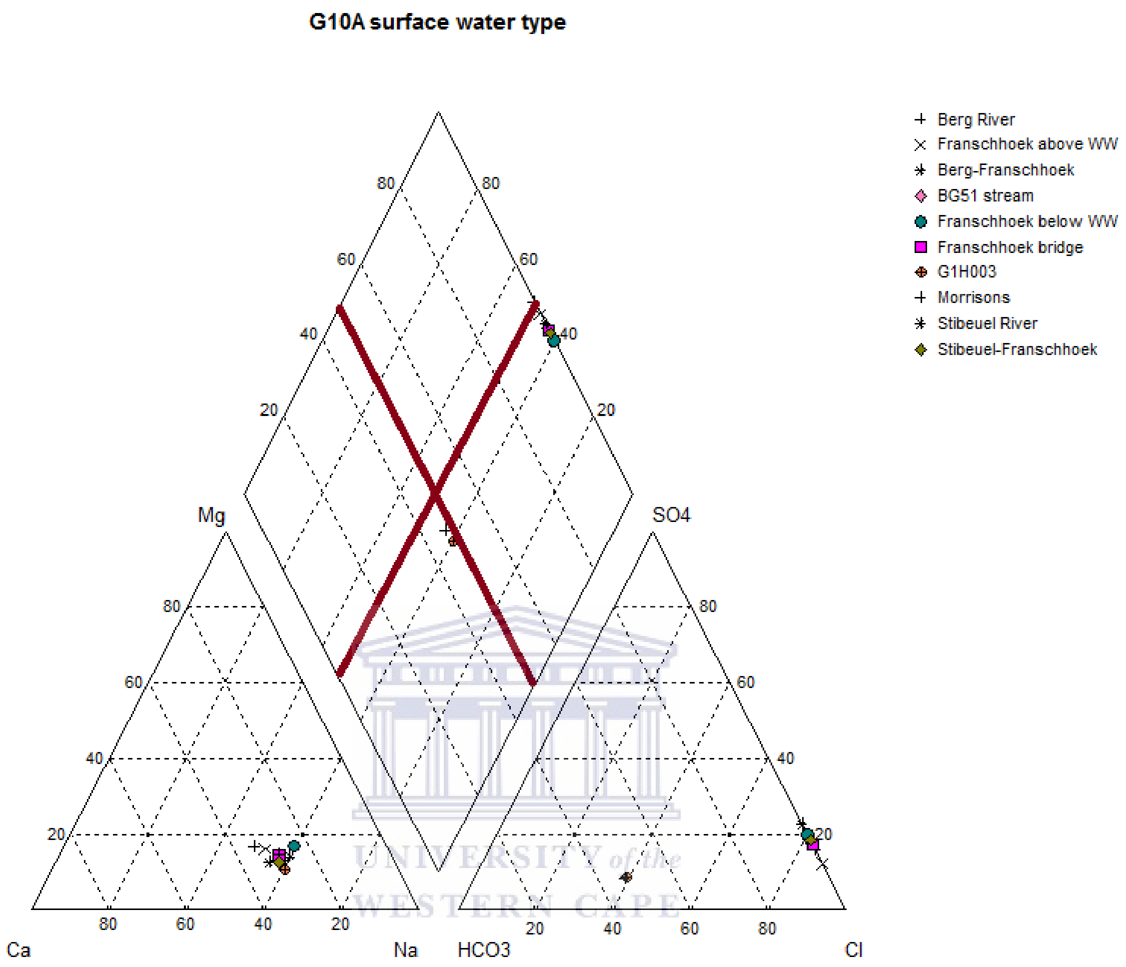


Figure 22: Typical water type of surface water in the upper Berg River catchment

Figure 22 shows the Piper Diagram for surface water sampled in the upper Berg River catchment. This plotting of the majority of surface water sampling sites on the right-hand quadrant of the diagram indicates that the dominant surface water facies were NaCl. The diagram also indicates that two samples (i.e. Morrison's and G1H003) were affected by the loading of HCO_3^-. This is indicative of the dissolution of carbonate geological material. However, the absence of such geology in the area and the relatively short residence times of surface water in the geological material indicate that the source of this HCO_3^-in the Franschhoek River could be from wastewater effluent rich in HCO_3^-. Furthermore, both sites were located along the Franschhoek River, which drains land primarily used for human settlements and agriculture. The sites were located below the Franschhoek wastewater treatment plant, which discharged its effluent into this river that could be the source of the elevated HCO_3^- in the stream.

Figure 23 shows a map illustrating the general water type in the upper Berg River catchment. This diagram shows the typical water type in the five marked sampled areas in the catchment, which summarizes the general water type in the upper Berg River catchment.

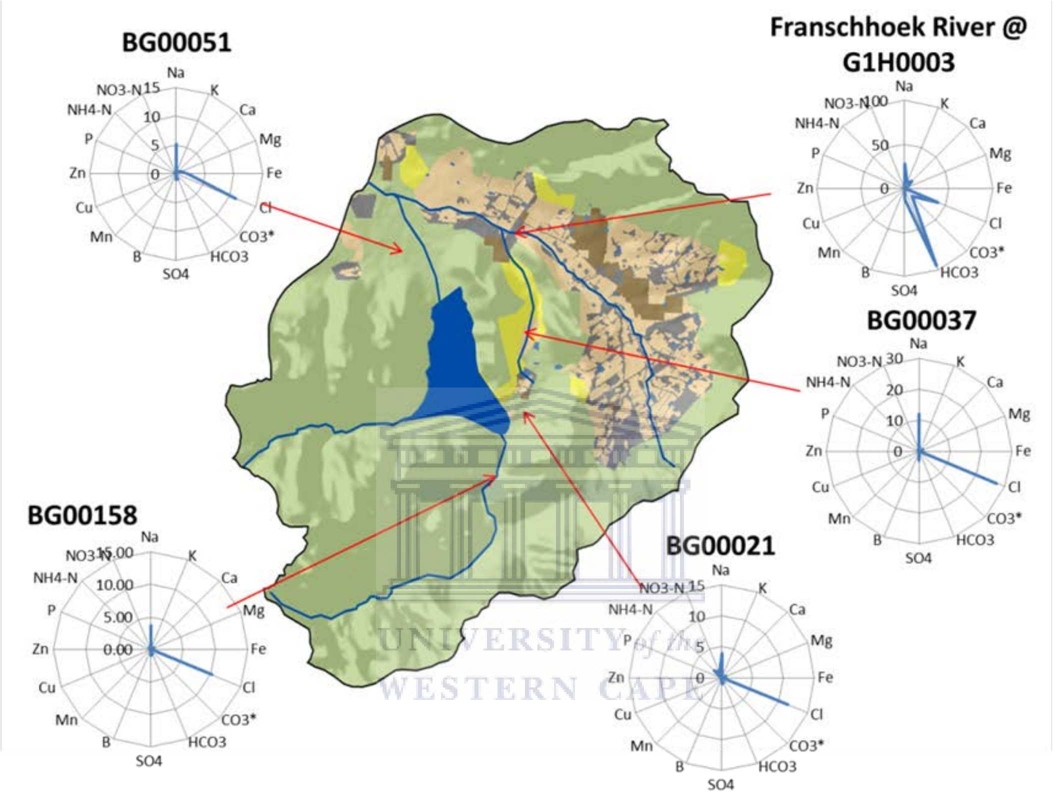


Figure 23: Map showing water type in upper Berg River catchment

6.2.1 Descriptive Statistical summary on groundwater and surface water physicochemical parameters

Table 13presents the statistical summary of the physicochemical parameters of groundwater and surface water measured from borehole (groundwater) and river (surface water) sampling sites in the upper Berg River catchment for the 2014 hydrological year.

Following a normality test (Q-Q plots) to check the distribution of all measured physicochemical parameters, the results indicated that not all parameters followed a normal distribution, while pH followed such a distribution. The pH values range (Figure 24) between moderately acidic to moderately alkaline waters. Acidic pH values in the Western Cape are generally found in groundwater and river water because of organic acids and plant roots. Alkaline pH values were measured in surface water sites affected by discharges from wastewater treatment works among other human activities that raise the pH of water. Boreholes located adjacent to such areas are at risk for contamination.

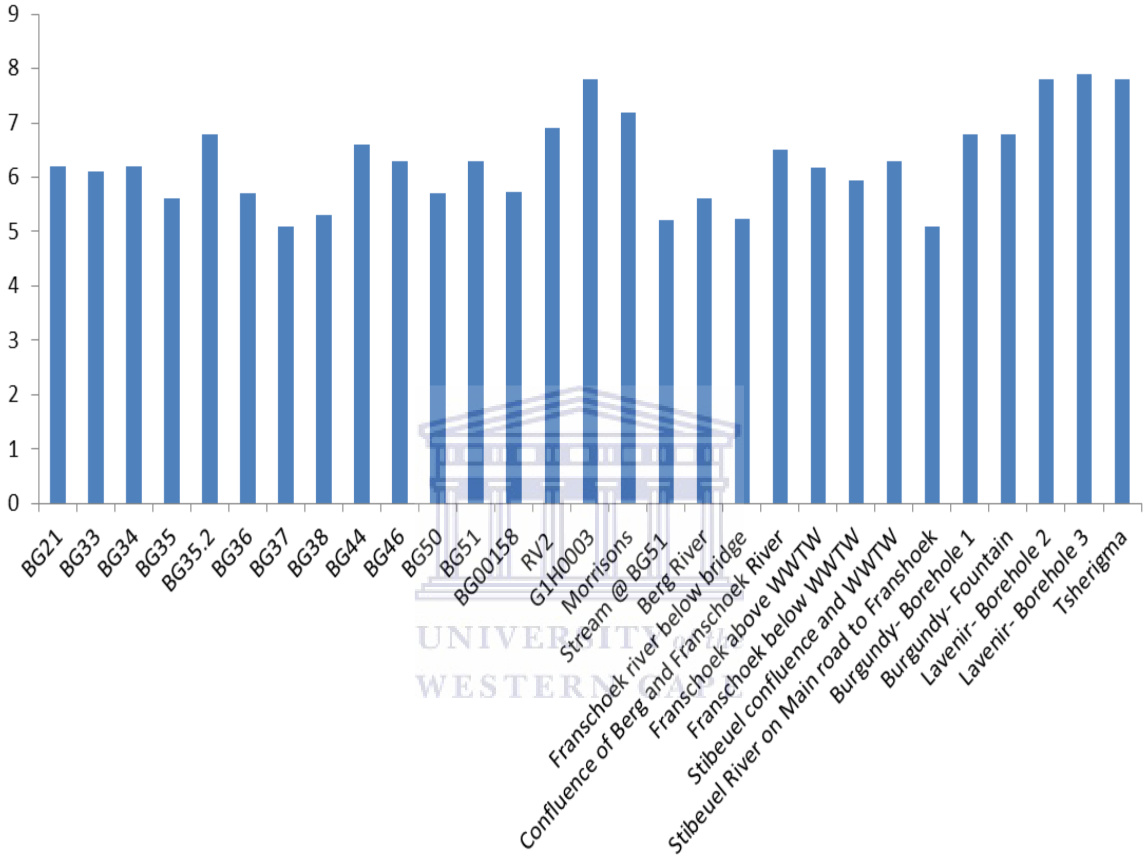


Figure 24: Bar graphs indicating the groundwater-surface water pH distribution in upper Berg River catchment

Table 13: Statistical summary of the upper Berg River catchment groundwater and surface water hydrochemistry for 2014

Variable	Minimum	Maximum	Mean	Std. deviation
Na+	2.800	28.100	10.403	6.308
K+	0.100	6.700	0.862	1.230
Ca+2	0.000	21.600	4.970	5.427
Mg+2	0.500	3.600	1.351	0.738
Cl-	5.500	52.200	19.516	10.606
HCO3-	0.000	94.700	19.528	26.592
SO4-	1.000	12.000	2.489	2.389
P	0.000	1.020	0.095	0.203
NH4-N-	0.050	10.000	0.730	1.649
NO3-N-	0.000	2.600	0.546	0.774
F	0.000	0.600	0.097	0.150
pH	5.100	7.900	6.533	0.874
EC mS/m	2.533	151.100	24.968	39.282
TDS	0.000	188.000	62.668	46.872

The dissolved chemical concentrations in both groundwater and surface water in the upper Berg River catchment comply with the guidelines set by the Department of Water and Sanitation (DWAF, 1996). This study documents the common physicochemical parameters measured from all the water samples.

Concentrations for all measured physicochemical parameters were within the allowed range for use in the irrigation of agricultural plants. However, the laboratory analysis of groundwater samples revealed that at BG46 Fe and Mn concentrations were classified as “Severe problems encountered clogging of drip irrigation systems (>1.5m/L)” (DWAF, 1996) (see appendix). This severe effect has potential to negatively impact on the agro-economy of the catchment by causing production delays due to infrastructure failure and repair. The standard deviation, which is a measure of how much the members of a group differ from the mean value for the group, indicated that conductivity had the greatest variation in all samples analyzed. Thus, this shows that conductivity of groundwater and surface water varies substantially within the upper Berg River catchment. However, due to a measurement error, an abnormally high conductivity was recorded, which thereby contributed to the large deviation from the mean, even though overall conductivity in the catchment was low.

6.2.1.1 Correlation of groundwater and surface water physicochemical parameters

Table 14 shows the correlation matrix for groundwater physicochemical parameters. The correlation matrix describes the interrelationships between the 14 physicochemical parameters in groundwater. From this table, the results show that a positive correlation exist between Na-Cl, Na-EC, Na-TDS, Na-Mg, Ca-HCO_3, Ca-P, Ca-EC, Ca-TDS, HCO_3-pH, HCO_3-P, HCO_3-F and EC-TDS, indicating that an increase/decrease in either will result in an increase/decrease in the other.. Furthermore, a positive correlation exists between numerous variables including Na-Ca, Na-SO_4, Na-TDS, Ca-TDS, and others (see Table 14). Contrary to these positive correlations found between hydrochemical parameters in groundwater, negative correlations were observed for many physicochemical parameters as seen in Table14.

Table 15 shows the correlation matrix for surface water physicochemical parameters. The table indicates that high(values closer to 1) positive correlation exists between numerous variables (see Table 15). This indicated that the concentrations of the correlated ions are directly related to each other. This suggests that 35.7% and 78.57% of the measured physicochemical parameters correlated with TDS while 28.57% of surface water and 7.14% of groundwater physicochemical parameters were correlated to pH. Therefore, an increase in surface water TDS resulted from increases in dissolved constituents, while a small proportionate decrease in pH resulted from an increase in dissolved constituents.

Ca, Mg, and HCO_3^- were the most abundant ions in natural waters, while Na and Cl provide an indication of deposition and dissolution of halite from atmospherically derived Na-Cl ions in areas close to the coast (Kura, et al., 2013). Additionally, the dominance of Na-Cl and Ca-Mg-HCO_3^- water indicates a mixing of new water with ancient/old saline groundwater (Younger, 2007). The very high positive correlation between Na and Cl indicates the dominance of Na-Cl rich recharge water from coastal origin.

Table 14: Groundwater correlation matrix of the physicochemical parameters

Variables	Na+	K+	Ca+2	Mg+2	Cl-	HCO3-	SO4-	P	NH4-N-	NO3-N-	F	pH	EC mS/m	TDS
Na+	1													
K+	0.315	1												
Ca+2	0.753	0.409	1											
Mg+2	**0.935**	0.309	0.730	1										
Cl-	**0.927**	0.195	0.552	**0.919**	1									
HCO3-	0.653	0.397	**0.957**	0.603	0.382	1								
SO4-	0.576	0.266	0.408	0.538	0.540	0.323	1							
P	0.576	0.265	**0.837**	0.515	0.360	**0.804**	0.261	1						
NH4-N-	-0.271	-0.181	-0.379	-0.232	-0.157	-0.422	-0.111	-0.264	1					
NO3-N-	0.395	0.408	0.226	0.387	0.335	0.208	0.258	0.115	0.015	1				
F	0.498	0.326	0.771	0.405	0.244	**0.870**	0.176	0.667	-0.427	0.120	1			
pH	0.427	0.484	0.795	0.407	0.207	**0.803**	0.156	0.719	-0.379	0.188	0.706	1		
EC mS/m	**0.918**	0.401	**0.939**	**0.894**	0.771	**0.874**	0.505	0.735	-0.377	0.382	0.700	0.682	1	
TDS	**0.881**	0.378	**0.829**	**0.872**	**0.805**	0.738	0.549	0.490	-0.319	0.382	0.589	0.536	**0.922**	1

Values in bold are different from 0 with a significance level alpha=0.05

Table 15: Surface water correlation matrix of the physicochemical parameters

Variables	Na+	K+	Ca+2	Mg+2	Cl-	HCO3-	SO4-	P	NH4-N-	NO3-N-	pH	EC mS/m	TDS
Na+	**1**												
K+	**0.974**	**1**											
Ca+2	**0.971**	**0.925**	**1**										
Mg+2	**0.935**	**0.857**	**0.958**	**1**									
Cl-	**0.978**	**0.951**	**0.928**	**0.906**	**1**								
HCO3-	**0.769**	**0.885**	**0.680**	0.582	**0.759**	**1**							
SO4-	**0.969**	**0.945**	**0.943**	**0.863**	**0.925**	**0.713**	**1**						
P	**0.917**	**0.966**	**0.850**	**0.786**	**0.867**	**0.907**	**0.897**	**1**					
NH4-N-	**0.801**	**0.901**	**0.714**	0.586	**0.800**	**0.980**	**0.768**	**0.894**	**1**				
NO3-N-	0.373	0.243	0.427	0.439	0.252	-0.133	0.484	0.237	-0.077	**1**			
pH	0.591	**0.705**	0.510	0.479	0.572	**0.840**	0.536	**0.799**	**0.752**	-0.266	**1**		
EC mS/m	0.251	0.050	0.376	0.434	0.218	-0.414	0.311	-0.071	-0.334	**0.720**	-0.415	**1**	
TDS	**0.997**	**0.977**	**0.978**	**0.922**	**0.972**	**0.782**	**0.971**	**0.915**	**0.820**	0.356	0.588	0.239	**1**

Values in bold are different from 0 with a significance level alpha=0.05

6.2.1.2 Extraction of principal factors

Principal Component Analysis (PCA) was applied to the 14-hydrochemical variables in groundwater and surface water and it yielded 14principal components. Table 16 and Figure 25 display the eigenvalue, variability, and cumulative percentage of each of the extracted components. According to Kaiser's criterion, the most commonly utilized criteria for solving the number of components problem in PCA (Kaiser, 1960; Subyani & Al Ahmadi, 2010; Yidana, et al., 2010), only the components with eigenvalues greater than one should be retained and interpreted. This is because each of the observed variables contributes one unit of variance to the total variation within the data set. Accordingly, any component with an eigenvalue greater than 1is believed to be responsible for a greater proportion of variation than is contributed by one variable. Components that fit into this criterion are responsible for significant amounts of variance and deserve to be retained.

Therefore, only the principal components with eigenvalues greater than 1 were considered the most important factors influencing the physicochemical characteristics of groundwater and surface water in the upper Berg River catchment. Using this exclusion criterion, only 5 principal components explained the composition of physicochemical parameters in groundwater and surface water, i.e. 1) groundwater recharge, 2) water-rock interactions and, 3) biological processes occurring in the subsurface. However, following Varimax rotation, two major PC's were extracted from the hydrochemical data. Cumulatively, these two PC's contributed 71.8% of the total variance observed in the data. These two PC's are indicative of the natural processes of groundwater recharge and the presence of shallow recently recharged groundwater. Table 16 shows the ions that dominated the ion loading in the respective PC's (D1 and D2). The respective ions revel the nature of the PC's and further reiterate the that both groundwater and surface water are largely influenced by natural process in the catchment.

Table 16:Eigenvalue, variability and cumulative % of each of the extracted components

Components	Eigenvalue	Variability (%)	Cumulative %
PC1	7.080	50.571	50.571
PC2	2.981	21.291	71.861
PC3	1.726	12.331	84.192
PC4	0.940	6.715	90.907
PC5	0.527	3.763	94.670
PC6	0.271	1.939	96.609
PC7	0.138	0.987	97.596
PC8	0.100	0.713	98.308
PC9	0.078	0.557	98.866
PC10	0.054	0.386	99.252
PC11	0.043	0.309	99.561
PC12	0.035	0.249	99.810
PC13	0.021	0.149	99.960
PC14	0.006	0.040	100.000

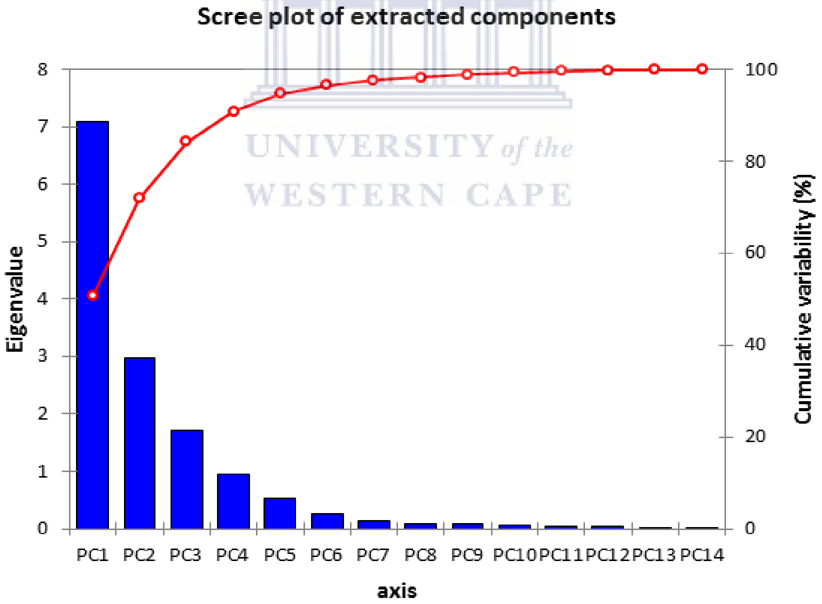


Figure 25: Scree plot of groundwater-surface water principal components

Collectively, the significant factors (PC1-3) extracted using PCA contributed 84.192% of the variation within the data. Following Varimax rotation, two principal factors (D1 and D2) were extracted, which cumulatively explained 71.861% of the initial 84.192% of variance observed in the data (see Table17).

Table 17: Percentage of variance after Varimax rotation

Dominant Factor	Variability (%)	Cumulative %
D1	36.491	36.491
D2	35.371	71.861

*** Components in bold are considered the most significant**

Table 18: Table showing hydrochemical ion loading by factor (D1 and D2

D1	D2
Na	Ca
Mg2+	pH
Cl-	HCO_3^-
HCO_3^-	P
SO_4^-	
EC	
TDS	

According to Yidana et al., (2010), the first principal component (D1) normally accounts for the most significant process, and in this study it explained 36.491% of the total variance. This component consists of Na, Mg, HCO_3^-, Cl, EC, and TDS. The process closely associated with the distribution of these ions as well as their grouping according to their dominant factor indicates the natural water-rock interaction processes occurring in the subsurface and the presence of shallow fresh groundwater.

The second dominant component explained 35.371% of the total variance with an Eigen value of 4.91. This factor consists of Ca, pH, HCO_3^- and P. This component was explained by the natural of groundwater recharge in the area. However, caution was exercised regarding the interpretation of the first component, as some of the ions (high loading of Ca-HCO_3) that comprise this grouping can be sourced from agricultural fertilizer/pesticide application (during the infiltration of surficial derived water), the corrosion of plumbing and of concrete structures (Franschhoek area including Langrug informal settlement), which are primarily found in human settlements. This was worsened by the high factor loading of the physiochemical parameter, pH (0.806), which plays an important role in the availability of dissolved ions in water. Furthermore, it was clear from the correlation matrix that pH was highly correlated with the presence of HCO_3^- and P. However, the concentrations of the abovementioned chemical elements are not a direct indicator of the aforementioned possible contributors, as these chemical elements can be derived from natural biogeochemical processes as well. Therefore, this warrants further analysis to be done to ascertain the sources of these elements.

6.2.1.3 Cluster Analysis

Cluster analysis was applied to the hydrochemical data set obtained from both groundwater and surface water sampling sites in the upper Berg River catchment. The resulting factors were categorized into three major groups based on the dissimilarities between variables and the sites from which they were collected. The data were presented in two dendrograms illustrating the different clusters and depicting the site composition of a grouping. This information was used to identify sites where groundwater and surface water physicochemical parameters were the same, thus indicating the exchange of water either from groundwater to surface water or vice versa.

Figure 26, illustrates a simplified dendrogram indicating the number of clusters the site information was grouped. Three major sub groups were created using hierarchical clustering. Clustering showed that sites in cluster 1 were distinct from the other two clusters. The latter groups were closely related to each other. This graph indicates that, based on the dissimilarities between variables and similarities between sites, sites situated in the same cluster grouping were closely related, while great difference was observed in clusters in different groupings.

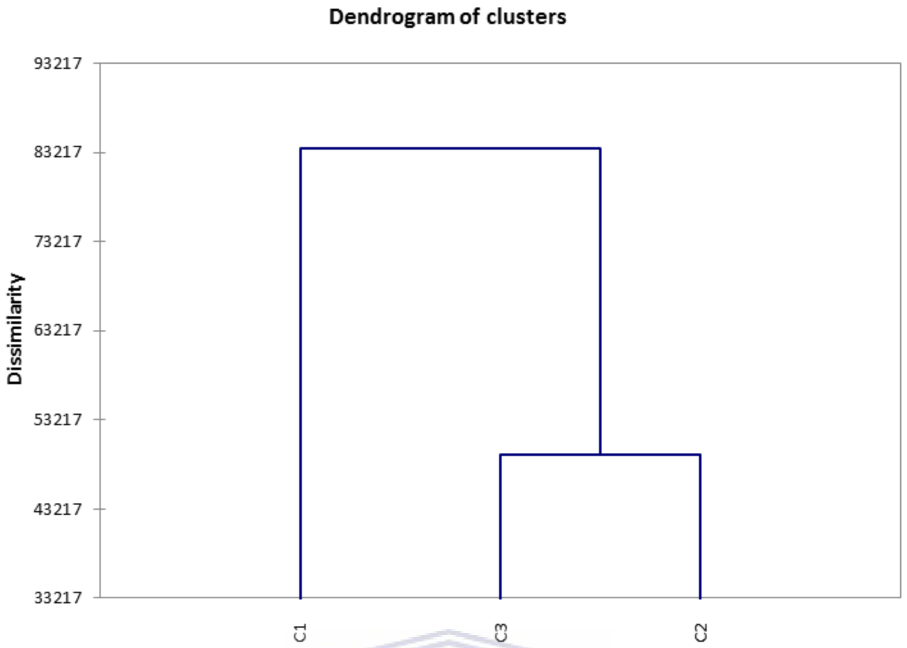


Figure 26: Dendrogram showing the various groups based on clustering of groundwater-surface water chemistry data

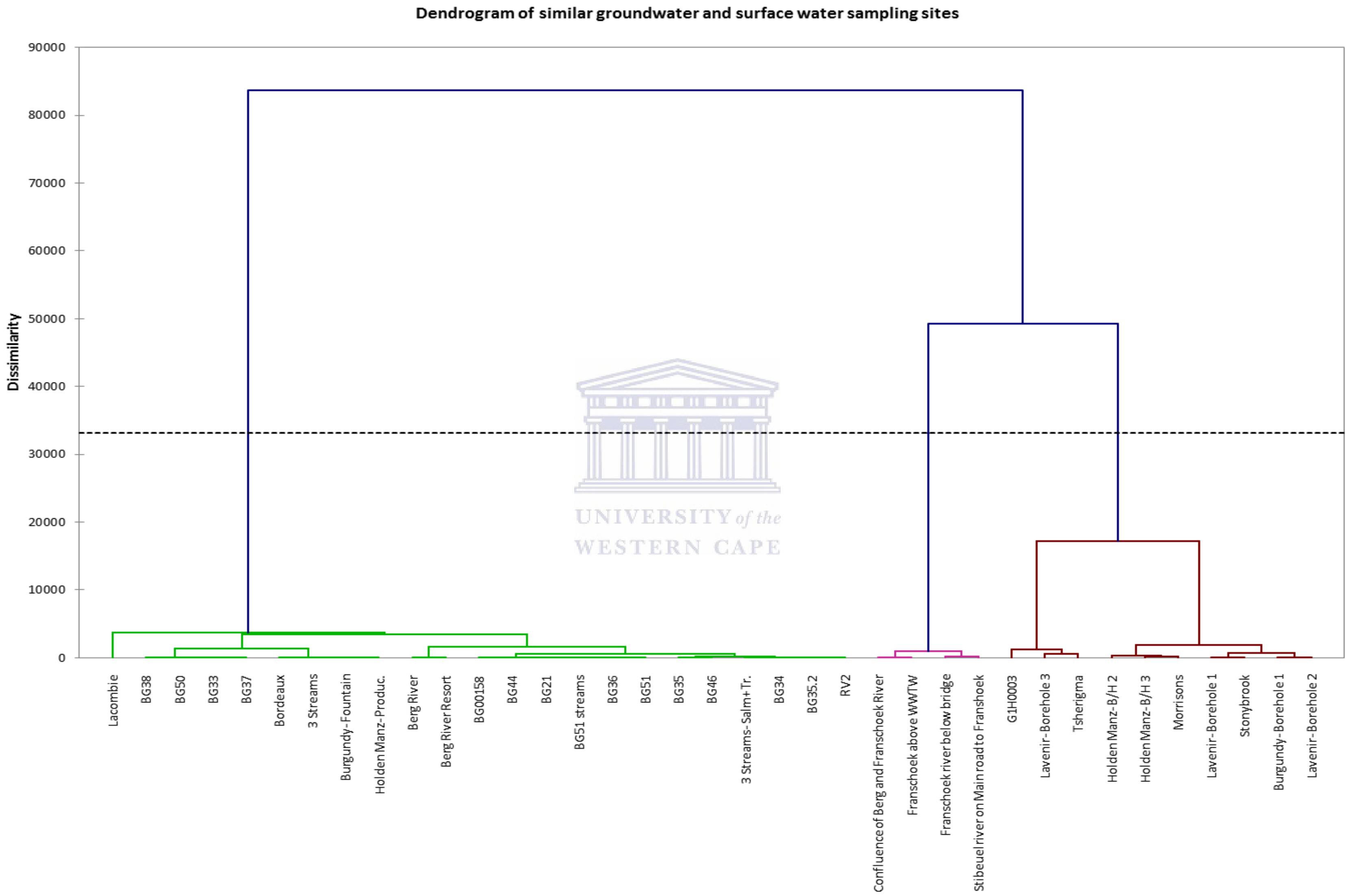


Figure 27: Dendrogram illustrating cluster groupings based on physicochemical dissimilarity between groundwater-surface water sampling sites in G10A

Table 19: Table illustrating groundwater-surface water site clustering

Cluster	1	2	3
Sites	BG21	Burgundy- Borehole 1	Franschhoek River below bridge
	BG33	Holden Manz- B/H 2	Confluence of Berg and Franschhoek River
	BG34	Holden Manz- B/H 3	Franschhoek below WWTW
	BG35	Lavenir- Borehole 1	Stibeuel river on Main road to Franshhoek
	BG35.2	Lavenir- Borehole 2	
	BG36	Lavenir- Borehole 3	
	BG37	Tsherigma	
	BG38	G1H0003	
	BG44	Morrison’s	
	BG46		
	BG50		
	BG51		
	BG00158		
	RV2		
	Bordeaux		
	Burgundy- Fountain		
	Holden Manz- Produc.		
	Lacombie		
	3 Streams		
	3 Streams- Salm+ Tr.		
	BG51 streams		
	Berg River		
	Franschhoek above WWTW		

Figure 27, 28, and Table 21 all show the various classes each site was clustered into based on the dissimilarities between variables and similarities between sites. From these four classes it was observed that the first class consisted of the following sites: BG21, BG33, BG34, BG35, BG35.2, BG36, BG37, BG38, BG44, BG46, BG50, BG51, BG158, RV2, Bordeaux, Burgundy- Fountain, Holden Manz- Production., Lacombie, 3 Streams, 3 Streams- Fountain, 3 Streams- Salm+ Tr., Stream at BG51, Berg River, Franschhoek above WWTW, and Berg River. Groundwater sampling sites as well as surface water sampling sites located in the areas of the upper Berg River catchment that had minimum anthropogenic activity dominated this cluster.

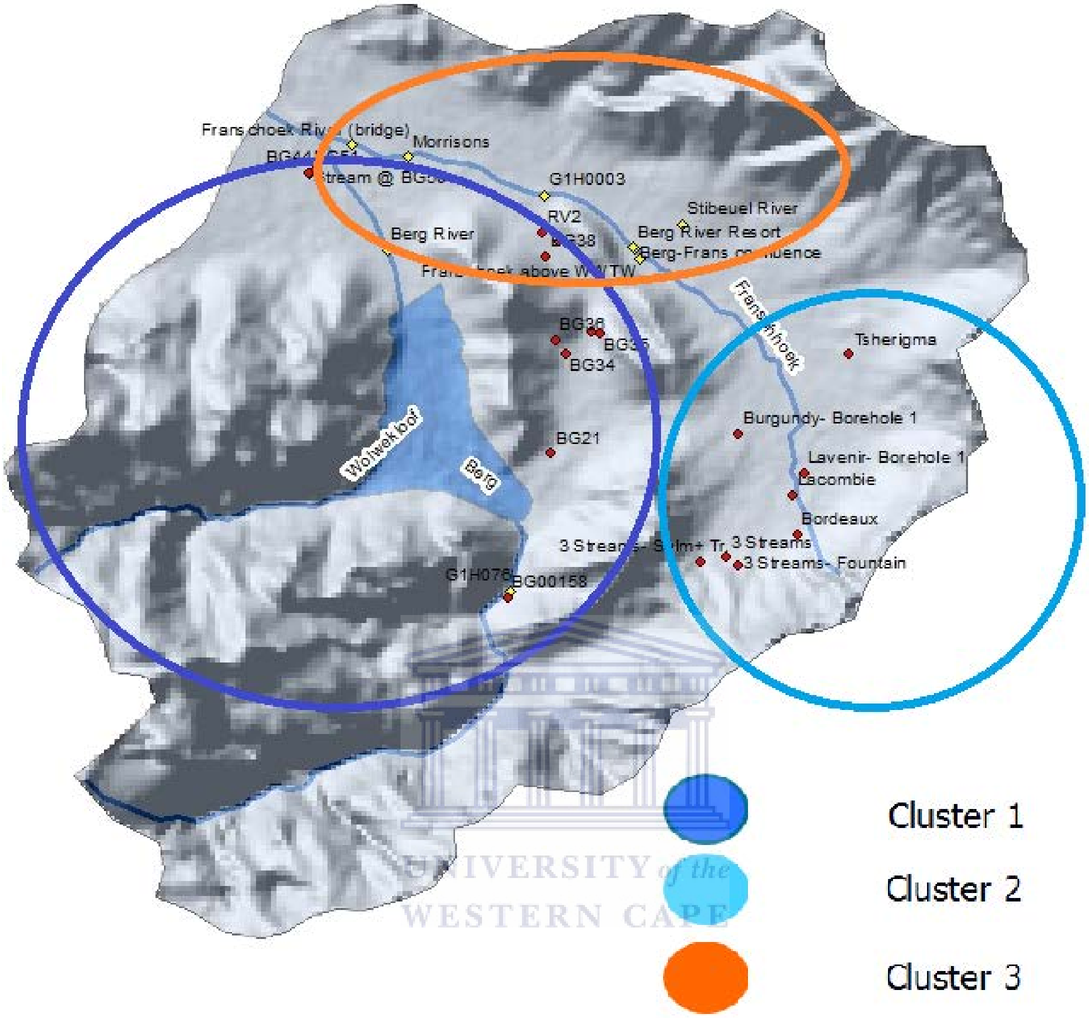


Figure 28: Groundwater-surface water sampling site clusters

The second class consists of sites located in the Franschhoek area of the upper Berg River catchment (Figure 28). The sites include boreholes located in farming areas as well as two sites located below the waste water treatment works in Franschhoek which includes Burgundy- Borehole 1, Holden Manz- B/H 2, Holden Manz- B/H 3, Lavenir- Borehole 1, Lavenir- Borehole 2, Lavenir- Borehole 3, Tsherigma, G1H003, and Morrison’s. The grouping of these sites in one cluster indicates that groundwater and water from the Franschhoek River have a distinct hydrochemical characteristic, compared to samples collected elsewhere within the upper berg River catchment. These results confirm the findings by de Villiers, (2007) and Jackson, et al., (2013), which report that the Franschhoek River is highly impacted by human activities ranging from human settlements to agricultural activities, with abnormally higher concentrations of nutrients and metals in the river water.

The third class consists of the sites located at the Franschhoek River below the bridge, confluence of Berg and Franschhoek River, Franschhoek below the wastewater treatment works, Stibeuel River, confluence of Stibeuel and wastewater treatment works. These sites are allocated in areas affected by discharges from agricultural activities, human settlements (informal and formal) and urban storm water drainage (towns). Contrary to this, the site situated above the wastewater treatment works plant on the Franschhoek River was classified with the sites in cluster 1, indicating an influence of the Stibeuel River and the Franschhoek wastewater treatment works plant on the quality of the river passing this area.

From Table 19, it was evident that groundwater and surface water sites in the classes 1, 2, and 3 were grouped together based on their physiochemical properties. This grouping shows a relationship between the concentrations in the surface waters as well as groundwater, thus inferring areas of interaction between the two hydrological zones based on physicochemical similarities (Figure 28).

6.3 Predominant water type, major clusters and their factors

The aims of the current chapter were to characterize groundwater and surface water quality and to identify the dominant processes affecting the quality of groundwater and surface water in the upper Berg River catchment by using *in situ* and hydrochemical analyses methods. The chapter argued that the use of groundwater and surface water physicochemical characteristics coupled with multivariate statistical analysis methods is an effective way: a) to characterize the quality of groundwater and surface water; b) to identify dominant process controlling the quality of groundwater and surface water, and c) to determine similarities in the quality of groundwater and surface water thereby inferring groundwater-surface water interactions.

Multivariate statistical methods (Principal Component and Cluster Analyses) were used to determine the major factors influencing groundwater and surface water quality and to group groundwater and surface water sampling sites according to similarities in physicochemical parameters. The predominant groundwater and surface water type in the upper Berg River catchment determined with the Piper Diagrams were Na-Cl, with slight inputs of Ca and HCO_3^-. This water type was indicative of the presence of recently (shallow) recharged water with high contents of Na-Cl and slight concentrations of Ca and HCO_3^-.

Many studies have used multivariate statistical analysis to ascertain the principal factors corresponding to the variation in groundwater quality (Cobbina, et al., 2012; Kenade & Gaikwad, 2011; Subyani & Al Ahmadi, 2010). The most commonly used approach was to employ factor, Principal component and cluster analyses to derive the dominant factors contributing to groundwater chemistry as well as to derive the groupings into which samples collected at different sites would fit. Belkhiri et al., (2012) used a combination of factor and cluster analyses to extract three hydrochemical factors as well as three cluster groups into which the samples fit. In their study, Belkhiri et al., (2012) only collected water samples from groundwater extraction points, and found that the variations in groundwater quality were mainly influenced by the presence and dissolution of carbonate, dolomitic, and evaporate minerals. Furthermore, groundwater quality in their study area was influenced by natural process as well as water-rock interactions within the subsurface (Belkhiri, et al., 2012). It was concluded from their study that multivariate statistical analysis in hydrochemical investigations could act as a useful tool.

In the present study, principal component and cluster analysis were used to determine the various groupings of samples based on their dissimilarities between sites and similarities within hydrochemical components. Furthermore, the principal component analysis indicated that three factors explain 90.1% of the variation in hydrochemistry. However, after employing Varimax rotation normalization, only two dominant factors were derived, which explained 71.8% of the variance within the water quality data. The two dominant factors extracted after Varimax Rotation included the presence of recently recharged water, and interactions between the recharging water and rock matrices, which was indicated by the accumulation of Ca and HCO_3^- from overlaying soil layers.

In the coastal area of Kimje, South Korea, Kim et al., (2005) used multivariate statistical analysis (cluster analysis and factor analysis) to identify the factors affecting groundwater quality in this coastal environment. Their results show that the use of multivariate statistical analysis methods such as Factor, Principal Component and Cluster analyses are powerful tools for the classification of groundwater and the identification of the most significant factors affecting groundwater quality. Furthermore, after plotting a Piper Diagram, the groundwater in the area was classified into two major water types, i.e., Na-Cl and Ca-Mg-NO_3^--Cl waters (Kim, et al., 2005). This approach combined with the cross referencing of the attained result with the water types explained in the factor analysis, showed that indeed these two water types were dominant in the catchment. In their study, three factors were found to contribute greatly to the chemical loading in groundwater, i.e. seawater intrusion, microbial activity and leaching of agricultural chemical fertilizers.

In the present study, two major factors were extracted after Varimax rotation. These two factors represent the natural processes of groundwater recharge as well as the process occurring during water-rock interaction associated with microbial activity in the overlaying soil layers. Thus, the water quality in the upper Berg River catchment was primarily driven by natural process; except for areas were immediate surficial anthropogenic activity discharges directly to the river systems. As such, after cluster analysis, most groundwater sites located in the unaffected areas of the catchment were classified into one group, while groundwater sites closer to the river systems showed similarities in their groupings, indicating the interaction of groundwater and surface water in these areas. Guggenmos, et al., (2011) used hydrochemistry and mulivariate statistical methods (PCA and CA) to identify groundwater-surface water interactions in the Wairarapa Valley in New Zealand. The study showed that groundwater and surface water grouped into similar clusters indicated regions of groundwater-surface water interaction potential recharge to aquifers and the dominance of base flow derived from subsurface water storages suggesting the transfer of chemical this characteristicsfrom underlaying aquifers. The study did not investigate the level of chemical characteristicstransfer, however indicated that the use of multivariate statistical methods can be used as a rapid method to identifying groundwater-surface water interactions at a regional scale using existing groundwater hydrochemical datasets.

The present study pursuedto identify areas of interaction between groundwater and surface water in the upper Berg River catchment using hydrochemistry and multivariate statistical approaches. The study has shown that the use of multivariate statistical analysis techniques is important in confirming priliminary graphical water quality represntations. Furthermore, this study has provided insights on the dominat processess controlling the quality of groundwater and surfac ewater in th upper Berg River catchment.

6.4 Significance of groundwater and surface water physicochemical characteristics

The present chapter aimed at characterizing and describing the quality of groundwater and surface water in the upper Berg River catchment using hydrochemistry and multivariate statistics. Using trilinear Piper Diagrams and multivariate statistical methods (PCA and CA), the analysis of the quality of groundwater and surface water has shown that the predominant water type in groundwater and surface water in the upper Berg River catchment was NaCl. This suggests that the natural processes of groundwater recharge as well as water-rock interactions occurring in the soil column mainly influenced the chemistry of groundwater and surface water. The physicochemical analysis of groundwater and surface water quality showed that none of the groundwater and surface water sampling sites as had physicochemical concentrations above Department of Water and Sanitation target water quality guidelines. Furthermore, the Sodium Absorption Ratios (SAR) computed for the samples indicated that the suitability of the water for use in agriculture is acceptable and below required guidelines.

The current chapter has shown that the use of hydrochemical multivariate statistical analyses methods can provide insights into areas of groundwater-surface water interaction at catchment scale based on similarities in physicochemical characteristics data. The present study and other studies in the literature have shown that the use of multivariate statistical methods is a suitable method to identify spatial zones of interaction as well as indicate the evolution of both groundwater and surface water. However, further work is required to investigate the direction and extent of interactions in the zones identified as interaction areas.

Chapter 7: Determining groundwater-surface water flow trend using differential stream gauging

7.1 Introduction

Results on the differential stream gauging field experimentsconductedduring the 2014 wet and dry seasons are presented in this chapter. The chapter aimes to evaluate differences in flow trends along a 600m reach (at 200m intervals) of the Berg River to infer the direction of groundwater and surface water exchange fluxes during wet and dry seasons.The chapter addresses the third specific objective, which was to determine flow trends along a selected reach using differential stream gauging to deduce their temporal variations groundwater-surface water interactions. The chapter argues that determining flow trends along a selected reach, is a practical approach to infer the groundwater-surface water interactions, and provides reach scale indications of groundwater-surface water interaction directions.

Streambed morphology commonly informs the choice and use of different stream gauging methods. Thus, due to irregular streambed morphology, the objective of this chapter was achieved byusing the dilution gauging method of stream gauing. Among the commonly used stream gauging techniques, dilution gauging is the most practical approach when gauging flows in streams with irregular streambed morphologies or high flows, that prevent the manual gauging of flows by a field practitioner.This chapter, arguesthat the use of dilution gauging is the most appropriate manual stream gauging method to be used in mountainous fractured rock environemts, where streambed morphology and flow velocities are sometimes not conducive for the velocity-area and othermanual methods for stream gauging. Furthermore, the use of dilution gauging as a tool to determine interactions between groundwater and surface water is agrued to be most suitable for manually gauging stream flows in mountainous catchments to indicate descrete reach sections of interaction at reachscales, where streams with steep gradients and heterogeneous streambed morphology are predominantly found.

Results are represented in graphical and tabular format which indicate the travel time of the dilution test and resultant discharge rates computed using Equation G. Moreover, mathamatical expressions were applied to the data generated to show the quantity of water flowing through each of the selected cross sections during the exersize times (Equation G). Additional mathematical expressions are used to compute the net loss/gains to stream flow over the selected cross sections (Equation L) to determine the interaction direction and rates at reach scale in the unimpacted upper Berg River catchment.

7.2 Results for dilution gauging

7.2.1 2014Wet season (High flow)

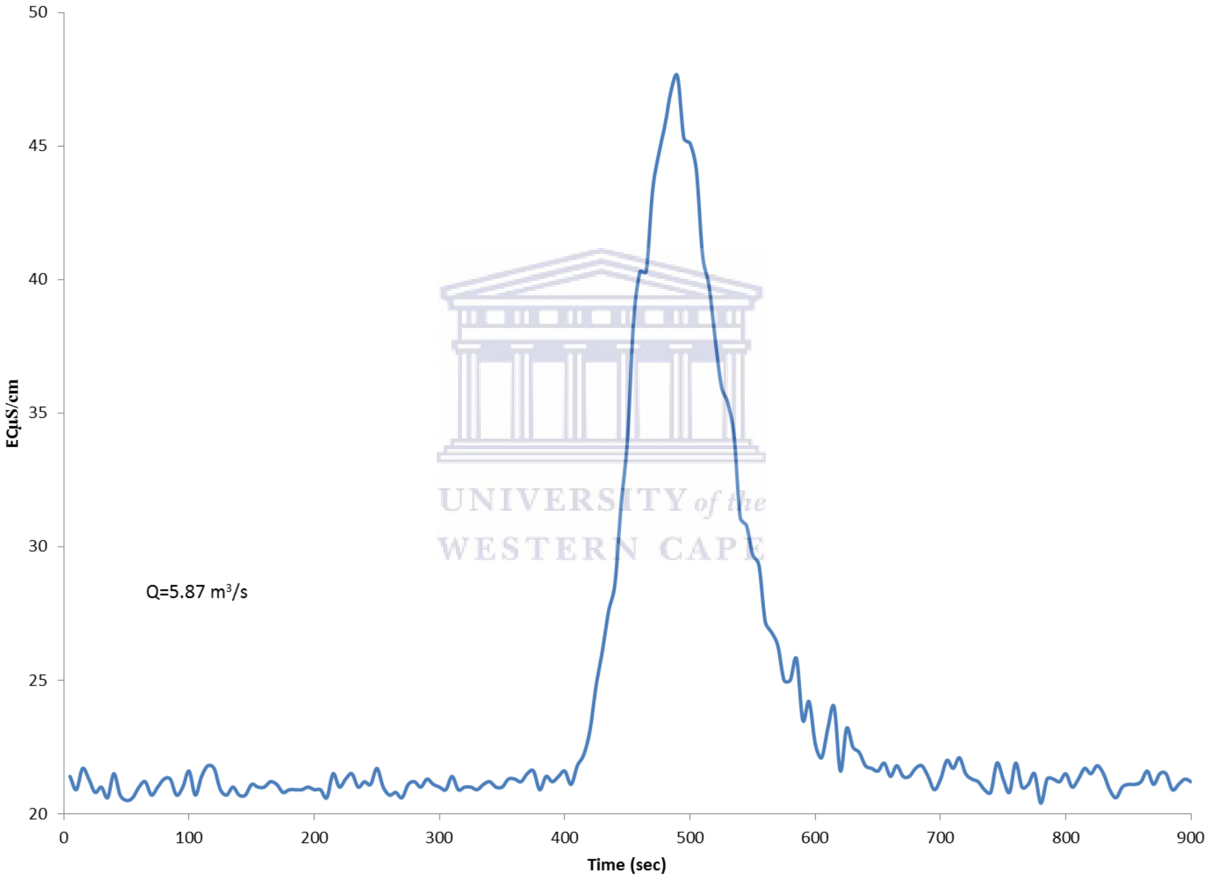


Figure 29: 600m-400m Salt wave recorded as EC during 2014 wet season at the 600m-400m reach of the Berg River at BRM1

Figure 29 illustrates the passage of the salt wave through the measuring point, 200m downstream. The figure includes the minor fluctuations in stream Electrical Conductivity (EC) caused by turbulent as well as small pool-riffle sequences flow prior to the passing of the saline water. The mean EC measured prior to salt wave inception was ≈ 21.09 µS/cm, with a sudden rise in measurement values after 425 seconds of salt-water mixture discharge to 47.6µS/cm at

490 seconds. The sharp rise in EC was mirrored by the rapid decline in measurement values to the previously measured value of 20.4µS/cm at 740 seconds. Further measurement continued for 160 seconds to ensure the complete measurement of the salt wave. Using the measured EC during the test, stream discharge was calculated to be 5.87m^3/s along the 600m-400m sub reach at BRM1.

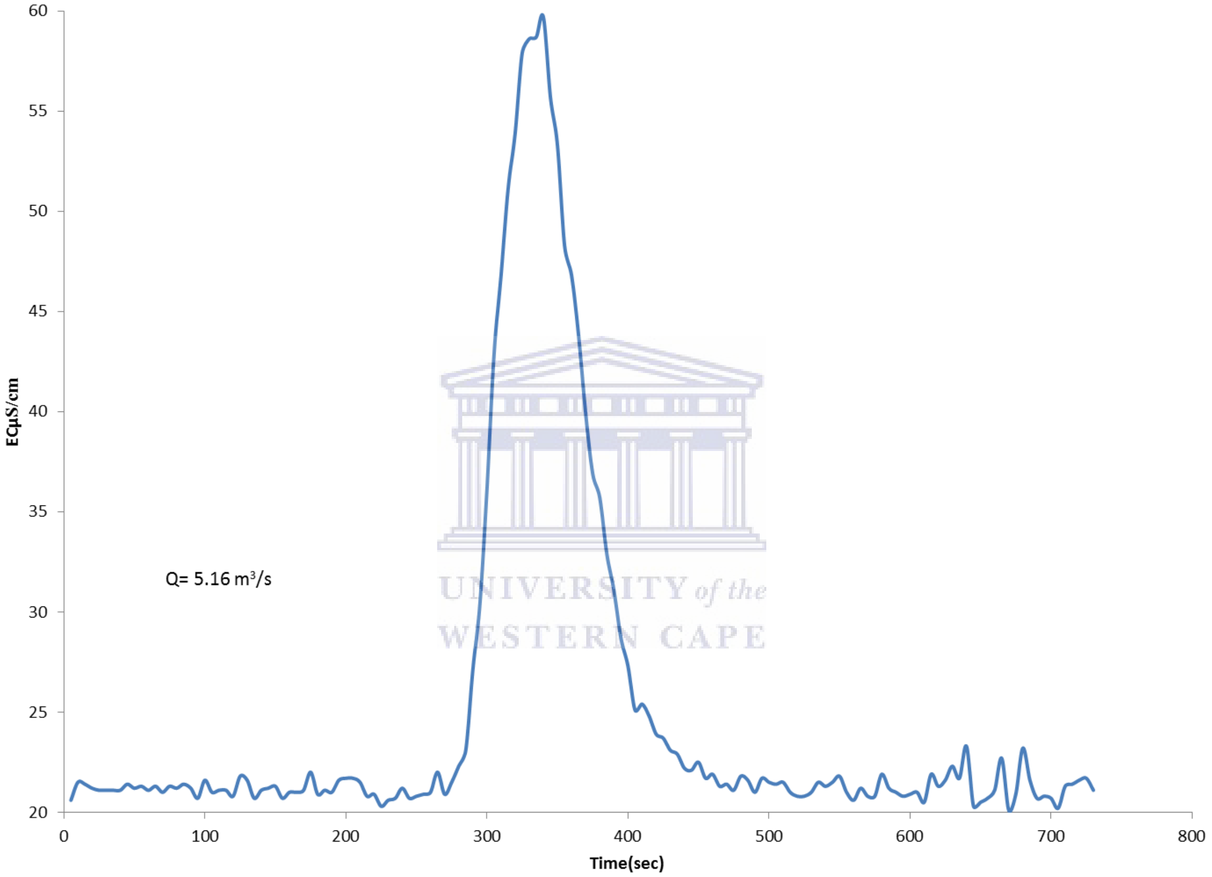


Figure 30: 400m-200m Salt wave recorded as EC during 2014 wet season at the 400m-200m reach of the Berg River at BRM1

The gauging of the sub reach 400m-200m (Figure 30) was done after a ten-minute break to allow the stream to remove all excess salt. During this dilution test, the mean pre-insertion EC was measured to be 21.15µS/cm for a period of 275-secondswith a sudden rise in measurement values thereafter. Values rose from 22.3 to 59.7µS/cm in 60 seconds and then declines as observed in the previous test. High EC measurements remained for 40 seconds with a sharp decline to ≈ 20.1µS/cm. A level of fluctuation existed after the decline of the salt wave, indicating the streams ability to forcefully dilute and discharge the salt tracer. Stream discharge was calculated to be 5.16m^3/s along the 400m-200m sub reach at BRM1.

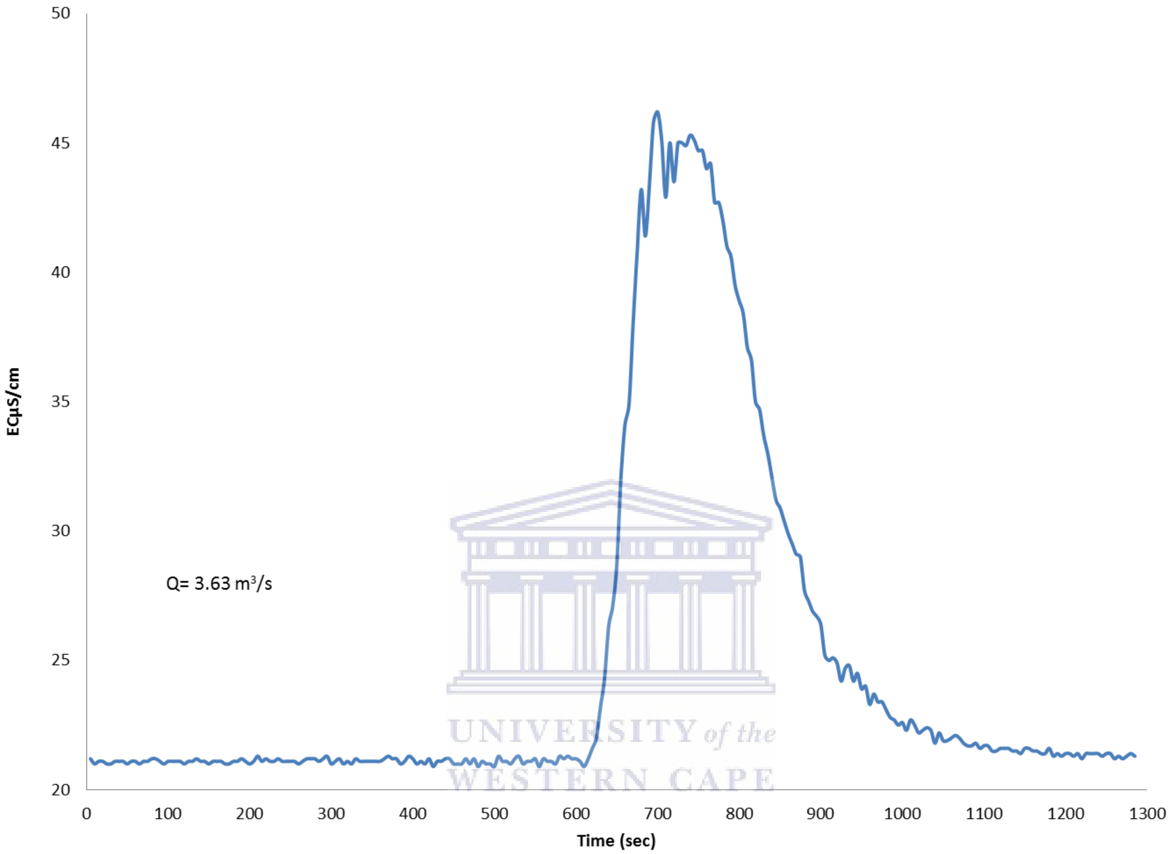


Figure 31: Salt wave recorded as EC during 2014dry season at the 200m-0m reach of the Berg River at BRM1

The last reach Figure 31 shows the salt wave passage at the 200m-0m stream reach at BRM1. Results of the dry season dilution gauging exercise indicated a longer period to the inception of the salt wave (695 seconds), with a mean EC of 20.9µS/cm. The complete passage of the salt wave peak was observed for a short period of time (with a rise to 45.89µS/cm, see Figure 31), similar to the previous two tests (600m-400m and 400m-200m).

However, the most distinctive aspect of this reach was that EC values returned to those measured prior the inception of the salt wave. This provided an indication of the influence of a change in stream slope, inflows of water along the valley sides, as well as the adjacent alluvial sediment terrace. In addition, the reservoir created near the weir may have also further influenced the dilution impact of the salt wave at this reach. Discharge calculated from the EC measurements was 3.63m^3/s.

7.2.2 2014 dry season (Low flow)

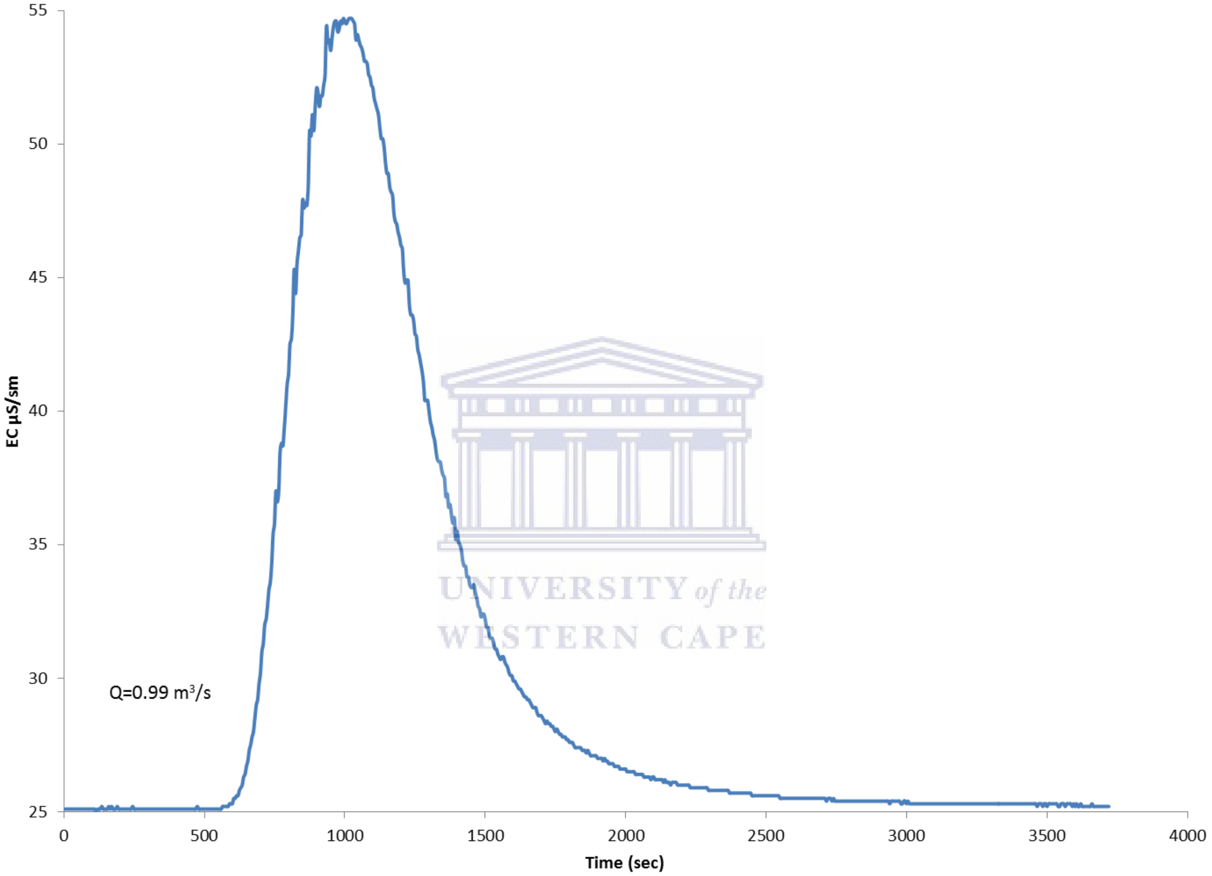


Figure 32:Salt wave recorded as EC during 2014 dry season at the 600m-400m reach of the Berg River at BRM1

Figure 32shows the salt wave passage of the through the measuring point (600m-400m). Minor fluctuations in stream conductivity were observed on the salt-waves' rising and recession limbs because of the input of water from the valley sides and the impact of the irregular streambed morphology (that retarded flow see Figure35). This was the influence of areas along the stream where water pooled, thus retarding the passage of the salt wave.

Mean conductivity measured prior to salt wave inception was ≈ 29.3µS/cm. A sudden spike in conductivity measurements was observed after 620 seconds of salt-water mixture input into the stream. The peak of 54.7µS/cm was observed at 995 seconds after the injection of the salt tracer solution. The rising and recession limbs of the salt wave indicate a sharp passage and rapid dilution of tracer along the reach. The decline of tracer concentration in the stream exhibits a jagged recession, confirming the influence of the abovementioned small pools that retain water and tracer. Further measurement continued for 160 seconds to ensure the complete measurement of the salt wave. Using the measured EC during the test, stream discharge was calculated to be 0.99m^3/s along the 600m-400m sub reach at BRM1 during 2014 dry season.

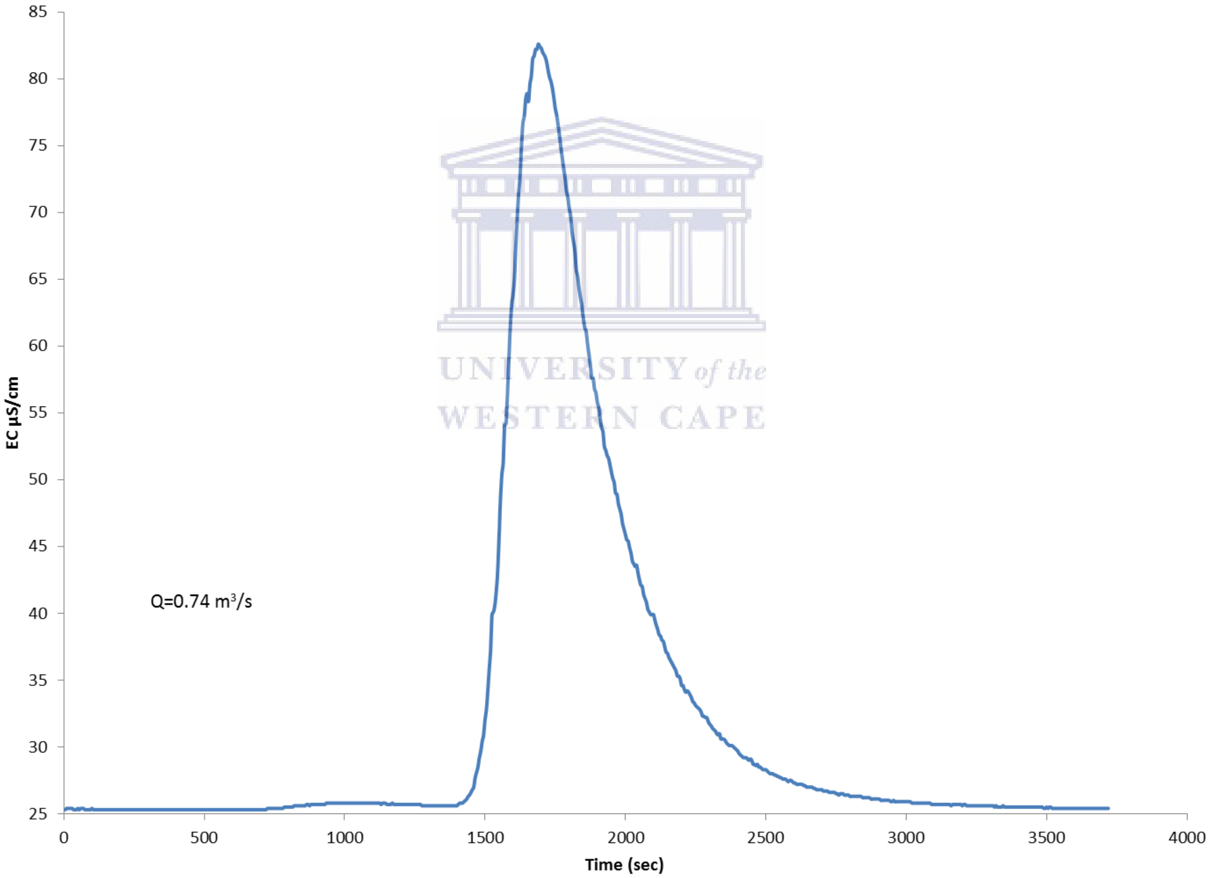


Figure 33: Salt wave recorded as EC during 2014 dry season at the 400m-200m reach of the Berg River at BRM1

Following the procedure used during the wet season (August2014) dilution test, time was allowed for the stream to flush out the entire tracer held within pools. Thereafter, constant measurements of stream conductivity were done allowing the initial conductivity to be described.

The initial conductivity measured during this test was as 25.3µS/cm after the input of the saline solution, at 500 seconds, an increase in stream conductivity was observed at approximately1500 seconds from salt tracer solution input (Figure 33).

Although the salt wave peaked at 82.6µS/cm, the salt waves' peak was short-lived, with a rapid decline following soon after to a relatively stable conductivity. Due to the influence of pools within the stream, the recession end of the salt wave had a higher conductivity than initial conductivity. 0.74m^3/s flow was measured for the 400m-200m sub reach.

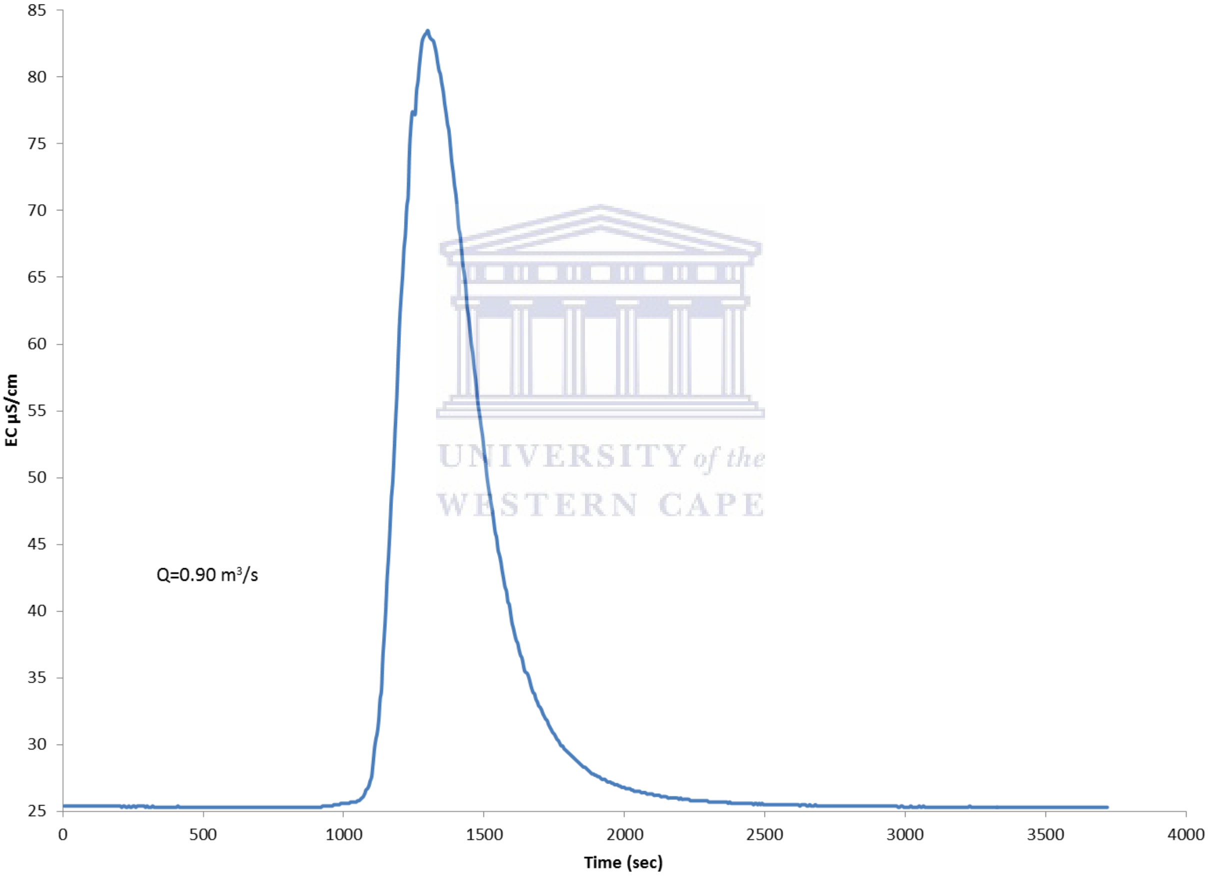


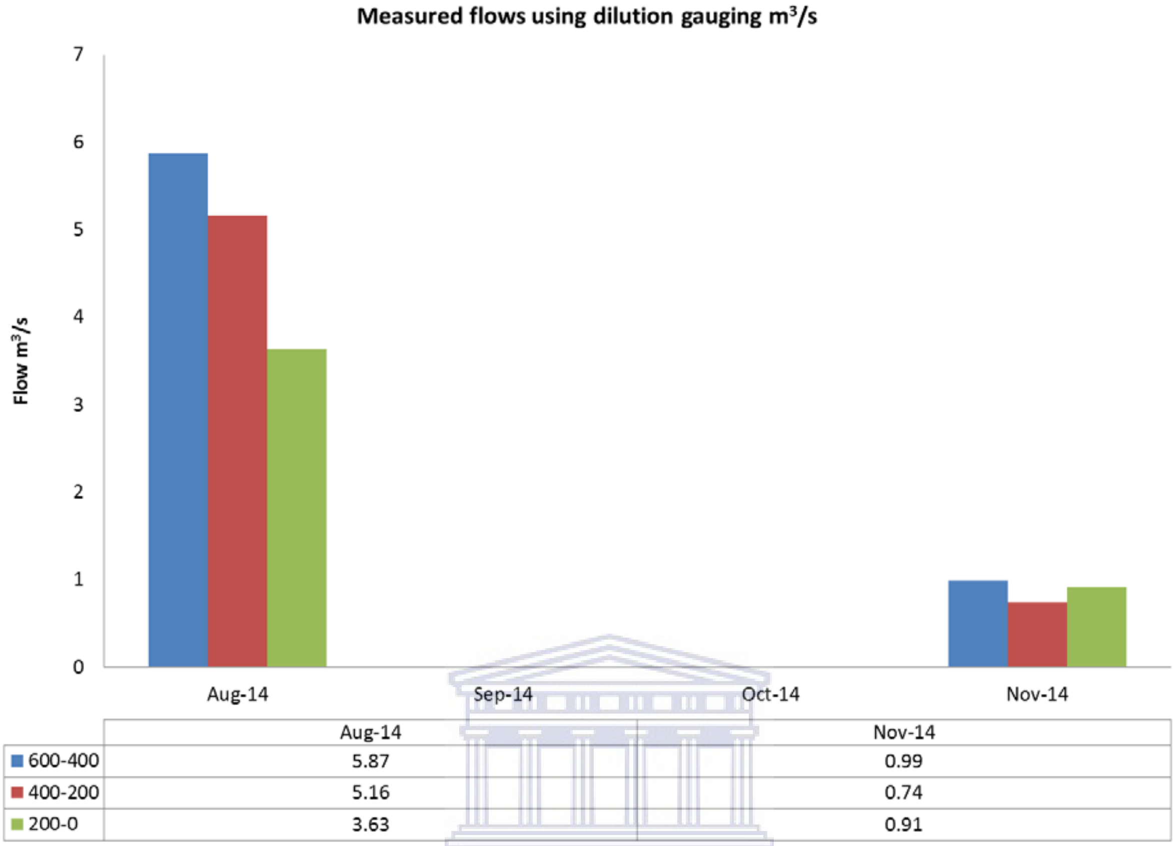
Figure 34: Salt wave recorded as EC during 2014 dry season at the 200m-0m reach of the Berg River at BRM1

The final reach (Figure 34) exhibits that the salt peak came quickly (with a rise to 83.5µS/cm); similar to the previous two tests (600m-400m and 400m-200m). However, the most distinctive aspect of this reach was that EC values returned to those measured prior the inception of the salt wave (25.3µS/cm) and remained stable at this value for a time in excess of 2000 seconds after the passage of the salt wave. The reach where the above-mentioned condition was measured was a straight reach, devoid of pools, however, with many riffles. The quick passage of the salt wave and the remaining constant conductivity was influenced by the change in streambed morphological structure. Discharge along the 200m-0m reach was calculated from the EC measurements was 0.90m^3/s.

Table 20: Table showing dilution gauging results at BRM1 during 2014 wet and dry seasons

2014 Season	Site	Reach length	Initial EC (µS/cm)	Peak EC (µS/cm)	Salt wave passage time (sec)	Discharge (m^3/s)
Wet	BRM1 600-400	200 m	20.4	54.7	900	5.87
Wet	BRM1 400-200	200 m	20.1	59.7	730	5.16
Wet	BRM1 200-0	200 m	20.9	46.2	1258	3.63
Dry	BRM1 600-400	200 m	25	54.2	4285	0.99
Dry	BRM1 400-200	200 m	25.3	82.6	3850	0.74
Dry	BRM1 200-0	200 m	25.3	83.5	3720	0.9

Table 20 shows the results from the wet and dry season dilution gauging tests. The table shows the discharge computed using Equation F, the initial and peak stream conductivity as well as the lengths of the selected reaches. The table indicates that during the wet season, the stream flow decreased with distance downstream, and indicating inflow of water into the subsurface. During the dry season, a similar pattern was observed. However, the difference between the two seasons was the rate of flow, which exceeded 5m^3/s during the wet season and were lower than 1m^3/s during the dry season.



	Aug-14	Nov-14
🟦 600-400	5.87	0.99
🟥 400-200	5.16	0.74
🟩 200-0	3.63	0.91

Figure 35: Measured flows using dilution gauging

7.2.3 Calculation of net inflows/outflows and their spatial distribution along the selected reach

During the 2014 wet season dilution test (August 2014), the difference in flow between the 1st and 2nd reach was calculated to be -1.53m^3/s, while the flow difference for the reach between the 2nd and 3rd reach, the difference was calculated to be -0.71m^3/s (Table 21). Both values indicated a net loss of water into the subsurface during this time. These results indicate that during the wet (high flow) season, groundwater was primarily recharged by surface water. The differences in flow computed between the selected reaches indicated that although flows were observed to decrease along some cross sections, the general flow trend was to surface water during dry seasons and towards groundwater during wet seasons. However, due to the presence of inflows along the valley sides as well as the presence of a reservoir behind the weir at BRM1, the overall trend in flows could not be completely identified.

During the 2014 dry season dilution test (November 2014), the difference in flow between the 1st and 2nd reach was calculated to be 0.17m^3/s, while the flow difference for the reach between the 2nd and 3rd reach, the difference was calculated to be -0.25m^3/s (Table 21). The decline in stream flow was seen at the reach between 400m-200m, which have many pools, which retard the passage of the salt wave and allow stream water to infiltrate into the streambed. However, this reach shows a gaining condition, with the lower reach (200m-0m) having a gain in stream flow which was indicated by the positive flow difference. These results indicate that during the wet season, groundwater is recharged by overlaying stream water, while the opposite occurs during the dry season with discharges form subsurface water storages contributing to stream flows.

Table 21: 2014 Seasonal flow differences in upper Berg River 600m

	Reach	Length (m)	Flow (m^3/s)	Difference
August 2014 (wet season)	200-0	200	3.63	-1.53
	400-200	200	5.16	-0.71
	600-400	200	5.87	5.87
	Reach	Length (m)	Flow (m^3/s)	Difference
November 2014 (dry season)	200-0	200	0.91	0.17
	400-200	200	0.74	-0.25
	600-400	200	0.99	0.99

Variation in the direction of exchange between groundwater and surface water observed along the 600m reach both during the wet and dry seasons. The morphological nature of the stream (Figure 36) throughout the selected reach caused much of the variation, as pools and riffles that retarded the flow of water were observed. However, the general direction of water flow along this reach was to groundwater during the wet season and towards the stream during the dry seasons.

Figure 36: Image showing irregular stream morphology

7.3 Discussion of differential stream gauging analysis results

The results presented in this chapter indicate that during the high flow (winter) season, the overlaying surface water recharges groundwater, while the opposite occurs during the low flow (summer) season. However, the presences of a weir and reservoir behind it have an influence of the direction of water. This is indicative of the impact of the weir and reservoir in retaining water below the streambed. It is unclear whether the water retained by the weir recharges groundwater, or remains afloat for discharge at a later stage. Differential stream gauging is an applicable method for determining the areas of groundwater-surface water interactions and determine the direction of flow during different seasons. In this study, this method proved useful in indicating the direction of interaction along the selected reach in the upper Berg River catchment. As previously stated, the presence of a gauging weir at the lower end of the study reach could have influenced the measurements. However, this approach has provided great insights on the directions of groundwater-surface water interactions in the pristine upper Berg River catchment.

Becker et al., (2004) used incremental (differential) stream flow gauging along a 40km long reach of the Ischua Creek and found a loss from the first two sites located up stream, to the last two sites located on the downstream reaches of the creek. These results, although generated in a longer stream reach, indicate that with distance downstream, the net gain of water changes to a net loss of water. Furthermore, it was found that although the measurements clearly indicated differences in discharge behavior, the resolution was not sufficient to identify point groundwater discharge or the distributed nature of discharges along the creek (Becker, et al., 2004). These results, compared to the ones generated in the current study, indicate that the differential stream gauging method does not provide the locations of inflow or outflow of water, and thus only give an indication of the flow dynamics in the studies reach. Thus, more spatially intense methodology should be used to determine the points where groundwater inflow/out flow is occurring.

Cey et al., (1998) applied the similar approach in a 450m reach of a small perennial stream boarded by agricultural lands in Ontario, Canada. In their study, it was reported that discharge increased from the upper reach to the lowest reach. The reason for such an increase was attributed to the differences in riparian zone width, vegetation and surface saturation conditions between the upper and lower reaches (Cey, et al., 1998). Consequently, this study by Cey et al., (1998) indicated that the stream flow measurements could not be used to infer net groundwater discharge/recharge on a small scale, however revealed the flow dynamics at the greater scale. Similarly, the present study indicates that the selected reach of the Berg River loses water during the dry season and gains water during the wet season. However, this indication may be affected by the presence of small contributing streams of water flowing along the valley as well as the water trapped by the weir and its reservoir.

Thus, the use of this methodological approach is insignificant in determining small-scale interactions; however, with the combination of other methods, it proves useful in determining larger scale interactions along reaches, to determine the directions and rates of exchange along the selected reach.

7.4 Summary of chapter

In summary, the present chapter aimed to address the third objective, which was to determine seasonal groundwater-surface water flow trends in a selected reach of the Berg River, using differential stream gauging in order to deduce spatial and temporal variations in groundwater-surface water interactions over the study period. The chapter showed that the use of the dilution gauging approach to stream gauging was an adequate tool for measuring stream flows in mountainous catchments with irregular streambed morphologies. The use of this method was also found to be sufficient for calculating any losses and/or gains to stream flow between consecutive stream reaches and to determine spatial and temporal groundwater-surface water flow trends. Thus, this approach can be applied to infer interactions between groundwater and surface water in such environments.

The results from the current chapter indicate a situation of net groundwater recharge (losses to stream flow) during wet (high flow) season, with a net discharge from subsurface water storages (gains to stream flow) during the dry (low flow) season. However, it was observed that this method alone does not provide points where groundwater-surface water interactions were occurring, but rather the larger scale seasonal stream flow variations within the selected reach. The present chapter confirmed that this was the case, with non-distinct points (reaches) identified where interaction between groundwater and surface water was occurring. This approach is a good approach to identifying streams dependent on discharges from subsurface water storages or streams that contribute to the recharge of water into the subsurface water storages. Thus, further work is required to identify the actual source of water in order to indicate that the gains or losses to stream flow are indeed from and to groundwater.

Chapter 8: Conclusion and recommendations

The main objective of this study was toapply a multi-methodological approach to determine groundwater-surface water interactions in a fractured rock environment. This approach was applied to a case study in the upper Berg River catchment to characterize and derive a proportion of stream flows contributed by subsurface base flows. The study comprised the application of three methods, i.e. hydrograph, hydrochemistry and differential stream gauging analyses. These methods were used to quantify and characterize interactions between groundwater and surface water to infer the possibility of decreases in the observed contamination.

Using the different filter algorithms yielded similar base flow contributions for all the selected gauging stations in the upper Berg River catchment (T test p-value =1). This approach showed that base flow contribution to stream flows in the catchment had seasonal variation in magnitude of contribution. However, discharges from subsurface water storages continue to discharge water throughout the year, with the greatest impact of this discharge observed during low flow periods. Activities such as stream flow diversions, damming and discharges from agricultural and human settlement areas are all shown to have a great effect on the base flow contribution computed at such sites. Consequently, the site located in the pristine area of the catchment provides the most representative depiction of the natural variations in base flow contributions under natural circumstances. Thus, it is recommended that continual stream flow measurements along with continuous tracer measurements be done to perform physically based base flow separation in order to define the actual source of water contributed from subsurface storages.

This section of the current study addressed the first objective, which was to establish the proportion of stream flows derived from groundwater discharges using automated base flow separation techniques. The main research question that was answered in this section was that of what the proportional contribution of groundwater to surface water flows during the dry and wet seasons was? It was shown that, indeed in the upper Berg River catchment, discharges from subsurface water storages maintain stream flows during periods of low flow, while also ensuring consistent source of water for the perennial Berg River. Base flow separation was achieved and indicated that at the Wolwekloof, Franschhoek and Berg River Dam gauging stations, stream flows were influenced by diversions, discharges from storm water drainage and irrigation return flows as well as the consistent discharge of water from the dam to maintain in-stream flow requirements (IFR’s).This finding shows that stream flow alterations, such as diversions and damming of rivers have profound impacts on the major components that generate stream flow. As such, diversions decrease the amount of water in a stream, while damming of rivers and the consistent release of water to maintain instream flow requirements, increase the contribution made by subsurface derived water. It is recommended that a more inclusive physically based separation be applied using more robust groundwater and surface water environmental isotopic information.

The second objective addressed by this section of the present study had the objective of characterizing groundwater and surface water quality and determine the main factors that control this water quality of water in the receiving water body. The effect of groundwater-surface water exchange fluxes on water quality was identified due to the similarities in groundwater and surface water sampling sites in the same vicinity having similar physicochemical signatures. Using multivariate statistical methods (Principal Component and Cluster Analyses), the dominant factors affecting groundwater and surface water quality were identified. Groundwater and surface water hydrochemistry in the upper Berg River catchment indicate that two major factors contribute to the predominant Na-Cl type, with slight inputs of Ca and HCO_3^-. The Na-Cl water type is indicative of the infiltration of Na-Cl rich surface waters. The slight contributions of Ca and HCO_3^-indicate natural biogeochemical process involved in interactions occurring between infiltrating water and aquifer material. Based on similarities in physicochemical characteristics, groundwater and surface water sampling sites in the upper Berg River catchment were grouped into three distinct groupings. The first group comprised groundwater and surface water sampling sites in the Berg River Dam area. Sites located in the Franschhoek River Valley area were grouped into one group. Surface water sampling sites located downstream of the confluence between the Franschhoek wastewater treatment works plant, Stibeuel River and Franschhoek Rivers were grouped into the last two clusters. These sites were characterized by high loadings of Cl and HCO_3^- Based on the similarities in groundwater and surface water physicochemical characteristics in the different clusters, interactions between groundwater and surface water in the sites within the cluster are inferred.

This finding suggests that proper management of surface activities is required in preventing contamination of groundwater resources. Furthermore, understanding the physicochemical characteristics of both groundwater and surface water is crucial to identifying areas of interactions. The hydrogeological conceptual model presented in Chapter 4 shows the shallow groundwater levels in this area and notes the presence of wetlands in the low-lying areas of the catchment. This shallow depth to water indicates that this catchment is prone to either discharge to surface water from groundwater or vice versa. This condition therefore places great threat on groundwater reserves to contamination from surficial derived contaminants and thus informs consistent groundwater and surface water monitoring to determine any detrimental effects that could be incurred as a result of the interaction between groundwater and surface water in this catchment. However, to combat this situation, increasing the number and spatial representation of the sampling sites within the catchment can aid in improving the knowledge on interactions between groundwater and surface water as well as indicate possible problem areas, *vis-à-vis* these interactions between groundwater and surface water.

Measurement of stream flow is a practical approach to infer groundwater-surface water interactions. In streams with irregular streambed morphologies, conventional stream gauging methods are inadequate. Thus, applying a tracer based approach to determine flows proved to be a good tool in such environments. The computation of differences in flows along a stream reach provided an indication of losing and gaining nature of the 600m reach. This approach confirmed results of the base flow separation, which indicate that groundwater is recharged by overlaying surface water bodies during the wet season and that the main source of water to stream flow was from a subsurface origin during low flow periods.

The third objective of this study was to determine the decreases and/or increases in stream flows as a result of interactions between groundwater and surface water in selected reaches of the Berg River, using differential stream gauging. This approach enabled the determination of temporal variations in groundwater-surface water exchange flux direction during the low and high flow periods. The research question that this objective aimed to answer was that of what the main direction of groundwater-surface water exchange fluxes was in the upper Berg River catchment. This section revealed that during high flow periods, groundwater was recharged by surface water, while the inverse was observed during periods of low flow. It is further noted that, although there is confirmation of this phenomena, the actual source of water that discharges into the stream is currently uncertain. Therefore, to understand the true source of water discharged to the stream it is recommended that further tracer analysis be conducted.

Findings of this methodological approach show that using dilution gauging was a good tool for stream gauging in mountainous catchments with irregular streambed morphologies. This approach, when used over consecutive cross sections, enables the computation of groundwater-surface water exchange directions. Although the quantities are not identified, as the difference in flow may result from streambed heterogeneity, this approach is a good indicator of areas of interaction between groundwater and surface water. This study further exasperates the requirement for a combination of field methods in order to identify, characterize and quantify groundwater-surface water interactions in mountainous catchments, such as the upper Berg River catchment.

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