Assessing river-aquifer interaction for sustained water abstraction, Lower Vaal Catchment, South Africa

By

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Declarations

I, Lucky Baloyi, declare that *assessing river-aquifer interaction for sustained water abstraction, Lower Vaal Catchment, South Africa is* my 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: Lucky Baloyi

Date:………………

Signed:………………………..

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Abstract

Several methods are available in the literature for the estimations of river-aquifer interactions. However, the selection of which depends on available data, local geographic and topographic conditions, the spatial and temporal scale required, and the reliability of results obtained by different methods. This study was caried out to assess the river-aquifer interaction for sustained water abstraction using the Lower Vaal River catchment as an example. The study aimed to improve knowledge and understanding of using multi-methods for the assessment of river-aquifer interactions. To achieve this, the study had three objectives namely, 1.) to investigate areas where river recharge aquifers exist (focussed recharge area), 2.) to determine areas where aquifer recharge river exist (aquifer discharge areas), and 3.) to develop a conceptual model of the groundwater process that explains interactions. The study question was "how are multi-methods applied for quantification and characterizing river-aquifer interaction". The argument was that unless the application of multi-methods to quantify and characterize river-aquifer interactions is improved, the feasible recommendation for sustainable water abstraction can be erroneous.

The study applied three different techniques to quantify and characterize river-aquifer interactions namely, hydrochemistry, stable water isotopes, and baseflow separations techniques. The field measurement, laboratory assessment, and record review methods were used for the collection of primary and secondary data. The piper diagram, scatter plot, Principal Component Analysis (PCA), and liquid water isotope analyser were used to analyse the chemistry data. The PCA was used to estimate the contributions of selected parameters based on similarities of chemistry data. The baseflow separation method was used to derive the composition of the aquifer water contribution to the total river flow. To achieve this, a 2-D line analysis method build on Microsoft excel was used to separate the component of total river flow derived from subsurface contribution. The hydrological time series river flow data was collected using the record review method from three river gauging stations namely: C9H003 upper stream, C9H009 middle stream, and C9H026 lower stream. Thereafter, one-parameter separation algorithms were applied to obtain estimates of discharges rates from the subsurface.

The results showed that all the river water samples maintained a single group water type classified as Ca-Mg-HCO_3 mixed of different water types. The aquifer water samples revealed four distinct groups of water types classified as Ca-HCO_3, Ca-Cl, Na-HCO_3, and Ca-Mg-HCO_3 mix types. The Ca-HCO_3 and Ca-Mg-HCO_3 were found in localities near the reaches (upper, middle, and lower stream locations) which were associated with active recently recharged areas, therefore, confirming river recharge aquifers. The isotopes plot showed that river water samples were much more exposed to evaporative enrichment (3.64% for $\boldsymbol{\delta}^{2}$H and $\boldsymbol{\delta}^{18}$O) in the dry season and less exposed (-7.58 $\boldsymbol{\delta}^{2}$H and -1.13% $\boldsymbol{\delta}^{18}$O) in the wet season as expected. The isotopes results showed that few of the aquifer water (9%) was recently recharged by the freshwater system in the upstream and midstream, of which the rest of the remaining water samples (91%) suggested an alternative source of aquifer recharge. The Na-HCO_3 water type was found in the upper stream location representing deep aquifer water mostly existing in discharge areas. This water type was not expected given that the geology (gravel and sand) does not contain the saline characteristics. Despite this, the results of the stable isotope did not confirm the source of discharge areas as suggested by hydrochemistry.

The baseflow index (BFI) results showed that the dependency of the total river flow to aquifer discharge contributed 7.24 % in the upper stream, 7.31% in the middle stream, and 7.32% in the lower stream. The study found that the groundwater flow regime was controlled by geology, structures, and topography as demonstrated by prominent andesite, gravel, and sandstone layers that typically form breaks in the hill slopes below which seepages (or interflow) were often observed. The conceptual model showed that the river was losing and gaining water in all reaches. These findings provided empirical evidence that the use of hydrochemistry, stable isotopes, and baseflow separation methods can improve knowledge and understanding of assessing recharge and discharge areas thereby confirming the interaction between river and aquifers.

Keywords: conceptual model, baseflow, discharge areas, hydrochemistry, multi-methods approach, recharge areas, stable isotopes.

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Chapter 1: General Introduction

1.1. Study overview

This study is about assessing the river-aquifer interaction. The study uses a multi-method approach to quantify and characterize river-aquifer interactions. The study aims to determine areas where the river is recharging the aquifer and where the aquifer discharging into the river. The fluxes from either water body are estimated using multi-methods. A conceptual model is developed to explain groundwater processes for the interaction in the study area. The information from the analysis on river-aquifer interaction informs the best practice for the sustained abstraction of water resources in the study area. A systematic literature review method refines the stated gap analysis and guides the selection of methods. Water samples on the desired parameters are collected and analyzed following standards procedures and reviewed methods. The study follows a quantitative research design where the focus is on field measurements and laboratory analyses. The secondary data on time-series streamflow patterns are accessed from various databases for analysis. The methods for the study include the baseflow separation technique for the fluxes analyses and environmental tracers (hydrochemistry and stable isotopes) for tracking the source of water in each water body.

1.2. Background of the study

Globally, the interaction between rivers and aquifers has recently received recognition as one area of research that can improve the knowledge and understanding of the hydrological cycle (Winter *et al,* 1998). Thus, there is a need to better understand the semi-arid river-aquifer interaction as it provides better scientific insight for sustainable water abstraction (Yang *et al*, 2013). Methods are available in the literature for the assessment of river–aquifer interactions. However, the selection of such methods depends on available data, local geographic and topographic conditions, the spatial and temporal scale required, and the reliability of results obtained by different methods (Islam *et al,* 2016). Common approaches employed in the investigation of river-aquifer interaction include quantification of changes in water stage and discharge, water temperature, environmental tracers (hydro chemical and isotopes), and hydrograph separation (Sophocleous, 2002). The selection of methods used in this study is informed by these methods.

Although these methods each have their benefits and limitations, it is generally accepted that a multi-method approach, in which various methods are combined to provide the most accurate picture of interaction with the greatest levels of certainty (Kalbus *et al.,* 2006). For example, (Oxtobee *et al,* 2002; Langhoff *et al,* 2006; Rautio *et al,* 2011) conducted studies for identifying interactions between rivers and aquifers using multiple field investigations methods. (Anderson *et al*., 2005; Marimuthu *et al*, 2005) used differences in hydraulic heads between river and aquifer. On the other hand, (Grindley, 1969; Hough et al., 1998; Chapman et al, 2002) used the traditional hydrogeological methods of hydrograph separation technique using time series data to derive baseflow from the total flow. (Okkonen *et al,* 2012) used water balance, and Darcy's method supplemented by river flow gauging and seepage measurements for better understanding and estimating aquifer recharge and discharge. These studies show that river-aquifer interaction is better understood when a multi-methods approach is used, hence the application of the multi-methods approach in this study was used.

Apart from traditional hydrogeological methods, hydrograph separation techniques using environmental (hydrochemical and isotopes) as tracers, water temperature tracers at the riverbed and combinations of different geophysical and tracer methods are widely used (Slash and Farvolden, 1979; Buttle, 1994; Uhlenbrook *et al*, 2008); Wenninger *et al*, 2008). Specifically, δ2H and δ18O are considered ideal conservative tracers that offer insights into the groundwater system's recharge and flow since they make up the actual water molecule and their compositions remain the same unless the flow path has phase changes or fractionation (Clark *et al,* 1997). This has informed the selection of environmental tracer methods (hydrochemistry and stable water isotopes) in this study because it has been widely used and proved to have yielded a robust result.

The current understanding of river-aquifer interactions and associated conflicts of sustainable water abstraction is well documented in the literature review. However, the challenges of selecting multi-methods techniques suitable for the estimation of river-aquifer interaction are not yet well documented, especially in the semi-arid region (Winter *et al*, 1998; Sophocleous 2002; Verry 2003; Barlow *et al,* 2012; Yang *et al,* 2017). Previous studies have suggested strong connections between aquifers and rivers (Sear *et al,* 1999; Jasechko *et al*, 2016). Thus, to further plan sustainable water abstractions, it is important to identify the groundwater recharge and discharge sources and their relative contributions to the present hydrogeological situation. This study provides knowledge and understanding on using the multi-methods approach for assessing river-aquifer interaction in the semi-arid region.

The reviewed literature in this section focuses on studies conducted in Africa excluding South Africa. The purpose of this review is to obtain insight into the current debate on the topic in the regional context. The river-aquifer studies in Africa have been carried out at a small-scale focusing on a catchment area (drainage region) or on an ad hoc basis, to define local fundamental aspects of river-aquifer interaction (recharge and discharge) such as its source, timing, magnitude, and distribution (Wang *et a.,* 2010). The processes of river-aquifer interactions are a fundamental part of the hydrological cycle. Therefore, in the semi-arid region, groundwater is often the major water resource of water supply and is likely to be prone to depletion due to unsustainable water abstraction (Wang *et al,* 2010). These studies adopt a local-scale perspective and address spatial and temporal variability of river-aquifer exchange, but they have primarily focused on small streams and low-order drainages in mountainous terrain. Despite this growing interest in conducting river-aquifer interactions studies, investigations of the effects of subsurface heterogeneity on river-aquifer exchange on larger scales are lacking. This remains a challenge with its untold implications for water resources.

In central Sudan, previous studies have been carried out on river-aquifer interaction using isotopes and numerical modelling. Their studies found that evapotranspiration loss of groundwater is the only prevailing discharge mechanism in the region. Head differences and increased isotopic concentration in the vicinity of the river suggested recharge from the river from the subsurface flow. Reduced chloride content and relatively heavier isotopic composition indicated recharge from the riverbed into unconfined aquifers. It was concluded that an average recharge of 4–8 mm/year is adequate to maintain the current hydraulic gradient, whereas a similar amount of evapotranspiration discharge kept the hydrogeologic system under natural equilibrium (Abdalla, 2012).

Leduc *et al.,* 2001) used an isotope tracer method to estimate groundwater recharge in semi-arid, Niger. Their study showed that unexpected groundwater levels rise despite the severe droughts of the 1970s and 1980s. In the continental terminal in the southwest of Niger, the recharge is explained by a change in land use. In Ethopia, Ayenew, (2008) carried out hydrological system analysis and groundwater recharge estimations using semi-distributed models and river discharge in the Meki River Basin. The river discharge method involved estimating recharge using river discharge records which use a digital recursive filter to separate baseflow from the total daily discharge. The channel loss was found to be 14.4 mm which confirmed indirect recharge from the Meki River to the underlying aquifer. Both long-term and field discharge records revealed that the total flow and recharge showed substantial spatial and temporal variations. The study recommended a detailed groundwater recharge estimation in the catchment demanding the installation of an automated river gauging station and tracer to help understand the recharge in the fractures and relationships between variables. These results have provided the significance of applying a multi-methods approach for evaluating recharge and discharge estimates in confined and unconfined aquifer systems.

In South Africa, since 1998 after the promulgation of the National Water Act, it has emerged that groundwater-surface interaction is poorly understood and even more difficult to quantify. In 2007, the Water Research Commission (WRC) together with the Department of Water Affairs (DWA) commissioned a national study identifying rivers dependent on groundwater for sustaining baseflow and developing methods and models to quantify the groundwater contribution to baseflow (DWA *et al*, 2007). The study used data sets generated during the Groundwater Assessment Phase II project (GRAII), the Pitman model to facilitate the quantification of the groundwater contribution to baseflow. This entailed consideration of recharge, groundwater discharge to streamflow, and abstraction. Since then, studies of the river-aquifer interactions on a local and regional scale have been taking place with increasing intensity over the past decade. However, little has previously been known about the nature of river-aquifer interaction, including the recharge and discharge mechanisms. This study aims to assess the river-aquifer interaction in the Lower Vaal River Catchment as an example. There are no previous records about the hydro geochemistry and the isotope hydrology data of rivers and aquifers stored in database systems about the study area. However, there are several similar relevant studies done in other parts of South Africa about river-aquifer interaction which have provided key insights on key aspects.

Welderufael *et al*, (2010) used stream flow analysis and comparison of methods for baseflow separation in Modder River, Free State Province, central South Africa. Four basic hydrograph separations methods were used to achieve the aim of the study, namely the Nathan and McMahon method, the Chapman method, Smakhtin, and Watkins, and the frequency distribution analysis. All the methods gave a higher percentage of the low flow component, except for the Smakhtin and Watkins method which underestimated it. The result revealed that the annual baseflow component ranged between 65%, and 75% with an average of 71%. The Chapman, (1999) method gave more consistent than the other methods. Findings of this nature provide evidence of why it is important to apply a multi-methods approach in assessing river-aquifer interaction for sustainable water abstraction, hence this study chose to follow a similar approach.

In another similar study in the Eastern Cape, Sami, (1992) used chemical and isotopic tracer methods to study the groundwater recharge mechanisms and geochemical processes in a semi-arid catchment. The hypothesized recharge and salinization mechanism was that large storm events periodically dissolve accumulated surficial meteoric salts and, after a period of evaporative enrichment at or near the soil surface, leach them into the groundwater. Geochemical variations imply that spatial differences exist in recharge volumes, evaporative enrichment, or the extent of leaching of surficial salts. This current study aims to explore the possibilities of using similar methods for the identification and quantification of river-aquifer interactions. This includes the baseflow separation techniques, hydrochemical, and stable isotopes tracers.

1.3. Problem statement

The assessment of the use of a multi-methods approach to quantify and characterize river-aquifer interactions remains poorly understood especially in a semi-arid region. This is the problem because the multi-methods approach has a great potential to improve the understanding of river-aquifer interaction and continue to provide reasonable estimates of recharge and discharge other than when using a single method. If this problem is not addressed, then the role of the multi-methods approach in the quantification and characterization of river-aquifer interaction will remain unknown. Globally, most studies show that river and aquifer water is a connected component of the hydrological cycle. An integrated approach that consists of multiple measuring methods has not yet been fully applied to investigate river-aquifer interactions. Ayenew, (2008) argued that the hydrological behavior of the groundwater is very much dependent on what happens in surface water or visa-visa. To understand the interaction between aquifers and river water, the quantification and characterizations of river-aquifer interaction are imperative to provide important scientific insight for integrated sustainable water abstraction. This is more relevant in semi-arid areas where groundwater is often the main source to feed river discharge and maintain groundwater-dependent ecosystems (Yang *et al*, 2014).

1.4. Research question

The question to be answered in this study is: that how are multi-methods applied for quantifying and characterizing river-aquifer interactions?

1.5. Research hypothesis

The current study argues that unless the application of multi-method for river-aquifer interaction improves, the feasible recommendation for the sustained abstraction of water can be erroneous.

1.6. Study aim and objectives

1.6.1. Study aim

The study aimed to assess river-aquifer interaction for sustained water abstraction to improve knowledge and understanding of using multi-methods for assessing river-aquifer interaction

1.6.2. Study objectives

a). To investigate areas where river recharge aquifers by estimating contributions of river water to the underlying aquifers (focussed recharge).
b). To determine areas of aquifers recharge river by estimating contributions of the underlying aquifer to river flow (aquifers discharge)
c). To develop a conceptual model of groundwater processes that explain interactions of river and aquifers water resources.

1.7. Study rationale

1.7.1. Significance of the study

With increasing interest in conducting river-aquifer interaction studies using multi-methods, significantly fewer studies have been conducted on river-aquifer interactions in the Lower Vaal catchment. Thus, little is known about the role of multi-methods applications for the quantification and characterization of river-aquifer interaction in the study area. The study is initiated based on contributing scientific knowledge and improving understanding of multi-methods application for assessing river-aquifer interaction. Understanding the interaction of river and aquifer is imperative for sustainable water abstraction at the catchment level.

Therefore, the broader contribution of this study is by presenting the findings to the local and international groundwater conferences. Furthermore, the findings of this study are important and beneficial to the field of hydrogeology by contributing to the published literature review material for learning and teaching. Previously published literature review materials showed that river-aquifer interaction studies focussed mainly on the physical, chemical, and biological processes as well as the physical properties of streambeds using a single method (Boano *et al*, 2014, Constantz, 2016). This study focuses on using the multi-methods approach to identify and quantify river-aquifer interaction to ensure reasonable estimates of recharge and discharge areas. This is important because the role played by using multi-methods in assessing river-aquifer interaction has increasingly been recognized in the field of hydrogeology (Stubbington., 2012; Groll *et al*, 2016). The knowledge acquired in this study informs the basis for the selection of appropriate methods applicable to assess river-aquifer interaction in the semi-arid region.

1.8. Study scope and nature

1.8.1. *The conceptualization of the study*

This current study is part of the bigger project initiated by the then Department of Water and Forestry (DWAF) in 1995 where the aim was to develop methodologies and data that support groundwater resource quantification per defined management unit (GRA II project). The second objective of that project was to review methods to quantify groundwater-surface water interactions and to develop a generic algorithm that can be applied to estimate groundwater-surface interaction on a national scale. While previously published studies used a single method approach to investigate groundwater-surface water interaction, this current study assesses river-aquifer interactions using the multi-methods approach to quantify the groundwater flow pathways. This current study consists of three specific objectives of which the third objective is to develop a conceptual model of groundwater processes that explain interaction to achieve the main objective of the study. The overall aim of this study is to obtain better improved knowledge and understanding of the use of the multi-methods approach for evaluating river aquifer interaction thereby improving support and recommendations for sustainable water abstraction.

1.8.2. Scope of the study

The current study is about the use of a multi-method approach for assessing river-aquifer interaction for sustained water abstraction. This study is mostly concerned with the understanding of the application of a multi-methods approach for assessing river-aquifer interaction in the semi-arid region. The study is mainly interested in quantification and characterization of the river-aquifer interactions to develop a conceptual model of groundwater processes that explain interaction. In addition, the study is further interested in identifying areas where river recharge aquifers, aquifer discharge, identifying flow pathways and directions.

1.8.3. Nature of the study

This study uses a quantitative research approach to address the three research objectives, research problem, and answer the research question. The quantitative approach involves the use of numerical data collected from different sites to establish the relationship between river and aquifers. The study area is characterized by a low flow river and reduced groundwater level due to insufficient rainfall recharge aquifers during the dry season. This study is using the multi-method approach for assessing river-aquifer interaction by estimating exchange fluxes using hydrochemistry as confirmatory analysis and stable isotopes techniques as a tracer to address objectives one and two while the baseflow separation technique is used to address objective two of the study. Objective three is addressed by collecting all the available data and information based on modeling purposes.

1.9. Outline of thesis report

The thesis outline consists of six chapters and is summarised as follows: Chapter 1 provides the background overview of the study, research problem, research question, research hypothesis, aim and objectives, significance, conceptualizations, scope, and nature of the study. Chapter 2 presents reviewed literature that informs the study from the global, regional, and national levels to conceptualize the study. The reviewed literature aims to show what is known and not known about the use of multi-method in assessing river-aquifer interaction. The reviewed literature has been presented systematically and analytically to support the need for the present study. The theoretical, conceptual, and research frameworks have been presented to guide the academic orientation of the present study. Chapter 3 describes the study area settings where the research is being conducted. In this chapter, the research explains in detail the physiographic features present and links the relationship of the features with the study aim. In other words, this chapter assesses the potential influence of the features in the study area on interaction. Chapter 4 provides the research designs and methods used to collect and analyse the data to address the three research objectives and answer the research question. Chapter 5 presents the research findings and provides a detailed analysis of the results and discussion to address the research question thereby defending the research argument with adequate and valid results. Lastly, Chapter 6 provides conclusions and recommendations on gaps identified during this study for future research development studies.

Chapter 2: Literature Review

2.1. Introduction

Chapter one has provided an introduction to the study in terms of the research problem, objectives, scope, nature, and rationale. The current chapter present reviewed literature that informs the study from the global to the national level to conceptualize the study. The reviewed literature aims to show what is known and not known about the study topic. The reviewed literature has been presented systematically and analytically to support the need for the present study. The theoretical, conceptual, and research frameworks have been presented to guide the academic orientation of the present study.

2.2. Previous studies on groundwater-surface water interaction

2.2.1. Global context of groundwater-surface water interaction

Globally, the groundwater-surface water interaction studies are becoming increasingly important areas of research due to their importance for the ecological health of streams and rivers (Winter, 2001; Woessner, 2000; Findlay, 1995; Ford *et al,* 1989) and groundwater ecosystems (Hancock *et al,* 2005; Humphreys, 2009). The global context in this study refers to previous studies conducted at the continent's level outside Africa. The groundwater-surface water interactions refer to the movement of water between groundwater and surface water systems leading to the mixing of their water qualities. Understanding pathways and quantifying the fluxes between surface water and groundwater systems are essential to addressing sustainable water abstraction. However, interactions between groundwater and surface water remain a challenge to characterize and quantify due to aquifer heterogeneities and the problem of integrating measurements at various scales (Sophocleous, 2002; Van Tol, 2016; Winter, 1999).

Research efforts relating to groundwater-surface interaction have recently focused on the use of a multi-method approach to estimate fluxes between aquifers and streams or rivers. Several methods have been developed to evaluate the interaction between groundwater and surface water ranging from direct, indirect, and a combination of both methods (Mary, 2006). Direct methods include seepage meters, piezometers, and stream flow measurements (Boulton., 1993; Baxter *et al,* 2003; Kalbus *et al,* 2006; Rosenberry., 2008) whereas indirect methods include indicators such as water chemistry and mixing properties, or tracers such as heat. Depending on the study purpose, appropriate methods should be chosen for the respective study aim, objectives, and study question. The methods are grouped concerning the hydrologic zone they are applied to, i.e., aquifer, surface water, and transition zone (Kalbus *et al,* 2006). This subdivision is somewhat in disagreement to consider groundwater and surface water an inseparable unit but seems reasonable for the sake of clarity (Kalbues *et al,* 2006). Scanlon *et al*, (2002) presented an overview of techniques for quantifying groundwater recharge on different space and time scales. Some of these methods can equally be applied to measure groundwater discharge to streams and recharge through the streambed. Landon *et al,* (2001) compared instream methods for measuring hydraulic conductivity aiming at determining the most appropriate techniques for use in sandy streambeds. Concerning the study aim, the knowledge and understanding of the application of the multi-methods approach in the semi-arid region are reviewed.

Andersen *et al,* (2008) analyzed stable isotopes 18O and 2H in water samples from rainfall, surface water, and groundwater within the semi-arid Namoi River catchment in New South Wales (NSW), Australia. The study was aimed to demonstrate that the analysis of the stable isotopes of water (18O and 2H) can be extremely useful in providing further knowledge and understanding of the hydrogeological processes occurring within a productive aquifer system. The shallow groundwater near the Namoi River shows considerable enrichment compared to average groundwater signatures and plots in between the Local Meteoric Water Line and the Local Evaporation Line on a 2H and 18O. The study reveals many complex hydrological processes occurring in the catchment. The results show that the groundwater sample near the river have been recharged from the Namoi River, demonstrating that there is a hydraulic connection between the two water resources. Their study concluded that δ^{18}O and δ^{2}H of rainfall, surface waters, and groundwater provide an important tool for understanding hydrological processes such as recharge and groundwater-surface water interaction within semi-arid catchments. In this study, the groundwater processes are used to explain river-aquifer interaction for sustained water abstraction.

In Germany, Kalbus *et al,* (2006) reviewed methods for measuring groundwater-surface water interactions. The purpose of the study was to provides an overview of the methods that are typically used in aquifers and surface waters when studying interactions and show the possibilities of application in the transition zone. The methods applied in studying the interactions between groundwater and surface water included firstly the analysis of regional groundwater flow concerning topographical characteristics and surface water bodies to determine what type of interaction may be occurring in the study region. The water-table map was used to deliver information on the elevation of the groundwater table and the direction of groundwater flow. The water-table contour lines were used to indicate whether a stream reach is gaining with contour lines pointing in the upward direction or losing with contour lines pointing in the downward direction. They revealed that methods differ in resolution, sampled volume, and the time scales they represent. Often, the choice of methods constitutes a trade-off between the resolution of heterogeneities and sampled subsurface volume. The study concluded by indicating that all methods have their limitations and uncertainties. However, a multi-scale approach combining multiple techniques can considerably reduce uncertainties and constrain estimates of fluxes between groundwater and surface water. The findings of this study have provided more evidence to support the need of conducting the current study. This is because of the limitations and uncertainties associated with the various methods.

In the mountainous Bringi catchment of Kashmir Himalaya, India, Nadeem *et al*, (2018) determined groundwater-surface water interactions using environmental isotopes. Water samples from precipitation, snow melt, streams, and springs were collected for δ18O, δ2H, and Tritium on a bimonthly basis. The strong correlation (r2 =0 .97) between the isotopic composition of streams and springs indicates the streams and springs either share similar catchments or the springs are recharged by the streams. Chloride mass balance and isotopic mass balance studies suggest that the surface recharge component averages 337.35m^3/s, which is about 75% of total stream discharge during the high flow period. Similarly, the contribution of surface water to groundwater recharge during the low flow period averages 7.5m^3/s, which is about 18.6% of total stream flow.

In the northeast China, Zhang, (2016) conducted a study on the interaction between surface water and groundwater and its effect on water quality in the Second Songhua River basin. The purposes of the study were to: quantitatively interpret the relationship between surface water and the groundwater by hydrogen and oxygen stable isotopes; simulate the hydro chemical composition and discuss the mixing processes of the surface water and groundwater and assess the water quality of surface water and groundwater. The result revealed that the water type of the river waters and shallow groundwater was Na–HCO3; however, the water type of the thermal spring was Na–Cl. The study also showed that the groundwater table was 6 m which was higher than the river stage height, indicating that the shallow groundwater may discharge into the river. The contributions of shallow groundwater and river water from the upper reaches to the river water at Wujin village were 18.7% and 81.3%, respectively, and according to the two-component mixing equation of oxygen stable isotope, the river water may recharge from the shallow groundwater from upper reaches.

In the United State of America, Killian *et al,* (2019) evaluated groundwater and surface-water interaction using hydrograph-separation techniques and groundwater-level data throughout the Mississippi Delta. The study aimed to provide a computationally simple means for quantifying temporal changes in streamflow using existing streamflow data to detect potential changes in groundwater level elevations that help to improve the understanding of groundwater-surface water interaction in alluvial settings. The spatial and temporal trends in streamflow and baseflow at five sites were quantified using the hydrograph-separation method to determine if observed streamflow and baseflow trends were statistically significant. The analysis was conducted using the United States Geological Survey Groundwater Toolbox open-source software and daily hydrologic data provided by a spatially distributed network of paired groundwater boreholes and stream gauge sites. The study found that statistically significant reductions in stream baseflow occurred in areas with substantial groundwater level declines. The baseflow contribution to streamflow was moderate to high (average annual BFI = 0.805) and varied seasonally. The groundwater contribution to streamflow in the most upstream study site was moderate to low (average annual BFI = 0.366), and the degree of baseflow index contribution varied between high- and low-flow events. A conclusion of the study was that characterizing and defining hydrologic relations between groundwater and surface water help water resource managers refine a regional groundwater flow that is used to aid water resource managers in future decisions concerning the alluvial aquifer. Thus, this study has an objective to determine the subsurface contribution to river flow using the baseflow separation technique.

2.2.2. Regional context of groundwater-surface water interaction

The regional context in this study refers to previous studies conducted in Africa excluding South Africa. The groundwater-surface water interactions studies in the regional context are limited despite the important influence that these studies have on the sustainability of water abstraction (Kebede *et al,* 2021). There is growing interest among hydrology and hydrogeology communities in understanding the role of multi-methods applications in evaluating groundwater-surface water interaction (Condon *et al,* 2020). Understanding groundwater-surface water interaction in the regional context is equally important considering the implications it has on water quality, water quantity, and the health of aquatic ecosystems (Kebede *et al*, 2021). For instance, contaminated groundwater discharge can degrade surface water bodies and associated habitats while over-abstraction of groundwater can result in the flow reduction of surface water resources and the contamination of freshwater aquifers. Methods are available that can be used to quantify and characterized groundwater-surface exchange in different physiographic environments. However, the selection of the most appropriate methods remains a challenge. Therefore, this study aims to provide knowledge and understanding of multi-method applications for assessing river-aquifer interaction at the catchment level.

Edjah *et al*, (2017) investigated hydrogeochemistry and stable isotope hydrology of surface water and groundwater systems in the Ellembelle District. of the Western region of Ghana. water samples from 7 rivers, 13 hand-dug wells, and 18 boreholes were sampled. For the rivers, the water samples were collected from the middle of the rivers to ensure the perfect mixing of the water. The dominant hydrochemical facies for the rivers were Na–K–HCO3- type while that of the groundwater (hand-dug wells and boreholes) were Na–Cl and Na–HCO3- type. According to the Gibbs diagram, the majority of the river samples plot in the evaporation crystallization field and the majority of the hand-dug wells and the boreholes water samples plot in the rock dominance field. From the stable isotope composition measurements, all the rivers appeared to be evaporated, 60 % of the hand-dug wells and 70 % of the boreholes clustered along and in between the global meteoric water line and the local meteoric water line, suggesting an integrative and rapid recharge from meteoric origin. Results of this nature are common in Africa; hence, a similar approach was followed in this study where hydrochemistry and stable isotopes techniques were applied to help to understand the areas of river recharge aquifers (recharge) and aquifers recharge river (discharge).

Kelly *et al*, (2019) investigated groundwater discharge to rivers in the Shire River Basin, Malawi in Malawi using the base flow index (BFI) approach. The study aimed to characterize groundwater discharge to rivers in the Shire River Basin. The objectives were to quantify the annual and seasonal baseflow index and to evaluate long-term trends in the baseflow index. The smoothed minima method was applied to river flow data from 15 gauges in the Basin (ranging from 1948 to 2012) and the Mann-Kendall (MK) statistical test was used to identify trends in the BFI. Expressing the baseflow index as a percentage, the results indicated that annual groundwater discharge to the rivers ranges from 19% in the Rivirivi River to 97% in the Shire River. Seasonally, a minimal difference was found between the annual and the wet season baseflow index. Generally, the dry season baseflow index was higher than those of the wet season with most rivers increasing to >75%. This current study is expected to provide similar insights into aquifer discharge findings. Of course, to achieve that, reliable and validated long-term hydrological time series data is required to separate the quick flow and base flow from the total river flow in the Lowe Vaal River catchment as a case study.

In East-Central Africa, Osman *et al,* (2012) investigated groundwater recharge and discharge in semi-arid regions interpreted from isotope and chloride concentrations in north White Nile Rift, Sudan. The study also examines the ability of stable isotopes and chloride concentration to recognize groundwater recharge/discharge relations. 84 water samples were collected from shallow and deep boreholes, rivers, and rainfall. Samples were analyzed for the stable isotopes Deuterium (D) and Oxygen-18 (18O) as well as for chloride ion concentration (Cl^-). The spatial and vertical variation in isotopic signature and chloride concentration in the groundwater showed similar patterns and indicate local recharge and evaporative discharge. Chloride concentration increases down the gradient from the recharge area and reaches its peak in the discharge zones indicating a lack of recharge from direct infiltration down the gradient, evaporation, and prolonged rock-water interaction. The study concluded that an average recharge of 4–8 mm/year is adequate to maintain the current hydraulic gradient, whereas a similar amount of evapotranspiration discharge keeps the hydrogeologic system under natural equilibrium. This study has deliberately excluded chloride mass balance methods, instead, the study chose to apply the hydrochemistry, stable isotopes, and baseflow separation methods to validate the hypothesis which argues that unless the application of multi-methods for river-aquifer interaction improves, the feasible recommendation for the sustained abstraction of water can be erroneous.

In Ethopia, Kebede *et al,* (2020) investigated the regional-scale interactions between groundwater and surface water under changing aridity: evidence from the River Awash Basin. The study aimed to integrate evidence from geochemical tracers and piezometric to advance the understanding and characterization of regional-scale, groundwater-surface water interactions in the River Awash Basin. A total of 40 sites were measured twice each on the main river channel and additional 16 measurements of Lake and adjacent groundwater were also conducted. Their study found that hydrological characteristics are consistent with those observed in other semi-arid and arid basins where rivers are predominantly losing and act as a source of recharge rather than as a sink for groundwater discharge. Further, regional groundwater flow originating from the highlands exits the catchment rather than discharging to the riverine drainage. In this study, the groundwater flow, recharge, and discharge distribution of the aquifer geometry were used to explain interaction processes at the catchment level which is what the third objective of this study aimed to address.

In the semi-arid Sokoto basin, northwestern Nigeria, Adelana *et al,* (2003) investigated the characteristics of groundwater-surface water interaction using isotope and geochemical analysis methods. The overall aim of the study was to evaluate and characterize water resources in the basin in terms of quality and quantity to aid planning and management to meet the demands of the growing population. In achieving the aim of their study, 190 samples from dug holes and tubeless, boreholes, lakes, and rivers were collected. As a reference to ground water, 10 rainwater samples were collected from 3 different stations (Goronyo, Wurno, and Sokoto) for isotope analyses. The results showed distinct water groups from both surface and groundwater. Hydrochemical character reveals that groundwater is of Ca-Mg-HCO_3 while surface waters (rain and rivers) are characterized by alkali-calcium-bicarbonate. A plot of isotopic composition showed five water groups that can be distinguished. Groups I-III are of groundwater origin while groups IV and V represent surface water origin. It was concluded that the aquifers of the Sokoto basin generally contain good quality groundwater of Holocene age (100 to 10,000 years BP). These findings provided knowledge and understanding of the implications of groundwater quality influencing surface water quality thereby confirming the interaction between the two water resources. Therefore, analyzing water chemistry can provide insight into groundwater-surface water interaction.

2.2.3. National context of groundwater-surface water interaction

In South Africa, Studies for groundwater-surface interactions have been conducted by Madlala, (2015) in the upper Berg catchment, western Cape. South Africa requires more studies for the understanding of groundwater-surface water interaction at local and national catchment levels using the multi-methods approach to facilitate appropriate sustainability of water resource abstraction (WRC, 2004). The national context in this study refers to all previous groundwater-surface water interaction studies conducted in nine provinces of South Africa. Similar to other countries in the world, South Africa has managed groundwater and surface water resources as a separate resource until the promulgation of the National Water Act (Act 36 of 1998) which required water resources to be protected, used, and managed in a holistic and integrated fashion. Since then, the ground water-surface water interaction started receiving increasing focus in South Africa due to its importance not only to ecologic systems, water quality, water quantity, and water allocations, but also important for the sustainability of water resource abstraction.

In the South African context, the Pitman model was acknowledged as state-of-the-art due to its widespread use and acceptance, ease of parameterization, and acknowledged reliability (DWAF, 2005). However, like most conceptual surface water models, it fails to simulate groundwater-surface interactions accurately and was designed as a surface water resource model. Xu *et al,* (2011) reviewed groundwater-surface water interaction in the South African context. His study aimed to review past research on conceptualization and quantification of the groundwater contribution to surface water bodies and flows in the context of the South African water hydrogeologic setting. The study found that the most common approach in South Africa for implementation of the groundwater-surface water interactions has been the estimation of average annual flux rates at the regional scale of quaternary catchments using baseflow separation techniques and then applying a water-balance approach, subtracting the groundwater discharge rate from the recharge rate using. Analysis of hydrochemistry and stable isotopes of oxygen and hydrogen has been the tool increasingly used to argue the investigation of groundwater-surface water interaction. The hydrochemistry, stable isotopes, and baseflow separation methods have been less applied in the Vaal catchment and it is where their selection in this study was based on to provide better-improved knowledge and understanding for assessing interaction using Lower Vaal as an example.

In the Western Cape, Madlala, (2015) investigated groundwater-surface water interaction to quantify and characterize the quality of water resources in a fractured rock aquifer system in the upper catchment of the Berg River. This study aimed to quantify groundwater-surface water fluxes and characterize the quality of the water to improve the observed declining water quality. The hydrograph separation method was used to provide estimates of aquifer contribution to river flow. The daily time series stream flow data retrieved from the DWS website was used and processed on Microsoft Excel™, while the hydrochemical analysis method provided insights on impacts of major land use activity in this catchment on water resources The hydrological time-series data obtained from various sources to separate baseflow from direct flow, groundwater, and river water samples to identify the predominant hydrochemical facies were collected. The study found that on average, the Berg River in the upper reaches was between 7.8 and 8.1% indicating a relatively significant contribution from subsurface storage during the dry season, compared to the insignificant contribution from subsurface water storage during the rainy season. Therefore, approximately 8% of river flows are derived from discharges from subsurface water storage. Dominant Na–Cl-type water indicates the quality of water from the upper Berg River was largely affected by natural processes including short residence times of aquifer water, rock–water interactions, and atmospheric deposition of NaCl ions, while the presence of HCO_3 suggests microbial and bio-geochemical processes occurring at the groundwater-surface water interface. The results of this study after using baseflow separation as the main method, hydrochemistry, and stable isotopes as supportive methods have provided evidence for further investigation into the role of using the multi-methods approach for assessing groundwater-surface water interactions.

In the Eastern Cape, Nyawo, (2017) investigated groundwater-surface water interaction using hydrochemical and stable environmental isotopes to study stream water and aquifer pollution in the Uitenhage artesian basin, swart op, and Coega aquifer. His study aimed to establish an understanding of groundwater and surface water interactions of the Table Mountain Group aquifers in the Uitenhage area using environmental isotopes, hydrochemistry, and faecal coliform bacteria. The groundwater and river water samples were collected at selected sites and the bacteriological assessment was used as a tracer to determine if hydraulic connections exist between groundwater and the polluted streams. The results of the study found that a strong relationship between groundwater level elevation and topography with a coefficient of 0.9. The environmental isotope results showed that the river was recharging the aquifer. The Na-Cl water-type dominated in both river and aquifer. The study concluded that the bacteria count found in the Swartkops aquifer is a result of the wastewater discharge from the Coega treatment works and it was established that the groundwater only flows from the Coega aquifer to Swartkops aquifer due to difference in the hydraulic gradient. Different from the Nyawo study, this study did not use bacteriological assessment approach as a tracer of the source of groundwater-surface water interaction, instead, used stable isotopes as a tracer of the source, hydrochemistry for confirmation of the interaction based on similarities and baseflow separation as a support method for compensation of the shortfall from other methods.

In Free State, in the city of Bloemfontein, Gomo *et al*, (2012) investigated groundwater recharge and stable isotopes characteristics in an alluvial channel in the Modder River catchment, downstream of the Krugersdrift Dam. The groundwater and river samples were collected in February and May. The water level fluctuation method was used to quantify groundwater recharge rates using monitored groundwater levels. The results indicate rapid groundwater level response to rainfall for the alluvial channel aquifer. In general, the magnitude of the water level rise in the alluvial channel aquifer is high as compared to the terrestrial aquifer. The groundwater Oxygen-18 (δ18O) and deuterium (δ2H) compositions plot below the local meteoric water line (LMWL) indicating that the groundwater in the aquifer was exposed to evaporation before or during the recharging process. The study showed that the groundwater level response to rainfall events can be used as a quantitative and qualitative tool to distinguish between discharge and preferential recharge mechanisms. This study has used groundwater level elevation to show the relationship between groundwater flow and surface topography based on their correlation coefficients.

2.3. Focused groundwater recharge areas

The recharge can be defined as an addition of water to a groundwater table that can cause a measurable water table to rise (Sophocleous, 1991). On the other hand, Rose, (2012) defines recharge as the replenishment of groundwater by the downward infiltration of precipitation, or by water that was temporarily stored on the earth's surface. Focused recharge is defined as recharge from mappable features such as rivers, canals, and lakes, and originates from discrete and remote areas (Healy, 2010).). Losing rivers can provide an important focused point source of recharge to the groundwater system (Winter *et al*, 1998]. The dominant process for groundwater recharge in the semi-arid and arid region is thought to be as focused, indirect recharge from streams and river losses. A wide range of methods is available to assess focussed groundwater recharge, based on hydrograph separation, modeling, environmental tracing, temperature tracking, and water balance, among others. Understanding groundwater focussed recharge is essential for the sustainable use of groundwater abstractions and assessment of the contaminant transport within the subsurface (Mair *et al*, 201; Lubis *et al*, 2008). The most commonly used approach may be hydrograph separation (Brodie et al., 2005; Constantz*, et al*, 2008; Monteiro *et al*, 2012; Lerch, 2005; Sophocleus *et al*, 2000; Salvador *et al*, 2012; Winter., 1995). This study combines multiple approaches to estimate river recharge to the aquifer. This includes hydrograph separation and environmental tracers of hydrochemical and stable isotopes.

Acworth *et al*, (2021) investigated focused groundwater-recharge response to flooding rains in the arid zone of Australia. The investigation used a wide range of hydrogeological techniques including, surface and borehole geophysics, groundwater hydraulics, streambed temperature, and hydrogeochemical and environmental tracer sampling. Their results showed found that substantial run-off as a potential source for focused indirect recharge, only produced enough actual recharge to the shallow aquifer to temporarily halt a long-term groundwater recession. The results suggested that the total magnitude of a flood event is not the main control of indirect groundwater recharge at the study location. Despite the numerous studies, the determination of groundwater recharge fluxes in the semi-arid region remains fraught with uncertainties. This section of the study highlights the knowledge and understanding of the methods used to quantify and characterized focussed groundwater recharge and their contributions to the underlying aquifers.

De Vries et al, (2002) investigated groundwater recharge: an overview of the process and challenges. The study aimed to summarise the current understanding of the recharge processes, identify recurring recharge-evaluation problems, and report on some recent advances in estimation techniques. Their study concluded that the multiple tracer approach offers the best potential for reliable results in local studies that require at-point information. However, other investigations have indicated that these approaches are not straightforward because in some cases preferential flow contributes as much as 90% of the estimated total recharge. Healy, (2010) indicated that groundwater recharge may occur as ‘indirect ’recharge, a subset of focused recharge whereby recharge occurs due to infiltration from streambeds such as ephemeral streams that predominantly drain most dryland. De Vries *et al*, (2000) proposed that the combination of reliable local data, remote sensing, and geographical information system (GIS) offers promise for a better understanding and quantification of recharge over large areas. This current study attempts to address the gap of knowledge and understanding of the use of a multi-method approach for assessing focussed groundwater recharge in the semi-arid regions.

In the regional context, groundwater recharge studies in Africa have usually been done at a small scale focussing on a small area on an ad hoc basis, to define local fundamental aspects of groundwater recharge, such as its source, timing, magnitude, and distribution (Macdonald *et al,* .2010). Macdonald *et al,* (2010) reported that the majority of existing groundwater recharge studies in Africa have been done on tropical, arid, and semi-arid environments. The sources of recharge in those setting include direct recharge from precipitation, localized recharge from depressions (e.g. Ponds) and rivulets, indirect recharge from rivers, irrigation losses, and urban recharge. Several methods to estimate recharge have been developed including direct measurement, water balance methods, Darcian approaches, tracer techniques, and empirical methods among others (Allison *et al,* 1994; Lerner *et al.,* 1990. The purpose of this review of literature is to identify methods estimates of groundwater recharge that have been undertaken in Africa or from outside Africa but that can be applied to the current study area setting.

These methods ranged from site-specific to regional scale. It is well documented in the literature that aquifers receiving water from rivers are increasingly becoming the main source of water supply for domestic and agricultural purposes in Africa. The tracer analysis is a useful tool for assessing the sources and rates of groundwater recharge, mapping out groundwater flow paths, reconstructing past climates, quantifying water fluxes across model boundaries, and complementing climate models (Cerling *et al,* 1993; Dansgaard, 1964). In addressing objective one of the study this study includes reviewing tracer studies where stable isotope, hydrochemical, and baseflow separations techniques are used as a method to highlight the contribution of river water recharge underlying aquifers. Water demand and over-reliance on groundwater resources for both domestic, mining, and agricultural use have increasingly become a source of water supply in Africa (Adelana *et al,* 2008, MacDonald *et al,* 2012, Taylor *et al,* 2013). As groundwater provides a crucial component of water resource supply, a better understanding of groundwater recharge at a regional scale is equally important for more sustainable groundwater resource abstraction.

In Eastern Africa, Oiro *et al,* (2018) used stable water isotopes to identify Spatio-temporal controls on groundwater recharge in two contrasting East African aquifer systems (Nairobi aquifer System and South Coast aquifer). The study, therefore, contributed to a better understanding of groundwater resources sustainability in the East African region. The main objective of the study was to identify and verify the source and origin of water recharging the groundwater of the two aquifer systems using water stable isotopes: The study analysed 368 samples from springs, groundwater, and rivers for stable isotopes and basic physicochemical parameters. Their results showed greater deviations from the meteoric lines are associated with higher evaporation experienced and are linked to low humidity conditions, which lead to kinetic fractionation. These deviations from the global network of isotopic precipitation, local meteoric water line a global meteoric water line illustrated the multiple evaporation processes, where moisture content in air masses was subjected to lesser effects before precipitation and eventual recharge. Most importantly, the study found that Nairobi Aquifer System, was characterized by direct rapid recharge favoured by faults, delayed recharge from impounded lakes, and focused event-based recharge in floodplains. It is well documented in the literature review of the Vaal River system pollution from agricultural activities and other anthropogenic activities for decades. However, little knowledge is available about the role of how multi-methods application can be provided to further advance the understanding of groundwater recharge estimated. This study attempts to use the Lower Vaal River system as an example to try an answer the question that arose from the scientific problem of this study.

In the Western Cape, Mutoti, (2015) estimated groundwater recharge using chloride mass balance in the upper Berg River catchment, South Africa. The main aim of the study was to assess the application of chloride mass balance, and water table fluctuations methods at a local scale alongside rainwater infiltration breakthrough and water table fluctuation methods to estimate the groundwater recharge as an indicator of groundwater availability. The chloride concentrations were determined in groundwater samples collected from boreholes and rainwater in rain gauges in the pilot area. The rainfall and borehole water levels in the pilot area were used in water table fluctuation and rainwater infiltration breakthrough analyses. The study found that the average groundwater recharge was 27.6 %, 23.67 %, and 22.7 % of the total precipitation received. The study concluded that the use of chloride mass balance and water table fluctuations methods have the potential to estimate groundwater recharge at the quaternary catchment level and can be tested at every catchment that possesses the same or similar physiographic and hydrogeologic settings. The chloride mass balance concentrations and water table fluctuations approaches were not considered as an alternative in this, however, these methods continued to enjoy the benefits of being the most preferred methods in the world due to their plausible compensation of producing reliable estimates. This current study used different approaches of environmental tracers and baseflow separation to estimate indirect focussed groundwater recharge from the riverbed in the Lower Vaal River catchment.

2.4. Determining groundwater discharge areas

Globally, there is a clear consensus that the groundwater discharge to streams depends on geologic and hydrologic conditions. It is also not in dispute that groundwater interacts with rivers when the elevation of a stream is lower than adjacent groundwater elevations and groundwater will then flow to the stream and is known as a gaining stream (DEP, 2019). Groundwater discharge represents the upward outflow of groundwater from the subsurface that occurs naturally or as the result of human activity, notably well pumping. The groundwater is induced to discharge from boreholes and naturally from the subsurface to oceans, springs, lakes, rivers (gaining streams), and wetlands. Hence, groundwater discharge can represent a significant control over ecosystems (Rose, 2012). The groundwater discharge in the semi-arid regions represents an essential component in the understanding of hydrogeologic systems and the management of their groundwater resources, thus, identifying discharge mechanisms and thelocation of the discharge zones is equally important (Abdalla, 2012). The groundwater discharge can be computed using multiple field base methods such as Darcy's law equation, baseflow separation, streamflow gauging, water balance, and environmental tracers among others.

The use of baseflow separation methods has been well established in the literature review. While on the other hand, environmental tracer's approaches to hydrochemistry and stable water isotopes are appreciated for their reliable estimates of groundwater discharge rates at all levels. The groundwater discharge is believed to dominate dry season flows in perennial river systems and sustain aquatic biodiversity. Quantifying baseflow contributions to streamflow is of great interest in the understanding, identification, and quantification of streamflow generation processes, where baseflow supports important ecosystems or provides critical dry season water supply (Smakhtin., 2001; Werner *et al.*, 2006). Baseflow is often considered to be the groundwater discharge component of streamflow commonly estimated using conceptual models, recursive filters, or a combination of the two. However, it is reputed as difficult to validate these methods due to the challenges of measuring baseflow in the field (Partington *et al, 2012*). This study has applied these methods with multiple objectives of which one was to determine areas where aquifers recharge river by estimating the contributions of underlying aquifers to the total river flow.

In Ethiopia, Asmerom, (2008) determines the groundwater contribution and recharge estimation in the upper Blue Nile River flows. The main aim of the study was to quantify the groundwater contributions and recharge estimations in large areas to establish a stream-groundwater exchanges relationship. Stream hydrograph analysis was carried out to determine the base flow component of the Blue Nile basin with recension analysis and baseflow separation techniques. For this analysis, average daily time series data of hydrometeorological and hydrological data for 12 gauged rivers with varying record lengths were tested to quantify the groundwater contribution using a recursive digital filter. It was found that 15% of the annual flow comes from the shallow groundwater aquifer and most of the contribution is obtained from the southern tributary which accounted for 44%. Additionally, the ungauged catchment revealed that the contribution varied between 45-303 mm/annum of the total flow. These results suggested high contributions from the ungauged catchment compared to the results from the gauged stations and such results analysis can be misleading if not applied carefully. It is for that reason that this study chose to estimate the groundwater contribution of individual catchments measured using baseflow separation techniques.

In Australia, (Crosbie *et al*, 2009) investigated groundwater recharge and discharge estimations across Northern Australia. The groundwater discharge to surface water has been estimated using a digital filter on stream gauging data; thus, only estimating the baseflow component of groundwater discharge. It has long been argued that the groundwater discharge to surface water is less than recharge due to groundwater extraction and evapotranspiration from the riparian zone where the two water resources are connected (Bredehoeft, 2007 and Theis, 1940). The groundwater discharge is one of the more complex components of the hydrological cycle to estimate but one that is becoming increasingly important as Australia turns to groundwater resources for future economic development (Crosbie *et al.*, 2009). Therefore, knowledge of groundwater discharge is required for the effective management of groundwater resources. As for discharge estimates, the results showed a range of magnitude ranging from less than 1 mm/annum to over 1000 mm/annum. Although many different options of methods of the baseflow separation are available for use worldwide. In South Africa, baseflow separations methods as proposed by Eckhardt, (2005), Nathan and McMahon et al, (1990)**,** Lynne et al., (1979), Smakhtin et al, (2000) have been less utilized for not being able to match the digital algorithm filter baseflow separations method as proposed by Chapman et al, (1999), thus this study chose to follow the Chapman and Maxwell algorithm filter method to address objective 2 of the study.

In the boundary of Northern Cape and Western Cape Province, South Africa, Mqondeki., (2019) assessed the influence of groundwater recharge mechanism on non-perennial river systems, Tankwa Karoo. The primary objective was to assess surface water-groundwater (river-aquifer) interactions in non-perennial river systems to provide an insight regarding how these water resources interact in semi-arid environments. Although this study was conducted in a non-perennial river system, the approach followed in this study is the same approach commonly used in a perennial river system. Samples from boreholes, a dug well, springs, surface water, and cumulative rainfall collectors were collected during the summer and winter seasons. The secondary data from records review and field data from hydrometric methods, geophysical surveys, and tracer techniques were collected. The hydrochemical analyses showed that during the dry season, four distinct water types in the study area were characterized. These were Ca-HCO3, Ca-SO4, Na-Cl, and Na-HCO3. These water types were associated with discharge zones thereby confirming the role of aquifers in recharging rivers. The study concluded that the methods chosen were suitable for the study area setting and recommended that the approach used in this study can be implemented elsewhere in a similar geographical setting. The findings of this study by Mkqodeki informed the selection of methods that can be used to collect both primary and secondary data as well as the selection of data analysis methods without hesitation.

2.5. Conceptual models of the groundwater processes

A conceptual model is defined as an overall representation of the hydrogeological units and the flow system of groundwater. Understanding the characteristics and dynamics of the system based on an interpretation of the available data is crucial for sustained water abstraction (Giacinto *et al,* 2010). The conceptual model has been used as an analytical tool mostly quantitative and visual representation of the groundwater system in the form of block diagrams where data interpretations and analysis are drawn from graphs, diagrams, and pictorial illustrations. Developing a conceptual model is imperative as it simplifies the complicated hydrogeological system being examined and organizes the data so the system can be analyzed effectively. A sound conceptual model of groundwater processes should consider recharge, discharge, and groundwater flow systems, and how they are linked (Peterson, 2012). The source, pathway, and receptor conceptual approaches are often used in hydrogeology as a basis for the assessment of the environmental impact (Tatomir *et al*, 2018). The same approach is applied in this current study to assess the groundwater processes of the Lower Vaal catchment where the source component is recharge, the pathway is represented by faults and fracture networks and the receptor is the aquifer and river through discharge. Sivakumar (2007), considers three main aspects in the models: processes, scale, and objectives. In this study, the purpose of creating a conceptual model was to explain the groundwater processes of river-aquifer interaction thereby addressing objective three of the study.

Preparation of a conceptual model involves identification of the study area, reviewing the existing understanding of the aquifer system by combining published literature, available data, and previously unpublished data, and estimation of sources. This review was supplemented by new hydraulic data, geological data, and geophysical data (Betancur, 2012) In theory, the closer the conceptual view approximates the real site-specific conditions, the more accurate the groundwater modeling results (Maidment *et al,* 2005). The characteristics of the real system include assessment of topography, geology, hydrometeorology, surface water information, aquifer properties, boundaries, groundwater flow directions, aquifer relationships, and water balances. This assessment varies in degree depending on the study site location, supplemented with new field investigations, laboratory analyses, and additional monitoring results A conceptual model serves to simplify assumptions describing the groundwater system produced by interpretation of all available information. In this study, reviewed literature informed the preparation of the conceptual model and understanding of the available secondary data on geology, rainfall, hydrological time series data, and chemistry data obtained through record review methods. The final step involved the integrations of all primary data on groundwater flow, recharge, and discharge rate obtained through field measurements and laboratory assessments.

Weitz *et al,* (2014) analyzed surface and subsurface geological information, groundwater head, hydrochemical and environmental isotope data to develop a conceptual model of aquifer–lake interaction in the Lake Sibayi Catchment, Eastern South Africa. The water samples from groundwater, surface water, lake, ocean, and rainfall sources were collected. The final developed model confirmed that a direct hydraulic link between groundwater and the lake exists. In the western section of the catchment, the model showed that the groundwater flows to the lake where the groundwater head was above the lake stage, whereas along the eastern section, the presence of mixing between lake and groundwater isotopic compositions indicated that the lake recharges the aquifer. The stable isotope signals further revealed the movement of lake water through and below the coastal dune cordon before eventually discharging into the

Indian Ocean. Based on these findings, the same approach was applied in this study where a conceptual model was created to show the groundwater processes that explain river-aquifer interactions.

Moseki, (2013) investigated surface water - groundwater interactions for the development of methodologies suitable for South African conditions. The methodology used entailed a review of national and international literature on related previous and current models, systems, and methods used in the assessment and quantification of water exchange between groundwater and surface water. The overall aim of the study was to develop appropriate method for assessment and evaluation of the surface water and groundwater interactions and thus, to quantitatively estimate groundwater contribution to surface flows or surface water contribution to the underlying aquifers. Their study found that various methods and classification systems are widely available but the applicability thereof under the South African conditions depends on the conceptual understanding of the area or system under investigation, the availability of data, and the basic assumptions associated with the method. The other finding was that the use of multiple techniques to reduce uncertainties and confirm the existence or non-existence of the interaction is essential. Preferably, at least one method should be utilized to trace flow or qualitatively establish the water exchange while the alternative method is used for quantitative estimation of the interaction between surface water and groundwater. The use of multiple methods has been a useful tool in many previous studies. In this study, stable isotopes, hydrochemistry, and baseflow separation have not been tested in the study area to investigate river-aquifer interactions. Therefore, their applicability in the study areas setting remains unknown.

2.6. Theoretical framework

The study uses the gravity-driven basin-scale of groundwater also known as regional groundwater flow as a theoretical framework. This theory assumes that the topography, which controls the water table position and shape, and geological framework play a fundamental role in guiding the groundwater flow direction (*Toth et al,* 2009). The specific goal of the theory is to understand the movement of a drop of water from the point of infiltration to the exit point of its subsurface travel journey. The gravity-driven flow system theory assumes that the recharge would be distributed on a slope and discharge would be concentrated in the lowest end of the basin. Hubbert (1940) and Toth *et al*, (2009) argue that only a small portion of the total infiltration returns to the lowest end rather than all of it because discharge is distributed over the entire half of the basin. The central message here is that the mathematical solution to this assumption may resolve the research problem, answer the research question, and address research objectives. This theory was chosen because the flow system concept has provided a unifying theoretical background for understanding numerous physical, chemical, and ecological phenomena as well as the role it plays in making groundwater flow processes clear as a geological agent. It also continues to provide an essential framework for the understanding natural processes and generating new ideas and models (Toth., 2015). The geologic agency of gravity-driven basinal groundwater flow is based on two basic principles namely: in situ interaction between water and its environment, and systematic and sustained patterns of flow. The in-situ interaction is caused by the disequilibria of chemical, thermal, mechanical, and other types of energy between the water and the surroundings. The present study intends to use the theory to assist in choosing the appropriate research design methods to guide field observation and its uses in the Lower Vaal catchment as its site of assessment. In addition, the interpretation of the results and the choice of the methods used are guided by this gravity-driven basinal groundwater flow theory.

2.7. Conceptual framework

The term interaction is the unit of analysis and thereby the conceptual framework for the current study. The interaction between aquifer and river water is well established in the scholarship of debate. For example, Hornbæk and Oulasvirta *et al,* (2017) define interaction as an action that occurs between two variables, typically in an exchange or transmission of information while Giancarlo *et al,* (2019) describe interaction as a structural notion that provides the link between the concepts of relationship whereas Sophocleous (2002) understand interaction as the hydrologic connections among aquifer and river water happen by subsurface horizontal passage through the unsaturated soil and by penetration into the immersed zones.

While there seems to be a common understanding in terms of the definition for interaction in the field of groundwater and surface water, the variables that are measured and the methods that are used to measure such interaction differ widely. For example, Zhou *et al* (2015) focus on precipitation, glacial meltwater, groundwater, and river water while Wenninger *et al* (2013) focused on river discharge, groundwater level, river stage, and temperature series whereas

Ahring and Steward (2012) studied groundwater elevations from the surface elevation provided by the digital elevation model (DEM). In addition, to establish or determine the interaction between groundwater and surface water, scholars employ various methods to measure the same interaction. For example, Brodie and Hosteler, (2005) used hydrograph separation methods which happen to be the most commonly used approach and Monteiro *et al*, (2012) used modeling whereas Lerch (2005) and Constantz *et al*, (2008) used environmental tracers and temperature tracers respectively.

Based on the commonly agreed definition of interaction, in this study, the definition by Sophocleous (2002) and Oulasvirta *et al*, (2017) was used. By extension, connectivity was also considered as interaction. In other words, the operation definition for interaction in this study refers to the hydrologic connection of groundwater and surface water to exchange water information which saves as a guiding concept of the study and therefore water quality and quantity variables are selected using field trial and laboratory assessment methods to measure the interaction between groundwater and surface water. This concept has been experimented with the Lower Vaal Catchment, South Africa. The operational definition for the concept of interaction informs the conceptual model that explains the groundwater processes i.e. recharge, discharge, and groundwater flow.

2.8. Research framework

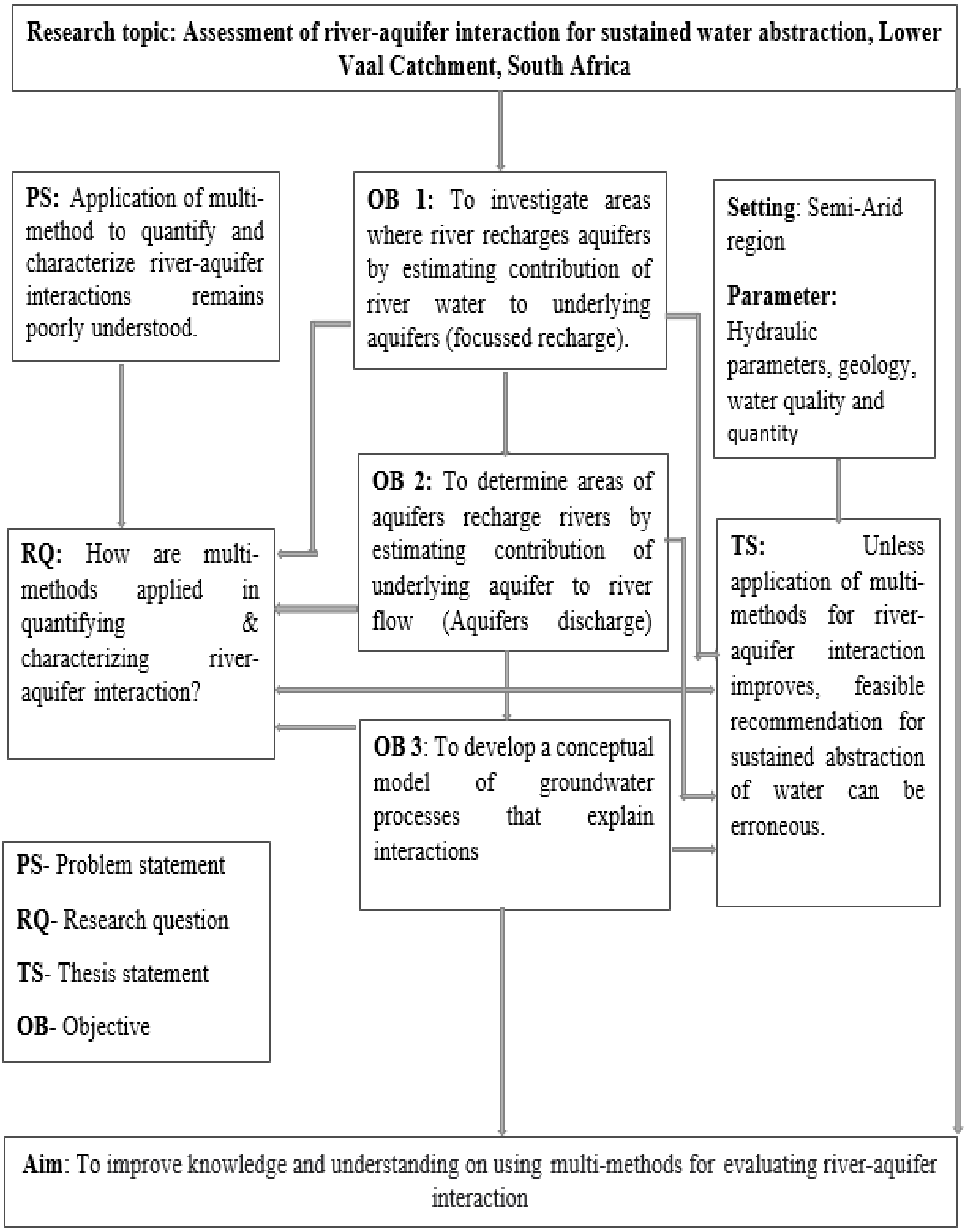


Figure 1: The research framework of the study

Chapter 3: Description of the study area

3.1. Introduction

This chapter describes the study area where the research was conducted. In this chapter, the physiographic features are described in detail to show the relationship between the features in the study area and the study aim. In other words, this chapter assesses the potential influence of the features on the study topic.

3.2. Description of the study area settings

3.2.1. Location of the study area

The Vaal River Catchment is one of the largest rivers in South Africa and is divided into three components namely: Upper Vaal, Middle Vaal, and Lower Vaal. Of the three categories, the study area is in the Lower Vaal River catchment in the Northern Cape, South Africa. The Vaal River is a vital water resource with several important tributaries along its length. The research study area covers places such as Riverton, Barkley West, Gong-Gong, and Long-Lands, all in the Frances Baard District Municipality. The study falls within the quintenary catchment C91E The study was piloted in three sections upper, middle, and lower stream locations between the geographical position 24.6931E and -28.5149S (upper stream); 24.5693E and -28.5439S (middle stream) and 24.4091E and -28.498S (lower stream). The study area is characterized by low rainfall during the dry season with temperatures often topping the 38°C mark with 45°C having been the highest mark recorded as expected. During the dry season, the average rainfall varies between 200-250mm with average temperatures varying between 0°C and 22°C. The elevation varies between 890-2050 meters above sea level.

Three gauging stations from DWS have been earmarked for river stage and flow data collections. The three gauging stations and sampling sites are located at the upper stream-C9H003, middle stream-C9H009, and lower stream-C9H026 of the study area. The upper stream and lower stream of the Vaal Dam are modified by anthropogenic activities such as agricultural return flows, sewage waste inflows, and industrial and mining return flows (DWAF., 2004). The landscape is generally plains and hills dominated by anthropogenic activities of small-scale alluvial diamond mining found along the riverbanks in shallow alluvial weathered kimberlite rocks and agricultural irrigations which influences the interaction between river and aquifers.

The study area is situated in the semi-arid region where the role of multi-methods application for assessing river-aquifer interaction remains poorly understood. Generally, in the semi-arid region, surface water resources are largely scarce, and groundwater remains the sole source of water supply. In this study, the influence of anthropogenic activities (irrigation and diamond mining) has rapidly grown with increasing water demand from surface water and groundwater resources which raises concerns of unsustainable water abstraction. This has provided the basis for the selection of the study area for greater understanding of the interaction between river and aquifers which is fundamentally an integrated feature in the hydrologic cycle (Haque *et al*, 2021). The study area was chosen to provide scientific evidence that supports the study topic and study aim based on scientific information of river-aquifer interactions.

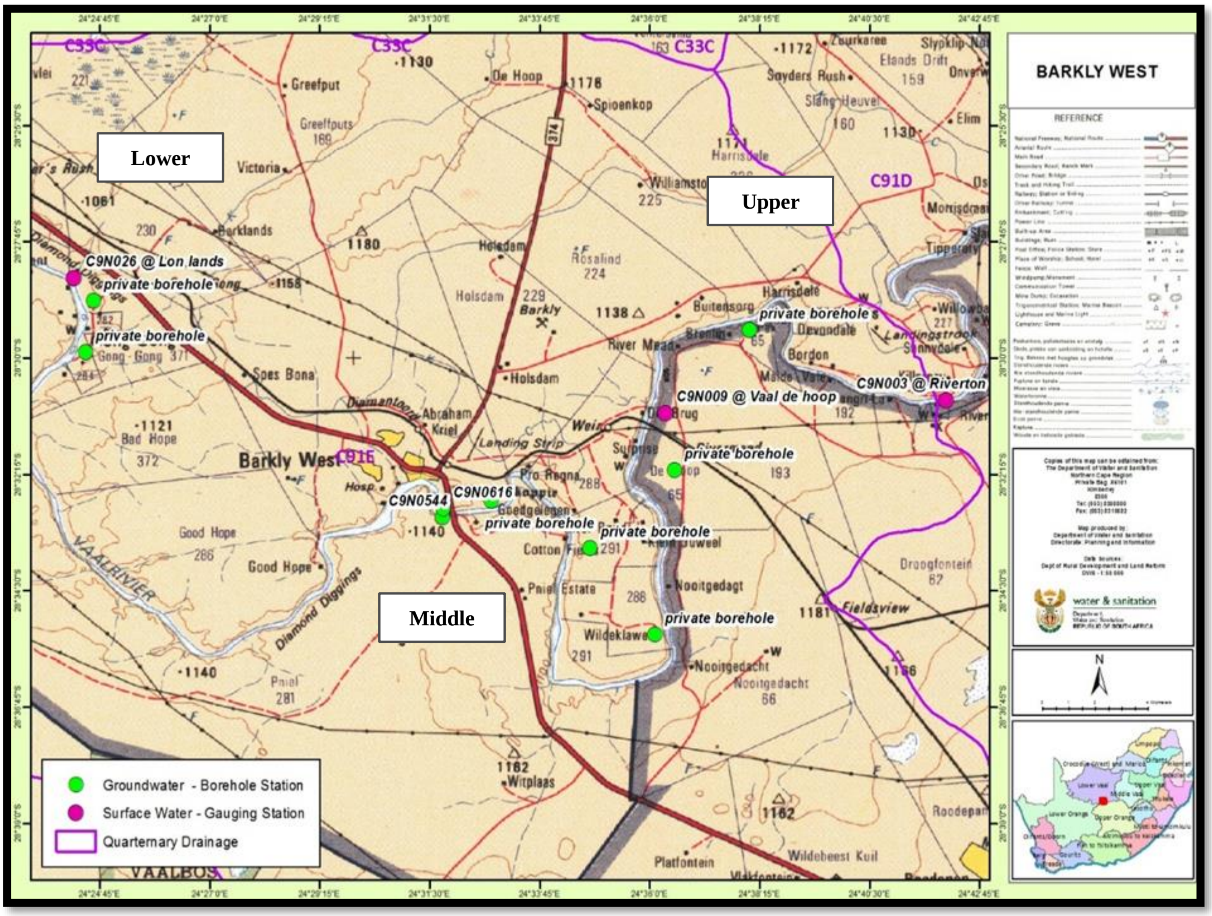


Figure 2: Locality map of the study area

3.2.2. Geological settings of the area

The major portion of the Frances Baard District Municipality is underlain by dolomite and chert bedrock belonging to the Campbell Rand Formation, Ghaap Group, Transvaal

Supergroup. The study area is covered by recent colluvium and alluvial sandy, gravelly, silty, and clayey soils overlying residual soils and bedrock belonging to the Karoo, Transvaal, and Ventersdorp Supergroups. The shale and “tillite” of the formation Dwyka outline the “lava”. alluvial deposits from the Vaal River form a flat terrace inside a riverbed just east of the study area (DWAF., 1986). The dimensions of the terrace are 8 x 3 km. The Ventersdorp lava outcrop is located east and south of the study area. This rock is covered by quartzites and shale of the Formation Vryburg. The contact between limestone and dolomite runs northeast-southwest within the study area but is covered by recent deposits. Further west towards the gap plateau, the contact between the Formation Vryburg and sludge, limestone, and dolomite, is from the Formation Scmidtsdrift. The position of the contact could not be located due to the presence of the surface deposits of limestone (DWAF, 1986). A high degree of geological features coupled with steep topography creates the condition whereby river and aquifer interact. These geological features in the semi-arid region are described as highly connected. However, their relationship is often poorly understood for evaluating recharge and discharge using a multi-method approach.

To the west of the Harts and Vaal Valley near Ulco mine, the geology comprises an uplifted dolomite plateau overlain by large areas of gravel and sand. This plateau can be said to comprise the eastern edge of the Kalahari to the east, including the major river valleys of the Harts and Vaal rivers, the major geological formations are sedimentary with scattered patches of shale, dolomite, dykes found along the eastern boundaries of the Dikgatlong Local Municipality. This pattern gives rise to the important mining and engineering geology of the area. Historically, this was an important aspect of the Municipality’s economic development although it is now diminishing in importance. Kimberlite pipes surface in the eastern part of the Municipality, particularly around Windsorton, is combinations of shale and tilite. Large deposits of limestone are found in the junction between the dolomite and sedimentary systems along the Ghaap Escarpment in the Ulco area (APD., 2009). The heterogeneity of the geology and lithological formations in the study area determines the dynamic of recharge, discharge, groundwater flow directions, flow pathways, and spatial distribution of river-aquifer interactions (Cai *et al*, 2020).

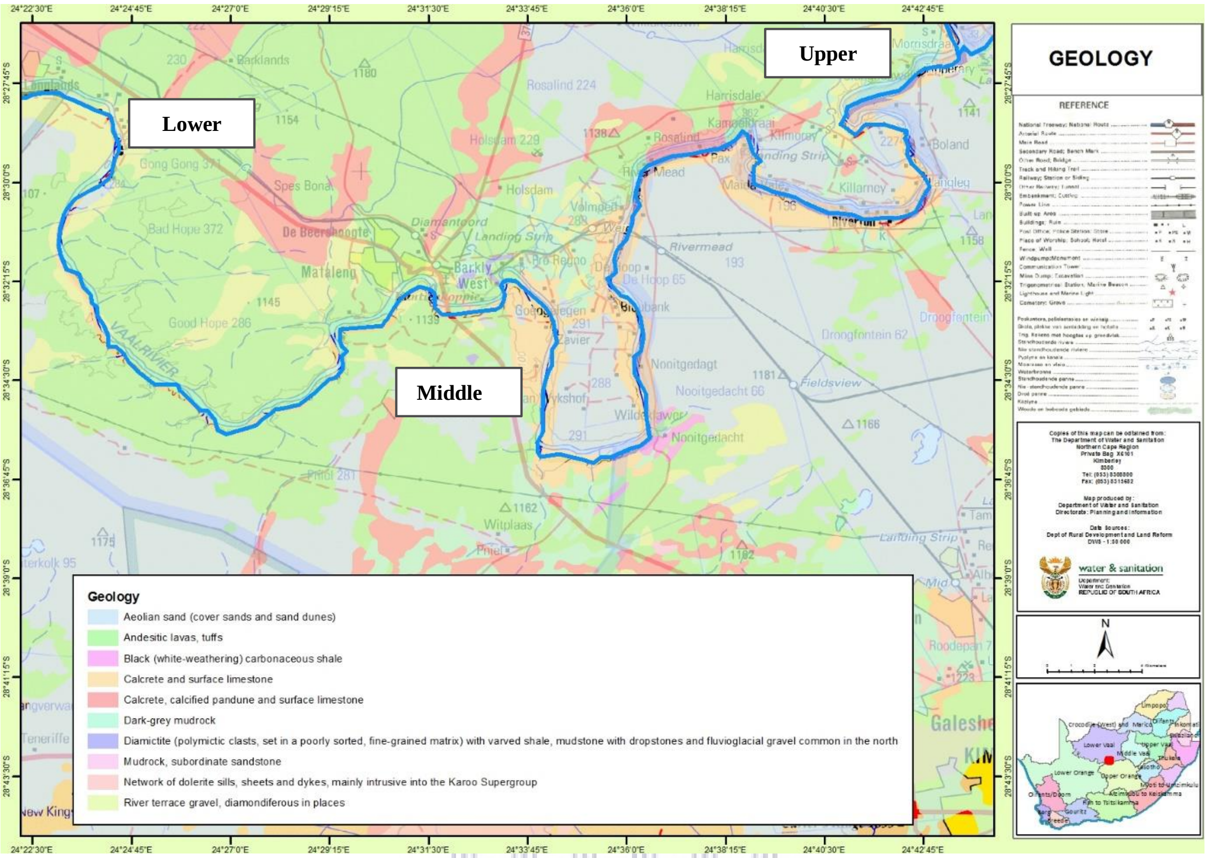


Figure 3: Geology of the area

3.2.3. Geohydrological Settings

The western and eastern side of the study area appears to be underlain by major aquifers and the details of the aquifers are elaborated under the geological settings above. The alluvial terrace forms a primary aquifer while the “lava”, shale, and “tillite” should be considered secondary aquifers. It is suspected that the alluvium material contains a strong infusion of slime and clay and besides that, it is classified as a shallow aquifer. From the other two aquifers, only the “lava” warrants further attention. Limited information was available regarding the quality of the water hidden in the alluvium deposits as well as the other two aquifers. The water in the “lava” is suspected to be freshwater with a TDS-value below 1 000 mg/l (DWAF., 1986). The Dwyka water is most probably of low quality (TDS above 1 500 mg/l). The alluvium water may be of good quality but in the case of irrigation, the quality can be negatively influenced. The groundwater harvest potential can be estimated at around 8 000 to 10 000 m3/km2/year. The mining potential of alluvium, if there are 10-15m of water-saturated thickness and reasonable permeability of the aquifer, may be up to 50% of the annual supplement. The mining potential of the other two aquifers is extremely minor (DWAF, 1986). The sustainable abstraction from river and aquifers requires better-improved knowledge and sound understanding of the use of multi-methods application for evaluating river aquifer interaction thereby addressing the study aim. The alluvium deposits belong to the primary aquifers. Unfortunately, nothing can be said about the water-bearing properties of the aquifer. The surface limestone may also have retained its primary porosity and strong water with an estimated yield of 3.4 L/s from a 30 m deep borehole. In the primary aquifers, the extraction potential can rise to 50%, if the water saturation thickness is more than 10m and the permeability of the aquifer has not been reduced by silt and clay. The other rock formation only has secondary porosity. Their water-bearing properties can be fairly low. The extraction potential of the secondary aquifers is expected to be low at around 10 % of the annual supplement (DWAF., 1986). During the winter season, only 0.2 l/s can be obtained from the ventersdorp lava. Few boreholes are available which makes it difficult to conceptualize river-aquifer interaction.

The andesitic lava of the allaridge formation (R-Val) can yield groundwater above 2l/s if fractures associated with faults and diabase or dolerite dyke are interested. Zones of deeper weathering can also be targeted. The boreholes targeting joints and intersecting bedding in the shale and sub-ordinate sandstone of Ecca group (Pe) away from dolerite intrusion commonly yield less than 0.5l/s. Yields above 0.5l/s can, however, be expected where dolerite sill and dyke contact zones are intersected (Hydrogeological series., 2003). The interaction of climate, particularly rainfall, and the underlying geology gives rise to the hydrological patterns in the study area. There are a series of non-perennial and perennial rivers other than the major two rivers of the Vaal and Harts. On the eastern side of the study area, the Vaal River forms a confluence with the Harts River and continues flowing downstream as the Vaal River. The weirs and dams play a major role in the ecosystem services of the study area in terms of water supply to irrigation schemes. The long history of alluvial diamond mining along the riverbed and high irrigation activities along the riverbanks have produced cracks and openings providing good space for river-aquifer interactions. As such, the multi-methods approach plays a fundamental role in assessing pathways of preferential flow from alluvium deposits through the catchment that further complicate the pattern of river-aquifer interactions.

3.2.4. Perennial and non-perennial river system in the study area

The South Africa National Water Act (Act No 36 of 1998) requires a sustainable water abstraction and management of surface water and groundwater at the catchment level. This study consists of three perennial rivers namely: Vaal River, and Hart's rivers. The Vaal River originates from Sterkfontein near Breyten in the Drakensberg escarpment, Mpumalanga Province and it flows 1,415 km in the southwest to meet with the Orange River at Douglas in the Northern Cape Province. The Harts River which is the tributary of the Vaal River system originates from North-West Province in Lichtenburg to connect with the Lower Vaal River in the Delporthoop area. The Vaal River system is one of the most important rivers in South Africa and it supplies water to the Vaal harts' irrigation scheme, mining, communities, Vaal Gamaraga pipeline, and agricultural activities along the riverbank.

The water quality of the Vaal River and Harts River is generally poor with relatively high salinity due to anthropogenic activities of agricultural irrigations and raw sewage discharge. For example, the Vaalharts irrigation Scheme abstracts water from the Vaalharts weir and discharges most of the leachate and excess water into the Harts River. Furthermore, these rivers area naturally flowing at low flowing in the dry season due to a lack of sufficient rainfall and high flow during the wet season. It is expected that these rivers may be hydraulically connected to shallow aquifers along the riverbanks. Multi-Methods for assessing river-aquifer interaction on perennial rivers have been well established in South Africa and the world, but the major challenge is that their applications in semi-arid environments remain poorly understood. It is on this scientific problem that this research study was based on.

Non-perennial rivers are also found in the study area, however, these rivers in drier climates have different characteristics and function very differently from perennial rivers and therefore they require focused attention in terms of research and management. It is predicted that, due to climate change, they may become even drier and more variable in flow than at present (Seely *et al*, 2002). Methods for establishing river-aquifer interactions for non-perennial rivers are still lacking. It is, therefore, important that methods are developed to assess river-aquifer interaction for non-perennial rivers with acceptable confidence (Rossouw. 2005). Although non-perennial rivers are found in all environmental settings, their relationship with shallow aquifers is often not well understood because of the knowledge gap associated with the use of a multi-method approach to quantify and characterize river-aquifer interactions.

3.2.5. Review of groundwater recharge and discharge

Groundwater recharge is the replenishment of groundwater by a downward infiltration of water that was temporarily stored on the land surface (Rose, 2009). Recharge is an important process through which groundwater in aquifers is replenished by precipitation. Without recharge, the groundwater resources would be completely depleted. An understanding of the groundwater recharge process is important for understanding groundwater flow and discharge processes for the effective management of groundwater abstraction. In general, the sustainable water abstraction and protection of groundwater resources require a comprehensive understanding of the recharge mechanisms and rates (Gomo *et al,* 2012). In sub-Saharan Africa, most regional and local recharge studies have been carried out only in the semi-arid area over the last three decades (Beekman *et al.,* 2003). The average groundwater recharge rates estimated over large areas between 40–374 000 km^2 range from 2 to 35 mm/annum representing 1–5% of long-term average annual rainfall (Scanlon *et al*, 2006). The focussed recharge beneath ephemeral streams and lakes and preferential flow mostly in fractured systems can go as high as 720 mm/annum. In irrigated areas, recharge varies from 10 to 485 mm/annum representing 1–25% of irrigation plus precipitation (Scanlon *et al*, 2006).

Recharge determination in areas with a large amount of surface water run-off and high anthropogenic activities such as mining seems to have been neglected. Most of these studies in such areas have focused on the assessment of the potential yield and sustainability of the aquifer using multi-method approaches (De Vries *et al,* 2002). Different groundwater recharge rates have been reported across Sub-Saharan Africa and the world using multiple techniques to provide a better insight into recharge rates (Taylor *et al*, 1996). In Cameroon, Wirmvem *et al,* (2017) investigated groundwater recharge and apparent age constitutes a valuable tool for its sustainable management using the stable isotopes of oxygen and hydrogen, and tritium. The study aimed to determine the recharge process, timing, rate of recharge, and residence time. The shallow groundwater showed low variability in d18O values (-2.7 to - 4.1 %) and 3H content (2.4–3.1 TU). The low variability suggests a similar origin, homogenous aquifer, good water mixing, and storage capacity of the groundwater reservoir. Later, Fantong *et al,* (2010) investigated recharge, apparent age, and flow direction at the same area using hydrochemistry and stable isotopes resulting in an improved recharge at an average of 74 mm/year. This means that the use of multiple methods can significantly improve the determination of groundwater recharge for sustained water abstraction.

Discharge represents the upward outflow of groundwater from the subsurface that occurs naturally or as the result of human activity, notably borehole pumping (Rose, 2012). In this study, groundwater discharge is defined as the discharge of water in the liquid state directly from the zone of saturation into the body of surface water such as rivers and streams. The groundwater naturally discharges into low-lying areas driven by the topography of the area. Methods to quantify and detect groundwater discharge are well established in literature review materials and the most commonly used method includes hydrochemistry, stable isotopes, and hydrograph separation of the baseflow. The dominant use of these three methods in south Africa and the world has been the basis for the selection of hydrochemistry and stable isotope as the main methods and baseflow separation as the supportive method.

The groundwater discharge is an important aspect of the global hydrological cycle and is critical to the analysis of groundwater flow systems and water budgets. These discharges may happen in different ways namely direct, indirect, and localize discharge. The most common would-be spring discharges which are normally associated with geological contact areas (Kotze., 2002). The geological groups that make contact have different water permeability where the one acts as an aquitard. These aquifer boundary conditions give rise to a semi-confined and confined aquifer that discharges water at these geological contacts provided that the water table is high enough or fully recharged. In the semi-arid environment, rejected recharge subsequently discharges as interflow at the downward catchment and subsequently contributes to the total river flow.

3.2.6. Land use and land cover in the study area

The study area is characterized by dry drainage features in which terrestrial vegetation grows slightly more densely to become visible on aerial imagery. Soils are predominantly deep sandy to loamy. They are, however, an important hydrological feature of the landscape, which may transport high volumes of water during precipitation events (Mofoko, 2016). The predominant vegetation type is Ghaap Plateau Vaalbosveld (63% cover), followed by Schmidsdrift Thornveld (19% cover) and Kimberley Thornveld (17% cover). The fertile land that lies alongside the Vaal River supports the production of some of the country's finest quality agricultural products. Owuor *et al*, (2016) investigated groundwater recharge rates in response to land use and land cover changes in semi-arid tropical environments. The study aimed to summarize current knowledge on land use and land cover change impacts on groundwater recharge. The results show that the land use and land cover areas have low groundwater recharge than induced land. The groundwater recharge decreased from 42% to 6 and 12% depending on the final land use and land cover change. Understanding the potential influence of land use and land cover on groundwater recharge is important for sustainable water resource abstraction. However, there is limited evidence on how the groundwater recharge responds to land use and land use cover changes for evaluating river-aquifer interactions in the study area. Therefore, there is a need to apply the multi-methods approach to better improve the knowledge and understanding of how land use and land cover change can influence river-aquifer interaction in the semi-arid environment.

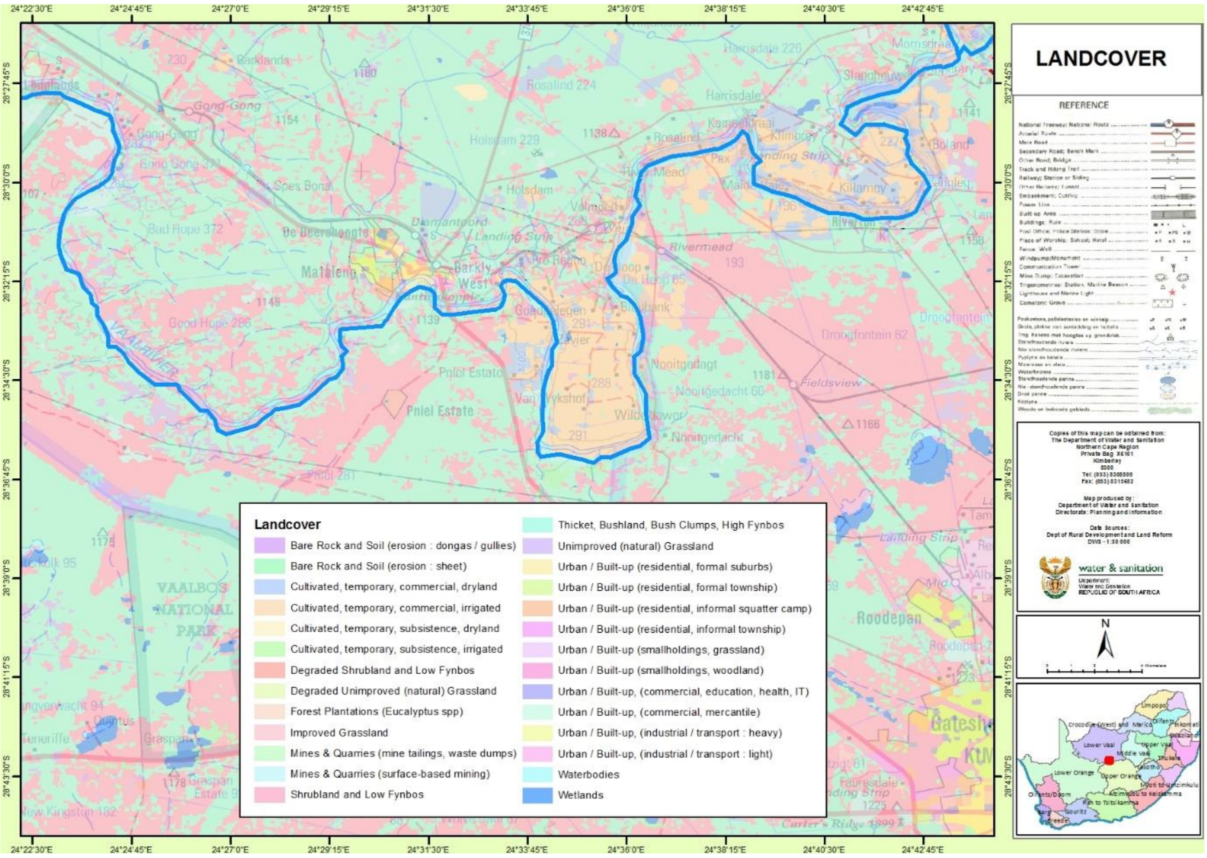


Figure 4: Land use and land cover map

Chapter 4: Research design and methodology

4.1 Introduction

Chapter 1 presented an introduction of the study in terms of the research problem, research question, aim, and objectives, study rationale, scope, and nature of the study. Chapter 2 presented the description of the study area describing features that can influence river-aquifer interactions. Chapter 3 presented a detailed review of the literature that informs the study from global, regional, and national contexts to conceptualize the study. The current chapter presents the description of the research design, research methods and methodology followed to collect and analyze data to answer the research question and address the research objectives of the study. This chapter highlights critical aspects such as data type, data sources, data collection procedure, data collection methods and tools, and data quality assurance. The main aim of this chapter is to provide a reader with a thorough research design and methodologies that are aligned with a research problem statement, research aim, research question, and justification of the study. The strength and weaknesses of data collection methods and data analysis methods are described, and the motivation of the chosen approach methods are provided.

4.2. Research design methods

4.2.1. Study design

The study design was intended to provide an appropriate framework for the study. The current research study chose to follow a case study design approach thereby an experimental design was being followed to generate an in-depth, multi-faceted understanding of the river-aquifer interactions. The experimental variables such as water quality parameters, water quantity, and stable isotopes of oxygen-18 and hydrogen-2 were measured at different sites within the study area. The study design allowed the use of a systematic approach of data collection and data analysis methods to be followed during dry and wet periods to incorporate possible seasonal variations in the measured data. The design was selected based on evidence that the approach has been tested before in various physiographic environmental conditions elsewhere in the world unlike observational design as described by the literature review, their application in this study was often not possible because of their limitations and complexity.

4.2.2. Sampling design

The sampling design provides the framework or road map that serves as the basis for selecting samples from the target population. In answering the research question and addressing the objectives, the present study chose to follow a systematic sampling approach to collect structured data at the selected sites. Firstly, in this study, field recognizance was executed through driving and walking around the study area to get a clear overview of the physiographical features that can potentially influence river-aquifer interactions. During this period, the following features were identified namely: surface geology, river water sampling sites, rainfall sampling sites, and aquifer water sampling sites. The river water sampling sites were identified alongside boreholes drilled on the riverbank near the river to establish river-aquifer interaction. As with all other probability sampling methods, systematic sampling methods allowed the use of a standardized sampling approach to collect and analyzed data to obtain results that are easy to summarize, compare, and generalize. The specific advantage of using the systematic sampling method was that the approach allowed the study to follow a procedure and logical sequence to obtain numerical data that can be analyzed statistically.

4.2.3. Data type and their sources

The data type needed to address objective one river recharge aquifers (focused recharge) included primary data on aquifer depth to water level which was collected from boreholes located near the river while chemistry data and isotopes data were obtained from aquifer and rainfall water samples. The secondary data on aquifer depth to water level and chemistry data were retrieved from the DWS database both hydstra and chat respectively. Additional data on aquifer hydraulic parameters were obtained from previously published and non-published reports. Hydstra is a software package designed ideally to store various hydrogeological data types such as water quality and quantity data. The water abstraction and water use data were obtained from Water Administration Registration and Management System (WARMS). The recharge, baseflow, and mean annual runoff (MAR) data were obtained from the reserve report published by DWS in 2011. The South Africa Weather Service (SAWS) was requested to supply 2 years of daily rainfall time series measurement records from 01 January 2015 to 01 January 2017. The primary time series rainfall data were measured directly from three rainfall gauging stations, of which one station was sourced from the DWS through a formal written agreement and the other two stations were installed for this study. The rainfall sample was collected from the rain gauge installed in the upper-middle and lower stream to obtain isotope signatures. The groundwater samples were collected from the privately owned and government own boreholes located near the river to obtain data on the major ion: Cl^-, CO_3^{2-}, SO_4^{2-}, HCO_3^-, Na^+, Mg^{2+}, K^+, and Ca^{2+} and isotopes data for δ^2H and $\delta^{18}O$ parameters. The additional information recorded at each borehole site involved measuring the aquifer depth to water level using the water level meter (dip meter). River discharge data for each gauging station was retrieved from the rating table calibrated from the river stage data.

To address the second objective of the study which entails aquifer recharge river (aquifer discharge), the primary data on hydrochemistry and isotopes data was collected from the river and rainfall water samples. The secondary data on hydrological time series river flow data records were retrieved from the three gauging stations managed by DWS while hydrochemistry data was obtained through laboratory assessments. The river water samples were collected from the selected sites adjacent to boreholes sampling sites located near the river to obtain data on the major ion: Cl^-, CO_3^{2-}, SO_4^{2-}, HCO_3^-, Na^+, Mg^{2+}, K^+, and Ca^{2+}. The rainfall sample was collected from the rain gauge installed by DWS to obtain data for δ^2H and $\delta^{18}O$ isotopic signature.

To address the third objective of the study, firstly, the study reviewed all available secondary data from published and unpublished reports to understand aquifer system geometry. The geology data, hydrogeology data, and aquifer hydraulic parameters were obtained from various database systems such as the council for geoscience database, water management system (WMS), hydstra system, and national groundwater archive (NGA), and water administration resource and management system (WARMS). Data on surface geology was obtained to construct the geological framework while the hydrogeological settings were obtained hydrogeological map to the generated hydrogeological framework of the study. The aquifer elevation data were collected from boreholes to generate groundwater flow directions. Lastly, the conceptual model of the study area was constructed by integrating all available secondary data coupled with findings obtained from objectives one and two recharge and discharge data of groundwater processes to explain interaction,

4.3 Methodological approach

The current study chose to follow the quantitative research methodological approach. The quantitative research methodology was chosen on the basis that the approach followed a systematic and logical way of solving a scientific research problem which says ‘’application of multi-methods to quantify and characterized river-aquifer interaction remain poorly understood’’ and answering a research question that asks how are multi-methods applied in quantifying and characterizing river-aquifer interactions? The approach used in this study was for testing the research hypothesis which argues that unless the multi-methods application for river-aquifer interaction improves, the feasible recommendation for the sustained abstraction of water can be erroneous. The quantitative research methodology objectively resolved a research problem, where data was controlled and measured to address the research objectives. The quantitative research approach used in this study was an approach based on measuring research objectives through analysis of data collected from boreholes, river, and rainfall gauging stations. This approach allowed data to be analysed statistically whereby numerical data collected through field trials were manipulated using the computational technique to establish the relationship between variables. The numerical results obtained during this process were tabulated and graphically represented to easily compare, summarise, and generalize the relationship between variables.

4.4 Research methods

The current study chose to follow the quantitative research methodological approach. The quantitative research methodology was chosen on the basis that the approach followed a systematic and logical way of solving a scientific research problem which says ‘’application of multi-methods to quantify and characterized river-aquifer interaction remain poorly understood’’ and answering a research question that asks how are multi-methods applied in quantifying and characterizing river-aquifer interactions? The approach used in this study was for testing the research hypothesis which argues that unless the multi-methods application for river-aquifer interaction improves, the feasible recommendation for the sustained abstraction of water can be erroneous. The quantitative research methodology objectively resolved a research problem, where data was controlled and measured to address the research objectives. The quantitative research approach used in this study was an approach based on measuring research objectives through analysis of data collected from boreholes, river, and rainfall gauging stations. This approach allowed data to be analysed statistically whereby numerical data collected through field trials were manipulated using the computational technique to establish the relationship between variables. The numerical results obtained during this process were tabulated and graphically represented to easily compare, summarise and generalize the relationship between variables.

4.4.1 Data collection, analysis methods, procedure, and tools used for objective one river recharge aquifers (focused recharge).

The first objective of the study entails investigating areas where rivers recharge aquifers by estimating the contributions of river water to underlying aquifers (focused recharge). The question to be answered here was that how are multi-methods applied in quantifying and characterizing river-aquifer interactions? The study argued that unless the application of multi-methods for river-aquifer interaction improves, the feasible recommendation for the sustained abstraction of water can be erroneous. The aquifer water and rainfall water samples were collected during wet and dry seasons for hydrogeochemical and stable water isotopes analysis using the field measurements method. The water samples were collected in October 2020 and February 2021 representing dry and wet season samples respectively. The procedure followed and tools used to collect aquifer water samples involved using a plastic bailer connected to a cable allowing it to submerge underneath the borehole to a specific depth until the bailer was filled with water before rolling it back to the ground surface.

The sample was then transferred into a sterile 2L plastic bottle and kept in a cooler box filled with ice packs. Where the boreholes were equipped with a pump, the water was allowed to discharge for at least 5-10 minutes before the aquifer water samples can be collected. Onsite measurements included testing the following physical parameters namely: pH, EC, and TDS using an EXTECH multi-parameter meter EC500. The procedure followed and tools used involved thorough assessment and understanding of the equipment used. Before collecting the final sample and testing the water, the bottle was rinsed three times to satisfy me with the quality of the sample collected. The final reading was then transferred into a field notebook and later inserted and stored on Microsoft Excel spreadsheets at the office. The aquifer water samples were sent to the UIS laboratory in Pretoria for the laboratory assessments of the following major ions: Cl^-, CO_3^{2-}, SO_4^{2-}, HCO_3^-, Na^+, Mg^{2+}, K^+, and Ca^{2+} using the ICP-OES technique a simultaneous optical system with axial and radial viewing of the plasma. The major ions parameters were selected since they comprise over 90% of all dissolved solids in aquifer water regardless of whether the water is fresh or saline (Banda, 2019). The aquifer depth to water (water level) was measured from both pumping and non-pumping boreholes. The depth to aquifer water levels was measured using a water level meter (dip meter) while the elevation was determined using the GPS receiver. The procedure followed to measure the aquifer depth to water level involved lowering the dip meter probe into the borehole until the buzzer tells when the weight is in the water. To obtain the correct depth, the cable was pulled up slowly with a finger holding the correct point to record the depth. Thereafter, the elevation of the aquifer water level was calculated by subtracting the depth to water level from the surface elevation collected using the GPRS receiver.

Data analysis methods followed a quantitative approach, whereby numerical figures were generated and analyzed. Analysis approaches included the use of hydrogeochemical and stable isotopes methods to establish the relationship between the two water resources based on their similarities. Firstly, the data required sorting and labeling of the data to prevent miss representations of data. To achieve this, hydrogeochemistry and stable isotopes data were inserted onto a Microsoft Excel spreadsheet and the descriptive and inferential statistics were generated. The statistical tests for normality in the distribution of physicochemical data were conducted to determine the statistical approach to be followed when describing the results. The classification methods were applied to hydrogeochemistry data to establish water types and produced piper diagrams using analysis tools (spread sheet) in Geochemist Workbench Software.

The results were presented on graphs, tables, and Piper and Durov's diagrams. These types of graphs, tables, and diagrams demonstrated aquifer water proportion of dissolved ions in sampled water, which distinguished the major ionic character of the water and illustrate differences in inflows and concentration levels between sampling points. The Principal Component Analysis (PCA) was the most widely used statistical method among the families of multivariate statistics. This method identified patterns in the data and presented them based on their similarities and dissimilarities in the dataset. The PCA was used to estimate the contributions of selected parameters. PCA reduced data sets for easy exploration and visualization and analysis. 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 rainfall water samples were collected by placing a V-shape funnel rainfall collector which is open at the top to allow rainfall to enter the funnel. Once the rainfall has entered the sampler, the water was transferred into a 500 ml plastic sterile bottle. The rainfall samples were collected once-off during the dry (October 2020) and wet seasons (February 2021). The stable isotopes (2H, 18O) compositions were analyzed at the Ithemba laboratory in Johannesburg using a Laser spectrophotometer. All samples were normalized to internal laboratory water standards. The stable isotopes data was presented in “delta notations” where δ (‰) is defined as:

Sample $$\delta = \left(\left(\frac{R_{sample}}{R_{standard}} \right) - 1 \right) * 100\% \qquad \text{(equation 1)}$$

Where:

R_{sample} and $R_{standard}$ = 18O/16O or 2H/1H.

The isotope data was then plotted along the global meteoric water line (GMWL) of Craig (1961), δ2H = 8δ18O +10, and a local meteoric water line (LMWL) as determined by Diamonds and Harris (1997) using the scatter plot analysis method for interpretation build in Microsoft Excel™ to trace the source of water-based on similarities of isotope composition. The GMWL represents the linear relationship between δ2H and δ18O based on rainfall data around the globe (Craig, 1961; Baxter *et.al*, 2013). Samples that plot on or slightly below GMWL indicated recharge origin from local rainfall and rivers (Ahmed *et.al*, 2013). A Local Meteoric Water Line was used in the analyses after considering the vastness of the study area. Microsoft® Excel was used to perform statistical analyses on the isotope data and to generate scatter plots.

4.4.2 Data collection method, analysis method, procedure, and tools used for objective two aquifer recharge river (aquifer discharge).

The second objective of the study entails determining areas of aquifers recharge river by estimating to contributions of aquifer discharge to river flow (aquifers discharge). The study had a question to a question to answer based on the research problem of how are multi-methods applied in quantifying and characterizing river-aquifer interactions? The research hypothesis argues that unless the application of multi-methods for river-aquifer improves, feasible recommendations for the sustained abstraction of water can be erroneous. The river water and rainfall water samples were collected during wet and dry seasons for hydrochemical and stable isotopes analysis field measurements method. The procedure followed and tools used to collect river water samples involved using a sterile 2L plastic bottle and then later transferred into a cooler box filled with ice packs. Onsite measurements of the river water were done by placing a probe into the water direct from the source following the standards and manufacturing specifications. The parameters tested included pH, EC, and TDS using an EXTECH multi-parameter meter EC500. The river water samples from the 2L bottles were sent to the UIS laboratory in Pretoria for the laboratory assessments of the following major ions: Cl^-, CO_3^{2-}, SO_4^{2-}, HCO_3^-, Na^+, Mg^{2+}, K^+, and Ca^{2+} using the ICP-OES technique a simultaneous optical system with axial and radial viewing of the plasma.

Firstly, the data analysis approaches included the use of hydrochemical and stable isotopes to establish the relationship between the two water resources based on their similarities. The collected data required sorting and labeling before analysis to prevent miss representations of data. To achieve this, hydrochemistry and stable isotopes data were inserted into a Microsoft Excel spreadsheet and the descriptive and inferential statistics were generated. The statistical tests for normality in the distribution of physicochemical data were conducted to determine the statistical approach to be followed when describing the results. The classification methods were applied to hydrochemistry data to establish water types and produced piper diagrams using analysis tools (spread sheet) in Geochemist Workbench Software. The results analysis was presented on graphs, tables, Piper and Durov's diagrams. These types of graphs, tables, and diagrams demonstrated aquifer water proportion of dissolved ions in sampled water, which distinguished the major ionic character of the water and illustrate differences in inflows and concentration levels between sampling points.

The PCA was the most widely used statistical method among the families of multivariate statistics. This method identified patterns in the data and presented them based on their similarities and dissimilarities in the dataset. The PCA was used to estimate the contributions of selected parameters. PCA reduced data sets for easy exploration and visualization and analysis.

The rainfall water samples were collected by placing a V-shape funnel rainfall collector which is open at the top to allow rainfall to enter the funnel. Once the rainfall has entered the sampler, the water was transferred into a 500 ml plastic sterile bottle. The rainfall samples were collected once off during the dry (October 2020) and wet season (February 2021). The stable isotopes (2H, 18O) compositions were analysed at the Ithemba laboratory in Johannesburg using a Laser spectrophotometer. All samples were normalized to internal laboratory water standards. The stable isotopes data was presented in "delta notations" where δ (‰) is defined as:

Sample $\delta = \left(\left(\frac{R_{sample}}{R_{standard}}\right) - 1\right)$*100% (Equation 1)

Where:

R_{sample} and $R_{standard}$ = 18O/16O or 2H/1H.

The isotope data was then plotted along the global meteoric water line (GMWL) of Craig (1961), δ2H = 8δ18O +10, and a local meteoric water line (LMWL) as determined by Diamonds *et al*, (1997) using the scatter plot analysis method for interpretation build in Microsoft Excel™ to trace the source of water-based on similarities of isotope composition. The GMWL represents the linear relationship between δ2H and δ18O based on rainfall data around the globe (Craig, 1961; Baxter *et.al*, 2013). Samples that plot on or slightly below GMWL indicated recharge origin from local rainfall and rivers (Ahmed *et.al,* 2013). A Local Meteoric Water Line was used in the analyses after considering the vastness of the study area. Microsoft® Excel was used to perform statistical analyses on the isotope data and to generate scatter plots.

Secondly, the data analysis approaches included the use of the baseflow separation method to derive the composition of the baseflow contribution to the total river flow. To achieve this, the 2-D line analysis method built on Microsoft excel was used to separate the component of total river flow derived from subsurface contribution. The hydrological time series river flow data was collected by the DWS officials in three gauging stations C9H003 located in the upper stream, C9H009 located in the middle stream, and C9H026 located in the lower stream were retrieved from the hydstra database system using the record review method. Microsoft Excel™ was used to produce a linear graph for interpretations. In determining the contribution of aquifer discharge through baseflow, the retrieved river flow time series data were processed on Microsoft Excel. Thereafter, one-parameter separation algorithms proposed by Chapman and Maxwell were applied to obtain estimates of discharges rates from the subsurface (Chapman *et al*, 1996). However, this approach was illustrated to produce repeatable results, using time series data and allowing the computation of the ratio between the quick flow component and the base flow component of a total river flow hydrograph. The most appropriate alpha and beta parameters to be input into the filtering algorithm were 0.925 and 0.5 respectively. These algorithms are as follows:

Chapman & Maxwell algorithm:

$$qf(i) = \frac{3\alpha-1}{3-\alpha}\ qf(i-1) + \frac{2}{3-\alpha}\ q(i) - \alpha\ q(i-1)) \qquad \text{(Equation 2)}$$

Lyne & Hollick algorithm:

$$qf(i) = \alpha\ f(i-1) + ((q(i) - q(i-1))\frac{1+\alpha}{2} \qquad \text{(Equation 3)}$$

where qf(i) represents the filtered quick flow component for the ith sampling instant, qf(i-1) represent the filtered quick flow for the previous sampling instant to i, q(i-1) represents the original river flow for the previous sampling instant to i and α represent the filter parameter. These digital filters, as mentioned, have no hydrologic basis and have been borrowed from signal analysis to separate the high-frequency quick flow signal to derive the low-frequency base flow signal as prescribed by Nathan *et al*, (1990). It should be noted that these separation algorithms provided only the component of river flow directly derived from direct runoff (rainfall) and to get the base flow contribution, it was important to find the difference between the filtered river flow and the total recorded river flow, using the proposed filter parameter (0.925 for α). Following the determination of the base flow component, the ratio between baseflow and baseflow index (BFI) was computed to indicate the proportion of total flow derived from the baseflow. The equations for baseflow (Equation 4) and the BFI (Equation 5) are:

Base flow:

$$QB(I) = Q(I) - qf(i) \qquad \text{(Equation 4)}$$

Base Flow Index:

$$BIF\% = Qb\,(i)/qf(i) \qquad \text{(Equation 5)}$$

The resultant index (Equation 5) indicates the river dependence of discharges from subsurface storage. However, this index or the separated baseflow does not indicate what the exact source of water discharged to the river during baseflow periods is, thus further sampling and analysis accompanied by the analysis of hydro chemical and stable isotopes was required to identify the true source of water.

4.4.3. Data collection methods analysis methods, procedure, and tools used for objective three to create a conceptual model of groundwater processes that explain interactions

The third objective of the study entails creating a conceptual model of groundwater processes that explain interactions. The study question asked was how are multi-methods applied in quantifying and characterizing river-aquifer interactions? The research hypothesis argues that unless the application of multi-methods for river-aquifer improves, feasible recommendations for the sustained abstraction of water can be erroneous. To address this objective, research question and confirm the hypothesis, the study committed to appropriate levels of environmental monitoring, review of appropriate aquifer water and river water level fluctuations, appropriate review of the water allocation, water use, and water abstraction, assessing the level of allocation for consumptive and non-consumptive water uses as well as environmental reserves using record review method (Lamontagne *et al,* 2012). This included data integration of the geologic, aquifer hydraulic parameters, groundwater flow, recharge, and discharge data to create the conceptual model of groundwater processes that explain interaction. Information from the geological maps was compiled to construct the geological structures, joints, lines, and polygons while the aquifer hydraulic parameters were obtained from previous studies conducted in the same study area settings using the record review method. Having this kind of information, the conceptual models of groundwater processes for sustained water abstractions on the study area was produced.

The Sufer golden software interface was used for the development of the conceptual model input parameters. Suffer golden software package is a software package designed to perform the functions of integrated hydrogeological modeling, for analyzing combined processes and use of groundwater data, unsaturated zone, and surface water processes of the hydrological cycle. The method of analysis was based on the computation of hydrogeological components of an integrated river-aquifer interaction that combines various hydrogeological features (Arnold *et al,* 1993; Kim *et al,* 2008; McDonald *et al,* 1988). The estimated recharge, discharge, and flow directions and pathways were integrated into the model. Thereafter the methods of analysis that account for both recharge and discharge based on sustainable water abstraction were introduced. To spatially reflect the distribution of aquifer recharge and discharge areas within the catchment, the conceptual model was created by overlaying surface geologic structures, topographic features, and finally integrating all results obtained from objectives one and two of the study using Suffer golden software. The tracing of each water source confirmed by hydrogeochemistry data was clearly defined and established within the conceptual model.

The method of analysis that explains exploitable aquifer water level within the catchment was also introduced using an integrated river-aquifer interaction conceptual model.

4.5. Quality assurance

4.6.1 Evidence on reliability and validity of the collected data

The reliability of the data on the physical parameter for aquifer water and river water samples, and data quality assurance were carried out throughout the study. This included following the water quality guidelines, standards, and procedures (DWS., 1996). Such procedures included calibrating measuring instruments before use according to the manufacturer's specifications. The bottles used for collecting the water samples were rinsed three times before sampling. Plastic bailers were used once off to avoid cross-contamination of one ample borehole to another. The river water sample bottles were also rinsed before use, this was done from one sampling site to another. For the hydrogeochemistry data obtained from the laboratory assessments, data were subjected to checking by evaluating the samples to determine which samples are eligible to be included in the water quality analysis. The common approach was to calculate the charge balance error (CBE) for each sample. This calculation was based on the principle that the total anion equivalents should equal the number of anions if charge neutrality was to be maintained. The process involved evaluating data uncertainties. The cation-anion balance values less than 5% were regarded to be accurate for all uses, while those with values between 5-15% were used with caution, and samples that have values above 15% were investigated (Younger., 2007). The CBE is expressed as:

$$\text{CBE \%} = \frac{\sum meqcations - \sum meqanions}{0.5 \sum meqcations + \sum meqanions} \; x \; 100\% \qquad \text{(equation 6)}$$

where:

ΣCations is the sum of cations (meq/L) and ΣAnions is the sum of anions (meq/L). After taking the sample data through the above-mentioned verification processes, the data with CBE within recommended range were declared valid and reliable to be used in this study.

For stable isotope (Hydrogen -2 and Oxygen-18) all samples were normalized to internal laboratory water standards that were previously calibrated relative to the Vienna Standard Mean Ocean Water (VSMOW). The isotopes data, standards were calibrated against international reference materials, and the analytical precision was estimated at 0.5% for O and

1.5% for H. To check the reliability of water quantity data, Hydstra was used as a quality control where data with a variable 100.0 was used for the river stage and 110.0 for aquifer depth to water level. After data was retrieved for each specific research objective, the data were subjected to quality assurance by cross-checking the gap and outliers (point out of the range) on time series data. The variables 100.0 and 110.0 referred to the quality code assigned to a final audited data which has gone through quality checking before being approved and stored in the Hydstra system.

Chapter 5: Results and Discussion

5.1. Introduction

The current chapter presents the results and discussion of the three objectives set for the study. The first objective was to investigate areas where river recharges aquifers by estimating the contributions of river water to the underlying aquifers. The second objective was to determine areas where aquifers recharge river by estimating the contributions of the underlying aquifers to river flow. The third objective was to explain interaction by using a conceptual model of groundwater processes. The description of the main data in the study area was presented using tables, graphs, photos, equations, and models. The descriptive and inferential statistics that explain the relationship and connectivity between rivers and aquifers are also presented. The interpretation results of the present study were objectively compared with the analysis results of the literature review from the previous studies. The main aim of this study in achieving the three objectives was to better improve the knowledge and understanding of multi-methods applications for evaluating river-aquifer interactions to identify flow pathways, recharge areas, and discharge areas. The chapter argues that unless the application of multi-methods for river-aquifer interaction improves, the feasible recommendation for the sustained abstraction of water can be erroneous. Therefore, the question that arose from the argument was, how are multi-methods applied for quantifying and characterizing river-aquifer interaction?

The approach used for the analysis of the results involved the application of three techniques namely: hydrogeochemical, stable isotopes, and baseflow separation techniques. The stable water isotopes traced the source whereas the hydrochemistry confirmed the source with chemical evidence. The baseflow separations technique provided the separation of the high-frequency quick flow component to derive the low flow frequency component of the baseflow of the river flow hydrograph. The field measurements and laboratory assessments methods were used to obtain the results of the hydrogeochemistry and stable isotope for objectives one and two while the record review method was used to obtain the baseflow results for objectives two and three of the study. The results analysis approach followed involved using tools (spreadsheet) in Geochemist Workbench to establish water type, PCA to estimate the dominance type, and scatter plot analysis tool to trace the source. The 2-D line analysis method was used to separate the component of total river flow derived from subsurface contribution using Microsoft Excel.

5.2. Description of main data

5.2.1. Main data on assessing interaction using hydrogeochemistry

The main data that were used in this study included the hydrogeochemistry data. These data were obtained through conducting field measurements and laboratory assessments of the river water and aquifer water collected during October 2020 (dry period) and February 2021 (wet period). Before data were used in this study, the data were subjected to cation-anion charge balance error calculations to check the reliability of the results to be included in the water quality analysis. The common approach was to calculate the CBE for each sample. The calculation was based on the principle that the total cation equivalents should equal the number of anions if charge neutrality is to be maintained. The process involved evaluating data uncertainties. Both Weight, (2008) and Younger, (2007) emphasized that cation-anion balance values less than 5% are regarded as accurate for uses, those with values between 5-15% should be used with caution, and samples that have values above 15% should be investigated or discarded. 82% (9) of the river water samples had a charge balance of less than 5%, meanwhile, 18% (2) varied between 5-15% in the dry season. In the wet season, 100% (11) river water samples were less than 5% and safe to be used in this study. Of the aquifer water samples, 9% (1) sample had a charge balance of less than 5% and 91% (10) samples ranged between 5-15% during the dry season. In the wet season, 18% (2) samples were less than 5% charged meanwhile 82% (9) samples ranged between 5-15%. Table 1 shows the cation-anion balance results

Table 1: The cation-anion balance error (CBE) results for river-aquifer samples

Dry season									
Source type	**Sample date**	**Time**	**CBE (%)**		**Sour ce type**	**Sample date**	**Time**	**CBE(%)**	
RW1	08/10/2020	10h14	5.53	Yes	AW1	08/10/2020	09:45	6.07	Yes
RW2	08/10/2020	12h24	4.65	Yes	AW2	08/10/2020	12:10	11.08	Yes
RW3	08/10/2020	14h01	4.56	Yes	AW3	08/10/2020	13:41	6.43	Yes
RW4	08/10/2020	15h45	3.45	Yes	AW4	08/10/2020	16:21	4.49	Yes
RW5	08/10/2020	16h37	4.05	Yes	AW5	08/10/2020	15:16	9.76	Yes
RW6	09/10/2020	10h50	3.48	Yes	AW6	09/10/2020	11:23	14.36	Yes
RW7	09/10/2020	12h45	4.62	Yes	AW7	09/10/2020	12:23	7.50	Yes
RW8	10/10/2020	07h49	3.89	Yes	AW8	10/10/2020	07:28	15.00	yes
RW9	10/10/2020	08h38	4.03	Yes	AW9	10/10/2020	09:03	14.84	Yes
RW10	10/10/2020	09h58	4.35	Yes	AW10	10/10/2020	09:41	7.92	Yes
RW11	10/10/2020	13h14	5.12	Yes	AW11	10/10/2020	12:33	12.30	Yes

Wet season									
Source type	**Sample date**	**Time**	**CBE (%)**		**Source type**	**Sample date**	**Time**	**CBE(%)**	
RW1	12/02/2021	10h25	3.6	Yes	AW1	12/02/2021	10h45	1.0	Yes
RW2	12/02/2021	09h53	3.4	Yes	AW2	12/02/2021	09h41	9.7	Yes
RW3	12/02/2021	17h55	3.3	Yes	AW3	12/02/2021	17h26	3.5	Yes
RW4	12/02/2021	18h08	3.4	Yes	AW4	12/02/2021	18h35	9.5	Yes
RW5	12/02/2021	12h19	3.7	Yes	AW5	12/02/2021	13h01	8.8	Yes
RW6	12/02/2021	12h39	3.7	Yes	AW6	12/02/2021	12h10	8.0	Yes
RW7	12/02/2021	11h16	3.4	Yes	AW7	12/02/2021	10h46	3.3	Yes
RW8	12/02/2021	09h27	4.5	Yes	AW8	12/02/2021	09h16	8.0	Yes
RW9	12/02/2021	14h59	3.9	Yes	AW9	12/02/2021	14h48	7.4	Yes
RW10	12/02/2021	14h26	3.4	Yes	AW10	12/02/2021	14h10	13.5	Yes
RW11	12/02/2021	16h05	3.6	Yes	AW11	12/02/2021	15h50	12.9	Yes
RW- River water **AW-** Aquifer water **CBE-** Charge balance error									

5.2.2. Main data on assessing interaction using stable isotopes

This section presents the main data used for the analysis of the stable isotopes of the rainfall water samples, river water samples, and aquifer water samples collected during the dry and wet seasons. The samples were analyzed for the selected oxygen -18 ($\delta\ ^{18}O$) and hydrogen-2 ($\delta\ ^{2}H$) isotopes signatures. These delta values were expressed as per mil deviation relative to a known standard mean ocean water (SMOW) for $\delta\ ^{18}O$ and $\delta\ ^{2}H$. The analytical precision was estimated at 0.5 % for oxygen (O) and 15 % for hydrogen (H). The isotopes for all the water samples were reproduced within the expected analytical limit error and are presented in $\delta^{18}O$ vs $\delta\ ^{2}H$/D space relative to the Global Meteoric Water Line (Craig, 1961).

5.2.3. Main data on assessing interaction using baseflow separation

The main data presented in this section included the hydrological time series data collected from the three river gauging stations C9H009 upper stream, C9H003 middle stream, and C9H026 downstream catchment of the study area. The data was collected using an electronic data logger pressure traducers configured to stored data on 12 minutes' intervals and then later capture into the Hydstra database system of DWS. For this study, a two years' hydrological time series river flow data from 2015-2017 was retrieved from the Hydstra system. To check the reliability of water quantity data, hydstra system was used as a quality control where data with variable 100.0 was used for the river stage and 110.0 for aquifer depth to water level. After data was collected and retrieved for each specific objective, the data were subjected to quality assurance by cross-checking the gap and outliers (point out of the range) on time series data. The output results for the baseflow separation analysis were obtained by applying the two selected filter algorithms as proposed by Chapman and Maxwell, and Lynne and Hollick on Microsoft Excel spreadsheets. The rainfall time-series data from the three rainfall stations (i.e Rockland station, Barkley west station, and Gon-gong station) managed by the South African Weather Service were obtained through email request. The results obtained from the three selected gauging stations were presented as hydrograph, descriptive and inferential statistics for interpretations.

5.3. Results interpretation

This section presents the interpretation of the results for the hydrochemistry, stable water isotopes, and baseflow separation. This section aims to characterize, compare, and interpret the results to determine the interactions between river and aquifers based on their similarities. The stable isotopes are an important tool for tracing the source while hydrogeochemistry results confirm with evidence the relationship between the two water resources. The results interpretation is also conducted to determine the flow pathways, recharge, and discharge areas within the study area.

5.3.1. pH, EC, and TDS of river and aquifer water

Table 2 summarised the EC, TDS, pH, and temperature characteristic of river water and aquifer water samples which was collected in October 2020 and February 2021 representing dry and wet season respectively. The results show that EC values ranged between 587 μS/cm and 1318 μS/cm for river water and 267 μS/cm and 1953 μS/cm for aquifer water with a mean value of 751.62 μS/cm and 953 μS/cm in dry season respectively, In the wet season, the EC values range between 456 μS/cm and 540 μS/cm for river water and 400 μS/cm and 2460 μS/cm for aquifer water with a mean of 503 μS/cm and 1227.23 μS/cm respectively, The EC level in both river and aquifers water were within the recommended limits as set out by South Africa National Standard (SANS241:2015). The TDS values varied between 225 mg/l and 1258 mg/l for river water and 275 mg/l and 636 mg/l for aquifer water with a mean of 586.3 mg/l and 378.15 in the dry season respectively, In the wet season, the TDS values varied between 220 mg/l and 263mg/l for river water and 191.4 mg/l and 2320 mg/l for aquifer water. The TDS concentrations were low (< 1000 mg/l) with an average of 241.85 mg/l for river water and 842.06 mg/l for aquifer water. The SANS 241 recommend the minimum TDS limits of 500mg/l and maximum limits of 1000 mg/l of the freshwater system. According to Freeze and Chery (1979) classification suggested both river water and aquifer water as a freshwater system based on TDS >1000 mg/l whereas Stanton *et al*., (2017), suggested that water with TDS from 1000 to 10,000 mg/L is generally considered brackish. These results suggested that both river water and aquifer water are classified as the freshwater system and can be suitable for use both in agriculture and stock water. If used for drinking purposes, it may require some minor to major treatment processes to meet standards for human consumption. The river water had an average pH value > 8 which confirmed an alkaline base water type while aquafer water varied between 6 and 9 which suggested a slightly acidic to alkaline base water type. The temperature in aquifer water was expected to be high on unconfined aquifers and low on confined aquifers. In this study, the temperature of the aquifer water has the same signature both in dry and wet seasons averaging 23 ℃ suggesting that the aquifer water samples were collected from unconfined aquifers. Slightly similar temperature values were observed in river water averaging 23 ℃ in the dry season and 26 ℃ reflecting the effects of evaporations as expected.

Table 2: The statistical summary of the river water and aquifer water hydrochemistry in dry and wet season

Parameters	River water				Aquifer water			
	Min	Max	Mean	STDEV	Min	Max	Mean	STDEV
Dry season								
pH	8.05	9.12	8.55	0.26	6.83	8.4	7.44	0.52
EC	8.87	1318	751.62	201.79	267	1953	953	452.73
TDS	225	1258	586	306.1	275	636	378.15	109.87
Temp.	20.7	25.8	23.61	1.4	19.5	25.2	23.13	1.58
Wet season								
pH	8.2	8.79	8.51	0.2	7.11	9.01	7.79	0.57
EC	456	540	503	23.93	400	2460	1258	563.53
TDS	220	263	241.85	10.9	191.4	2320	842.06	590.23
TDS	23.8	29.6	26.53	1.74	20.8	28.4	23.95	2.96

5.3.2. *The cations and anion hydrochemistry characterization*

The results of the hydrogeochemistry characteristics of river water and aquifer water samples are summarised on table 3. In dry season, the cations followed an orderly pattern of Ca>Na>Mg>K for river water and Na>Ca>Mg>K for aquifer water meanwhile the anions followed an orderly pattern of HCO_3>SO_4>Cl>CO_3 for river water and SO_4>HCO_3>Cl>CO_3.

aquifer water. The calcium and sodium were the dominant dissolved cations meanwhile the bicarbonate and sulphate were the dominant dissolve anions in river and aquifer water samples respectively. The average concertation values of Ca^{2+} and Na^{+} in river water samples were in the range of 114 mg/l and 86.5 mg/l with the standard deviation value of 75 mg/l and 58.8 mg/l respectively. In aquifer water, the average concertation values of Ca^{2+} and Na^{+} were in the range of 39.8 mg/l and 56.9 mg/l with a standard deviation of 11 mg/l and 7.3 mg/l respectively. The average concertation values of HCO_3^- and SO_4^{2-} in river water samples were 368.5 mg/l and 189.6 mg/l with a standard deviation of 109 mg/l and 175 mg/l respectively. The aquifer water samples had average concertation values 119.5 mg/l and 133.1mg/l with a standard deviation of 26.9 mg/l and 45.3 mg/l respectively. The concertation values of Na major cations were within the recommended of 200 mg/l with a slight increase in Ca^{2+} concertation exceeding the recommended limit of 75mg/l in river water. Meanwhile, the HCO_3^- and SO_4^{2-} were also within the recommended limits of 250 mg/l and 500 mg/l as set by WHO and SANS 241 limits

In the wet season, the sequence of the cations followed an orderly pattern of Ca>Mg>Na>K for river water and Na>Ca>Mg>K for aquifer water meanwhile anions followed an orderly pattern of HCO_3>SO_4>Cl>CO_3 for river water and HCO_3>SO_4>Cl>CO_3 for aquifer water during the wet season. Similarly, the river water and aquifer water samples have maintained their dominance of $Ca2^{+}$ and Na^{+} dissolved cations and HCO_3^- and SO_4^{2-} which dominated the dissolved anion respectively, The average concertation values of Ca and Na dissolved cation in river water samples were in the range of 118.4 mg/l and 72.18 mg/l with the standard deviation of 63.3 mg/l and 43.16 mg/l meanwhile the aquifer water samples had an average concertation value of 38.4 mg/l and 42.5mg/l with the standard deviation values of 0.9 each respectively, On the other hand, the HCO_3^- and SO_4^{2-} dissolved anion in river water samples had an average concertation value of 331.5 and 195.0 mg/l with the standard deviation of 154.2 mg/l and 163.5 mg/l meanwhile aquifer water samples were in the range of 107.2 mg/l and 101.9 mg/l with the standard deviation values of 3.16 mg/l and 2.18 mg/l respectively, The concertation values of major cation and anion were within the recommended limits of 75mg/l for Ca^{2+} and 200 mg/l for Na^{+} and 250 for HO_3^- and 500 mg/l for SO_4^{2-} as set by the Word Health Organisation and SANS241 respectively, The major contributor of the HCO_3^-, ions in the study area was due to anthropogenic activities like agricultural irrigation whereas the source of Ca^{2+} and Na^{+} are attributed to dissolution of minerals during water-rock mixing.

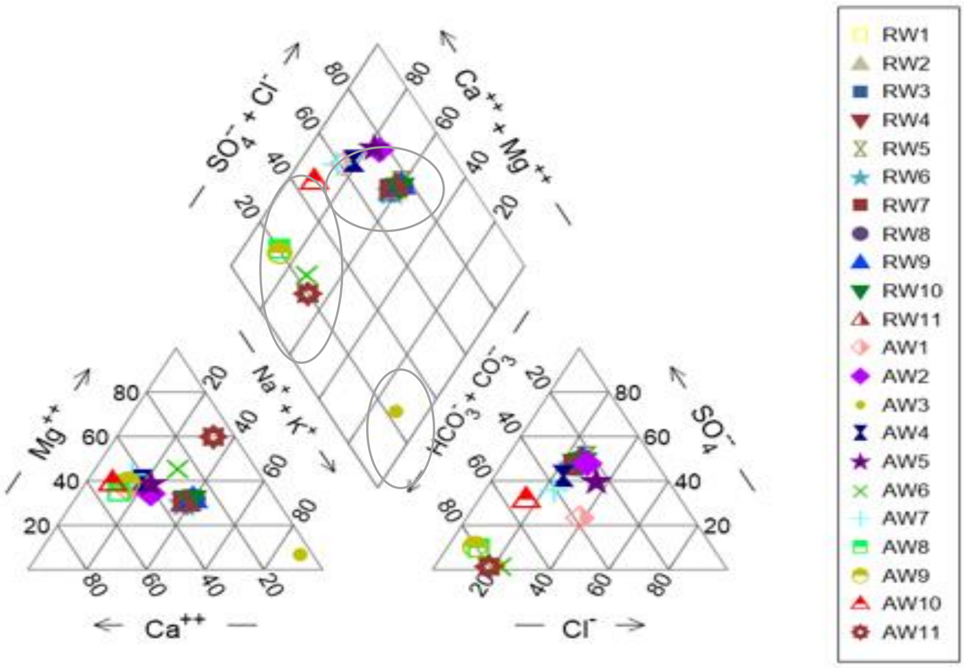
Table 3: Statistical summary of river water and aquifer water in the dry and wet season (hydro-geochemistry)

Parameters	River water				Aquifer water			
	Min	Max	Mean	STDEV	Min	Max	Mean	STDEV
Dry season								
Ca^{2+} (mg/l)	1	250	114	75	7.6	49.5	39.8	11
Mg^{2+} (mg/l)	6.7	124	66.2	35.3	23.8	37.1	28.1	3.4
Na^{+} (mg/l)	29	186	86.5	58.8	37.7	64.3	56.9	7.3
K^{+} (mg/l)	0.51	26.1	5.5	7.7	2.5	11.1	9.5	2.4
CO_3^{2-} (mg/l)	0.01	6.53	1.1	2	0	0.02	0.01	0
HCO_3^{-} (mg/l)	177	607	368.5	109	94	196	119.5	26.9
Cl^{-} (mg/l)	30.1	250	120.6	82.8	27.6	66.3	57.01	10.8
SO_4^{2-} (mg/l)	4.8	550	189.6	175	1	165	133.1	45.3
Wet season								
Ca^{2+} (mg/l)	5.4	233	118.38	63.25	37.4	40	38.37	0.86
Mg^{2+} (mg/l)	33.5	120	72.77	26.81	18.7	20.6	19.45	0.55
Na^{+} (mg/l)	28.2	170	72.18	43.16	41.1	43.3	42.46	0.97
K^{+} (mg/l)	0.46	20.6	4.53	5.74	8.25	9.44	8.61	0.33
CO_3^{2-} (mg/l)	0.6	30.8	5.25	9.11	0.6	0.6	0.6	0
HCO_3^{-} (mg/l)	122	567	331.54	134.18	103	113	107.15	3.16
Cl^{-} (mg/l)	24.5	260	120.08	79.72	44.5	47.9	45.84	0.94
SO_4^{2-} (mg/l)	0.98	543	195.03	163.49	99.3	105	101.95	2.18

5.3.3. Piper diagram plot of the major ions

a). Assessments of the river-aquifer interaction using hydro-geochemistry in the dry season

The hydro-geochemical results obtained from the laboratory were used to establish the water type of the river and aquifer water samples. Figure 5 present the plot of the concentrations of the major ions in river water and aquifer water. The objective here was to determine areas of rivers recharge aquifers or aquifer recharge rivers. To archive that, aquifer water and river water samples were collected during the dry and wet seasons. The results showed that the river water was classified as Ca- Mg- HCO_3 (100%) mixed water type. The aquifer water samples were plotted at three distinct areas on the diamond shape piper diagram which confirmed that they differ from one another. Three distinct groups of water type were identified classified as Na- HCO_3 (9%) type, and Ca- HCO_3 (45.5%) type, and Ca- Mg- HCO_3 (45.5%) mixed water type. The identification of Ca^{2+}- Mg^{2+}- HCO_3^- and Ca- HCO_3 was crucial for the determination of the flow path thereby confirming interactions. The Ca- HCO_3 water type was found in the middle stream and lower streams locations dominated by Ca^{2+} and HCO_3^- ions with lesser K^+ and CO_3^{2-} which represented recently recharged fresh aquifer water (Madlala., 2015: Lipfert, et al., 2004). During river recharge aquifer, the chemistry was controlled by dissolution or mixing of carbonate-rich minerals resulting in high Ca^{2+}, Mg^{2+} and HCO_3^- ions and subsequently mixed water type of Ca-Mg-HCO_3 found in the middle stream and upper streams locations. These water types were expected given that the study area was predominately underlined by andesite, dolomite, and chert bedrock of kimberlite pipes characterised by moderate permeability. The Na-HCO_3 water type was found at the middle stream locations dominated by Na^{2+} and HCO_3^- ions with lesser K^+ and CO_3^- ions. This water type (Na-HCO_3) represented deep aquifer water influenced by saline water intrusion and was associated with discharge areas (Lipfert, et al., 2004). This water type was not expected considering that the study area was situated over 500km away from the sea and the geology had no potential to generate saline water.



RW- River water

AW- Aquifer water

Figure 5: Piper diagram plot of river water and aquifer water in the dry season.

b). Assessments of the river-aquifer interaction using hydro-geochemistry in the wet season

Figure 6 presents the hydro-geochemistry results of the river water and aquifer water samples collected in the dry and wet seasons. The objective here was to determine the areas where river recharge aquifers or aquifers recharge river. The hydro-geochemistry results of river water samples maintained its composition of mixed Ca-Mg-HCO_3 (100%) mixed water type as observed. The aquifer water samples retained two groups of water types as observed in dry season classified as Ca-HCO_3 (45.5%) and Ca-Mg-HCO_3 (18.2%) mixed water type. A new group water type of Ca-Cl (36.3%) was identified and confirmed by aquifer water samples plotted at the top diamond shape piper diagram, Similarly, Ca-HCO_3 was found at the middle stream and lower stream locations as observed in dry season which represented recently recharged fresh aquifer water. The existence of Ca-Mg-HCO_3 water type demonstrated possible water-rock interaction and mixing of ion exchange. The mixing water type of aquifer water and river water was found in the upper stream and middle stream locations and their similarities inferred evidence of ion exchange thereby confirming hydraulic connectivity. A strong dominance of Ca^{2+} and Cl^- ions typically represented directly recharged aquifer water mainly through rainfall infiltrations. The Ca-Cl water type was found to have dominated the upper and middle stream locations underlined by limestone, gravel, and sand material. The hydrogeochemical facies supported the dominance of alkaline earth metal over alkali earth metal which confirmed the dominance of weak acid over strong acidic water type

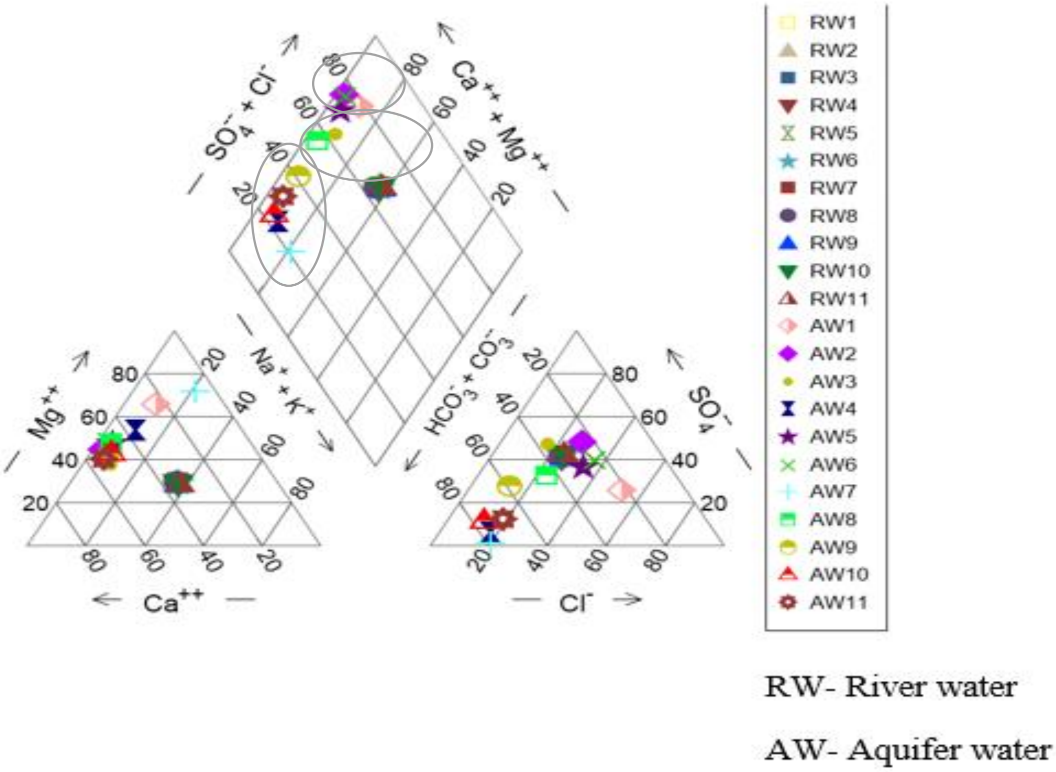


Figure 6: Piper diagram plot of river water and aquifer water in the dry season.

Durov's diagram has been used as an analytical tool to assess the similarities of water holistically. The purpose of using Durov's plot diagram was to show the mixing of water between rivers and aquifers in the study area. The river water and aquifer water were plotted alongside to observe similarities and differences of the major ions' hydro-geochemistry. All river water samples (100%) were plotted at the centre of the rectangular diagram which indicated mixing of different freshwater types with pH> 8 and TDS<1000 mg/l. 45% of the aquifer water samples were plotted at the centre together with river water with the pH >8 which supported the alkaline earth over alkalis metal composition. These results confirmed and agreed with the results of the piper diagram. These similarities were inferred as evidence to confirm that the river had recharged aquifers as confirmed by the existence of both Ca-HCO_3 and Ca-Mg-HCO_3 which were linked to recharged areas. The average was TDS<1000 mg/l and EC <10 000 μS/cm for the river water which represented the freshwater system in the dry season. The average TDS and EC values were low and slightly increased in the wet season but still within recommended limits. The increased TDS and EC values in the wet season were linked to dilutions which subsequently influenced water chemistry. The rest of the aquifer water samples plotted right side of the rectangular diagram with TDS <1000 mg/l representing Na and SO_4 dominated water, Na and Cl source affected water, and freshwater with a high degree of Na ion exchange respectively.

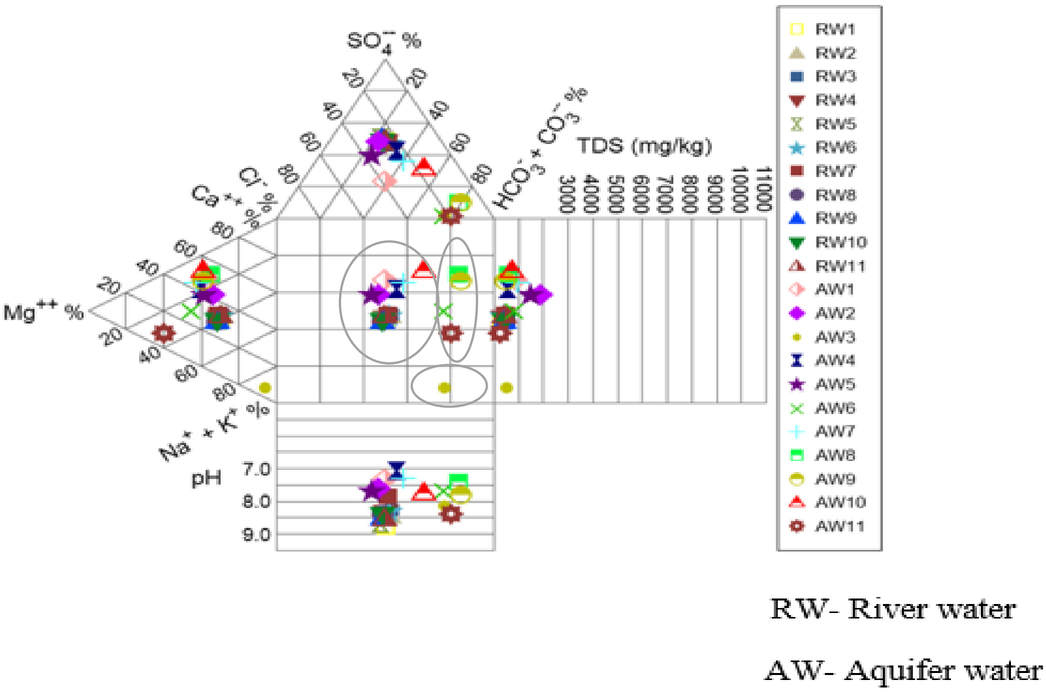


Figure 7: Durov's plot for river water and aquifer water

The mixing of water as suggested by the piper diagram was confirmed and supported by Durov's plot of river and aquifer water samples (Figure 8). As observed in the dry season, 100% of the river water samples maintained their chemical composition classified as mixing of different water types with TDS <1000mg/l. A distinct hydrogeochemical composition of the aquifer water was observed. 45% of the aquifer water were plotted together with the river water samples at the centre of the rectangular shape diagram which indicated the dominant mix of different water types influenced by the dissolution of ion exchange. According to Lloyd and Heathcoat (1985) classifications, these water signatures were classified as fresh recently recharged water exhibiting simple dissolution with no dominant major anion or cation. The majority of the remaining aquifer water samples plotted on the top right corner of the rectangular diagram indicate freshwater with a high degree of Na ion exchange and TDS <1000mg/l in the lower stream except for AW2 which suggested brackish water type with TDS >1000mg/l in the middle stream location. Few samples in the middle stream were mostly SO_4 and Na dominant with TDS <1000mg/l represented freshwater system. The overall results suggested more water in the aquifers came from freshwater systems as focussed recharge.

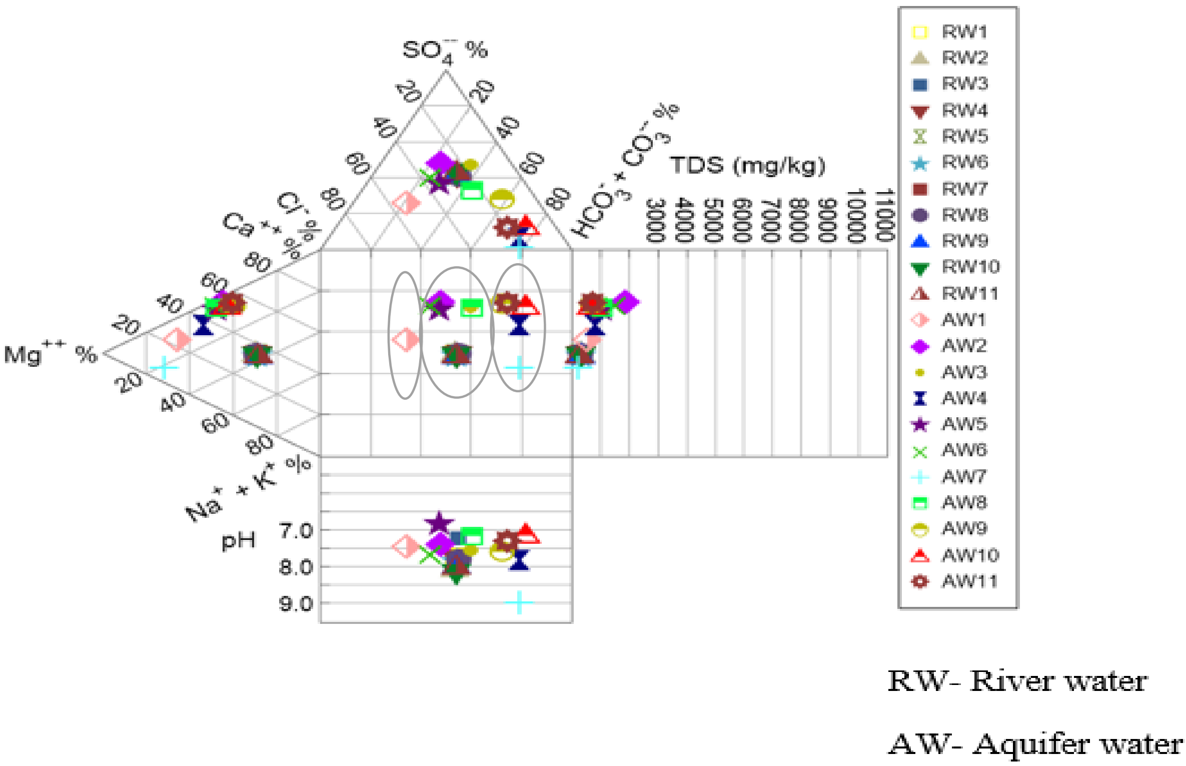


Figure 8: Durov's plot for river water and aquifer water in the wet season

5.4. GMWL and LMWL composition

The global meteoric water line (GMWL) equation defined as $\delta^2H=8\delta^{18}O + 10\%$ Craig (1961) and local meteoric water line (LMWL) has been widely used in isotopes analysis as a reference line to the local evaporation lines (LEL). The Kuruman Local Meteoric Water Line (KLMWL) was constructed from the rainfall data collected between 2003 and 2008 at three rainfall stations namely: Bokfontein, Abtonia, and Hartland all situated in Kuruman (Van Wyk, 2010). This study acknowledged the availability of other LMWL already established in other parts of South Africa including Cape Town Local Meteoric Water Line (CLMWL) and Pretoria Local Meteoric Water Line (PLMWL). By comparing the stable isotopes of $\boldsymbol{\delta}$ ^{18}O and $\boldsymbol{\delta}$ ^{2}H to the closest LMWL interpreted the isotopes results much easier than when compared to the GMWL as the LMWL better represents the local rainfall regime (Earman, 2018). This analysis approach informed the selection of the KLMWL since was the closest to the study area. In tracing the source of recharge and discharge, it was important to obtain the local rainfall data, river water, and aquifer water data to establish enrichment and depleted water samples.

The International Atomic Energy Agency (IAEA) reported that warm regions are characterized by more enriched isotopic values of ^{2}H and ^{18}O while cooler regions are characterized by more depleted isotopic values of δ ^{2}H and δ ^{18}O (IAEA, 2015). Similarities between the Kuruman area and the current study area were drawn in the context of both areas falling within the same water management area characterized by hot temperatures where the rainfall occurrence usually occurs during summer and subsides during winter. During this period, the isotopes composition was expected to be more enriched in summer due to hot or warm temperatures and depleted in winter due to condensation. In this study, the stable isotopes of 18O and 2H are used to determine the source of recharge and discharge to assess the interaction between river and aquifers.

5.4.1. Stable water isotopes techniques

The isotopes composition of δ^{2}H and δ^{18}O in river water, aquifer water, and rainfall water are presented in Table 2. The river water composition ranged between 15.3% and 21.5% for δ^{2}H and 2.97% and 4.51% for δ^{18}O in the dry season. The aquifer water samples also show that the isotopes composition ranged from -26.1% and 19.6% for δ^{2}H and -4.68% and 4.92% for δ^{18}O in the dry season. In the wet season, the river water composition ranged between -9.73% and 5.42% for δ^{2}H and -1.51 and -0.77% for δ^{18}O meanwhile the range for aquifer water composition was -27.86% and 2.47% for δ^{2}H and -4.89% and 1.06% for δ^{18}O. It has been observed that the river water isotopes composition was more enriched and depleted aquifer water samples in the dry season. The average values of the isotopes signatures of aquifer water samples were less than that of the river water samples in the dry season, which indicated that the proportion of the recharge by control dam releases was more and laterally provided evidence of external flow recharging river system. Furthermore, the result of the isotope of the aquifer water suggested multiple sources of aquifer recharge water as same source of river recharge. This study also collected the rainfall samples during the dry and wet seasons to observe the effects of temperature, condensations, and humidity on samples enrichment and depletions. All the rainfall water samples were considerably depleted with δ^2H ranging from -19.1% and 2.7% and δ^{18}O more enriched with isotopes composition ranging from -3.41% and -0.84% in the dry season. A similar observation was made in the wet season where the rainfall composition showed that the isotopes signature was from -76.37% and -56.12 for δ^2H enriched and -10.88% and -7.88% for δ^{18}O depleted. These results were indicative of the fact that rainfall was exposed to evaporative enrichment before the aquifer recharged despite low temperatures in the wet season.

Table 4: Statistical summary of stable isotopes in river and aquifer water samples

Parameters	Dry season period				Wet season period			
	River water		Aquifer water		River water		Aquifer water	
	δ2H	**δ18O**	**δ2H**	**δ18O**	**δ2H**	**δ18O**	**δ2H**	**δ18O**
Minimum	15.3	2.97	-26.1	-4.68	-9.73	-1.51	-27.86	-4.89
Maximum	21.5	4.51	19.6	4.92	-5.42	-0.77	2.47	1.06
Mean	18.2	3.64	-5.29	-0.39	-7.58	-1.13	-10.35	-1.48
Median	17.8	3.5	-3.6	-0.08	-8.31	-1.24	-7.66	-1.06
Stdev.	2.22	0.54	14.4	2.76	1.77	0.29	12.12	2.26

Table 5: Statistical summary of the stable isotopes of the rainfall water composition samples

parameters	Rainfall water samples			
	Dry season		Wet season	
	2H	**18O**	**2H**	**18O**
Minimum	-19.10	-3.41	-76.37	-10.88
Maximum	2.67	-0.84	-56.12	-7.88
Mean	-7.70	-1.90	-56.12	-7.88
Median	-5.65	-0.98	-46.27	-7.44
Standard deviation	10.98	1.44	25.59	4.32

Assessments of the river-aquifer interaction using stable isotopes plot in the dry season

Figure 6 presents the scatter plot of δ^2H and δ^{18}O results for river water, aquifer water, and rainfall water samples. As expected, all the river water samples were plotted at the top end of the local evaporative line (LEL) due to hot temperature variability in the dry season. The isotopes signature tracers confirmed the results by hydrogeochemistry although isotopes suggested a different focused recharge point. The isotopes composition suggested that 9 % of the boreholes located near the river were like that observed in river water samples which indicated that the aquifer recharge source was the freshwater from the Vaal River system. The rest of the remaining aquifer water samples deviated from the LMWL and GMWL on the left and right sides but were distributed along the LEL which indicated significant effects of evaporations and alternative sources of recharge. These results were supported by aquifer water and rainfall samples that were plotted near the intersection of LEL and LMWL which provided empirical evidence of the input water into the catchment (Gibson *et al.*, 2005). The river water samples had $\delta^{18}O$ depleted and aquifer water more $\delta^{2}H$ enriched which was indicative of aquifer recharged by the combination of river water and another source in the wet season. The river water recharged aquifer had contributed less water than recharged water from other alternative sources in the wet season. These results addressed objective one which entitled investigating areas where river recharge aquifers by estimating contributions of river water to underlying aquifers. These alternative sources were not investigated because they did not address the objectives of the current study.

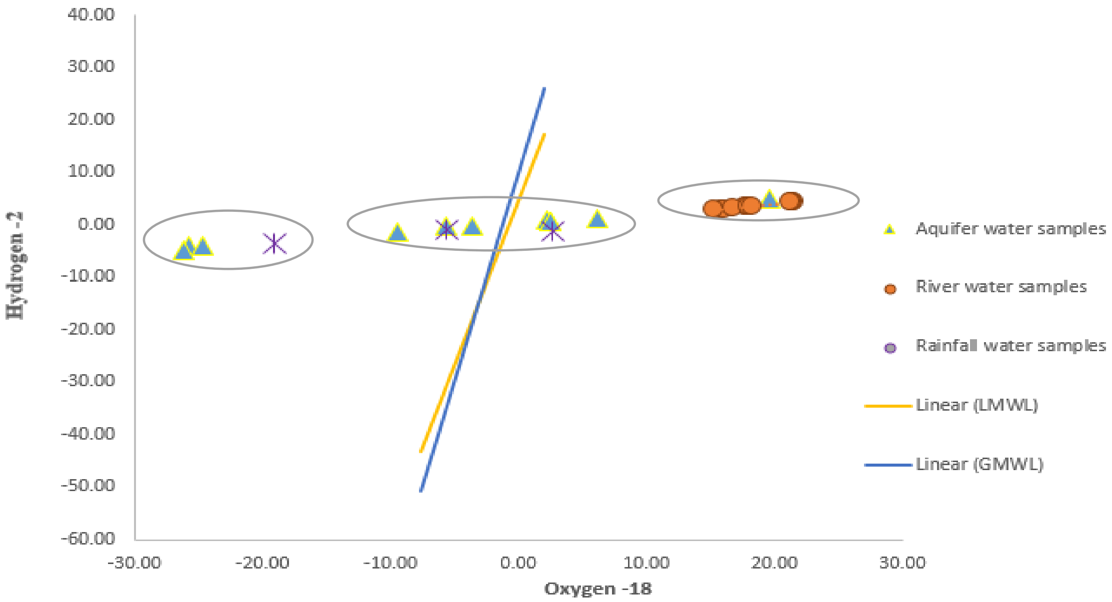


Figure 9: Plot of $\delta^{2}H$ and $\delta^{18}O$ isotopes composition for rainfall water, river water, and aquifer water during the dry season.

Assessments of the river-aquifer interaction using stable isotopes plot in the wet season

The isotopes composition of the river water, aquifer water, and rainfall water samples were plotted along with LMWL and GMWL. All river water samples were plotted on a depleted portion under the LMWL while most of the aquifer water samples were plotted at the top and center but distributed along the LEL which indicated the effects of evaporation despite low temperatures in the wet season. Based on similarities, the isotopes composition showed that 27% of the boreholes located near the river mixed with 100% freshwater system from the river which indicated that the river was hydraulically connected to the underlying aquifers in the upper stream. The aquifer water samples that plotted along the GMWL suggested that the aquifer water was recharged from the meteoric water (rainfall). These results indicated that most of the water from the river came from the same source of recharge possibly through control dam releases from the Bloemhof dam located in the upper stream. A variation in isotope signatures was observed in aquifer water samples in the wet season. These variations in isotopic compositions indicated that the aquifer water was recharged by multiple sources mainly from the river and rainfall recharge.

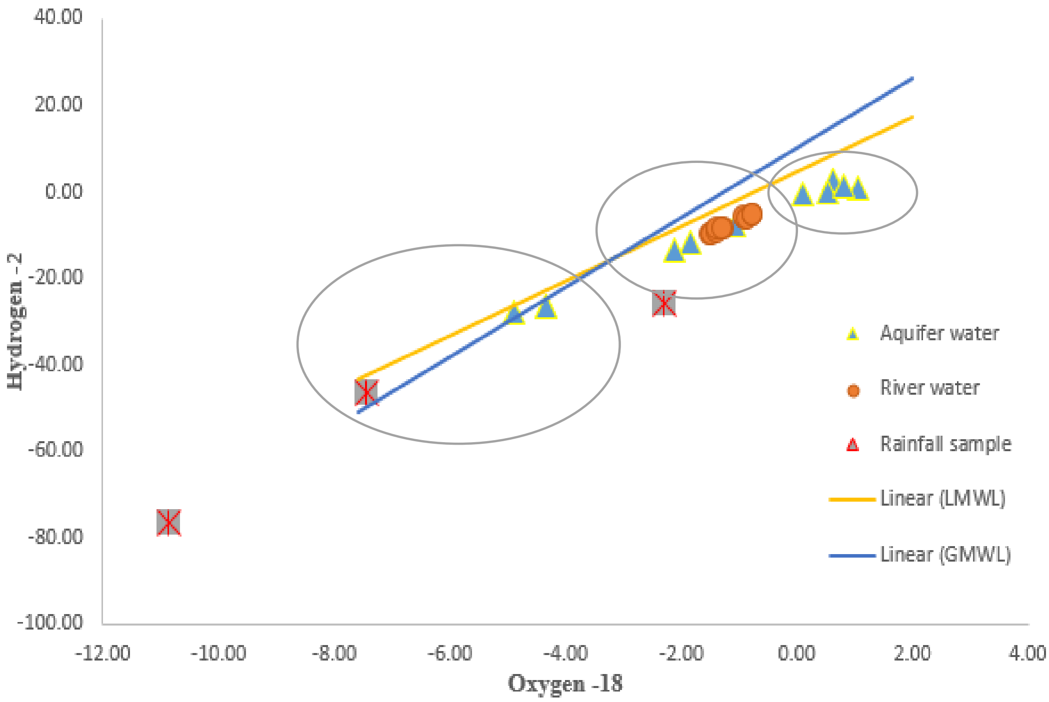


Figure 10: Plot of δ^2H and δ^{18}O isotopes composition for rainfall water, river water, and aquifer water during the wet season.

5.5. Hydrograph separation technique

5.5.1. Assessments of aquifer discharge using baseflow separation in the upper stream

Table 6 presents the descriptive statistics for daily flow, surface flow, base flow, and baseflow index (BFI). The daily flow ranged between 11.443 m^3/s and 31.413 m^3/s while the mean and standard deviation was 19.848 m^3/s and 1.081 m^3/s respectively. The surface flow varied between 10.590 m^3/s and 29.189 m^3/s while the mean and standard deviation was 18.413 m^3/s and 3.796 m^3/s respectively. The baseflow components were 0.853 m^3/s and 2.263 m^3/s with a mean of 1.435 m^3/s meanwhile the baseflow index (BFI) varied between 5.846% and 8.329% with a mean of 7.2%. These results showed how much the river was dependent on aquifer discharge. A BFI close to 0% meant a river had low proportion baseflow contributions and 100% meant high a proportion baseflow. Therefore, in this study, the BFI was 7.24 % in the upper stream which was below the BFI range indicating that the proportion of the baseflow contribution to total river flow was low.

Table 6: Descriptive statistics at gauging station C9H003 upstream

Parameter	**Daily flow (Q)(t)**	**Surface flow (Q)(t)**	**Baseflow (Q)(t)**	**BFI%**
Minimum	11.443	10.590	0.853	5.846
Maximum	31.413	29.189	2.263	8.329
Mean	19.848	18.413	1.435	7.239
Standard deviation	4.081	3.796	0.290	0.272

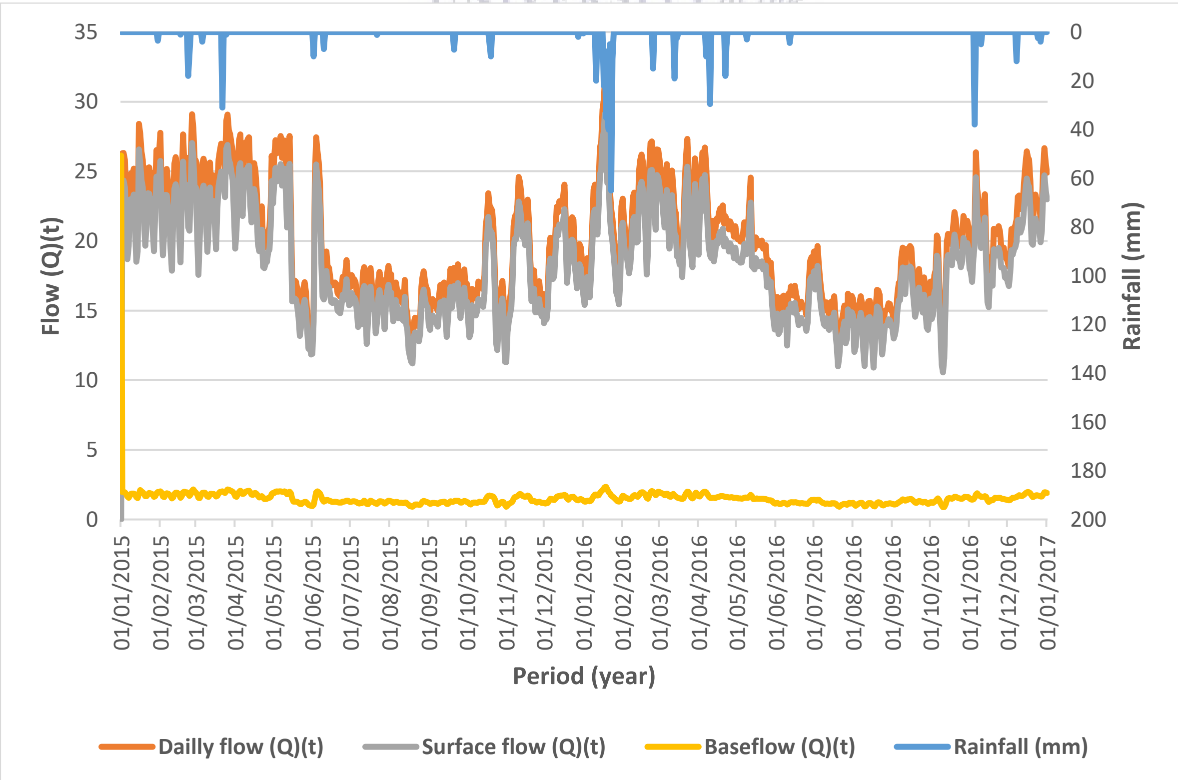


Figure 11. Daily flow series along with filtered baseflow and surface flow components using Chapman and Maxwell algorithm

Figure 11 illustrates the total daily time series discharge obtained from the gauging station C9H003 alongside the filtered surface flow and baseflow in response to the seasonal daily rainfall in the study area. The objective of using this method was to quantify how much water in the river came from the aquifer discharge. The assessment was conducted in the upstream section of the river at gauging station C9H003. In this study, the river flow patterns responded well to the rainfall patterns which indicated dry and wet spell periods as well as the influence of control dam releases on the total river flow. The river flow increased in response to rainfall events between February-March 2015, January-April 2016, and November-December 2016 represents the wet season.

During these periods, the delayed baseflow contribution also increased but to a much lesser volume. In addition, a slight increase in river flow during the dry season between May-October was observed and attributed to control dam releases required by dam operating rules. The results showed that in the upper part, the river discharge was 7.24% dependent on the subsurface contributions. These results meant that in the upper stream catchment, the river discharge was less dependent on subsurface contributions compared to the middle stream (BFI 7.31%) and lower stream (BFI 7.32%) catchment possibly due to geological restrictions to aquifer water pathways. These variabilities in baseflow indexes (BFI) indicted different baseflow contributions to the total river flow which was attributed to geological heterogeneity in the study area.

5.5.2. Assessments of the aquifer discharge using baseflow separation in the middle stream

Table 7 illustrates the descriptive statistics for daily flow, surface flow, base flow, and baseflow index presented as a minimum, maximum, mean, and standard deviation. The minimum and maximum values varied between 0.646 m^3/s and 19.459 m^3/s for daily flow, 0.597 m^3/s and 18.422 m^3/s for surface flow, 0.049 m^3/s, and 1.355 m^3/s for the baseflow as well as 4.343% and 17.698% for the baseflow index whereas the mean and the standard deviation varied between 5.263 m^3/s and 2.648 m^3/s for daily flow, 4.882 m^3/s, and 2.463 m^3/s for surface flow, 0.381 m^3/s and 0.188 m^3/s for the base flow and 7.31% and 0.714% for the BFI. A baseflow index close to 0% meant a river had a low proportion of baseflow contributions and 100% meant a high proportion of baseflow. Therefore, in this study, the BFI ratio was slightly higher in the middle stream than what was observed in the upper stream but still fall below the BFI range which indicated that the proportion of the baseflow contribution to total river flow was low. Furthermore, these results showed that aquifers continued to discharge water into the river, which provided empirical evidence that sustainable water abstraction can be recommended because the water was available within the system

Table7: Descriptive statistic at gauging station (C9H009)

Parameters	Daily flow rate (Q(t))	Surface flow (Q(t))	Baseflow (Qb(t)	BFI (%)
Minimum	0.646	0.597	0.049	4.343
Maximum	19.459	18.422	1.355	17.698
Mean	5.263	4.882	0.381	7.313
Std. deviation	2.648	2.463	0.188	0.714

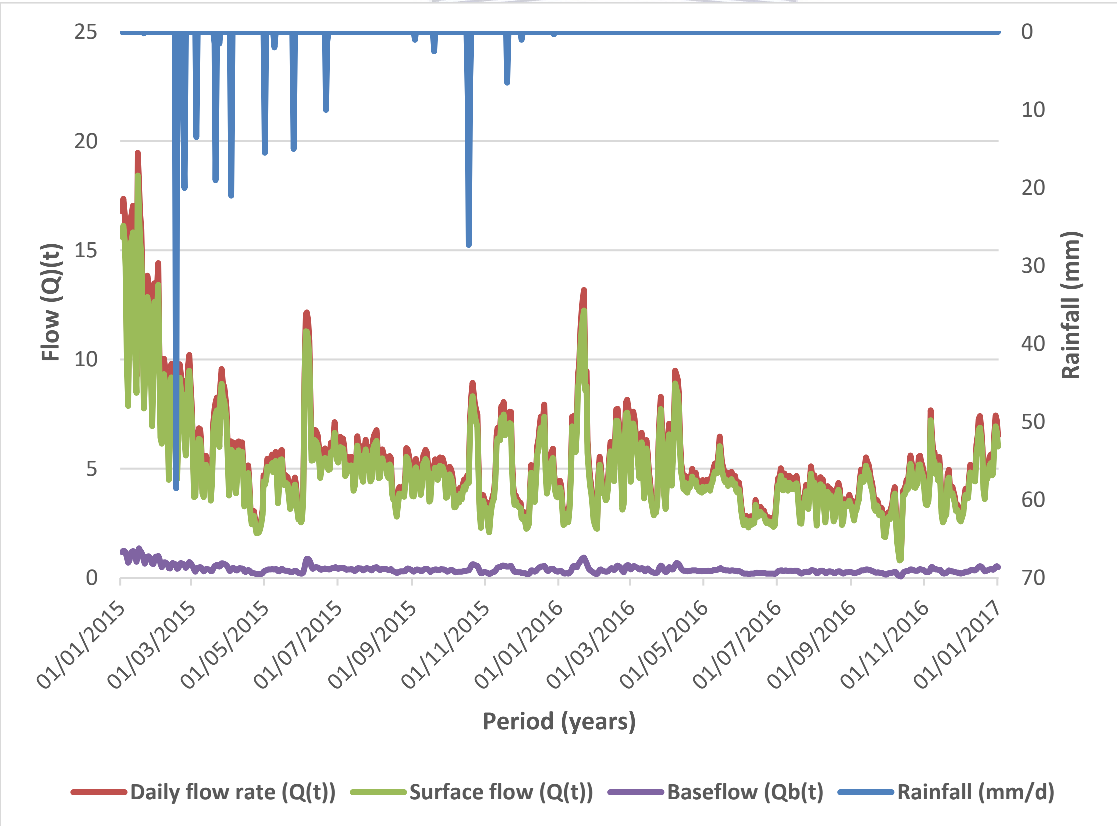


Figure 12: Daily flow series along with filtered baseflow and surface flow components using Chapman and Maxwell algorithm

The daily flow time series data obtained from the river gauging station C9H009 in the mid-stream were plotted along with the filtered surface flow, baseflow, and daily rainfall. The objective here was to quantify how much water in the river came from the aquifer discharge. This assessment was done in the middle stream section of the river using the time series data obtained from gauging station C9H009. These results showed that in the middle stream, the baseflow contributions were 7.31% dependent on the subsurface flow. What these results meant was that the amount of water contributed to total river flow increased going downstream because of the high aquifer discharge. The river flow and the rainfall patterns at the gauging station C9H009 did not complement each other well except in November 2015.

The results showed that the total river discharge decreased from January to May 2015 despite high rainfall that occurred from mid-February to mid-June 2015. During these periods, the baseflow contributions also decreased in response to decreased river flow. In mid-February 2015, an estimated 67 mm rainfall was recorded followed by 29 mm rainfall recorded during November 2015. The river flow continued decreasing after the peak recorded in June 2015 to October 2015 representing the dry periods. From November 2015 to January 2017, the study area experienced no rainfall where the river flow was reduced and sustained by control dam releases. During these low flow periods of no rainfall, the baseflow component remains relatively stable and continues to sustain river flow but at a much lower discharge rate. Thus, the delayed baseflow component in response to the rainfall prevalence was high in the wet season and low in the dry season.

5.5.3. Assessments of the aquifer discharge using baseflow separation in the lower stream

Table 8 illustrates the descriptive statistics for daily flow, surface flow, base flow, and baseflow index presented as a minimum, maximum, mean, and standard deviation. The minimum and maximum values varied between 0.111 m^3/s and 49.523 m^3/s for daily flow, 0.101 m^3/s and 47.221 m^3/s for surface flow, 0.008 m^3/s, and 2.350 m^3/s for the baseflow and 4.592% and 15.175% for the baseflow index (BFI). A baseflow index close to 0% meant a river had low proportion of baseflow contributions and 100% meant a high proportion of baseflow. Therefore, in this study, the BFI ratio was slightly increased in the lower stream compared to upper and middle stream ratios but still below the BFI range which indicated that the proportion of the baseflow contribution to river flow was low. An increased BFI ratio indicated high permeable geological pathways thereby leading to aquifer discharged water into the river. These BFI findings are usually supported by comparing river stage and aquifer depth to water level at the gauging station. However, in this study, such comparison was not investigated due to unavailable boreholes at each gauging station.

Table 8: Descriptive statistics of time series at gauging station C9H026)

Parameters	Daily flow(Q(t))	Surface water (Q)(t)	Baseflow(Q)(t)	BFI%
Minimum	0.111	0.101	0.008	4.592
Maximum	49.523	47.221	2.350	15.175
Mean	3.178	2.950	0.228	7.319
Standard deviation	2.497	2.347	0.225	0.747

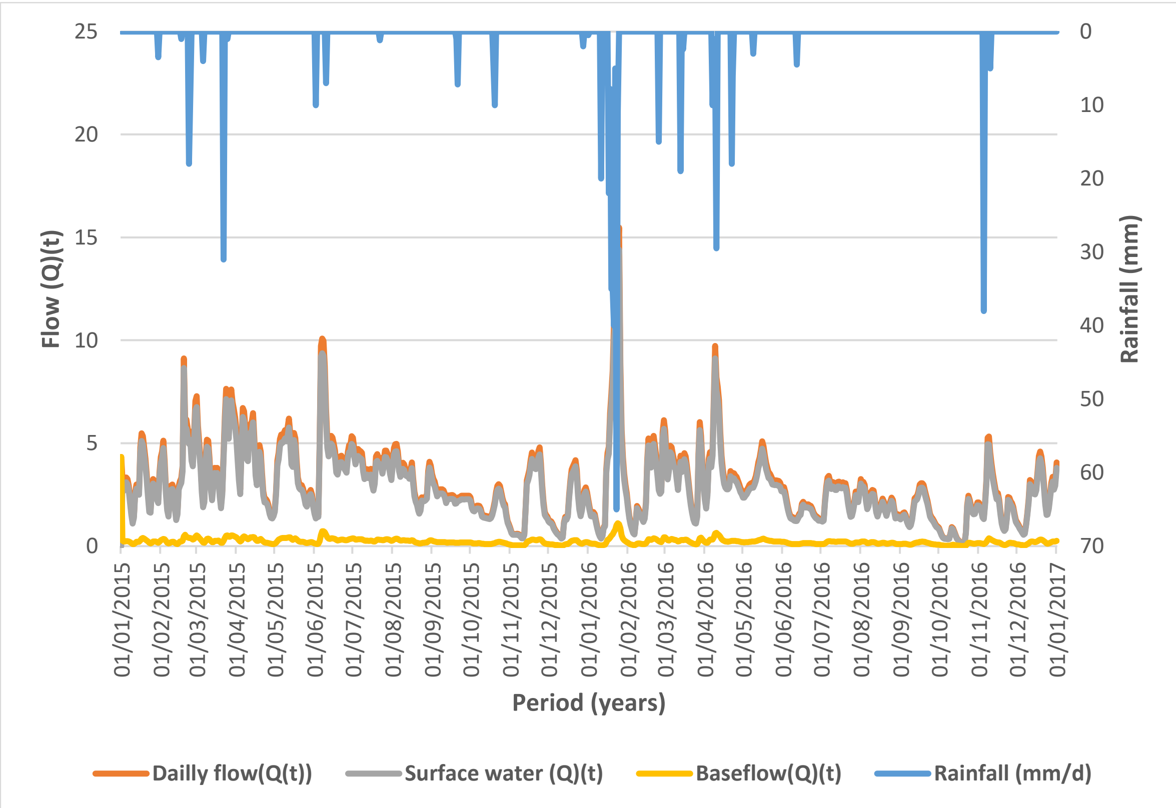


Figure 13: Daily flow series along with filtered baseflow and surface flow components using at the gauging station C9H026 downstream.

Figure 13 shows the hydrograph for daily river flow plotted together with the filtered surface flow, filtered base flow, and rainfall over two years between the 2015 and 2017 hydrological years. The gauging station C9H026 was located in the lower stream where the areas are characterized and dominated by small-scale diamond mines mining along the river banks and bed. In this section of the river, the daily flow complimented well the daily rainfall event that occurred in the lower stream area. The river flow increased between January-Apri 2015 and November 2016 with the highest peak recorded in February 2016 at 15 m^3/s responding to the high rainfall event that occurred in the wet season. During this period, the baseflow component increased with increased river flow volume but to a much lesser volume. The river flow started to decrease from June to November 2016 and from mid-April to mid-October 2016 representing dry spell periods.

The objective of applying the baseflow separation method here was to quantify how much water in the river came from the subsurface discharge. The results showed that river flow was 7.32% dependent on aquifer discharged water from the subsurface systems. These results continued to show that the river depended on aquifer discharges sustained river flow and evidence for this situation has been provided in this study. Furthermore, these results confirmed with evidence that the application of the baseflow separation technique has provided a quantifiable amount of aquifer discharged water to the river, but assumptions of this method were not explored.

5.6. Conceptualization of the groundwater processes that explain the interaction

5.6.1 Hydrogeological conceptual model of river-aquifer interaction

Generally, the groundwater in and around the study area occurs in the unconfined mafic or ultramafic extrusions rocks such as basalt and andesite formations (APD, 2009). The underlying geological formation consists of low to medium-yielding aquifers. This includes dolomite and chert bedrock appear to be the two main aquifers systems that underlain the western and eastern surface areas of the study area. Large deposits of limestone are found in the junction between the dolomite and sedimentary systems in the western part of the study area. Andesite, colluvial, and alluvial diamondiferous gravel, red and grey aeolian dune sand overlying residual soils and bedrock belonging to the Karoo, Transvaal, and Ventersdorp Supergroups (Nyamoki Consulting., 2020).

The river water in the study area was classified as Ca-Mg-HCO_3 mix of different water types characterized by total dissolved solids (TDS) values <1 000 mg/l and low electrical conductivity (EC) values <10 000 μS/cm dominated by calcium (Ca^{2+}) and bicarbonate (HCO_3^-) ions. On the other hand, the aquifer water had four different groups water types of Ca-HCO_3

freshwater type, $Na\text{-}HCO_3$ mostly found in the deeper aquifer, Ca-Cl typically linked to rainfall recharged aquifers, and $Ca\text{-}Mg\text{-}HCO_3$ represented mixed of different water types with average TDS <1000 mg/l and the majority of EC <10 000 μS/cm on the majority of samples. The water quality from alluvium formations was of good quality but in the case of irrigation, the quality was negatively influenced while aquifer harvest potential was estimated at around 8 000 to 10 000 m3/km^2/year (DWAF, 1986). Their water-bearing properties are low with the extraction potential expected to be low at around 10 % of the annual supplement in the wet season meanwhile during the dry season, only 0.2 l/s can be obtained from the ventersdorp lava (DWAF., 1986; Smith *et al,* 2002).

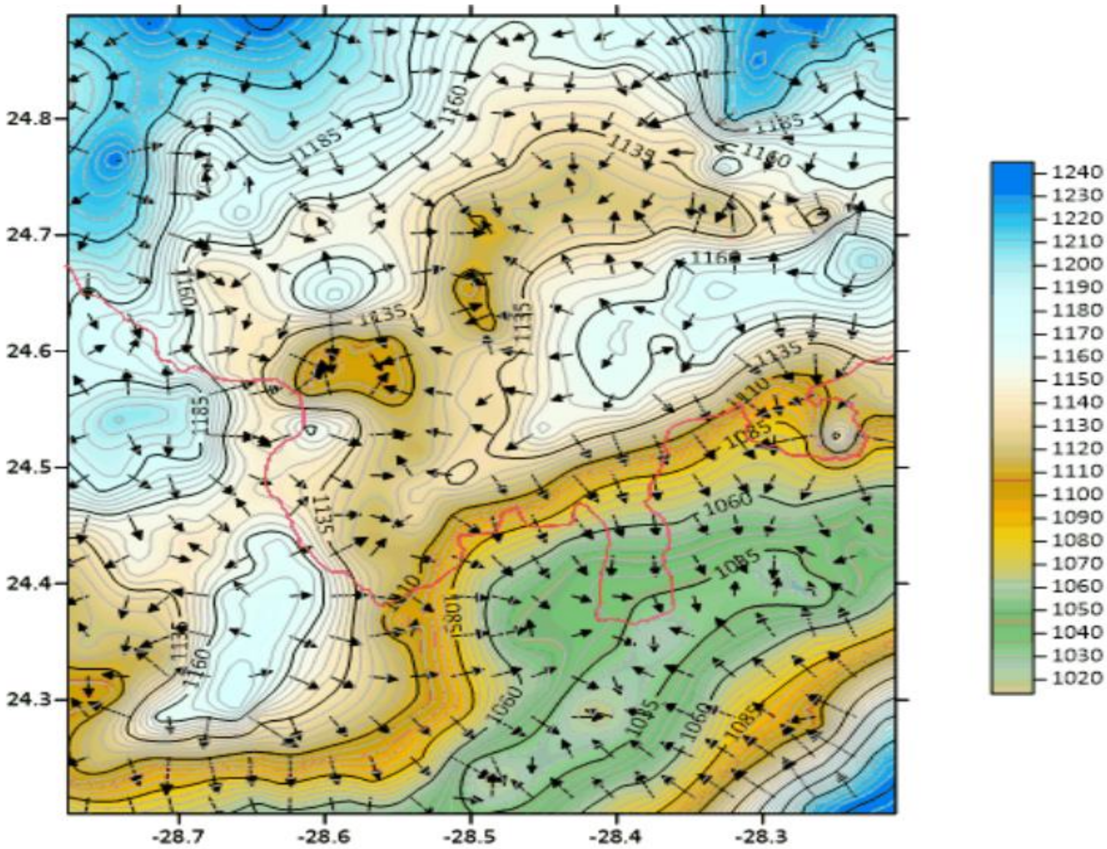


Figure 14: Contour map and flow direction

Figure 14 shows the contour map and the flow direction of the groundwater in the Lower Vaal catchment of South Africa. The objective here was to visualize the groundwater flow direction estimated from surface elevations data. The hydraulic gradient played a pivotal role in determining flow direction. The estimated flow direction was found to agree with the constructed elevation contour map. These results indicated that the groundwater flow direction mimics the topography flowing towards the river from the northwest, northeast, and southeast. The groundwater was distributed from the hilltops (slope) and concentrated in the lowest end of the basin. The flow mainly occurred in dolomite and chert bedrock formation through Kimberlite pipes and andesite, colluvial and alluvial diamondiferous.

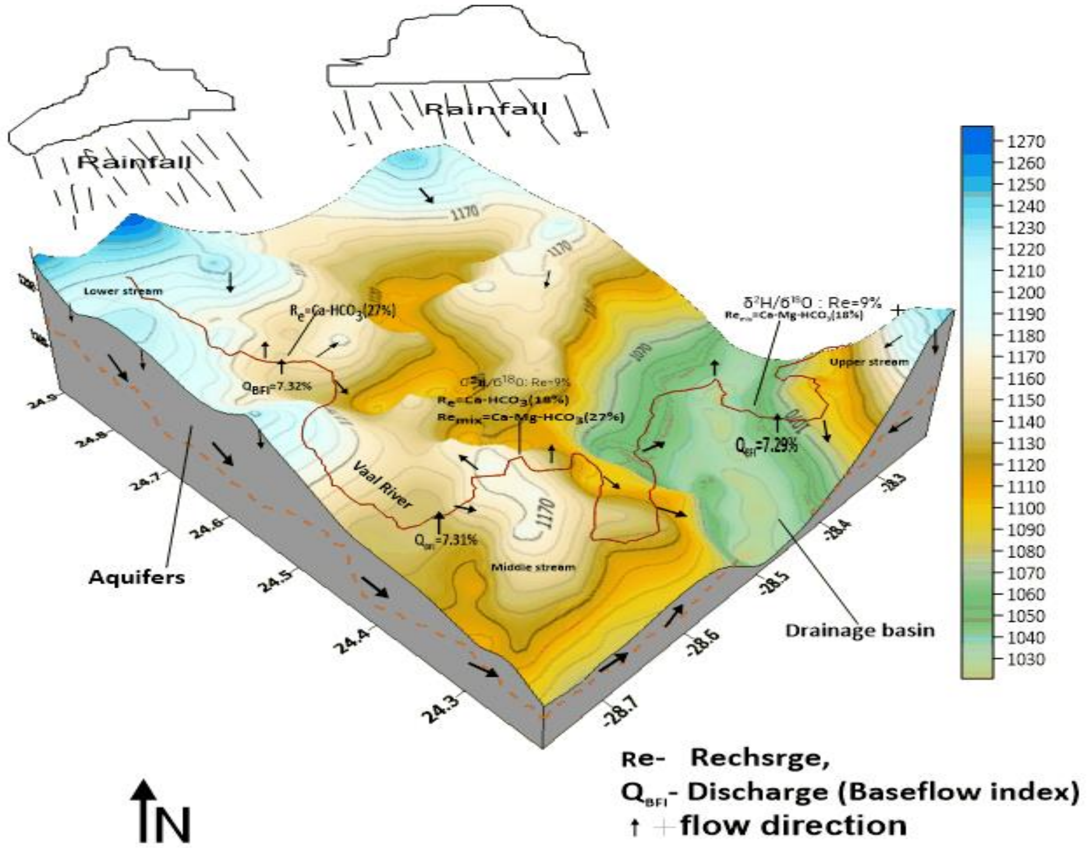


Figure 15: Conceptual model of groundwater processes

Figure 15 illustrates the conceptual model of the groundwater process that explains river-aquifer interaction in the study area namely: groundwater flow, recharge, and discharge areas. To achieve this, firstly, data was collected from all the available sources and information based on modeling purposes using record review. Secondly, determined aquifer system geometry and hydrodynamic properties to assess river-aquifer interactions and evaluate lateral in-out of groundwater flows. Thirdly, integrated the results obtained from objectives one and two to produce a final conceptual model sketch. Finally, checked the accuracy of the conceptual model using the groundwater balance input and output analysis. The model showed that the Vaal River gained water in some reaches and lost water in other reaches (Winter *et al*, 1998).

The direction of the exchange flow, recharge, and discharge rates depended on aquifer heterogeneity and similarities of hydrogeochemistry and stable isotopes compositions in water samples. Kalbus *et al*, (2006) and Winter *et al*, (1998) reported that in gaining reaches, the elevation of the aquifer water table was higher than the elevation of the river stage. Conversely, in losing reaches the elevation of the aquifer water table was lower than the elevation of the river stage. The results of this study indicated that the river-aquifer interaction occurred in two ways: Firstly, the river water infiltrated downward through the riverbed into the underlying aquifers (losing stream), and secondly, the aquifer water discharged water from subsurface systems upward through the riverbed and banks to sustain river flow during low flows (gaining stream). Furthermore, the model showed that the river lost water to recharge underlying aquifers in the upper and middle stream sections and gained water from aquifer discharge in all reaches (upper stream, middle stream, and downstream locations. The results showed that the groundwater contribution from subsurface discharge increased from the upper stream going downstream sections due to heterogeneity in geology formations.

5.7. Aquifer water and river water abstraction and use

The river water was found to be a core pillar in freshwater resources supply which was used for both socio-economic and environmental purposes. Table 9 shows the registered water use authorization volumes in terms of section 21 of the National Water Act (Act No 36 of 1998). Data on the registered water use authorizations were obtained from the Water Administration Registration and Management System (WARMS) from the Department of Water and Sanitation (DWS) to obtain insight into the extent of aquifer water and river water abstractions and use. From this data, the aquifer water, and river water-stressed index was calculated to determine the level of impacts within the catchment. In the study area, understanding the connectivity of the aquifer water and river water, as well as abstraction and use, was so important in ways that necessitated an integrated approach to sustainable water abstraction. To address this, it did not require only an understanding of the water quality and quantity, however, required an understanding of the river-aquifer interactions, thus, promoting the sustainability of water abstractions.

A total of 109 water users have been registered and authorized for taking water from a water resource in terms of section 21(a) water use. Section 21(a) provides a water user with a legal right to take water from water resources. The sources of water abstraction ranged from aquifer and river water. The results showed that the aquifer water abstraction and use were estimated at 3.2 % (1 049 142 Mm^3/a) meanwhile the river water abstraction and use were estimated at 96.8% (32 185 181.15 Mm^3/a) of the freshwater use. The cumulative abstraction rate from both river and aquifer water was estimated at 33 227 323.05 Mm^3/a. The water uses activities ranged from agriculture, small-scale diamond mining, livestock farming, industry, and local government water supply. The demand for water supply has been increasing rapidly with the growing population in the study area.

Table 9: Summary of the registered water use (WARMS)

<table>
<tr><th>Source type</th><th colspan="2">Water Use sector</th><th>Catch ment</th><th colspan="2">Registered volume in terms of S21 (m^3/a)</th></tr>
<tr><td rowspan="3">Aquifer water (boreholes)</td><td>Agriculture (irrigation and Livestock</td><td>06</td><td rowspan="6">C91E</td><td>282415</td><td rowspan="3">1 049 142.0 Mm^3/annum</td></tr>
<tr><td>Mining</td><td>14</td><td>735 077. 2</td></tr>
<tr><td>Industry and water supply</td><td>03</td><td>31649.8</td></tr>
<tr><td rowspan="3">River water (Scheme)</td><td>Agriculture (irrigation and Livestock</td><td>72</td><td>31721678.25</td><td rowspan="3">32 185 181.15 Mm^3/annum</td></tr>
<tr><td>Mining</td><td>14</td><td>458 502.9</td></tr>
<tr><td>Industry and water supply</td><td>0</td><td>0</td></tr>
<tr><td></td><td></td><td>109</td><td colspan="3">Total volume registered: 33 227323.05 Mm^3/a</td></tr>
</table>

Since there was no information available on aquifer and river water abstraction impacts, this study has taken the direction of calculating the stress index between the two water resources. To achieve this, data from WARMS and Resource Directed Measures (RDM) were used. Parsons and Wentzel (2007) describe the class and stress index as follows: <0.05 to 0.2 unstressed, 0.2 to 0.75 moderate, 0.75 to 0.95 stressed, and >0.95 critically stressed. Table 9 present the summary of the reserve information of the catchment C91E.

Table 10: Summary of the reserve

Groundwater reserve								
Catchment	**Area (km^2)**	**Recharge (Mm^3/a)**	**Population**	**Baseflow (Mm^3/a)**	**EWR (Mm^3/a)**	**BHN Reserve (Mm^3/a)**	**EWR as % of recharge**	**BHN as % of recharge**
C91E	1 506	8.32	50 000	5.84	2.92	0.46	35.09	5.83

Surface water reserve							
Quaternary catchment	**Water resource**	**Ecological Reserve (% MAR)**	**BHN Reserve (%MAR)**	**Ecological reserve volume (Mm^3)**	**Total reserve (% PDMAR)**	**PDMAR (m^3)**	**NMAR (m^3)**
C91E	Vaal River	85.95	0.03	107.203	85.96	124.72	147.85

where EWR is the ecological water requirements, BHN is the basic human needs, PDMAR is the present-day mean annual rainfall and NMAR stands for natural mean annual rainfall. The stress index equation is as follows:

$$AW_{\text{stress index}} = \frac{\text{Groundwater abstraction}}{(\text{Recharge} - \text{Baseflow})} \times 100 \qquad RW_{\text{stress index}} = \frac{\text{Surface water abstraction}}{(\text{Recharge} - \text{Baseflow})} \times 100$$

$$= \frac{1\,049\,142 \text{ m3/a}}{(8.32 - 5.84)\text{m3/a}} \qquad = \frac{32\,185\,181.2 \text{ m3/a}}{(147.85 - 107.203)\text{m3/a}}$$

$$= \frac{2\,874.5 \text{ m3/day}}{6\,794.5 \text{ m3/day}} \qquad = \frac{88\,175.5 \text{ m3/day}}{111.506.8 \text{ m3/day}}$$

= *0.4* **Moderate stressed (40%)** = ***0.8 Stressed (80%)***

where the $AW_{\text{stress index}}$ is the aquifer water stress index and $RW_{\text{stress index}}$ is the river water stress index. The aquifer water stress index was 0.4 while the river water index was 0.8. These results showed that 40% of aquifer water has been allocated suggesting that the catchment was moderately stressed. Similarly, 80% of the river water has been allocated which indicated that the catchment was stressed, Therefore, sustainable groundwater abstraction can be recommended because the water was available while on the other hand sustainable surface water cannot be recommended due to water unavailability within the catchment.

5.8. Comparative analysis of the results

This section presents the results and discusses the first objective which was to determine areas where river recharge aquifers by estimating river contribution to the underlying aquifers. To achieve this, hydrogeochemistry as confirmatory analysis and stable isotope as a tracer were used to quantify and characterize recharge and discharge areas in the Lower Vaal River catchment. The results showed that all river water samples were characterized and classified as Ca-Mg-HCO_3 mixed of different water types. The aquifer water samples revealed four different groups of water types classified as Ca-HCO_3, Ca-Cl, Na-HCO_3, and Ca-Mg-HCO_3. mix type. The Ca-HCO_3 and Ca-Mg-HCO_3 were found in upper, middle, and lower stream locations which and were associated with active recently recharged areas, therefore confirmed river recharge aquifers and were expected based Ca^{2+} and HCO_3^- rich geology. The Ca-Cl was in the upper stream which was expected and was linked to direct rainfall recharge. The average TDS values were 586 mg/l for river water and 378.15 mg/l in the dry season and 241.85 mg/l and 842.06 mg/l in the wet season. The average EC values were 751.60 μS/cm and 953 μS/cm in the dry season and 503 μS/cm and 1258 μS/cm in the wet season. Based on the classification of Freeze et al., (1979), these results confirmed the dominance of the freshwater system of both river and aquifer water across all sections of the study areas.

Similar results were found by Adelana *et al*, (2003) who investigated the characteristics of groundwater-surface water interaction using isotope and geochemical analysis methods in the semi-arid Sokoto basin, north-western Nigeria. Their study found distinct groups of groundwater types while the river water was of Ca-Mg-HCO_3 mixed type characterized by alkali-calcium-bicarbonate. These findings improved knowledge and understanding that the application of the hydrochemistry method can be a tool to provide insights into the estimated volumes of river recharge aquifers. Similar results were found by Ravikumar *et al*, (2015) in a comparative study to evaluate and identify the hydrogeochemistry of water and the involved chemical processes using Durov and Piper diagrams from the SRLIS river basin, Karnataka, India. Their findings showed the dominance of Ca-Mg-HCO_3 (70.84%) mixed water type while Durov specified the dominance of simple dissolution or mixing (83.34 %) with no dominant major anion or cation although the two studies had significant percentage variations. Zhang (2016) conducted a study on the interaction between surface water and groundwater and its effect on water quality in the Second Songhua River basin. Their study found the water types of the river water and shallow groundwater was Na–HCO_3 and the contribution of the river water was 81.3% in the upper reaches. The study also showed that the groundwater table was 6 m which was higher than the river stage height, indicating that the shallow groundwater may discharge into the river. The agreement of the previous studies with the findings of the current study confirmed that the results of this study were not isolated, The plot for isotopic signature in river water samples was much more exposed to evaporative enrichment (3.64% for $\boldsymbol{\delta}^2$H and $\boldsymbol{\delta}^{18}$O) as expected due to hot temperature conditions and lack of rainfall while the aquifer water samples were depleted (-5.29% $\boldsymbol{\delta}^2$H and -0.39% $\boldsymbol{\delta}^{18}$O) in the dry season. Conversely, in the wet season, the plot for isotope signature in river water samples was less exposed to evaporative enrichment (-7.58 $\boldsymbol{\delta}^2$H and -1.13% $\boldsymbol{\delta}^{18}$O) due to the influence of condensation and rainfall effects also as expected while the aquifer water samples were depleted (-10.35% and -1.48% for $\boldsymbol{\delta}^2$H and $\boldsymbol{\delta}^{18}$O) in stable isotopes compositions. The isotopes results suggested that 9.1% of the aquifer water was recently recharged by the freshwater system in the upstream and midstream. The rest of the remaining water samples (90.9%) suggested an alternative source of recharge of which, few of those samples that plotted near or at the intersection of LEL and LMWL suggested a source of recharge coming from meteoric water. These results were in line with those found by Andersen et al, (2008) where the author investigated δ^{18}O and δ^2H in the Namoi River catchment – elucidating recharge sources and the extent of surface water-groundwater interaction. The study found that the groundwater sampled near the river has been recharged from the Namoi River, demonstrating that there is a hydraulic connection between the two water resources. Their study concluded that $\boldsymbol{\delta}\ ^{18}$O and $\boldsymbol{\delta}\ ^2$H of rainfall, surface waters, and groundwater provide an important tool for understanding hydrological processes such as recharge and surface water/groundwater interaction within semi-arid catchments. In Eastern Africa, Oiro *et al*, (2018) used stable water isotopes to identify Spatio-temporal controls on groundwater recharge in two contrasting East African aquifer systems (Nairobi aquifer System and South Coast aquifer). Their results showed similarities with that of this study where greater deviations from the meteoric lines (LMWL and GMWL) were observed because of higher evaporation experienced linked to low humidity conditions, which lead to kinetic fractionation. Deviations from the global network of isotopic precipitation, local meteoric water line, and global meteoric water line illustrated the multiple evaporation processes, where moisture content in air masses was subjected to lesser effects before precipitation and eventual recharge.

This section presents the results and discusses objective two which entailed determining areas where aquifer recharge river by estimating contributions of aquifer water to total river flow. The hydrochemistry and stable isotopes methods were used to quantify and characterized the contribution of subsurface discharge to river flow. The results of the current study revealed one group associated to discharge areas classified as Na-HCO_3 mostly found in deeper aquifers. The Na-HCO_3 water type was found in the middle and lower stream locations. This water type was associated with active discharged areas dominated by Na and HCO_3 ions and was not expected given the fact that the study area was situated over 500 km away from the sea. The Na-HCO_3 had an average TDS < 1000 mg/l and EC< 10 000 μS/cm values represented fresh water with less mineralization. These results were like those found in the boundary of Northern Cape and Western Cape Province, South Africa by Mqondeki, (2019). Who assessed the influence of groundwater recharge mechanism on non-perennial river systems using environmental tracers in, Tankwa Karoo, South Africa. The study found four distinct water types characterized by Ca-HCO_3, Ca-SO_4, Na-Cl, and Na-HCO_3. These water types were associated with discharge zones thereby confirming the role of aquifers in recharging river. The study concluded that the methods chosen were suitable for the study area setting and recommended that the approach used can be implemented elsewhere in similar geographical settings.

In this study, Na-HCO_3 water type identification confirmed possible discharge areas usually found in deeper aquifers. However, since the water type was not identified in river water samples did not confirm the role of aquifer recharge river. Concerning stable isotopes signatures of $\boldsymbol{\delta}^2$H and $\boldsymbol{\delta}^{18}$O, the results did not suggest that the recharge in the river came from aquifer discharge, instead, indicated that the river had other sources which supplemented meteoric water. These results were like those found by Modie, (2018) who conducted a study on groundwater and surface water interactions using stable isotopes in Botswana. Despite hydrogeochemistry results, the stable isotopes and EC methods in his study did not confirm aquifer discharge zones as suggested by hydrochemistry compositions.

In this study, the contribution of the subsurface discharge to the total river flow was also estimated using the baseflow separation method. Following the determination of the baseflow component, the ratio between baseflow and total flow (BFI%) was calculated to indicate the proportion of total flow derived from the baseflow. This approach was carried out using the hydrological time-series flow data from three gauging stations from the 2015-2017 period. The mean base flow as derived from the total river flow for the gauging station C9H003 was 1.44 m^3/s in the upper stream location, gauging station C9H009 was 0.38 m^3/s in the middle stream, and gauging station C9H026 was 0.23 m^3/s in the lower stream location. The baseflow index (BFI) result showed that the dependency of the total river flow to aquifer discharge contributed

7.24 % in the upper stream, 7.31% in the mid-stream, and 7.319% in the downstream. The mean baseflow and baseflow index have complimented each other well ranging from high to low in the upper and lower stream locations respectively.

Similar to the approach used in this study, Madlala *et al,* (2018) used baseflow separation methods to determine groundwater-surface water interaction, the upper Berg River catchment, South Africa. Their study found that the river dependency on the subsurface discharge ranged between 7.49% and 7.79% of total stream flows gauged. The study by Killian *et al,* (2019) used hydrograph-separation techniques and groundwater-level data to evaluate groundwater and surface-water interaction throughout the Mississippi Delta. The study found that the baseflow contributions to streamflow in the middle stream site were moderate to high (average annual BFI = 0.805), while in the most upper stream site was moderate to low (average annual BFI = 0.366), and the degree of baseflow index contribution varied between high- and low-flow events. Orlova *et al,* (2014) investigated surface water and groundwater contributions to streamflow in the James Bay Lowland, Canada. Their study found that relative contributions of bedrock-derived groundwater to streamflow increased with a catchment area from <20 to >40% under dry conditions and were ~50% lower under wet conditions across all catchments. Meanwhile, Asmerom, (2008) used the average daily time series data of hydro-meteorological and hydrological data for 12 gauged rivers stations to determine groundwater contribution and recharge estimation in the upper Blue Nile. The results showed found that 15% of the annual flow came from the shallow groundwater aquifer and most of the contribution was obtained from the southern tributary which accounted for 44%. In addition, a study by Maurer *et al,* (2004) indicated that in areas of recharge and discharge, more detailed delineations were warranted for accurate prediction of hydrologic response to obtain better-improved knowledge and understanding of river-aquifer interaction for sustained water abstractions. The groundwater contoured map for the aquifers in the study areas was constructed from the elevation extracted from the google earth pro within the study area.

The contoured map allowed the determination of groundwater flow direction. The observed groundwater flow direction mimics the topography flowing from north-west, north-east, and south-east in dolomite and chert bedrock through kimberlite rock pipes and andesite, colluvial, and alluvial diamondiferous formations towards the Vaal River system. Therefore, geology and topography have driven the direction of groundwater flow pathways and are assumed to be concentrated in low-lying areas which subsequently discharge into the Vaal River system through baseflow. The findings from this current study agreed with those found by Reid *et al*, (2009) who found that geology and surface topography effectively determine the direction of groundwater flow. Despite this, the stable isotopes did not confirm tracing the source of water as suggested by hydrochemistry. However, the baseflow separation method demonstrated that the proportion of the groundwater discharge varied from high to low. Therefore, what these results meant was that the aquifer was dependent on river recharge in the upper stream and middle stream reaches thereby confirming losing river and was dependent on aquifer discharge in all reaches thereby confirming gaining river.

In the upper stream, the aquifer was overlaid by gravel and sand while in the mid-stream and downstream the aquifer is overlaid by an andesite, colluvial and alluvial diamondiferous gravel, red and grey aeolian dune sand overlying residual soils, and bedrock belonging to the Karoo, Transvaal, and Ventersdorp Supergroups which are sufficiently high permeable to unconfined aquifers. The current study has shown that topography and geology influence recharge, discharge, and flow direction. The study by Moseki, (2013) agreed with this approach. He investigated surface water-groundwater interaction for the development of a suitable methodology for South African conditions. The aim of his was to investigate, identify and recommend methodologies that are suitable for South African conditions to quantify groundwater processes that explain interaction and used conceptual knowledge of structural controls to show the occurrence and movement of water from the groundwater to the surface water component or visa-visa. The study found that the groundwater flow regime was controlled by geology, structures, and topography as demonstrated by prominent sandstone layers that typically form breaks in the hill slopes below which seepages (or interflow) were often observed. The study by Weitz *et al,* (2014) analyzed surface and subsurface geological information, groundwater head, hydrochemical, and environmental isotope data to develop a conceptual model of aquifer–lake interaction in the Lake Sibayi Catchment, Eastern South Africa.

In the western section of the catchment, the model showed that the groundwater flows to the lake where groundwater head was above lake stage, whereas along the eastern section, the presence of mixing between lake and groundwater isotopic compositions indicated that the lake recharged the aquifer. The stable isotope signals further revealed the movement of lake water through and below the coastal dune cordon before eventually discharging into the Indian Ocean. These findings provided empirical evidence that the use of hydrochemistry, stable isotopes, and baseflow separation methods can improve knowledge and understanding on assessing recharge and discharge areas thereby confirming the interaction between river and aquifers. Therefore, analyzing water chemistry and river flow time series data can provide insight into river-aquifer water interaction.

5.9. Evaluation of the study

The evaluation of the study entailed carrying out a structured assessment of the efficiency of the methodological approach used to address the aim and objectives of the study. The study aimed to better improve knowledge and understanding for evaluating river-aquifer interactions for sustained water abstractions. A quantitative methodological approach was used which allowed the collection of field data that was consistent, precise, and reliable to analyse using different analytical methods of hydrochemistry, stable isotopes, and baseflow separation techniques. The secondary data on hydrological time series and rainfall data stored in various database systems were obtained. This has reduced the time needed to execute field investigations. The sample selection and findings were generalized as representative of the whole study area population. This methodology was the most appropriate in the application of systematics and standardized comparison approach.

Initially, this current study had a plan to use the river flow gauging method as the fourth method of assessing river aquifer interaction. However, later it became evident that the application of the method was not feasible due to the unavailability of river gauging equipment. It would have been beneficial for the current study to have obtained primary data for the river flow discharge to validate the direction and the extent of river-aquifer interactions from the three river gauging stations. Should the study have financial resource support, it would have been beneficial to have drilled boreholes along the river to obtain a geological log for the characterization of the subsurface systems. Implementations of the geophysical survey would have improved the knowledge and understanding of the groundwater-bearing structures for drilling purposes. To overcome this, the study relied on secondary data from various database sources, published review literature, and unpublished consultant reports. The COVID-19 pandemic was an unforeseen circumstance that affected the entire schedule of undertaking field assessments and data collections as planned. However, the first round of data collection was executed in October 2020 and February 2021 during the lockdown alert level 3. During this period, the lockdown regulations were eased to allow traveling without a permit.

Although the current study was confronted by several challenges, the use of a multi-method approach to quantify and characterize river-aquifer interaction proved to be a powerful tool to provides a reliable estimate of such interactions in semi-arid regions. The results of the current study showed that the use of hydrochemistry, stable isotopes, and baseflow separation analyses methods provided insight into identifying recharge and discharge areas. Therefore, the application of the multi-methods approach has increased scientific knowledge and understanding for evaluating river-aquifer interactions.

5.10. Implication of the findings

The application of multi-methods for the assessment of river-aquifer interaction was important for understanding the chemical, biological and physical processes in the hydrological cycle. The three selected methods i.e. hydrochemistry, stable isotopes, and baseflow separation had an agreement that the river gained water from the aquifer discharge and lost water through river recharge aquifers at all reaches. The implication of this was significant for determining water quality and quantity. The first objective was to determine river recharge aquifers had the potential to transfer pollution from the river water to the aquifer water and conversely, the pollution from aquifer water degraded river water quality. Thus, recommendation of the sustainable water abstraction requires an understanding of the relationship between aquifer water and river water in any given hydrologic setting. Locations where aquifer water and river water interacted served as contaminant transport pathways. The second objective which was to determine the aquifer recharge river provided an important insight into the aquifer discharge contributions to the total river flow. Furthermore, it was important to note that the baseflow contributions averaged 7% of the total fresh aquifer discharge in all reaches meanwhile the river recharge aquifers accounted for an average of 45% of freshwater which came from the river. What these results meant was that the contributions of the aquifer discharge played a less significant role in sustaining a long flow period.

The interactions between river water and aquifers can be significantly affected by anthropogenic activities both agriculture and alluvial diamond mining activities within the catchment. Their implications in gaining reaches where aquifer discharge to river, groundwater pumping reduces the rate of inflow to the river. Conversely, where groundwater pumping is sustainable, the river can be losing and provide recharge to the groundwater aquifers (Winter et al. 1998). In this study, the aquifer continued discharging into the river at all reaches and lost water in the upper and middle stream location. Therefore, water abstraction can be recommended because the water was available. Furthermore, the recharge and discharge areas in this study were identified as flow pathways responsible for the transportation of river and aquifer water exchange. However, further work is required to model the contaminate age and transport that determines the average rates of chemical reactions that take place during transport.

5.11. Summary of the chapter

This section provided the summary of the results obtained for the assessment of river-aquifer interaction for sustained water abstraction. The hydrochemistry, stable water isotopes, and baseflow separation techniques were used as methods to analyse data thereby addressing the objectives of the study. The first objective was to investigate areas where the river recharges aquifers by estimating the contribution of the river water to underlying aquifers. The second objective was the determine areas where aquifers recharge river by estimating the contribution of the aquifer water to the total river flow. The third objective was to develop a conceptual model of groundwater processes that explain interactions. The intention for objectives one and two was to identify focussed recharge and discharge areas. The study argued that unless the application of multi-methods for river-aquifer interaction improves, the feasible recommendation for the sustained abstraction of water can be erroneous. The question that had to be answered was ‘’how multi-methods are applied for quantifying and characterizing river-aquifer interactions".

The results showed that the river water was characterized by a single group water type classified as Ca-Mg-HCO_3 mixed type. The TDS and EC values were less than 1000 mg/l and 10 000 μS/cm representing freshwater dominated by elevated Ca and HCO_3 ions. The aquifer water samples revealed four different groups of water types classified as Ca-HCO_3, Ca-Cl, Na-HCO_3, and Ca-Mg-HCO_3. mix type. The Ca-HCO_3 and Ca-Mg-HCO_3 types were found in upper, middle, and lower stream locations represented fresh recharged water associated with active recently recharged areas therefore confirming river recharge aquifers and were expected. The Ca-Cl type was found in upper and middle stream locations represented a direct recharged water possibly through rainfall infiltration and was expected. one group associated to discharge areas classified as Na-HCO_3 mostly found in deeper aquifers. The Na-HCO_3 found in the upper stream location represented deep aquifer water mostly found in discharge areas. This water type was not expected given that the geology (gravel and sand) does not contain the saline characteristics.

The stable isotopes results showed that both river water, aquifer, and rainfall water deviated from LMWL and GMWL and plotted along the LEL indicated that the water was exposed to server evaporative enrichments in the dry season as expected. 9% aquifer water isotope signatures were most river water isotope signatures which suggested river recharge aquifers. Most aquifer waters were like rainfall samples indicating recharged water from meteoric water origin. 27% of aquifer water samples had a similar signature to river water samples indicating river recharge aquifer with minor evaporation before recharging despite low temperatures in the wet season. The baseflow index (BFI) result showed that the dependency of the total river flow to aquifer discharge contributed 7.24 % in the upper stream, 7.31% in the mid-stream, and 7.319% in the downstream. The mean baseflow and baseflow index have complimented each other well ranging from high to low in the upper and lower stream locations respectively. The conceptual model showed that generally, the aquifer water flows from high elevation areas towards the Vaal River. The low elevation areas also acted as the drainage basin. Furthermore, the model showed that the river was losing and gaining water at all reaches (upper, middle, and lower stream locations).

Chapter 6: Conclusions and Recommendations

6.1. Conclusions

The focus of this study was to assess river-aquifer interaction for sustained water abstraction in the Lower Vaal River catchment using a multi-methods approach to quantify and characterized such interactions. The study was subdivided into three sections i.e upper stream, middle stream, and lower stream catchments. The purpose was to simplify the results to make a comparison of the findings obtained in a different section of the study area. The study used three different methods i.e hydrochemistry, stable isotopes, and baseflow separation techniques to quantify and characterized the river-aquifer interaction between the two water resources. The main aim of this study was to obtain a better-improved knowledge and understanding of river-aquifer interaction for sustainable water abstraction. The question that was to be answered here was how are multi-methods applied for quantifying and characterizing river-aquifer interactions? The study argument was that unless the application of multi-methods for river-aquifer interaction improves, the feasible recommendation for the sustained abstraction of water can be erroneous.

This paragraph of the current study concludes the findings on objective one which entailed investigating areas where river recharge aquifers by estimating the contributions of river water to the underlying aquifers. In addressing this, hydrochemistry as a confirmatory analysis and stable isotopes as a tracer of the source were used to quantify and characterize areas of river recharge aquifers. To achieve this, the study conducted a field trial to collect river water and aquifer water samples to generate water quality data through laboratory assessments. The study further collected the rainfall water samples to generate the isotopes data for $\delta^{2}H$ and $\delta^{18}O$ during the dry and wet seasons. The hydraulic connectivity was based on similarities of the hydrogeochemistry and stale isotopes composition between the two water resources. The study found that the river was losing water to the underlying aquifer in the upper stream, middle stream, and lower stream locations.

This paragraph of the study concludes the findings on the second objective which was to determine areas where aquifers recharge river by estimating the contributions of aquifer water to the total river flow (aquifer discharge). To address this objective, the study used three distinct methods i.e hydrochemistry, stable isotopes, and baseflow separation techniques at three river gauging stations. For hydrochemistry and stable isotope analysis, the study conducted a field trial to collect river water, aquifer water, and rainfall water samples to generate water quality data through laboratory assessment. The hydrochemistry results showed the existence of $Na-HCO_3$ water type in the middle stream which was linked to deep aquifer water. This water type was not expected in the study area as typically found on discharge aquifers near the sea. Despite these results, the results of the stable isotope did not confirm the results as suggested by hydrochemistry, instead, samples with different stable isotopes compositions were observed suggesting that the river may have come from an alternative source. Few of the river water samples plotted near or at the intersection of LEL and LMWL provided further evidence of recharge through meteoric water. With the baseflow separation techniques, the study used secondary data obtained from a record review. A two-year record of hydrological times series flow data was retrieved from DWS systems while the rainfall data was obtained from South Africa Weather Service (SAWS) systems. The baseflow results continued to confirm that river depended on aquifers discharges and that aquifers sustained the river. Evidence for this situation has been provided in this study. A BFI close to 0% meant a river has a low proportion base flow and 100% meant a high proportion baseflow. Therefore, in this study, the BFI in all three sections was on average 7% which was below the BFI range.

This section addresses the third objective of the study which was to explain interaction by creating a structural conceptual model of the groundwater process. To achieve this, we have collected all the information of interest to obtain the secondary data using the record review method. The results obtained from objectives one and two using hydrochemistry, stable isotopes, and baseflow analysis were integrated into the model. The conceptual model showed that the river was losing and gaining water in all reaches (upper, middle, and lower). Therefore, the application of multi-methods has provided a quantifiable amount of water recharging aquifers and discharging to river, but assumptions of each method were not explored.

6.2. Recommendations

The aquifers have continuously discharged water into the river and the river recharge aquifers. Therefore, sustainable water abstraction can be recommended because the water was available in the catchment. Furthermore, the study recommended that a continuous river-aquifer interaction monitoring program must be established to determine the impacts of water abstractions thereby improving knowledge and understanding of water resource management.

The raw sewage had contributed to bacteriological load into the Vaal River system; Therefore, it is recommended that the tracer analysis using faecal coliform can improve knowledge and understanding of river-aquifer interaction.

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