UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Water Quality Indices in the Upper Vaal River Catchment

By:

Gabrielle K Kwambana

(1619923)

Supervisor: Prof. Tamiru Abiye

A Research Report submitted to the Faculty of Science, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Hydrogeology

September 2022

DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

______ Gabrielle Kudakwashe Kwambana ____

Signature: GKwambana

23 September 2022

ABSTRACT

The main objective of this research was to assess the change in the quality of surface water and groundwater in the Upper Vaal River Catchment (UVRC), both spatially and temporally. The UVRC is one of South Africa's most reliable freshwater sources; however, it is stressed by multiple pervasive land use activities. Therefore, water quality variability should be understood in relation to land use types in the catchment. This study aims to determine the change in water quality with time and space and how land uses have also contributed to the deterioration or improvement in water quality.

Surface water and groundwater historical data were acquired from the Department of Water and Sanitation. In addition, the land use data were obtained from the Department of Forestry, Fisheries and Environment. Daily water quality data were averaged into monthly data to calculate the weighted arithmetic Water Quality Index (WQI) for the Vaal River, its main tributaries and aquifers in the UVRC. At the same time, the land use data were used to calculate the percentages of land use changes with the years in the catchment.

The WQI was calculated for the Vaal, Klip, Mooi, Suikerbosrant, Sterkfontein, Wilge, Rietspruit, Blesbokspruit, Leeuspruit, Wonderfonteinspruit, Waterval and Tweefontein rivers. The WQI for all the rivers showed a relative seasonal control of water quality, with the wet months having lower WQI than the dry months. This was attributed to the dilution by rainwater. The water quality for all the rivers also deteriorated over time; for example, from 2000 to 2004, rivers mainly had ‘poor’ (WQI = 51– 75) to ‘very poor’ (WQI = 76 – 100) water quality. On the contrary, the water quality for the same rivers is mainly classified as ‘very poor’ to ‘unfit for consumption’ (WQI > 100) from 2012 to 2016. The generated pollution flowed downstream along the Vaal River, resulting in higher WQI values downstream. Vaal F is the most downstream point and was classified under ‘unfit for consumption’ almost all year round.

There is a massive difference between surface water and groundwater quality in the UVRC. There was seasonal variation in surface water quality, as most dry months and years were characterised by higher WQI. In contrast, the groundwater WQI did not show seasonal variations. The Vaal F, Wilge, Suikerbosrant, Waterval, Mooi and Wonderfonteinspruit boreholes (named after rivers closest to them) showed an average of ‘excellent’ (WQI = 0 – 25) to ‘good’ (WQI = 26 – 50) water quality conditions. However, Borehole Waterval (BH

Waterval) had a deterioration of water quality as it started with ‘good’ WQI in 2000 and then ranged between ‘poor’ to ‘very poor’ from 2002 until 2016.

The land uses in the UVRC were dominated by vegetation cover in 2000, while agriculture dominated the catchment land uses in 2016. The drastic changes in land use between 2000 and 2016 coincided with an increase in the WQI of rivers during the same period. Therefore, it was concluded that the land use types significantly influence the WQI of the UVRC surface water sources.

DEDICATION

I would like to dedicate this research to my father (Mr Blessing Kwambana), who financially and morally supported me throughout my academic journey.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my deep and sincere gratitude to Professor T. Abiye for providing his invaluable guidance throughout my MSc academic journey.

I would also like to thank the Department of Water and Sanitation for collecting and providing the data used for this research.

Lastly, I would like to thank my parents, family and friends for their continued encouragement and support.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

1. BH – Borehole
2. Cl – Chloride
3. CMAs – Catchment management Agencies
4. CGS – Council for Geoscience
5. DWS – Department of Water and Sanitation
6. DWA – Department of Water Affairs
7. DWAF – Department of Water Affairs and Forestry
8. EC – Electrical Conductivity
9. GIS – Geographic Information System
10. Mg – Magnesium
11. MS – Microsoft
12. NO_3 – Nitrate
13. NW – Northwest
14. SANS – South African National Standard
15. Na – odium
16. SASOL – South African Synthetic Oil Limited
17. SO_4 – Sulphate
18. UVRC – Upper Vaal River Catchment
19. WHO – World Health Organisation
20. WQ – water quality
21. WQI – Water quality index

22. WWTP – Waste Water Treatment Plant

UNITS OF MEASUREMENTS

1. mg/l – milligrams per litre
2. m - meters
3. mm – millimetres
4. L/s – litters per second
5. mbgl – meters below ground level
6. mS/m – millisiemens per metre
7. km – kilometre

CHAPTER 1 – INTRODUCTION

1.1 Research Background

Water is a precious resource that is considered a necessity for all living organisms, and therefore, its quality is of utmost importance. South Africa is in an arid to semi-arid region that has variable rainfall. It experiences a lack of clean water mainly because of anthropogenic impacts from mining, urbanisation and agriculture (Van Heerden *et al.*, 2006). Approximately 65% of the country receives <500 mm annual rainfall, which is below the 800 mm/year global average (Hobbs *et al.*, 2013). Unevenly distributed water and high evaporation rates make clean water a very scarce resource in many parts of the country (Bezuidenhout *et al.*, 2013). In 2011, the Department of Water Affairs (DWA) predicted that the water demand rate would exceed the supply rate if the quality and quantity management were not improved (Oberholster *et al.*, 2008).

For centuries, the South African landscape has been physically and chemically manipulated to meet societal water and food security needs. These land use changes have caused negative impacts on hydrological responses and most importantly, water resources (Warburton *et al.*, 2012). Like water, land is one of the most critical resources needed for the survival of humankind as it provides nutrition, energy sources, and living space (Robson, 2005; Pillay *et al.*, 2014). Therefore, deterioration in the quality of land resources can compromise water quality, especially surface water or groundwater, as it infiltrates down. Rapid growth in the human population coupled with climate change and pollution has exerted significant pressure on land resources (Pillay *et al.*, 2014).

The Vaal River is one of the most essential and major rivers in South Africa; in its upper catchment, there are multiple diversions into dams and other sources of important activities, including agriculture and domestic use. However, the water quality of this vital river continues to be compromised by many factors, especially human activities, for example, the dumping of untreated sewage into the river. The Vaal River is subdivided into three primary catchments: the Lower Vaal, Middle Vaal and Upper Vaal River Catchments (llunga, 2017). According to du Plessis (2017), the Upper Vaal River Catchment (UVRC) water quality has been rapidly declining, and its management practices have been fraught by conflicting approaches.

Available data from previous studies show that the surface water in the UVRC is of poor quality, which might be deteriorating with time. In contrast, the groundwater quality varies depending on the location/reservoir (Remilekun *et al.*, 2021). For example, Marakanye *et al.* (2022) studied the effects of land use changes on nitrate and orthophosphate pollution in the Lower Vaal River Catchment. The study showed that an increase in built-up and irrigated land from 1980 to 2018 caused a significant increase in pollution loads. However, many surface water quality assessments completed in the UVRC have focused on either the Vaal River or one of its major tributaries, such as Tweefontein and Kliprivier sub-catchments. For instance, an environmental risk assessment done on the Kliprivier using WQI found that the water was unfit for aquatic, domestic and agricultural purposes (Marara and Palamuleni, 2019).

The WQI is beneficial for communicating water quality data to all stakeholders ranging from scientists to non-technical individuals. According to Banda and Kumarasamy (2020), the conversion of complex scientific data into simple and systematically structured formats makes the WQIs fundamental elements of the water quality monitoring agenda. Therefore, the WQI will be used in this research project to investigate and record the variations in water quality in the UVRC with time.

According to the Integrated Water Quality Management (IWQM) policy, the management of water should be sustainable, ensuring a balance between water management and achieving the economic activities that are important for an area (DWS, 2016). In addition, if the changes in the catchment area are causing water quality deterioration, there should be a solution as these factors are co-dependent, and the decrease in water quality will, in turn, affect the economic activities that are crucial for the GDP of a country. Therefore, this research project focuses on quantifying the contribution of land cover changes to selected water quality parameters and temporal and spatial variation of the water quality index of water in the Upper Vaal catchment.

1.2 Problem Statement

The UVRC has substantial water transfer systems and water resource structures that supply most of the Gauteng province, which is the economic hub of South Africa (llunga, 2016). These developments and economic activities have caused widespread water quality deterioration in the UVRC (DWA, 2010). A case study in the Vaal River Basin revealed that variations in groundwater quality were caused by anthropogenic and natural activities (Masindi and Abiye, 2018). Furthermore, the continued population growth and poor maintenance of water treatment plants and sanitation facilities are some of the leading causes of water quality challenges within the UVRC (du Plessis, 2017). According to Odume *et al.* (2018), the increase in industrial activities in the UVRC has consequently led to an increase in population and wastewater load.

Identifying the main pollution hotspots and their effects on the water quality is, therefore, paramount to ensure the maintenance and improvement of acceptable water quality standards and sustainable development in the system. This research project will assess how land use such as built-up, mining, and agricultural within the Upper Vaal catchment have impacted groundwater and surface water quality with time.

1.3 Aims and Objectives

1.3.1 Aims

This research aims to understand the spatial and temporal change in water quality based on the estimation of the WQI for surface water and groundwater in the UVRC between 2000-2004 and 2012-2016. It also aims to quantitatively estimate the impact and contribution of land cover changes to water quality in the UVRC. The research project aims to improve the availability of information needed to establish catchment management guidelines.

1.3.2 Objectives

The main objectives are:

a. To apply the weighted arithmetic WQI on the acquired surface and groundwater data to evaluate temporal and spatial variations.
b. To use the Geographic Information System (GIS) software to assess whether changes in land use from 2000 to 2016 have caused any significant contribution to the degradation of water quality, thereby improving the accuracy of calculated data. This will be achieved by comparing the water quality changes from 2000-2004 to 2012-2014 with the land use changes in their respective sub-catchments.

CHAPTER 2 – STUDY AREA

2.1 Location

The UVRC is located in the central north-eastern part of South Africa (Figure 2.1). It is characterised by industrial and urban development and mining in the headwaters. The catchment extends over four provinces: Mpumalanga, Gauteng, Free State and North-West provinces (Boyd and Tompkins, 2011). It has a total area of 55,565 km^2 and comprises natural, built-up, degraded, cultivation, water bodies and plantations (llunga, 2016). The catchment receives large quantities of water from the Lesotho Highlands Project whilst also transferring some of its water to neighbouring catchments, for example, the Middle Vaal catchment (du Plessis, 2017).

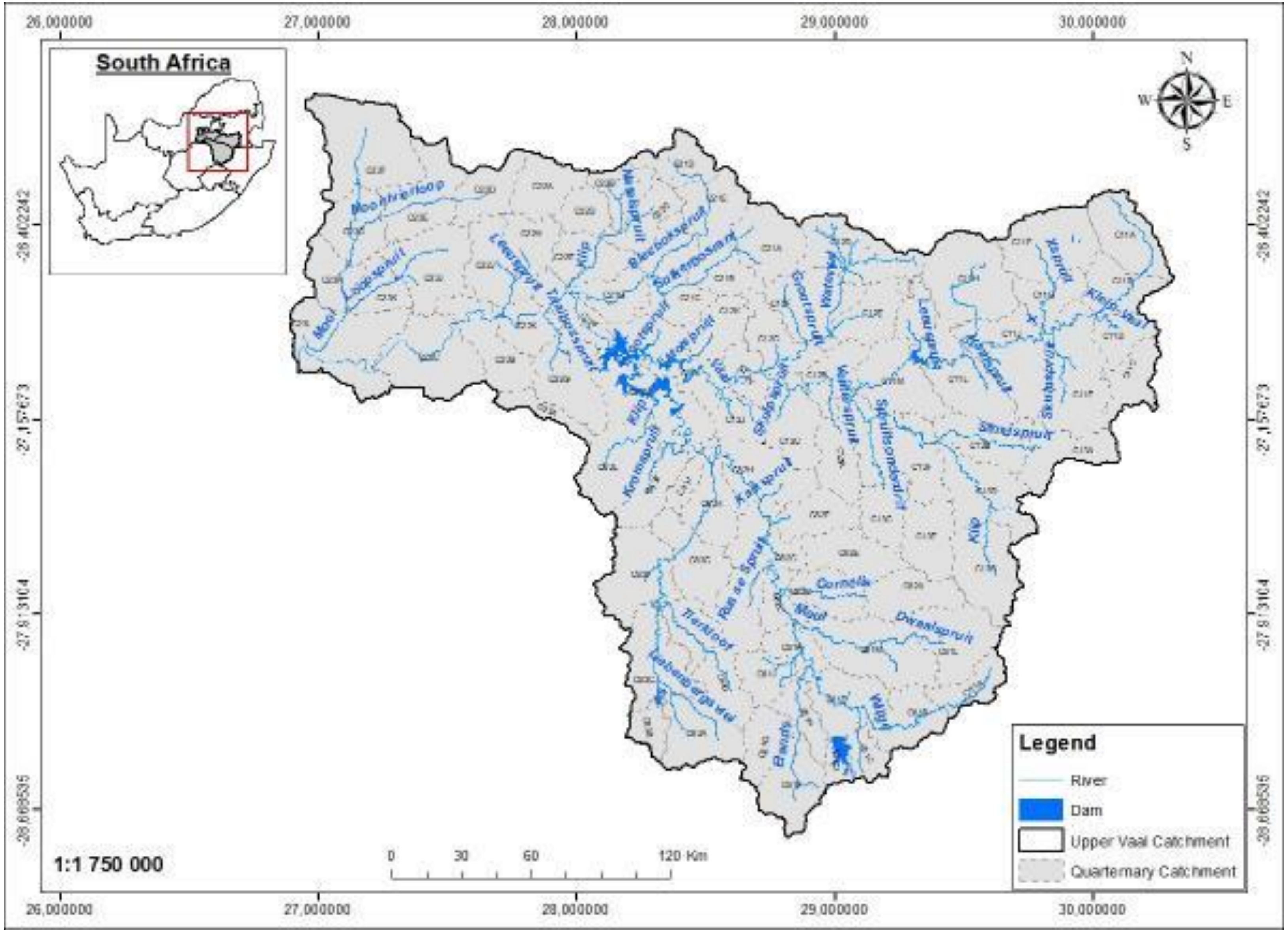

Figure 2.1: Map showing the UVRC and its main river, the Vaal River, and its tributaries.

The catchment's water resources are of great importance as they support a population of more than 12 million people (DWAF, 2009). The Vaal River flows in a south-westerly direction (Masindi and Abiye, 2018). It is the primary water source in the Vaal River Catchment, followed by its numerous tributaries (DWA, 2010b). It supports three major dams: the Grootdraai Dam, Vaal Dam, and Sterkfontein Dam. Due to the high alterations and developments in the catchment's water resources, there has been a widespread deterioration of water quality over the years. According to Anja de Plessis (2021), water quality in the Upper Vaal River Catchment has been declining rapidly due to many reasons, including poor coordination. The great need for effective and systematic assessment as well as monitoring of water quality in the catchment has been continuously highlighted (Nhamo *et al.,* 2018, WEF, 2020).

2.2 Drainage and Climate

The Vaal River is the main river in the UVRC; it drains from the Drakensburg escarpments while continuing down to the Middle Vaal River Catchment area. The main tributaries of the Vaal River in the UVRC include Mooi, Klip and Groot rivers (Figure 1). From an elevation of about 1800 m above mean sea level in the East, the catchment gently slopes to about 1450 m in the West (DWA, 2010a). There are multiple interbasin water transfer schemes that bring water into the UVRC from areas such as Lesotho, while other schemes transfer water out of the UVRC to support operations such as SASOL (DWAF 2009a).

The catchment's climate is characterised by strong seasonal rainfall during the summer months (from October to April). From January and February, the catchment commonly experiences peak rainfall and maximum daily temperatures, while July experiences minimum daily temperatures (Hobbs *et al.*, 2013). However, there is a variation in the mean annual precipitation ranging from 1000 mm to approximately 500 mm from East to West. According to DWA (2004), the altitude of the catchment causes frost and light snow to commonly occur during winter seasons. The vegetation mainly comprises Savannah grassland with sparse bushveld (Rademeyer, 2009).

According to DWAF (2004a), the UVRC population is generally clustered near water supply sources, with the highest population densities near the Vaal Dam and Johannesburg. A 2005 report by the Department of Water Affairs and Forestry (DWAF) highlighted that the discharge of untreated and partially treated sewage into the Vaal River and its main tributaries causes significant faecal pollution in the Vaal River (Odume *et al.,* 2018). Furthermore, the UVRC supports the water needs of the densely populated Johannesburg and Vaal Triangle regions (DWAF 2009a; Odume *et al.*, 2018). The multiple UVRC flow modifications without strict regulation policies have consequently developed a legacy of water quality issues. The catchment is characterised by high levels of salinity, sulphate, eutrophication and phosphate (DWAF, 2009a). Outcomes of these include fish death, increased microalgae and diarrhoeal diseases (Tempelhoff, 2009). The DWAF (2009b) also reported that the water quality upstream of the Vaal Dam decreased sharply and did not meet management targets.

2.3 Geology

The UVRC is underlain by a mosaic of different geologic strata comprising the Basement rocks, the Witwatersrand, Ventersdorp, Transvaal and Karoo Supergroups, intrusions, Tertiary and Quaternary deposits, as shown in Figure 2.2 (Hobbs *et al.*, 2013). The basement rocks comprise gneiss, granitoid and migmatite, and they occur in a few localities in the northern portion of the catchment (Masindi and Abiye, 2018). The Witwatersrand, Ventersdorp and Transvaal Supergroups occur mainly in the north-west, with the older (>3600 Ma) Swazian strata (Tooth *et al.*, 2004). In comparison, the eastern and southern parts of the study area are dominated by the Karoo Supergroup rocks (Tooth *et al.*, 2004). The Witwatersrand Supergroup, which hosts gold deposits, comprises sedimentary rocks mainly of fluvial deposits such as conglomerates, shales, and quartzite (Smith *et al.*, 2013). In contrast, the Ventersdorp Supergroup consists of late Randian Era sedimentary and volcanic rocks (Humbert *et al.*, 2019). The Transvaal Supergroup consists of dolomite, quartzite and shale, intrusions and lavas (Moore *et al.*, 2001). The Karoo Supergroup, along with alluvial deposits covering about two-thirds of the study area, comprises unconsolidated soils and sedimentary rocks that include shales and coal and dolerite sills and dykes (du Plessis, 2017).

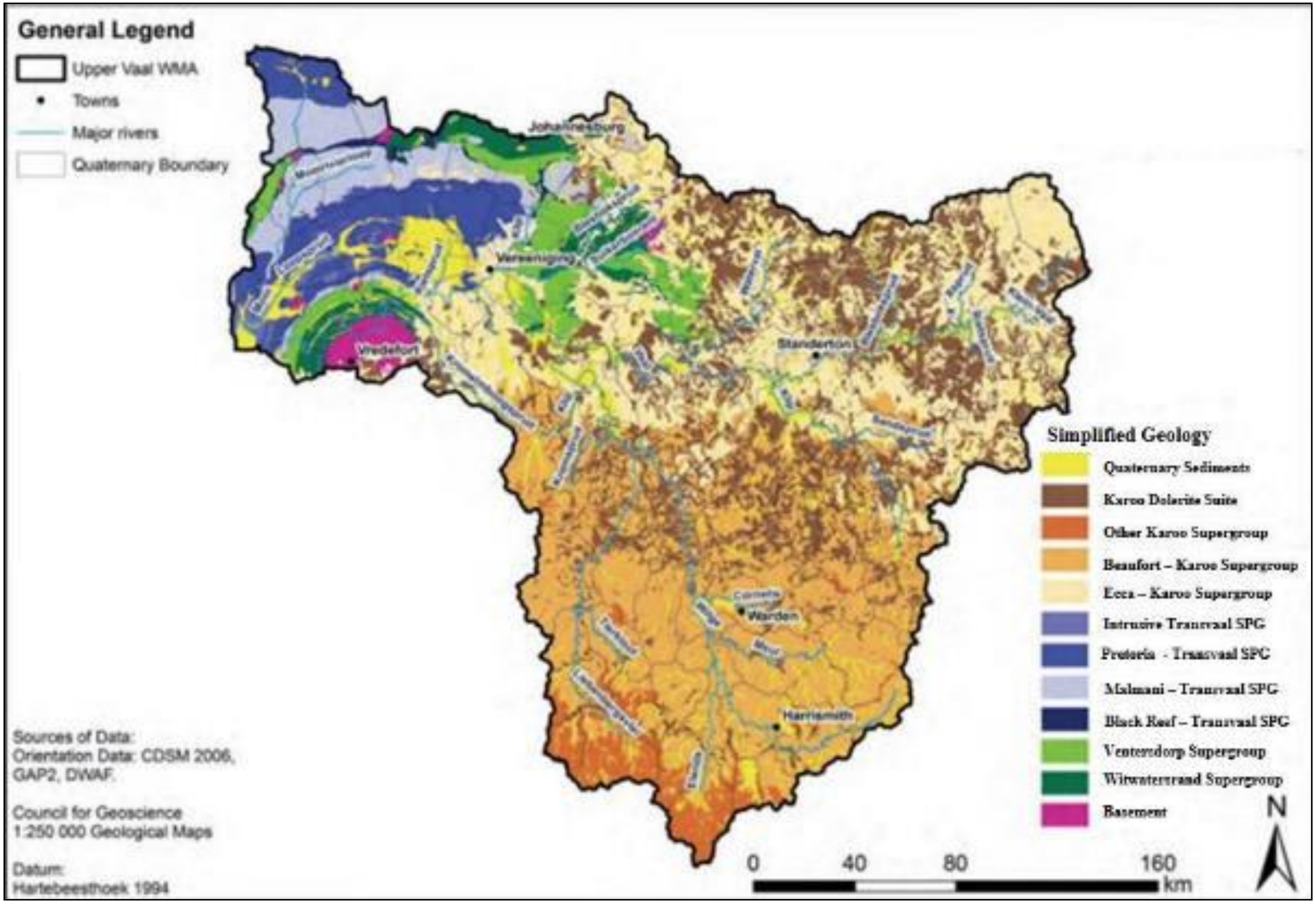

Figure 2.2: Map showing the simplified geological map of the Vaal River Catchment (Adapted from CGS, South Africa; Hobbs *et al.*, 2013).

2.4 Hydrogeology

Approximately 75% of the UVRC is underlain by the Karoo Supergroup strata, characterised by fractured and intergranular aquifers (Hobbs *et al.,* 2013; Masindi and Abiye, 2018). These aquifers have dual porosity from the primary porosity of the sedimentary rock mass and the secondary porosity from fractures, bedding planes and joints that intersect the rock mass (DWA 2003b). In the south and western portions, the median borehole yield in the Beaufort Group sediment ranges from 0.5 to 5.0 L/s (Figure 2.3). The yield in the Ecca Group ranges from 0.1 to 0.5 L/s (Hobbs *et al.,* 2013). However, in the central and southern parts of the catchment, the boreholes in the fractured and intergranular aquifers of the Karoo Supergroup have low yield (<0.5 L/s) (Hobbs *et al.,* 2013). Furthermore, some of the intrusive and basement rocks of the Witwatersrand, Transvaal and Ventersdorp Supergroups in the north-western parts are also characterised by a dual porosity. Their median borehole yield rarely exceeds 0.5 L/s (Hobbs *et al.,* 2013).

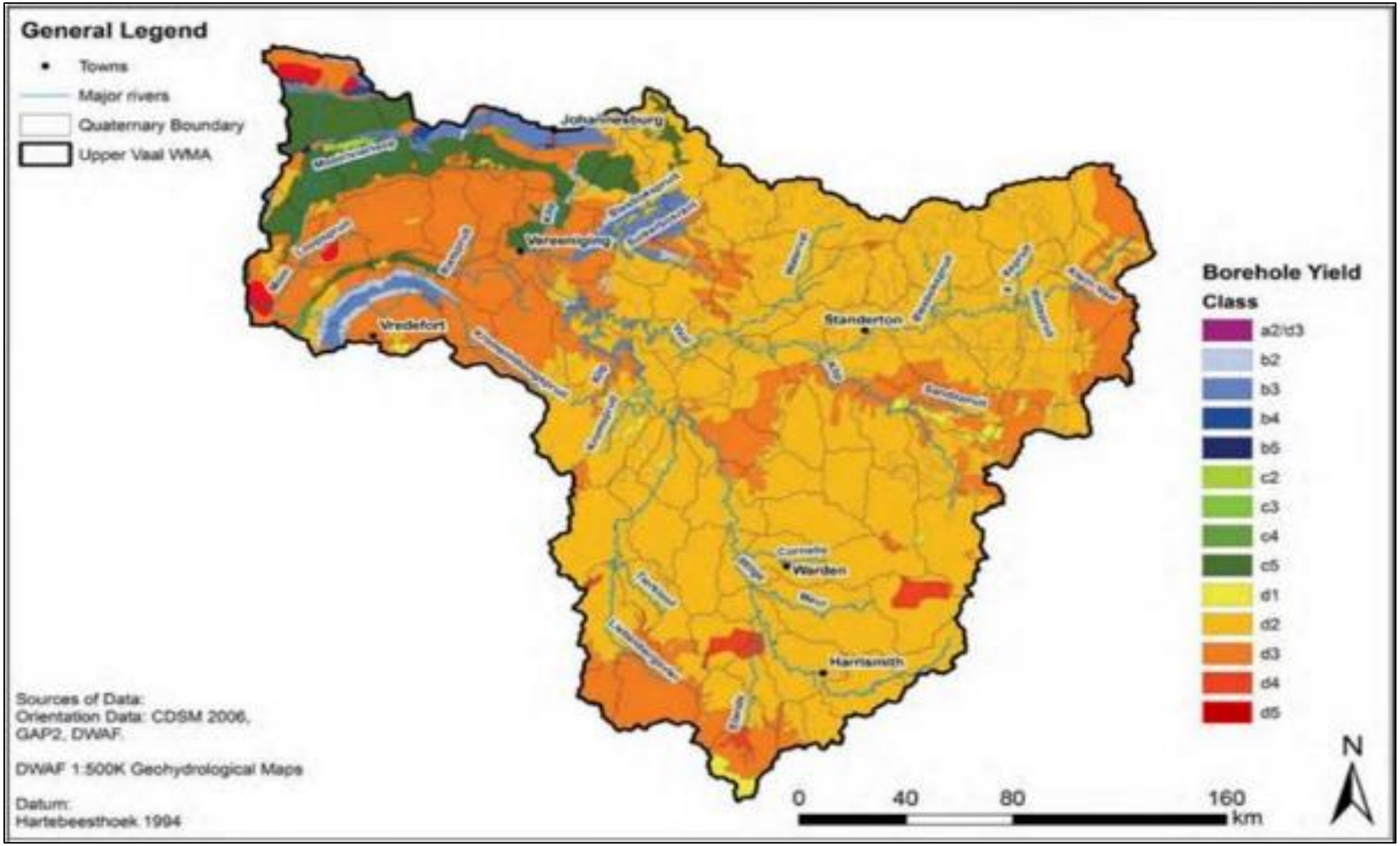

Figure 2.3: UVRC map showing the distribution of borehole yields per quaternary catchment (Adapted from CGS, South Africa; Hobbs et al., 2013).

Key:

Aquifer Type	**Median Borehole Yield Class (L/s) excluding Dry Boreholes**				
	0.0-0.1	**0.1-0.5**	**0.5-0.2**	**0.2-5.0**	**>5.0**
Intergranular	a1	a2	a3	a4	a5
Fractured	b1	b2	b3	b4	b4
Karst	c1	c2	c3	c4	c5
Intergranular and fractured	d1	d2	d3	d4	d5

The Witwatersrand, Transvaal and Ventersdorp Supergroups constitute a fractured aquifer system in the basin. However, the borehole yield varies greatly, ranging from 0.2 to 0.5 L/s. The spaced joints and massive nature of the andesitic lavas of the Ventersdorp Supergroup make them aquitards in this catchment. High-yield boreholes characterise the northern and western parts of the fractured and karst aquifers (DWA, 2005b). Nevertheless, high borehole yields are found along major faults, joints and structural lineaments, but they rarely exceed 2.0 L/s (DWAF, 2006; Hobbs *et al.*, 2013).

The chert-poor assemblages in the Malmani subgroup dolomites of the Chuniespoort Group (Transvaal Supergroup) have a very low storage potential as they weather evenly, promoting poor porosity (DWA, 2003b). While the preferential weathering in the chert-rich assemblages produces much more productive aquifers (du Pleis, 2017). Both assemblages form compartmentalised units due to the sills and dykes that intruded the Group. The dolomites in the north-western areas of the catchment form karst aquifers (DWAF, 2006).

Lastly, the alluvial aquifers are limited to a few meters in thickness and are not extensively explored or represented as they are not considered significant groundwater resources (Hobbs *et al.*, 2013). According to a study done by Masindi and Abiye (2018), the two main water types in the catchment are $Ca–Mg–Cl–SO_4$ and $Ca–Mg–HCO_3$. Groundwater plays a crucial role in some of the catchment areas; however, it only caters for approximately 3% of the total water requirements in the UVRC catchment (du Pleis, 2017).

CHAPTER 3 – LITERATURE REVIEW

3.1 Introduction

The maintenance or improvement of freshwater quality has economic, health and ecological implications (Shakya and Tiwari, 2001). Surface water and groundwater quality are essential as they determine whether water is suitable for drinking or irrigation purposes (Brindha and Kavitha, 2014). If the surface water quality is poor, this may lead to a decrease in the groundwater quality

Therefore, it is necessary to quantify and track changes that may impact the water quality and classify freshwater resources at national and catchment levels. Changes in land use can alter the partitioning of rainwater into critical hydrological components. It can also create pollution sources in nearby water resources (Warburton *et al.*, 2012). For the current work, land use type refers to the biophysical condition of the earth's surface and immediate subsurface, divided into broad categories such as agriculture, mining and natural or human settlement.

Changes in land use can increase runoff, flooding, and non-point source pollution, which degrades downstream water bodies (Bhaduri *et al.*, 2001). However, a poor understanding of what constitutes a significant degradation effect has been one of the main reasons there has been a constraint in reducing environmental impacts from pollution sources for river systems (Jordan and Bezuidenhout, 2001). According to Jackson *et al.* (2001), the increase in urbanisation, overpopulation and climate change will cause water to be an even more limiting resource. In addition, the introduction of chemical compounds from leakages, dumping, or cross-connection results in the deterioration of drinking water quality (Napacho and Manyele, 2010). Therefore, assessing the potential hydrologic impacts of land use changes before and after catchment development is crucial (Bhaduri et al., 2001).

There is a strong relationship between land use and water quality parameters at a catchment level which can influence freshwater ecosystems at a regional and broader geographic scale (Namugize *et al.*, 2018). According to de Mello *et al.* (2018), land use changes can negatively impact the concentration of specific water quality variables. Therefore, water problems cannot be treated in isolation without attention to land use activities that influence them. A growing population is one of the most significant factors that result in the transformation of natural habitats into anthropogenic landscapes (de Mello *et al.*, 2018). These landscapes include mining, agricultural lands and urban areas, which are globally known for increasing nutrients, salt, acids, sediments and other contaminants within freshwater ecosystems.

According to Kang *et al.* (2010), it is difficult to determine the impact of land use changes on surface water quality because rivers continuously receive water input from upstream. Furthermore, the degree of modification and location of specific land use types in a catchment play a crucial role in determining whether the change will influence the hydrogeological response or streamflow of the catchment. According to Rai and Sharma (1998), in the Himalayas, hydro-ecological sustainability in a catchment can only be attained if good forest cover, dense forests, and agroforestry are maintained.

Teshome (2020) used the WQI on water samples collected from Lake Hawassa, Ethiopia, during the dry and rainy seasons to examine its suitability for domestic use and the influence of seasonal variation on water quality. Due to a dense population in the watershed, the lake faces water quality problems from factors such as domestic waste, agriculture activities and industrial seepage (Teshome, 2020). The WQI results showed that the water quality was unsuitable for domestic use in both winter and summer seasons. However, the summer had a higher WQI than winter, and the difference was attributed to higher loads of pollutants in water bodies during summer. Similarly, Ahmad *et al.* (2012) observed the same WQI trend in Iraq, whilst Yogendra and Puttaiah (2008) reported that the dry season had higher WQI than the wet WQI in Kamataka, India. In addition, an assessment of the water quality status of the Doyang river in India found that the WQI for upstream sampling locations had higher WQI due to the presence of a hydroelectric dam, land use changes and increasing settlements (Lkr *et al.*, 2020).

Groundwater is the most preferred water source due to its high quality and requires continuous monitoring and protection (Olatunji *et al.*, 2015). Therefore, WQI was used to assess groundwater sources in Jordan, Iran, where groundwater is the key source of drinking water (Abbasnia *et al.*, 2018). Although about 52.1% of the sampling points were classified as excellent and good, the quality and quantity of most locations were generally significantly declining due to excessive extraction and anthropogenic activities (Abbasnia *et al.*, 2018).

A study conducted in Chaugachcha and Manirampur Upazila of Jashore District, India, found that the WQIs for the Chaugachcha Upazila groundwater resources were lower than those from the Manirampur Upazila sampling locations (Sarwar *et al.*, 2020). The WQI was higher mainly due to an increase in mineral elements in groundwater. The difference was attributed to the variations in geographical position and parent materials from which the soil was formed

(Sarwar *et al.*, 2020). High potassium concentrations were linked to either the leaching of K-fertilisers or the high concentration of K-silicate minerals present in the soil (Shaibur et al., 2019a; Sarwar *et al.*, 2020).

A study conducted in Ado Ekiti, Nigeria, used the WQI to analyse and classify the groundwater and surface water bodies close to a major municipal dumpsite (Oni and Fasakin, 2016). Due to the high lead contents in the water, the WQI classified groundwater and surface water bodies as very poor. The study concluded that the WQI method is a highly effective tool for determining the quality of water susceptible to leachate pollution (Oni and Fasakin, 2016). In residential areas, groundwater deterioration is mainly caused by anthropogenic sources, especially faecal contamination, which is indicated by high nitrate concentration (Olatunji *et al.*, 2015). However, high Calcium levels could be sourced from underlying rocks that are rich in plagioclase, pyroxene, and amphiboles.

3.2 Local Overview

Prioritisation of the socio-economic growth by South Africa has led to a loss in its environmental stability. The mines, industrial activities, agriculture and built-up environments cause point and non-point sources of pollution into water resources. Population growth in Gauteng has also been fuelled by economic growth, which has led to the overloading of the municipal Wastewater Treatment Plants resulting in pollution (DWS, 2016). If these issues are not addressed, they may cause irreversible damage to South African water resources, exacerbated by frequent droughts and global warming (DWA, 2016).

In 1998 South Africa adopted the National Water Act (Act 36 of 1998), in which the Catchment Management Agencies (CMAs) would develop, investigate, and advise on the use of catchment management strategies and also promote community participation (RSA, 1998: 88). However, according to Bourblanc and Blanchon (2014), due to multiple reasons that include lack of technical capacity, the CMAs were reduced from 19 to only 9 (Figure 3.1).

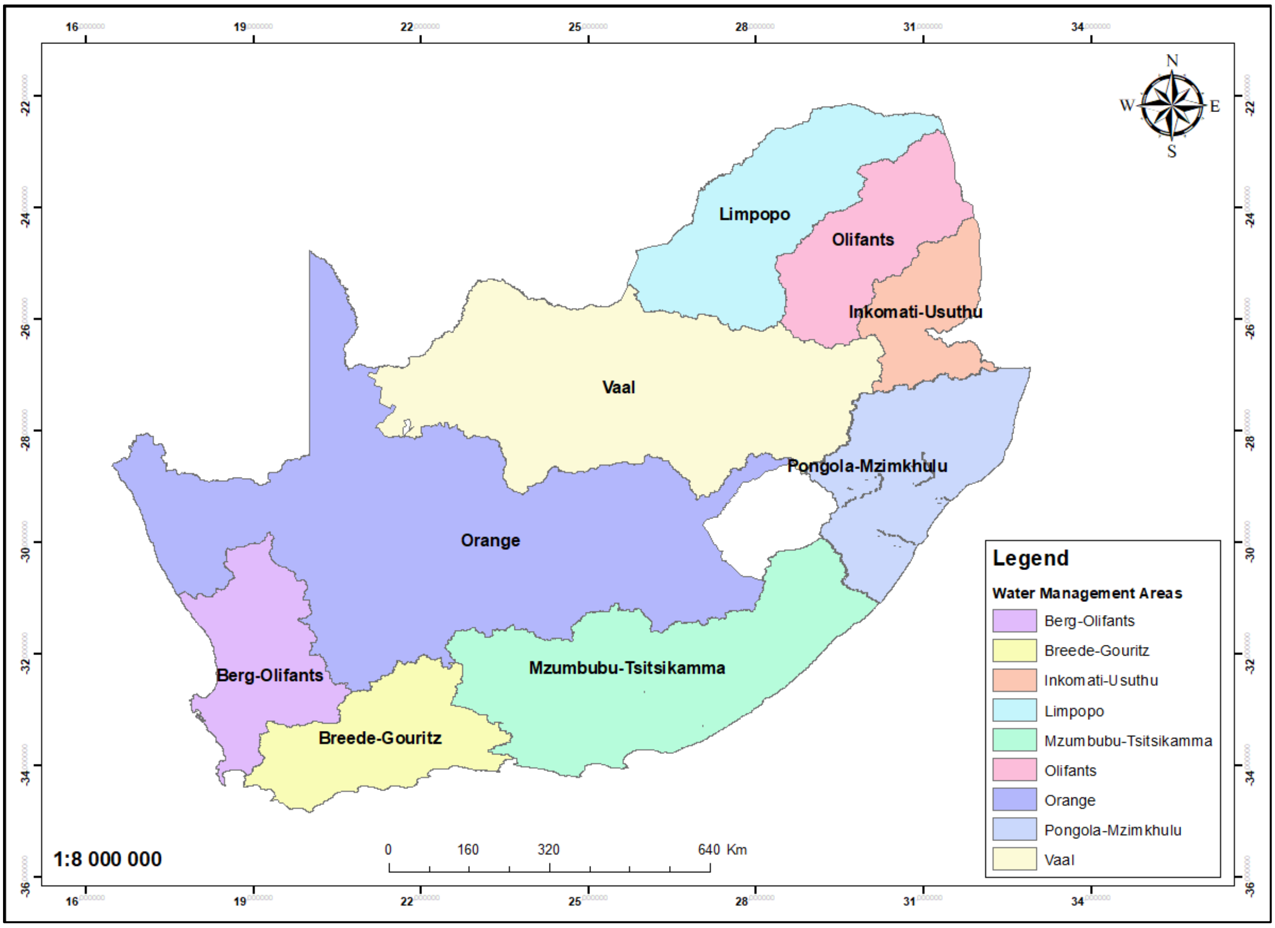

Figure 3.1: Map showing the locations of the nine South African CMAs.

In South Africa, land use changes have been one of the most significant factors that affect catchment hydrology; for example, in the Umngeni catchment in KwaZulu Natal province, agriculture and industries are key drivers of water quality deterioration (Namugize *et al.*, 2018). South Africa implemented new management strategies upon realising that regulating drinking water quality could not occur at a national level since there are many variables for one large group to solve (Boyd and Tompkins, 2011). The new strategies include Integrated Water Resource Management (IWRM), which promotes equitable and sustainable use of water resources and CMAs (DWAF, 2009).

The UVRC is mainly characterised by dry land cultivation for products such as maize and livestock farming. However, there is significant irrigation along the Vaal River (DWAF, 2009). Along the northern part of the Vaal River, there is extensive mining, industrial and urban development (Rademeyer, 2009). The urbanised area is mainly situated in the Gauteng province and extends beyond the UVRC. However, it is extremely hard to determine the precise non-point pollution sources due to the catchment's complex water and land patterns interactions.

The UVRC experiences the highest pollution and anthropogenic pressures as it is the primary water source for the highest densely populated province (Gauteng) in South Africa (Tempelhoff *et al.*, 2007, Anja du Plessis, 2021). The Vaal River is considered the 'work horse' of South Africa as the largest metropolitan area in the country dumps its treated wastewater into the river and also depends on it for clean water (Braune, 1987, Wepener *et al.*, 2011).

3.2.1 Overview of the UVRC's water resources

The Vaal River is the main river in the catchment, followed by the largest tributary Wilge River which drains in the south-eastern portion of the catchment (DWA, 2003b; Figure 2.1). A significant amount of surface water flow in the catchment (46%) is contributed by the Vaal River upstream of the Vaal Dam (Hobbs *et al.*, 2013). The Liebenbergsvlei and Wilge Rivers contribute a combined flow of 36%, whilst the tributaries downstream of the Vaal dam contribute the remaining 18% (DWA, 2003b). Although there are no natural lakes occurring in the catchment, several marshes are present and essential wetlands are located along the Klip River. Numerous farm dams constructed upstream have compromised surface water inflow to the Vaal Dam (Braune and Roger, 1987).

The catchment has multiple transfer schemes, such as the Lesotho Highlands Water Project and Tugela Transfer Schemes that transfer water into the catchment. At the same time, some of the water is also transferred out of the catchment for several purposes, such as the Eskom and Sasol operations (Odume *et al.*, 2018). Despite having the highest concentration of the country's economic development, the catchment only produces about 8% of the country's mean annual runoff (Braune and Roger, 1987).

Groundwater movement and recharge zones generally occur along fracture networks, dissolution cavities and fissures (Abiye *et al.*, 2011). Due to these conditions, groundwater recharge is extremely variable across the catchment (Hobbs *et al.*, 2013; DWAF, 2004). Large quantities of groundwater are extracted for irrigation and domestic use, and some of the dolomitic compartments in the northwest part of the catchment have been dewatered for mining purposes (DWS, 2004).

3.2.2 Parameters

Several parameters with sufficient data were chosen based on a literature review on their relationship with the most dominant land uses in the UVRC. Statistical analysis was then done to streamline the parameters. Only the parameters with significant contributions to the physical and chemical nature of the water were used to calculate the WQI. Electrical Conductivity (EC), nitrate (NO_3), sulphate (SO_4), magnesium (Mg), chloride (Cl) and sodium (Na) were chosen to calculate WQI in the UVRC.

3.2.2.1 Electrical Conductivity (EC)

Electrical Conductivity (EC) measures the water's ability to carry an electric current (Puri *et al.*, 2011). This ability is mainly facilitated by the presence, valence, concentration and mobility of ions in the water (Gorde and Jadhav, 2013). Water with a concentration of inorganic acids, salt and bases tends to have high EC values as they are good electrical conductors (Puri *et al.*, 2011). Therefore, measuring EC is a valuable screening tool for detecting pollution and can provide detailed information about anthropogenic sources of contaminant discharges (Patil *et al.*, 2012).

3.2.2.2 Nitrate (NO_3)

Nitrate is the end product of the oxidation of nitrite and ammonia (Bowen, 1979). Although nitrate is a crucial natural plant nutrient, excess nitrate concentration above five mg/L may cause a bitter taste and cause phycological distress (WHO, 1984). According to Akoteyon *et al.* (2011), nitrate concentration in water may be due to pollution from sewage disposal, urban and agricultural runoff. Owing to surface runoff and oxidation of nitrogenous waste, nitrate concentration in surface water can change rapidly (WHO, 1984). Since the catchment has a significant percentage of farms and many WWTPs in different municipalities, as shown in Appendix A, nitrate was also considered for WQI determination.

3.2.2.3 Magnesium (Mg)

Magnesium is an alkaline metal that forms magnesium hydroxide and magnesium oxide when it reacts with water (Bowen, 1979). Together with calcium, they are responsible for water hardness. An intake of 250 mg/day is essential; however, when in excess, it causes a bitter taste and may result in heart and kidney diseases (WHO, 2009). The UVRC is rich in dolomite with magnesium-containing minerals that can increase magnesium concentrations. Magnesium can also be sourced from industry effluents and fertilisers. The South African National Standards (SANS) recommended drinking limit is 50 mg/L, and its interpretation should be made in conjunction with major ions such as sulphate and chloride (SABS, 2015).

3.2.2.4 Chloride (Cl)

Chloride is an anion of Chlorine; it is highly soluble in water, and once in solution, it tends to accumulate (Bowen, 1979). It may be sourced from irrigation return flow, natural sources, animal manure, sewage and industrial waste (Ayeni *et al.*, 2011). The Cl limit set by the SANS for drinking is 50 mg/L; however, it can only be detected by taste at concentrations greater than 200 mg/L. High levels of Cl concentrations in water could result in metal corrosion, thereby increasing metal concentration in water (WHO, 1984).

3.2.2.5 Sulphate (SO_4)

The highest SO_4 concentrations usually occur in groundwater from sulphate-containing minerals. Sulphate can be sourced from manure, industrial effluent and even atmospheric deposition. The drinking limit for SO_4 is 250 mg/L (SABS, 2015). According to Todd and Mays (2005), water with SO_4 concentration above 1000 mg/L may be cathartic. Sulphate concentrations are increasing in fresh-water ecosystems worldwide and find their way into water systems via mining discharge, agricultural and urban run-off, as well as industrial effluents (Greenwood and Earnshaw, 1984). SO_4 and NO_3 are fundamental parameters as they show the anthropogenic pollution status and load in rivers (Suthar, 2010).

3.2.2.6 Sodium (Na)

Sodium is commonly associated with chloride as sodium chloride. Although it is essential for maintaining blood pressure and muscle function, a concentration of sodium that exceeds 200 mg/L may result in an unacceptable taste (WHO, 2011). It is used as a cooling agent in nuclear reactors and applied as a synthetic fertiliser; as such, it can be found in industrial effluents that end up in water sources.

CHAPTER 4 – METHODOLOGY

4.1 Data Collection and Analytical Methods

Considering that the water quality monitoring process requires a considerable number of resources, a wealth of data collected by the Department of Water and Sanitation (DWS) over several decades was used for this study. This includes annual water quality data for groundwater and surface water from 2000-2004 and 2012-2016. The years 2005 to 2011 were excluded because of significant data deficiencies in the DWS database. The water samples were collected by qualified employees and processed at certified laboratories. Specialists and experts audited and checked if the data were correct or not. The data were collected from boreholes and sampling stations across the UVRC and along major rivers and tributaries flowing through the different land use types of concern.

4.1.1 Water Quality Index

The WQI is a method used to assess the quality of water resources in a complex way by measuring the degree of contamination (Banda and Kumarasamy, 2020). The indexing scale is vital for communicating water quality data as it produces results that can easily be understood by planners, managers, developers and non-technical individuals. This will provide critical information that can be used to develop long-term catchment management plans that will protect their water supply (Bhaduri *et al.,* 2001). WQI can be used for both surface water and groundwater quality assessment and is the most popular method for showing the water quality of surface water resources (Yang *et al.,* 2012). The WQI is also used as a management tool in the decision-making process as it helps with the formulation of management plans.

The WQI transforms the given sets of water quality data into a single value, allowing extensive interpretation of water quality parameters for many purposes (Bora and Goswami, 2016). Each contributing variable was assigned its unique rating based on the SANS and World Health Organisation (WHO) water quality limits. Therefore, the WQI is a weighted average of all the parameters considered. It shows the degree to which the water quality was affected by anthropogenic activities in the catchment. According to Wanda *et al.* (2016), the WQI is the most effective tool on a visual scale that presents water quality deterioration.

Globally, numerous standard water quality indices include the Canadian Council Environment WQI, National Sanitation Foundation WQI, Oregon WQI and the Weighted Arithmetic WQI. However, the universal WQI model, which applies the weighted arithmetic method, was adopted for this study as it is widely used and has been found to be the most effective (Horton, 1965; Tyagi *et al.*, 2013). Therefore, the WQI was applied in the following steps (Alobaidy *et al.*, 2010; Dzwairo *et al.*, 2012; Nel *et al.*, 2013; Gajendran and Jesumi, 2013; Banda and Kumarasamy, 2020):

a. Water quality variables that showed significant variations with time were selected upon data analysis.
b. The different units of all the parameters were converted to a common scale.
c. Relative weightage coefficients were established for these variables according to their importance relative to overall water quality.
d. Sub-index rating curves and sub-index functions were then formulated, and an appropriate water quality index was developed.
e. Statistical analyses were done using MS office excel.

These steps are represented mathematically as shown in the equations below:

Step 1: Calculate the unit weight (W_n) factors for each parameter by using the formula (Horton, 1965; Table 4.1):

$$W_n = \frac{K}{S_n}$$

Where:

$$K = \frac{1}{\frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \cdots + \frac{1}{S_n}}$$

$$= \frac{1}{\Sigma \frac{1}{S_n}}$$

S_n = Standard desirable value of the nth parameters

On summation of all selected parameters, unit weight factors W_n = 1 (unity)

Table 4.1: Table showing the parameters used to calculate the WQI and the limits recommended by (SABS, 2015) and (WHO, 2004) for drinking water. The relative unit weight for each parameter is also given.

Parameter	Unit	Limit for drinking	Relative Unit Weight (Wn)
EC	mS/m	^{S}170	0.02284
NO_3	mg/R	^{W}5	0.77655
SO_4	mg/L	^{S}150	0.02589
Mg	mg/L	^{S}50	0.07766
Cl	mg/L	^{S}50	0.07766
Na	mg/L	^{S}200	0.01941

^{S} *as recommended by SABS (2015).*

^{W}*as recommended by WHO (2004).*

For this research project, unit weight factors were calculated using the above equation in an Excel spreadsheet, as shown in Table 4.2. NO_3-NO_2-N was converted to NO_3 by multiplying the NO_3-NO_2-N by 4.8.

Table 4.2: Table showing the calculation of unit weight factors for all the parameters of interest.

Parameters	Unit	BIS Standards (Sn)	1/Sn	∑1/Sn	K=1/(∑1/Sn)	Wn=K/Sn
EC	mS/m	170	0.0059	0.25755	3.88276	0.0228
SO_4	mg/L	150	0.0067	0.25755	3.88276	0.0259
Mg	mg/L	50	0.02	0.25755	3.88276	0.0777
NO_3	mg/L	5	0.2	0.25755	3.88276	0.7766
Cl	mg/L	50	0.02	0.25755	3.88276	0.0777
Na	mg/L	200	0.005	0.25755	3.88276	0.0194
Sum			0.25755			1

Step 2: Calculate the Sub-Index (Q_n) value, which is the quality rating, by using the formula (Horton, 1965):

$$Q_n = \frac{(V_n - V_o)}{(S_n - V_o)} \times 100$$

Where:

V_n = mean concentration of the measured value of the nth parameters

S_n = Standard desirable value of the n^{th} parameters

V_o= Ideal value of the parameters in pure water (generally $V_o = 0$, for most parameters except for pH and DO). For example:

$$Q_{pH} = \frac{(V_{pH} - 7)}{(8.5 - 7)} \times 100$$

Step3: Combining Step 1 and Step 2, WQI is calculated as follows

$$WQI = \frac{\Sigma W_n Q_n}{\Sigma W_n}$$

The results are presented as a relative scale ranging from zero to one hundred, representing best and worst water quality, respectively. The classification is based on five categories, class one (1) represents good water quality, and class five (5) represents awfully bad water quality, as shown in table 4.3.

Table 4.3: Showing the classification of water samples depending on their WQI value (Horton, 1965).

WQ Index	**WQ Status**
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very poor
>100	Unfit for consumption

4.1.1.1 Calculation of the WQI

The calculation of WQI and the water quality rating for **Mooi A** for 2000 will be shown in full. The same method was applied to the rest of the UVRC, so the lengthy process will not be detailed for the other rivers. Daily water quality data were processed using Excel to determine all the parameters' spread and nature. Parameters with the most significant variance and very low p-value were then selected for the WQI calculation: EC, NO_3, Cl, Mg, Na, and SO_4 (Table 4.4). The daily water quality data were averaged into monthly data values. Due to limitations of the historical database, the data were grouped into two halves: 2000 – 2004 and 2012 – 2016. The monthly values were then processed using equations 1 to 5 on pages 15 and 16, as shown in Table 4.5.

Table 4.4: Table showing the monthly averages of EC, SO4, Mg, NO3, Cl and Na for the Mooi A monitoring point.

2000

Parameters	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
EC	mS/m	70.414	59.173	48.491	50.397	60.339	66.307	70.929	74.124	77.515	74.778	73.212	70.978
SO_4	mg/L	105.91	73.262	89.866	50.693	66.261	74.229	85.686	94.432	103.011	105.36	101.808	102.13
Mg	mg/L	40.225	32.944	29.707	25.432	32.978	37.429	38.515	44.396	44.272	42.644	41.122	41.674
NO_3	mg/R	7.701	5.743	6.149	5.217	6.438	7.201	7.238	8.175	8.290	8.179	7.763	6.898
Cl	mg/L	37.478	33.621	33.066	20.233	25.264	26.928	28.864	30.592	37.923	36.969	33.884	33.170
Na	mg/L	33.559	30.964	33.958	20.474	23.983	26.058	29.199	28.387	33.287	34.044	32.034	31.831

Table 4.5: The calculation of the January WQI, written in bold (134.767) using equations mentioned in the Methodology.

2000/Jan

Parameters	Unit	BIS Standards (Sn)	1/Sn	∑1/Sn	K=1/(∑1/Sn)	Wi=K/Sn	MEAN CONC VALUE (Vn)	Vn/Sn	Vn/Sn*100 =Qn	WnQn
EC	mS/m	170	0.0059	0.25755	3.88276	0.0228	70.41429	0.414202	41.4202	0.94603
SO_4	mg/L	150	0.0067	0.25755	3.88276	0.0259	105.913	0.706087	70.6087	1.82771
Mg	mg/L	50	0.02	0.25755	3.88276	0.0777	40.22483	0.804497	80.44967	6.24733
NO_3	mg/R	5	0.2	0.25755	3.88276	0.7766	7.700667	1.540133	154.0133	119.599
Cl	mg/L	50	0.02	0.25755	3.88276	0.0777	37.4775	0.74955	74.955	5.82064
Na	mg/L	200	0.005	0.25755	3.88276	0.0194	33.5585	0.167793	16.77925	0.32575
Sum			0.25755			1				**134.767**

The calculated monthly WQI were compiled into a table, and the WQI ratings were assigned accordingly (Table 4.6).

Table 4.6: The summary of WQI values and ratings of the Mooi A monitoring point.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	88	Very poor	Jan	106	Unfit	Jan	96	Very poor	Jan	98	Very poor	Jan	87	Very poor
Feb	78	Very poor	Feb	99	Very poor	Feb	86	Very poor	Feb	102	Unfit	Feb	88	Very poor
Mar	72	Poor	Mar	88	Very poor	Mar	89	Very poor	Mar	105	Unfit	Mar	91	Very poor
Apr	83	Very poor	Apr	87	Very poor	Apr	94	Very poor	Apr	102	Unfit	Apr	92	Very poor
May	89	Very poor	May	90	Very poor	May	93	Very poor	May	111	Unfit	May	99	Very poor
Jun	92	Very poor	Jun	101	Unfit	Jun	94	Very poor	Jun	90	Very poor	Jun	99	Very poor
Jul	96	Very poor	Jul	100	Unfit	Jul	99	Very poor	Jul	88	Very poor	Jul	97	Very poor
Aug	97	Very poor	Aug	104	Unfit	Aug	101	Unfit	Aug	90	Very poor	Aug	100	Unfit
Sep	101	Unfit	Sep	104	Unfit	Sep	104	Unfit	Sep	85	Very poor	Sep	101	Unfit
Oct	97	Very poor	Oct	100	Unfit	Oct	104	Unfit	Oct	81	Very poor	Oct	90	Very poor
Nov	92	Very poor	Nov	92	Very poor	Nov	106	Unfit	Nov	79	Very poor	Nov	86	Very poor
Dec	88	Very poor	Dec	88	Very poor	Dec	96	Very poor	Dec	79	Very poor	Dec	89	Very poor

2012			2013			2014			2015			2016		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	82	Very poor	Jan	92	Very poor	Jan	88	Very poor	Jan	79	Very poor	Jan	96	Very poor
Feb	78	Very poor	Feb	93	Very poor	Feb	90	Very poor	Feb	79	Very poor	Feb	83	Very poor
Mar	121	Unfit	Mar	95	Very poor	Mar	94	Very poor	Mar	78	Very poor	Mar	80	Very poor
Apr	86	Very poor	Apr	93	Very poor	Apr	94	Very poor	Apr	78	Very poor	Apr	95	Very poor
May	93	Very poor	May	96	Very poor	May	89	Very poor	May	78	Very poor	May	95	Very poor
Jun	93	Very poor	Jun	95	Very poor	Jun	100	Unfit	Jun	78	Very poor	Jun	82	Very poor
Jul	102	Unfit	Jul	105	Unfit	Jul	88	Very poor	Jul	78	Very poor	Jul	80	Very poor
Aug	104	Unfit	Aug	110	Unfit	Aug	103	Unfit	Aug	78	Very poor	Aug	95	Very poor
Sep	104	Unfit	Sep	110	Unfit	Sep	96	Very poor	Sep	79	Very poor	Sep	95	Very poor
Oct	97	Very poor	Oct	104	Unfit	Oct	92	Very poor	Oct	79	Very poor	Oct	83	Very poor
Nov	91	Very poor	Nov	91	Very poor	Nov	95	Very poor	Nov	78	Very poor	Nov	80	Very poor
Dec	95	Very poor	Dec	97	Very poor	Dec	93	Very poor	Dec	79	Very poor	Dec	95	Very poor

4.1.2 Geographic Information System (GIS)

Geographic Information System (GIS) is mainly used for mapping and analysing spatial data. The necessity to integrate GIS has been increasing recently due to its increased affordability and availability. Together with Google Earth, GIS was used to identify and assess the catchment's temporal and spatial landscape changes. This will help provide a visual scale of water quality changes in the catchment, contributing to more accurate results.

The land use data were obtained from the Environmental Geographical Information Systems website, under the Department of Forestry, Fisheries and Environment. The data was then cleaned using Microsoft Office Excel. In addition, the data were then streamlined to the study area and divided into six land use classes: bare, vegetated, water, built-up environment, mining and agriculture (Figure 5.1). Using ARC GIS-Pro Statical software, land cover datasets were evaluated to establish land cover changes within the UVRC. Google earth was also used as it allows free access to satellite imagery on current and past land cover uses and allows one to zoom in to land features in any part of the world.

The maps were adapted from 1990 and 2018 South African National Land-Cover Datasets, which were generated from automated mapping models using multi-seasonal Landsat-5 imagery and multi-seasonal 20 m resolution Sentinel-2 satellite imagery, respectively. The accuracy assessment for the 2018 dataset is 90.14%, while no assessment was done for the 1990 dataset due to the absence of historic reference data.

4.1.3 Statistical Analysis-Pearson

Graphs, tables and statistical analysis for the water quality parameters were developed using an Excel spreadsheet. The Pearson correlation method was used to assess correlations between multiple parameters for certain rivers. Guided by the Pearson correlation analysis for this research, correlation coefficients will be described using the following guidelines:

Table 4.7: Table showing categorisation of coefficient correlations for this research.

Correlation coefficient	Relationship
+/- 0.70 – 1	Strong
+/- 0.50 – 0.69	Moderate
+/- 0 – 0.49	Weak

4.2 Study Area Description

The WQI was calculated for the following rivers Vaal, Klip, Mooi, Suikerbosrant, Sterkfontein, Wilge, Rietspruit, Blesbokspruit, Leeuspruit, Wonderfonteinspruit, Waterval and Tweefontein (Figure 4.1). The monitoring points were named after their respective river name for this research. For rivers that had more than one monitoring point, they were given the river's name followed by a letter, for example, Vaal A and Vaal B. The WQI was also calculated for groundwater data from boreholes relatively close to the surface water monitoring points. The boreholes were named after the rivers closest to them that were considered for the WQI analysis; for example, a borehole close to the Mooi River is named Borehole Mooi (BH Mooi). The assessed boreholes for this research are Vaal E, Wilge, Suikerbosrant, Waterval, Mooi and Wonderfonteinspruit boreholes (Figure 4.1).

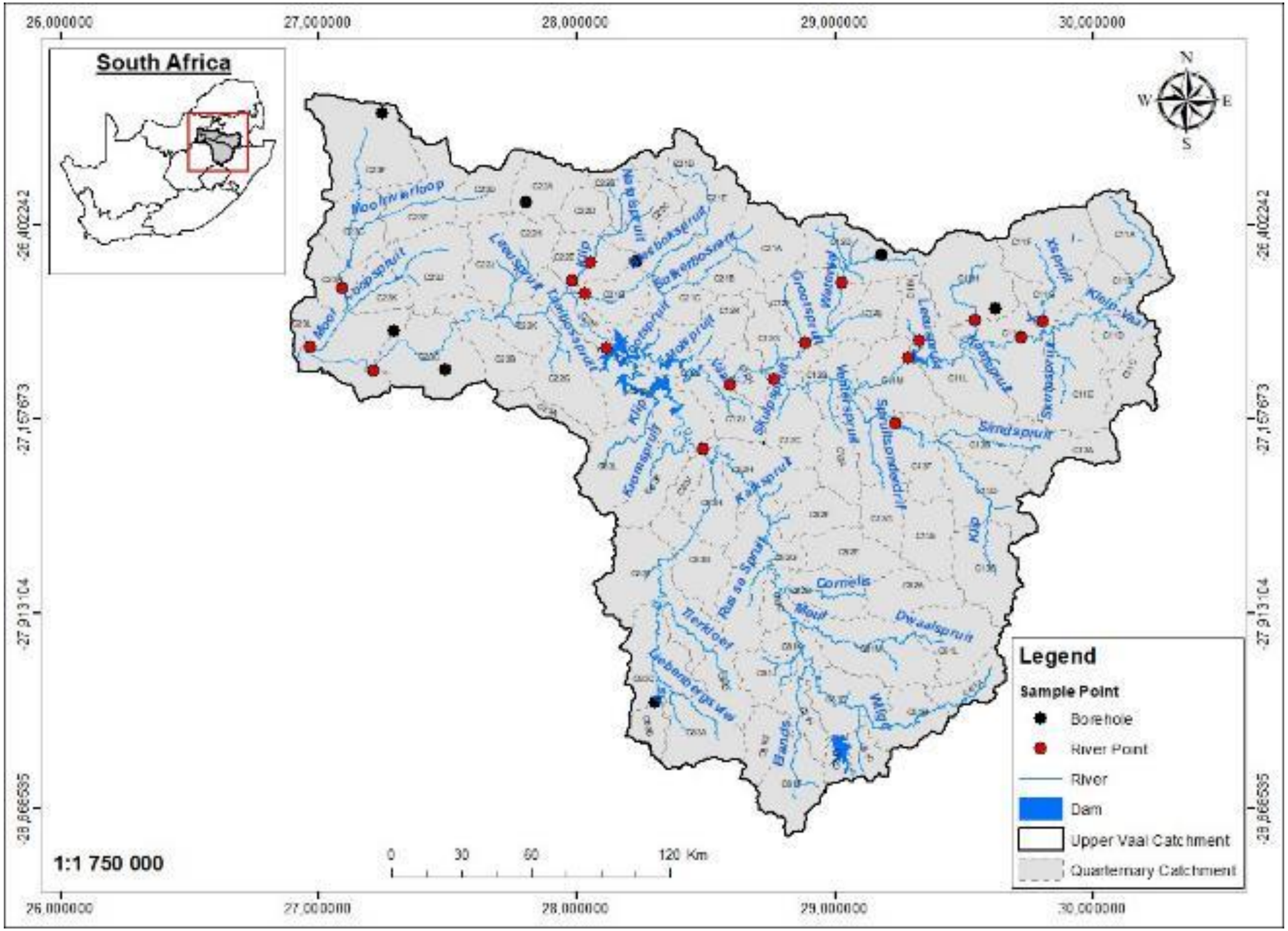

Figure 4.1: Map showing the location of surface water and groundwater sampling points along the Vaal River and its tributaries.

4.2.1 Vaal River

Vaal River has the most surface water monitoring points as it is the main river receiving input from tributaries in the catchment. This research considered six monitoring points as they had enough data for WQI calculations. Vaal River A represents the most upstream monitoring point, while Vaal River F represents the most downstream monitoring point.

4.2.1.1 Vaal A

This point is the most upstream monitoring point for the Vaal River, and the region is mainly characterised by agriculture that depends on the Vaal River for irrigation purposes. It is located downstream of the Tweefontein River, a major Vaal River tributary (Figure 4.2). The farms also have dams that limit the amount of runoff in the river.

Figure 4.2: Locality map for the Vaal River A sampling point (Adapted from Google Earth, 2022).

4.2.1.2 Vaal B

Located at approximately 82 km from the Vaal A monitoring point, this monitoring point is downstream of the Leeuspruit tributary (Figure 4.3). It is located by the exit of the Grootdraai Dam along the Vaal River.

Figure 4.3: Locality map for the Vaal B monitoring point (Adapted from Google Earth, 2022).

4.2.1.3 Vaal C

The monitoring point is approximately 108 km from the Vaal B monitoring point. It is located downstream of the Klip tributary; there are many circular farmlands along its riverbanks (Fig 4.4).

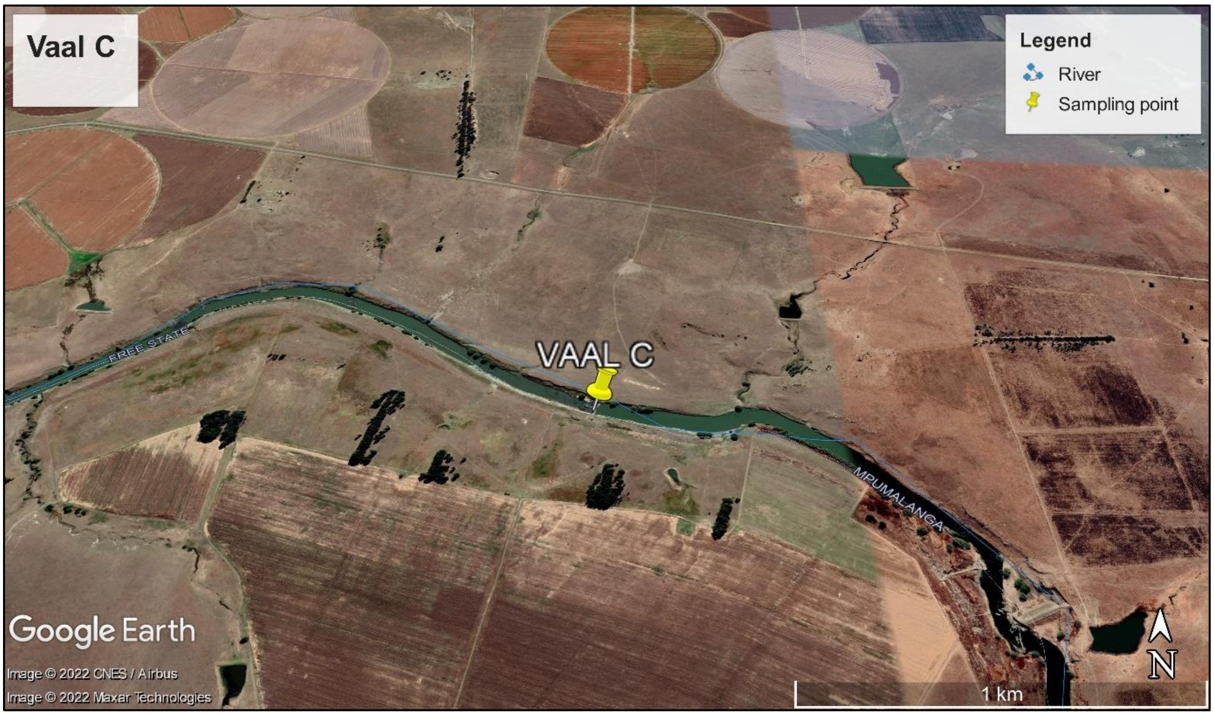

Figure 4.4: Locality map for the Vaal River C sampling point (Adapted from Google Earth, 2022).

4.2.1.4 Vaal D

The Vaal D sampling point is located approximately 38.8 km from the Vaal C monitoring point. The sample point is located next to the Villiers bridge along the Vaal River (Figure 4.5). Free State town Villiers under Mafube Municipality is situated along the Vaal River D banks, and it supports 17 315 people. There are two WWTPs along the Vaal River banks downstream of the Waterval tributary.

Figure 4.5: Locality map for the Vaal River D sampling point (Adapted from Google Earth, 2022).

4.2.1.5 Vaal E

The monitoring point is approximately 102 km from the Vaal D monitoring point. It is located next to the dam wall of the Vaal Dam along the Vaal River, downstream of the Wilge tributary (Figure 4.6). The Vaal Dam is used for the extraction of water that will be treated for drinking water purposes in the province.

Figure 4.6: Locality map for the monitoring point E (Adapted from Google Earth, 2022).

4.2.1.6 Vaal F

It is approximately 165 km from the Vaal E monitoring point. Downstream of Rietspruit, Kliprivier and Suikerbosrant tributaries (Figure 4.7). On the Schoemansdrift Bridge across the Vaal River. In a mountainous Vrederfort region in Free State province.

Figure 4.7: Locality map for the Vaal River F (Adapted from Google Earth, 2022).

4.2.2 Tweefontein River

The river supports the Tweefontein wetland. The primary land use in the catchment is mining and farming (Figure 4.8). The sub-catchment is characterised by low mean annual precipitation (about 6.59 %) that ends as runoff since most of the runoff is retained within the catchment and supports wetland habitats (DWA, 1991; Lubbe, 2013).

Figure 4.8: Locality map for the Tweefontein monitoring point (Adapted from Google Earth, 2022).

4.2.3 Leeuspruit River

Leeuspruit is an intermittent stream located in the Free State Province, South Africa. The estimated terrain elevation is 1426 metres above sea level. The monitoring point is situated by the Grootdraai dam on a bridge along a major road (Figure 4.9). There are residential areas, an Eskom power station and farming upstream of the river.

Figure 4.9: Locality map for the Leeuspruit monitoring point (Adapted from Google Earth, 2022).

4.2.4 Kliprivier

Kliprivier is found upstream of the Vaal River on the northern side of the Vaal River in the catchment (Figure 4.10). The Kliprivier separates the Free State province from Mpumalanga province. The sampling point is 38.6 km from its confluence with the Vaal River. Kliprivier is found upstream of the Vaal River on the northern side of the Vaal River in the catchment.

Figure 4.10: Locality map for the Kliprivier sample point (Adapted from Google Earth, 2022).

4.2.5 Waterval River

Historically, the river's sub-catchment is mainly dominated by farming, with 40% of its area used for agriculture while 30% is used for mining and industrial purposes. (Waterval Forum, 2005b). The river flows south-westerly towards the Vaal River (Gyedu-Ababio and van Wyk, 2004). The area is also surrounded by urban settlements experiencing rapid expansion (Waterval Forum, 2005a). The topography of this sub-section comprises < 8%, with local relief of 30 m to 90 m (Evander Gold Mines, 1995). However, these characteristics have been modified by mining through the formation of slime and ash dumps (Gyedu-Ababio and van Wyk, 2004). The riverbanks and floodplains have been eroded due to bad agriculture practices and fires (Wates et al., 1997). The monitoring points are Waterval A (upstream) and Waterval B (downstream).

4.2.5.1 Waterval A

The monitoring point is located downstream of significant mines, farms and towns. It is situated along a meander bend next to a major road (Figure 4.11).

Figure 4.11: Locality map for the Waterval A sample point (Adapted from Google Earth, 2022).

4.2.5.2 Waterval B

The monitoring point is approximately 47.8 km from the upstream monitoring point. It is located along irrigation farms (Figure 4.12).

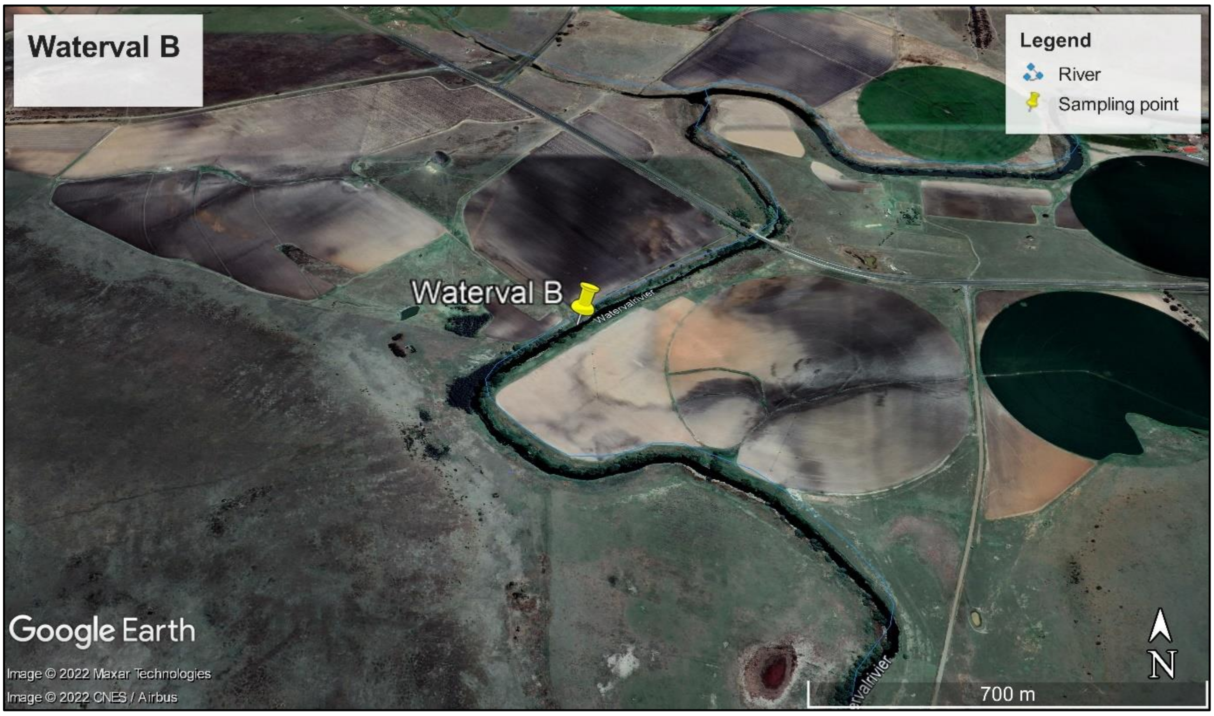

Figure 4.12: Locality map for the Waterval B sample point (Adapted from Google Earth, 2022).

4.2.6 Wilge River

From the Wilge River, about 50% of water is used for irrigation and domestic purposes. It also receives significant re-usable returns from its agriculture, urban and rural users (Farrell *et al.*, 2015). Along with the Liebenbergsvlei River, the Wilge River contributes 36% of surface water in the UVRC, making them the second surface water provider after the Vaal River (DWAF, 2003b). The upper Wilge River is of great significance. It includes the Sterkfontein Dam, a storage facility that releases water into the Wilge river to be delivered into the Vaal Dam (Farrell *et al.,* 2015). The monitoring point is 50.9 km away from the confluence with the Vaal Dam. Frankfort town in Free State is built along its banks (Figure 4.13).

Figure 4.13: Locality map for the Wilge monitoring point (Adapted from Google Earth, 2022).

4.2.7 Mooi River

This is one of the main Vaal River tributaries, located in the Northwest (NW) province of South Africa, originating near a predominantly farming small town of Koster. The NW province is well known for its farming, especially maize farming. Grasslands dominate the area, and it is very commonly associated with frost, fires and heavy grazing by cattle and sheep. The river's catchment is heavily degraded due to overgrazing of the grasslands and the expansion of communities. The sub-catchment mainly supports agriculture and irrigation, as well as the mining of gold and coal (Cowling et al., 1997; Low and Rebelo). Farmers along the river in the province use pesticides in Mar/Apr and Aug/Oct, which is the onset of the planting seasons (Ansara-Ross et al., 2008).

The Wonderfonteinspruit, one of the main Mooi River tributaries, originates from the abandoned gold mines and their residue deposits in the far West Rand of Gauteng. Close to the confluence of the two rivers, the water table is shallow due to large scale mining, which is the primary land use along the river, and it causes the formation of sinkholes (Winde. 2010b). According to du Pleis (2013), the river receives pollution from multiple sources, including active and abandoned gold mines and growing informal and formal developments such as

Rietvallei, Kagiso, and Mohlakeng. The monitoring points for this river are Mooi A (upstream) and Mooi B (downstream).

4.2.7.1 Mooi A

The monitoring point is located downstream of the Wonderspruit tributary and Boskop Nature Reserve along the meandering stretch of the river (Figure 4.14). It is also located downstream of the Potchefstroom town and Potchefstroom Dam. There is farming next to the banks along the stretch part of the river.

Figure 4.14: Locality map for the Mooi A sample point (Adapted from Google Earth, 2022).

4.2.7.2 Mooi B

The monitoring point is located downstream of the Vaal F sampling point and close to its confluence with the Vaal River. There are numerous irrigated farms along the river (Figure 4.15). It is about 1.93 km from its confluence with the Vaal River.

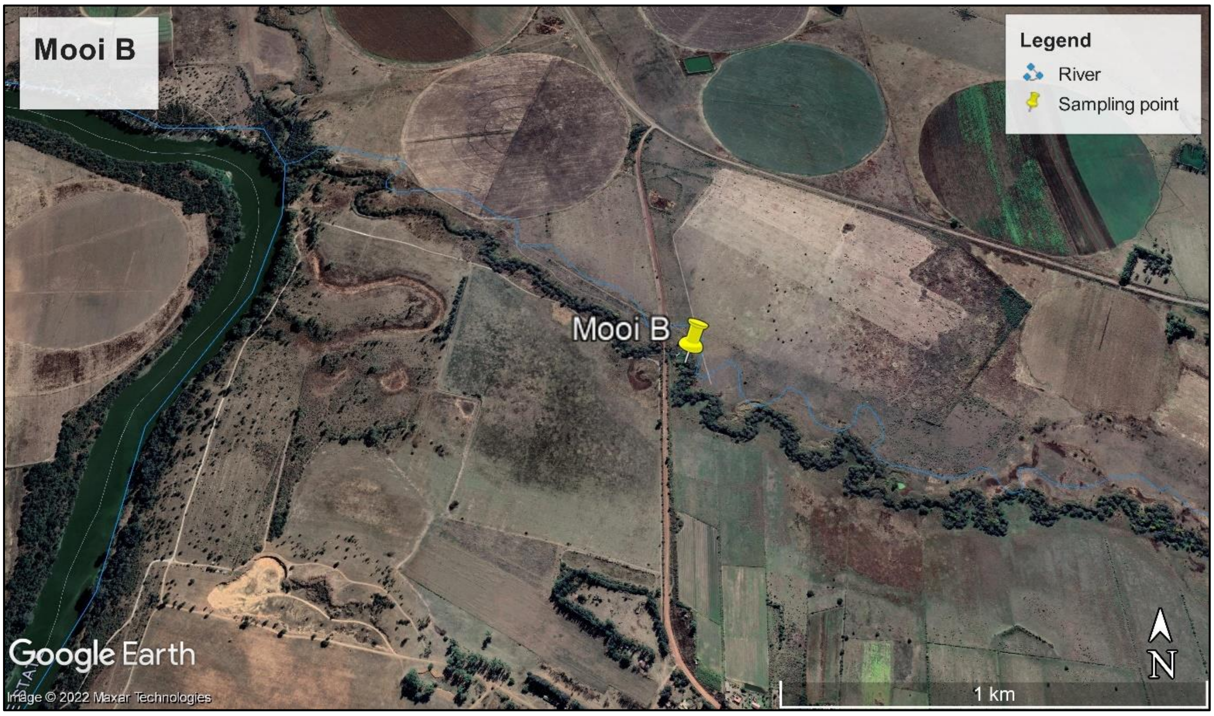

Figure 4.15: Locality map for the Mooi B sample point (Adapted from Google Earth, 2022).

4.2.8 Borehole Vaal F (BH Vaal F)

The monitoring borehole for groundwater is located 27.6 km from the Vaal River F monitoring point. However, it is only 8.27 km away from the Vaal River section, which flows past Parys town in the Free State province (Figure 4.16). Therefore, it is presumed that the river may not have any influence on the groundwater quality of the borehole water.

Figure 4.16: Location of the BH Vaal F borehole (Adapted from Google Earth, 2022).

Using the borehole data provided by the DWS, the simple stratigraphic column was drawn using the Strater 5 software (Figure 4.17). The first few meters from the ground surface of the stratigraphy comprise alluvium. After 10.5 m below the ground level, the aquifer comprises meta-pelites, quartzite and ironstones.

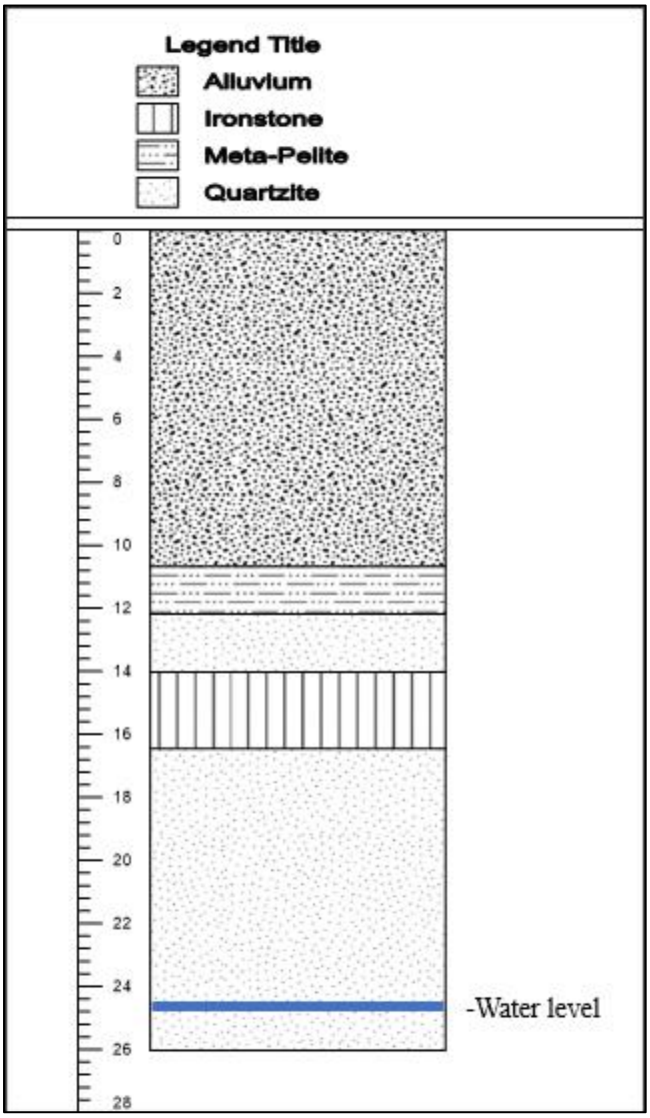

Figure 4.17: Stratigraphic column for the BH Vaal F borehole.

Due to data limitations, the water level was only calculated from 2001 to 2004. The monthly water level data were averaged into each year's wet and dry season data. The same procedure was followed for the other borehole water level data. The BH Vaal F has an average seasonal water level variation of 1.40 m with a relatively deep intermediate water level of 25.5 m (Table 4.8). There was a 4 m decline in the water table from the 2001 wet season to the 2004 dry season.

Table 4.8: Table showing the water level seasonal averages for the BH Vaal F borehole.

BH Vaal F	2001 wet season	2001 dry season	2002 wet season	2002 dry season	2003 wet season	2003 dry season	2004 wet season	2004 dry season
Average Water level (mbgl)	23.52	24.315	23.32	24.03	25.88667	28.8	28.755	27.55667
Average seasonal water level changes (m)	0.795		0.71		2.913		1.198	

4.2.9 Borehole Waterval (BH Waterval)

The BH Waterval monitoring point is 19.6 km from the Waterval A monitoring point. It is located in-between the SASOL Oil Refinery plant that produces oil from coal and the Secunda town in Mpumalanga (Figure 4.18).

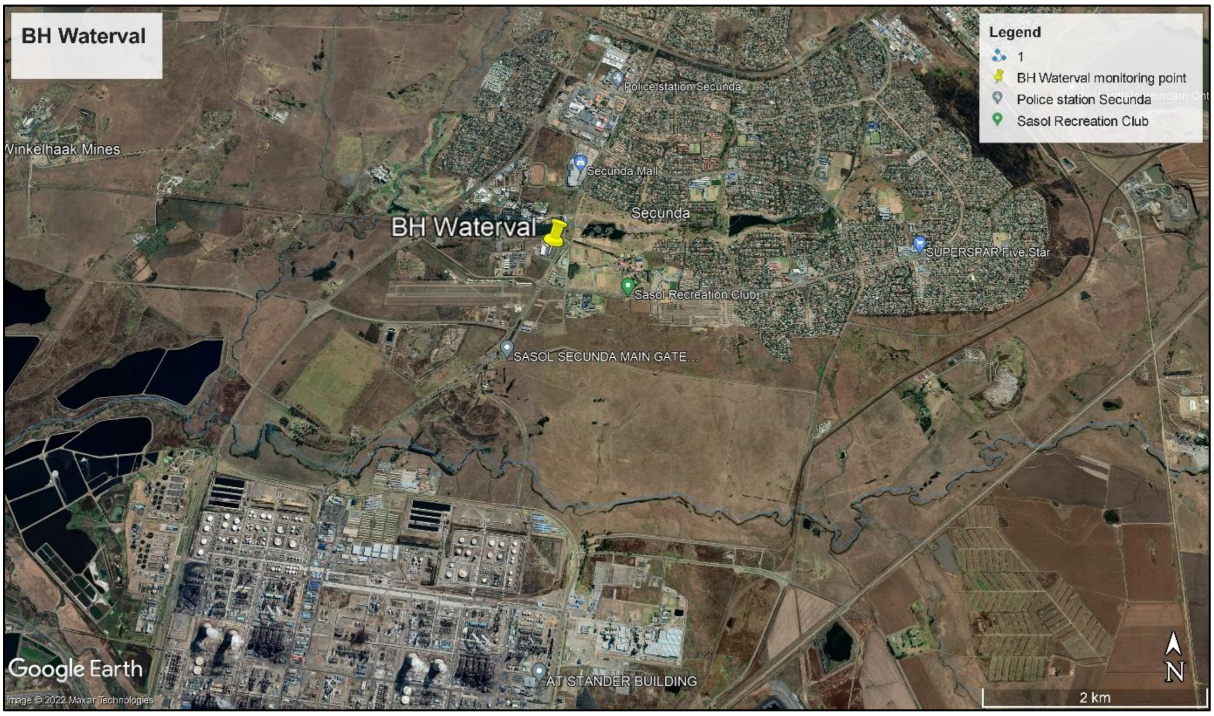

Figure 4.18: Location of the BH Waterval monitoring borehole.

The stratigraphy of this borehole comprises alluvium (1 – 1.2 m) and alternating sandstone and shale units from 1.2 m – 69.5 m (Figure 4.19).

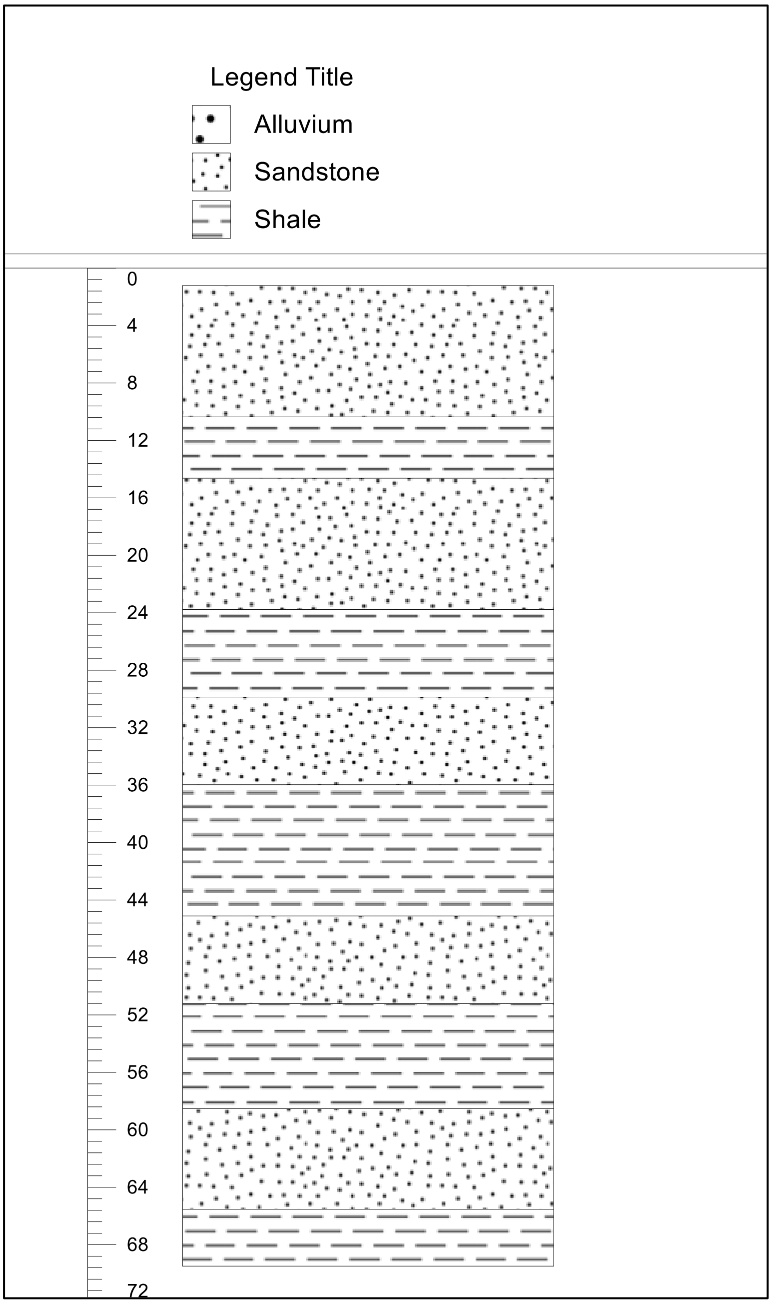

Figure 4.19: Stratigraphic column for the BH Waterval monitoring borehole.

4.2.10 Borehole Wonderfonteinspruit (BH Wonderfonteinspruit)

It is located in-between the Wonderfonteinspruit, a major tributary to the Mooi River and the Klip River. It is also located close to Soweto and Mohlakeng townships (Figure 4.20).

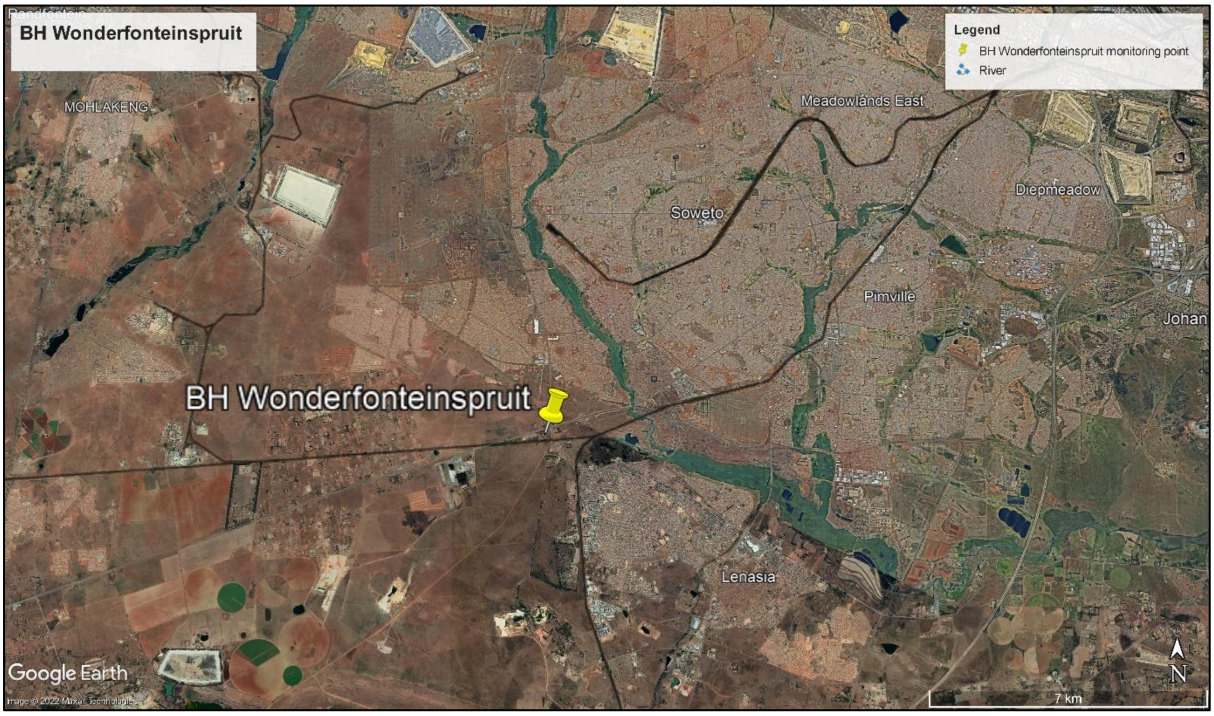

Figure 4.20: Locality map for the BH Wonderfonteinspruit monitoring borehole (Adapted from Google Earth, 2022).

The stratigraphy above the water table comprises highly weathered and metamorphosed granite gneiss and granite units (Figure 4.21).

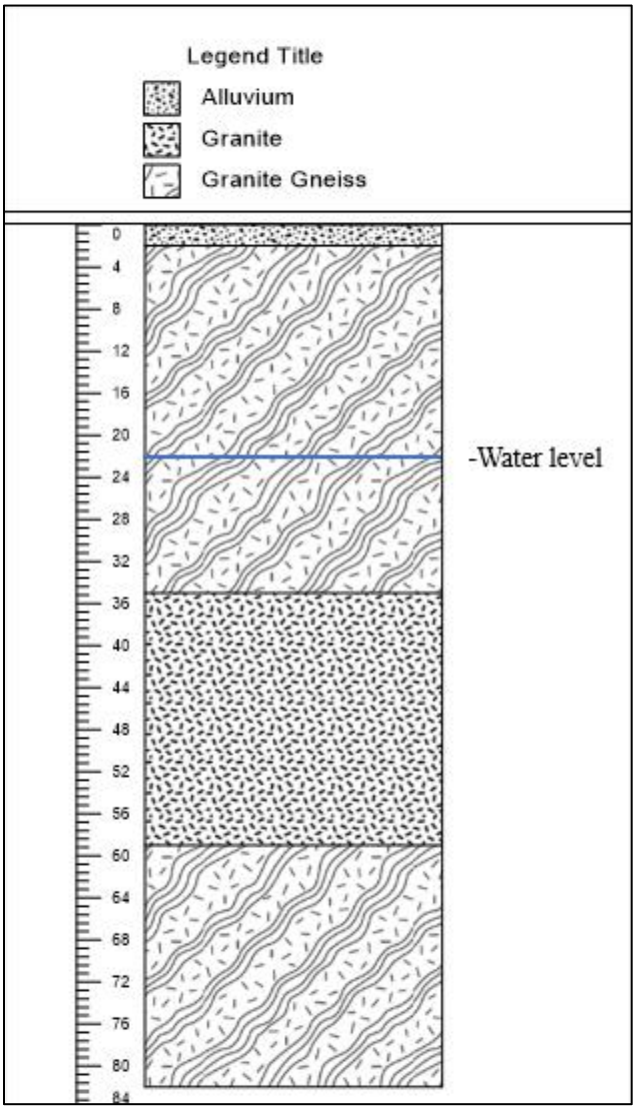

Figure 4.21: Stratigraphic column for the BH Wonderfonteinspruit groundwater monitoring borehole.

The water level in this borehole has relatively normal seasonal water level fluctuations averaging 0.43 m (Table 4.9). The water level is relatively deep, with an average of 22 m below ground level.

Table 4.9: Water level averages of the BH Wonderfonteinspruit monitoring borehole.

BH Wonderfonteinspruit								
Borehole details for the Groundwater monitoring data	**2001 wet season**	**2001 dry season**	**2002 wet season**	**2002 dry season**	**2003 wet season**	**2003 dry season**	**2004 wet season**	**2004 dry season**
Average Water level (wbgl)	-	21.655	21.94	22.67167	22.93333	23.17333	23.372	23.68
Average seasonal water level changes (m)	-		0.73		0.24		0.308	

4.2.11 Borehole Suikerbosrant (BH Suikerbosrant)

It is located in the Suikerbosrant Nature Reserve, 8.2 km from the Suikerbosrant River. The monitoring point is situated between the Klip River and Suikerbosrant River but closer to the latter. It is located close to the R42 highway and in the valley of big Hills. It is located approximately 10 km from the Heidelberg WWTP (see Appendix A). The most significant sewage works are situated in the Suikerbosrant and Klip River catchments (Figure 4.22).

Figure 4.22; Locality map for the BH Suikerbosrant borehole (Adapted from Google Earth, 2022).

The borehole has significantly deep-water levels that experience relatively low water level fluctuations (Table 4.10).

Table 4.10: A summary of average water level data for the BH Suikerbosrant borehole from 2001-2004.

BH SUIKERBOSRANT

Borehole details for the Groundwater monitoring data	2001 wet season	2001 dry season	2002 wet season	2002 dry season	2003 wet season	2003 dry season	2004 wet season	2004 dry season
Average Water level (mbgl)	76.56667	76.405	76.56333	76.86333	77.27	77.765	78.21143	78.65
Average seasonal water level changes (m)	0.162		0.3		0.495		0.439	

4.2.12 Borehole Wilge (BH Wilge)

This borehole is located along the N5 road by the Lorch Athlone lake next to Bethlehem town in Free State (Figure 4.23). It is located along one of the Wilge River tributaries.

Figure 4.23; Location of the BH Wilge borehole (Adapted from Google Earth, 2022).

The stratigraphy of the BH Wilge is characterised by large dolerite dykes with 16.77 m of thickness, followed by 7.92 m thick conglomerates and 19.55 m thick sandstones (Figure 4.24).

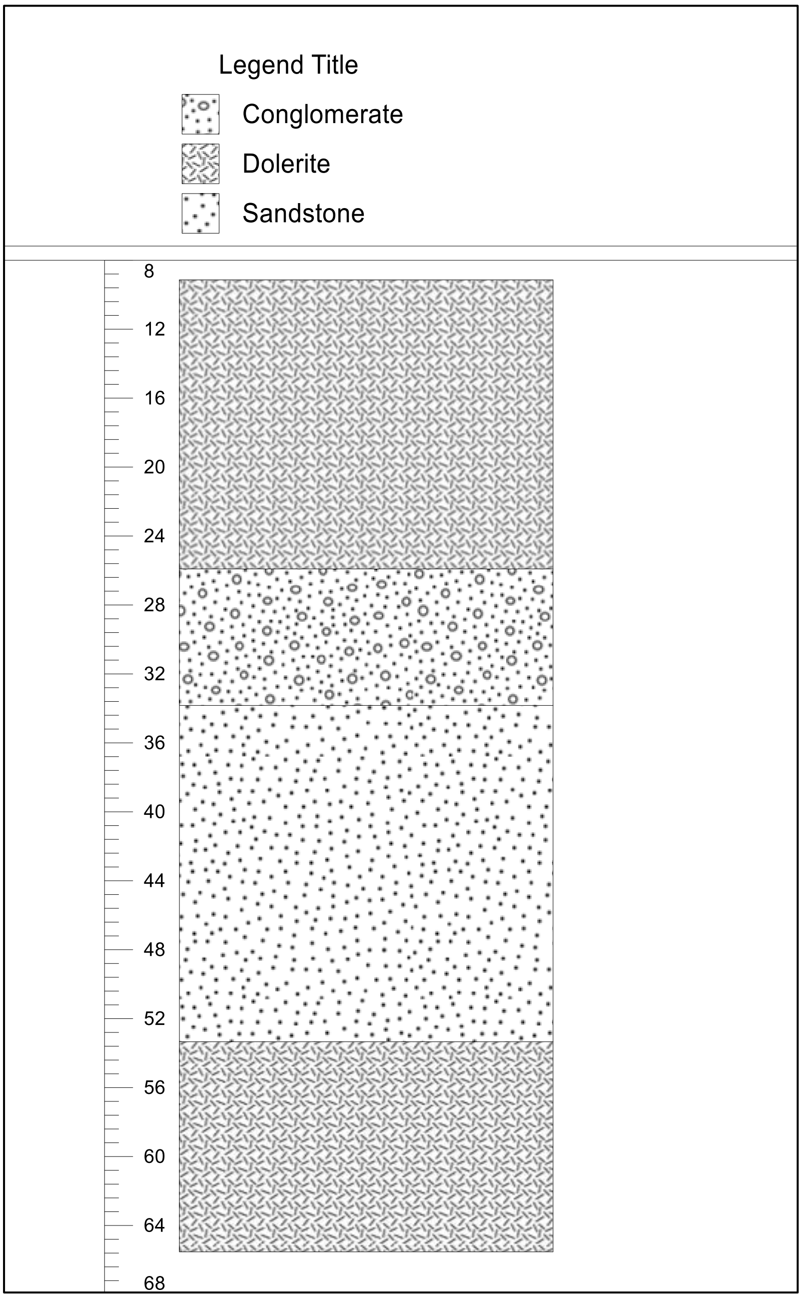

Figure 4.24: Stratigraphic column for the BH Wilge borehole.

CHAPTER 5 – RESULTS AND DISCUSSION

5.1 Introduction

Water quality data were collected for the period spanning from 2000 – 2004 to 2012 – 2018. The physicochemical parameters included in this study were Electrical Conductivity (EC), nitrate (NO_3), sulphate (SO_4), magnesium (Mg), chloride (Cl) and sodium (Na). The WQI was then calculated using the drinking water limits based on the South African National Standard (SANS) and the World Health Organisation (WHO). Due to the lack of data, the monthly intervals shown for rivers differ from groundwater points. The land use change maps were made for two time periods, 2000 and 2016. Lastly, the "unfit for consumption" category was reported as "unfit" in tables and graphs. A summary of the capacity of the major water treatment works run by Johannesburg Water and Erwat that release water into the UVRC is listed in Appendix 1.

5.2 Distribution of Land use

The land use types were divided into six classes: bare, vegetated, water, built-up environment, mining and agriculture. Human activities mainly influenced the change in land use in the UVRC from 2000 to 2016. In 2002, 47.41 % of land use in the catchment area was vegetation. In contrast, farming dominated the catchment with 26.29% land cover in 2016. Agricultural land use increased by 18.42 %, while bare land use category increased by 9.63 % (Figures 5.1 and 5.2). There was a 36.26 % decrease in vegetated land use, which is the most significant change during this period. The mining land use increased by 2.35 %, while the built-up land uses increased by 20.11 %. Land covered by water in 1990 was reduced by 14.25 in 2018.

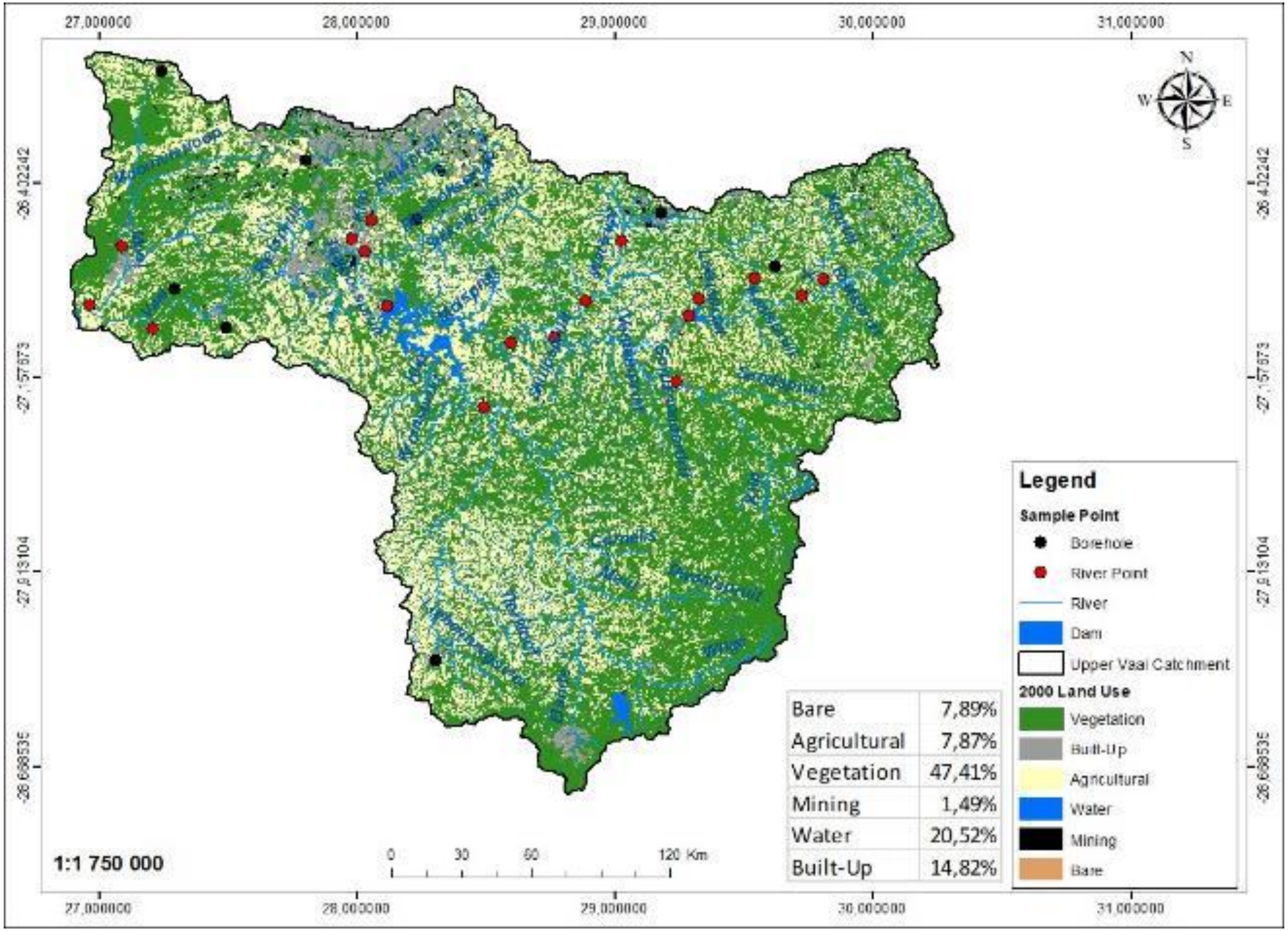

Figure 5.1: The 2000 land use distribution map for UVRC.

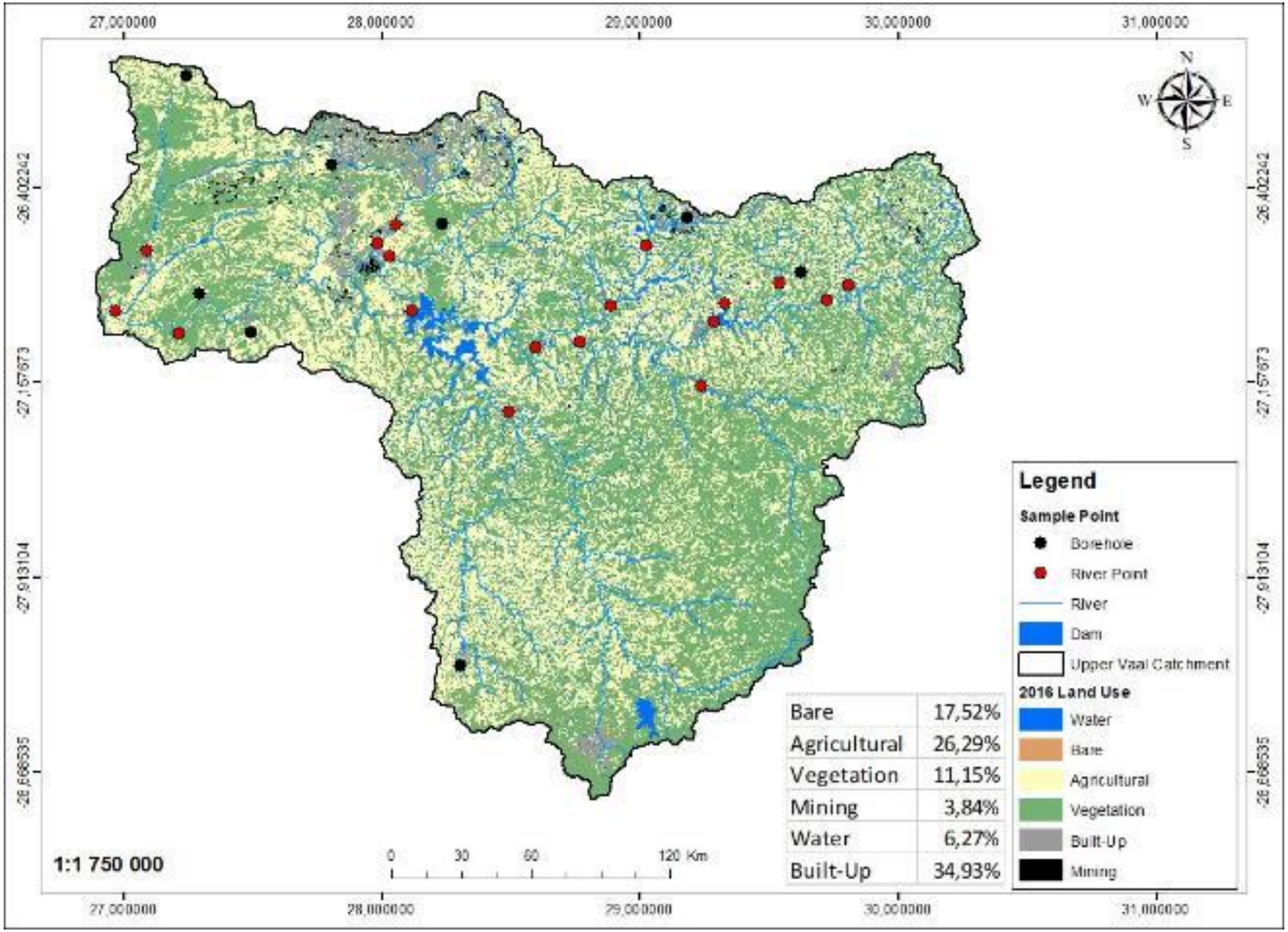

Figure 5.2: The 2016 land use distribution map for the UVRC.

5.3 Vaal Monitoring points (A to F)

Generally, wet months (October to March) have lower WQI than dry months (April to September) for the six sites (Bourblanc and Blanchon, 2014). According to Attua (2014), the Vaal River has less water volume in dry months than in wet months (Figure 5.3). The seasonal difference may be due to the fact that concentrations of parameters were diluted by rainwater during the wet season. A study by Karikari and Ansa-Asare (2006) found that EC levels were lower during the rainy season due to dilution from increased recharge.

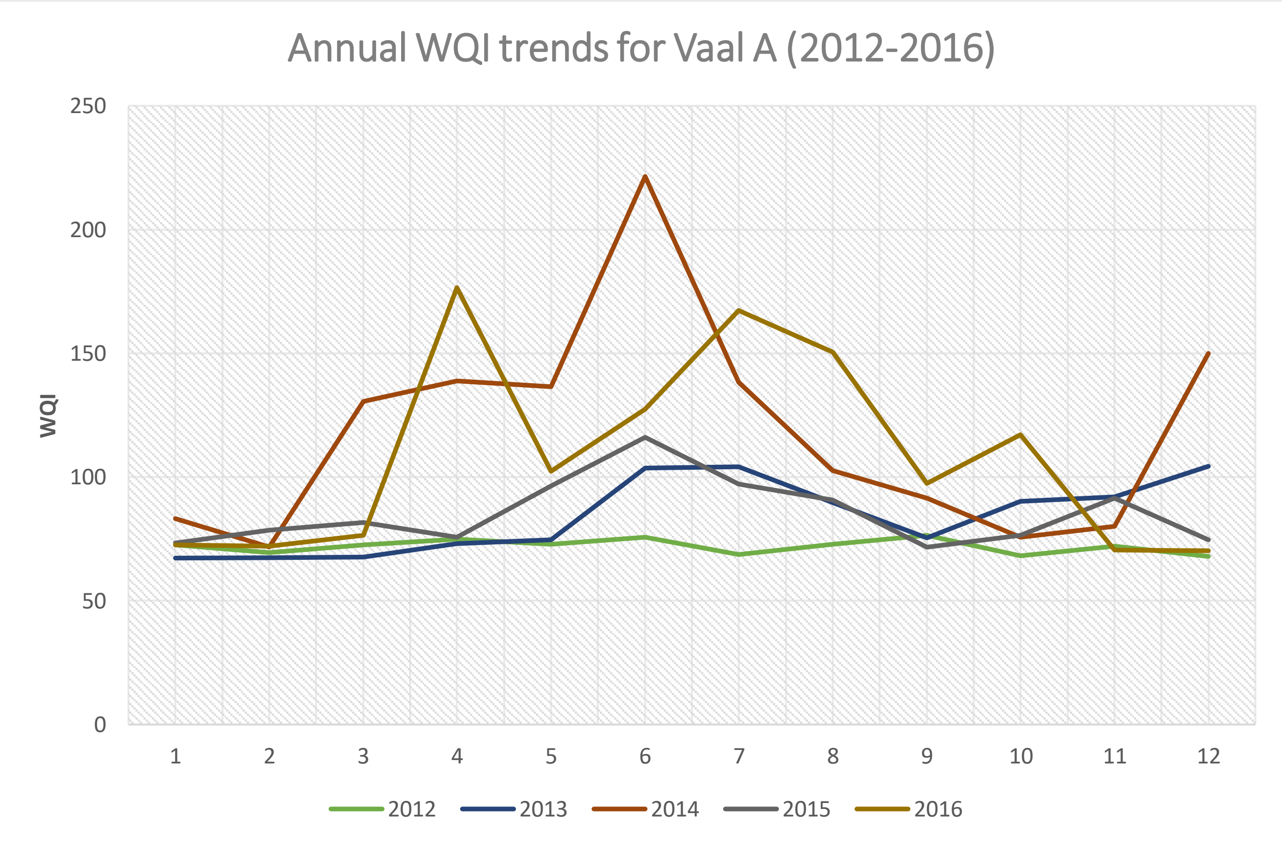

Figure 5.3: Line graph showing the changes in monthly WQI of Vaal A from 2012 to 2016.

From 2000 until 2004, the water quality varied between ‘poor’ and ‘very poor’ classes, with WQI values ranging between 66 to 75 for Vaal A, C, D and E (Table 5.2 to 5.6). Whilst from 2012 to 2016, the WQI varied between ‘very poor’ and ‘unfit for consumption’ except for a few outlier months with lower WQI. This shows a deterioration of water over the years within these rivers due to an increase in pollution sources in the catchment. This is suggested to be true as statistical and GIS results showed that agriculture land use increased by 18.42%, while bare land use category increased by 9.63% (Figure 5.2). There was also a 36.26% decrease in vegetated land use. The increase in parameter concentration with years could be attributed to the reduction in vegetated land over the years, which could have resulted in insufficient vegetation to buffer pollutants. In addition, this could also be attributed to the increase in industrial and wastewater affluents due to an increase in population and industries.

Table 5.1: The summary of WQI values and ratings of the Vaal A monitoring point.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	68	Poor	Jan	68	Poor	Jan	73	Poor	Jan	78	Very poor	Jan	70	Poor
Feb	72	Poor	Feb	69	Poor	Feb	75	Poor	Feb	78	Very poor	Feb	69	Poor
Mar	70	Poor	Mar	71	Poor	Mar	77	Very poor	Mar	69	Poor	Mar	69	Poor
Apr	74	Poor	Apr	71	Poor	Apr	69	Poor	Apr	69	Poor	Apr	70	Poor
May	77	Very poor	May	73	Poor	May	75	Poor	May	66	Poor	May	70	Poor
Jun	73	Poor	Jun	75	Poor	Jun	77	Very poor	Jun	70	Poor	Jun	71	Poor
Jul	72	Poor	Jul	76	Very poor	Jul	77	Very poor	Jul	72	Poor	Jul	72	Poor
Aug	72	Poor	Aug	76	Very poor	Aug	94	Very poor	Aug	70	Poor	Aug	75	Poor
Sep	78	Very poor	Sep	74	Poor	Sep	80	Very poor	Sep	70	Poor	Sep	72	Poor
Oct	82	Very poor	Oct	78	Very poor	Oct	75	Poor	Oct	69	Poor	Oct	74	Poor
Nov	69	Poor	Nov	81	Very poor	Nov	77	Very poor	Nov	69	Poor	Nov	74	Poor
Dec	69	Poor	Dec	76	Very poor	Dec	73	Poor	Dec	70	Poor	Dec	74	Poor

2012			2013			2014			2015			2016		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	73	Poor	Jan	67	Poor	Jan	83	Very poor	Jan	73	Poor	Jan	72	Poor
Feb	69	Poor	Feb	67	Poor	Feb	72	Poor	Feb	79	Very poor	Feb	72	Poor
Mar	72	Poor	Mar	68	Poor	Mar	131	Unfit	Mar	82	Very poor	Mar	76	Very poor
Apr	75	Poor	Apr	73	Poor	Apr	139	Unfit	Apr	76	Very poor	Apr	177	Unfit
May	73	Poor	May	75	Poor	May	136	Unfit	May	96	Very poor	May	102	Unfit
Jun	76	Very poor	Jun	104	Unfit	Jun	221	Unfit	Jun	116	Unfit	Jun	127	Unfit
Jul	69	Poor	Jul	104	Unfit	Jul	138	Unfit	Jul	97	Very poor	Jul	167	Unfit
Aug	73	Poor	Aug	90	Very poor	Aug	103	Unfit	Aug	91	Very poor	Aug	150	Unfit
Sep	76	Very poor	Sep	75	Poor	Sep	91	Very poor	Sep	72	Poor	Sep	98	Very poor
Oct	68	Poor	Oct	90	Very poor	Oct	76	Very poor	Oct	77	Very poor	Oct	117	Unfit
Nov	72	Poor	Nov	92	Very poor	Nov	80	Very poor	Nov	91	Very poor	Nov	70	Poor
Dec	68	Poor	Dec	104	Unfit	Dec	150	Unfit	Dec	75	Poor	Dec	70	Poor

Table 5.2: WQI values and the Vaal B monitoring point rating summary.

2000

Year	WQI	RATING
Jan	86	Very poor
Feb	81	Very poor
Mar	83	Very poor
Apr	107	Unfit
May	105	Unfit
Jun	81	Very poor
Jul	72	Poor
Aug	72	Poor
Sep	77	Very poor
Oct	111	Unfit
Nov	109	Unfit
Dec	76	Very poor

2001

Year	WQI	RATING
Jan	70	Poor
Feb	74	Poor
Mar	75	Poor
Apr	75	Poor
May	76	Very poor
Jun	74	Poor
Jul	74	Poor
Aug	76	Very poor
Sep	83	Very poor
Oct	84	Very poor
Nov	93	Very poor
Dec	133	Unfit

2002

Year	WQI	RATING
Jan	80	Very poor
Feb	75	Poor
Mar	81	Very poor
Apr	75	Poor
May	70	Poor
Jun	71	Poor
Jul	75	Poor
Aug	77	Very poor
Sep	75	Poor
Oct	77	Very poor
Nov	469	Unfit
Dec	80	Very poor

2003

Year	WQI	RATING
Jan	114	Unfit
Feb	122	Unfit
Mar	95	Very poor
Apr	79	Very poor
May	88	Very poor
Jun	77	Very poor
Jul	71	Poor
Aug	72	Poor
Sep	76	Very poor
Oct	75	Poor
Nov	80	Very poor
Dec	96	Very poor

2004

Year	WQI	RATING
Jan	93	Very poor
Feb	76	Very poor
Mar	89	Very poor
Apr	70	Poor
May	70	Poor
Jun	71	Poor
Jul	72	Poor
Aug	73	Poor
Sep	73	Poor
Oct	77	Very poor
Nov	78	Very poor
Dec	86	Very poor

2012

Year	WQI	RATING
Jan	223	Unfit
Feb	94	Very poor
Mar	89	Very poor
Apr	79	Very poor
May	81	Very poor
Jun	80	Very poor
Jul	76	Very poor
Aug	74	Poor
Sep	124	Unfit
Oct	79	Very poor
Nov	91	Very poor
Dec	233	Unfit

2013

Year	WQI	RATING
Jan	95	Very poor
Feb	91	Very poor
Mar	82	Very poor
Apr	134	Unfit
May	74	Poor
Jun	383	Very poor
Jul	74	Poor
Aug	73	Poor
Sep	74	Poor
Oct	89	Very poor
Nov	230	Unfit
Dec	118	Unfit

2014

Year	WQI	RATING
Jan	86	Very poor
Feb	70	Poor
Mar	69	Poor
Apr	69	Poor
May	70	Poor
Jun	72	Poor
Jul	73	Poor
Aug	79	Very poor
Sep	76	Very poor
Oct	77	Very poor
Nov	150	Unfit
Dec	131	Unfit

2015

Year	WQI	RATING
Jan	70	Poor
Feb	81	Very poor
Mar	96	Very poor
Apr	94	Very poor
May	72	Poor
Jun	78	Very poor
Jul	84	Very poor
Aug	73	Poor
Sep	79	Very poor
Oct	84	Very poor
Nov	114	Unfit
Dec	126	Unfit

2016

Year	WQI	RATING
Jan	293	Unfit
Feb	129	Unfit
Mar	225	Unfit
Apr	144	Unfit
May	214	Unfit
Jun	141	Unfit
Jul	131	Unfit
Aug	133	Unfit
Sep	139	Unfit
Oct	141	Unfit
Nov	183	Unfit
Dec	139	Unfit

Table 5.3: The summary of WQI values and the Vaal C monitoring point ratings.

2000			2001			2002			2003			2004		
Year	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**
Jan	73	Poor	Jan	70	Poor	Jan	72	Poor	Jan	71	Poor	Jan	70	Poor
Feb	71	Poor	Feb	69	Poor	Feb	72	Poor	Feb	69	Poor	Feb	75	Poor
Mar	83	Very poor	Mar	69	Poor	Mar	73	Poor	Mar	72	Poor	Mar	70	Poor
Apr	78	Very poor	Apr	70	Poor	Apr	69	Poor	Apr	73	Poor	Apr	75	Poor
May	78	Very poor	May	71	Poor	May	98	Very poor	May	71	Poor	May	70	Poor
Jun	78	Very poor	Jun	73	Poor	Jun	70	Poor	Jun	69	Poor	Jun	70	Poor
Jul	71	Poor	Jul	73	Poor	Jul	71	Poor	Jul	71	Poor	Jul	72	Poor
Aug	73	Poor	Aug	71	Poor	Aug	73	Poor	Aug	72	Poor	Aug	78	Very poor
Sep	75	Very poor	Sep	78	Very poor	Sep	74	Poor	Sep	72	Poor	Sep	74	Poor
Oct	78	Very poor	Oct	71	Poor	Oct	79	Very poor	Oct	72	Poor	Oct	74	Poor
Nov	71	Poor	Nov	87	Very poor	Nov	79	Very poor	Nov	70	Poor	Nov	74	Poor
Dec	76	Very poor	Dec	78	Very poor	Dec	71	Poor	Dec	87	Very poor	Dec	92	Very poor

2012			2013			2014			2015			2016		
Year	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**
Jan	76	Very poor	Jan	82	Very poor	Jan	77	Very poor	Jan	69	Poor	Jan	87	Very poor
Feb	68	Poor	Feb	100	Unfit	Feb	84	Very poor	Feb	72	Poor	Feb	104	Unfit
Mar	69	Poor	Mar	68	Very poor	Mar	83	Very poor	Mar	75	Poor	Mar	68	Poor
Apr	69	Poor	Apr	78	Very poor	Apr	80	Very poor	Apr	72	Poor	Apr	71	Poor
May	71	Poor	May	77	Very poor	May	73	Poor	May	166	Unfit	May	73	Poor
Jun	72	Poor	Jun	69	Poor	Jun	72	Poor	Jun	117	Unfit	Jun	79	Very poor
Jul	101	Unfit	Jul	70	Poor	Jul	73	Poor	Jul	92	Very poor	Jul	87	Very poor
Aug	81	Very poor	Aug	73	Poor	Aug	81	Very poor	Aug	88	Very poor	Aug	100	Unfit
Sep	103	Unfit	Sep	75	Poor	Sep	80	Very poor	Sep	86	Very poor	Sep	69	Poor
Oct	77	Very poor	Oct	73	Poor	Oct	121	Unfit	Oct	72	Poor	Oct	75	Poor
Nov	69	Poor	Nov	93	Very poor	Nov	82	Very poor	Nov	78	Very poor	Nov	75	Poor
Dec	90	Very poor	Dec	72	Poor	Dec	123	Unfit	Dec	73	Poor	Dec	99	Very poor

Table 5.4: WQI values and the Vaal D monitoring point rating summary.

2000

Year	WQI	RATING
Jan	73	Poor
Feb	74	Poor
Mar	76	Very poor
Apr	82	Very poor
May	88	Very poor
Jun	80	Very poor
Jul	78	Very poor
Aug	75	Poor
Sep	73	Poor
Oct	78	Very poor
Nov	73	Poor
Dec	78	Very poor

2001

Year	WQI	RATING
Jan	71	Poor
Feb	77	Very poor
Mar	72	Poor
Apr	75	Poor
May	78	Very poor
Jun	77	Very poor
Jul	75	Poor
Aug	73	Poor
Sep	73	Poor
Oct	72	Poor
Nov	74	Poor
Dec	73	Poor

2002

Year	WQI	RATING
Jan	71	Poor
Feb	72	Poor
Mar	72	Poor
Apr	72	Poor
May	73	Poor
Jun	70	Poor
Jul	70	Poor
Aug	70	Poor
Sep	70	Poor
Oct	70	Poor
Nov	72	Poor
Dec	71	Poor

2003

Year	WQI	RATING
Jan	74	Poor
Feb	76	Very poor
Mar	72	Poor
Apr	74	Poor
May	67	Poor
Jun	69	Poor
Jul	68	Poor
Aug	68	Poor
Sep	72	Poor
Oct	69	Poor
Nov	73	Poor
Dec	70	Poor

2004

Year	WQI	RATING
Jan	70	Poor
Feb	69	Poor
Mar	73	Poor
Apr	78	Poor
May	74	Poor
Jun	72	Poor
Jul	74	Poor
Aug	70	Poor
Sep	66	Poor
Oct	71	Poor
Nov	75	Poor
Dec	66	Poor

2012

Year	WQI	RATING
Jan	68	Poor
Feb	68	Poor
Mar	69	Poor
Apr	75	Poor
May	68	Poor
Jun	70	Poor
Jul	70	Poor
Aug	69	Poor
Sep	69	Poor
Oct	68	Poor
Nov	69	Poor
Dec	68	Poor

2013

Year	WQI	RATING
Jan	78	Very poor
Feb	71	Poor
Mar	71	Poor
Apr	74	Poor
May	74	Poor
Jun	73	Poor
Jul	72	Poor
Aug	71	Poor
Sep	71	Poor
Oct	74	Poor
Nov	70	Poor
Dec	73	Poor

2014

Year	WQI	RATING
Jan	82	Very poor
Feb	83	Very poor
Mar	72	Poor
Apr	81	Very poor
May	83	Very poor
Jun	82	Very poor
Jul	80	Very poor
Aug	73	Poor
Sep	70	Poor
Oct	78	Very poor
Nov	78	Very poor
Dec	86	Very poor

2015

Year	WQI	RATING
Jan	191	Unfit
Feb	85	Very poor
Mar	82	Very poor
Apr	81	Very poor
May	77	Very poor
Jun	96	Very poor
Jul	85	Very poor
Aug	73	Poor
Sep	70	Poor
Oct	71	Poor
Nov	75	Poor
Dec	73	Poor

2016

Year	WQI	RATING
Jan	71	Poor
Feb	71	Poor
Mar	110	Unfit
Apr	70	Poor
May	80	Very poor
Jun	83	Very poor
Jul	79	Very poor
Aug	78	Very poor
Sep	71	Poor
Oct	78	Very poor
Nov	82	Very poor
Dec	76	Very poor

Table 5.5: WQI values and the Vaal E monitoring point rating summary.

2000		
Year	WQI	RATING
Jan	82	Very poor
Feb	60	Poor
Mar	91	Very poor
Apr	91	Very poor
May	87	Very poor
Jun	92	Very poor
Jul	93	Very poor
Aug	92	Very poor
Sep	91	Very poor
Oct	82	Very poor
Nov	84	Very poor
Dec	84	Very poor

2001		
Year	WQI	RATING
Jan	73	Poor
Feb	70	Poor
Mar	70	Poor
Apr	73	Poor
May	78	Very poor
Jun	77	Very poor
Jul	76	Very poor
Aug	77	Very poor
Sep	74	Poor
Oct	72	Poor
Nov	75	Poor
Dec	74	Poor

2002		
Year	WQI	RATING
Jan	74	Poor
Feb	69	Poor
Mar	69	Poor
Apr	70	Poor
May	75	Poor
Jun	77	Very poor
Jul	79	Very poor
Aug	77	Very poor
Sep	77	Very poor
Oct	79	Very poor
Nov	79	Very poor
Dec	74	Poor

2003		
Year	WQI	RATING
Jan	71	Poor
Feb	69	Poor
Mar	70	Poor
Apr	71	Poor
May	74	Poor
Jun	75	Poor
Jul	74	Poor
Aug	74	Poor
Sep	73	Poor
Oct	75	Poor
Nov	77	Very poor
Dec	70	Poor

2004		
Year	WQI	RATING
Jan	75	Poor
Feb	70	Poor
Mar	70	Poor
Apr	88	Very poor
May	72	Poor
Jun	76	Very poor
Jul	80	Very poor
Aug	78	Very poor
Sep	82	Very poor
Oct	73	Poor
Nov	70	Poor
Dec	71	Poor

2012		
Year	WQI	RATING
Jan	89	Very poor
Feb	67	Poor
Mar	67	Poor
Apr	70	Poor
May	72	Poor
Jun	73	Poor
Jul	73	Poor
Aug	71	Poor
Sep	73	Poor
Oct	74	Poor
Nov	72	Poor
Dec	65	Poor

2013		
Year	WQI	RATING
Jan	71	Poor
Feb	71	Poor
Mar	73	Poor
Apr	73	Poor
May	79	Very poor
Jun	77	Very poor
Jul	77	Very poor
Aug	86	Very poor
Sep	81	Very poor
Oct	79	Very poor
Nov	80	Very poor
Dec	84	Very poor

2014		
Year	WQI	RATING
Jan	95	Very poor
Feb	89	Very poor
Mar	91	Very poor
Apr	90	Very poor
May	87	Very poor
Jun	91	Very poor
Jul	85	Very poor
Aug	82	Very poor
Sep	87	Very poor
Oct	70	Poor
Nov	87	Very poor
Dec	87	Very poor

2015		
Year	WQI	RATING
Jan	78	Very poor
Feb	72	Poor
Mar	70	Poor
Apr	74	Poor
May	72	Poor
Jun	73	Poor
Jul	70	Poor
Aug	73	Poor
Sep	69	Poor
Oct	71	Poor
Nov	72	Poor
Dec	83	Very poor

2016		
Year	WQI	RATING
Jan	76	Very poor
Feb	71	Poor
Mar	73	Poor
Apr	75	Poor
May	75	Poor
Jun	109	Unfit
Jul	84	Very poor
Aug	83	Very poor
Sep	84	Very poor
Oct	78	Very poor
Nov	78	Very poor
Dec	91	Very poor

Table 5.6: Summary of WQI and ratings for the Vaal River F.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	103	Unfit	Jan	87	Very poor	Jan	105	Unfit	Jan	82	Very poor	Jan	91	Very poor
Feb	115	Unfit	Feb	79	Very poor	Feb	118	Unfit	Feb	82	Very poor	Feb	86	Very poor
Mar	117	Unfit	Mar	81	Very poor	Mar	106	Unfit	Mar	83	Very poor	Mar	160	Unfit
Apr	119	Unfit	Apr	102	Unfit	Apr	86	Very poor	Apr	89	Very poor	Apr	108	Unfit
May	121	Unfit	May	146	Unfit	May	156	Unfit	May	99	Very poor	May	149	Unfit
Jun	157	Unfit	Jun	158	Unfit	Jun	196	Unfit	Jun	134	Unfit	Jun	174	Unfit
Jul	231	Unfit	Jul	195	Unfit	Jul	179	Unfit	Jul	182	Unfit	Jul	171	Unfit
Aug	239	Unfit	Aug	182	Unfit	Aug	194	Unfit	Aug	198	Unfit	Aug	162	Unfit
Sep	171	Unfit	Sep	154	Unfit	Sep	186	Unfit	Sep	143	Unfit	Sep	146	Unfit
Oct	130	Unfit	Oct	174	Unfit	Oct	154	Unfit	Oct	90	Very poor	Oct	112	Unfit
Nov	108	Unfit	Nov	183	Unfit	Nov	88	Very poor	Nov	87	Very poor	Nov	101	Unfit
Dec	98	Very poor	Dec	110	Unfit	Dec	83	Very poor	Dec	89	Very poor	Dec	121	Unfit

2012			2013			2014			2015			2016		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	139	Unfit	Jan	116	Unfit	Jan	135	Unfit	Jan	136	Unfit	Jan	79	Very poor
Feb	117	Unfit	Feb	116	Unfit	Feb	138	Unfit	Feb	79	Very poor	Feb	129	Unfit
Mar	108	Unfit	Mar	79	Very poor	Mar	113	Unfit	Mar	92	Very poor	Mar	110	Unfit
Apr	86	Very poor	Apr	168	Unfit	Apr	177	Unfit	Apr	215	Unfit	Apr	156	Unfit
May	213	Unfit	May	181	Unfit	May	173	Unfit	May	250	Unfit	May	268	Unfit
Jun	216	Unfit	Jun	253	Unfit	Jun	225	Unfit	Jun	294	Unfit	Jun	251	Unfit
Jul	224	Unfit	Jul	242	Unfit	Jul	241	Unfit	Jul	292	Unfit	Jul	328	Unfit
Aug	219	Unfit	Aug	251	Unfit	Aug	202	Unfit	Aug	294	Unfit	Aug	352	Unfit
Sep	228	Unfit	Sep	218	Unfit	Sep	217	Unfit	Sep	264	Unfit	Sep	248	Unfit
Oct	168	Unfit	Oct	125	Unfit	Oct	164	Unfit	Oct	202	Unfit	Oct	269	Unfit
Nov	147	Unfit	Nov	99	Very poor	Nov	209	Unfit	Nov	110	Unfit	Nov	275	Unfit
Dec	123	Unfit	Dec	176	Unfit	Dec	260	Unfit	Dec	101	Unfit	Dec	212	Unfit

On the contrary, the most downstream monitoring point, Vaal F, has had most of its monthly WQI under the ‘unfit for consumption’ class from 2000 – 2014 and 2012 – 2016 (Table 5.6; Figures 5.4 and 5.5). This could be because it also receives all the pollutants from the upstream Vaal catchment and its tributaries, resulting in a higher concentration of contaminants. The river’s terrible water conditions at Vaal D can be seen in the picture taken close to the monitoring point (Figure 5.6).

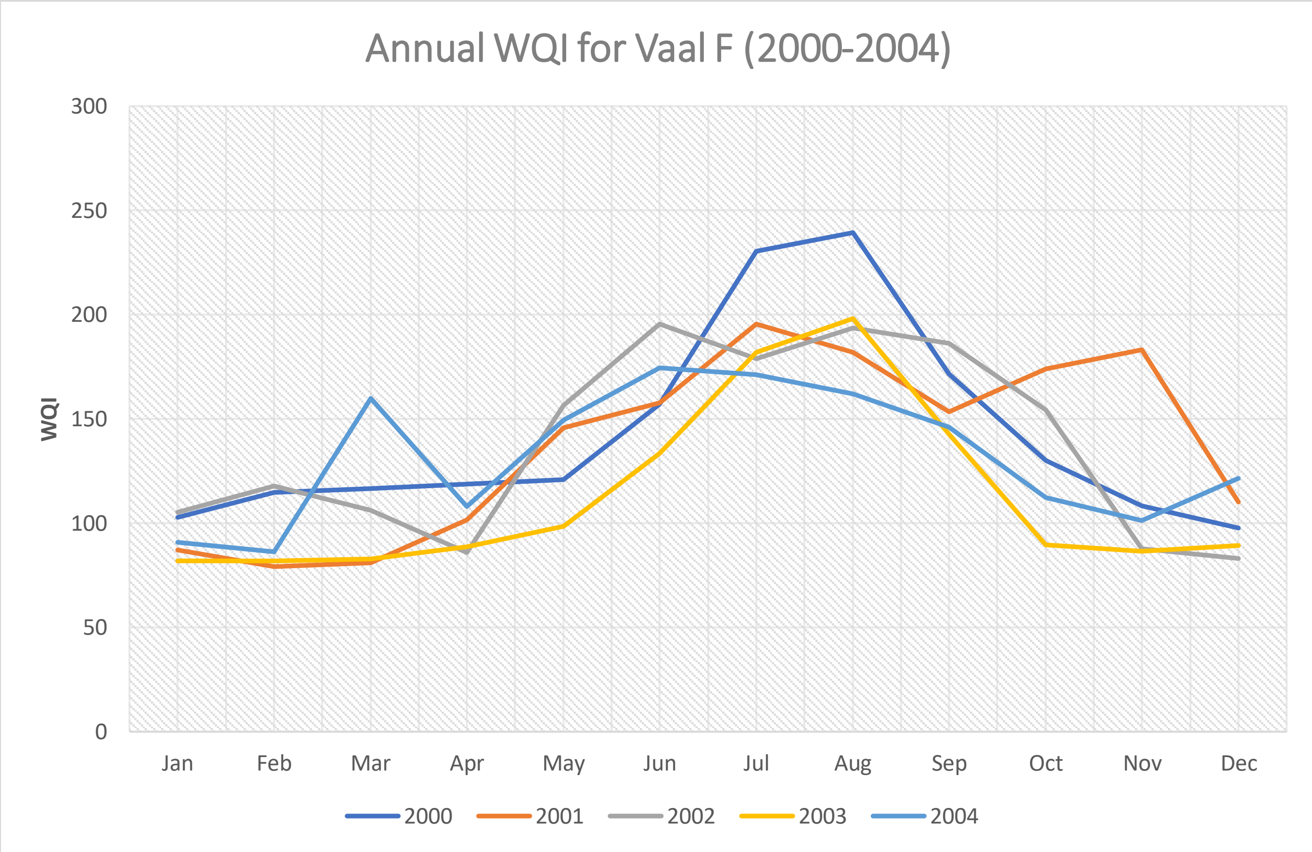

Figure 5.4: Line graph showing annual WQI for Vaal F that generally had above 100 WQI values from 2000 to 2004.

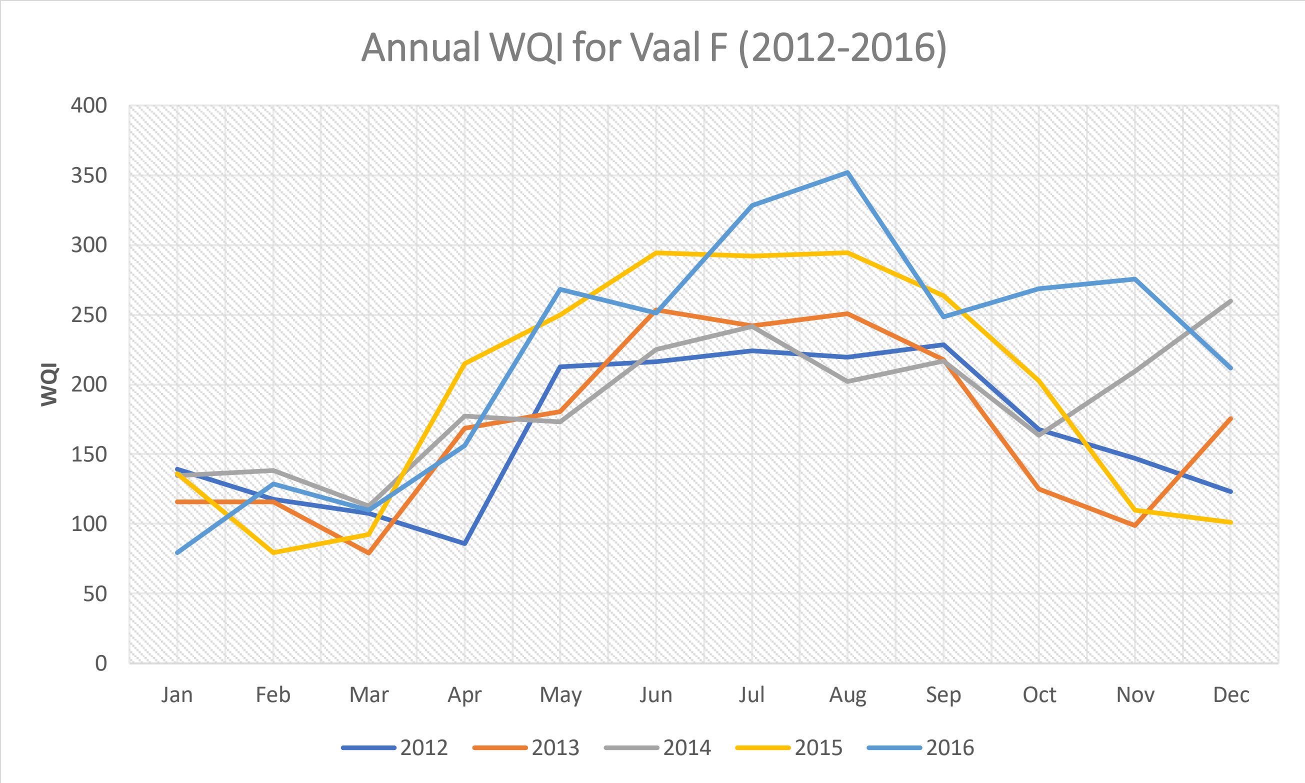

Figure 5.5: Line graph showing annual WQI for Vaal F that generally had above 100 WQI values from 2012 to 2016.

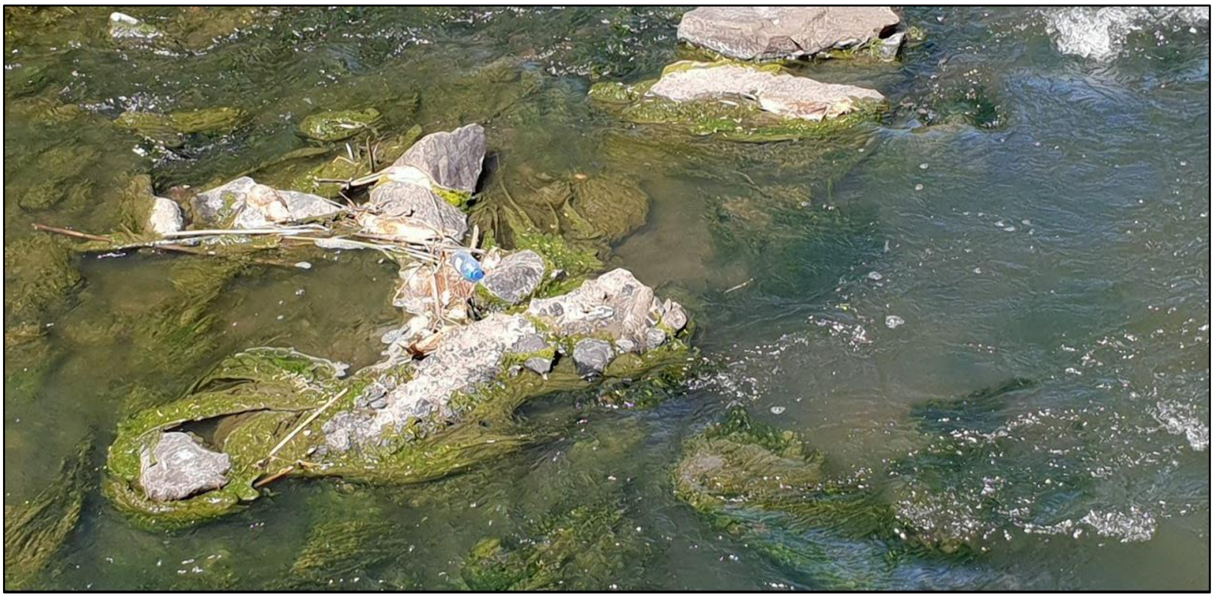

Figure 5.6: A picture showing the poor water quality conditions (plastics and algae) close to the Vaal D monitoring point. Photo credit (Google Earth: K Calitz).

Statistical analysis showed a strong correlation between Cl and Na with an average correlation coefficient of 0.71 (Figure 5.7). EC is strongly correlated with Cl, Na and Mg, with correlation coefficients of 0.82, 0.89 and 0.91, respectively (Table 5.7). This correlation is closely linked with the SO_4 correlation and high NO_3 concentrations, which can potentially be related to sewage, industrial and agricultural discharge into the river as Vaal D is located next to Villiers town. Sewage and agriculture are major sources of NO_3, which is mainly produced when urea is hydrolysed to form ammonia, which converts into highly mobile nitrate (Yoshioka *et al.*, 2016). According to WHO (2010), Na and Cl concentrations can be elevated by industrial effluents, irrigation drainage and sewage effluents.

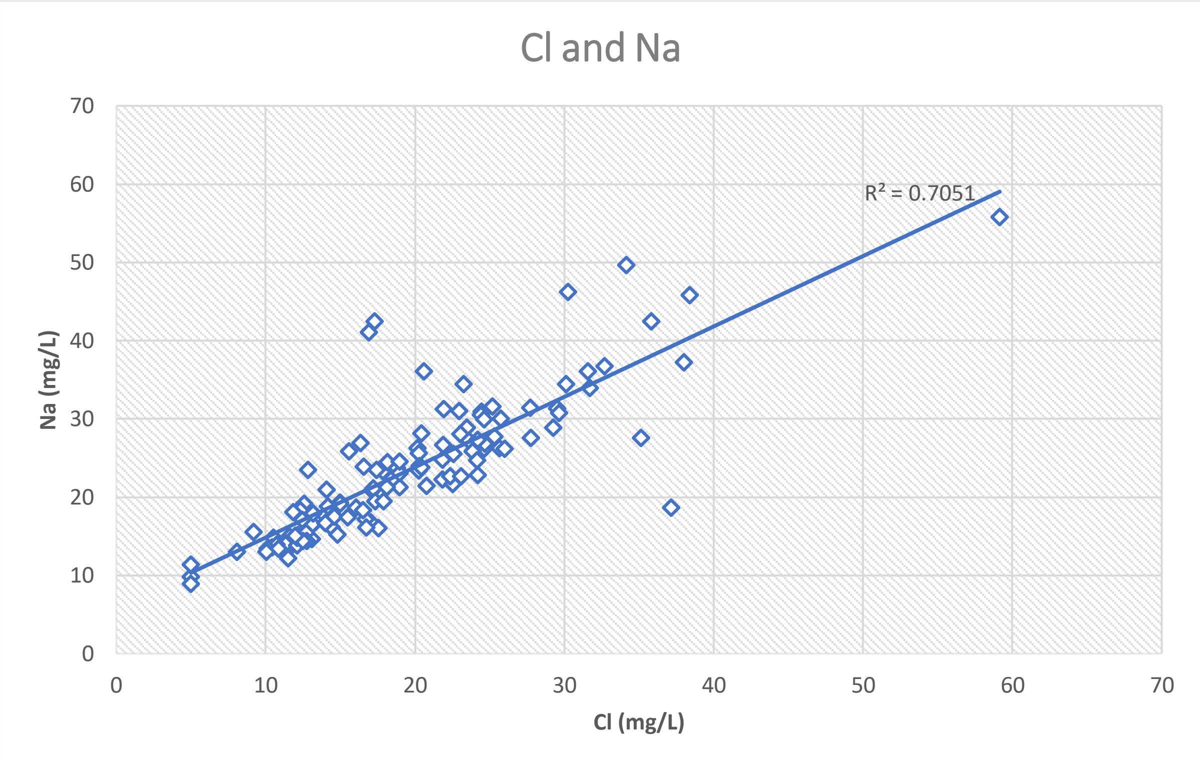

Figure 5.7: A scatter diagram showing the strong correlation between Cl and Na for Vaal B.

Table 5.7: Correlation matrix showing the correlation between all the parameters for Vaal D.

	EC	*NO₃*	*SO₄*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	-0.04967	1				
SO_4	0.663946	0.158869	1			
Mg	0.912009	-0.05921	0.491897	1		
Cl	0.827683	0.169919	0.809714	0.72715	1	
Na	0.886515	0.070934	0.716876	0.787718	0.839713	1

5.4 Tweefontein River

The water quality in this river has deteriorated over the years (Figure 5.8). From 2000 to 2004, the WQI rating mostly ranged between 'poor' and 'very poor' classes, while it shifted to mostly 'unfit for consumption' from 2012 to 2016 (Table 5.8). This could have been caused by the increase in pollution volumes in the river over the years due to land use changes. The WQI for this river was also seasonally controlled as the lowest WQI values were recorded during the wet season, which could be attributed to rainwater's dilution of the water quality parameters. An increase in nitrate levels mainly contributed to the sudden increase in WQI from 2014 to 2016. This could be attributed to the population increase in the catchment, which resulted in an increase in wastewater effluent volumes from WWTPs (Figure 5.10).

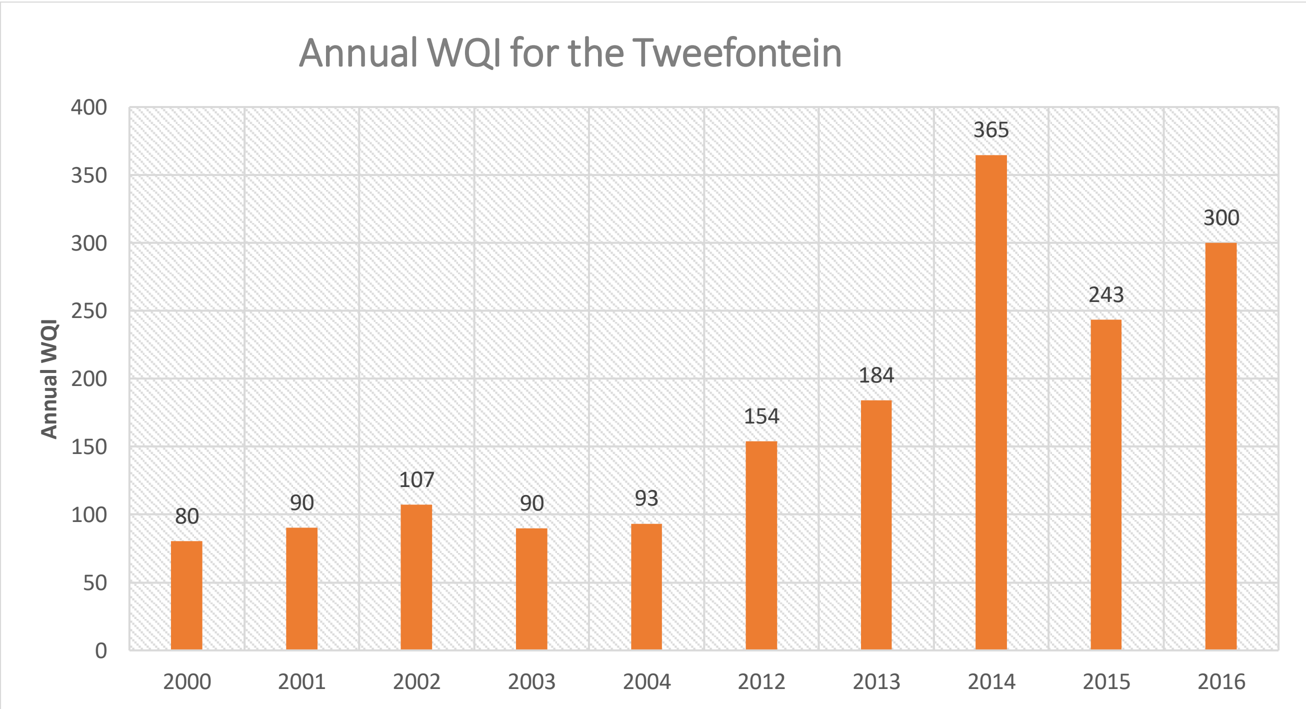

Figure 5.8: Bar graph showing the increase in annual WQI of the Tweefontein River.

Table 5.8: The summary of WQI values and ratings of the Tweefontein River monitoring point.

2000			2001			2002			2003			2004		
Year	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**
Jan	71	Poor	Jan	77	Very poor	Jan	81	Very poor	Jan	79	Very poor	Jan	86	Very poor
Feb	82	Very poor	Feb	80	Very poor	Feb	102	Unfit	Feb	80	Very poor	Feb	78	Very poor
Mar	78	Very poor	Mar	77	Very poor	Mar	117	Unfit	Mar	70	Poor	Mar	72	Poor
Apr	80	Very poor	Apr	112	Very poor	Apr	75	Poor	Apr	76	Very poor	Apr	74	Poor
May	83	Very poor	May	87	Very poor	May	81	Very poor	May	74	Poor	May	91	Very poor
Jun	79	Very poor	Jun	85	Very poor	Jun	82	Very poor	Jun	194	Unfit	Jun	91	Very poor
Jul	81	Very poor	Jul	96	Very poor	Jul	166	Unfit	Jul	83	Very poor	Jul	117	Unfit
Aug	75	Poor	Aug	134	Very poor	Aug	251	Unfit	Aug	98	Very poor	Aug	110	Unfit
Sep	89	Very poor	Sep	79	Very poor	Sep	78	Very poor	Sep	77	Very poor	Sep	152	Unfit
Oct	79	Very poor	Oct	92	Very poor	Oct	82	Very poor	Oct	79	Very poor	Oct	90	Very poor
Nov	88	Very poor	Nov	87	Very poor	Nov	81	Very poor	Nov	87	Very poor	Nov	85	Very poor
Dec	79	Very poor	Dec	77	Very poor	Dec	89	Very poor	Dec	78	Very poor	Dec	74	Poor

2012			2013			2014			2015			2016		
Year	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**
Jan	186	Unfit	Jan	96	Very poor	Jan	101	Unfit	Jan	105	Unfit	Jan	109	Unfit
Feb	140	Unfit	Feb	71	Poor	Feb	134	Unfit	Feb	117	Unfit	Feb	342	Unfit
Mar	150	Unfit	Mar	97	Very poor	Mar	194	Unfit	Mar	100	Unfit	Mar	118	Unfit
Apr	142	Unfit	Apr	108	Unfit	Apr	301	Unfit	Apr	169	Unfit	Apr	162	Unfit
May	188	Unfit	May	129	Unfit	May	335	Unfit	May	324	Unfit	May	252	Unfit
Jun	160	Unfit	Jun	257	Unfit	Jun	293	Unfit	Jun	356	Unfit	Jun	335	Unfit
Jul	246	Unfit	Jul	306	Unfit	Jul	550	Unfit	Jul	414	Unfit	Jul	484	Unfit
Aug	292	Unfit	Aug	357	Unfit	Aug	554	Unfit	Aug	361	Unfit	Aug	516	Unfit
Sep	90	Very poor	Sep	261	Unfit	Sep	487	Unfit	Sep	176	Unfit	Sep	469	Unfit
Oct	94	Very poor	Oct	271	Unfit	Oct	447	Unfit	Oct	568	Unfit	Oct	170	Unfit
Nov	82	Very poor	Nov	136	Unfit	Nov	872	Unfit	Nov	119	Unfit	Nov	546	Unfit
Dec	76	Poor	Dec	120	Unfit	Dec	108	Unfit	Dec	110	Unfit	Dec	96	Very poor

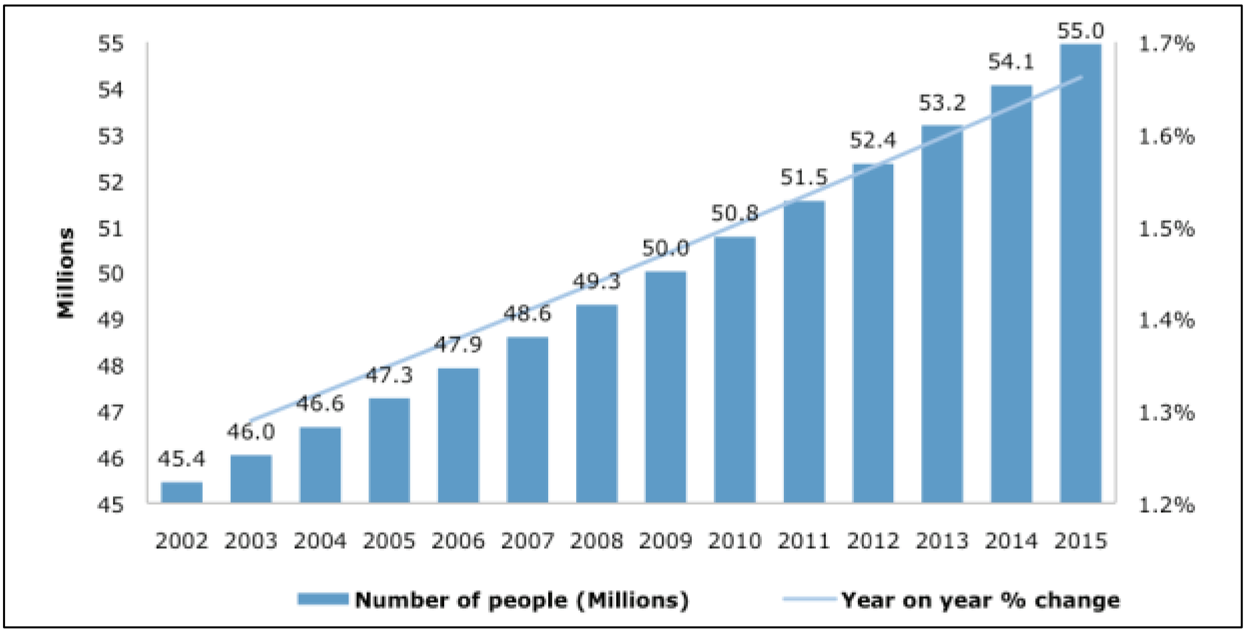

Figure 5.9: Bar graph showing an increase in the South African population between 2002 to 2015 (Statistics South Africa, 2015).

There is a strong correlation between EC with Cl, Mg and Na, as shown in Table 5.9. This makes it highly likely that these parameters had multiple sources, such as sewage effluents, runoff from agriculture and built-up land uses. According to Williams (2001), the loss in vegetation cover is mainly associated with erosion which may increase salinity, EC and nitrogen concentrations in rivers. The loss of vegetated land in the catchment could have facilitated the pollution of this river. According to Yoshioka *et al.* (2016), sewage wastewater is rich in NaCl since human excretions contain NaCl from ingested foods such as common salt.

Table 5.9: Correlation matrix for EC, NO3, SO4, Mg, Cl and Na for the Tweefontein River. All values in bold are significant, with correlation coefficients above 0.70.

	EC	*NO_3*	*SO_4*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	0.222797	1				
SO_4	0.660281	-0.02371	1			
Mg	**0.788916**	-0.0313	0.572682	1		
Cl	**0.87785**	0.301867	0.541085	0.488491	1	
Na	**0.879629**	0.338196	0.550933	0.472425	**0.960484**	1

5.5 Blesbokspruit River

The river experienced seasonal variation in WQI, with its wet months having the least WQI values (Table 5.10). The correlation matrix shows a moderate to strong correlation between all the parameters except for NO_3 (Table 5.11). NO_3 has weak correlations with the other five parameters, with the lowest correlation coefficient of 0.01 with Cl. This suggests that these anions do not have a similar source, for example, wastewater or agriculture; thus, the river's pollution source could be mainly from mines that contributed to the high chloride load. This is consistent with previous research on the river since the most publicised pollution source for the Blesbokspruit river is discharged polluted underground water pumped from mines in its sub-catchment (Bernard, 2000; Van Wyk, 2001; De Wet and Sidu, 2013; Lourenco and Curtis, 2021).

Table 5.10: The summary of WQI values and ratings of the Blesbokspruit River monitoring point.

2000			2001			2002			2003			2004		
Year	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**
Jan	71	Poor	Jan	72	Poor	Jan	72	Poor	Jan	81	Very poor	Jan	72	Poor
Feb	72	Poor	Feb	82	Very poor	Feb	72	Poor	Feb	70	Poor	Feb	70	Poor
Mar	71	Poor	Mar	71	Poor	Mar	74	Poor	Mar	71	Poor	Mar	71	Poor
Apr	77	Very poor	Apr	73	Poor	Apr	73	Poor	Apr	72	Poor	Apr	80	Very poor
May	72	Poor	May	76	Very poor	May	101	Very poor	May	71	Poor	May	75	Poor
Jun	79	Very poor	Jun	82	Very poor	Jun	74	Poor	Jun	72	Poor	Jun	79	Very poor
Jul	77	Very poor	Jul	81	Very poor	Jul	77	Very poor	Jul	78	Very poor	Jul	81	Very poor
Aug	78	Very poor	Aug	81	Very poor	Aug	83	Very poor	Aug	83	Very poor	Aug	82	Very poor
Sep	80	Very poor	Sep	82	Very poor	Sep	83	Very poor	Sep	82	Very poor	Sep	82	Very poor
Oct	84	Very poor	Oct	86	Very poor	Oct	90	Very poor	Oct	83	Very poor	Oct	82	Very poor
Nov	78	Very poor	Nov	86	Very poor	Nov	92	Very poor	Nov	81	Very poor	Nov	85	Very poor
Dec	81	Very poor	Dec	92	Very poor	Dec	85	Very poor	Dec	72	Poor	Dec	79	Very poor

2012			2013			2014			2015			2016		
Year	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**
Jan	79	Very poor	Jan	79	Very poor	Jan	72	Poor	Jan	148	Unfit	Jan	73	Poor
Feb	71	Poor	Feb	70	Poor	Feb	72	Poor	Feb	75	Poor	Feb	75	Poor
Mar	74	Poor	Mar	71	Poor	Mar	73	Poor	Mar	113	Unfit	Mar	72	Poor
Apr	75	Poor	Apr	97	Very poor	Apr	77	Very poor	Apr	73	Poor	Apr	74	Poor
May	78	Very poor	May	81	Very poor	May	80	Very poor	May	79	Very poor	May	77	Very poor
Jun	80	Very poor	Jun	74	Poor	Jun	89	Very poor	Jun	81	Very poor	Jun	88	Very poor
Jul	81	Very poor	Jul	91	Very poor	Jul	84	Very poor	Jul	82	Very poor	Jul	79	Very poor
Aug	122	Unfit	Aug	82	Very poor	Aug	87	Very poor	Aug	73	Poor	Aug	92	Very poor
Sep	124	Unfit	Sep	84	Very poor	Sep	95	Very poor	Sep	156	Unfit	Sep	82	Very poor
Oct	97	Very poor	Oct	93	Very poor	Oct	85	Very poor	Oct	82	Very poor	Oct	84	Very poor
Nov	175	Unfit	Nov	95	Very poor	Nov	86	Very poor	Nov	96	Very poor	Nov	85	Very poor
Dec	77	Very poor	Dec	80	Very poor	Dec	92	Very poor	Dec	85	Very poor	Dec	95	Very poor

Table 5.11: Correlation matrix for EC, NO3, SO4, Mg, Cl and Na for the Blesbokspruit River. All values in bold are significant, with correlation coefficients above 0.70.

	EC	*NO_3*	*SO_4*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	-0.10674	1				
SO_4	0.670232	-0.02019	1			
Mg	**0.927984**	-0.20306	**0.725071**	1		
Cl	**0.947575**	-0.01512	0.616108	**0.801916**	1	
Na	**0.951351**	-0.04347	0.609347	**0.818567**	**0.985005**	1

Other sources could be agriculture and natural sources as there are many farms along its course and across the sub-catchment. The river also appears to be red on Google Earth maps due to the underlying red loamy soils.

5.6 Leeuspruit River

The river's WQI range from 'poor' to 'unfit for consumption', with dry months having the highest WQI values (Table 5.12). EC strongly correlates with SO_4, Mg, Na and Cl with correlation coefficients of 0.79, 0.89, 0.94 and 0.93, respectively (Table 5.13). This indicates that the parameters could be from similar sources. The parameters could be sourced from sewage and industrial effluent as well as agricultural run-off. When different sources mix with variable salinity concentration, the EC values increases, resulting in 'unfit for consumption' water quality states. According to Suthar (2010), high conductivity in water indicates the mixing of sewage and industrial water.

Table 5.12: The summary of WQI values and ratings of the Leeuspruit River monitoring point.

2000		
Year	WQI	RATING
Jan	71	Poor
Feb	75	Poor
Mar	73	Poor
Apr	86	Very poor
May	75	Poor
Jun	73	Poor
Jul	76	Very poor
Aug	82	Very poor
Sep	89	Very poor
Oct	91	Very poor
Nov	75	Very poor
Dec	73	Poor

2001		
Year	WQI	RATING
Jan	70	Poor
Feb	77	Very poor
Mar	70	Poor
Apr	71	Poor
May	73	Poor
Jun	74	Poor
Jul	76	Very poor
Aug	75	Poor
Sep	77	Very poor
Oct	125	Unfit
Nov	92	Very poor
Dec	80	Very poor

2002		
Year	WQI	RATING
Jan	73	Poor
Feb	72	Poor
Mar	70	Poor
Apr	70	Poor
May	74	Poor
Jun	74	Poor
Jul	74	Poor
Aug	78	Very poor
Sep	81	Very poor
Oct	77	Very poor
Nov	77	Very poor
Dec	69	Poor

2003		
Year	WQI	RATING
Jan	75	Poor
Feb	69	Poor
Mar	72	Poor
Apr	69	Poor
May	73	Poor
Jun	71	Poor
Jul	73	Poor
Aug	73	Poor
Sep	73	Poor
Oct	74	Poor
Nov	75	Very poor
Dec	74	Poor

2004		
Year	WQI	RATING
Jan	70	Poor
Feb	70	Poor
Mar	98	Very poor
Apr	72	Poor
May	72	Poor
Jun	73	Poor
Jul	75	Very poor
Aug	77	Very poor
Sep	82	Very poor
Oct	74	Poor
Nov	76	Very poor
Dec	77	Very poor

2012		
Year	WQI	RATING
Jan	77	Very poor
Feb	76	Very poor
Mar	75	Poor
Apr	72	Poor
May	73	Poor
Jun	74	Poor
Jul	77	Very poor
Aug	74	Poor
Sep	82	Very poor
Oct	77	Very poor
Nov	79	Very poor
Dec	78	Very poor

2013		
Year	WQI	RATING
Jan	72	Poor
Feb	106	Unfit
Mar	69	Poor
Apr	89	Very poor
May	84	Very poor
Jun	77	Very poor
Jul	80	Very poor
Aug	79	Very poor
Sep	76	Very poor
Oct	72	Poor
Nov	178	Unfit
Dec	132	Unfit

2014		
Year	WQI	RATING
Jan	70	Poor
Feb	72	Poor
Mar	71	Poor
Apr	79	Very poor
May	75	Very poor
Jun	75	Very poor
Jul	83	Very poor
Aug	82	Very poor
Sep	77	Very poor
Oct	79	Very poor
Nov	88	Very poor
Dec	102	Unfit

2015		
Year	WQI	RATING
Jan	73	Poor
Feb	71	Poor
Mar	73	Poor
Apr	86	Very poor
May	89	Very poor
Jun	88	Very poor
Jul	90	Very poor
Aug	89	Very poor
Sep	89	Very poor
Oct	82	Very poor
Nov	79	Very poor
Dec	73	Poor

2016		
Year	WQI	RATING
Jan	153	Very poor
Feb	91	Very poor
Mar	71	Poor
Apr	75	Very poor
May	88	Very poor
Jun	73	Poor
Jul	73	Poor
Aug	79	Very poor
Sep	71	Poor
Oct	74	Poor
Nov	114	Unfit
Dec	74	Poor

Table 5.13: Correlation matrix for EC, NO_3, SO_4, Mg, Cl and Na for the Leeuspruit River. All values in bold are significant, with correlation coefficients above 0.70.

	EC	*NO_3*	*SO_4*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	-0.13608	1				
SO_4	**0.792019**	-0.04231	1			
Mg	**0.890217**	-0.14173	0.517149	1		
Cl	**0.936589**	-0.06048	**0.862436**	0.718455	1	
Na	**0.932436**	-0.12076	**0.905865**	0.69166	**0.967345**	1

5.7 Kliprivier

The water quality is generally ‘poor’ to ‘very poor’, with a gradual increase in WQI values from 2000 until 2016. The latter has the most months classified under ‘very poor’ during its wet season (Table 5.14). The poor water quality in the Kliprivier could be attributed to the discharge of effluent from WWTP, return flow from irrigated fields, and industrial processes in the Kliprivier sub-catchment. Marara and Palamuleni (2019) attributed the elevated heavy metal concentrations in the Kliprivier to agriculture, mining, wastewater and industrial effluents within the river’s sub-catchments. The correlation matrix shows a strong correlation between Mg, Na and EC, while the rest of the other parameters have moderate to weak correlations (Table 5.15). This could be so because the river’s sub-catchment doesn’t have many major mines, municipalities, or WWTP, as it is mainly a farming area. Having fewer pollution sources could be why it has better quality than the Vaal River.

Table 5.14: The summary of WQI values and ratings of the Kliprivier monitoring point.

2000			2001			2002			2003			2004		
Year	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**
Jan	67	Poor	Jan	68	Poor	Jan	70	Poor	Jan	68	Poor	Jan	68	Poor
Feb	66	Poor	Feb	72	Poor	Feb	69	Poor	Feb	68	Poor	Feb	69	Poor
Mar	68	Poor	Mar	71	Poor	Mar	68	Poor	Mar	68	Poor	Mar	69	Poor
Apr	69	Poor	Apr	69	Poor	Apr	68	Poor	Apr	68	Poor	Apr	69	Poor
May	81	Very poor	May	71	Poor	May	68	Poor	May	70	Poor	May	69	Poor
Jun	71	Poor	Jun	77	Very poor	Jun	70	Poor	Jun	70	Poor	Jun	70	Poor
Jul	77	Very poor	Jul	70	Poor	Jul	70	Poor	Jul	70	Poor	Jul	70	Poor
Aug	68	Poor	Aug	70	Poor	Aug	70	Poor	Aug	70	Poor	Aug	71	Poor
Sep	67	Poor	Sep	78	Very poor	Sep	75	Poor	Sep	70	Poor	Sep	72	Poor
Oct	68	Poor	Oct	70	Poor	Oct	71	Poor	Oct	71	Poor	Oct	72	Poor
Nov	72	Poor	Nov	71	Poor	Nov	73	Poor	Nov	74	Poor	Nov	75	Poor
Dec	67	Poor	Dec	72	Poor	Dec	70	Poor	Dec	69	Poor	Dec	81	Very poor

2012			2013			2014			2015			2016		
Year	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**
Jan	77	Very poor	Jan	69	Poor	Jan	68	Poor	Jan	70	Poor	Jan	82	Very poor
Feb	74	Poor	Feb	67	Poor	Feb	70	Poor	Feb	69	Poor	Feb	83	Very poor
Mar	69	Poor	Mar	70	Poor	Mar	73	Poor	Mar	75	Very poor	Mar	69	Poor
Apr	69	Poor	Apr	68	Poor	Apr	71	Poor	Apr	69	Poor	Apr	72	Poor
May	72	Poor	May	69	Poor	May	72	Poor	May	70	Poor	May	70	Poor
Jun	70	Poor	Jun	76	Very poor	Jun	72	Poor	Jun	70	Poor	Jun	70	Poor
Jul	71	Poor	Jul	70	Poor	Jul	73	Poor	Jul	71	Poor	Jul	72	Poor
Aug	71	Poor	Aug	70	Poor	Aug	89	Very poor	Aug	75	Poor	Aug	72	Poor
Sep	69	Poor	Sep	72	Poor	Sep	73	Poor	Sep	72	Poor	Sep	76	Very poor
Oct	72	Poor	Oct	73	Poor	Oct	73	Poor	Oct	74	Poor	Oct	73	Poor
Nov	67	Poor	Nov	71	Poor	Nov	79	Very poor	Nov	75	Poor	Nov	81	Very poor
Dec	82	Very poor	Dec	73	Poor	Dec	75	Poor	Dec	69	Poor	Dec	82	Very poor

Table 5.15: Correlation matrix for EC, NO3, SO4, Mg, Cl and Na for Kliprivier. All values in bold are significant, with correlation coefficients above 0.70.

	EC	*NO_3*	*SO_4*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	-0.22651	1				
SO_4	0.234751	0.14575	1			
Mg	**0.965362**	-0.19598	0.217585	1		
Cl	0.404835	0.07962	0.231118	0.430744	1	
Na	**0.873637**	-0.10692	0.192742	**0.827532**	0.469027	1

5.8 Waterval monitoring points

The upstream Waterval A has had its water quality mainly classed under the 'unfit for consumption' since 2000 (Table 5.16). On the contrary, the downstream Waterval B water quality has deteriorated over the years. It has changed from being 'very poor' before 2004 to mostly being 'unfit for consumption' after 2012 (Table 5.17). The locality map shows that other small tributaries join the Waterval between points A and B (Figure 4.12). The better WQI for the downstream point could be due to dilution by inputs from these tributaries. Both ends experience seasonal variations in WQI. For example, Waterval B has its highest WQI values during the dry season ranging between 102 to 304. Since Waterval A is located downstream of big mines, the water quality could be impacted by effluent discharge from the mines. The pollution concentration gets diluted during the rainy season, thereby lowering the WQI values.

Table 5.16: The summary of WQI values and ratings of the Waterval A monitoring point.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	180	Unfit	Jan	91	Very poor	Jan	75	Poor	Jan	180	Unfit	Jan	66	Poor
Feb	237	Unfit	Feb	101	Unfit	Feb	110	Unfit	Feb	128	Unfit	Feb	81	Very poor
Mar	176	Unfit	Mar	167	Unfit	Mar	74	Poor	Mar	435	Unfit	Mar	159	Unfit
Apr	323	Unfit	Apr	207	Unfit	Apr	181	Unfit	Apr	197	Unfit	Apr	321	Unfit
May	369	Unfit	May	247	Unfit	May	174	Unfit	May	171	Unfit	May	219	Unfit
Jun	315	Unfit	Jun	241	Unfit	Jun	175	Unfit	Jun	119	Unfit	Jun	233	Unfit
Jul	368	Unfit	Jul	235	Unfit	Jul	122	Unfit	Jul	196	Unfit	Jul	224	Unfit
Aug	229	Unfit	Aug	193	Unfit	Aug	156	Unfit	Aug	169	Unfit	Aug	211	Unfit
Sep	257	Unfit	Sep	129	Unfit	Sep	156	Unfit	Sep	128	Unfit	Sep	272	Unfit
Oct	376	Unfit	Oct	138	Unfit	Oct	152	Unfit	Oct	142	Unfit	Oct	202	Unfit
Nov	198	Unfit	Nov	368	Unfit	Nov	161	Unfit	Nov	114	Unfit	Nov	131	Unfit
Dec	73	Poor	Dec	224	Unfit	Dec	355	Unfit	Dec	94	Very poor	Dec	227	Unfit

2012			2013		2014	2015			2016					
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	147	Unfit	Jan	90	Very poor	Jan	57	Poor	Jan	370	Unfit	Jan	81	Very poor
Feb	464	Unfit	Feb	76	Very poor	Feb	97	Very poor	Feb	218	Unfit	Feb	199	Unfit
Mar	387	Unfit	Mar	126	Unfit	Mar	104	Unfit	Mar	137	Unfit	Mar	208	Unfit
Apr	268	Unfit	Apr	102	Unfit	Apr	57	Poor	Apr	40	Unfit	Apr	234	Unfit
May	139	Unfit	May	167	Unfit	May	251	Unfit	May	291	Unfit	May	195	Unfit
Jun	342	Unfit	Jun	61	Poor	Jun	228	Unfit	Jun	73	Poor	Jun	456	Unfit
Jul	445	Unfit	Jul	57	Poor	Jul	269	Unfit	Jul	443	Unfit	Jul	465	Unfit
Aug	292	Unfit	Aug	59	Poor	Aug	363	Unfit	Aug	400	Unfit	Aug	474	Unfit
Sep	238	Unfit	Sep	54	Poor	Sep	427	Unfit	Sep	441	Unfit	Sep	408	Unfit
Oct	194	Unfit	Oct	118	Unfit	Oct	224	Unfit	Oct	426	Unfit	Oct	66	Poor
Nov	259	Unfit	Nov	104	Unfit	Nov	300	Unfit	Nov	370	Unfit	Nov	60	Poor
Dec	206	Unfit	Dec	260	Unfit	Dec	83	Very poor	Dec	117	Unfit	Dec	91	Very poor

Table 5.17: The summary of WQI values and ratings of the Waterval B monitoring point.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	216	Unfit	Jan	102	Unfit	Jan	112	Unfit	Jan	224	Unfit	Jan	77	Very poor
Feb	104	Unfit	Feb	77	Very poor	Feb	89	Very poor	Feb	136	Unfit	Feb	87	Very poor
Mar	182	Unfit	Mar	75	Poor	Mar	98	Very poor	Mar	103	Unfit	Mar	117	Unfit
Apr	274	Unfit	Apr	81	Very poor	Apr	74	Poor	Apr	146	Unfit	Apr	115	Unfit
May	343	Unfit	May	96	Very poor	May	107	Unfit	May	257	Unfit	May	102	Unfit
Jun	207	Unfit	Jun	89	Very poor	Jun	98	Very poor	Jun	80	Very poor	Jun	82	Very poor
Jul	121	Unfit	Jul	81	Very poor	Jul	136	Unfit	Jul	80	Very poor	Jul	85	Very poor
Aug	165	Unfit	Aug	95	Very poor	Aug	82	Very poor	Aug	81	Very poor	Aug	84	Very poor
Sep	83	Very poor	Sep	111	Unfit	Sep	82	Very poor	Sep	80	Very poor	Sep	82	Very poor
Oct	81	Very poor	Oct	84	Very poor	Oct	81	Very poor	Oct	84	Very poor	Oct	83	Very poor
Nov	105	Unfit	Nov	300	Unfit	Nov	87	Very poor	Nov	81	Very poor	Nov	130	Unfit
Dec	114	Unfit	Dec	207	Unfit	Dec	162	Unfit	Dec	81	Very poor	Dec	144	Unfit

2012			2013			2014			2015			2016		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	238	Unfit	Jan	108	Unfit	Jan	108	Unfit	Jan	162	Unfit	Jan	70	Poor
Feb	143	Unfit	Feb	105	Unfit	Feb	105	Unfit	Feb	145	Unfit	Feb	164	Unfit
Mar	194	Unfit	Mar	85	Very poor	Mar	85	Very poor	Mar	94	Very poor	Mar	155	Unfit
Apr	93	Very poor	Apr	177	Unfit	Apr	177	Unfit	Apr	114	Unfit	Apr	212	Unfit
May	153	Unfit	May	203	Unfit	May	203	Unfit	May	119	Unfit	May	137	Unfit
Jun	80	Very poor	Jun	178	Unfit	Jun	178	Unfit	Jun	161	Unfit	Jun	163	Unfit
Jul	115	Unfit	Jul	146	Unfit	Jul	146	Unfit	Jul	131	Unfit	Jul	153	Unfit
Aug	215	Unfit	Aug	120	Unfit	Aug	120	Unfit	Aug	213	Unfit	Aug	180	Unfit
Sep	118	Unfit	Sep	115	Unfit	Sep	115	Unfit	Sep	130	Unfit	Sep	86	Very poor
Oct	197	Unfit	Oct	114	Unfit	Oct	114	Unfit	Oct	80	Very poor	Oct	84	Very poor
Nov	174	Unfit	Nov	156	Unfit	Nov	156	Unfit	Nov	81	Very poor	Nov	101	Unfit
Dec	243	Unfit	Dec	162	Unfit	Dec	158	Unfit	Dec	77	Very poor	Dec	103	Unfit

For Waterval B, statistical data analysis shows a moderate to strong correlation ranging from 0.65 to 0.99 between Mg, SO_4, Cl and Na (Table 5.18). The strong correlation between SO_4, Na and Cl and a negative correlation between SO_4 and EC further suggests that there might be pollution from agriculture. According to Sidle *et al.* (2000), sulphate-bearing fertilisers, atmospheric deposition, and bacterial oxidation are primary sulphate sources. Considering that there was an 18.42 % increase in agricultural land use between 2000 to 2016, fertilisers could have been the reason the water quality of this borehole and some of the rivers deteriorated over the years.

Table 5.18: Correlation matrix for EC, NO3, SO4, Mg, Cl and Na for the Waterval B. All values in bold are significant, with correlation coefficients above 0.70.

	EC	*NO_3*	*SO_4*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	-0.24448	1				
SO_4	-0.11566	-0.05762	1			
Mg	-0.11838	-0.05844	**0.999989**	1		
Cl	-0.11508	-0.05926	**0.999991**	**0.999993**	1	
Na	-0.11489	-0.05935	**0.999991**	**0.999993**	**0.999999**	1

The strong correlation between EC and Cl at Waterval A could also be due to increased agricultural land uses. The strong correlation suggests that most of the Cl concentrations were in solid form hence contributing to the EC of the river. Braune (1987) indicated that irrigation return flows could contribute to high EC levels rich in Cl from the TDS in rivers.

5.9 Wilge River

All the months and years were classified under the ‘unfit for consumption’ WQI class (Table 5.19). For the years that have a good variation of WQI values with months, for instance, 2003, the highest WQI values are in dry months while the wet season had the lowest. The statistical analysis showed that SO_4 and Mg have a strong positive correlation with a correlation coefficient of 0.89 (Figure 5.11). This suggests that the sources of pollution could be from wastewater which is one of the primary sources of SO_4 and Mg in water. This agrees with the suggestion made by Farrell *et al.* (2015) that the river receives significant reusable returns from its agriculture, and urban and rural users, which also add to the baseflow of the river system.

Table 5.19: The summary of WQI values and ratings of the Wilge River monitoring point.

2000			2001			2002			2003			2004		
Year	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**
Jan	197	Unfit	Jan	195	Unfit	Jan	194	Unfit	Jan	192	Unfit	Jan	193	Unfit
Feb	195	Unfit	Feb	194	Unfit	Feb	195	Unfit	Feb	192	Unfit	Feb	192	Unfit
Mar	196	Unfit	Mar	197	Unfit	Mar	198	Unfit	Mar	192	Unfit	Mar	184	Unfit
Apr	191	Unfit	Apr	196	Unfit	Apr	199	Unfit	Apr	196	Unfit	Apr	192	Unfit
May	197	Unfit	May	194	Unfit	May	199	Unfit	May	196	Unfit	May	195	Unfit
Jun	196	Unfit	Jun	197	Unfit	Jun	202	Unfit	Jun	202	Unfit	Jun	197	Unfit
Jul	197	Unfit	Jul	192	Unfit	Jul	200	Unfit	Jul	203	Unfit	Jul	208	Unfit
Aug	197	Unfit	Aug	189	Unfit	Aug	206	Unfit	Aug	196	Unfit	Aug	208	Unfit
Sep	196	Unfit	Sep	192	Unfit	Sep	207	Unfit	Sep	201	Unfit	Sep	211	Unfit
Oct	195	Unfit	Oct	190	Unfit	Oct	208	Unfit	Oct	201	Unfit	Oct	212	Unfit
Nov	191	Unfit	Nov	191	Unfit	Nov	194	Unfit	Nov	198	Unfit	Nov	216	Unfit
Dec	188	Unfit	Dec	193	Unfit	Dec	192	Unfit	Dec	204	Unfit	Dec	215	Unfit

2012			2013			2014			2015			2016		
Year	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**	**Year**	**WQI**	**RATING**
Jan	188	Unfit	Jan	191	Unfit	Jan	191	Unfit	Jan	196	Unfit	Jan	193	Unfit
Feb	195	Unfit	Feb	190	Unfit	Feb	191	Unfit	Feb	196	Unfit	Feb	194	Unfit
Mar	195	Unfit	Mar	187	Unfit	Mar	191	Unfit	Mar	196	Unfit	Mar	189	Unfit
Apr	197	Unfit	Apr	185	Unfit	Apr	196	Unfit	Apr	196	Unfit	Apr	191	Unfit
May	192	Unfit	May	192	Unfit	May	197	Unfit	May	195	Unfit	May	193	Unfit
Jun	186	Unfit	Jun	194	Unfit	Jun	195	Unfit	Jun	197	Unfit	Jun	189	Unfit
Jul	195	Unfit	Jul	190	Unfit	Jul	198	Unfit	Jul	195	Unfit	Jul	196	Unfit
Aug	195	Unfit	Aug	188	Unfit	Aug	197	Unfit	Aug	187	Unfit	Aug	197	Unfit
Sep	192	Unfit	Sep	194	Unfit	Sep	197	Unfit	Sep	193	Unfit	Sep	195	Unfit
Oct	189	Unfit	Oct	186	Unfit	Oct	200	Unfit	Oct	195	Unfit	Oct	195	Unfit
Nov	194	Unfit	Nov	192	Unfit	Nov	197	Unfit	Nov	197	Unfit	Nov	189	Unfit
Dec	198	Unfit	Dec	193	Unfit	Dec	195	Unfit	Dec	194	Unfit	Dec	193	Unfit

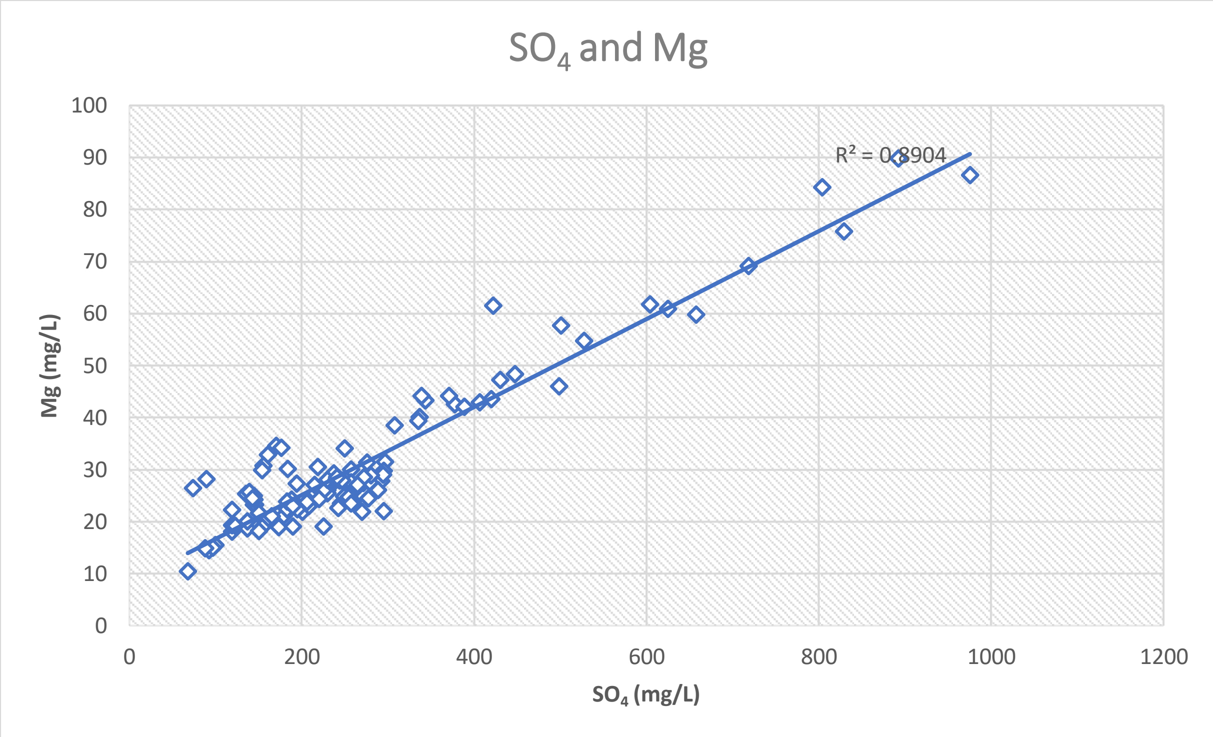

Figure 5.10: Scatter diagram for SO4 and Mg.

5.10 Mooi monitoring points

The downstream monitoring point Mooi B is mainly classified under 'unfit for consumption'. In contrast, the upstream monitoring point Mooi A alternates between 'very poor' in wet months and 'unfit for consumption' in dry months (Table 5.20 and 5.21). The WQI of the Mooi B show multiple peaks between Mar/Apr and Aug/Oct (Figure 5.11). This could be so because it has diverse pollution sources and hence receives pollutants at specific and different periods during the year. This could be true since the river is in a region that supports agriculture and irrigation as well as the mining of gold and coal (Cowling *et al.*, 1997; Low and Rebelo, 1998). In addition, according to Ansara-Ross *et al.* (2008), farmers along the river in the province use pesticides in Mar/Apr and Aug/Oct, which are the onset of the planting seasons. These pesticides could be contributing to the peaks of concentration in the Mooi River.

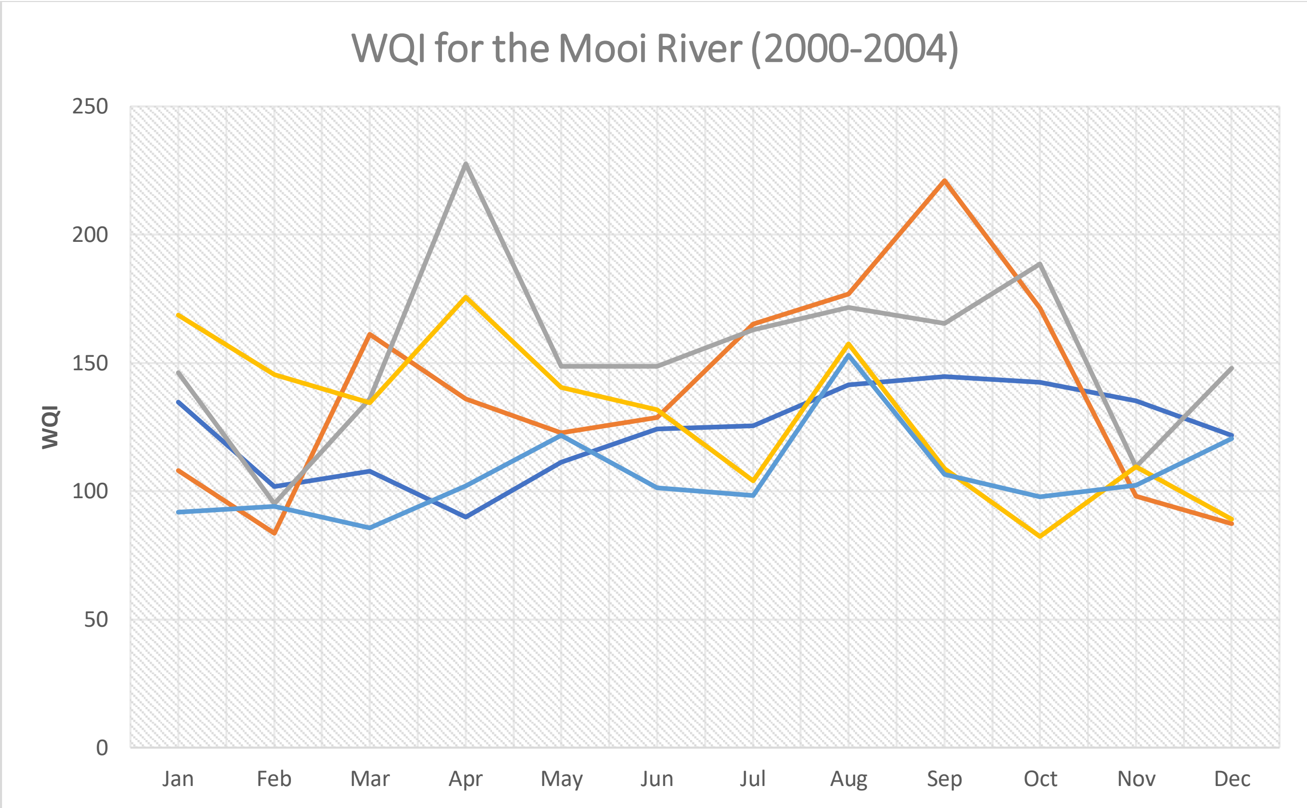

Figure 5.11: Line graph showing the multiple peaks of WQI with years for the Mooi River from 2000 to 2004.

Table 5.20: The summary of WQI values and ratings of the Mooi A monitoring point.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	88	Very poor	Jan	106	Unfit	Jan	96	Very poor	Jan	98	Very poor	Jan	87	Very poor
Feb	78	Very poor	Feb	99	Very poor	Feb	86	Very poor	Feb	102	Unfit	Feb	88	Very poor
Mar	72	Poor	Mar	88	Very poor	Mar	89	Very poor	Mar	105	Unfit	Mar	91	Very poor
Apr	83	Very poor	Apr	87	Very poor	Apr	94	Very poor	Apr	102	Unfit	Apr	92	Very poor
May	89	Very poor	May	90	Very poor	May	93	Very poor	May	111	Unfit	May	99	Very poor
Jun	92	Very poor	Jun	101	Unfit	Jun	94	Very poor	Jun	90	Very poor	Jun	99	Very poor
Jul	96	Very poor	Jul	100	Unfit	Jul	99	Very poor	Jul	88	Very poor	Jul	97	Very poor
Aug	97	Very poor	Aug	104	Unfit	Aug	101	Unfit	Aug	90	Very poor	Aug	100	Unfit
Sep	101	Unfit	Sep	104	Unfit	Sep	104	Unfit	Sep	85	Very poor	Sep	101	Unfit
Oct	97	Very poor	Oct	100	Unfit	Oct	104	Unfit	Oct	81	Very poor	Oct	90	Very poor
Nov	92	Very poor	Nov	92	Very poor	Nov	106	Unfit	Nov	79	Very poor	Nov	86	Very poor
Dec	88	Very poor	Dec	88	Very poor	Dec	96	Very poor	Dec	79	Very poor	Dec	89	Very poor

2012			2013			2014			2015			2016		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	82	Very poor	Jan	92	Very poor	Jan	88	Very poor	Jan	79	Very poor	Jan	96	Very poor
Feb	78	Very poor	Feb	93	Very poor	Feb	90	Very poor	Feb	79	Very poor	Feb	83	Very poor
Mar	121	Unfit	Mar	95	Very poor	Mar	94	Very poor	Mar	78	Very poor	Mar	80	Very poor
Apr	86	Very poor	Apr	93	Very poor	Apr	94	Very poor	Apr	78	Very poor	Apr	95	Very poor
May	93	Very poor	May	96	Very poor	May	89	Very poor	May	78	Very poor	May	95	Very poor
Jun	93	Very poor	Jun	95	Very poor	Jun	100	Unfit	Jun	78	Very poor	Jun	82	Very poor
Jul	102	Unfit	Jul	105	Unfit	Jul	88	Very poor	Jul	78	Very poor	Jul	80	Very poor
Aug	104	Unfit	Aug	110	Unfit	Aug	103	Unfit	Aug	78	Very poor	Aug	95	Very poor
Sep	104	Unfit	Sep	110	Unfit	Sep	96	Very poor	Sep	79	Very poor	Sep	95	Very poor
Oct	97	Very poor	Oct	104	Unfit	Oct	92	Very poor	Oct	79	Very poor	Oct	83	Very poor
Nov	91	Very poor	Nov	91	Very poor	Nov	95	Very poor	Nov	78	Very poor	Nov	80	Very poor
Dec	95	Very poor	Dec	97	Very poor	Dec	93	Very poor	Dec	79	Very poor	Dec	95	Very poor

Table 5.21: The summary of WQI values and ratings of the Mooi B monitoring point.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	135	Unfit	Jan	108	Unfit	Jan	146	Unfit	Jan	169	Unfit	Jan	92	Very poor
Feb	102	Unfit	Feb	84	Very poor	Feb	95	Very poor	Feb	145	Unfit	Feb	94	Very poor
Mar	108	Unfit	Mar	161	Unfit	Mar	136	Unfit	Mar	135	Unfit	Mar	86	Very poor
Apr	90	Very poor	Apr	136	Unfit	Apr	228	Unfit	Apr	176	Unfit	Apr	102	Unfit
May	111	Unfit	May	123	Unfit	May	149	Unfit	May	141	Unfit	May	122	Unfit
Jun	124	Unfit	Jun	129	Unfit	Jun	149	Unfit	Jun	132	Unfit	Jun	101	Unfit
Jul	126	Unfit	Jul	165	Unfit	Jul	163	Unfit	Jul	104	Unfit	Jul	98	Very poor
Aug	142	Unfit	Aug	177	Unfit	Aug	172	Unfit	Aug	157	Unfit	Aug	153	Unfit
Sep	145	Unfit	Sep	221	Unfit	Sep	165	Unfit	Sep	109	Unfit	Sep	106	Unfit
Oct	143	Unfit	Oct	171	Unfit	Oct	189	Unfit	Oct	82	Very poor	Oct	98	Very poor
Nov	135	Unfit	Nov	98	Very poor	Nov	109	Unfit	Nov	109	Unfit	Nov	102	Unfit
Dec	122	Unfit	Dec	87	Very poor	Dec	148	Unfit	Dec	89	Very poor	Dec	121	Unfit

2012			2013			2014			2015			2016		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Jan	96	Very poor	Jan	184	Unfit	Jan	207	Unfit	Jan	200	Unfit	Jan	90	Very poor
Feb	96	Very poor	Feb	106	Unfit	Feb	147	Unfit	Feb	98	Very poor	Feb	89	Very poor
Mar	105	Unfit	Mar	109	Unfit	Mar	108	Unfit	Mar	142	Unfit	Mar	86	Very poor
Apr	140	Unfit	Apr	120	Unfit	Apr	105	Unfit	Apr	125	Unfit	Apr	105	Unfit
May	115	Unfit	May	102	Unfit	May	99	Very poor	May	103	Unfit	May	110	Unfit
Jun	241	Unfit	Jun	90	Very poor	Jun	95	Very poor	Jun	110	Unfit	Jun	176	Unfit
Jul	99	Very poor	Jul	108	Unfit	Jul	103	Unfit	Jul	109	Unfit	Jul	144	Unfit
Aug	99	Very poor	Aug	94	Very poor	Aug	111	Unfit	Aug	119	Unfit	Aug	115	Unfit
Sep	113	Unfit	Sep	120	Unfit	Sep	97	Very poor	Sep	100	Very poor	Sep	127	Unfit
Oct	116	Unfit	Oct	110	Unfit	Oct	104	Unfit	Oct	92	Very poor	Oct	90	Very poor
Nov	120	Unfit	Nov	110	Unfit	Nov	114	Unfit	Nov	103	Unfit	Nov	120	Unfit
Dec	122	Unfit	Dec	105	Unfit	Dec	159	Unfit	Dec	94	Very poor	Dec	90	Very poor

The Mooi A river point has high NO_3, SO_4 and Mg concentrations. According to the statistical analysis results, EC significantly correlates with Mg, Na and Cl, with correlation coefficients of 0.78, 0.79 and 0.81, respectively. There is also a strong correlation between SO_4, Cl and Na (Table 5.22). The substantial concentrations of these inorganic and chemical parameters further suggest that the river is mainly polluted by anthropogenic sources especially farming and wastewater, which are the primary sources of SO_4 and NO_3. The river supports farming and growing informal and formal developments such as Rietvallei, Kagiso, and Mohlakeng. According to Attua *et al.* (2014), nitrate concentration in rivers is mainly influenced by urban expansion. In addition, Madlala *et al.* (2019) stated that high nitrate concentrations in river water indicate the influence of informal settlements and lack of wastewater treatment. At the same time, Bermudez-Couso *et al.* (2007) concluded that agriculture is one of the primary non-point sources of pollution for rivers.

Table 5.22: Correlation matrix for EC, NO3, SO4, Mg, Cl and Na for the Mooi A. All values in bold are significant, with correlation coefficients above 0.70.

	EC	*NO_3*	*SO_4*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	-0.16057	1				
SO_4	0.677693	-0.13785	1			
Mg	**0.782354**	-0.07029	0.541808	1		
Cl	**0.80771**	-0.25088	0.695184	0.579297	1	
Na	**0.789322**	-0.23433	0.621144	0.584815	**0.922321**	1

5.11 Borehole Vaal F (BH Vaal F)

Initially, the aquifer alternated between 'good' and 'excellent'; then, from 2012 to 2016, the aquifer was classified as 'good' (Table 5.23). The 'good' class varies from 26 to 46, while the 'excellent' class values range from 20 to 25. SO_4 and Cl have the most significant correlation, with a correlation coefficient of 0.71 (Table 5.24). At the same time, EC has moderately weak negative relationships with the rest of the parameters but contributed the most to the WQI along with Mg. Since the borehole is located next to farms, the Cl and SO_4 concentrations could be arising from the seepage of fertilisers and manure into the aquifer. However, the concentrations are relatively low due to the relatively deep-water table.

Table 5.23: The summary of WQI values and ratings of the BH Vaal F groundwater monitoring borehole.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Apr	37	Good	Apr	38	Good	Apr	36	Good	Apr	39	Good	Apr	39	Good
Oct	40	Good	Oct	36	Good	Oct	45	Good	Oct	40	Good	Oct	38	Good
2012			**2013**			**2014**			**2015**			**2016**		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Apr	52	Poor	Apr	57	Poor	Apr	–	–	Apr	59	Poor	Apr	67	Poor
Oct	62	Poor	Oct	54	Poor	Oct	63	Poor	Oct	61	Poor	Oct	44	Good

Key:

WQ Index	WQ Status
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very poor
>100	Unfit for consumption

Table 5.24: Correlation matrix for EC, NO3, SO4, Mg, Cl and Na for groundwater data from the BH Vaal F monitoring point. All values in bold are significant, with correlation coefficients above 0.70.

	EC	*NO_3*	*SO_4*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	0.246188	1				
SO_4	-0.34656	0.266816	1			
Mg	-0.07907	0.365564	0.609667	1		
Cl	-0.35317	0.4795	0.713178	0.581034	1	
Na	-0.24013	0.172915	0.607659	0.455317	0.428973	1

5.12 Borehole Wilge (BH Wilge)

The years considered in the assessment fall under the 'excellent' range, as shown in Table 5.25. However, it should be noted that the values are on the higher end of the class limits varying from 15 to 24, and there is no apparent seasonal influence on the WQI. The most significant parameters' correlation is between EC with Cl, Mg and Na, with a correlation coefficient of 0.71 between EC and Cl (Table 5.26). The low concentration values coupled with the 71 % correlation between Cl, Mg and EC for BH Wilge could indicate they were sourced from the aquifer lithology since the stratigraphy above the aquifer comprises sandstone, conglomerate and dolerite rocks. According to Singh *et al.* (2012), igneous and metamorphic rocks can produce magnesium from ferromagnesium minerals such as olivine and biotite. While the high EC and Cl correlation could have been sourced from the recharging water, rainfall, leached fertilisers and wastewater discharge that percolated from the surface into the aquifer. According to Abdalla (2009), the chloride concentrations increase with distance from the recharge area, which could be due to evaporation, prolonged rock/water interactions and lack of direct recharge.

Table 5.25: The summary of WQI values and ratings of the BH Wilge groundwater.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Apr	22	Good	Apr	19	Excellent	Apr	18	Excellent	Apr	15	Excellent	Apr	17	Excellent
Oct	22	Good	Oct	18	Excellent	Oct	17	Excellent	Oct	16	Excellent	Oct	16	Excellent
2012			**2013**			**2014**			**2015**			**2016**		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Apr	21	Excellent	Apr	18	Excellent	Apr	17	Excellent	Apr	15	Excellent	Apr	17	Excellent
Oct	24	Excellent	Oct	15	Excellent	Oct	18	Excellent	Oct	18	Excellent	Oct	15	Excellent

Key:

WQ Index	**WQ Status**
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very poor
>100	Unfit for consumption

Table 5.26: Correlation matrix for BH Wilge groundwater monitoring borehole.

	EC	*NO₃*	*SO₄*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	-0.19379	1				
SO_4	0.408324	0.019013	1			
Mg	0.638289	-0.10355	0.684369	1		
Cl	**0.712352**	-0.13752	0.402933	0.67151	1	
Na	0.580402	0.026401	0.391756	0.36501	0.488543	1

5.13 Borehole Waterval (BH Waterval)

The groundwater alternates between 'poor' and 'very poor' except for 2000, when the class was ‘good’ in April (Table 5.27). This was one of the few boreholes with ‘poor’ and ‘very poor’ ratings. However, this could be mainly because of the long-term groundwater pollution caused by contamination from the South African Synthetic Oil Limited (SASOL) Oil refinery plant located close to the borehole since the aquifer’s water level is generally shallow. Fly ash from the SASOL plant could be causing the leaching of metals such as sulphate, sodium, chloride and calcium. This also agrees with the results from the study done by Masindi and Abiye (2018), which found that both natural and anthropogenic activities influence groundwater variation in the UVRC.

Table 5.27:The summary of WQI values and ratings of the BH Waterval groundwater.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Apr	47	Good	Apr	70	Poor	Apr	76	Very poor	Apr	77	Very poor	Apr	92	Very poor
Oct	66	Poor	Oct	78	Very poor	Oct	77	Very poor	Oct	98	Very poor	Oct	81	Very poor
2012			2013			2014			2015			2016		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Apr	82	Very poor	Apr	83	Very poor	Apr	76	Very poor	Apr	76	Very poor	Apr	78	Very poor
Oct	83	Very poor	Oct	66	Poor	Oct	74	Poor	Oct	88	Very poor	Oct	71	Poor

Key:

WQ Index	**WQ Status**
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very poor
>100	Unfit for consumption

There is a strong positive correlation between EC and Na, as shown in Table 5.28. At the same time, Na and EC have negative correlations with all the other parameters. Mg strongly correlates with SO_4 and Cl with correlation coefficients of 0.77 and 0.73, respectively. This suggests the concentrations of these parameters could be from sewage and industrial wastes that are located less than 2 km from the borehole.

Table 5.28: Correlation matrix for the BH Waterval borehole.

	EC	*NO_3*	*SO_4*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	-0.29918	1				
SO_4	-0.19367	0.19209	1			
Mg	-0.38367	0.241429	0.770564	1		
Cl	-0.34776	0.172868	0.673826	0.737034	1	
Na	0.624542	-0.36712	-0.35582	-0.58637	-0.21704	1

5.14 Borehole Wonderfonteinspruit (BH Wonderfonteinspruit)

The groundwater quality alternates between ‘excellent’ and ‘good’ (Table 5.29). The wet WQI value for 2001 has an outlier of a ‘poor’ rating. There is a strong correlation between EC with SO_4, Cl and Na, while SO_4 also strongly correlates with Mg and Na (Table 5.30). Mg and Na could be sourced from the weathered and metamorphosed gneiss and granite rock units during the percolation of water in the aquifer. However, the SO_4, Na and Cl correlation and concentrations could have resulted from poorly treated sewage effluent seepage. Herlihy *et al.* (1998) stated that clear sources for Na and Cl in urbanised areas are related to human sewage. Since the borehole is located downstream of multiple urban centres, the concentrations could be from seepage of poorly treated wastewater, although in small amounts.

Table 5.29: The summary of WQI values and ratings of the BH Wonderfonteinspruit groundwater.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Apr	49	Good	Apr	47	Good	Apr	27	Good	Apr	23	Excellent	Apr	35	Good
Oct	27	Good	Oct	59	Poor	Oct	-	-	Oct	27	Good	Oct	-	-

2012			2013			2014			2015			2016		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Apr	28	Good	Apr	26	Good	Apr	23	Excellent	Apr	28	Good	Apr	32	Good
Oct	26	Good	Oct	23	Excellent	Oct	-	-	Oct	-	-	Oct	36	Good

Key:

WQ Index	**WQ Status**
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very poor
>100	Unfit for consumption

Table 5.30: Correlation matrix for the BH Wonderfonteinspruit.

	EC	*NO_3*	*SO_4*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	0.003396	1				
SO_4	0.714876	0.375855	1			
Mg	0.522744	0.539594	0.851718	1		
Cl	-0.03447	0.013397	-0.15575	-0.05191	1	
Na	0.731712	0.270872	0.829211	0.663485	0.133438	1

5.15 Borehole Suikerbosrant (BH Suikerbosrant)

The aquifer's water quality moderately alternates between 'good' and 'excellent' classes. The quality of the aquifer is mostly 'excellent'; however, there are four years out of nineteen where the quality was classified as 'good' (Table 5.31). The 'good' class ranges from 26 to 42 while the 'excellent' type varies from 13 to 23, all the values for both classes plot close to the upper limit of the class ranges. The status could be accurate considering that it has a deep-water level with slight seasonal variations, according to the annual averages calculated from 2001 to 2004.

Table 5.31:The summary of WQI values and ratings of the BH Suikerbosrant groundwater.

2000			2001			2002			2003			2004		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Apr	39	Good	Apr	12	Excellent	Apr	41	Good	Apr	35	Good	Apr	31	Good
Oct	22	Excellent	Oct	9	Excellent	Oct	17	Excellent	Oct	30	Good	Oct	33	Good
Dec	-	-	Dec	-	-	Dec	-	-	Dec	-	-	Dec	30	Good

2012			2013			2014			2015			2016		
Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING	Year	WQI	RATING
Apr	14	Excellent	Apr	-	-	Apr	20	Good	Apr	40	Good	Apr	19	Excellent
Oct	25	Good	Oct	28	Good	Oct	32	Good	Oct	27	Good	Oct	16	Excellent
Dec	-	-	Dec	-	-	Dec	-	-	Dec	-	-	Dec	-	-

Key:

WQ Index	**WQ Status**
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very poor
>100	Unfit for consumption

EC has a weak negative correlation with SO_4, Cl and Na, with correlation coefficients of 0.16, 0.03 and 0.01, respectively (Table 5.32). The poor correlation suggests that these anions have different sources, for example, natural sources, sewage and industrial pollution.

Table 5.32: Correlation matrix for the BH Suikerbosrant groundwater monitoring borehole.

	EC	*NO_3*	*SO_4*	*Mg*	*Cl*	*Na*
EC	1					
NO_3	0.21046	1				
SO_4	-0.16584	-0.27163	1			
Mg	0.049181	0.111667	0.250857	1		
Cl	-0.02763	0.088601	0.204821	0.486133	1	
Na	-0.00837	0.029405	0.520689	0.231289	-0.14361	1

CHAPTER 6 – CONCLUSION

In conclusion, the WQI was applied on average monthly values for the rivers and groundwater monitoring points of the UVRC. The WQI was calculated using Electrical Conductivity (EC), nitrate (NO_3), sulphate (SO_4), magnesium (Mg), chloride (Cl) and sodium (Na) average monthly concentrations.

This study, therefore, concludes that:

- There is a significant difference between surface water and groundwater WQI in the UVRC. The surface water WQI mostly averaged between ‘poor’ to ‘unfit for consumption’ while groundwater quality averaged between ‘excellent’ to ‘good’. Only BH Waterval from all the assessed boreholes had “poor” to “very poor” ratings.
- The WQI of surface water in the UVRC area is affected by changes in seasonality because of the dilution of parameters during the wet season. All the Vaal River monitoring points had higher WQI in dry months and lower values in wet months.
- Monitoring points found downstream of Vaal and other main tributaries like Mooi river experience a higher degree of quality deterioration than upstream monitoring points because of accumulation of load with distance and additional pollution load received from the tributaries along its course.
- There is a massive difference in land use cover from 2000 to 2016 due to a significant increase in agricultural, built-up and mining land uses in 2016 compared to 2000. This was coupled with a substantial decrease in vegetated and water land covers. This increase in the alteration of the natural land cover could be one of the significant contributors to the deterioration of surface water from 2000 to 2016.
- Most rivers had SO_4 and NO_3 concentrations that strongly correlated with Na, Cl and Mg, which could have been influenced by water inputs from farming, wastewater and industrial effluent discharged into the rivers. The increase in agriculture and mining could be one of the reasons why the surface water quality deteriorated over the years.
- The concentrations and correlations of parameters varied widely and greatly across the catchment, which was attributed to variation in land use across the UVRC.
- Most of the aquifers in the UVRC are disconnected from the rivers in the catchment and hence have water suitable for drinking.

- The WQI in the UVRC varies significantly in relation to changes in climatic and land use changes.

6.1 Limitations

The DWS only tracks and monitors rivers that have been affected by spills or floods. This results in gaps in water quality data for some of the years. Due to these limitations and time constraints, the author only compared the water quality from 2000-2004 with 2012-2016.

6.2 Recommendations

The author suggests that the DWA should be proactive since the catchment rivers supply the country's most economically active province (Gauteng). Furthermore, other rivers might be indirectly affected by the same spillages through processes such as seepage but are currently not being monitored until it is too late. Although most of the water from Vaal tributaries is no longer used for water treatment for drinking water by municipalities, many informal sectors and animals still use the water for domestic and drinking purposes. Based on the results found from this thesis, the author suggests that industries that discharge water into these rivers should be heavily fined to encourage them to adhere to recommended limits. For future studies, the author suggests that the WQI should be calculated from 1990 to 2022 to assess if there are any cyclic changes in WQI. Lastly, the monitored parameters should be consistent with years; that way, researchers can track any changes easily before they are critical.

CHAPTER 7 – REFERENCE

Abbasnia, A., Alimohammadi, M., Mahvi, A.H., Nabizadeh, R., Yousefi, M., Mohammadi, A.A., Pasalari, H. and Mirzabeigi, M., 2018. Assessment of groundwater quality and evaluation of scaling and corrosiveness potential of drinking water samples in villages of Chabahr city, Sistan and Baluchistan province in Iran. Data in brief, 16, pp.182-192.

Abdalla, O.A., 2009. Groundwater recharge/discharge in semi-arid regions interpreted from isotope and chloride concentrations in north White Nile Rift, Sudan. *Hydrogeology Journal*, *17*(3), pp.679-692.

Ahmad, A.B., 2014. Evaluation of Groundwater Quality Index for drinking purpose from some villages around Darbandikhan district, Kurdistan Region-Iraq. *IOSR Journal of agriculture and veterinary science*, *7*(9), pp.34-41.

Akoteyon, I.S., Omotayo, A.O., Soladoye, O. and Olaoye, H.O., 2011. Determination of water quality index and suitability of urban river for municipal water supply in Lagos-Nigeria. *European Journal of Scientific Research*, *54*(2), pp.263-271.

Alobaidy, A., Abid, H. and Maulood, B. (2010). Application of Water Quality Index for Assessment of Dokan Lake Ecosystem, Kurdistan Region, Iraq. Water Resource and Protection 2(9), 792-798.

Ansara-Ross T.M., Wepener V., Van den Brink P.J. and Ross M.J. 2008. Probabilistic risk assessment of the environmental impacts of pesticides in the Crocodile (West) Marico catchment, North West Province. Water SA. Vol. 34 No. 5: 637- 644.

Attua, E.M., Ayamga, J. and Pabi, O., 2014. Relating land use and land cover to surface water quality in the Densu River basin, Ghana. *International Journal of River Basin Management*, *12*(1), pp.57-68.

Ayeni, A.O., Balogun, I.I. and Soneye, A.S.O., 2011. Seasonal assessment of physico-chemical concentration of polluted urban river: a case of Ala River in Southwestern Nigeria.

Banda, T.D. and Kumarasamy, M.V., 2020. Development of Water Quality Indices (WQI): A Review. *Polish Journal of Environmental Studies*, *29*(3).

Barnard, H., 2000. An explanation of the 1: 50,000 general hydrogeological map. *DWAF, Pretoria*.

Bezuidenhout C.C. *et al.* 2013. A large-scale study of microbial and physico-chemical quality of ground and surface water in the North West Province, South Africa. WRC Pretoria, Research Report No. K5/1966.

Bhaduri, B., Minner, M., Tatalovich, S. and Harbor, J., 2001. Long-term hydrologic impact of urbanisation: a tale of two models. *Journal of Water Resources Planning and Management*, *127*(1), pp.13-19.

Bora, M. and Goswami, D. 2016. Water quality assessment in terms of water quality index (WQI): a case study of the Kolong River, Assam, India. Applied Water Science, 7(6): 3125-3135.

Bourblanc, M. and Blanchon, D., 2014. The challenges of rescaling South African water resources management: Catchment Management Agencies and interbasin transfers. *Journal of Hydrology*, *519*, pp.2381-2391.

Boyd, L. and Tompkins, R. 2011. A new mindset for integrated water quality management for South Africa. International Journal of Water Resources Development, 27(1): 203-218.

Braune, E. and Roger, K.H., 1987. *The Vaal River catchment: problems and research needs*. South African National Scientific Programmes Report No 143, South Africa. pp.3-21.

Brindha, K. and Kavitha, R., 2015. Hydrochemical assessment of surface water and groundwater quality along Uyyakondan channel, south India. Environmental Earth Sciences, 73(9), pp.5383-5393

Cowling, R.M., Richardson D.M. and Pierce S.M. 1997. Vegetation of South Africa. Cambridge: Cambridge University Press.

de Mello, K., Valente, R.A., Randhir, T.O., dos Santos, A.C.A. and Vettorazzi, C.A., 2018. Effects of land use and land cover on water quality of low-order streams in Southeastern Brazil: Watershed versus riparian zone. Catena, 167:130-138.

De Wet, L. and Sidu, S., 2013. Water quality and compliance monitoring of treated underground and surface water at the Grootvlei Proprietary Mines and the Blesbokspruit wetland, Springs, South Africa. *Proceedings of the International Mine Water Association*.

Department of Water Affairs (DWA). 2010. Resource Directed Measures for protection of water resources: Methods for the Determination of the Ecological Reserve for Estuaries. Water Resource Protection and Assessment Policy Implementation Process. Version 3. Pretoria.

Department of Water and Sanitation. (2015). ATC150821: Report of the Portfolio Committee on Water and Sanitation on an oversight visit to Gauteng Province 4-5 February 2015.

Department of Water Affairs and Forestry (DWAF). 2002. Directorate: Water Resources Planning Upper Vaal Water Management Area water resources situation assessment main report final. Report No. P RSA C000/00/2305/1, Pretoria.

Department of Water Affairs and Forestry (DWAF). 2004. Internal Strategic Perspective Upper Vaal Water Management Area. Report Number: P WMA 08/000/00/0304

Department of Water Affairs and Forestry (DWAF). 2009. Integrated Water Quality Management Plan For The Vaal River System: Task 2: Water Quality Status Assessment of the Vaal River System. Report No. P RSA C000/00/2305/1, Pretoria.

Department of Water Affairs, RSA. 1991. Water Resources Planning of the Olifants River Basin - Study of Development Potential and Management of the Water Resources.

Department of Water and Sanitation (DWS). 2016. Water Quality Management Policies and Strategies for South Africa. Report No. 2.1. Note on the WQM Policy Principles. Water Resource Planning Systems Series, DWS Report No.: 000/00/21715/12, Pretoria.

du Plessis, A., 2017. Primary water quality challenges for South Africa and the Upper Vaal WMA. In *Freshwater Challenges of South Africa and its Upper Vaal River* (pp. 99-118).

du Plessis, A., 2021. The necessity of making water smart for proactive informed decisive actions: A case study of the upper vaal catchment, South Africa. *Environmental Challenges*, *4*, p.100.

Du Plessis, A., Harmse, T. and Ahmed, F., 2014. Quantifying and predicting the water quality associated with land cover change: a case study of the Blesbok Spruit Catchment, South Africa. *Water*, *6*(10), pp.2946-2968.

DWA (2010a). National Groundwater Strategy, 2010. Department of Water Affairs, Republic of South Africa.

DWA (2010b). Resource Directed Management of Water Quality. Planning Level Review of Water Quality in South Africa. Sub-Series No. WQP 2.0. Directorate Water Resources Planning Systems: Water Quality Planning. Department of Water Affairs (DWA), Pretoria, South Africa.

DWA. 2005b. Groundwater Resource Assessment Phase II. Department of Water Affairs and Forestry. Pretoria.

DWAF (2003a) Department of Water Affairs and Forestry, South Africa, Report No. P WMA 08/000/00/0203. Upper Vaal Water Management Area: Overview of Water Resources Availability and Utilisation. Compiled by BKS (Pty) Ltd as part of the development of the National Water Resources Strategy, 2003.

DWAF (2003b) Department of Water Affairs and Forestry, South Africa, Report No. P WMA 09/000/00/0203. Middle Vaal Water Management Area: Overview of Water Resources Availability and Utilisation. Compiled by BKS (Pty) Ltd as part of the development of the National Water Resources Strategy, 2003.

DWAF (Department of Water Affairs and Forestry) (2003b) Report No. P WMA09/000/00/0203, Middle Vaal Water management area: overview of water resources availability and utilisation

DWAF. 2006. A guideline for the assessment, planning and management of groundwater resources within dolomitic areas in South Africa. Edition 1. IHP Project no. 14/14/5/. Department of Water Affairs and Forestry. Pretoria.

Dzwairo, B., Otieno, F.A.O., Ochieng, G.M., and Bezuidenhout J.J. (2012). Raw water quality weight factors: Vaal basin, South Africa. Water Science and Technology, *IWA.Edition. American Public Health Association*, American Water Works Association, Water.

Evander gold mines. 1995. Environmental Management Programme Report. Evander Gold Mines, Evander, 354pp.

Farrell, K., van Vuren, J.H.J. and Ferreira, M., 2015. Do aquatic macroinvertebrate communities respond to land use effects in the Wilge River, Mpumalanga, South Africa? *African Journal of Aquatic Science*, *40*(2), pp.165-173.

Gajendran, C. and Jesumi, A. (2013). Assessment of Water Quality Index in Cauvery River Basin: A Case Study on Tiruchchirappalli District, Tamil Nadu, India. Environmental Research and Technology 3 (2), 136-140.

Gorde, S.P. and Jadhav, M.V., 2013. Assessment of water quality parameters: a review. *J Eng Res Appl*, *3*(6), pp.2029-2035.

Gyedu-Ababio, T.K. and van Wyk, F., 2004: Effects of human activities on the Waterval River, Vaal River catchment, South Africa. African Journal of Aquatic Science, 29, 75-81. Holtzhausen, L., 2005: When water turns deadly – Investigating Nitrate in South Africa's.

Herlihy, A.T., Stoddard, J.L. and Johnson, C.B., 1998. The relationship between stream chemistry and watershed land cover data in the mid-Atlantic region, US. *Water, Air, and Soil Pollution*, *105*(1), pp.377-386.

Hobbs P, Colvin C, Maherry A, Bugan R, Clarke S, Petersen S, Rose C, Carstens M (2013). GROUNDWATER RESERVE DETERMINATION FOR THE UPPER VAAL WATER MANAGEMENT AREA (WRC Project No. KV 312/13).

Horton, R.K., 1965. An index number system for rating water quality. *J Water Pollut Control Fed*, *37*(3), pp.300-306.

Humbert, F., de Kock, M., Lenhardt, N. and Altermann, W., 2019. Neoarchaean to Early Palaeoproterozoic Within-Plate Volcanism of the Kaapvaal Craton: Comparing the Ventersdorp Supergroup and the Ongeluk and Hekpoort Formations (Transvaal Supergroup). In *The Archaean Geology of the Kaapvaal Craton, Southern Africa* (pp. 277-302). Springer, Cham.

Kang, J.H., Lee, S.W., Cho, K.H., Ki, S.J., Cha, S.M. and Kim, J.H., 2010. Linking land use type and stream water quality using spatial data of faecal indicator bacteria and heavy metals in the Yeongsan river basin. *Water Research*, *44*(14), pp.4143-4157.

Karikari, A.Y. and Ansa-Asare, O.D., 2006. Physico-chemical and microbial water quality assessment of Densu River of Ghana. *West African Journal of Applied Ecology*, *10*(1).

Lal, R., 1997. Deforestation effects on soil degradation and rehabilitation in western Nigeria. IV. Hydrology and water quality. *Land Degradation and Development*, *8*(2), pp.95-126.

Lkr, A., Singh, M.R. and Puro, N., 2020. Assessment of water quality status of Doyang river, Nagaland, India, using water quality index. *Applied water science*, *10*(1), pp.1-13.

Lourenco, M. and Curtis, C., 2021. The influence of a high-density sludge acid mine drainage (AMD) chemical treatment plant on water quality along the Blesbokspruit Wetland, South Africa. *Water SA*, *47*(1), pp.35-44.

Low A.B. and Rebelo A.B. 1998. Vegetation of South Africa, Lesotho and Swaziland. Department of Environmental Affairs and Tourism, Pretoria. 2nd ed.

Lubbe, N., 2013. Wetland Assessment of the Tweefontein Optimisation Project Amendment (TOPA). Available from sahris.sahra.org.za [Accessed on 12 March 2022].

Madlala, T., Kanyerere, T., Oberholster, P. and Xu, Y., 2019. Application of the multi-method approach to assess groundwater-surface water interactions for catchment management. *International Journal of Environmental Science and Technology*, *16*(5), pp.2215-2230.

Marara, T. and Palamuleni, L.G., 2019. An environmental risk assessment of the Klip river using water quality indices. *Physics and Chemistry of the Earth, Parts A/B/C*, *114*, p.102799.

Masindi, K. and Abiye, T., 2018. Assessment of natural and anthropogenic influences on regional groundwater chemistry in a highly industrialised and urbanised region: a case study of the Vaal River Basin, South Africa. *Environmental earth sciences*, *77*(20), pp.1-14.

Moore, J.M., Tsikos, H. and Polteau, S., 2001. Deconstructing the Transvaal Supergroup, South Africa: implications for Palaeoproterozoic palaeoclimate models. *Journal of African Earth Sciences*, *33*(3-4), pp.437-444.

Namugize, J.N., Jewitt, G. and Graham, M. 2018. Effects of land use and land cover changes on water quality in the uMngeni river catchment, South Africa. Physics and Chemistry of the Earth, 105(18):247-264

Nel, N., Parker, A. and Silbernagl, P. (2013). Improving water quality in stormwaterand river systems: an approach for determining resources. South African Institution of Civil Engineering, 55 (1) 22–35.

Nhamo, L., Ndlela, B., Nhemachena, C., Mabhaudhi, T., Mpandeli, S. and Matchaya, G., 2018. The water-energy-food nexus: Climate risks and opportunities in southern Africa. *Water*, *10*(5), p.567.

Oberholster, P.J., Botha, A.M. and Cloete, T.E. 2008. Biological and chemical evaluation of sewage water pollution in the Rietvlei nature reserve wetland area, South Africa. Environmental Pollution, 156(1): 184-192.

Odume, O.N., Griffin, N. and Mensah, P.K., 2018. Literature Review and Terms of Reference for Case Study for Linking the Setting of Water Quality License Conditions with Resource Quality Objectives and Site-Specific Conditions in the Vaal Barrage Area and Associated Rivers within the Lower Sections of the Upper Vaal River Catchment.

Olatunji, J.A., Odediran, O.A., Obaro, R.I. and Olasehinde, P.I., 2015. Assessment of groundwater quality of Ilorin metropolis using water quality index approach. *Nigerian journal of technological development*, *12*(1), pp.18-21.

Oni, O. and Fasakin, O., 2016. The use of water quality index method to determine the potability of surface water and groundwater in the vicinity of a municipal solid waste dumpsite in Nigeria. *American Journal of Engineering Research*, *5*(10), pp.96-101.

Patil, P.N., Sawant, D.V. and Deshmukh, R.N. 2012. Physico-chemical parameters for testing of water. A review. International Journal of Environmental Sciences, 3(3): 1194.

Puri, P.J., Yenkie, M.K.N., Sangal, S.P., Gandhare, N.V., Sarote, G.B. and Dhanorkar, D.B., 2011. Surface water (lakes) quality assessment in Nagpur city (India) based on water quality index (WQI). *Rasayan Journal of Chemistry*, *4*(1), pp.43-48.

Rademeyer, S., Coleman, T., Van Rooyen, P. and Wegelin, W., 2009. Vaal River system: large bulk water supply reconciliation strategy. *Civil Engineering= Siviele Ingenieurswese*, *2009*(v17i5), pp.9-13.

Rai, S.C. and Sharma, E., 1998. Comparative assessment of runoff characteristics under different land-use patterns within a Himalayan watershed. *Hydrological processes*, *12*(13-14), pp.2235-2248.

Remilekun, A.T., Thando, N., Nerhene, D. and Archer, E., 2021. Integrated assessment of the influence of climate change on current and future intra-annual water availability in the Vaal River catchment. *Journal of Water and Climate Change*, *12*(2), pp.533-551.

SABS (South African Bureau of Standards) (2015) South African National Standard 241-1:2015 Drinking water, Part 1: Microbiological, physical, aesthetic and chemical determinants. 241-2:2015 drinking water, Part 2: Application of SANS 241-1. SABS, Pretoria

Sarwar, S., Ahmmed, I., Mustari, S. and Shaibur, M.R., 2020. Use of Weighted Arithmetic Water Quality Index (WAWQI) to Determine the Suitability of Groundwater of Chaugachcha and Manirampur Upazila, Jashore, Bangladesh. Environ. *Biolog. Res*, *2*(2), pp.22-30.

Shaibur, M.R., Shamim, A.H.M. and Khan, M.H., 2019. Water quality of different sources at Buri Goalini and Gabura unions of Shyamnagar upazila, Bangladesh. *Environmental and Biological Research*, *1*(1), pp.32-43.

Shakya, L. and Tiwari, S. R. 2014. Impact of Land-uses Changes on Bagmati River. (In Proceedings of IOE Graduate Conference. P. 251.

Sidle, W.C., Roose, D.L. and Shanklin, D.R., 2000. *Isotopic Evidence for Naturally Occurring Sulfate Pollution of Ponds in the Kankakee River Basin, Illinois-Indiana* (Vol. 29, No. 5, pp. 1594-1603). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Singh, A.K., Mahato, M.K., Neogi, B., Tewary, B.K. and Sinha, A., 2012. Environmental geochemistry and quality assessment of mine water of Jharia coalfield, India. *Environmental Earth Sciences*, *65*(1), pp.49-65.

Smith, A.J., Beukes, N.J. and Gutzmer, J., 2013. The composition and depositional environments of Mesoarchean iron formations of the West Rand Group of the Witwatersrand Supergroup, South Africa. *Economic Geology*, *108*(1), pp.111-134.

South African Wetlands Conservation Programme (1998). Blesbokspruit. South Africa. Information sheet on the site designated to the List of Wetlands of International Importance in terms of the Convention of Wetlands.

Statistics South Africa. 2015. Mid-year population estimates, South Africa 2005. Statistical release P0302. Pretoria: Statistics South Africa.

Suthar, S., Sharma, J., Chabukdhara, M. and Nema, A.K. 2010. Water quality assessment of river Hindon at Ghaziabad, India: impact of industrial and urban wastewater. Environmental Monitoring and Assessment, 165(1-4): 103-112.

Suthar, S., Sharma, J., Chabukdhara, M. and Nema, A.K., 2010. Water quality assessment of river Hindon at Ghaziabad, India: impact of industrial and urban wastewater. *Environmental monitoring and assessment*, *165*(1), pp.103-112.

Tempelhoff, J., Jaka, H., Mahabir, S., Ginster, M., Kruger, A., Mthembu, N., and Nkomo, L. (2019). The Anthropocene and the hydrosphere: A case study of sanitation governance in Emfuleni Local Municipality (2018 - 19). Potchefstroom: North West University.

Tempelhoff, J., Munnik, V. and Viljoen, M., 2007. The Vaal River Barrage, South Africa's hardest working water way: an historical contemplation. *TD: The Journal for Transdisciplinary Research in Southern Africa*, *3*(1), pp.107-133.

Teshome, F.B., 2020. Seasonal water quality index and suitability of the water body to designated uses at the eastern catchment of Lake Hawassa. *Environmental Science and Pollution Research*, *27*(1), pp.279-290.

Todd, D.K. and Mays, L.W., 2004. *Groundwater hydrology*. John Wiley and Sons. pp.271-329.

Tooth, S., Brandt, D., Hancox, P.J. and McCarthy, T.S., 2004. Geological controls on alluvial river behaviour: a comparative study of three rivers on the South African Highveld. *Journal of African Earth Sciences, 38*(1), pp.79-97.

Tyagi, S. Sharma, B. Singh, P. and Dobhal, R. (2013). Water Quality Assessment in terms of Water Quality Index, Water Resources 1 (3), 34-38.

Van Heerden, D., van Rensburg, P.J., Nikinmaa, M. and Vosloo, A. 2006. Gill damage, metallothionein gene expression and metal accumulation in Tilapia sparrmanii from selected field sites at Rustenburg and Potchefstroom, South Africa. African Journal of Aquatic Science, 31(1): 89-98.

Van Wyk, F. (2001). An Integrated Manual for the Management, Control and Protection of the Vaal River Barrage Reservoir. Unpublished Masters mini-thesis. Rand Afrikaans University. Johannesburg.

Wanda, E. M. M., Mamba, B. B., and Msagati, T. A. M. 2016. Determination of the water quality index ratings of water in the Mpumalanga and North West provinces, South Africa. Physics and Chemistry of the Earth, 92: 70–78.

Water Resources of South Africa. 2016. Salinity Modelling of the Upper Vaal, Middle Vaal and Lower Vaal sub-Water Management Areas (new Vaal Water Management Area). Report No. TT 688/16, Pretoria.

Waterval Forum, 2005a: Waterval Catchment monitoring results: Jan 2004 – Oct 2005. Available from: http://www.reservoir.co.za. (Accessed 07 March 2022).

Waterval Forum, 2005b: Waterval Forum Catchment Maps. Available from: http://www.reservoir.co.za. (Accessed 07 March 2022).

Wates, Meiring and Barnard LTD. (1997). Secunda Collieries EMPR. Secunda Collieries, Secunda, South Africa, 306pp.

Wepener, V.V., Van Dyk, C., Bervoets, L., O'brien, G., Covaci, A. and Cloete, Y., 2011. An assessment of the influence of multiple stressors on the Vaal River, South Africa. *Physics and Chemistry of the Earth, Parts a/b/c*, *36*(14-15), pp.949-962.

Winde F. 2010b. Uranium pollution of the Wonderfonteinspruit, 1997-2008 Part 2: Uranium in water, concentrations, loads and associated risks. Water SA. Vol. 36 No. 3: 257-278.

World Economic Forum, 2020. The Global Risk Report 2020. World Economic Forum.

World Health Organisation (WHO). 2009. Calcium and magnesium in drinking-water: public health significance. World Health Organisation.

World Health Organisation (WHO). 2011. Guidelines for drinking-water quality. WHO Chronicle, 38(4), pp.436-466.

World Health Organisation 1984. Guidelines for Drinking-water Quality,

World Health Organisation, WHO. and World Health Organisation Staff, 2004. *Guidelines for drinking-water quality* (Vol. 1). World Health Organisation.

Yang, D., Zheng, L., Song, W., Chen, S. and Zhang, Y. 2012. Evaluation indexes and methods for water quality in ocean dumping areas. Procedia Environmental Sciences, 16: 112-117.

Yogendra, K. and Puttaiah, E.T., 2008. Determination of water quality index and suitability of an urban waterbody in Shimoga Town, Karnataka. In *Proceedings of Taal2007: The 12th world lake conference* (Vol. 342, p. 346).

Yoshioka, R.M., Kim, C.J., Tracy, A.M., Most, R. and Harvell, C.D., 2016. Linking sewage pollution and water quality to spatial patterns of Porites lobata growth anomalies in Puako, Hawaii. *Marine pollution bulletin*, *104*(1-2), pp.313-321.

CHAPTER 8 – APPENDIX

Appendix A: Location and details of WWTPs that discharge into the UVRC (DWA, 2010/2011).

Name of wastewater treatment works	Peak rated design flow capacity (Mℓ/day)	Treatment process description	Effluent disposal process
Ancor WCW	13.5	Biofilters and activated sludge	Discharge into the Blesbokspruit
Bickley WCW	3.59	Biofilters and activated sludge	Discharge into the Blesbokspruit
Blyvooruitzicht Gold Mines WCW	Unknown	Unknown	Discharge into the Wonderfonteinspruit
Carletonville (Oberholzer)	8	Biological filtration system (activated sludge and oxidation dam)	Discharge into the Wonderfonteinspruit
Daveyton WCW	16	Conventional	Discharge into the Blesbokspruit
Dekema	36	Biofilters and activated sludge	Discharge into the Natalspruit
Doornfontein Gold Mine WCW	Unknown	Unknown	Discharge into the Wonderfonteinspruit
Flip Human	50	Activated sludge systems	Discharge into the Wonderfonteinspruit
Hannes van Niekerk	26.5	Activated sludge systems and biofiltration systems	Discharge into the Wonderfonteinspruit
Harrismith STW (1)	3.9	Biofilters and activated sludge	Discharge into the Wilge River
Heidelberg WCW	8	Biofilters	Discharge into the Blesbokspruit
Khutsong	7.5	Activated sludge	Discharge into the Wonderfonteinspruit
Leeuwkuil	41	Activated sludge and biofiltration systems	Discharge into the Vaal River
Olifantsvlei (construction of an additional 50 Mℓ/d has begun. To be completed by 2015)	200, currently being upgraded	Activated sludge	Discharge into the Klip River
Standerton STW	Unknown	None	Discharge into the Vaal River
Standerton (Sakhile)	Unknown	None	Discharge into the Vaal River
Vlakplaats	83	Activated sludge	Discharge into the Natalspruit
Waterval	105	Activated sludge	Discharge into the Klip River
Wedela	2	Activated sludge	Discharge into the Loopspruit
Welgedacht	77 increasing to 177 in the near future	Unknown	Discharge into the Blesbokspruit
Welverdiend	1	Activated sludge	Discharge into the Wonderfonteinspruit
Rietspruit WCW (in Vanderbijlpark for Emfuleni Municipality)	36	Activated sludge and biofiltration systems	Discharge into the Rietspruit