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Assessment of the impacts of agricultural activities on surface water and groundwater quality: a case study in the Brits area, North-West Province, South Africa



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Research Report submitted for the partial *Fulfilment* of the degree *Master of Science in Hydrogeology* at the University of the Witwatersrand, Johannesburg.

Date: 05 June 2025

CANDIDATE DECLARATION

This is a declaration that this research report is solely my work. It is being submitted for the Degree of Master of Science at the University of Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any University.



…….

(Signature of Candidate)

February 2025

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ABSTRACT

The growing demand for food, driven by population growth, has resulted in the intensification of agricultural practices. To meet the demands, farmers have increased their use of pesticides and fertilisers to enhance food production. This has adverse effects on ecosystems, particularly aquatic ecosystems. In recent years, the impact of agricultural activities on water quality has received limited attention, particularly in South Africa. This study aims to investigate the effects of agricultural activities such as irrigation, pesticide application, and fertiliser use on groundwater and surface water quality in the Brits area of the North West Province. Twenty samples were collected, comprising thirteen groundwater samples, five samples along the Crocodile River and two samples from Hartbeespoort Dam and Roodekoptjes Dam. Prescribed sampling procedures were followed, and pH, temperature, and electrical conductivity were recorded on-site.

Samples were analysed for Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, PO_4^{3-}, CO_3^{2-} and HCO_3^{-} concentrations. These concentrations were used to evaluate irrigation suitability using methods such as SAR, %Na, Pl, MAR, and RSC. Chlorophyll-a was also measured in water samples. Most parameter concentrations fell within the permissible drinking water limits defined by the World Health Organisation and South African Water Quality Standards. Chlorophyll-a levels were significantly lower in groundwater but elevated in surface water samples, Roodekoptjes Dam recording the highest concentration of 25 µg/L, indicating the influence of agricultural runoff. The pesticide residues were below the detection limit in all the samples. The study found that, in addition to agricultural contributions to nutrient enrichment, wastewater and sewage spillages play a significant role. The presence of nutrients, pesticides, and chlorophyll-a in water indicates agriculture-related contamination, which poses risks to aquatic ecosystems and public health and necessitates appropriate remedial measures.

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ABBREVIATIONS

SAWQS - South African Water Quality Standards

DWS – Department of Water and Sanitation

DWA – Department of Water Affairs

OECD – Organisation for Economic Co-Operation and Development

WHO – World Health Organisation

EPL – Environmental Pollution Laboratory

EPA MCL – Environmental Protection Agency Maximum Contaminant Level

EC – Electrical conductivity

GPS – Global Positioning System

ICP-OES – Inductively Coupled Plasma Optical Emission Spectrometry

HCH – Hexachlorocyclohexane

DDT – Dichlorodiphenyltrichloroethane

DDE – Dichlorodiphenyldichloroethylene

mg/L – milligrams per litre

meq/L = milliequivalent per litre

µg/L – micrograms per litre

µS/cm – microSiemens per centimetre

1.0 INTRODUCTION

1.1 Background

Water covers approximately 71% of the Earth's surface, however, only about 0.3% of this water is freshwater. Groundwater represents the largest accessible freshwater resource and is extensively utilised across various sectors, including agriculture and industry. It is particularly vital in arid and semi-arid regions, characterised by low precipitation, limited availability of surface water, and high evapotranspiration rates (Wang et al., 2023). Moreover, concerns about available freshwater quality persist, as both groundwater and surface water must possess acceptable mineral content to be suitable for domestic and agricultural use. The increasing food supply has enhanced crop production and livestock farming to support the ever-growing population, and more land has been cleared to support agriculture. Agricultural production relies heavily on irrigation from surface and groundwater sources. However, water scarcity is becoming increasingly prevalent due to the growing unpredictability of precipitation, influenced by climate change (Khatri and Tyagi, 2015).

Apart from climatic factors, anthropogenic interventions such as population growth, land use changes, water exploitation, and pollution have adversely affected both the availability and quality of groundwater and surface water. Agriculture plays a significant role in economic growth and poverty alleviation in most developing countries, including South Africa. Many countries have increased investment in the agricultural sector to improve livelihoods through job creation, food security, nutritional balance, and sustainable environmental management (Maponya et al., 2014; Gunawardhana et al., 2016). According to Khatri and Tyagi (2015), irrigation is important for high agricultural yield and quality, specifically in arid and semi-arid regions. The development of irrigated agriculture is essential for supporting population growth, particularly in arid regions. However, it alters natural hydrological cycles and contributes to aquifer contamination through chemical inputs, which can lead to water mixing, evaporation, and hydrochemical reactions (Wang et al., 2023). Globally, more than 20% of irrigated areas are experiencing groundwater quality deterioration, return flows from irrigation are insufficient to mitigate the negative impacts of over-extraction. Improper irrigation practices can lead to water quality degradation and declining groundwater levels, resulting in significant economic losses for agriculture and other groundwater-dependent industries. In terms of water quality, salinisation, nutrient loading, and pesticide

contamination are among the primary agricultural concerns. Over-irrigation can lead to the transport of soil, nutrients, pesticides, and heavy metals into deeper groundwater zones.

Excessive irrigation of crops contributes to soil salinisation and desertification. According to Pulido-Bosch et al. (2018), approximately 30% of globally withdrawn irrigation water returns to local hydrological systems via recharge to groundwater and discharge to rivers. Continuous groundwater abstraction to meet agricultural irrigation demands has led to overexploitation of the resource and subsequent degradation of water quality (Tweed et al., 2018).

Pesticides and fertilisers are widely used to improve food production, protect crops, and maintain harvest quality. Pesticides, in particular, contribute significantly to yield increases by controlling pests and diseases that severely impact crops (Khatri and Tyagi, 2015). The intensive use of fertilisers containing nitrates, phosphorus, and potassium has led to agricultural run-off, resulting in groundwater pollution through leaching into the subsurface. These nutrients may also be transported to surface water bodies via run-off, often in concentrations high enough to cause eutrophication. Phosphorus is known to be a limiting nutrient for algal growth in freshwater.

Various agricultural residues are dispersed into ecosystems via drainage, run-off, or drift, and can be detected in both groundwater and surface water, indicating that such residues may be transported far from their original application site (Hildebrandt et al., 2008). Excessive nutrient loading into water bodies degrades water quality for various uses. Additionally, topography, soil type, farming practices, and crop type influence the movement and the dispersal of nutrients and pesticides (Khatri and Tyagi, 2015). Natural processes such as rock weathering, wind deposition, and soil drainage can also alter water quality by affecting pH, increasing alkalinity, contributing to phosphorus loading, and elevating sulphate concentrations. However, anthropogenic activities typically result in significantly higher concentrations of nutrient loads (Khatri and Tyagi, 2015).

Hundreds of different pesticides are used in agriculture, and they are classified according to importance, with organochlorine and organophosphorus compounds regarded as the most important and common ones. Organochlorine pesticides are resistant to biodegradation, and they are found in concentrated food chains and produce a remarkable increase in concentration at the end of the chain (Sankararamakrishnan et al., 2005). The use of pesticides has been banned in developed countries since they have a huge health risk; however, in developing countries, organochlorine pesticides are still being used because they are inexpensive to produce and highly

effective. In contrast, organophosphorus pesticides degrade rapidly in the environment, although their degradation rate depends on factors such as the application method and environmental conditions (Sankararamakrishnan et al., 2005).

In most rural communities, water is sourced from boreholes, rivers, dug wells, and springs, and is often consumed without being tested for its suitability for drinking (Aneck-Hahn et al., 2012). Consumption of untested and untreated water results in potential health problems (Mukonazwothe et al., 2022). Poor groundwater quality due to salinity can also result in slow crop growth, which causes poor crop production. Nitrate contamination is most common in groundwater sources, and it can be caused by agriculture due to the application of fertilisers to increase crop production. Other sources, such as wastewater, also contribute to an increase in nitrate contamination (Malki et al., 2017a; Arrey et al., 2019). Most rural communities practice livestock farming, and these practices result in nitrate contamination through harvest waste and manure that are drained from the fields. Other emerging agricultural pollutants are from veterinary medicines such as vaccines, antibiotics, and hormones that support growth, which pollute water sources through movement from farms to ecosystems and drinking water sources (Malki et al., 2017).

Agriculture is, therefore, regarded as hugely contributing to diffuse contamination of water resources (Conrad and Colvin, 2018). Transportation of contaminants in groundwater is often associated with hydrological variability in soil zones and rock formations that make up the vadose zone. These contaminants frequently reach groundwater systems, where their impacts are moderated by natural attenuation processes within the vadose zone (Arrey et al., 2019).

Many communities and farmers lack knowledge of the implications of agricultural activities on the quality and quantity of groundwater and surface water sources (Tweed et al., 2018). Physicochemical and biological parameters are used to assess water quality against a set of limits or standards that determine the suitability for consumption or its safety for the environment (Khatri and Tyagi, 2015). Water quality can be analysed by periodically collecting samples from monitoring stations, with the resulting data indicating changes in surface water and groundwater quality. Hydrochemical constituents should fall within the prescribed limits set by the South African Water Quality Standards (SAWQS) and the World Health Organisation (WHO), as this is important for determining the suitability of water for domestic use and irrigation purposes (Mukonazwothe et al., 2022).

1.2 Aims and Objectives

1.2.1 Aims

- To evaluate and assess the impacts of agricultural activities on surface water and groundwater quality with a case study in the Brits area, Northwest Province, South Africa.

1.2.2 Objectives

- To test for physical and chemical parameters from identified boreholes
- Compare the spatial water quality from the upstream dam (Hartbeespoort Dam), along the Crocodile River and Roodekoptjes Dam (downstream)
- To determine the severity and distribution of fertilisers in groundwater
- Assess the eutrophication of the Crocodile River that receives water from the eutrophied Hartbeespoort Dam and establish the extent of blue-green algae through the analysis of nitrate, phosphate, and chlorophyll-A concentration
- Conduct a critical analysis of the spatial variation in the Crocodile River discharge from upstream and downstream points to understand the level of agricultural runoff
- To validate the impacts that agricultural activities such as the use of fertilisers, irrigation, use of pesticides, mining effluents and municipal wastewater have on contaminating groundwater sources
- Implications for groundwater quality and management of groundwater resources in this area.

1.3 Rationale

Increased agricultural practices, including irrigation and the use of fertilisers and pesticides, have implications for water quality in sources such as groundwater and surface water. Agriculture is a significant contributor to the deterioration of water quality, primarily through the excessive use of fertilisers, which leads to nutrient runoff (notably nitrates and phosphates) that can leach into groundwater or run off into surface water bodies. This contributes to problems such as eutrophication and contamination of drinking water supplies. Excessive use of pesticides in agriculture can result in environmental persistence, leaching into groundwater, and runoff into surface water sources, potentially posing health risks to humans and animals. Over-irrigation can

also lead to groundwater depletion, degradation of water quality, and reduced suitability for drinking and agricultural use.

This study area was selected as it is a major agricultural region where irrigation is practised for cultivating crops such as maize, wheat and citrus. In addition to irrigation, the intensive use of fertilisers and pesticides makes this region suitable for investigating the impacts of agriculture on water resources. The study area lies between the Hartbeespoort Dam, which is upstream and Roodekoptjes Dam, located downstream, and it is also situated around the Crocodile River, which makes it ideal for studying interactions between agricultural runoff and water quality. This research also considers other sources of contamination that may contribute to water deterioration, including mining, wastewater discharges and sewage spillage in the Brits area. Understanding these impacts supports the development of strategies to mitigate water contamination, safeguard public health, and preserve ecosystem services. Furthermore, as agricultural intensification aims to meet the demands of population growth, it is essential to balance productivity with environmental protection by promoting practices that minimise water contamination. This research can inform policymakers, farmers, and other stakeholders by guiding the implementation of sustainable agricultural practices and water quality regulations and by highlighting the consequences of inadequate maintenance of sewer pump stations by local municipalities.

1.4 Limitations of the study

- The study faced challenges from having access to most boreholes that had been preselected before the site visit, which became a problem during water sample collection.
- In most sampling sites, pictures/photographs were not allowed to be taken
- Monitoring and analysing groundwater and surface water was done within one season. Monitoring over multiple seasons is important in identifying temporal changes in groundwater and surface water.
- Most farmers were reluctant to respond to certain questions concerning the use of fertilisers and pesticides.

2.0 LITERATURE REVIEW

Agricultural activities such as irrigation and the application of fertilisers and pesticides have a significant impact on water sources, including both groundwater and surface water. In South Africa, several case studies have been conducted to examine these effects and the extent of water contamination. Groundwater quality monitoring at Loerie Flats and subsurface irrigation return flow to the upper Gamtoos estuary was conducted over a two-year period. The study focused primarily on nutrient loading and estuarine health (Pearce and Schumann, 2001). Analysis of the results revealed high concentrations of nitrate up to 163 mg/L and phosphorus in groundwater, with the peaks corresponding to the timing of fertiliser applications. Each year, groundwater discharge into the estuary contributes a load of 0.52 tons of nitrate-N, 0.02 tons of nitrite-N, and 0.10 tons of total phosphorus. These nutrients originate from less than 20% of the agricultural area located near the estuary, indicating concentrated effects from specific zones. Nutrient concentrations in groundwater varied in response to agricultural practices, rainfall, and irrigation patterns. Seasonal fluctuations in the water table influenced both flow dynamics and nutrient transport.

In the Middle Olifants Catchment, which is the second largest irrigation scheme in South Africa, an assessment was conducted to determine the interactions between irrigated agriculture and surface water, focusing primarily on phosphate and nitrate concentrations, which are associated with eutrophication (Mudaly, 2020). Phosphate-phosphorus (PO_4-P) concentrations in this catchment exceeded the eutrophication threshold of 0.025 mg/L during the summer rainfall period, indicating a direct link between PO_4-P levels, agricultural activities, and nutrient enrichment in water. Wastewater treatment works were also found to be a major contributor to the phosphate-phosphorus levels in water, surpassing contributions from agricultural sources. Nitrate concentrations remained below the eutrophication threshold; however, spatial variability was observed, with concentrations increasing downstream. Water quality in rivers and reservoirs deteriorated downstream as a result of agricultural activities and wastewater discharge.

Irrigation influences groundwater levels, salinity, and flow at the Vaalharts Irrigation Scheme, one of the oldest and largest irrigation projects in South Africa. Irrigation has led to significant salinisation and waterlogging in the area. Total dissolved solids (TDS) in groundwater have increased over time, with an annual mean increase of 19.25 mg/L (Pearce and Schumann, 2001).

Irrigation contributed significantly to the groundwater system, increasing salt loads and altering flow paths towards the Harts River. Elevated salinity levels in both soil and water pose a threat to crop productivity.

A similar study was conducted to evaluate the impacts of irrigation and agricultural activities on water quality in the Crocodile (West) and Marico catchments in South Africa, where crop production is practised (Du Preez et al., 2018). The evaluation spanned ten years and revealed nutrient contamination, with high levels of inorganic nitrogen and orthophosphate (phosphorus) observed in the Hartbeespoort and Crocodile (West) irrigation schemes, exceeding water quality guidelines. Nutrient loading resulting from agricultural runoff led to eutrophication and contributed to harmful algal blooms. High salt concentrations of salt and elevated electrical conductivity were also recorded in the Crocodile (West) Irrigation Scheme. Elevated salinity levels affect soil quality, reduce crop yields, and adversely impact irrigation infrastructure.

Temporal and spatial variations were observed during high-flow periods, nutrient concentrations were diluted, whereas, in low-flow periods, nutrient and salt accumulation occurred in water sources. Hartbeespoort Dam, a major water source for irrigation, exhibited hypertrophic conditions associated with nutrient loading, which intensified downstream in the Crocodile (West) River system (Du Preez et al., 2018). In addition to agricultural runoff, mining activities and untreated sewage also contributed to the degradation of water quality.

A study was conducted on irrigation water quality in the Philippi farming area of the Cape Flats, Cape Town, South Africa. Groundwater is the main source of irrigation, and this water was drawn from the Cape Flats aquifer and stored in ponds before being used for irrigation. Analysis of water samples for salinity and other major and minor ions revealed concentrations of chloride, nitrate, potassium and sodium in both groundwater and pond water exceeded the recommended guidelines of the South African Department of Water Affairs and Forestry (DWAF) and the Food and Agriculture Organisation (FAO). Elevated nitrate concentrations in pond water indicated contamination from agricultural fertilisers, which leach into water sources through irrigation return flow. The practice of pumping groundwater for irrigation, storing it in ponds, and reusing it has led to increased evaporation and salt accumulation. The geological formation of the area has also contributed to the accumulation of salts, as the aquifer naturally contains salt, and rock-water interactions and dissolution of minerals have led to water contamination. Ultimately, groundwater

and pond water from the study area were considered moderately suitable for irrigation but require the implementation of improved irrigation techniques and improved drainage to reduce salt accumulation.

Due to the extensive use of pesticides in agriculture, their residues are frequently detected in water quality studies conducted in agricultural areasto determine seventeen organochlorine pesticide concentrations at six sampling points along the Buffalo River in the Eastern Cape Province of South Africa, over two seasonal periods. The aim was to assess the ecological health of the water body and the risk posed to the aquatic system by these contaminants (Yahaya et al., 2017). Organochlorine pesticide concentrations ranged from 313 ng/l in autumn to 4 403 ng/l in summer. These concentrations exceeded the United States Environmental Protection Agency (USEPA) limit of 100 ng/l, indicating significant contamination.

Residual organochlorine pesticides such as aldrin, heptachlor epoxide, DDE, and DDT were commonly detected. Seasonal variations showed higher concentrations in summer, attributed to increased rainfall and runoff, compared to lower levels observed in autumn. Similar results were observed in a case study conducted in the Swartkops and Sundays River estuaries in South Africa, where organochlorine pesticide concentrations varied seasonally and spatially values ranging from 16.7 to 259 ng/l across different seasons and sites (Olisah et al., 2019). Higher concentrations of organochlorine pesticides were associated with periods of increased rainfall, which enhanced runoff and soil leaching. The most detected organochlorine pesticides were α-HCH, β-HCH, p,p'-DDE, p,p'-DDT, aldrin, dieldrin, and endrin, primarily introduced into the estuaries through agricultural runoff. In some locations, concentrations exceeded permissible limits, posing a significant risk to aquatic ecosystems. Continuous contamination reflects the persistence and slow degradation of these compounds in the environment. Table 1 summarises the main impacts of agricultural activities for each site.

Table 1: Main impacts of agricultural activities for each site

Site	Main impacts of agricultural activities
Loerie Flats	High concentration of nitrate and phosphorus in groundwater
Middle Olifants Catchment	Nutrient enrichment
Vaalharts Irrigation Scheme	High levels of salinity
Crocodile West and Marico Catchments	Nutrient loading High levels of salinity
Hartbeespoort Dam	Nutrient loading
Philippi (Cape Flats)	High nitrate concentration, increased evaporation and salt accumulation
Buffalo River (Eastern Cape)	Organochlorine pesticide concentration detected
Swartkops and Sunday River	Organochlorine pesticide concentration detected

3.0 STUDY AREA

3.1 Location

The study area is situated between the Hartbeespoort Dam (upstream) and Roodekoptjes Dam (downstream), with the Brits town at the centre. The Brits area's land-use cover is characterised by agricultural land, natural vegetation, and human settlements (Figure 1). The study area forms part of the A21J quaternary catchment. This quaternary catchment covers an area of 1 151 km^2, where irrigation schemes are practised. Hartbeespoort Dam serves as the main source for irrigation, and excess irrigation water drains back into the Crocodile River, eventually flowing into the Roodekoptjes Dam (Du Preez et al., 2018). The quaternary catchment is also known for the extraction of economic minerals such as vanadium, platinum and ferrochrome and rock (norite).

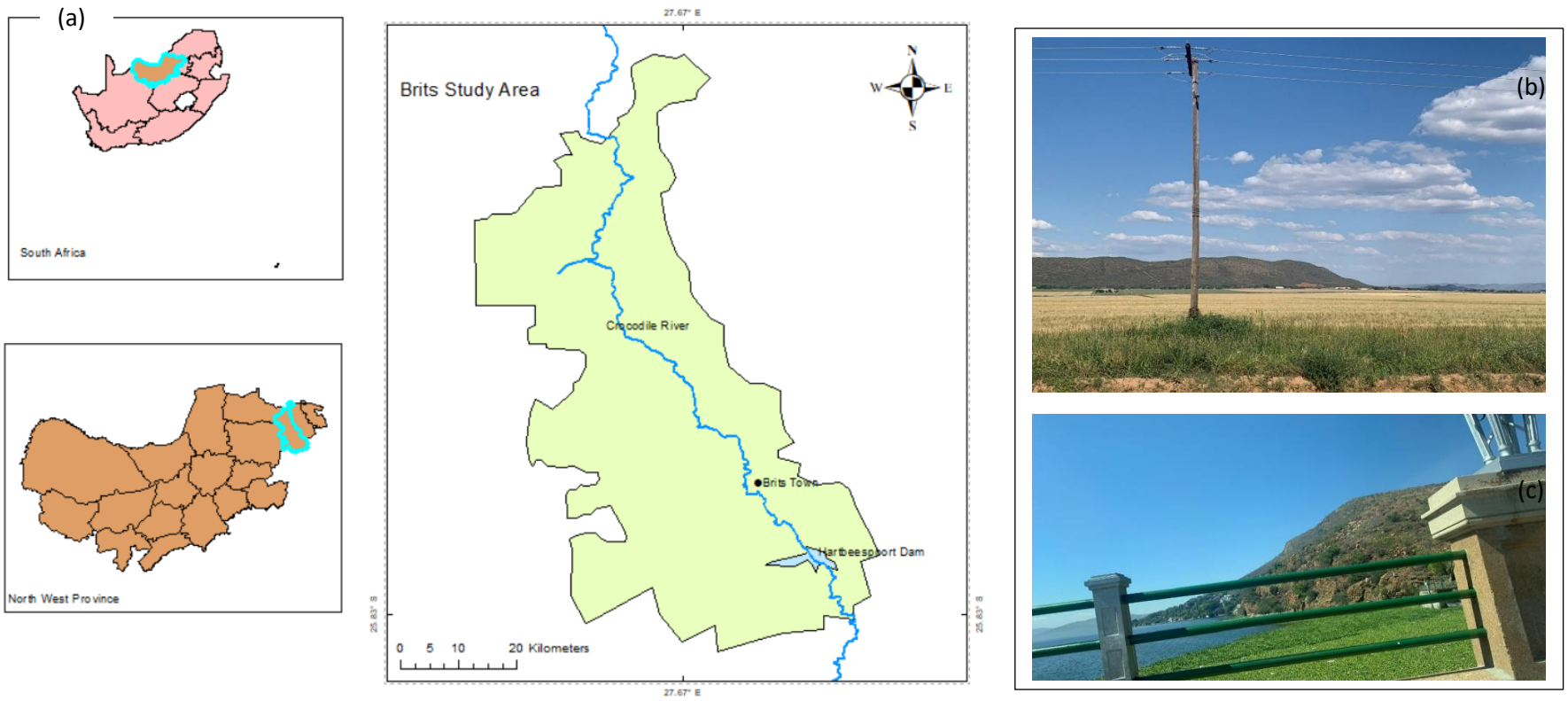

Figure 1: In (a) Map showing the study area around Brits, North West in South Africa; (b) photo showing the agricultural land use; (c) photo showing the eutrophied Hartbeespoort Dam

3.2 Climatic Setting

The Brits area is located between 1000 and 1500 m above sea level and is characterised by a dry subtropical highland climate, which is influenced by altitude. Annual temperatures in Brits range from 0 to 35 ℃ (Figure 2). Summers (October to March) are hot and humid, with high levels of precipitation, particularly in December and January. The annual rainfall ranges between 500 to 700 mm (Cochet et al., 2015). The winter season, from May to July, is cold and dry, with minimal rainfall averaging as little as 2-5 mm per month (Cochet et al.,2015). In Brits, most rainfall occurs during the hot summer seasons, contributing significantly to groundwater recharge; however, some of it is lost due to high evaporation.

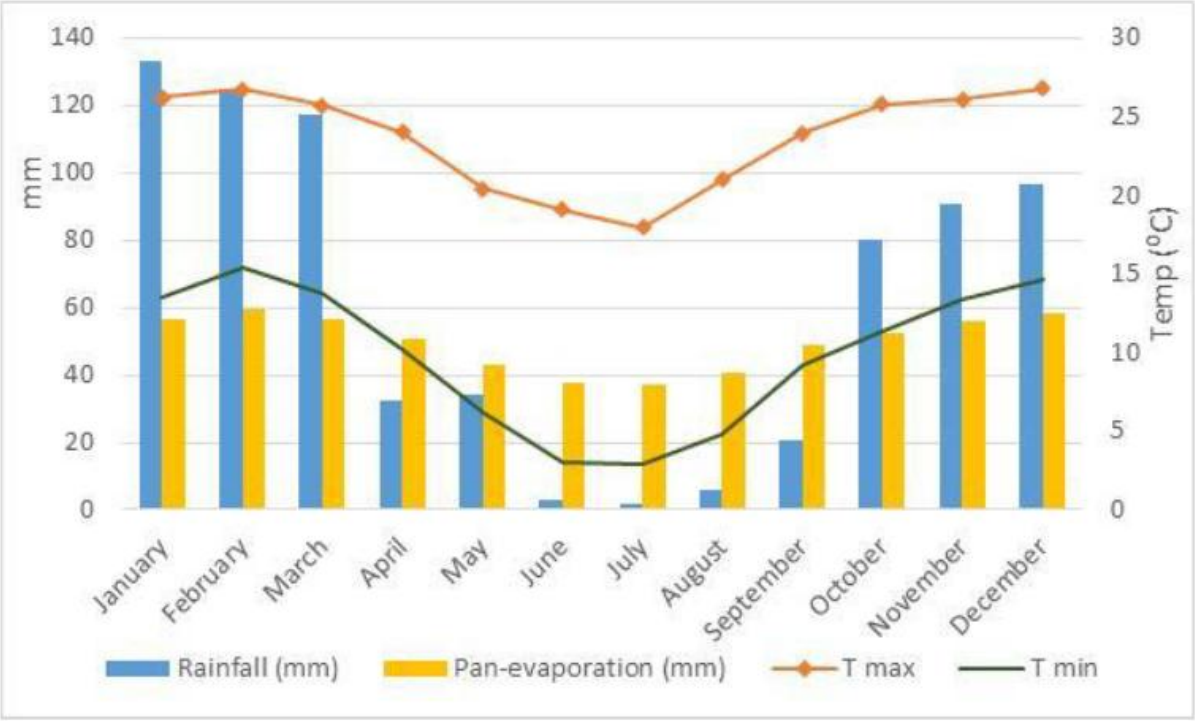

Figure 2: Rainfall, temperature and pan-evaporation records from 1996 to 2017, acquired from four UCRB climate stations. (Source: Leketa, 2019).

3.3 Water Resources

Brits is situated along the Crocodile River, which flows from south-east to north-west (Cochet et al., 2015). The Hartbeespoort Dam is primarily fed by the Crocodile River, which supplies approximately 90% of the annual inflow, with the Magalies River (Figure 3) joining from the western direction (Leketa et al., 2018; Ibrahim and Ishiga, 2019). The Crocodile River flows through industrialised and densely populated areas (Ali et al., 2022; Pindihama et al., 2024). Other

minor tributary streams that supply water to the Dam include Swartspruit and Leeuspruit. Water from Hartbeespoort Dam flows further northwards into the Roodekoptjes Dam and eventually is discharged into the Limpopo River.

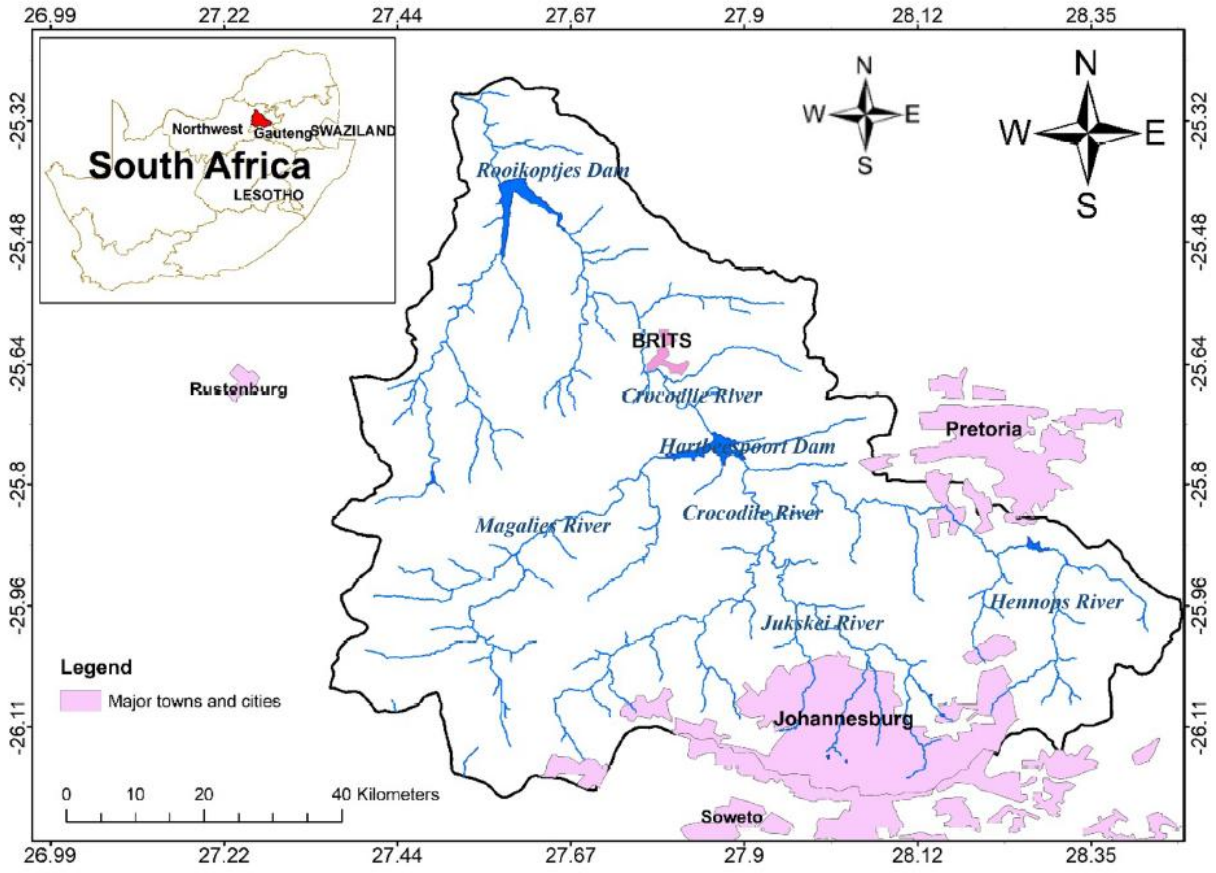

Figure 3: Map of the study area and its different drainage systems (Leketa et al., 2018)

The quality of water is particularly important in this region, as more than half of the water in the Hartbeespoort Dam originates from upstream urban, industrial and mining areas primarily around Johannesburg. Elevated levels of phosphates, nitrates and heavy metals in the water pose a challenge for farmers who rely on the dam for irrigation. Additionally, eutrophication resulting from nutrient loading promotes algal growth and the proliferation of water hyacinth, which obstructs irrigation canals (Cochet et al., 2015).

3.4 Agricultural practices

3.4.1 Fertiliser and Pesticide use

The Brits area is known to be a grain-producing region, primarily cultivating maize, along with other crops such as sunflowers, soybeans, wheat, and various citrus fruits. To enhance crop

production, growth, and yield, farmers apply fertilisers such as ammonium nitrate (NH_4NO_3) combined with NPK (Nitrogen, Phosphorus, Potassium). Depending on the target yield, application rates range from 300 to 800 kg of fertiliser per hectare per season. According to local farmers, pesticides such as Roundup are also used; typically, 2 to 5 litres per hectare are applied, mixed with 200 to 300 litres of water to support crop growth.

3.4.2 Irrigation practices

Borehole water is used for small gardens, and during the rainy season, farmers often depend on rainfall for irrigation. However, for most farms, the primary water supply is from the Hartbeespoort Dam. Most farms use pivot irrigation, which operates on spray mechanisms, while a few farms with relatively smaller land areas utilise the flood irrigation system.

According to the Water Administration System (WAS) which is an integrated management tool for irrigation schemes that distributes water through a network of canals, pipelines and rivers, the total volume of water allocated for all uses annually from the Hartbeespoort Dam is 99 280 117 m^3, with 86 249 627 m^3 allocated for irrigation purposes. Each hectare of scheduled irrigation land is allocated 6 200 m^3 of water per year, and the total irrigated area spans 13 911.23 hectares. Most farmers in this area rely on surface water for irrigation; however, some depend on groundwater extractions (Leketa, 2019). Water from the Hartbeespoort Dam is distributed through canals as shown in Figure 4 below.





Figure 4: Distribution of water from the Hartbeespoort Dam through canals. (Source: www.wateradmin.co.za).

3.5 Geological Setting

The study area is characterised by a geological setting that is represented by the Transvaal Supergroup and the Bushveld Igneous Complex in the western limb. The Transvaal Supergroup includes the Black Reef quartzites, Malmani dolomites and the Pretoria Group. The Pretoria Group includes the Silverton Formation and the Magaliesberg Formation, which consist of shale that is, to a lesser extent, resistant to erosion and quartzite that is more resistant to erosion. These Formations outcrop at the Hartbeespoort Dam area (Eales and Cawthorn, 1996; Leketa, 2019). The Magaliesberg Ridge has tectonically deformed quartzite that has been tilted northwards. In the middle section of the Hartbeespoort Dam, two vertical semi-parallel northwest-southeast faults created a graben that has a displacement of approximately 1280m to the south, a width of 5.6 km and a vertical displacement of 390 m (Hall and du Toit, 1923; Leketa, 2019). These major faults have shaped the geology of this region by altering the original stratigraphy, where the western fault of the Commando Nek has contributed to the depression in the Magaliesberg Ridge, and the eastern fault follows the Crocodile River, which controls the river's path (Hall and du Toit, 1923).

According to Hall and du Toit (1923), it is challenging to determine the northern extent of the major faults due to the presence of the low-lying basic margin of the Bushveld Complex, which continues into the southern part of the granophyre hills. In addition to these major faults, there are several other smaller faults and crush lines which are not parallel to the main east fault but run obliquely from south-south-west to north-north-east. These small faults form a series of steps which influence rock deformation and water flow, and they may have served as conduits of later igneous intrusions which sought zones of weakness (Hall and du Toit, 1923).

Rocks in the Transvaal Supergroup have been intensively metamorphosed by the intrusion of igneous rocks which are compositionally similar to those making up the main mass of the Bushveld Complex and include a few dyke rocks and it has undergone low-grade metamorphism which is found farther from the intrusion, preserving sedimentary features (Hall and du Toit, 1923). The sediments of this section of the Transvaal Supergroup consist mainly of quartzites and alternating layers of shales. The Bushveld Complex intruded into the highest beds of the Pretoria Group, where there are two distinct sills formed within the quartzites and a prominent dolerite dyke which extends northwest and is not affected by the major faults, it cuts across different quartzite layers including the Middle Quartzite (Hall and du Toit, 1923).

The Bushveld rocks are found in the northern upper part of the study area, and they consist of the Rashoop granophyre, Rustenburg Layered Suite, and the Lebowa granite (Bumby et al., 1998) as shown in Figure 5. The Rustenburg Layered Suite consists of mafic and ultramafic rocks (Yao et al., 2021), and is represented by norite, gabbro, pyroxenite, and anorthosite (Bumby et al., 1998; Leketa, 2019). The Lebowa Granite and the Rashoop Granophyre rocks are represented by the Nebo granite and granodiorite (Leketa, 2019).

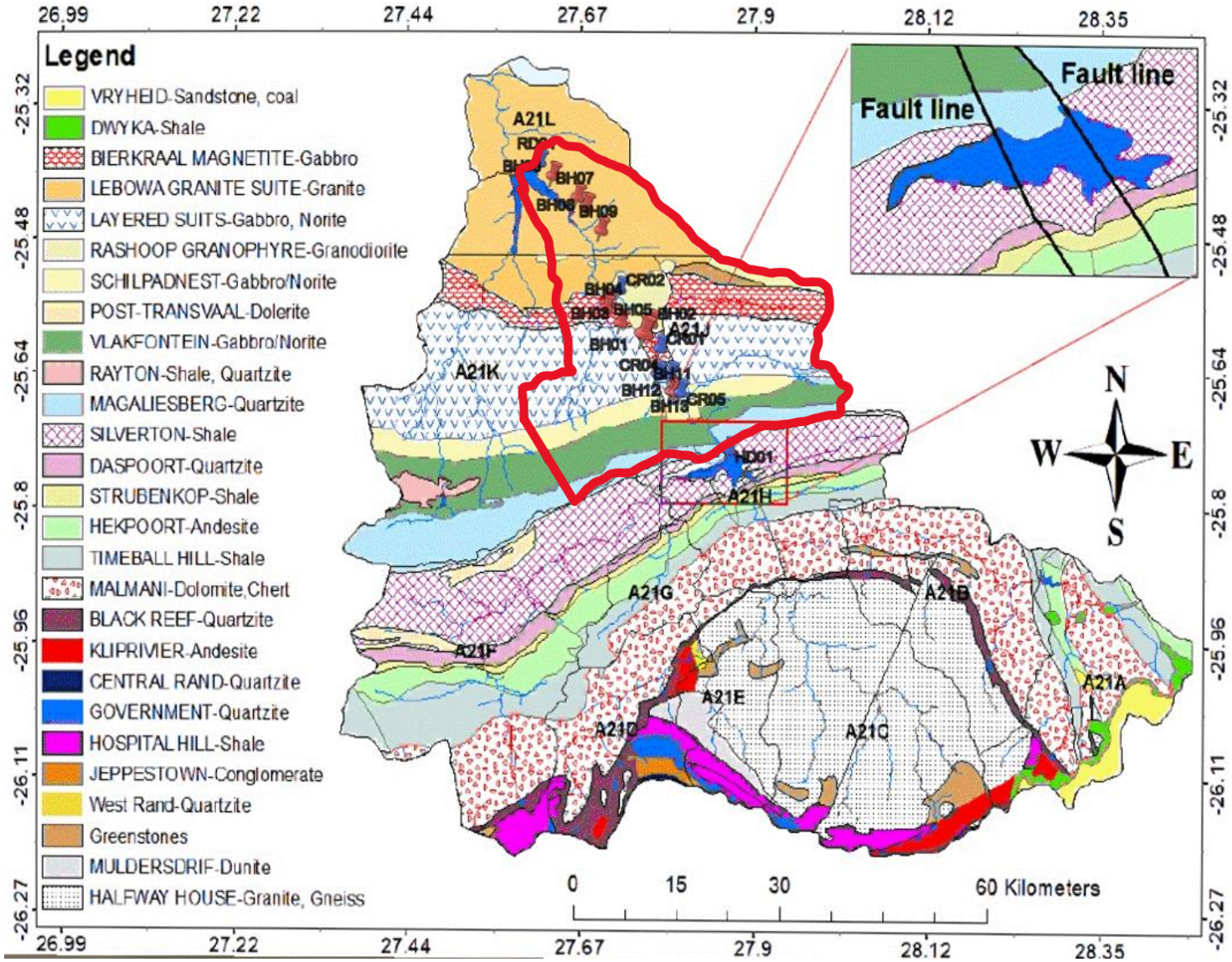

Figure 5: Geological map of the Upper Crocodile River Basin (UCRB) showing the A21J quaternary catchment highlighted in red. The distribution of the sampled boreholes (BH), surface water samples (CR, HD, RD) is also shown in the figure. (Source: Leketa, 2019).

Nyebelele (2019) constructed a geological cross-section to visualise the subsurface geology of the area, as presented Figure 6.

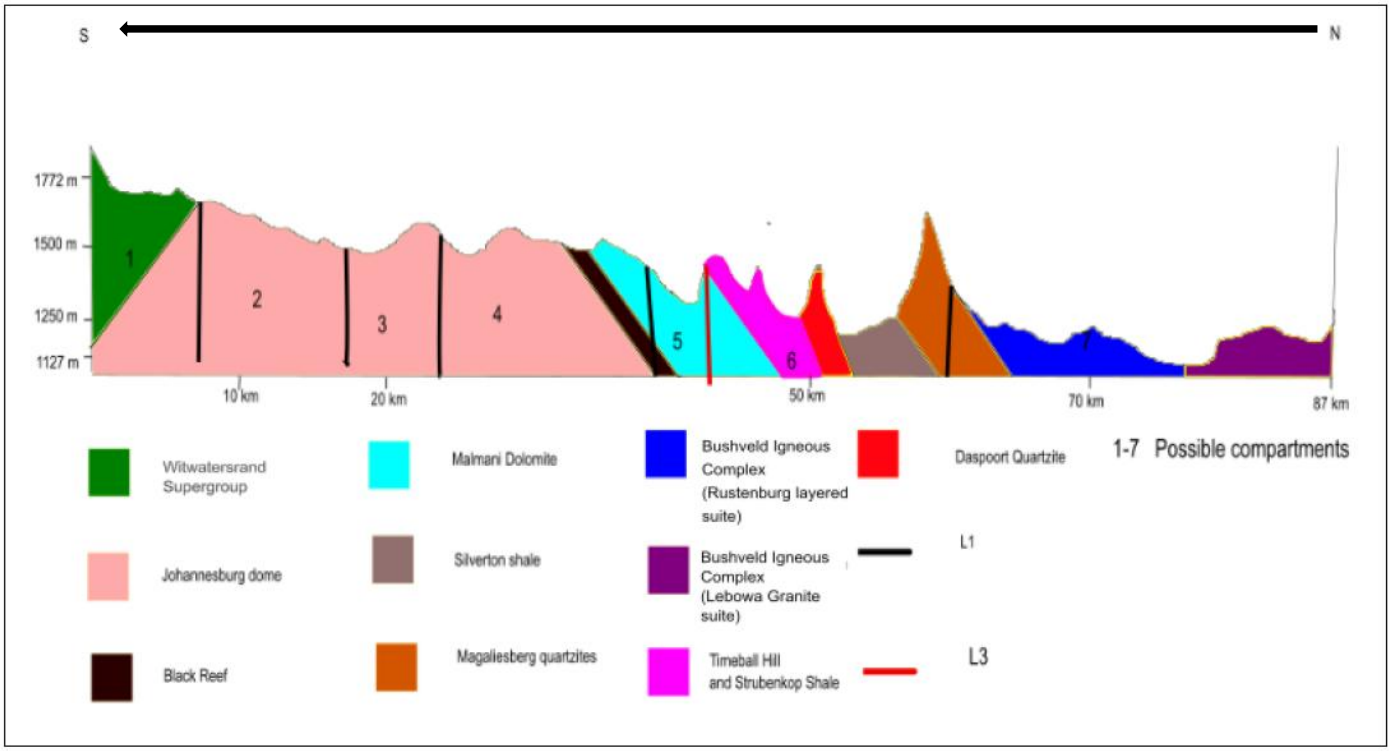

Figure 6: A geological cross-section of the study area, trending in the N-S direction (Nyebelele, 2019)

3.6 Hydrogeological Setting

Groundwater occurrence in the study area is defined by four types of water-bearing interstices, which are intergranular, fractured, karst, and both intergranular and fractured aquifers (Barnard, 2000). According to Barnard (2000), the Magaliesberg Formation of the Pretoria Group, part of the Transvaal Supergroup, constitutes a fractured aquifer, whereas the Silverton Formation is characterised by both intergranular and fractured aquifers. In the Silverton Formation, groundwater is typically found within weathered shale joint zones and specific zones of contact between the shale and the intrusive dolerite dykes and sills. Water from Hartbeespoort Dam is contributing to groundwater recharge as Hartbeespoort Dam is constructed along the Magaliesberg ridge, which is characterised by fault lines, bedding planes and graben (Leketa, 2019). These geological features act as conduits in recharging groundwater downstream of the dam.

Crystalline rocks such as norites and pyroxenites within the Bushveld Igneous Complex have insignificant matrix porosity and permeability. Groundwater occurrence in these rocks is generally

restricted to zones of secondary permeability, such as faults, fractures, and weathered zones (Titus et al., 2009). These fractured zones may exhibit relatively high permeability, particularly where fractures are well-connected; however, they offer limited groundwater storage. Significant groundwater storage is primarily associated with highly porous materials such as weathered regolith or alluvial deposits. As illustrated in Figure 7, aquifer systems within crystalline rock settings include a perched aquifer, which is semi-confined and situated within the regolith derived from the disintegration of underlying noritic rocks (Chilton and Foster, 1995).

Rustenburg Layered Suite, the Rashoop Granophyre Suite, and the Lebowa Granite Suite host both intergranular aquifers, primarily in intensively weathered zones, and fractured aquifers. Groundwater in granitic rocks, particularly within the Lebowa Granite Suite, is typically found in the intergranular (upper weathered) zones and associated fractured aquifer. The Rashoop Granophyre rocks are often associated with weathering zones, brecciation, and jointing. In the Rustenburg Layered Suite, groundwater usually occurs in deeply weathered and fractured mafic and ultramafic rocks. The Bushveld Igneous Complex has productive boreholes due to its favourable hydrogeological nature. Flood and pivot irrigation practised around the study area facilitate the transportation of contaminants through fractured aquifers, and the channel overflow joins the Crocodile River.

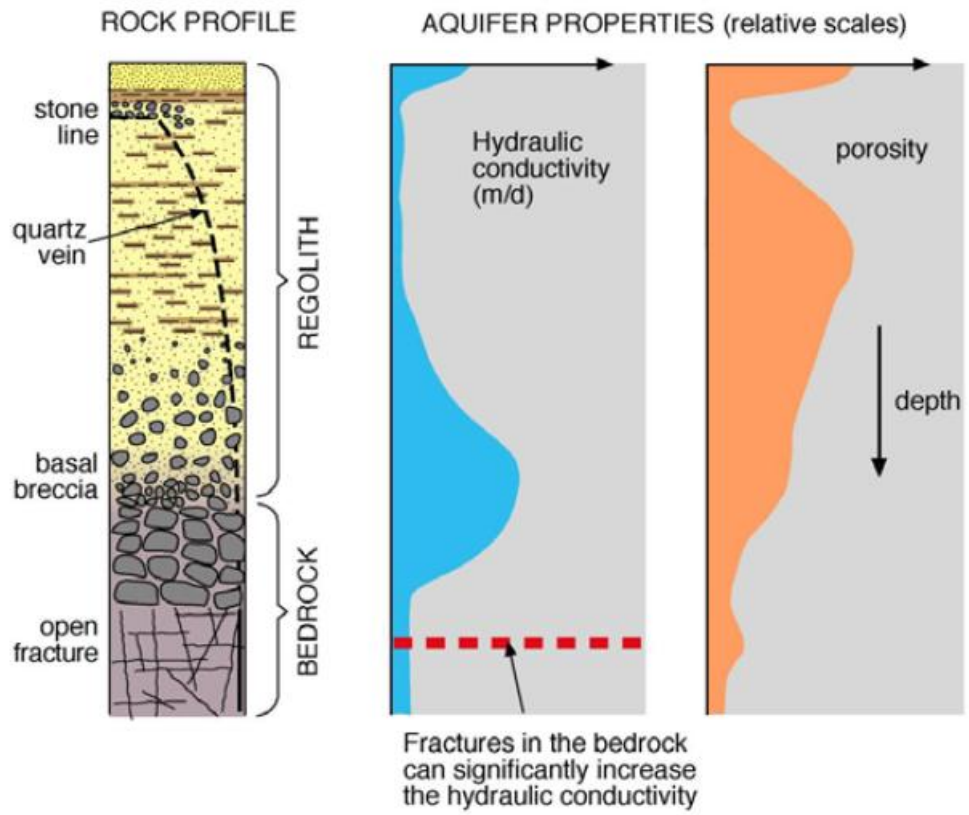

Figure 7: Profile showing weathered and fractured basement rocks (Source: Chester and Foster, 1995)

The type of material that makes an aquifer influences the flow of groundwater and controls the hydraulic conductivity and transmissivity of the aquifer system. According to Titus (2019), borehole yields in basement aquifers are usually low, with yields of 0.5 to 1 l/s, and 2 l/s is proposed for long-term abstractions. The aquifer model for the Bushveld Complex has a perched, shallow aquifer in the weathered zones, which is underlain by a deeper, semi-confined fractured bedrock aquifer (Titus et al., 2019). According to data obtained from the Department of Water and Sanitation (DWS) from boreholes around the Brits area (Table 2), borehole discharge rates range from 0.01 to 7.6 l/s at varying depths and water levels.

Table 2: Record of some borehole depths, water level and discharge rates around the Brits area (data source: DWS)

GeositeType	Latitude	Longitude	Water Level depth (m)	Discharge Rate (l/s)	Depth To Bottom (m)
Borehole	-25.72631	27.65189	14.452	4.345	31
Borehole	-25.71999	27.6516	13.116	0.9125	29.5
Borehole	-25.71673	27.79969	10	1.7	75
Borehole	-25.71656	27.66205	11.644	1.7825	42
Borehole	-25.71311	27.76525	30	3.23	85
Borehole	-25.70924	27.68218	12.56	0.95	38.5
Borehole	-25.70075	27.73302	24	0.01	75
Borehole	-25.69867	27.67564	19.0325	0.54333	39
Borehole	-25.6973	27.67962	19.358	1.4075	37
Borehole	-25.6687	27.76636	34.75	0.25	79.55
Borehole	-25.66867	27.76637	6.1	0.04	27.14
Borehole	-25.66729	27.67469	8.53	2.35	30.37
Borehole	-25.66447	27.59926	20.564	0.972	33.67
Borehole	-25.6585	27.62413	41.604	0.1975	49
Borehole	-25.65784	27.71636	15.24	0.46	35.05
Borehole	-25.64645	27.70441	6.09	3.78	35.05
Borehole	-25.62375	27.73302	14.33	0.08	39.62
Borehole	-25.61452	27.77469	11.7325	0.98	45.3375
Borehole	-25.60118	27.79135	21.26	7.595	48.4625
Borehole	-25.60062	27.67469	10.97	0.1	45.11
Borehole	-25.56153	27.60845	19.725	0.7	25.33
Borehole	-25.42652	27.64969	8.7842	0.765	48.25

From Table 2, it is evident that groundwater levels in the Brits area vary significantly, ranging from 6.09 m to 41.604 m. This variation suggests the presence of both shallow and deeper aquifers, influenced by local geological and hydrogeological conditions. The borehole depths range from 27.14 m to 85 m, highlighting the variation in the hydrogeological conditions in the area. Boreholes with moderate depths and shallow water levels may indicate the presence of unconfined aquifers, where the water table is relatively close to the surface. In contrast, low discharge rates of 0.01 to 0.25 l/s are characteristic of poorly permeable zones with limited fracturing, while higher discharge rates, reaching up to 7.595 l/s, suggest more permeable zones and fractured zones, possibly within a confined or unconfined aquifer system.

4.0 MATERIALS AND METHODS

With the aim of assessing the impact of agricultural activities on surface water and groundwater quality, a field trip to the Brits area of the North West Province was undertaken. Before sample collection, calibration of field instruments was performed to ensure accuracy. The pH metre was calibrated using standard buffer solutions with a pH of 4 and 7, while the electrical conductivity (EC) metre was calibrated using standard solutions of 84 µS/cm and 1413 µS/cm.

4.1 Sampling procedure

A total of 20 samples were collected from both groundwater and surface water sources. These comprised 13 borehole samples, one sample from Hartbeespoort Dam (upstream of the study area), one from Roodekoptjes Dam (downstream), and five samples from different locations along the stretch of the Crocodile River. The borehole samples were collected within close proximity to the agricultural fields, at distances ranging from 20 to 130 metres, while river samples were collected at distances ranging from 40 to 200 metres from irrigated land. These sampling locations were established to capture potential contamination from agricultural activities and to facilitate the assessment of spatial variation in water quality across the study area.

GPS coordinates for each sampling location were recorded and subsequently plotted using Google Earth (Figure 8a and Figure 8b). A temporal assessment of land use changes, based on satellite imagery on Google Earth, was used in selecting the most appropriate sites to collect samples from (Figure 8b). The green areas visible in both Figure 8a and Figure 8b correspond to agricultural fields that are irrigated by the Hartbeespoort irrigation system, indicating zones of intense agricultural activity. The fields are also located near the Crocodile River, highlighting their potential influence on both surface and groundwater quality.


(a)
Brits Study Area
Sampling points around the Brits area
BH07
BH08
BH09
CR02
BH04
BH05
BH03
BH02
BH01
CR01
BH10
CR03
CR04
BH13
BH12
CR05
BH11
HD1
Legend
Borehole sampling points
Dam sampling points
River sampling points
Google Earth
8 mi
N



Figure 8: Google Earth image showing sampling locations in the Brits study area. (a) All sampling locations; (b) zoomed-in image of sampling locations showing the dense agricultural landuse around the area.

Boreholes are drilled into aquifers to access groundwater for household consumption, and storage tanks enable regulated water distribution and ensure availability during periods of high usage (Figure 9).



Figure 9: A picture shown depicts a borehole used for domestic supply with a storage tank.

At each sampling site, standard field procedures were followed, including the identification of potential pollution sources, taking a photograph of the site, and a brief written description of the site. Boreholes were pumped for 30 minutes or more before obtaining a sample to eliminate stagnant water from within the casing and to obtain a representative groundwater sample. Sampling bottles were rinsed five times with the sample water before collecting samples to minimise the risk of cross-contamination (Figure 10). For surface water samples, such as rivers and dams, sampling bottles were submerged below the water surface, facing the direction of the flow of water.



Figure 10: A picture showing bottle washing of the sample bottles from the Crocodile River (A) and water from the Hartbeespoort dam (B).

Observations of algal bloom were also recorded where applicable (Figure 11). At each sampling site, two sample bottles were taken, one 2L dark-colored plastic sampling bottle and a 200ml brown, amber sampling bottle to accommodate different analytical requirements.



Figure 11: Pictures showing sampling points from the Crocodile River (A) and Roodekoptjes Dam (B), showing the extent of algal bloom.

The physical condition of the water, including its colour and odour, was recorded during sampling as illustrated in Figure 12. Figure 12A depicts clear water with no visible impurities, whereas Figure 12B shows algal residues exhibiting a greenish colour indicative of algal presence.

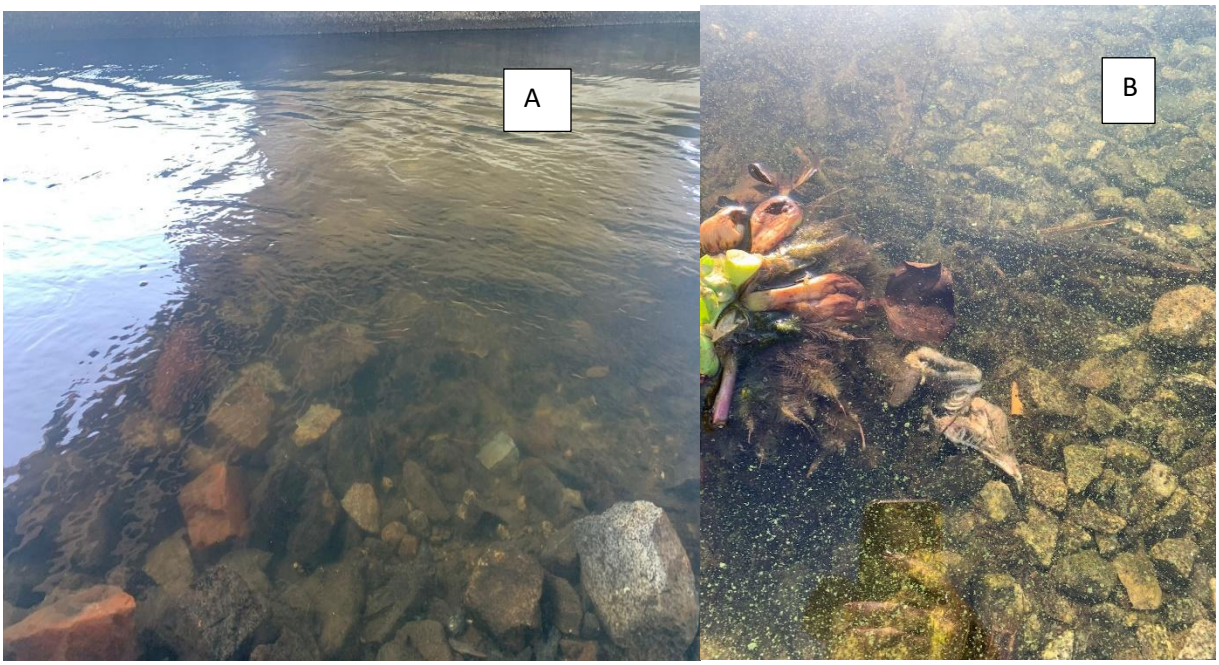

Figure 12: Pictures showing variations in the water quality with (A) clear water in one of the sampling points from the Crocodile River and (B) showing algae residuals in the Roodekoptjes Dam.

At all sampling sites, sampling bottles were clearly labelled with site name, date, and sample ID as illustrated in Figure 13.



Figure 13: Picture showing the 200ml amber sample bottle with sampling labels

These sampling bottles were filled and tightly capped, and placed in a cooler box full of ice to preserve the samples from degradation. Physical parameters such as pH, temperature and electrical

conductivity (EC) of the water samples were measured in the field at the time of sample collection by a multiparameter probe (Figure 14). For the reliability of the values read from the multiparameter probe, calibration was also performed on sampling sites.



Figure 14: A photo showing pH, temperature, and electrical conductivity testing on one of the sampling sites.

Furthermore, the types of irrigation methods and usage of agricultural inputs such as fertilisers and pesticides were also recorded. An assessment was conducted on some farmers in the study area to build capacity and stimulate communication on groundwater protection while getting appropriate and useful information on the uses of groundwater and pollution problems. This assessment included getting information on the type of crops grown in the area, the type of pesticides and fertilisers commonly applied, and the irrigation techniques adopted across the area.

4.2 Laboratory Analysis

Water samples were submitted to accredited laboratories, including the Environmental Pollution Laboratory (EPL) and the Magalies Water Laboratory (Figure 15). The analysis focused on determining the concentrations of major ions such as Mg^{2+}, Ca^{2+}, K^{+}, Na^{+}, HCO_3^{-}, CO_3^{2-}, SO_4^{2-}, Cl^{-}, PO_4^{3-}, NO_3^{-}, P-alk as $CaCO_3$ and M-alk as $CaCO_3$. These parameters were measured using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). In addition, the samples were analysed for the presence of pesticides, particularly organophosphorus and organochlorine.

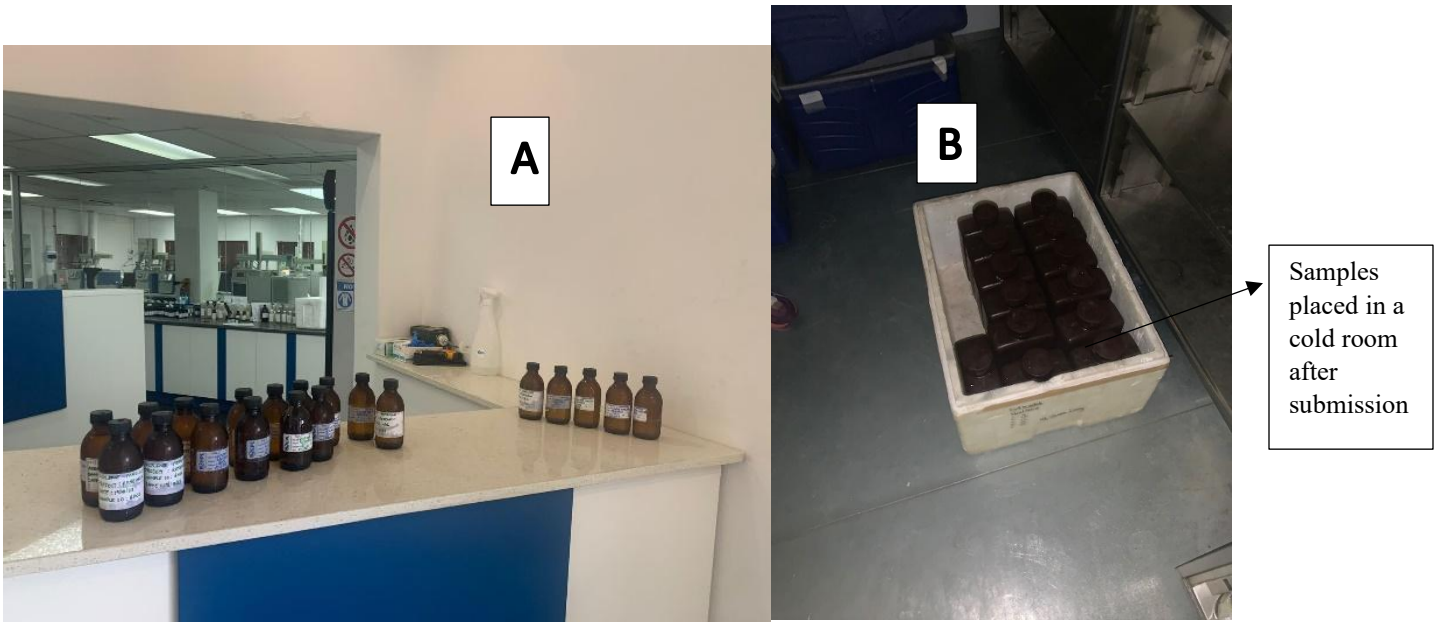

Figure 15: Samples submission and recounting at EPL laboratory (A) and Magalies Laboratory (B).

For the analysis of *chlorophyll-a,* water samples were submitted to the Magalies Water Laboratory in Brits. Chain of Custody (COC) forms were provided by the Environmental Pollution Laboratory (EPL) upon sample submission. These forms contained essential information, including the sample identification, dates and times of collection, project details, sample temperature at collection, sample matrix, and the analytical parameters requested. Sample IDs labelled on the bottles were verified with those listed on the COC forms, and the physical condition of the samples was carefully inspected for any signs of leakage or contamination. Upon submission, all samples were stored in a cold room to prevent degradation before analysis.

4.3 Data Accuracy

In acquiring data, there are often errors that occur due to water samples being mishandled and contaminated, data accuracy is used to minimise such errors. The error margin or threshold accepted in water quality should be within 10% (Mukonazwothe et al., 2022). Monitoring was done and recorded in mg/L; the monitoring data was converted to meq/L (in milliequivalents per litre) based on equation 1.

$$\text{Ionic Balance} = \frac{\Sigma \text{ cations} - \Sigma \text{ anions}}{\Sigma \text{ cations} + \Sigma \text{ anions}} \times 100 \quad \text{equation 1}$$

where both the sum of cations and the sum of anions are meq/L. To check the reliability of the results, an ionic balance was calculated. In general, the ionic balance for all samples was within the acceptable threshold of 10%, except for one sample.

4.4 Data Analysis

The results were presented in the form of tables and graphs using Microsoft Excel. Ground Water Chart software was used to prepare a Piper diagram, which classifies water types and was compared with the SANS:241 (2015), WHO (2022), and DWAF (1996) guidelines for domestic water use and irrigational purposes. In addition, a Durov diagram was constructed using Grapher software to further interpret the hydrochemical characteristics of the water samples.

4.4.1 Maps and Image Generation

Maps were generated by ArcGIS showing the study area, the Crocodile River and the Hartbeespoort Dam. Images showing sampling points were generated by Google Earth, using the coordinates recorded during sampling.

4.4.2 Suitability of water quality for drinking purposes

To evaluate the suitability of groundwater for potable use, the laboratory analysis results were compared with the South African Water Quality Standards (SAWQS) and the World Health Organisation (WHO) guidelines for drinking water quality. Calcium and Magnesium concentrations for each sample were used to calculate the total hardness of the water. The calculation was performed using the following equation:

$$\text{Total Hardness (mg/L as } CaCO_3) = 2.5 \text{ x Cal conc (mg/L as } Ca^{2+}) + 4.12 \text{ x Mg conc (mg/L as } Mg^{2+}) \quad \text{equation 2}$$

The results obtained from the calculation were subsequently used to classify water according to hardness, based on the classification criteria shown in Table 3.

Table 3: Classification of water based on hardness (Ramesh and Elango, 2012)

Hardness as CaCO3 (mg/L)	Water Class
<75	Soft
75-150	Moderate hard
150-300	Hard
>300	Very Hard

4.4.3 Water quality suitability for irrigation purposes

The chemical composition of irrigation water has a direct impact on crop health and soil quality, potentially leading to reduced agricultural productivity. Consequently, water quality assessment for irrigation is essential to support sustainable crop production in the Brits area. To evaluate the suitability of groundwater and surface water for irrigation use, key agricultural water quality parameters were derived from laboratory assay results. These include Sodium Adsorption Ratio (SAR), Magnesium Adsorption Ratio (MAR), Residual Sodium Carbonate (RSC), Permeability Index (PI), Kelly's Ratio and Sodium percentage (%Na), all calculated in meq/L. The calculated values were subsequently compared to the South African Water Quality Standards (SAWQS) and World Health Organisation (WHO) irrigation water quality guidelines. This comparison is necessary, as irrigation water must meet specific physicochemical criteria to be considered suitable for agricultural use.

Sodium Adsorption Ratio (SAR)

SAR is a measure of the amount of sodium (Na) relative to calcium (Ca) and magnesium (Mg) in water. The suitability of water for irrigation is based on the concentration of Na relative to the sum of Ca and Mg.

If there are high concentrations of sodium in soils, it means that water movement will be restricted, and crop production will be affected. It can also indicate that sodium in the irrigation water will replace Ca and Mg ions in the soil, and this will result in the degradation of the soil structure. The equation for SAR (meq/L) is given by equation 3:

$$SAR = \frac{Na+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}}$$ equation 3

i. Magnesium Adsorption Ratio (MAR)

Another method to assess the suitability of groundwater for irrigation is the Magnesium Adsorption Ratio (MAR). According to Mukonazwothe et al. (2022), this method defines the condition and equilibrium between Ca and Mg, where the soil will be more alkaline, and the quality of the soil is lost, resulting in low crop production. It is a critical chemical prerequisite that needs to be considered first before the use of a water resource for irrigation. The equation of MAR (equation 4) is expressed in meq/L:

$$MAR = (\frac{Mg^{2+}}{Ca^{2+}+Mg^{2+}}) \times 100$$ equation 4

ii. Sodium percentage (%Na)

%Na equation is expressed and given by equation 5:

$$\%\text{Na} = \frac{(Na^{+}+K^{+}) \times 100}{Ca^{2+}+Mg^{2+}+Na^{+}+K^{+}}$$ equation 5

iii. Permeability Index (PI) is expressed (meq/L) and given by equation 6:

$$PI = [(Na^{+} + HCO_3^{-}) / (Ca^{2+} + Mg^{2+} + Na^{+})] \, x \, 100$$ equation 6

iv. Residual Sodium Carbonate (RSC) is expressed and given by equation 7:

$$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+})$$ equation 7

v. Kelly's Ratio

$$KR = Na^{+} / (Ca^{2+} + Mg^{2+})$$ equation 8

Table 4 was used as a reference to evaluate the suitability of water from different sampling sites for irrigation purposes, based on calculations derived from key agricultural water quality parameters.

Table 4: Classification of groundwater for suitability for irrigation (Ramesh and Elango, 2012; Lalumbe and Kanyerere, 2021)

Parameter	Range	Water Class
%Na	<20	Excellent
	20-40	Good
	40-60	Permissible
	60-80	Doubtful
	>80	Unsuitable
SAR	<2	Excellent
	2 to 8	Good
	8 to 15	Doubtful
	>15	Unsuitable
MAR (%)	<50	Suitable
	>50	Unsuitable
PI	Class I (>75)	Good
	Class II (75-50)	Permissible
	Class III (<25)	Unsuitable
RSC (meq/L)	<2.5	Suitable
	>2.5	Unsuitable
KR	<1	Suitable
	>1	Unsuitable
E.C (µS/cm)	<250	Excellent
	250 - 750	Good quality
	750 -2250	Acceptable quality
	>2250	Unacceptable quality

5.0 RESULTS AND DISCUSSION

5.1 Reliability analysis

The ionic balance calculated for the samples was <10% for most, except for one sample (BH04), shown in Table 5. Ionic balance values exceeding 10 % are considered unreliable for interpretation; therefore, sample BH04 is excluded from further analysis (Sarkar and Islam, 2019; Wang et al., 2023).

Table 5: Ionic balance calculated from the samples.

Sample ID	Latitude	Longitude	Sum of cations	Sum of anions	Ionic Balance (%)
BH01	-25.605	27.7439	15.4	14.5	3.0
BH02	-25.588	27.7548	12.5	11.0	6.2
BH03	-25.588	27.7153	4.4	4.0	4.7
BH04	-25.571	27.6963	14.8	11.7	11.6
BH05	-25.565	27.6972	10.5	8.8	9.0
BH06	-25.416	27.6254	13.2	11.2	8.0
BH07	-25.441	27.6578	12.6	11.0	6.7
BH08	-25.451	27.6693	11.8	10.8	4.8
BH09	-25.479	27.6884	11.6	10.3	6.2
BH10	-25.647	27.7634	28.2	26.2	3.7
BH11	-25.669	27.7866	17.7	14.6	9.4
BH12	-25.668	27.7821	13.8	12.4	5.5
BH13	-25.666	27.7828	12.0	10.2	7.9
CR01	-25.617	27.7661	7.5	7.0	3.8
CR02	-25.59	27.7129	7.4	7.3	0.8
CR03	-25.648	27.7645	7.5	6.7	5.8
CR04	-25.648	27.7797	7.4	6.7	4.9
CR05	-25.668	27.7886	7.6	6.5	7.4
HD01	-25.728	27.8517	7.1	6.6	4.2
RD01	-25.4	27.6087	8.1	7.1	6.7

5.2 Physicochemical characteristics

Hydrogeochemical results from additional groundwater and surface water data within the study area from the Department of Water and Sanitation are presented in Table 6. The physicochemical parameters of the data were averaged. Total alkalinity was converted to HCO_3^- and CO_3^{2-} for use in plotting the Piper and Durov diagrams.

Table 6: Average of hydrochemical parameters of groundwater and surface water within the Brits area (data source: DWS)

Monitoring ID	Type	pH	Temp °C	E.C µS/cm	Ca^{2+} mg/l	K^{+} mg/l	Mg^{2+} mg/l	Na^{+} mg/l	Cl^{-} mg/l	$N0_3$ - $N0_2$ mg/l	PO_4-P mg/l	SO_4^{2-} mg/l	Total Alkalinity
192740 (DWS1)	S. W	7.6	-	2256	102.73	33.39	40.133	296.67	325.76	16.05	3.82	411	386.45
192721 (DWS2)	S. W	7.9	-	2 948.4	102.46	23.86	52.22	442.7	537.88	8.13	2.33	100.22	309.39
192722 (DWS3)	S. W	8.3	-	3 795.2	88.02	18.7	65.66	537.5	710.5	1.9	0.587	221.62	237.87
89928 (DWS4)	G. W	7.95	21.8	2 402. 8	137.12	1.1278	115.749	67.57	202.67	8.81	0.01651	252.373	303.156
89930 (DWS5)	G. W	7.51	23.52	824	35.81	11.14	10.12	89.01	143.42	3.12	0.032	43.01	66.78
1000012205 (DWS6)	G. W	8.15	-	2 035.7	117.9	0.6562	91.96	177.8	260.28	6.17	0.024	279.011	196.05
1000012207 (DWS7)	G. W	7.78	-	2 537.1	81.206	7.98	140.69	244.09	336.082	2.67	0.078	195.56	251.88
1000012209 (DWS8)	G. W	8.1	-	2 347.9	67.2	8.66	128.41	200.28	307.94	5.35	0.022	208.39	241.69
1000012211 (DWS9)	G. W	8.16	-	1 707.1	59.823	0.4712	115.81	127.73	149.75	16.23	0.229	195.93	243.43
1000013585 (DWS10)	G. W	8.09	-	1 930	86.224	0.433	73.633	201.219	265.84	3.783	0.028	166.954	384.67

5.3 Temporal changes in water quality

Hartbeespoort Dam

Monitoring long-term water quality at a specific site provides insights into temporal changes in the severity of contamination. Figure 16 presents long-term water quality variation recorded from 1968 to 2023 at Hartbeespoort Dam by the Department of Water and Sanitation (DWS). The figure illustrates water quality trends, including salinity, major ions, and nutrients, in relation to water levels. The period from 1968 to 1980 showed a more stable period with moderate fluctuations in water chemistry; however, this apparent stability may reflect incomplete or limited data records. It may also indicate that industrial effluent and sewage runoff were relatively manageable during this period, with a lesser impact on water chemistry. From the mid-1980s onwards, major ion concentrations increased, accompanied by a rise in nutrient loading, particularly phosphates, total phosphorus and nitrate and nitrite concentrations. A sharp increase in phosphate concentrations throughout the recorded period suggests heightened eutrophication risks due to elevated nutrient loads. Sodium concentrations increased from 24 mg/L to 53.4 mg/L from post-1980, indicating possible wastewater inflows.

Major ions display variable trends, with Ca^{2+} showing a sharp increase from 3.5 mg/L in 1984 to 42.6 mg/L in 2018. Similarly, Cl^-, Mg^{2+} and SO_4^{2-} concentrations also increased over the specified period. The period from 1968 exhibited relatively stable chemistry with moderate fluctuations, likely reflecting incomplete or sparse data coverage. However, the post-1980 data indicate an increase in ammonium (NH_4^+) concentrations. This trend suggests an increased discharge of raw or partially treated sewage, as ammonium is a common by-product of organic nitrogen decomposition in water. In contrast, NO_2 + NO_3 as N did not exhibit significant long-term change, which may suggest limited nitrification. PO_4^{3-} and total phosphate concentrations increased after 1980, indicating elevated phosphorus loading into the Hartbeespoort Dam. This increase is consistent with increased domestic wastewater discharge, including inputs from household detergents and dishwashing agents, which are rich in phosphates. These inputs are major contributors to eutrophication, particularly in impounded water systems like the Hartbeespoort Dam.

Total Dissolved Solids (TDS) increased significantly from 82.4 mg/L in 1984 to 653 mg/L in 2005, indicating a significant rise in salinity. Water levels were lower from 1968 to 1974 and again from

the late 1980s to the 1990s. These periods coincide with elevated electrical conductivity, TDS and nutrient concentrations. In contrast, higher water levels observed between 2000 and 2010 correspond with a reduction in salinity, although nutrient concentrations remained elevated. The temporal trends suggest that nutrient enrichment from urban wastewater discharges, agricultural runoff, and industrial effluents, together with an increase in salinity, continue to degrade water quality in this region. Hartbeespoort Dam experiences ongoing contamination from multiple inflow sources.

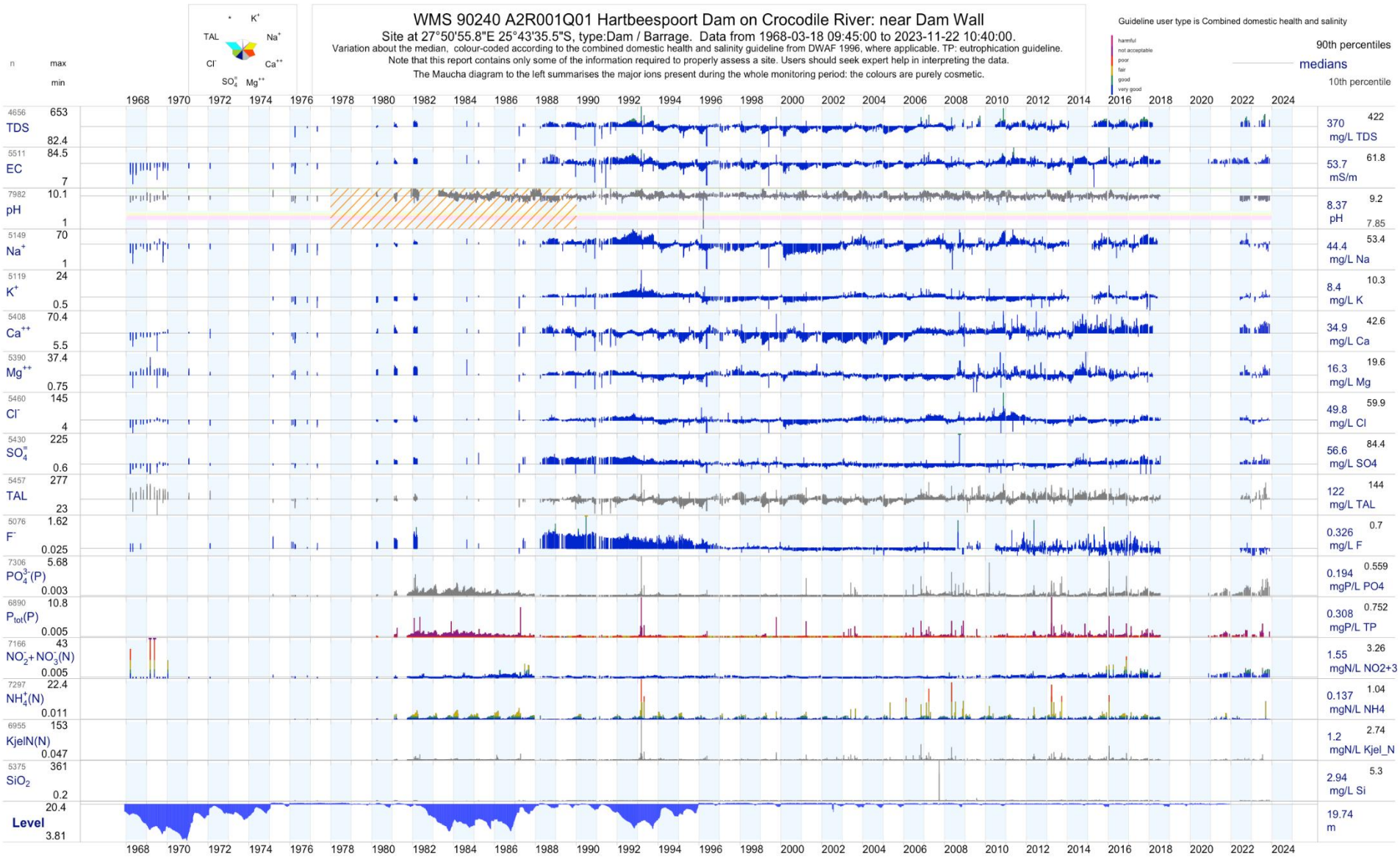

Figure 16: Temporal changes of water quality in Hartbeespoort Dam on Crocodile River from 1968-2023 (Source: Department of Water and Sanitation).

The temporal plot in Figure 17 illustrates water quality changes along the Crocodile River, which is located downstream of the Hartbeespoort Dam at the Crocodile Drift/Brits pump station. Calcium (Ca^{2+}) concentrations increased significantly from 11.6 mg/L to 49.4 mg/L, exceeding those at Hartbeespoort Dam and potentially indicating upstream industrial or agricultural inputs. Sulphate concentrations increased significantly from 13 mg/L in the early 1980s to 113 mg/L, surpassing levels recorded at the dam, further suggesting upstream industrial effluent discharge. Magnesium concentrations are higher upstream than downstream and have exhibited a sharper increase, likely to suggest mineral loading.

Nutrient loading from total phosphorus has increased notably, although concentrations remain lower than those recorded at Hartbeespoort Dam, indicating that nutrient accumulation is more pronounced downstream. Phosphate concentrations increased during the 1980s but declined in the 1990s. Overall, Hartbeespoort Dam exhibits higher nutrient concentrations compared to the upper part of the Crocodile River, further suggesting that reservoirs promote nutrient accumulation.

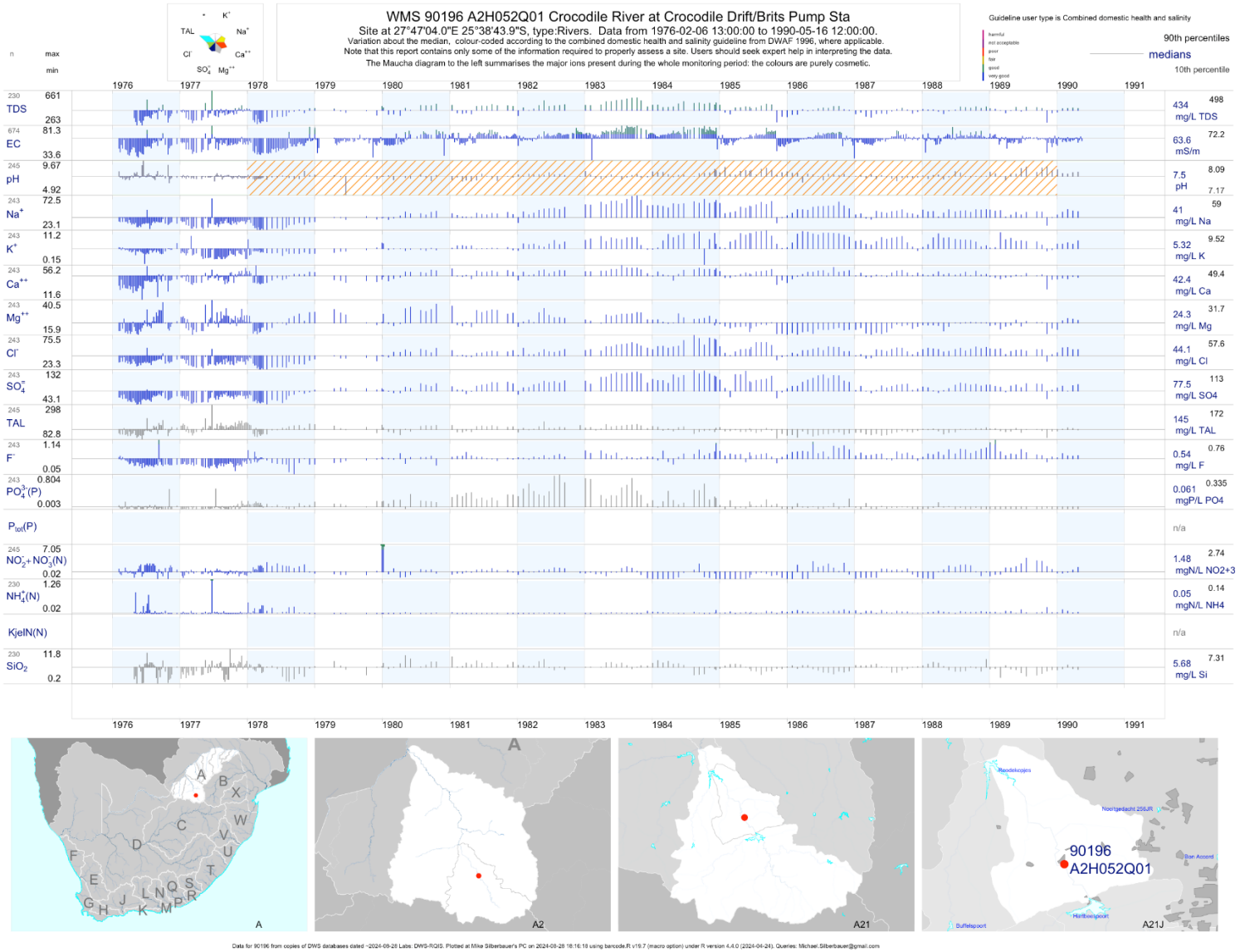

Figure 17: Temporal changes in water quality showing major ions concentrations from 1976 to 1991 in the Upper part of the Crocodile River (Source: Department of Water and Sanitation).

5.4 Water Quality

Table 7 summarises the key water quality parameters measured in groundwater and surface water, along with their permissible limits for drinking water as specified by the SANS241:2015 and WHO (2022) guidelines.

Table 7: Physicochemical parameters and major ion concentration in the analysed samples for this research, with WHO (2022) and SANS241 drinking water guidelines.

	Groundwater samples													Surface water samples								
Parameters	BH01	BH02	BH03	BH04	BH05	BH06	BH07	BH08	BH09	BH10	BH11	BH12	BH13	CR01	CR02	CR03	CR04	CR05	HD01	RD01	WHO (2022)	SANS241:2015
pH	6.85	6.76	7.16	6.87	7	6.44	6.82	7.02	6.83	7.34	7.12	7.12	7.05	7.04	7.07	7.4	7	7.38	7.2	7.8	6.5 - 8.5	5 - 9.5
Temp	24.1	24	32.7	24.1	27.5	27.4	23.3	28.1	23	22	23.9	24.2	23.3	21.9	24.7	22.4	22.5	21.8	20.9	28.2	30	
E.C	801	582	390	607	488	671	545	508	590	632	648	582	513	530	381	735	358	555	536	368	400 - 1000	50 - 1500
Colour	C	C	C	C	C	C	C	C	C	C	C	C	C	G	G	G	G	G	G	G	-	-
Odour	N	N	N	N	N	N	N	N	N	N	N	N	N	GR	GR	GR	GR	GR	GR	M	-	-
Total Hardness mg/L as $CaCO_3$	630	492	38.85	614.4	424.4	402.5	467.2	337.1	310.2	1020.5	952.94	697.8	339.5	239.6	239.24	239.3	239.66	245.6	226.27	267.27	-	-
Ca^{2+} (mg/L)	129.2	98.8	11.55	158.4	105.5	108.8	151.7	106.2	98.8	164.6	137.6	113	94.26	54.28	54.43	52.82	54.78	57.37	53.79	60.12	75	<150
Na^{+} (mg/L)	65.53	60.68	81.94	57.72	47.29	104.6	74.6	115	121.7	179.8	55.62	60.84	52.7	56.84	54.94	57.2	55.16	55.25	54.19	58.34	200	<200
K^{+} (mg/L)	0.1	0.1	0.74	1.34	0.1	22.9	1.97	4.61	6.23	0.47	3.4	0.48	1.48	9	8.99	9.21	9.1	9.77	9.73	7.9	12	<50
Mg^{2+} (mg/L)	74.53	59.93	2.42	53	38.98	31.68	21.34	17.37	15.33	147.8	100.8	66.84	54.83	25.21	25.04	26.03	24.93	24.79	22.28	28.39	50	<400
Cl^{-} (mg/L)	195.2	78.7	10.14	104.4	64.21	148.8	120.1	127.8	130.6	305.8	103.7	77.85	62.36	59.64	71.53	60.16	56.83	55.09	52.84	67.04	250	1
SO_4^{2-} (mg/L)	155.6	112.8	6.46	167.9	82.89	236.8	186	121.2	137.9	429.2	124.7	142	106.4	87.41	92.28	82.96	83.29	79.22	79.81	94.01	250	11
PO_4^{3-} (mg/L)	1.63	0.2	0.81	1.02	0.53	0.2	1.9	1.61	1.33	0.39	0.33	1.52	2.02	1.65	1.45	1.25	1.46	1.84	1.84	1.03		
NO3- (mg/L)	7.34	2.3	1.2	9.83	9.71	3.35	13.75	0.5	11.71	2.8	10.17	6.19	6.12	2.76	2.57	3.52	2.82	2.45	0.89	1.29	50	45
P-alk as CaCO3 (mg/L)	6.47	5.5	<0.6	<0.6	<0.6	<0.6	<0.6	6	<0.6	8.02	<0.6	8.6	<0.6	0.94	<0.6	<0.6	<0.6	0.71	<0.6	1.12	-	-
M-alk as CaCO3 (mg/L)	280.4	321.8	175	255	254.8	100.5	175	228.5	174.6	430	447.5	353.2	305	166.6	162.4	158.2	164.9	160.4	166.5	157.7	-	-
CO-3 (mg/L)	7.76	6.6	<1.2	<1.2	<1.2	<1.2	<1.2	7.2	<1.2	9.62	<1.2	10.32	<1.2	1.13	<1.2	<1.2	<1.2	0.85	<1.2	1.34	30	-
HCO3- (mg/L)	326.3	376.2	213.5	311.1	310.9	122.6	213.5	264.1	213	505	546	409.9	372.1	201	198.1	193	201.2	194	203.1	189.7	500	-

C- clear, M- Musty, GR- Grassy, G- Greenish, N- No smell

5.4.1 pH

Based on the data presented in Table 7, pH levels of surface water range between 7.0 to 7.38, while groundwater ranges from 6.44 to 7.34. The groundwater samples fall within the acceptable drinking water limits according to SANS241:2015 and WHO (2022) guidelines. Surface water samples fall within the permissible irrigation range of 6.5 to 8.4, as specified by DWAF (1996).

5.4.2 Electrical conductivity

The electrical conductivity (EC) of groundwater in the study area ranges from 390 to 801 µS/cm, slightly higher than that of surface water, which ranges from 358 to 735 µS/cm. There is a general trend of increasing electrical conductivity, with higher values observed at the upstream sampling points compared with the downstream sampling points.

Higher electrical conductivity in groundwater indicates that various ions are dissolved in water, suggesting potential salinity issues. Elevated concentrations of Na^{+}, Ca^{2+}, SO_4^{2-}, Cl^{-}, NO_3^{-} and PO_4^{3-} were observed in groundwater compared with surface water in this study area. The electrical conductivity of groundwater samples remains within the permissible drinking water limits set by SANS241 and WHO (2022). The electrical conductivity of surface water samples is classified as suitable for irrigation purposes based on the irrigation water suitability criteria outlined in Table 4. According to the United States Department of Agriculture (USDA) classification, this range falls within the medium salinity class, indicating that damage to salt-sensitive crops may occur and that appropriate managerial strategies may be required (Sarkar and Islam, 2019).

The electrical conductivity of groundwater samples from the monitored boreholes, shown in Table 6, is higher, ranging from 824 to 2 537.1 µS/cm, compared with the concentrations recorded in Table 7. These substantial differences may be due to the greater depths of these boreholes, which often reach more mineralised groundwater, thereby increasing electrical conductivity. A longer residence time may also contribute to elevated salinity. Higher electrical conductivity in the monitored boreholes indicates that various ions, such as Na^{+} and Cl^{-}, are dissolved in water. These ions show higher concentrations, ranging from 67.57 to 244.09 mg/L for Na^{+} and 143.42 to 336.082 mg/L for Cl^{-}, compared with the sodium and chloride concentrations recorded in Table 7. This indicates salinity issues, which in turn raise electrical conductivity levels.

5.4.3 Temperature

Generally, drinking cool water is more favourable than warmer water, as the temperature of water can influence chemical contaminants and other inorganic constituents that may affect taste (WHO, 2022). According to Table 7, groundwater temperatures are slightly higher, ranging from 22 to 32.7 ºC, while surface water exhibits lower temperatures, ranging from 20.9 to 28.2 ºC. Water collection was carried out during the summer season, which may have contributed to slightly warmer temperatures in both groundwater and surface water bodies. Groundwater retains heat for longer periods, and due to the geothermal gradient, agricultural runoff and wastewater discharge, which are potential sources of warmer effluents, the temperature of groundwater may be elevated. Additionally, water temperatures above 20℃ promote microbial growth and favour cyanobacterial blooms (Pindihama et al., 2024).

5.4.4 Colour and Odour

The colour and odour of water varied across the different sampling points, reflecting both natural and anthropogenic factors. Surface water samples exhibited slight colouration, which may be attributed to suspended solids, decaying organic matter, and agricultural runoff. In contrast, groundwater samples were generally clear and colourless, indicating limited exposure to surface contaminants. A distinctive odour was not detected in most groundwater samples; however, grassy to musty odours were noted in surface water samples. The presence of odour in these samples may be linked to elevated levels of organic pollutants or microbial activity.

5.4.5 Bicarbonate and Carbonate

The carbonate concentration in surface water ranged from below the detection limit of <1.2 mg/L to 1.3 mg/l, indicating a generally low presence of carbonates in these samples. In contrast, groundwater samples exhibited a broader range, with carbonate concentrations ranging from below the detection limit to 9.6 mg/L. Values reported as <1.2 mg/l reflect concentrations below the method's detection limit, which is based on the detection limit of p-alkalinity (0.6 mg/L). These concentrations are significantly lower than the WHO (2022) permissible drinking water limit of 30 mg/L. Groundwater also exhibited significantly higher bicarbonate concentrations, ranging from 122 to 546 mg/L, compared with surface water, which ranged from 189.7 to 203 mg/L. Some groundwater samples exceed the WHO (2022) permissible limit of 500 mg/L for drinking water, whereas bicarbonate concentrations in surface water remained within this permissible limit. Carbonate and bicarbonate are introduced into groundwater through chemical weathering, rainfall,

and carbon dioxide-derived soil processes (Masindi and Abiye, 2018). The Transvaal Supergroup, which underlies parts of the Bushveld Complex, has dolomitic formations that contribute to bicarbonate concentrations through dissolution. Dolomite dissolution significantly influences groundwater chemistry, contributing to elevated alkalinity in aquifers associated with the Transvaal Supergroup.

The geology of the sampled area is dominated by igneous rocks such as granites, gabbros, and norites, which are poor in carbonate minerals; therefore, minimal ion exchange. The pH range of the sampled water is 6.44 to 7.38, and within this range, bicarbonate ions dominate. Carbonate ions typically dominate only under highly alkaline conditions.

5.4.6 Calcium and Magnesium

Calcium naturally occurs in varying concentrations in most water sources, as well as magnesium, and it is also regarded as one of the main contributors to water hardness, where soft water contains calcium concentrations that are low and hard water, and vice versa (DWAF, 1996). In some of the groundwater samples, calcium concentrations slightly exceeded the SANS241:2015 drinking water limit of (<150 mg/L), where the highest recorded calcium concentration was 164.6 mg/L, and according to WHO (2004), calcium does not have a health-based limit, but a desirable level of taste and scaling is around 75 mg/L. In surface water, calcium concentration ranged from 52.8 to 60.1 mg/L. There is no trend in the increase in calcium concentration from downstream to upstream in the study area. Concentrations of calcium in groundwater may be caused by both natural processes and human impact.

The major source of calcium in groundwater is the dissolution of calcium-bearing minerals and ion exchange processes (Ramesh and Elango, 2012). The dissolution of dolomitic rocks can result in elevated calcium concentrations. In addition, agricultural runoff may contribute dissolved calcium to the groundwater system, although the irrigation water sourced from Hartbeespoort Dam contains relatively low calcium concentrations. Elevated calcium levels in groundwater may also result from the use of calcium-rich fertilisers such as lime, which is applied to neutralise acidic soils, and calcium nitrate, which is highly soluble in water.

Magnesium concentrations in surface water range from 22.3 to 26 mg/L, while groundwater exhibits a broader range of 2.42 to 148 mg/L. Among the groundwater samples, 50% exceed the WHO (2022) guideline of 50 mg/L, and some fall within the SANS241:2015 operational

classification range of 70 to 100 mg/L (class 2). Magnesium concentrations in groundwater may be attributed to agricultural and industrial activities. Fertilisers such as dolomitic lime, which contain both magnesium and calcium, are commonly used to neutralise acidic soils and contribute to elevated Mg levels. Industrial effluents are also potential sources of magnesium contamination. In contrast, surface water typically shows lower concentrations due to dilution effects, as rivers and dams are regularly replenished by precipitation.

5.4.7 Total Hardness

According to WHO (2022), hardness in water is caused by various polyvalent metallic ions, particularly calcium and magnesium cations. The degree of hardness in water is important for aesthetic acceptability by consumers. Total hardness in the groundwater samples varies significantly, ranging from as low as 38.85 mg/L in sample BH03 to a maximum of 1,020.45 mg/L in BH10. Using the classification guidelines for water hardness shown in Table 3, BH03 falls within the soft water category, while samples BH12, BH13 AND BH08 fall into the hard water range. The remaining groundwater samples, including BH01, BH02, BH04, BH05, BH06, BH07, BH09, BH10, and BH11, are categorised as very hard water, with concentrations exceeding 300 mg/L.

The surface water samples, on the other hand, show consistent hardness values ranging from 226.27 to 267.27 mg/L, which classifies them as hard water, but not excessively so. The elevated hardness in groundwater is influenced by the dissolution of calcium and magnesium minerals such as dolomite, as well as anthropogenic sources such as the use of lime-based fertilisers. This data indicates a clear distinction in hardness levels between groundwater and surface water, with groundwater generally exhibiting much higher hardness, reflecting intensive rock-water interactions and potential anthropogenic contributions in the subsurface environment.

5.4.8 Sodium and Potassium

According to DWAF (1996), elevated concentrations of sodium are mostly observed in runoff or leachates from soils irrigated with industrial waste and domestic wastewater. Sodium in surface water is lower, ranging from 54.2 to 58.3 mg/L, and the target water quality range for irrigation is 70 mg/L based on DWAF (1996). In groundwater, sodium concentration varies more widely, ranging from 47.3 to 180 mg/L. This concentration range is lower than the limits of 200 mg/L for

drinking water set by SANS241:2015 and WHO (2022); however, the highest sodium concentration approaches the guideline limit, indicating potential salinity issues.

According to Sarath Prasanth et al. (2012), potassium is a naturally occurring element, and its concentration is typically lower than that of calcium, magnesium and sodium. Potassium levels in drinking water are often below 20 mg/L. In this study, the potassium concentration in groundwater ranges from 0.1 to 6.2 mg/L, meeting both the SANS241:2015 (50 mg/L) and WHO (2022) (12 mg/L) limits. However, in surface water, the potassium concentration ranges from 7.9 to 9.8 mg/L. Elevated potassium concentrations in surface water suggest an influence from agricultural runoff, where excessive irrigation results in the transport of potassium-rich fertilisers into nearby water bodies. Despite the potassium concentration being relatively low, its detection in the water samples indicates possible contamination at low levels.

5.4.9 Chloride

According to WHO (2022), chloride in drinking water originates from natural sources, such as weathering of rocks, industrial effluents, sewage and intrusion of saline water. Chloride concentrations in groundwater are within the permissible drinking water limits of SANS241:2015 (200 mg/L) and the WHO (2022) limits (250 mg/L). In this study, chloride concentrations in groundwater range from 10.1 to 195 mg/L, while surface water concentrations range from 55 to 71.5 mg/L.

With the area having fault zones and fractured aquifers, which enhance groundwater flow, deep circulation of water through mineralised zones will dissolve chloride-bearing minerals. Deeper aquifers can also store older groundwater, which typically has higher chloride concentrations due to prolonged water-rock interactions. Groundwater systems generally have longer residence times than surface water, allowing for greater accumulation of dissolved salts such as chloride. Elevated chloride levels in groundwater may also result from the application of chloride-containing fertilisers, such as potassium chloride, and organochlorine pesticides that leach into aquifers through irrigation practices. Additionally, evaporation-enriched irrigation return flow can increase chloride concentrations (Lwimbo et al., 2019). Industrial effluents and wastewater discharge, particularly from chlorinated water treatment processes, further contribute to chloride contamination, especially in areas like Brits, where sewage management is inadequate.

5.4.10 Sulphate

Sulphate levels in groundwater vary widely between 6.46 to 429.20 mg/L, with some values exceeding the SANS241:2015 and WHO (2022) permissible limits of 250 mg/L. Sulphate concentrations above this threshold are not acceptable, as they pose acute health risks. In contrast, sulphate concentration in surface water ranges from 79.2 to 92.3 mg/L, which falls within the acceptable limits of both SANS241:2015 and WHO (2022). The presence of sulphate ions in both surface water and groundwater, across low to high levels, indicates contamination potentially arising from sulphate-rich fertilisers. Brits lie within a mining region, where the oxidation of sulphide minerals can elevate sulphate concentrations in groundwater. Irrigation is also a significant contributor to sulphate levels, as saline water may increase concentrations through return flows. Additionally, partially treated wastewater may contain sulphate from sewage sources, which can be discharged into surface water bodies.

5.5 Water Classification

The Piper diagram in Figure 18 illustrates the classification of water types for both groundwater and surface water samples. Additional data from the Department of Water and Sanitation around the Brits area were also plotted to show spatial variation. Most of the samples are classified as calcium-sulphate waters, including groundwater samples such as BH01, BH06, BH07, BH08, BH09, BH10, 899928,1000012207, 1000012209, 1000012211, 1000013585. Among the surface water samples, the Roodekoptjes Dam sample (RD01) and Crocodile River samples (CRO2 and CR03) also fall within the calcium-sulphate water type. A greater number of samples with this water type are located downstream of the study area, with only five situated upstream, suggesting a localised influence on water quality. Sample 89930, a groundwater sample, is classified as a sodium-chloride water type, along with surface water samples from the Crocodile River, namely samples 192749, 192721 and 192722.

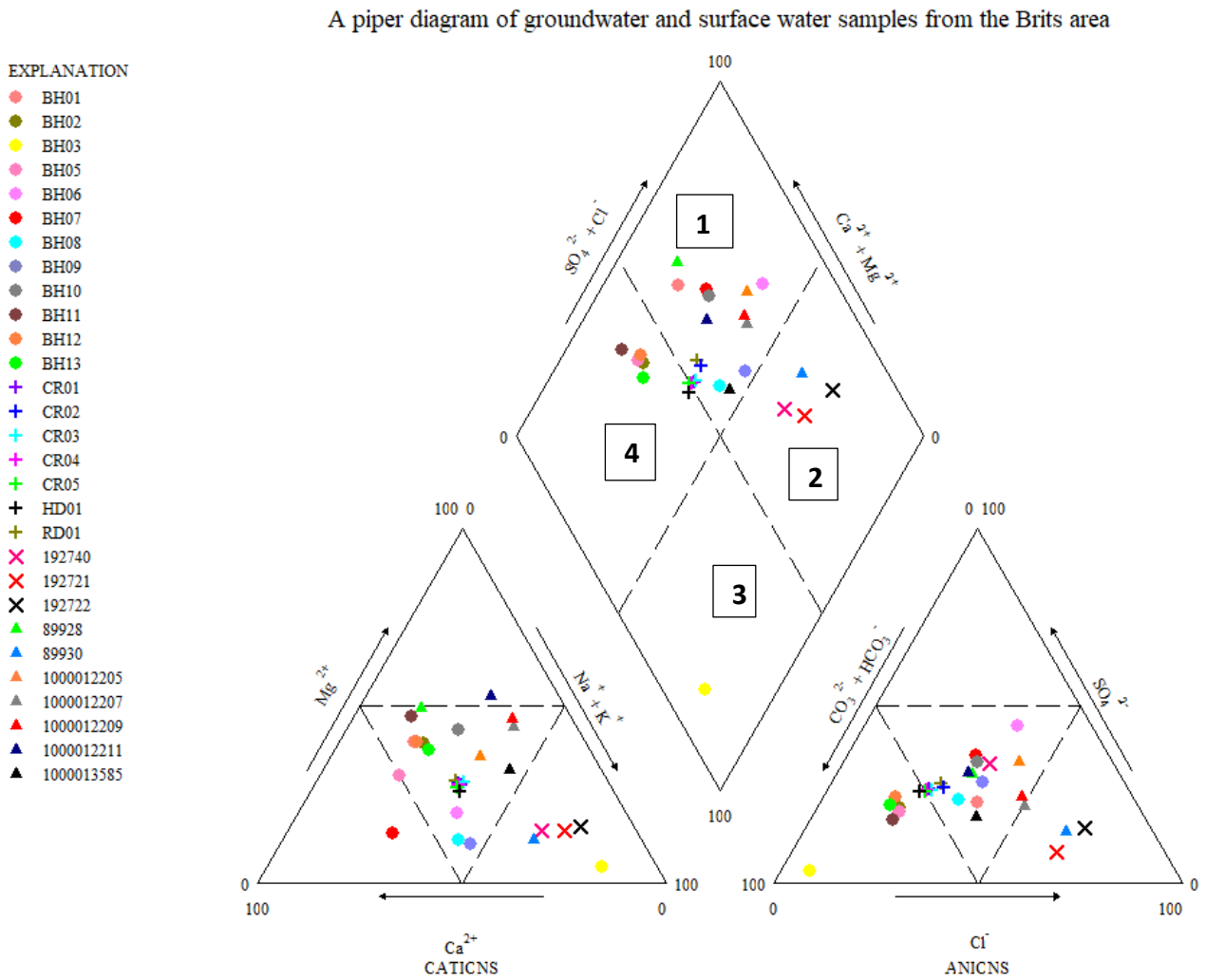

Figure 18: Piper plot diagram showing the major ion geochemistry of groundwater and surface water samples. Samples were arranged according to different sampling areas. The numbers indicate the chemical dominance: (1) Calcium-Sulphate waters (2) Sodium-Chloride waters (3) Sodium-Bicarbonate (4) Calcium-Bicarbonate

One groundwater sample (BH13) is classified as a sodium-bicarbonate type. Five groundwater samples BH01, BH02, BH11, BH12 and BH13 are classified as calcium-bicarbonate water type, along with surface water samples with other surface water samples such as HD01 and CR05. These sampling points are located in the upstream part of the study area. Crocodile River samples CR04 and CR05 are dominated by two water types, reflecting a mixing effect. These results indicate that the dominant cation in most of the samples is calcium, while the sulphate anion is relatively more dominant in several samples.

The Piper diagram shows that concentrations of cations are in the order $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$, whereas the anion order is $SO_4^{2-} > HCO_3^{-} > Cl^{-} > CO_3^{2-}$. This also indicates that the alkaline earth ($Ca^{2+} + Mg^{2+}$) exceeds the alkalies ($Na^{+} + K^{+}$), while $SO_4^{2-} + Cl^{-}$ exceed $CO_3^{2-} + HCO_3^{-}$. The dissolved ions that determine the quality of water in the study area are largely controlled by natural processes such as water-rock interactions and anthropogenic activities. Cation exchange and the dissolution of carbonate and sulphate minerals are the main sources of Ca^{2+}, HCO_3^{-}, Mg^{2+}, SO_4^{2-}, Na^{+}, NO_3^{-}, and Cl^{-} (Wang et al., 2023). Most of the samples taken in the downstream part of the study area are classified as calcium–sulphate, while upstream samples are mostly of the calcium-bicarbonate water type.

A Durov diagram (Figure 19) is a graphical representation used to evaluate and identify the hydrogeochemistry of water and the hydrochemical processes involved (Ravikumur et al.,2015).

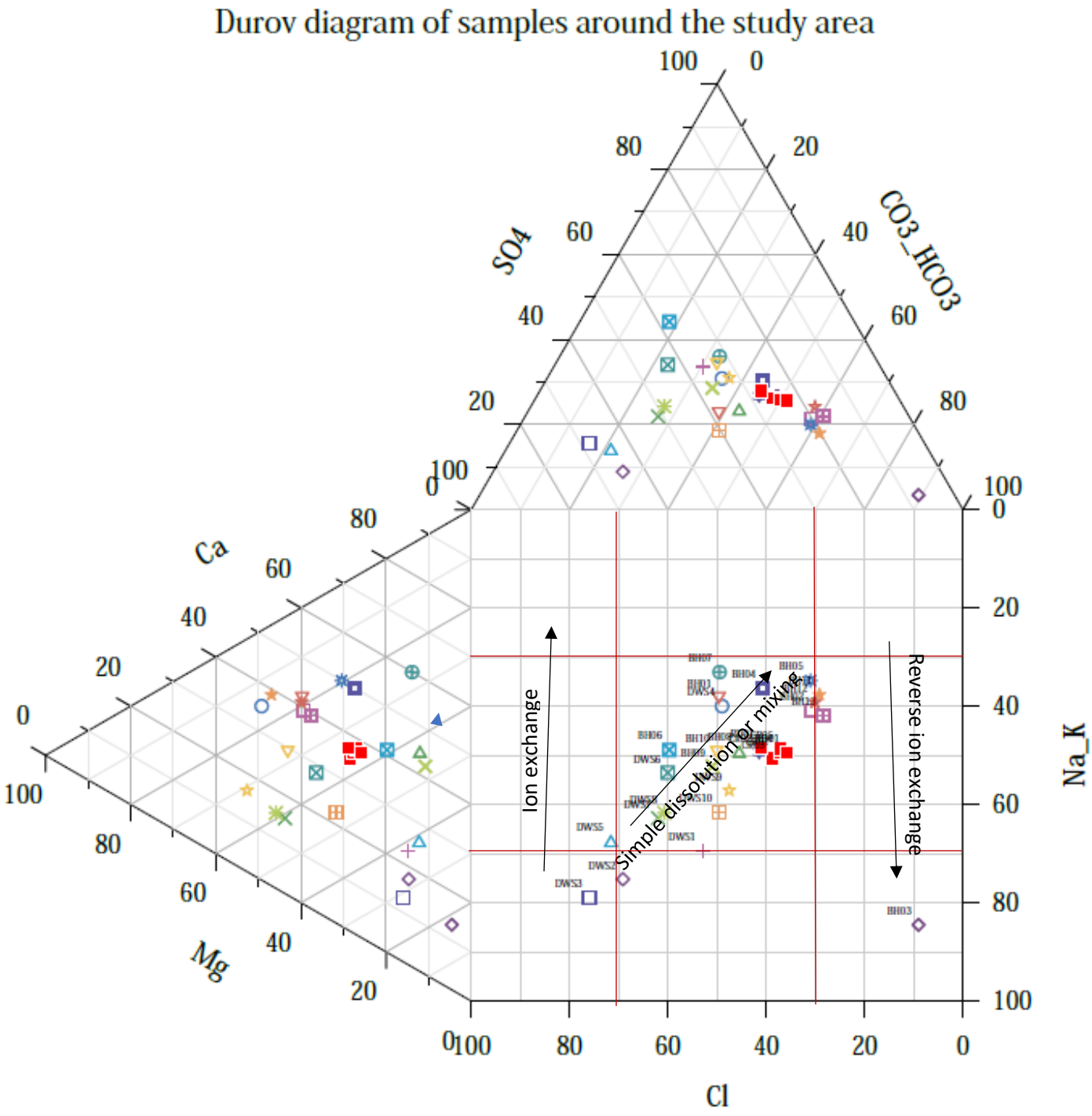

Figure 19: A Durov diagram depicting hydrochemical data covering the study area.

Based on Lloyd and Heathcoat (1985) classification of a Durov plot, the clustering of sampling points highlights the hydrochemical facies and water types in the study area. Most of the samples specified the dominance of simple dissolution or mixing processes. The dissolution of minerals from rocks such as pyroxenite, norite and gabbro of the Bushveld Complex results in the release of Mg^{2+} and Ca^{2+} from plagioclase and pyroxene weathering. Feldspar dissolution also contributes to the K^{+} and Na^{+} concentrations, while sulphates arise from the oxidation of sulphide minerals and the use of sulphate-rich fertilisers in the area. These observations also suggest mixing of different water types due to irrigation return flow and runoff.

5.6 Nutrient enrichment

Nutrient enrichment in freshwater bodies results in eutrophication, which facilitates the growth of harmful algal blooms. Phosphate is the main contributor to eutrophication, followed by nitrate. Phosphorus originates from both point and non-point sources and is known to be the limiting nutrient in freshwater (Mudaly, 2020). Point sources of phosphorus include wastewater treatment works and industrial discharges, while nonpoint sources involve agricultural runoff, where the overapplication of nitrogen and phosphate-rich fertilisers leads to accumulation in soils, groundwater, and surface water sources.

Nutrient enrichment, particularly in the Hartbeespoort Dam, is enhanced by return flows from Waste Water Treatment Works (WWTW). Venter and Maré (2011) calculated point source inputs of phosphorus to the Hartbeespoort Dam based on monitoring data from the Department of Water Affairs (DWA, 2009), as shown in Table 8 below. According to the table, the Johannesburg Northern Works (WWTW) is a major contributor with a soluble reactive phosphate load of 149.65 tP/a.

Table 8: Discharge of phosphate from the WWTW in the Hartbeespoort Dam (Source: DWA, 2009)

Catchment	Resource Name	WWTW	Flow x10^6 m^3/a	SRP load (t)/a	SRP load at 1 mgP/l (t)	SRP load at 0.5 mgP/l (t)	%
A21D	Bloubankspruit	Percy Steward	9.855	44.3475	9.86	4.9275	16.25
A21D	Bloubankspruit	Randfontein	7.3	2.92	7.3	3.65	1.07
A21A	Hennops	Hartbeesfontein	16.425	5.84	16.43	8.213	13.04
A21A	Hennops	Olifantsfontein	38.325	35.59	38.33	19.16	7.35
A21B	Hennops	Sutherland Ridge	16.425	20.08	16.43	8.213	54.82
A21C	Jukskei	Northern WWTW Johannesburg	149.65	149.65	149.65	74.825	0.94
A21C	Jukskei	AECI	2.56	2.56	2.56	1.28	2.14
A21C	Jukskei	Modderfontein	5.84	5.84	5.84	2.92	2.01
A21E	Wilgespruit	Driefontein	9.125	5.48	9.13	4.56	1.34
A21H	Hartbeespoort	Rietfontein	0.73	3.65	0.73	0.365	0.05
A21F	Magalies	Magalies	0.128	0.13	0.13	0.064	1.00
A21H	Hartbeespoort	Schoemansville	0.55	2.74	0.55	0.275	1.00
		Return flow/day	**256.9**	**272.965**	**240.48**	**120.24**	**100**

SRP – soluble reactive phosphate

Phosphate concentrations in surface water from this study ranged from 1.03 to 1.84 mg/L, while groundwater concentrations ranged from 0.2 to 2.02 mg/L (Table 7). These ranges exceed the eutrophication threshold of 0.025 mg/L, indicating a high risk of nutrient enrichment and algal blooms. Seventy percent of the samples exceeded the South African wastewater effluent limit of 1 mg/L, suggesting nutrient contamination from agricultural runoff (fertilisers) and untreated sewage discharges, both of which contribute to elevated phosphate levels in water. Raw sewage from spills from overflowing and leaking sewer systems in the area has been a persistent concern, particularly as the Hartbeespoort Dam catchment includes approximately 16 sewage treatment works, which periodically overflow due to burst pipes, as illustrated in Figure 20. In groundwater, this suggests leaching of fertilisers and infiltration of wastewater into aquifer systems.



Figure 20: A picture showing sewage on a farmer's residence (Source: Kormorant, 2024)

Concentrations of nitrate in water arise from decaying organic matter, sewage, and fertilisers from agricultural runoff (Ramesh and Elango, 2012). Nitrate as N concentrations vary across the study area, with surface water concentrations ranging from 1.29 to 3.52 mg/L, which is below the permissible drinking water limits of SANS241 and WHO (2022). However, nitrate as N concentrations in groundwater range from 0.5 to 13.75 mg/L, with values exceeding the drinking water limits of 11 mg/L SANS241 and 10 mg/L WHO (2022). The elevated nitrate as N

concentrations in groundwater are indicative of anthropogenic contamination, particularly from excessive fertiliser application and leaching from sewage effluent and animal waste, posing potential health risks, especially for infants. Nitrate as N concentrations are higher in groundwater than in surface water due to the close proximity of boreholes to agricultural land. This indicates that the application of nitrate-based fertilisers has a more pronounced impact on elevating nitrate levels in groundwater. In addition to agricultural activities, sewage and effluents from septic tanks can percolate into groundwater systems, contributing to elevated nitrate concentrations. The presence of intensive fracturing in the Bushveld Igneous Complex (BIC), coupled with excessive irrigation, facilitates the infiltration of contaminants into shallow groundwater systems.

There is no clear trend in nitrate concentration levels from upstream to downstream, which suggests that nitrate contamination is localised. This indicates that certain farms use nitrate-rich fertilisers more intensively than others, and depending on the volume of irrigation, this may influence the degree of contamination. Over-fertilisation of crops by farmers during the growing season results in detectable concentrations of Nitrate as N in groundwater. Most boreholes around the Brits area are situated near agricultural land, which makes the groundwater systems more susceptible to contamination by agricultural activities.

5.7 Chlorophyll-a

Chlorophyll-a concentration serves as an indicator of algal biomass and potential eutrophication in aquatic systems. Figure 21 presents the chlorophyll-a concentrations measured in the sampled water.

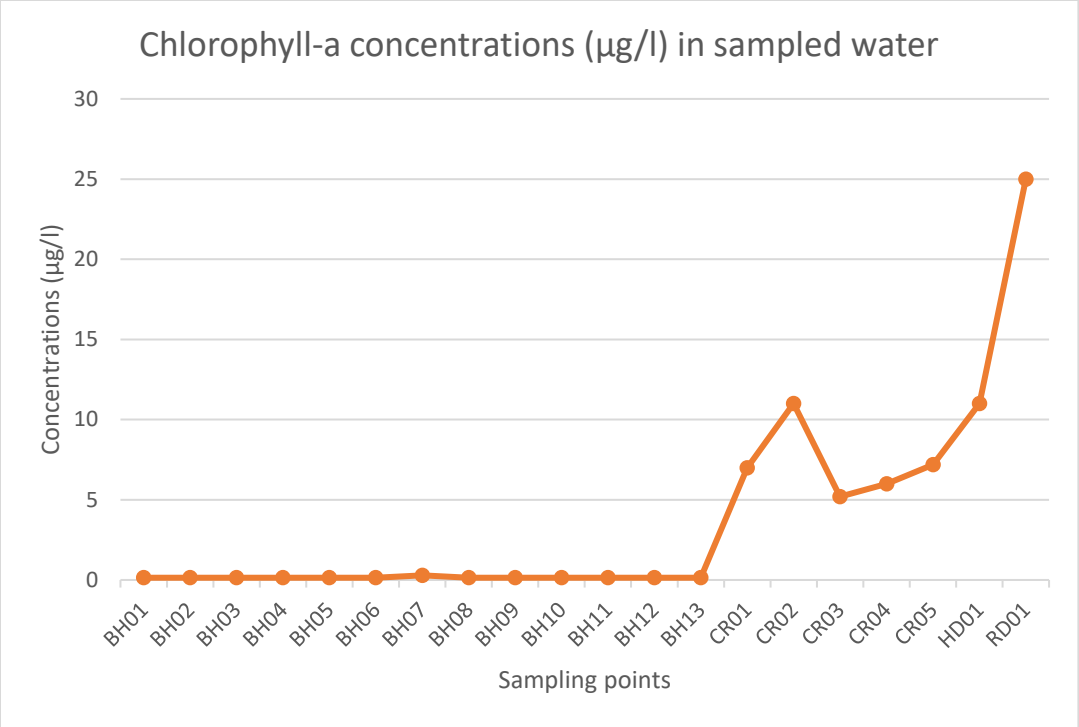

Figure 21: Chlorophyll-a concentrations tested in sampled water.

Figure 21 shows that groundwater samples, except for sampling point BH07, have chlorophyll-a concentrations below 0.14 µg/L. At BH07, chlorophyll-a concentration is 0.29 µg/L, most likely due to localised nutrient enrichment. Chlorophyll-a residues in groundwater may result from over-irrigation with eutrophied water from Hartbeespoort Dam, which has high chlorophyll-a concentrations that infiltrate the fractured rocks and enter the groundwater system. Crocodile River samples exhibit chlorophyll-a concentrations ranging from 5.2 to 11µg/L, with values fluctuating downstream. The order of surface water sampling points along the Crocodile River, moving downstream, is CR05, CR04, CR03, CR01 and CR02. There is a decrease in chlorophyll-a concentration from the first upstream surface water sampling point, CR05, to the third sampling point downstream, CR03. Chlorophyll-a concentrations are elevated by nutrient inputs, primarily phosphates, therefore, the concentrations vary with nutrient loading, resulting in both increases and decreases across sampling locations. From CR01 to CR02, chlorophyll-a concentrations increase, with CR02 exhibiting the highest value 11 µg/L, indicating localised nutrient enrichment.

Sample HD01, located upstream, also has a chlorophyll-a concentration of 11µg/L. Sample RD01, located downstream, where water from the Hartbeespoort Dam is discharged into the Crocodile

River, has the highest chlorophyll-a concentration of 25 µg/L, which is significantly elevated, suggesting eutrophic condition that needs urgent attention. This indicates that chlorophyll-a is being transported from the source (HD01) and accumulates along the Crocodile River before being discharged downstream to Roodekoptjes Dam, where further nutrient enrichment occurs. Varying water qualities with differing nutrient levels contribute to the progressive increase in chlorophyll-a concentrations along the river. Over-irrigation by farmers, canal overspills, and heavy rainfall events facilitate the downstream transport of contaminants. Chlorophyll-a detected in groundwater indicates infiltration of contaminated surface water. The trophic status of water sources is defined by the level of plant nutrients and the extent of plant growth. Table 9 presents chlorophyll-a and total phosphorus thresholds for various trophic levels, as defined by the OECD and the South Africa Department of Water Affairs (2008).

Table 9: Chlorophyll-a and Total Phosphorus limits set by OECD and DWA (2008)

Trophic Status	**Classification criteria**			
	International (OECD,1982)		South African (DWA, 2008)	
Parameter	Chlorophyll a (µg/L)		TP (µg/L)	
	OECD	DWA	OECD	DWA
Oligotrophic	≤2.5	≤10	≤10	≤15
Mesotrophic	2.5-8	10-20	10-35	15-47
Eutrophic	8-25	20-30	35-100	48-130
Hypertrophic	≥25	≥30	≥100	≥130

Based on the classification criteria using the DWA (2008), chlorophyll-a limits, the trophic levels for the sampling points with chlorophyll-a concentration of less than 10 µg/L are categorised as oligotrophic. These include samples BH01 to BH13, CR01, CR03, CR04 and CR05. The oligotrophic status indicates that the water body has low nutrient levels and is generally clear, with limited plant growth. CRO2 and HD01 fall within the mesotrophic category (10 -20µg/L), indicating that the water body contains moderate nutrient concentrations, supporting more biological productivity. The highest chlorophyll-a concentration was recorded in RD01, which had 25µg/L, classifying it as eutrophic. This status reflects a nutrient-enriched water body, which promotes excessive plant growth and may lead to algal blooms (Mitchell and Crafford, 2016).

Eutrophication in the Hartbeespoort Dam is primarily caused by excess phosphorus in the water, and total phosphorus concentrations show a positive correlation with chlorophyll-a levels (Ali et

al., 2022). The elevated chlorophyll-a concentrations in the Hartbeespoort Dam result from multiple nutrient sources within the catchment. According to Ali et al. (2022), Hartbeespoort Dam is one of the most productive eutrophic systems in South Africa, receiving inflows from rivers and streams that drain both formal and informal settlements in the Johannesburg region. Agricultural and industrial activities also contribute significantly to nutrient enrichment in the dam. Treated and partially treated effluent from Waste Water Treatment Works (WWTW) is discharged into the dam at a discharge rate of 5000 L/s (Leketa et al., 2018), a substantial volume that exacerbates water quality deterioration.

Water sources located downstream are more vulnerable to contamination and nutrient enrichment, as they are readily impacted by agricultural runoff, untreated wastewater, and sewage discharges. In addition to agricultural inputs, sewage discharge is a significant contributor to water pollution in the Brits area. The Brits Sewer Scheme includes numerous sewer pump stations, which have increased operational complexity and costs to such an extent that the local municipality struggles to manage them effectively. This has led to widespread operational failures and maintenance neglect. As a result, there have been persistent sewage spillages, with some residential properties being permanently flooded with sewage. A notable case involves a farmer who has been in an ongoing legal dispute with the Madibeng Municipality for over six years due to continuous sewage discharge on his property (Kormorant, 2024). There are also reports of spillages near cemeteries, raising serious public health concerns. Additionally, frequent sewer line bursts, attributed to poor maintenance, have been documented. These sewage spillages discharge directly into nearby rivers, promoting algal growth, and in some instances, leach into the groundwater system, exacerbating nutrient pollution.

Both wastewater discharge and agricultural runoff have contributed to elevated concentrations of nitrates and phosphates in the water system. The interaction of these nutrients promotes eutrophication, which in turn stimulates excessive algal growth, particularly in downstream reservoirs such as Roodekoptjes Dam. In these downstream water bodies, the cumulative input of nutrients tends to concentrate due to reduced flow velocities, allowing for nutrient settling and accumulation. This stagnant condition facilitates the proliferation of algal blooms, as indicated by elevated chlorophyll-a concentrations observed in the dam.

During periods of high irrigation return flow and heavy rainfall, excess water often spills from canals and runs off into the Crocodile River. A portion of this water also percolates through the soil, recharging the groundwater. However, this infiltrating water frequently carries dissolved salts, nutrients from fertilisers, and pesticide residues. Although return flows from Wastewater Treatment Works (WWTWs) and agricultural activities contribute to sustaining water volumes in rivers and dams, they significantly degrade water quality by increasing concentrations of organic matter and nutrients.

5.8 Irrigation water classification

Table 10 presents the calculated agricultural water quality parameters for five sampling points where water is utilised for irrigation purposes (BH02, BH08, BH13, HD01, and RD01).

Table 10: Results of the calculated MAR, SAR, %Na, Kelly's Ratio, PI, RSC and E.C. and the irrigation classifications.

Sampling points	SAR	SAR Class	MAR (%)	MAR Class	%Na	%Na Class	KR	KR Class	RSC	RSC Class	PI	PI Class	E.C µS/cm	E.C. Class
BH02	0.84	Excellent	50	Suitable	21.1	Good	0.35	Suitable	-3.43	Suitable	70.8	Permissible	582	Good quality
BH08	1.93	Excellent	21.2	Suitable	43.2	Permissible	0.78	Suitable	-2.16	Suitable	79.5	Good	508	Good quality
BH13	0.9	Excellent	49	Suitable	23.1	Good	0.38	Suitable	-3.12	Suitable	73.9	Permissible	513	Good quality
HD01	1.11	Excellent	40.6	Suitable	36.6	Good	0.56	Suitable	-1.19	Suitable	82.7	Good	536	Good quality
RD01	1.1	Excellent	43.8	Suitable	33.9	Good	0.52	Suitable	-2.18	Suitable	71.6	Permissible	368	Good quality

The suitability of water for irrigation was assessed through the estimation of various indices, including SAR, MAR, %Na, KR, RSC, and PI, while EC was measured in the field. The SAR values for the selected sampling points ranged from 0.84 to 1.93. According to the irrigation water quality classification (refer to Table 4), these values fall within the excellent category, indicating a minimal risk of sodium-induced soil salinity. SAR is a critical parameter that evaluates sodium and alkali hazards to crops and provides insight into the overall suitability of water for irrigation use.

Additionally, elevated sodium concentrations relative to calcium and magnesium can lead to increased salinity in irrigation water. The Magnesium Adsorption Ratio (MAR) is an important parameter for assessing the impact of magnesium on soil quality. High MAR values can lead to soil alkalinity, which reduces crop yields by impairing soil permeability and nutrient availability (Mukonazwothe et al., 2022). In this study, MAR values ranged from 21.24 to 50, indicating variability in magnesium concentration across the sampled points. These values fall within the range classified as suitable for irrigation, with BH02 recording the highest MAR value at the upper threshold of 50. Although these values meet the acceptable criteria for irrigation use, sustained exposure to high magnesium levels may gradually increase soil alkalinity, thereby negatively impacting long-term soil productivity if not adequately managed.

Sodium percentage (%Na), which indicates the proportion of sodium ions relative to the total concentration of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}), ranged from 21.13 to 43.21 across the sampled sites. The highest %Na value was recorded at BH08. According to irrigation water quality classification standards, four of the sampling points fall within the good category for irrigation, while BH08 is classified as permissible. Although these values are within acceptable thresholds for irrigation use, sustained application of water with high sodium levels can lead to sodium accumulation in soils, which adversely affects soil structure, permeability, and fertility over time. Therefore, proper irrigation management practices are essential to mitigate long-term impacts on soil health.

Kelly's Ratio (KR) and Residual Sodium Carbonate (RSC) values for the selected sampling points range from 0.3486 to 0.7777 and -3.4267 to -1.1887, respectively. According to established irrigation water quality guidelines, these values fall within the suitable category for irrigation purposes. Kelly's Ratio, which evaluates the sodium content relative to calcium and magnesium,

indicates that all sampled waters pose a low sodium hazard to soil and crops. Similarly, RSC, which assesses the potential for carbonate and bicarbonate to react with calcium and magnesium in water, provides insight into the risk of forming precipitates that may reduce soil permeability and induce alkalinity. These ranges are classified as suitable for irrigation based on the classification in Table 4. Residual Sodium Carbonate (RSC), which assesses carbonate and bicarbonate hazards in water in relation to calcium and magnesium, can result in total precipitation of calcium and magnesium if high concentrations of bicarbonates and carbonates are experienced. If the carbonates are excessive, this can be hazardous to the compounds of soil structures (Mukonazwothe et al., 2022). The calculated RSC values show that the water is suitable for irrigation, and this indicates that the water has a low risk of causing soil alkalinity problems.

The Permeability Index (PI), which evaluates the long-term effects of irrigation on the soil permeability, was calculated for selected sampling points, with values ranging from 70.82 to 82.707. According to the classification criteria, PI values greater than 75 fall within class 1 (good for irrigation), while values below 75 are placed in class 2 (permissible for irrigation). Based on these results, samples BH02, BH13, and RD01 fall into class 2, suggesting permissible use. Although class 2 waters can be used for irrigation, they are considered to be of lower quality, and their long-term use may lead to reduced soil permeability, especially if bicarbonate levels increase relative to calcium. This could compromise soil structure and affect crop productivity. Therefore, continued monitoring and proper soil management practices are recommended to mitigate any potential adverse effects.

Long-term irrigation using groundwater from BH08 and surface water RD01 will lead to a gradual deterioration of soil quality, particularly if sodium, magnesium or bicarbonate concentrations increase over time. Although current classifications indicate that the water is within acceptable limits for irrigation, prolonged use without appropriate management can result in adverse effects, such as soil salinisation, alkalinity and reduced permeability. To mitigate these risks, it is essential to implement continuous water quality monitoring and adopt proactive soil management strategies, including the use of soil amendments, crop rotation, and proper drainage systems. These practices can help sustain soil health and maintain agricultural productivity over the long term.

5.9 Pesticide Residuals

Table 11 presents the concentrations of organochlorine pesticide parameters detected across all sampling points.

Table 11: Recorded organochlorine pesticide concentrations from sampled points in µg/L.

Parameter	BH 01	BH 02	BH 03	BH 04	BH 05	BH 06	BH 07	BH 08	BH 09	BH 10	BH 11	BH 12	BH 13	CR 01	CR 02	CR 03	CR 04	CR 05	HD 01	RD 01	DWAF (1996) guidelines µg/L	WHO (2022) Guidelines µg/L
Alpha-HCH	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	X	2
Beta-HCH	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	X	2
Gamma-HCH	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	X	2
Delta-HCH	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	X	2
Alpha-Chlordane	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	X	2
Gamma-Chlordane	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.025	0.2
Aldrin	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.01	0.03
Dieldrin	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.2	<0.2	<0.2	<0.2	<0.2	0.005	0.03
Heptachlor	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.005	0.03
Heptachlor Epoxide Isomer B	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	X	0.03
4,4'-DDD	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	X	X
4,4'-DDE	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	X	X
4,4'-DDT	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.5	2
Methoxychlor	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.02	0.02
Endrin	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	0.002	0.6

X – does not have a guideline value available

All organochlorine pesticide residues detected across the sampling points were present at concentrations below the detection limit.

Table 12 below shows the concentration of organophosphate pesticide residues detected in all the sampling points.

Table 12:Recorded organophosphorus pesticide concentrations from different tested sampling points in µg/L.

Parameter	BH01	BH02	BH03	BH04	BH05	BH06	BH07	BH08	BH09	BH10	BH11	BH12	BH13	CR01	CR02	CR03	CR04	CR05	HD01	RD01	DWAF (1996) guidelines µg/L	WHO (2022) guidelines µg/L
Dichlorvos	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	X	X
Fenchlorphos	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	X	X
(Ronnel)																						
Methyl	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	X	X
Parathion																						
Chlorpyrifos (Dursban)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	X	X
Prothiofos ((Tokuthion)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	X	30
Mocap (Ethoprophos)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	X	X
Disulfoton	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	X	X
Guthion (Azinphos-methyl	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	X	X

X – does not have a guideline value available

All organophosphorus pesticide residues detected across the sampling points were present at concentrations below the detection limit.

6.0 CONCLUSION

Groundwater and surface water chemistry in this study are influenced by agricultural drainage, wastewater drainage, mineral dissolution, enhanced water-rock interactions, and mining effluents. The geology of the study area has contributed significantly to water quality in the Brits area, and the dissolution of dolomitic rocks in contact with the Bushveld Complex has contributed to elevated bicarbonate concentrations. Higher electrical conductivity in groundwater (390 - 801µS/cm) compared to surface water indicates mineral dissolution, which has resulted in elevated concentrations of sodium, calcium, magnesium, sulphates, nitrates, phosphates and chloride concentrations. This study indicates that agricultural activities are a major contributor to the degradation of water quality. Nutrient residues such as nitrate and phosphates were detected in all samples, with groundwater exhibiting significantly higher concentrations, ranging from 0.5 to 13.75 mg/L and 0.2 to 2.02 mg/L, respectively, compared to surface water. This also highlights the shallow nature of the aquifers and suggests that their close proximity to irrigated land facilitates contaminant transfer through fractures.

The elevated levels of nutrients from agricultural activities, sewage, and industrial effluents have contributed to the eutrophication of dams. The use of eutrophic water from Hartbeespoort Dam for irrigation is contaminating both groundwater and surface water due to its high chloropyll-a concentrations. As surface water flows from the upstream Hartbeespoort Dam through the Crocodile River, it becomes increasingly enriched with nutrients and mixes with various water sources from irrigation return flows. Roodekoptjes Dam exhibits the highest chlorophyll-a concentration of 25 µg/L, indicating that as water flows downstream, it accumulates a range of contaminants. This dam is therefore classified as eutrophic and requires the implementation of remedial measures.

Pesticide residuals were detected at all the sampling points, indicating that pesticide application in the study area, particularly through irrigation, is playing a significant role in surface runoff, as these are being found far from their original points of application and are percolating into the groundwater systems. The calcium-sulphate water type is indicative of agricultural contributions to contamination. In addition to agricultural sources, the presence of wastewater discharges from WWTW and sewage spillages is further contributing to nutrient enrichment and contamination of water sources. Over time, the combined influence of agricultural inputs and urban effluents poses

a risk of further degradation of water quality, particularly in downstream ecosystems, which are already at risk. Groundwater used for drinking purposes contains pesticide residues and other contaminants, and continued use may pose significant health risks. Similarly, water used for irrigation is gradually degrading crop quality, and the contaminants dispersed through runoff are harmful to the environment.

Mining in the Brits area has significantly impacted water quality, resulting in elevated sulphate concentrations and increased levels of total dissolved solids, which in turn contribute to higher electrical conductivity in water. Water that leaches through mining tailings dissolves minerals and transports them into surface and groundwater systems. The continuous use of such contaminated water may have a considerable impact on both water quality and agricultural produce. This study has demonstrated that agricultural activity in the Brits area has adversely affected the quality of both surface and groundwater.

7.0 RECOMMENDATIONS

- Policy makers and environmental regulators should enforce policies to minimise the effects of agricultural activities and wastewater discharges that are resulting in nutrient enrichment in water
- Water Management Authorities like the Department of Water and Sanitation should lower the phosphate concentration levels in Hartbeespoort and Roodekoptjes Dam by the process of lime dosing.
- The Department of Agriculture should promote rational farming practices by providing education and training programs to farmers.
- Farmers should implement appropriate fertiliser formula-based practices that align with the mineralisation of the soil and its organic matter.
- Implementation of drip irrigation by farmers to preserve water resources is recommended.
- Municipalities should be encouraged to improve the management of wastewater infrastructure.
- Use of remote sensing by environmental agencies and monitoring authorities for effective water quality monitoring is also recommended.

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