



**Assessing the Degree of Pollution of Groundwater by Heavy Metals  
in and around Kolomela Mine, Northern Cape Province**

**by  
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**Submitted to University of South Africa  
in Fulfilment of the Requirements for the Master's Degree in  
Environmental Science**

**In the  
  
Department of Environmental Sciences  
College of Agriculture and Environmental Sciences University  
of South Africa**

**May 2026**

## **DECLARATION**

I, Goitseone Precious Tsele, do hereby declare that this dissertation is the result of my own investigation and research and that it was not submitted in part or full for any other degree or to any other university.

## **ACKNOWLEDGEMENTS**

For the various activities conducted towards the completion of my research project and meeting requirements for the Master's (MSc) degree qualification in Environmental Management, there are various individuals and organisations who have contributed positively and meaningfully, thus worthy of acknowledgement. I am very thankful to Kolomela Mine located at Postmasburg (Northern Cape) which is an important operation for Anglo-American-Kumba. We are grateful for the permission they granted and allowing us the opportunity to research the pollution aspects of some of their mining activities. Similarly, I am indebted to the guidance and training provided to me by my supervisor, Professor Isaac T. Rampedi. The commentary he provided during the course of the research project is gratefully acknowledged. I am also appreciative about the administrative support provided to me by the Department of Environmental Sciences at the University of South Africa (UNISA). The bursary opportunity I received from UNISA helped my financial situation to execute my research project successfully. I wish to thank Professor Solomon G. Tesfamichael for some of the maps that he contributed towards their accurate design and to the highest geoinformatics standards possible, thus readable and complete with appropriate detail. Similarly, my daughter, Warona Gosego Tsele, has been incredibly kind and caring during my enrolment and research period at UNISA, and she always supported, encouraged and believed in me in all of my endeavours.

## ABSTRACT

This study has assessed the extent of heavy metal contamination in groundwater around the Kolomela iron ore mine in the Northern Cape Province of South Africa. A case study research design was employed, focusing on four existing groundwater monitoring boreholes (BH1–BH4) located in and around the mine. Groundwater samples were collected repeatedly over an eight-month period, thus covering different seasonal conditions to capture temporal variability or similarity in metal concentrations. Sampling followed standardised groundwater collection–procedures, and laboratory analyses were conducted to determine concentrations of selected heavy metals, including Lead (Pb), Calcium (Ca), Copper (Cu), Chromium (Cr); Manganese (Mn); Nickel (Ni), Thallium (Tl); and Zinc (Zn). The data were analysed in the laboratory by means of Inductively Coupled Plasma–Optical Emission Spectroscopy and their patterns and trends were summarised by the use of descriptive statistical methods. The results were evaluated against South African drinking water standards (SANS 241) and World Health Organization (WHO) guideline values to assess groundwater quality. The results revealed a spatially and seasonally heterogeneous distribution of heavy metals across the monitored boreholes. While several metal concentrations remained within acceptable limits, elevated levels of certain metals were observed at specific boreholes and sampling periods, thus exceeding recommended guideline values and indicating potential risks to groundwater quality. These findings demonstrate that groundwater quality in mining environments may vary significantly over space and time, even within a single mining operation. The study highlights the need for improved groundwater management and regulatory oversight at Kolomela Mine, particularly in semi-arid regions where communities rely heavily on groundwater as a primary water source. The research indicates the importance of routine groundwater monitoring, adherence to national water quality standards, and transparent reporting of water quality data to regulatory authorities and affected communities. Thus, the findings provide an empirical basis to support evidence-based mine water management and policy implementation aimed at protecting groundwater resources and safeguarding environmental and public health in South Africa’s mining sector.

**Keywords:** Heavy metal contamination; Groundwater quality; Kolomela Mine; Northern Cape; Mining pollution; Water quality management.

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## CHAPTER 1

### INTRODUCTION AND BACKGROUND TO THE STUDY

#### 1.0 Introduction

The environmental and health impacts of heavy metals are receiving global research attention due to their magnitude and significance (Goudie, 2018; Jomova et al., 2025; Mitra et al., 2022; Qureshi, 2021). Some of the areas that have been affected the most are located in close proximity to mining activities, especially for precious metals such as platinum group metals, gold, copper and others. According to Bernade et al. (2025), Of significant concern are heavy metals, a pervasive component of waterborne pollutants, that is infiltrating both surface water bodies and subterranean aquifers. According to Elumalai, Brindha and Lakshmanan (2017), metals sourced from the confluence of natural geological processes and human activities such as mining and industrial practices, are contributing to the release of these pollutants into the environment.

Among these activities, the mining industry is widely regarded as a significant source of heavy metal contamination, primarily through the generation of metal-bearing wastes. Mining activities produce tailings, waste rock, and acid mine drainage, which lead to the dissolution and transport of heavy metals into underlying groundwater systems, thereby posing risks to water quality and public health (Fashola, Ngole-Jeme, & Babalola, 2016). The extraction and processing of minerals, that is integral to mining operations, is resulting in the production of diverse waste materials laden with heavy metals and chemical residues. As Aznar-Sánchez et al. (2018) pointed out, these mining-related wastes, comprising flotation tailings, fragmented rock-soil residuals, and other by-products, often contain elevated concentrations of heavy metals and acidic compounds. Ebenebe et al. (2017) are of the view that the disposal of such waste, often inadequately managed, leads to rampant contamination of surrounding ecosystems and groundwater systems, thereby adversely affecting communities residing near mining areas.

#### 1.1 Background to the Study

As mentioned earlier, mining activities generate large volumes of waste materials such as waste rock, tailings, and slag that often contain high concentrations of heavy metals and

acidic compounds (Hudson-Edward & Dold, 2015; Elumalai et al., 2017b). If not properly managed, these wastes can leach and seep into surrounding soils and water bodies, thereby leading to contamination of surface and groundwater resources (Aznar-Sánchez et al., 2018; Tiwari et al., 2025). According to various studies, the disposal of mining waste without adequate safeguards has caused widespread environmental degradation, including the pollution of aquifers that supply drinking and irrigation water (Punia & Singh, 2021; Talukder et al., 2024). Groundwater is especially vulnerable because it is a primary source of freshwater in many regions and once contaminated, it is difficult to remediate. Globally, groundwater constitutes about 98% of the planet's available fresh water and supports a significant portion of the population's water needs (Velis et al., 2017). In South Africa, groundwater is a critical resource, particularly for rural communities and arid regions (Turton et al., 2006). Approximately two-thirds of South Africa's rural inhabitants rely on groundwater for domestic water supply (Ngema et al., 2024). This heavy reliance means that any degradation in groundwater quality can directly threaten community health, economic activities, and ecological systems.

Once in the subsurface, heavy metals such as lead (Pb), arsenic (As), cadmium (Cd), mercury (Hg), and others can persist and accumulate, thereby posing long-term environmental and health risks. These metals are non-biodegradable and can biomagnify through food chains and water-based pathways, thus endangering both ecosystems and human populations (Tiwari et al., 2025). Health impacts of excessive heavy metal exposure are well documented. For instance, arsenic in drinking water has been linked to skin lesions, growth abnormalities, and cancers, while lead poisoning can impair cognitive development in children while contributing to cardiovascular problems in adults (Al Osman et al., 2019; Rheman et al., 2018). It is for these reasons that the World Health Organization (WHO) classifies arsenic, lead, cadmium, and mercury as some of the top ten chemicals of major public health concern (WHO, 2020). Protecting water resources from such contaminants is therefore a national and global priority.

South Africa's mining legacy has underscored these concerns, as the country has experienced several instances of water pollution related to mining (Kengni & Mostert, 2022). In particular, acid mine drainage (AMD) has emerged as a significant environmental challenge in mining regions (Mogashane et al., 2025). AMD occurs when sulphide-bearing minerals mostly common in gold and coal deposits are exposed to oxygen and water,

producing acidic water that leaches heavy metals from rock formations (Lazo, 2020). Historic gold and coal mining areas in South Africa's Witwatersrand and Mpumalanga regions have suffered severe groundwater and surface water pollution from AMD, with elevated levels of metals such as iron, manganese, uranium, lead and others detected in affected waters (Abiye & Ali, 2022; Fosso-Kankeu et al., 2016). This pollution has degraded ecosystems and water supplies, despite the existence of environmental regulations designed to prevent such outcomes. For example, the Department of Water Affairs and Forestry (DWAF) reported as early as 2002 that industrial effluent discharge and mining activities were contaminating groundwater with heavy metals in some watersheds (Elumalai et al., 2017). Although South Africa's laws such as the National Water Act (Act No. 36 of 1998) and mining regulations mandate environmental protection, enforcement gaps and the challenge of rehabilitating abandoned mines mean that contamination episodes continue to occur (Kuipa & Lekunze, 2024). Communities near mining operations are therefore at risk if rigorous water quality monitoring and management are not in place. Given the country's dependence on groundwater for agriculture and drinking needs (Adam et al., 2012; Colvin et al., 2008), there is a pressing need for site-specific studies that evaluate the impact of mining on groundwater quality and provide data to guide remediation and policy measures.

The Kolomela Mine, located near Postmasburg in the Northern Cape, operates in a semi-arid region where groundwater is a valuable resource for both the mine and local communities (Department of Water & Sanitation [DWS], 2008; DWS, 2018). The Northern Cape is South Africa's driest province, characterised by low and highly variable rainfall, high evaporation rates, and limited surface water availability, resulting in a strong dependence on groundwater for domestic, agricultural, and industrial use (DWS, 2008; Statistics South Africa, 2022). In such water-scarce regions, any deterioration in groundwater quality can have significant implications for water security, ecosystem integrity, and human health (WHO, 2017).

Despite the scale and economic importance of iron ore mining in the Postmasburg area, there is limited publicly available data, empirical studies on groundwater quality and heavy metal contamination specifically associated with the Kolomela Mine. Existing national and provincial groundwater assessments generally provide regional overviews and do not offer mine-specific evaluations of heavy metal concentrations (DWS, 2018). Mining

environments differ markedly in the type, mobility, and concentration of contaminants, depending on the local geology, hydrogeology, and mining practices (Bowell et al., 2023; United States Geological Survey (UGS, 2020). Although iron ore mining is typically associated with a lower risk of acid mine drainage compared to coal or gold mining, the disturbance of ore bodies and waste rock can still mobilise naturally occurring metals such as iron, manganese, arsenic, and trace metals through weathering, blasting, and water–rock interactions (Bratkova & Tsvetkov, 2024; Simate & Ndlovu, 2014)

Given the strategic economic role of Kolomela Mine and the reliance of surrounding communities on groundwater as a primary water source, there is a clear need for site-specific assessment of groundwater quality in the area. This study was therefore undertaken to address this knowledge gap by systematically assessing heavy metal concentrations in groundwater in and around Kolomela Mine, with particular attention to spatial and seasonal variability. By generating empirical, site-specific data, the study provides an evidence base to support groundwater management, environmental monitoring, and regulatory decision-making within South Africa's mining sector.

## **1.2 Problem Statement**

Mining has long been a cornerstone of South Africa's economy; however, it is also associated with significant environmental and public health challenges (Matebesi, 2021). One of the most critical concerns is the contamination of water resources by toxic heavy metals released through mining activities. Despite the existence of modern environmental regulations, the disposal of heavy metal–laden mine waste continues to threaten soil and groundwater quality in many mining regions (Barrett, Gilligan, & Kaur, 2019). Heavy metals commonly associated with mining activities, including lead, arsenic, cadmium, copper, zinc, and nickel, are of particular concern due to their toxicity, persistence, and tendency to accumulate in environmental systems (WHO, 2017). Numerous studies conducted globally and within South Africa have demonstrated that groundwater in the vicinity of mining operations often contains elevated concentrations of heavy metals that exceed drinking water standards, posing direct risks to human health and ecosystems (Elumalai et al., 2017; Mthembu et al., 2022; Rashid et al., 2023; Wang et al., 2022). For instance, investigations in South African coal mining areas have documented the leaching of metals such as iron, manganese, and lead into groundwater at concentrations above permissible limits,

exposing dependent communities to long-term health risks such as neurological impairment, organ damage, and increased cancer susceptibility (Nephalama & Muzerengi, 2016). The persistence and bioaccumulative nature of these contaminants underscore the need for continuous groundwater monitoring and effective management interventions.

In the context of the Kolomela Mine in the Northern Cape Province, the central problem addressed by this study is the lack of site-specific empirical evidence regarding the extent of heavy metal contamination in local groundwater resources. Prior to this investigation, it had not been clearly established whether mining activities at Kolomela Mine have resulted in elevated concentrations of heavy metals in the surrounding aquifer system relied upon by the mine and nearby communities. While mining-related groundwater contamination has been well documented in other regions of South Africa (Belle et al., 2021; Ochieng et al., 2010), the absence of comparable assessments at Kolomela Mine represents a critical knowledge gap. This study addresses that gap by systematically assessing the concentrations of selected heavy metals (Pb, Zn, Cu, As, and Ni) in groundwater from boreholes around Kolomela Mine and evaluating these concentrations against national drinking water standards (SANS 241) and international guideline values (WHO). The core problem, therefore, lies in determining whether mining activities at Kolomela Mine have compromised groundwater quality through heavy metal contamination to levels that pose environmental and human health risks, thereby necessitating targeted management and mitigation measures to protect groundwater resources in the area.

### **1.3 Research Aim, Objectives and Questions**

#### **1.3.1 Aim of the study**

The aim of the study was to assess the pollution of groundwater by heavy metals due to mining activities at Kolomela Mine in the Northern Cape Province.

#### **1.3.2 Research objectives**

The study was guided by the following objectives:

- To assess the concentrations of heavy metals in groundwater around Kolomela Mine

- To determine the influence of temporal variations on these levels.
- To analyse the seasonal and spatial variations of heavy metal concentrations in groundwater from boreholes at Kolomela Mine

### **1.3.3 Research questions**

The study was guided by the following questions:

- What heavy metals are present in groundwater at Kolomela Mine in the Northern Cape Province, South Africa, and what are their respective concentration levels?
- What are the different impacts on the water quality of affected areas?
- What are the spatial and temporal variations in the pollution load based on different seasons of the year?

### **1.3.4 Rationale and Justification of the Study**

The Northern Cape Province is widely recognised for large-scale mining activities, including iron ore extraction at Kolomela Mine, which form a major component of South Africa's mineral sector. In this arid province, groundwater represents a critical water resource for rural communities, supporting domestic use, livestock watering, and small-scale agricultural activities. However, groundwater resources in the Northern Cape are increasingly under pressure due to expanding mining activities and competing water demands, raising concerns about both water availability and quality (Farmers Weekly, 2012; Eyewitness News [EWN], 2025).

Mining activities have the potential to adversely affect groundwater quality through the mobilisation of heavy metals, including arsenic (As), lead (Pb), mercury (Hg), and cadmium (Cd), into underlying aquifers. Such contamination has been widely documented in mining-impacted groundwater systems, where elevated concentrations of heavy metals have been linked to ecological degradation and potential human health risks. These risks are of particular concern in communities that rely directly on untreated groundwater sources for daily use.

Although heavy metal contamination of groundwater has been investigated in other mining and rural regions of South Africa, including Limpopo Province where borehole groundwater has been assessed for trace metal levels and potential health risks (Mutleni

et al., 2023), there remains limited published, site-specific information on groundwater quality within the immediate environment of Kolomela Mine.

### **1.3.5 Environment**

The primary rationale of this study stems from the urgent need to comprehend and mitigate the environmental degradation caused by heavy metal contamination in groundwater, primarily in regions surrounding mining areas. The rampant pollution attributed to mining activities poses a significant threat to the integrity of natural ecosystems, emphasising the imperative to safeguard critical environmental resources from irreversible damage (Zhang et al., 2023).

### **1.3.6 Local Communities**

The implications of heavy metal contamination in groundwater extend far beyond environmental concerns; they directly impact the health and livelihoods of the communities surrounding the Kolomela Mine in the Northern Cape Province, which is reliant on these water sources. Thus, the study aimed to shed light into the potential toxicity and health risks posed by contaminated groundwater, thereby advocating for the wellbeing of residents and fostering informed decision-making for sustainable water usage.

### **1.3.7 Policy Makers and Government Regulations**

The study is poised to furnish empirical evidence crucial for policymaking and regulatory interventions. Insights garnered from this research can inform the formulation and implementation of robust environmental regulations, ensuring the preservation of groundwater quality and the conservation of natural resources.

## **1.4 Study Limitations (Inclusions and Exclusions)**

The research included and excluded the following aspects as illustrated below:

- Sampling sites: Boreholes BH1, BH2, BH3, and BH4 were the only designated and sampled study locations.

- Pollutants of interest: These are the heavy metals that were tested in current research whether they were detected or not (e.g., lead, calcium, copper, zinc, chromium, and manganese; nickel, and thalium).
- Time frame: There was 8 months (February-October 2023) data collection period, thus allowing for seasonal variations to be delineated.
- Groundwater quality parameters: parameters such as pH, electrical conductivity, and possibly other hydrochemical indicators were not investigated in this research.
- Case study scope: Focused specifically on Kolomela Mine and its immediate surroundings, thus not generalized to other mines.

The following aspects must be regarded as exclusions to the study:

- Other pollutants: Non-metal contaminants (e.g., nitrates, sulfates, hydrocarbons, microbiological contaminants) are outside the scope of the current study.
- Surface water bodies: Rivers, streams, or dams near mine are excluded unless explicitly linked to groundwater recharge.
- Extended geography: Areas beyond the immediate vicinity of Kolomela Mine are not part of the study.
- Long-term monitoring: Impacts beyond the nine-month period are excluded, meaning no conclusions about long-term trends were drawn in this study.
- Socio-economic impacts: Human health outcomes, agricultural effects, or community perceptions are not studied in this research.

### **1.5 Structure of the Dissertation**

The dissertation is structured into five chapters, each addressing a specific aspect of the study. Chapter 1: Introduction and Background outline the research problem, provides context for the study area, and states the research aim, objectives and questions. Chapter 2: Literature Review reviews relevant literature on groundwater pollution by heavy metals, including the sources of contamination, the environmental and health impacts, case studies from other mining regions, and existing mitigation strategies and regulations. Chapter 3: Study Area and Research Methodology describe the geographic and environmental characteristics of the Kolomela Mine area and details the research design, data collection procedures, and analytical methods

used in the study. Chapter 4: Presentation and Discussion of Results presents the findings on heavy metal concentrations in the groundwater (organised by borehole and season) and discusses these results in the context of South African water quality guidelines and findings from the literature. Chapter 5: Recommendations and Conclusion summarise the key research findings and conclusions regarding the degree of groundwater pollution, provides recommendations for mitigating heavy metal contamination and improving groundwater management, and suggests potential areas for future research.

## **CHAPTER 2: LITERATURE REVIEW**

### **2.0 Introduction**

Chapter 2 provides an overview of existing knowledge on groundwater contamination by heavy metals, with emphasis on mining-related contexts. Section 2.1 begins by explaining fundamental groundwater concepts and the importance of groundwater as a resource is summarised in Section 2.2 to 2.3. The review then examines how mining activities contribute to groundwater pollution and identifies the various sources of heavy metals that can leach into aquifers on (Section 2.4). Key heavy metal contaminants and their characteristics are discussed on Sections 2.5 and 2.6, along with factors (chemical, physical, seasonal) that influence their distribution and mobility in groundwater. Section 2.7 highlights documented cases of heavy metal pollution from mining around the world to contextualize the severity and scope of the issue. In Sections 2.8 to 2.10, the impacts of heavy metal-contaminated groundwater on water quality, ecosystems, and human health are explored, demonstrating why this issue is of concern. Finally, Section 2.11 outlines relevant regulatory frameworks for water protection, particularly in South Africa, and touches on common mitigation strategies. Together, these sections build a foundation for understanding the extent of groundwater pollution by heavy metals and the need for the present study. Section 2.12 is based on a brief summary of the literature review.

### **2.1. The nature and concept of groundwater**

Johnson et al. (2020) defined groundwater as the water that is held underground in soil, silt, or porous rock formations. Being mostly derived from precipitation that seeps into the earth, it fills in the gaps in the subsurface and is an essential part of the hydrological cycle. In addition, groundwater provides millions of people worldwide with their main supply of drinkable water, particularly in areas where access to clean surface water is scarce. As Nascimento et al. (2023) explained, supporting irrigation systems that are necessary for agricultural production and guaranteeing food security, groundwater plays a crucial role in agriculture and industrial operations such as manufacturing, and energy generation rely significantly on groundwater.

Groundwater is recognised as a vital freshwater resource for communities all around the world. This is according to a recent report by WHO (2021). The report highlights how vital groundwater is satisfying water demands for agriculture, drinking and maintaining the ecosystems. Considering the growing demand and possible dangers like pollution and overexploitation, the report also emphasises the need for sustainable management techniques to protect this vital resource. Ettazarini et al. (2021b) pointed out that maintaining the health of ecosystems, securing dependable water supplies for people, and securing the durability of this essential resource for future generations all depend on sustainable groundwater management.

## **2.2 Groundwater pollution by mining activities**

Mining activities are well-documented as a major source of groundwater pollution across the globe. Acid mine drainage (AMD) is a prime example; and is based on the oxidation of sulphide minerals exposed by mining. AMD generates highly acidic water rich in metals, which can leach into aquifers (Bu et al., 2024). This process has been observed in mining regions worldwide and leads to elevated concentrations of iron, manganese, copper, zinc, and other heavy metals in nearby waters (Zhou et al., 2020). Improper disposal of mine wastes is another critical pathway for contamination. For instance, tailings storage facilities can seep or even collapse, releasing metals into soil and groundwater. Fashola et al. (2016) noted that in mining areas of Nigeria, elevated lead and cadmium in groundwater have been traced to such waste mismanagement. These examples underscore the consensus that mining-related pollution is a serious, and persistent problem (Ettazarini et al., 2021b). Heavy metal generation from mines pose long-term risks because they do not biodegrade and can accumulate in aquifers for decades.

Importantly, mining is not the sole cause of groundwater contamination, natural geochemical processes and other industries also contribute, but numerous studies confirm that mining operations are among the dominant anthropogenic contributors to heavy metals in groundwater. For instance, recent case studies in Germany's historic mining districts show that arsenic and chromium from abandoned mine tailings continue to leach into groundwater, thus exceeding safety levels (Dönig et al., 2020). Similarly, in Argentina, intensive mining without proper water protection led to toxic levels of metals in local aquifers until strict regulations were enacted (Villarino et al., 2021). The environmental and social implications are severe: heavy metal contamination from mines threatens the

health of communities and ecosystems reliant on groundwater. As Yusoff et al. (2022) reported, persistent contaminants like arsenic and lead around mining areas have been linked to diseases such as cancer, organ damage, and natural ecosystem disruption. This growing body of recent literature reinforces the ideas that mitigating groundwater pollution from mining is both an environmental and public health priority.

### **2.3 Sources of heavy metals in groundwater**

Heavy metals can enter groundwater from a variety of natural and anthropogenic sources. On the natural side, geologic processes slowly release metals: as metal-bearing rocks and minerals weather and dissolve, elements like arsenic, manganese, and iron can leach into groundwater over time (Raessler, 2018). For example, in parts of Bangladesh, naturally high arsenic in aquifer sediments has led to groundwater contamination without any industrial activity (Ahmed et al., 2018; Islam & Mostafa, 2024). These geogenic contributions form the background levels of heavy metals in groundwater.

#### **2.3.1 Other Potential Sources**

Human activities are often the dominant sources of elevated heavy metal concentrations (Alloway, 2013). Key anthropogenic sources include:

**Industrial Effluents:** Factories and industrial processes can discharge heavy metals in wastewater. For instance, metal plating and battery manufacturing release lead, cadmium, chromium, and others if effluents are not adequately treated. Liu et al. (2022) reported groundwater contamination by lead and nickel near a smelter in China, thus illustrating how improper handling of industrial waste can pollute underlying aquifers.

**Agricultural Runoff:** Intensive use of agro chemicals adds metals to the environment. Certain fertilizers and pesticides contain trace metals (cadmium, copper, zinc) which can accumulate in soils and eventually percolate down to groundwater (Arias et al., 2020). In many farming communities, long-term application of phosphate fertilizers has been linked to elevated cadmium levels in shallow groundwater above WHO limits.

**Urban and Domestic Waste:** Landfills and sewage can introduce heavy metals (from disposed electronics, paints, etc.) into groundwater. If landfills lack proper liners, leachate

containing metals like mercury or lead can seep into the subsurface. Similarly, septic systems in densely populated areas can release metals (along with other pollutants) into groundwater over time (WHO, 2021).

### **2.3.2 Mine Related Sources**

Mining-related sources are among the most acute and localized contributors of heavy metals to groundwater. The crushing, grinding, and processing of ore can directly introduce contaminants. For example, lead, arsenic, and chromium are often mobilized during the extraction of metal ores (Johnson et al., 2020). Moreover, large volumes of mining waste are typically stored in tailings dams or waste rock piles, which pose a long-term contamination risk. As Nascimento et al. (2023) explained, these waste repositories can leach metals like nickel, cadmium, and arsenic into groundwater through acid drainage or rainwater infiltration. Accidental releases also occur, as Nkono et al. (2020) documented cases where failures in mine infrastructure (e.g. ruptured pipelines or tailings dam breaches) led to sudden spikes in groundwater metal levels. Mercury contamination of groundwater has been observed near gold processing sites when containment measures fail, directly endangering community water supplies. In summary, natural sources (geogenic weathering) set the baseline, but anthropogenic sources, especially industrial discharges, agricultural inputs, urban waste, and mining activities are responsible for most instances of hazardous heavy metal concentrations in groundwater.

## **2.4 Type of heavy metals in groundwater**

Groundwater contamination from mining activities releases a variety of heavy metals, each of which presents unique risks to human health and the environment. Heavy metals from waste materials and ores are the main sources of emission during mining operations (Chavan et al., 2020). There are a few common heavy metals found in groundwater affected by mining.

- **Lead (Pb):** Lead ores are frequently associated with zinc, copper and gold. It poses serious health dangers, particularly to children and pregnant women, and seeps into groundwater through waste items and abandoned mines (Liu et al., 2022).

- **Asbestos (As):** This element is frequently found naturally in ores such as arsenopyrite and is discharged during mining operations. Because arsenic is carcinogenic, its pollution of groundwater in mining sites across the world is a serious problem (Chavan et al., 2020).
- **Mercury (Hg):** Mercury is used widely in the procedures of extracting gold, but contaminates soil and water and changes into methylmercury, which is more dangerous. There are serious health risks associated with its build-up in aquatic environments due to groundwater contamination (Goudie, 2018a).
- **Cadmium (Cd):** Found in zinc ores, cadmium contaminates groundwater through mining runoff and harms people's health over time. It may cause cancer, bone issues and renal damage, among other hazards (Aznar-Sánchez, 2018).
- **Sulphide:** ores are frequently linked to the metals copper (Cu), zinc (Zn) and nickel (Ni). According to Wang et al. (2020), although necessary in trace levels, their increased concentrations brought about by mining operations cause environmental imbalances and can be harmful to aquatic life.

There are several ways that heavy metals might enter groundwater as a result of mining activity. It may enter the environment throughout the mining process through procedures including drilling, blasting and excavation. Following their immersion in water, these metals disintegrate and seep into the groundwater. Furthermore, heavy metal pollution in nearby soil and water sources is exacerbated by the management, storage, and disposal of mining waste, tailings, and effluents without the required containment (Ettazarini et al., 2021b). Developing efficient mitigation and remediation solutions to safeguard groundwater quality requires a thorough understanding of these sources and kinds of heavy metals.

## 2.5 Physical and chemical properties

According to Netshiongolwe (2018b), the solubilities of certain metals in water differ, and affects how they move and transported through groundwater. Lead and mercury are usually less soluble than arsenic and chromium. A metal's oxidation state as Rautio

et al., (2022) explained, can impact both its toxicity and behaviour in the environment. For example, chromium is more hazardous in its hexavalent (Cr (VI)) form than in its trivalent (Cr (III)) form. In groundwater, organic materials and inorganic particles can bind to heavy metals, changing the transit and bioavailability of those particles.

## **2.6 Seasonal and spatial variations in heavy metal contamination**

Heavy metal concentrations in groundwater are not static; they fluctuate over time and space due to environmental and anthropogenic factors (Akhtar et al., 2021). Recent research emphasizes understanding these patterns to better predict contamination risks. In particular, variations can be observed on multiple scales:

**Seasonal Fluctuations:** Groundwater heavy metal levels often change with seasons. During wet seasons, increased rainfall can leach metals from contaminated soil or mine waste into aquifers, thus temporarily raising metal concentrations. A study by Ettazarini et al. (2021b) found higher arsenic and lead levels in groundwater immediately following heavy rains at a mining site, as percolating rainwater mobilized those contaminants. Conversely, in dry seasons, reduced recharge may concentrate existing metals due to lower dilution. A study in West Africa observed that cadmium and nickel concentrations were 20–30% higher in the dry season than the rainy season, and this was attributed to evaporation and lack of flushing (Nkono et al., 2020). Recent data from Bu et al. (2024) confirm these trends: in a karst aquifer affected by acid mine drainage, metal levels peaked in the wet season when runoff was high, then subsided during dry months. Such seasonal patterns are critical for designing monitoring programs and timing any remediation measures.

**Spatial Heterogeneity:** Heavy metal contamination tends to be unevenly distributed across different locations. Complex interactions between geology, hydrology, and pollution sources create spatial hotspots of contamination. For instance, groundwater near a mine tailings dam or down-gradient from a waste dump often exhibits much higher metal concentrations than wells further away (Bu et al., 2024). Wang et al., (2020) **noted** that factors like soil composition, groundwater flow paths, and proximity to contamination sources such as mines, industrial sites, and others, result in spatial variability. In practice, this means two wells only a few kilometres apart can have very different water quality if one lies in the path of a contamination plume. Mapping studies like those conducted by

Dheeraj et al. (2024) used GIS to visualize such heterogeneity, thereby identifying clusters of high heavy metal concentration in groundwater around specific mining zones while other areas remain relatively unaffected. Recognizing spatial patterns allows for targeted interventions, such as installing treatment systems at the most contaminated sites or focusing remediation efforts where they are needed most.

**Long-Term Temporal Trends:** Beyond short-term seasonal swings, heavy metal levels can exhibit long-term trends over years. Ongoing monitoring has revealed that in some mining regions, metal concentrations gradually increase year-on-year as contaminants accumulate in the aquifer (Ettazarini et al., 2021b). In other cases, the implementation of pollution controls causes a slow decline in groundwater metal content over time. For example, a decade-long study in northern China showed a steady decrease in lead and cadmium in groundwater after a nearby mine closed and remediation began (Sun et al., 2023). Tracking these temporal patterns is crucial: it helps determine whether contamination is worsening, stabilizing, or improving. Bu et al. (2024) emphasize that only with multi-year data can we distinguish transient spikes from true trends in groundwater quality. Such insights inform the effectiveness of mitigation measures and the need for any new interventions.

**Local Environmental Factors:** Site-specific conditions can amplify or mitigate contamination levels. Key factors include groundwater pH, redox potential, and the presence of other chemicals or sediments. For instance, low-pH groundwater (often a result of acid mine drainage) greatly increases metal mobility – under acidic conditions, metals like iron, zinc, and manganese are more likely to dissolve and spread (Simate & Ndlovu, 2014). Wang et al. (2020) explained that alkaline conditions, by contrast, can cause certain metals to precipitate or adsorb onto soil particles, thus reducing their dissolved concentrations. Redox conditions also play a role: in oxygen-poor (reducing) aquifers, elements like arsenic and manganese may be released from minerals into water (Rautio et al., 2022). Additionally, the depth of the well and aquifer characteristics (e.g., fractured vs. porous media) determine how quickly contamination moves and where it concentrates. Comprehending these local variances is vital for accurate risk assessment and for designing remediation strategies that account for the site's unique hydrogeology.

In summary, heavy metal contamination of groundwater is dynamic, and is varying with seasons, locations, and time (Jin et al., 2025). Some of the latest studies (Gómez-Escalonilla et al., 2024; Bu et al., 2024) reinforce that understanding these patterns improves our ability to predict when and where contamination will be most severe, and thus to implement timely and targeted mitigation. Rather than a static snapshot, continuous groundwater monitoring should be an ongoing effort capturing these fluctuations to fully protect water resources.

## **2.7 Case studies of heavy metal pollution in mining settings**

Heavy metal pollution from mining is a global concern, but responses and outcomes vary by region. Around the world, numerous cases illustrate both the severe impacts of mining on groundwater and the efforts taken to address them. On a global scale, many countries have experienced groundwater contamination due to mining and have implemented measures to combat it. For example, arsenic contamination has been a critical issue in iron ore mining regions of Asia. In Liaoning Province, China, leakage from tailings dams and oxidation of arsenic-rich minerals led to high arsenic levels in local groundwater, rendering well water unsafe. Remediation in that area has focused on improved tailings management and installing arsenic removal units for community water. Likewise, in Malaysia, Yusoff et al. (2022) reported elevated arsenic concentrations in both surface and groundwater near iron mines, prompting the government to tighten monitoring and push for better waste disposal practices. These cases underscore that mining-associated arsenic pollution is a widespread problem requiring proactive management.

Chromium pollution provides another cautionary case. In the Sukinda Valley of India, one of the world's largest chromite mining areas, groundwater samples contained hexavalent chromium (Cr (VI)) far above WHO guidelines, thus posing carcinogenic risks to local populations (Chavan et al., 2020). This contamination has affected agricultural wells and drinking supplies, spurring public health interventions. Across the globe in Albania, Shkurtaj et al. (2023) found that decades of chromite mining likewise left a legacy of chromium in groundwater and surface streams. Both studies call for cleaner mining techniques and treatment of mine effluents to prevent further leaching of toxic metals. These international examples highlight common themes that without proper controls,

mining can introduce dangerous metals into water, but acknowledging the issue is the first step toward remediation.

Some countries have responded with strict regulations and technological upgrades to protect water resources from mining pollution. Chile is a notable success story: faced with severe copper and arsenic contamination in the early 2000s, Chilean authorities enacted some of the world's toughest water quality standards for mining in 2014. The regulations forced mining companies to implement better wastewater treatment. As a result, studies recorded significant drops in copper and arsenic concentrations in rivers near major copper mines, and communities downstream experienced fewer cases of heavy metal exposure. Similarly, Germany tackled coal-mining pollution by strengthening legal requirements. The Federal Water Act amendments of 2009 mandated rigorous treatment of mine water. A subsequent evaluation by Lecher et al. (2023a) showed marked improvements: watercourses that had been degraded by acid mine drainage saw pH normalization and reductions in dissolved metals, and even mercury levels in fish declined as water quality recovered. These cases demonstrate that strong governance, enforcing strict discharge limits and modern treatment technologies, can yield positive outcomes in mitigating mining's impact on groundwater and ecosystems.

Looking at the African context, the challenges remain substantial. South Africa has grappled with acid mine drainage for a long time and heavy metal pollution from its extensive mining industry. For instance, in the Witwatersrand goldfields, uncontrolled mine water discharge led to acidic, metal-laden water contaminating aquifers and streams in Gauteng province (McCarthy, 2011). This has caused deaths of fish and other aquatic life and required costly water treatment initiatives by the government. In response, South Africa has begun implementing policies such as mandatory water management plans for mines and active treatment of acidic mine water (Mazwi, 2025). Moreover, other studies in southern Africa illustrate the long-term groundwater impacts of mining activities. In Zambia's Copperbelt, legacy copper and cobalt mining have been shown to contaminate groundwater through seepage from tailings impoundments (von der Heyden, 2004). Similarly, studies in Zimbabwe have reported elevated trace metal concentrations in groundwater near abandoned mine sites, thus prompting calls for rehabilitation measures and the provision of alternative clean water sources for affected communities (Kanda et al., 2021). These African case studies, though not geographically closer to Kolomela, show

that the region faces similar issues of heavy metal contamination. They reinforce the need for vigilant monitoring and intervention at mines like Kolomela to prevent long-term environmental damage.

In summary, heavy metal pollution of groundwater in mining regions is a global phenomenon, from Asia to Africa and to the Americas, with well-documented cases of both severe impacts and effective responses. The broad trend is that where mining operations proceed without adequate environmental safeguards, groundwater contamination follows, often with serious health and ecological consequences. Conversely, implementing strict regulations, modern treatment technology, and continuous monitoring can significantly reduce these impacts. This study at Kolomela Mine is situated within that global context. By learning from the international examples and considering local realities, it aims to identify any emerging heavy metal pollution and inform strategies to ensure the surrounding communities have access to clean and safe groundwater.

## **2.8 Impact on groundwater quality and ecosystems**

Heavy metal contamination of groundwater has far-reaching impacts on both water quality and living ecosystems. Yusoff et al. (2022) noted that when metals like arsenic, lead, or cadmium enter groundwater, they render the water unsafe for human consumption and irrigation, and they simultaneously pose grave threats to ecological systems. Heavy metals in groundwater can lead to a cascade of environmental problems: reduced species diversity in wetlands and streams, toxicity to aquatic organisms, and contamination of crops and soil if the water is used for agriculture (Guo et al., 2023).

In mining regions, where heavy metal contamination is often most acute, groundwater becomes a vector carrying pollutants into connected ecosystems. Once metals seep into an aquifer, they can travel and emerge in springs or rivers, spreading contamination. Elevated metal concentrations in groundwater make it unsuitable for drinking, farming, or livestock, as these metals can accumulate in plants and animals. Communities that rely on such water face serious health risks, for instance, chronic exposure to cadmium and lead from contaminated wells has been linked to kidney disease, neurological damage, and developmental issues in children (Elumalai et al., 2017a).

Moreover, as Guo et al. (2023) emphasized, heavy metals disrupt aquatic ecosystems. Metals like mercury, lead, and cadmium can accumulate in the tissues of fish and other aquatic organisms, leading to bioaccumulation (build-up in an organism) and biomagnification (increasing concentration up the food chain). Top predators (birds, larger fish) then receive harmful doses that can affect their reproduction and survival. As these metals bio-accumulate through the food web, they throw aquatic biodiversity and ecological equilibrium off balance, with entire populations of sensitive species declining in their numbers. For instance, mercury from mining can concentrate in fish; predators like otters or eagles that eat those fish may suffer neurological damage or breeding failure. With aquatic biodiversity and the stability of ecosystems disrupted, the services those ecosystems provide (like water purification, fisheries, etc.) are also compromised.

Heavy metal-laden groundwater can also lead to soil contamination when it rises to the surface or is used for irrigation. Over time, irrigating crops with contaminated water causes metals to accumulate in soils and plant tissues. This hampers plant growth and reduces agricultural productivity (Aznar-Sánchez et al., 2018). Crops grown in such conditions may yield less and carry health risks for consumers, as highlighted by Liu et al., (2022) who found even low-level cadmium in irrigation water can impair soil microbes and plant health. Contaminated soils may remain toxic for years, making land remediation costly and challenging.

In summary, the infiltration of heavy metals into groundwater from mining activities has a dual impact: it degrades water quality, making the water a hazard for human use, with aquatic biodiversity and ecological balance also being severely affected. The synergistic effect is a decline in environmental health, polluted water yields polluted soils and biota, ultimately affecting human communities through loss of clean water, food safety issues, and ecosystem services. These interlinked impacts underscore the importance of preventing heavy metal contamination at the source and remediating polluted groundwater before it cascades through the environment.

## **2.9 Multifaceted impact of contaminated water**

Heavy metal contamination of groundwater from mining activities can have wide-ranging socio-economic impacts on surrounding communities. While water pollution in general

carries costs, contamination traced to mining operations often has a distinctive profile, it can be geographically concentrated yet profound in effect, especially in resource-dependent regions (Rashid et al., 2023). In the next subsection, the key areas of impact are reframed in the context of mining-related groundwater pollution:

### **2.9.1 Reduced agricultural productivity**

When groundwater used for irrigation is contaminated by mining-derived metals, crop yields and soil health suffer. More broadly, studies across African mining regions demonstrate that mining activities, irrespective of the specific mineral extracted, can adversely affect agricultural systems through the contamination of water and soils with elevated metal concentrations. Evidence from copper- and cobalt-mining regions of the African Copperbelt, as well as other mining contexts, shows that irrigation with contaminated water can impair soil quality and crop performance, thus underscoring the vulnerability of farming systems located near large-scale mining operations (Muimba-Kankolongo et al., 2021; Mununga Katebe et al., 2023). Ndam & Madzimbamuto (2023) similarly showed that even trace amounts of heavy metals such as lead and cadmium in irrigation water can accumulate in crops, reducing yields and making produce unsafe for market. This directly threatens farmers' livelihoods in various ways: produce may be rejected due to contamination, and consumers lose trust in crops from the area. In mining regions of China, farmers around a lead-zinc mine experienced financial losses when their metal-tainted rice was deemed unfit for human consumption (Williams et al., 2009). The broader consequences are on food security, and if productive land is lost or outputs drop, local food supply and prices are affected (Hu et al., 2019; Liu et al., 2013). The World Bank (2023) warns that water pollution (including heavy metals from industrial and mining sources) could cause up to a 30% reduction in global food production, which would raise food prices and worsen food insecurity. Moreover, heavy metal contamination can persist in soils long after the mining stops, creating long-term fertility problems. Over years, metals like arsenic or mercury from mine waste can sterilize soil or kill beneficial microbes, making the land less productive even for future generations (Liu et al., 2022). In sum, mining-driven water pollution can undermine agriculture, thus translating into economic hardship for farming communities and higher costs for society to replace lost produce.

### **2.9.2 Recreation and Tourism**

Areas impacted by mining pollution often see a decline in recreational use of water bodies. If a mine's runoff turns a local river orange with iron or leaves oily sheens from other pollutants, tourists and residents will avoid these waters. This has been observed in parts of Gauteng, South Africa, where acid mine drainage from gold mines made rivers unsuitable for fishing or swimming, thus leading to the collapse of local recreational businesses (McCarthy, 2011). Chauhan et al. (2023) provide a parallel example: although their case was coastal, it showed a 20% drop in tourism revenue when water quality degraded. In mining towns, loss of recreational fishing or boating due to metal contamination similarly hits the local economy, equipment rentals, tour operators, and hospitality venues all suffer. Heavy metals also decimate fish populations as noted by Wu et al. (2023) where industrial metal pollution led to a 40% decline in fishing, which affects both commercial fisheries and angling tourism. The ripple effect extends to property values: waterfront or riverside properties near a mine can lose significant value if the water is polluted and unsightly. A U.S. study by Guignet et al. (2022) found home values along polluted rivers were ~15% lower than similar homes on clean rivers. We can expect a similar trend in mining-affected areas, properties near contaminated streams or with polluted well water become less desirable, thus reducing homeowners' equity and municipal tax bases. Thus, mining-related water contamination not only poses health risks but also erodes the recreational and economic vibrancy of communities.

### **2.9.3 Treatment and Mitigation Costs**

Once groundwater is contaminated by mining, costs escalate to treat the water and deal with health consequences. Removing heavy metals like arsenic or chromium from drinking water requires advanced filtration (e.g., reverse osmosis, ion exchange) which is expensive to install and maintain. Many mining companies and local governments face the financial burden of treating polluted mine water or providing alternative water supplies. For example, the South African government spends millions of rand annually on pumping and treating acid mine drainage water to make it usable (McCarthy, 2011). Globally, the World Bank (2023) estimates that over \$1 billion per year is spent in the United States on removing heavy metals from municipal water; a figure that includes areas impacted by legacy mining and industrial sites. In developing countries, such costs can be prohibitive, meaning communities may go without adequate treatment. Additionally, health care costs

rise when people consume mining-polluted water. Chavan et al. (2020) showed a clear link between arsenic-laden groundwater and increased incidence of cancers and heart disease. Treating these chronic illnesses imposes long-term costs on families and public health systems. Preventing exposure in the first place, through strict mining waste management, would be far cheaper than medical treatments after the fact. There are also infrastructure costs: water pipelines, wells, or distribution networks might require upgrades to avoid contaminated sources. Aging infrastructure can exacerbate contamination (Fashola et al., 2016), so investments must be made to modernize and protect water delivery in mining regions. All these expenses highlight an economic truth: pollution prevention is far less costly than remediation. Taking pre-emptive steps to contain mine pollutants and monitor groundwater saves money in the long run by avoiding the need for extensive clean-up, water substitution, and health care for affected populations (Guo et al., 2023).

In conclusion, heavy metal contamination of groundwater due to mining has multidimensional socio-economic impacts: it undermines agricultural output and food security, diminishes recreational and property value, and incurs heavy costs for water treatment and health care. Importantly, these impacts reinforce the need for mining companies to adopt responsible practices and for regulators to enforce standards. The economic incentives align with environmental ones, protecting groundwater from contamination not only safeguards health and ecosystems, but also preserves livelihoods and avoids substantial costs to communities and governments.

## **2.10 Ecological fallout of heavy metal contamination**

Mining-related heavy metal contamination inflicts severe ecological damage, often illustrated through case studies of impacted environments. Heavy metals emanating from mines, whether via acid mine drainage, tailings leakage, or dust deposition, can decimate local ecosystems in both immediate and insidious ways.

Firstly, acute toxic events have been observed in mining areas. When a sudden surge of metals enters a waterway (for example, after a tailings dam burst or a heavy rain washing mine waste into streams), it can cause rapid and massive fish kills. A stark case occurred in 2015 with the Mariana (Samarco) mine tailings dam disaster in Brazil:

the release of metal-rich sludge led to immediate fish deaths and loss of benthic organisms for tens of kilometres downstream (Bu et al., 2024). Similarly, Wang et al. (2020) documented how elevated concentrations of copper and zinc, derived from upstream mining operations, resulted in widespread fish mortality in a river system, entire populations of sensitive species were wiped out within days. These acute incidents show how mining pollution can suddenly upset entire aquatic populations, creating an ecological void that may take years to recover.

Beyond outright kills, even sub-lethal exposure to heavy metals from mining can undermine wildlife over time. Mercury is a notable example, often introduced to water bodies by gold mining and coal burning. Sun et al. (2023) found that in a reservoir contaminated by historic mining, fish exposed to low levels of mercury exhibited abnormal behaviours, they foraged less efficiently and had reduced reproductive success. These changes, though not immediately deadly, led to gradual declines in fish populations as affected individuals failed to thrive and reproduce. In mining regions of Canada, low-level lead from old mining sites has been shown to cause neurological effects in birds (e.g., waterfowl feeding in contaminated wetlands became easier prey due to impaired motor skills). Such sub-lethal impacts demonstrate that even when contamination isn't killing organisms outright, it can erode their fitness and ecological roles, leading to population declines over a span of seasons or years.

Heavy metal pollution from mining also triggers cascading effects through food webs. In many mining-impacted lakes and rivers, top predators accumulate very high metal loads through bioaccumulation and biomagnification. Saidon et al. (2024) observed this in a marine context, but the principle holds in freshwater: small organisms take up metals from water or sediment, larger fish eat many contaminated preys and concentrate those metals, and apex predators (or humans) then get the highest doses. For example, in a lake near a former lead mine in Scandinavia, researchers found predatory pike contained lead levels several times higher than fish from an uncontaminated lake, correlating with lower reproductive rates in the polluted lake's pike (Lidman et al., 2023). These high metal burdens can be hazardous to predators' health and breeding, causing declines in their numbers. In addition, heavy metals can alter interactions in the food chain. A study of a mercury-polluted river (impacted by historic gold mining) showed that fish with mercury-induced behavioural changes

(slower escape responses) were more frequently eaten by predators, shifting the balance of species in the community (Montana et al., 2021). Thus, metal pollution doesn't just affect single species in isolation, it reshapes predator-prey dynamics and can lead to overpopulation of some species (e.g., hardy prey multiply if predators dwindle) and crashes of others, ultimately disrupting the entire ecosystem structure.

Another critical aspect in mining areas is that heavy metals often end up in sediments, thus creating a long-term source of pollution. Lakes and riverbeds near mines can become sinks for metals like arsenic, lead, and chromium; these pollutants settle into mud and sand. While sediment-bound, they might be less immediately toxic, but they effectively lie in wait. Shkurtaj et al. (2023), investigating an Albanian river below a chromite mine, showed that under certain conditions (like a change in pH or disturbance of sediment), stored heavy metals can be released back into the water column. This means a river can continually re-poison itself long after the initial contamination and every heavy storm or dredging event might re-introduce a pulse of heavy metals from the sediment. Sediment contamination also affects bottom-dwelling organisms: many invertebrates live in or on sediment and can uptake those metals, entering the food chain (Gómez-Escalonilla et al., 2024). Essentially, contaminated sediments are an ecological time bomb left by mining, causing chronic exposure for generations of aquatic life unless remediated (e.g., via sediment removal or capping).

Heavy metal pollution also disrupts microbial communities and other foundational ecological processes. In a healthy ecosystem, microbes in water and sediment perform functions like nutrient cycling and organic matter decomposition. Gómez-Escalonilla et al. (2024) found that in streams contaminated by mine runoff, microbial diversity and activity were sharply reduced, beneficial bacteria were less abundant, and processes like nitrification were impaired. This has ripple effects: if microbes that normally detoxify water or support nutrient availability are knocked out by metals, water quality worsens and algae or other organisms might overgrow. In mining regions of Montana (USA), for example, researchers noted that streams with high copper and zinc had altered algal communities and oxygen dynamics because the usual microbial grazers and decomposers were missing (Poulton et al., 1995; Eldridge & Hornberger, 2023). The loss of these "invisible" ecosystem members weakens the whole system's

resilience and can lead to issues like algal blooms or accumulation of undecomposed organic matter.

Ultimately, the ecological fallout from mining-related heavy metals threatens not only individual species but the integrity of entire ecosystems that humans also rely on. Important ecosystem services, such as fisheries, clean water provision, flood regulation by wetlands, and even pollination can be degraded (Johnson et al., 2020). Guo et al. (2023) argue that the cascading impacts observed (from microbes to top predators) highlight how urgent it is to enforce strict environmental legislation and mitigation in mining regions. Protecting aquatic ecosystems from heavy metal pollutants is about maintaining the fundamental life-support functions of those systems. For instance, if a mining area's wetlands are contaminated and cease to filter water, downstream communities lose a natural water treatment buffer, compounding pollution issues. Therefore, preserving ecosystem health in mining areas is as much an economic and social imperative as it is an environmental one.

In summary, heavy metal contamination from mining can produce devastating ecological effects, massive kills, subtle population declines, altered food webs, persistent sediment pollution, and impaired ecosystem processes. Case studies from around the world consistently show that without intervention, these “sneaky pollutants” will continue to harm biodiversity and ecosystem services in the long term. A robust response is required to mitigate these impacts and preserve the integrity and functioning of ecosystems in mining regions.

## **2.11 Water quality regulations and standards**

South Africa has a comprehensive framework of laws and standards designed to protect water resources from mining pollution. Key among these is the National Water Act (NWA) (Act 36 of 1998), which serves as the foundation for water resource management in the country. NWA prohibits the pollution of water resources and establishes the polluter-pays principle, holding that the polluter is responsible for remediation (Republic of South Africa, 1998). Under this Act, mining companies are required to obtain a Water Use Licence (WUL) for activities that may impact water resources, including water abstraction, storage, disposal of effluent, and dewatering. The licence specifies conditions under which water may be used or discharged,

ensuring compliance with limits on effluent quality, protection of groundwater and surface water, and the implementation of monitoring and reporting requirements as determined by the Department of Water and Sanitation (DWS). For example, any mine intending to abstract groundwater or discharge treated effluent must operate under a WUL that prescribes water-quality thresholds and mandates continuous or periodic monitoring to ensure compliance and minimise environmental risk (DWS, 2017; DWS, 2022).

To further operationalise NWA, South Africa introduced Government Notice No. 704 of 1999, issued under the Act, specifically to control water pollution from mining and related activities. This regulation requires mines to implement systems that prevent uncontrolled seepage of contaminated water, design tailings storage facilities with adequate safety factors, and avoid mining in close proximity to water bodies unless strict preventative measures are in place (Republic of South Africa, 1999). Essentially, GN 704 obliges mines to take proactive steps to ensure that heavy metals and other hazardous pollutants do not reach groundwater or surface water resources. The Mine Water Management Policy (2022) developed by the Department of Water and Sanitation further reinforces these requirements by emphasising sustainable mine water use, mandatory treatment of acid mine drainage, water reuse, and long-term post-closure water management, all aligned with the objectives of the National Water Act (DWS, 2022).

Another critical piece of legislation is the Minerals and Petroleum Resources Development Act (MPRDA) (Act No. 28 of 2002) which, through its environmental provisions, compels mining companies to prevent environmental degradation, including water pollution. Under MPRDA and its associated regulations, holders of prospecting rights, mining rights, or mining permits are required to prepare and implement Environmental Management Programmes (EMPrs) or plans that set out how environmental impacts of mining operations, including effects on surface water and groundwater, will be managed, monitored, and rehabilitated throughout the life cycle of the project. These EMPrs form part of the rights application and approval process and must include monitoring frameworks and mitigation measures to protect water resources and other environmental media (Republic of South Africa, 2002).

These measures typically include lining of tailings facilities, recycling of process water, monitoring of groundwater through boreholes, and management of heavy-metal-laden effluents. Failure to comply with these requirements may result in administrative penalties, suspension, or withdrawal of mining rights.

In addition to mining-specific legislation, South Africa's National Environmental Management Act (NEMA) (Act No. 107 of 1998) provides an overarching legal framework that promotes sustainable development and enforces the polluter-pays principle across all sectors, including mining (Republic of South Africa, 1998b). NEMA requires that mining projects undergo Environmental Impact Assessments (EIAs) prior to authorisation, during which potential impacts on water resources must be identified, mitigated, and monitored. Where significant or negligent pollution of water resources occurs, NEMA empowers competent authorities to issue rehabilitation and compliance directives and, where appropriate, to pursue criminal liability against responsible parties (Republic of South Africa, 1998; DEA, 2014).

South Africa also applies specific water quality standards and guidelines. The Department of Water and Sanitation (formerly the Department of Water Affairs and Forestry) published the South African Water Quality Guidelines (DWAf, 1996), which provide guideline values for protecting aquatic ecosystems, irrigation water, and livestock health. In addition, SANS 241:2015 (Drinking Water Quality) stipulates maximum allowable concentrations for heavy metals in potable water, including limits of  $\leq 0.01$  mg/L for lead and  $\leq 0.005$  mg/L for cadmium (SANS, 2015). These standards are commonly used as benchmarks when assessing groundwater quality around mining operations, particularly where communities rely on borehole water.

On the international front, South Africa also aligns its regulatory framework with World Health Organization (WHO) Guidelines for Drinking-water Quality, which provide internationally recognised threshold values for heavy metals such as arsenic, chromium, and mercury (WHO, 2017; WHO, 2021). These guidelines inform national standards and help ensure that South African water regulations remain consistent with global best practices for protecting human health.

Importantly, regulatory enforcement plays a central role in the effectiveness of these laws. Oversight is shared between the Department of Water and Sanitation (DWS) and the Department of Mineral Resources and Energy (DMRE). DWS is responsible for auditing compliance with water use licence conditions, including inspections of tailings facilities, water treatment systems, and groundwater monitoring data, while DMRE oversees compliance with approved environmental management programmes. Instances of non-compliance have resulted in compliance notices, directives to halt mining activities, and legal enforcement actions, particularly in coal-mining regions such as Mpumalanga, where risks to surface water quality associated with mining have been widely reported (DWS, 2018; WWF-SA, 2019).

In conclusion, South Africa's regulatory framework addresses mining-related water pollution through an integrated system of comprehensive water legislation (National Water Act), mining-specific controls (MPRDA and GN 704), overarching environmental governance (NEMA), and enforceable water quality standards (SANS 241 and national water quality guidelines). When effectively enforced, this framework obliges mining companies to minimise the release of heavy metals into groundwater and surface water, and to take responsibility for remediation where contamination occurs. Ongoing regulatory refinements, including the Mine Water Management Policy of 2022 and updates to national water quality standards, reflect the growing recognition that protecting water resources from mining pollution remains a critical and evolving priority in South Africa.

### **2.11.1 Water quality standards and their potential**

Water quality standards are a basic safety net for ecosystems, human health and the economy. They are not just a formality, as argued by Yusoff et al. (2022), noting that people must remain steadfast in their commitment to enforcing these vital water regulations, since surpassing heavy metal limits might set off a series of unfavourable impact, as discussed below.

#### **Economic impact**

According to Yusoff et al. (2022), polluted water supplies can reduce the amount of industrial and agricultural activities, thereby having a negative impact on the general economic performance of a country, since clean water is essential for a healthy nation.

## **Human health at stake**

Excessive exposure to heavy metals presents a serious risk to human health. A study by Lecher et al. (2023b) indicated that there is a link between high concentrations of several metals, such as chromium, lead and arsenic to several serious health conditions, that include cancer, organ damage and developmental abnormalities. They add that prolonged exposure to some heavy metals such as chromium and arsenic can raise the chance of acquiring skin, bladder and lung cancers, among other malignancies. Liu et al. (2022) pointed out that the accumulation of heavy metals in organs such as the brain, kidneys and liver can cause long-term harm and malfunction. Lead exposure, for instance, has been linked to neurological abnormalities and can hinder a child's cognitive development.

## **Ecosystems under siege**

Aquatic ecosystems are fragile, and their delicate equilibrium is easily disrupted by heavy metal intrusion. According to Rautio et al. (2022), excessive concentrations of heavy metals can damage aquatic life, reduce biodiversity and interfere with ecological processes. Decreased development and reproduction, and even mortality can result from exposure to heavy metals in fish, invertebrates and other aquatic animals (Yusoff et al., 2022). As a result of contamination's ability to bioaccumulate up the food chain and increase predators' metal concentrations, whole ecosystems may be affected (Jia et al., 2023). Heavy metals can change the chemical and physical characteristics of water, making it less suitable for several purposes, including irrigation and drinking.

## **2.12 Summary**

The literature clearly establishes that mining activities pose a substantial risk to groundwater quality through the mobilisation of heavy metals, primarily via tailings seepage, waste-rock runoff, and acid mine drainage. Although natural geogenic sources of metals may occur, mining operations frequently create concentrated pollution pathways that elevate metal concentrations beyond background levels. Metals such as arsenic, lead, cadmium, mercury, and chromium consistently emerge as priority contaminants due to their persistence, toxicity, and implications for human and ecological health.

Groundwater contamination patterns are shown to be highly context-specific and dynamic, shaped by geological conditions, hydrogeological pathways, and climatic variability.

Seasonal changes in recharge and evaporation can significantly influence metal mobility and concentration, thus underscoring the importance of site-specific and temporally sensitive monitoring rather than reliance on isolated measurements. The impacts of contaminated groundwater extend beyond environmental degradation to include public health risks, reduced agricultural productivity, and broader socio-economic consequences, particularly in regions where communities rely heavily on groundwater resources.

The literature further highlights the critical role of governance in mitigating mining-related water pollution. Regulatory frameworks and water quality standards provide essential benchmarks for protection, but their effectiveness is contingent on consistent enforcement and sound mine water management practices. Evidence from well-regulated mining jurisdictions demonstrates that strong institutional oversight can substantially reduce groundwater contamination risks.

Despite extensive global research, mine-specific groundwater data remain limited, especially for individual operations operating under unique geological and climatic conditions. For Kolomela Mine, an iron ore operation in an arid region of South Africa, the literature suggests potential vulnerability to metals such as arsenic and lead, as well as pronounced seasonal variability. However, the absence of published site-specific groundwater assessments necessitates empirical investigation. This study addresses this gap by evaluating heavy metal concentrations in groundwater around Kolomela Mine over time, providing an evidence-based foundation for assessing contamination risks and informing responsible mine water management.

## **CHAPTER 3:**

### **STUDY AREA AND RESEARCH METHODOLOGY**

#### **3.0 Introduction**

Chapter 3 describes the study area as shown in Section 3.1 and explains the methods used to carry out this research. The chapter begins by situating the research geographically and environmentally, providing details on the Kolomela Mine's location, geological setting, climate, and other factors that contextualize groundwater conditions. It then details the research design and methodology in Section 3.2, including the overall approach (a case study of Kolomela Mine's groundwater system) and specific procedures for data collection and analysis in Sections 3.4 and 4.5. It outlines how borehole sites were selected for water sampling, the frequency and timing of sample collection, and the on-site measurements. The chapter also addresses how data quality was ensured and notes any limitations of the chosen methods in Section 3.6. In summary, Chapter 3 establishes where the study took place and how the research was conducted, thus providing a transparent roadmap from fieldwork to analysis that underpins the results presented in Chapter 4.

#### **3.1 Description of Study Area**

Kolomela is an iron ore mine (Figure 3.1) located 22 km from Postmasburg in the Northern Cape Province of South Africa. The mine produces direct shipping iron ore and comprises three separate ore bodies located on the southern tilt of the iron bearing belt that hosts the Sishen deposit towards the north. The lithologies are identified to be of Griqualand West Supergroup. The ore bodies delineate the western margin of the Kaapvaal Craton in the Northern Cape Province (Mining Technology, 2020). The ore bodies measure up to 2 km in length, 400m in width and 300m in depth. The deposit consists of four varieties of high-grade haematite ores, namely clastic-textured (29%), laminated (53%), collapse breccia (10%) and conglomeratic (8%). The lump to fine ratio of the ore is 60:40. The mine is operated by the Anglo-American group company of Kumba Iron Ore through its subsidiary Sishen Iron Ore Company (SIOC). SIOC is 76.3% owned by Kumba while the remaining interest is held by Black Economic Empowerment (BEE) shareholders. Anglo American holds a 64.7% stake in Kumba (Mining Technology, 2020). The Industrial Development Corporation holds

14% and the remaining is free float. Toxic chemicals used in the treatment process include mercury, silver, lead and cyanide.

Other metals also extracted on-site from the gold ore are copper, zinc, cobalt and arsenic (Fashola et al., 2016). The method of extraction of these metals is the cyanide extraction process (Fashola et al., 2016).

The local communities living near Kolomela Mine depend solely on groundwater for all their domestic needs as there is no surface water (Kumba Iron Ore, 2017). Unused and waste products generated during the processing of mined ores are discarded into the slime dams. However, these slime dams are allegedly built with inadequate materials and have been reported to fail and accidentally release tailings containing heavy metals into waterways (Kossoff et al., 2014). The surface water and groundwater quality in and around the mine may thus have been affected by disposed effluents containing heavy metals. Furthermore, mining operations such as those at Kolomela Mine may be associated with heavy metals including lead (Pb), copper (Cu), mercury (Hg), arsenic (As), chromium (Cr), manganese (Mn), and cadmium (Cd), which are of environmental health concern due to their toxicity, persistence, and potential to accumulate in soils and water resources (Laniyan et al., 2013; Hailelassie & Gebremedhin, 2015). Although trace amounts of these heavy metals are permissible (DWA, 1996; WHO, 2011), higher concentrations in the environment are toxic (Bhateria & Jain, 2016). Public health may be affected by heavy metals in groundwater. Such polluted water could be hazardous both to local communities and natural ecosystems. Of key concern are the low pH levels which can occur in water bodies impacted by AMD. Low pH conditions result in the mobilisation of heavy metals (Fashola et al., 2016; McCarthy, 2011), and hence greater potential for impacts on environmental health. Also, potentially exacerbating heavy metal contamination of water, South Africa's fluctuating ambient temperatures ranging from 4°C to 40°C may increase the concentration of heavy metals in solution in the receiving water bodies (Bhateria & Jain, 2016).

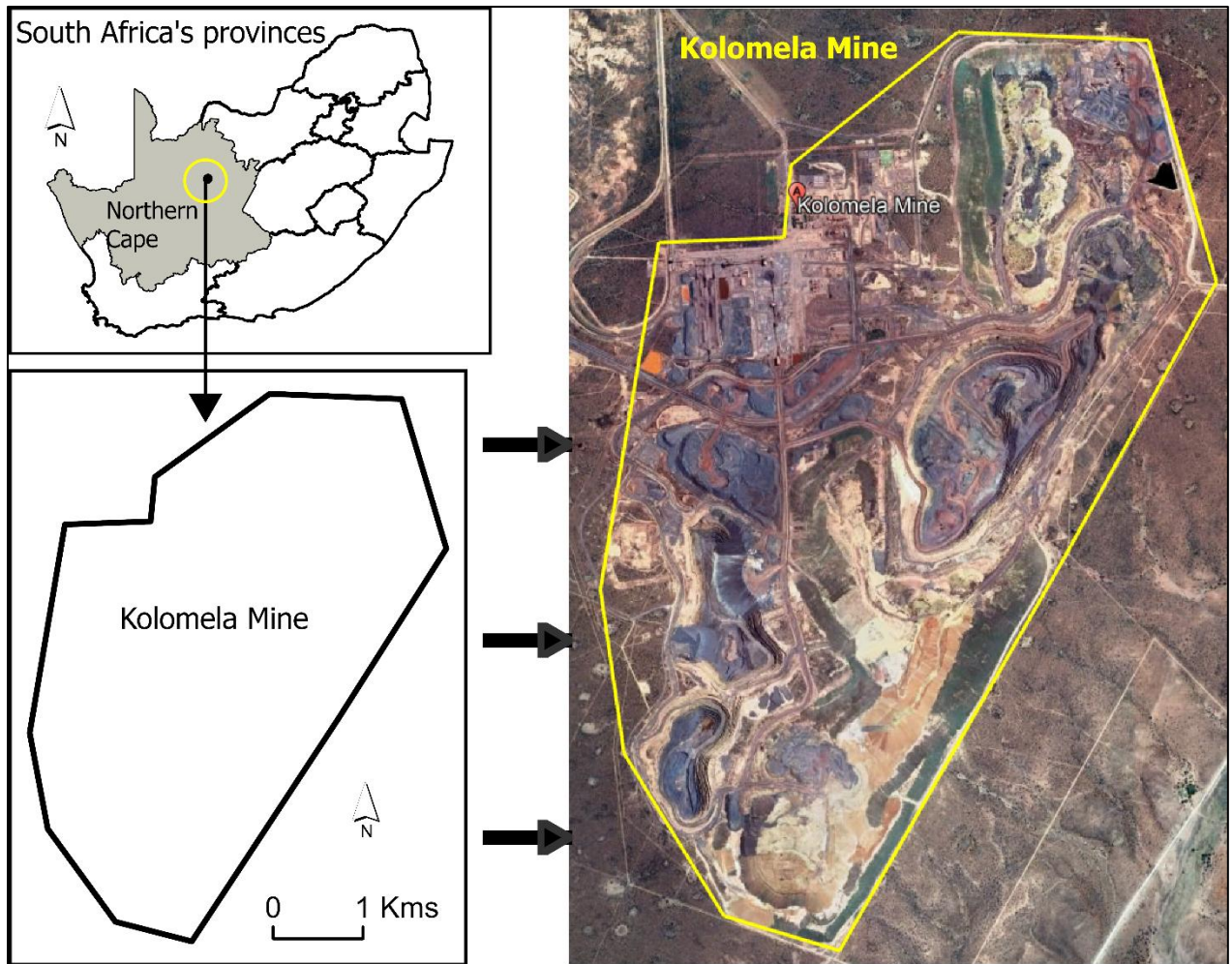


Figure 3.1: Geographical location of Kolomela Mine in the Northern Cape Province of South Africa.  
Source: Google Earth (2025).

### 3.2 Research Design

This study employed a case study research design, which is particularly suited for in-depth exploration of groundwater pollution by heavy metals at the Kolomela Mine, Northern Cape Province. A case study design enables in-depth analysis of site-specific conditions and processes, allowing researchers to examine environmental phenomena as they occur in practice rather than in isolation. As noted by Yin (2018), a case study focuses on the detailed examination of a bounded system to understand contextualised outcomes, making it particularly suitable for environmental studies that require localised assessment of pollution sources and contamination levels. In this study, Kolomela Mine in the Northern Cape Province represents a bounded system where groundwater quality is assessed to characterise the types and concentrations

of heavy metals, thereby providing a detailed understanding of groundwater contamination within the study area.

### **3.2.1 Case Study Approach**

Unlike a broad survey or purely theoretical analysis, a case study enabled the current research to investigate Kolomela mine's specific context, considering its unique geology, mining methods, and environmental management practices. Burns (2019) maintained that case studies are particularly valuable for the study of certain environmental issues, as they provide a nuanced interplay of factors at one site. In line with that, the approach combines quantitative water quality measurements with contextual information about Kolomela Mine.

In practice, treating Kolomela as a case study meant that the study defined clear boundaries such as the mine lease area and adjacent boreholes and analysed these data holistically to understand the extent of groundwater pollution. This approach is appropriate because the goal is not to generalize about all mines, but rather to deeply understand what is happening at this particular mine. By doing so, the research identified site-specific contamination patterns and their causes, which may inform management at Kolomela and provide insights applicable to similar settings. Importantly, while the term "case study" often implies qualitative analysis, the study included quantitative data (metal concentrations, etc.) analyses. The study is grounded in Kolomela's real-world conditions throughout, thus ensuring that the findings and conclusions are directly relevant to the mine and its stakeholders.

### **3.2.2 Advantages of Case Study**

- **Offering Detailed Insights**

Case studies allow for the collection of extensive data, leading to a deeper understanding of the research context. For example, this study captures detailed data on heavy metal concentrations, seasonal variations, and their impacts on groundwater quality.

- **Exploration of Variables**

Case studies enable the examination of multiple variables and their relationships (Halkias & Neubert, 2020). For instance, this study explores how mining activities, borehole locations, and seasonal changes influence groundwater pollution.

- **Contemporary Relevance**

Case studies are highly effective for investigating modern phenomena in real-life settings (Patnaik & Pandey, 2019), such as the ongoing environmental challenges posed by mining at the Kolomela Mine.

### **3.2.3 Disadvantages of Case Study**

- **Limited Generalisability**

Since case studies focus on a single or limited number of cases, the findings may not be universally applicable (Sandars, 2021). The results of this study, for example, are specific to Kolomela Mine and may not fully apply to other mining regions.

- **Potential for Researcher Bias**

The interpretive nature of case studies can introduce bias, as researchers may unconsciously emphasise certain findings over others. Strategies like peer review and triangulation are necessary to minimise bias.

- **Time-Consuming**

The in-depth nature of case studies requires significant time for data collection, analysis and interpretation. This study involved an eight-month longitudinal investigation, which required repeated sampling and thorough data analysis.

Several researchers in South Africa have used case studies in their investigations. For example, Netshiongolwe (2018) utilised a case study approach to examine the impact of mining on South Africa's water resources, thus emphasising the need for localised environmental management, while Fashola et al. (2016) conducted case studies on mining-related water contamination to assess the ecological and public health implications in African mining regions.

By adopting this approach, the study not only investigates the specific case of the Kolomela Mine but also contributes valuable insights into broader environmental and mining-related research. It bridges the gap between localised findings and their implications for sustainable resource management.

### **3.3 Sampling Techniques and Procedures**

This section provides an overview of the sampling strategy, the rationale behind the choice of sampling technique, and the step-by-step procedure followed in selecting and analysing groundwater samples. The sampling approach of the study was designed to capture spatial and temporal variations in pollution levels while maintaining a high level of accuracy in assessing heavy metal contamination across different boreholes.

#### **3.3.1 Population and target population**

Population in research refers to the complete set from which one seeks to draw conclusions (Knechel, 2019). It extends beyond individuals to include anything eligible for study, ranging from objects, communities, occurrences, organisations, nations, species and organisms (Taherdoost, 2016). In the context of the current study, the population includes all the water boreholes within Postmasburg Mine in the Northern Cape Province of South Africa.

According to Ussif et al. (2020), a target population refers to specific group/s or individuals that a researcher is interested in studying and to whom they intend to generalise their research findings. It is a well-defined group that possesses characteristics that are of interest to the research problem. In this study, the target population are all the twenty (20) water boreholes around Kolomela Mine area, which is within Postmasburg town in the Northern Cape Province.

#### **3.3.2 Sampling and sample size**

The study employed a purposive sampling approach. Thus, the selection of groundwater monitoring boreholes followed a non-probability (purposive) sampling strategy, as borehole locations were pre-existing and fixed based on existing hydrogeological and

operational considerations. In contrast, groundwater samples collected from within each borehole were obtained using a probability-based approach, specifically simple random sampling, to support objective quantitative analysis of groundwater quality parameters and thus reducing sampling bias (DWAF, 1998; EPA, 2017).

The sample comprised groundwater samples collected from four monitoring boreholes (BH1–BH4) located around Kolomela Mine. These boreholes constituted the available and accessible groundwater monitoring points within the study area and therefore defined the spatial scope of the investigation. Each borehole represented a distinct monitoring location within the mine’s hydro-environmental setting.

The sample size was determined by the number of available monitoring boreholes and the number of sampling events conducted at each borehole during the study period. Within each borehole, individual groundwater samples were collected randomly across the defined sampling timeframe to minimise investigator bias and to ensure that measured physicochemical and heavy metal parameters reflected typical groundwater conditions at each location. This approach is consistent with established groundwater quality studies, where fixed or pre-existing monitoring infrastructure constrain the numbers of sites that may be monitored (DWAF, 1998; EPA, 2017). However, the resulting dataset provided sufficient observations to enable descriptive statistical analysis and comparison of measured groundwater quality parameters against relevant guideline values. While the sample size does not support statistical generalisation beyond the monitored locations, it is appropriate for assessing site-specific groundwater quality and potential mining-related impacts within the study area.

### **3.4 Data collection**

Groundwater samples were collected from four pre-existing and fixed groundwater monitoring boreholes (BH1 to BH4) located within the Kolomela Mine in the Northern Cape Province. The boreholes constituted the available and accessible infrastructure for monitoring within the study area and defined the spatial scope of the investigation. A purposive sampling strategy was applied to the borehole selection, based on logistical accessibility and operational relevance to the mine’s hydro-environmental context. The boreholes were not selected based on proximity to specific contamination

sources such as tailings dams or agricultural land use, as verified spatial data were unavailable; instead, selection was based on their function as established monitoring points within the mine's hydro-environmental system.

However, within each borehole, a simple random sampling technique was employed during each sampling event to ensure that groundwater collected was representative of typical conditions. This involved drawing water samples several times at consistent depths and time intervals using sterilised equipment, with appropriate field quality control measures such as rinsing, labelling, and sample preservation following standard protocols.

The sample size was defined by the number of monitoring boreholes available and the number of repeated sampling events carried out over the study period. While limited in spatial scale, this approach aligns with groundwater monitoring standards where infrastructure constraints necessitate small-sample designs, and scientific robustness is achieved through repeated, randomised, and standardised procedures (DWAF, 1998; EPA, 2017). All samples were transported in cooled containers to a SANAS-accredited laboratory for analysis. During laboratory analysis, the concentrations of selected heavy metals (e.g., calcium; chromium, copper, lead, manganese, nickel, and zinc) were determined. Chain-of-custody procedures were maintained throughout to ensure sample integrity.

### **3.5 Sampling Frequency, Statistics, and Analytical Techniques**

The objective of data analyses was to identify and describe patterns and trends in groundwater quality over time. Data analysis involved laboratory testing of water samples collected from four (4) groundwater boreholes, with measured parameters compared against the World Health Organization (WHO) drinking water quality guidelines and relevant South African national standards to assess groundwater quality status (WHO, 2017; Department of Water Affairs [DWAF], 1998). The eight-month longitudinal monitoring design adopted for groundwater pollution assessment in the vicinity of the Kolomela Mine was therefore analysed using descriptive statistical techniques only, consistent with the study's observational and site-specific nature. All analyses were conducted using SPSS version 29. The exclusive use of descriptive statistical analysis was justified by the purpose and design of the study, which focused on the systematic

collection, organisation, and summarisation of observed groundwater quality data rather than hypothesis testing or population-level inference. Variables analysed included heavy metal concentrations in groundwater samples. Descriptive statistics are appropriate in this context because they provide clear, concise summaries of measured data and enable the direct characterisation of groundwater quality conditions at each monitoring borehole (Field, 2013; Helsel, 2012).

Repeated measurements collected at each borehole over the eight-month period were analysed descriptively to examine temporal trends and variability within each sampling point. In line with established environmental monitoring guidance, repeated observations were used to track changes over time and to describe fluctuations in groundwater quality parameters, rather than to test statistical significance or make inferential generalisations (Helsel & Hirsch, 2002; EPA, 2017). This approach is consistent with best practice for longitudinal groundwater monitoring studies where sampling locations are fixed and the objective is to document observed conditions and trends.

### **3.5.1 Laboratory Analyses**

There are various laboratory techniques for the detection and measurement of heavy metals in groundwater samples. For instance, the Atomic Absorption Spectroscopy (AAS) is a proven, standardized, cost-effective, and reliable method for quantifying heavy metals in water, thereby ensuring accurate monitoring of contamination in mining-affected boreholes (Song et al., 2015; Aquisman et al., 2019; Idris et al., 2021). Existing literature (Zangina et al., 2019; Idris et al., 2021; Bunu et al., 2023) shows that this technique is highly effective for detecting and quantifying trace levels of metals such as calcium, chromium, copper, zinc, manganese, lead, nickel, and thallium. However in this research, the Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES) was chosen over the AAS technique. This is because the ICP-OES technique can measure many metals at the same time in a single run whereas the AAS technique measures only one element at a time, thus it can be a slow and inefficient for groundwater with multiple metals (Welna et al., 2015; Da Cruz et al., 2022; Petrean et al., 2023). In summary form, ICP-OES technique entailed the following apparatus and setup (Pillay, 2020; Khan et al., 2022; Petrean et al., 2023):

- **Instrument setup:** ICP-OES spectrometer, plasma torch, nebulizer, spray chamber, detectors;
- **Support systems:** Argon gas supply, peristaltic pump;
- **Sample prep tools:** Digestion systems, glassware, filtration;
- **Calibration materials:** Certified standards and QC samples.

### 3.6 Validity of the Study

The validity of this study was ensured through careful field preparation, instrument calibration, and strict adherence to standard sampling and laboratory quality control procedures rather than through a formal pilot study. Prior to full-scale data collection, the researcher conducted a brief reconnaissance visit to the Kolomela Mine area in January 2023. This visit was undertaken to confirm the accessibility and physical condition of the selected groundwater boreholes and to test the practicality of the sampling procedures under field conditions, as recommended for environmental monitoring studies (APHA, 2017; EPA, 2017).

During this preliminary visit, a single trial sample was collected from one borehole (BH3). The purpose of this trial was operational rather than analytical, focusing on verifying the functionality of the submersible pump, pH meter, and sample containers, as well as confirming that filtration, preservation, and transport procedures were appropriate for maintaining sample integrity. Such preliminary operational checks are considered sufficient for ensuring methodological validity in studies based on direct physicochemical measurements rather than experimental manipulation or surveys (WHO, 2017; APHA, 2017). The trial also confirmed that measured heavy metal concentrations fell within the detection limits of the selected analytical methods, indicating that laboratory instrumentation and analytical settings were suitable for the study objectives (EPA, 2017).

No methodological adjustments were required following this preliminary check, as all procedures functioned as intended. Given the nature of the study, based on direct environmental measurements rather than surveys or experimental manipulation, a traditional pilot study involving hypothesis testing or respondent instruments was neither necessary nor appropriate (Creswell & Creswell, 2018). Consequently, no pilot data analysis was conducted.

Instrument and analytical validity were further strengthened through routine calibration of all field equipment in accordance with manufacturer specifications and laboratory protocols prior to sampling (APHA, 2017). Laboratory analyses were conducted under established internal quality assurance and quality control (QA/QC) procedures, including the use of blanks, duplicate samples, and spiked samples, in line with internationally accepted guidelines for water quality assessment (EPA, 2017; WHO, 2017). All QA/QC results met acceptance criteria, providing confidence in the accuracy and consistency of the generated data. A summary of these QA/QC outcomes is provided in the Chapter 4 appendices.

Overall, the validity of the study was achieved through equipment testing, methodological consistency, and compliance with recognised environmental sampling and laboratory standards, ensuring that the findings accurately reflect observed groundwater quality conditions in the study area.

### **3.7 Reliability of the Study**

In the context of environmental monitoring, reliability refers to the consistency and repeatability of measurements obtained using the same methods and instruments under similar conditions (APHA, 2017; EPA, 2017). Reliability in this study was ensured through the use of standardised sampling procedures applied consistently across all four boreholes and throughout the eight-month monitoring period. The same field equipment and analytical techniques were used for all sampling events, and instruments were routinely calibrated to minimise measurement variability. In addition, laboratory reliability was supported through the analysis of duplicate samples and adherence to internal QA/QC protocols, which confirmed the stability and reproducibility of the measured groundwater quality parameters over time (WHO, 2017).

### **3.8 Ethical Considerations**

This study obtained ethical clearance (2023/CAES\_HREC/1096) from the College of Agriculture and Environmental Sciences Health REC of the University of South Africa. Additionally, the study adhered to ethical principles throughout the research process, with focus on informed consent, data anonymity, confidentiality, lack of coercion and the absence of negative repercussions to respondents. The following ethical considerations are outlined:

### **3.8.1 Informed Consent**

At Kolomela Mine, the Environmental Department was fully informed about the purpose, scope and objectives of the study beforehand. Key steps include providing clear explanations about the aim of the study to assess groundwater pollution by heavy metals around the mine; ensuring that management understood their rights, including the right to withdraw from the study at any stage without penalty; and written consent, which was obtained from the management before collecting any data.

### **3.8.2 Data Anonymity**

Data collected from boreholes was anonymised using unique codes instead of identifiable data for each borehole.

### **3.8.3 Confidentiality**

Data were securely stored and accessible only to authorised research team members, with findings presented in an aggregated manner to ensure anonymity. No coercion, direct or indirect, was exerted during sample collection, and management was informed that their decision to grant permission would not affect their relationship with the research team, the mine, or local authorities. Additionally, the environmental department was assured that the data collected would not result in negative consequences for them, their communities, or the environment, and all water sampling methods were conducted to prevent environmental disturbance or contamination. The study adhered to ethical standards set by the University of South Africa's ethical clearance committee, as well as local and national regulations governing environmental research, water sampling and participant rights.

## **3.9 Methodological Assumptions and Limitations**

The study was undertaken under the following methodological assumptions. Groundwater samples that were collected from boreholes were assumed to represent the broader aquifer system in and around the study area and to depict contamination levels due to mining activities. Similarly, the seasonal and temporal variations in the concentrations or amounts of pollutants were assumed to be captured accurately by the chosen sampling intervals (e.g., monthly intervals). The study did not make any provision for pollution from

other sources in the study area such as agriculture or natural geochemical background. Lastly, the boreholes selected for sampling are assumed to adequately represent spatial variability across the mine's influence zone.

In terms of methodological limitations, the following points are explained. Given the limited number of boreholes, the scope of sampling may not fully capture the heterogeneity of groundwater contamination across the entire mine area. Moreover, the detection limits of instruments may prevent the identification of certain trace concentrations, especially for metals like thallium or nickel. If not detected, they were not discussed any further in any specific borehole sample. Some elements of bias may be brought by seasonal variations as they are influenced by rainfall variability, evaporation rates, or recharge conditions that are not fully controlled in the selected research design. Thus, the study findings are very site-specific to Kolomela Mine and may not be generalized to other mines or regions with different geology and hydrology.

However, in spite of these constraints, the data collection strategy enabled the study to examine patterns of contamination and seasonal variability over the study period. The longitudinal approach provided valuable insights into the dynamics of groundwater pollution, thus laying the groundwork for informed environmental management strategies and future research endeavours.

## **CHAPTER 4:**

### **PRESENTATION AND DISCUSSION OF RESULTS**

#### **4.1 Introduction**

This section presents the results on the concentrations of selected heavy metals (lead, calcium, copper, zinc, chromium and magnesium) measured in groundwater samples collected from four boreholes (BH1, BH2, BH3 and BH4) at Kolomela Mine. Samples were collected during four sampling periods (February, April, July and October 2023) to capture potential seasonal variations. The results are presented descriptively, focusing on observed concentrations, spatial differences between boreholes and temporal patterns over the sampling period.

Overall, the concentrations of heavy metals varied across boreholes and sampling periods. Certain metals, such as lead, remained consistently below detection limits, while others, including calcium and magnesium, were present at comparatively higher concentrations. These patterns are typical of groundwater systems influenced by both natural geochemical processes and seasonal recharge dynamics in mining environments. Similar spatial and temporal variability in groundwater metal concentrations has been reported in studies conducted in mining-affected aquifers (Ettazarini et al., 2021; Bu et al., 2024).

Lead concentrations across all sampling points were below the analytical detection limit, indicating minimal lead contamination during the study period. In contrast, calcium and magnesium showed moderate to elevated concentrations across all boreholes, reflecting groundwater hardness associated with mineral dissolution rather than anthropogenic pollution. Trace metals such as chromium, zinc and copper exhibited minor temporal fluctuations, which are commonly linked to seasonal influences such as dilution during recharge periods and concentration effects during drier conditions (Nkono et al., 2020).

In general, most measured concentrations complied with South African National Standards (SANS 241-1:2015) and World Health Organization (WHO) drinking water guideline values. However, the observed variability highlights the importance of continued groundwater monitoring in mining environments to detect potential long-term changes in water quality.

### 4.3 Sampling Site: BH1

This section presents and interprets the results of heavy metal concentrations measured in groundwater samples collected from borehole BH1 during the four sampling periods. The results are evaluated against South African National Standards (SANS 241-1:2015) and WHO drinking water guideline values to assess groundwater quality at this sampling site.

#### 4.3.1 Interpretation of the data

Based on the data in Figure 4.1, the following is an interpretation of the heavy metals and groundwater quality in BH1 at Kolomela Mine, based on the South African National Standards (SANS) 241-1:2015 and IRMA Drinking Water Quality Criteria.

##### 4.3.1.1 Lead (Pb)

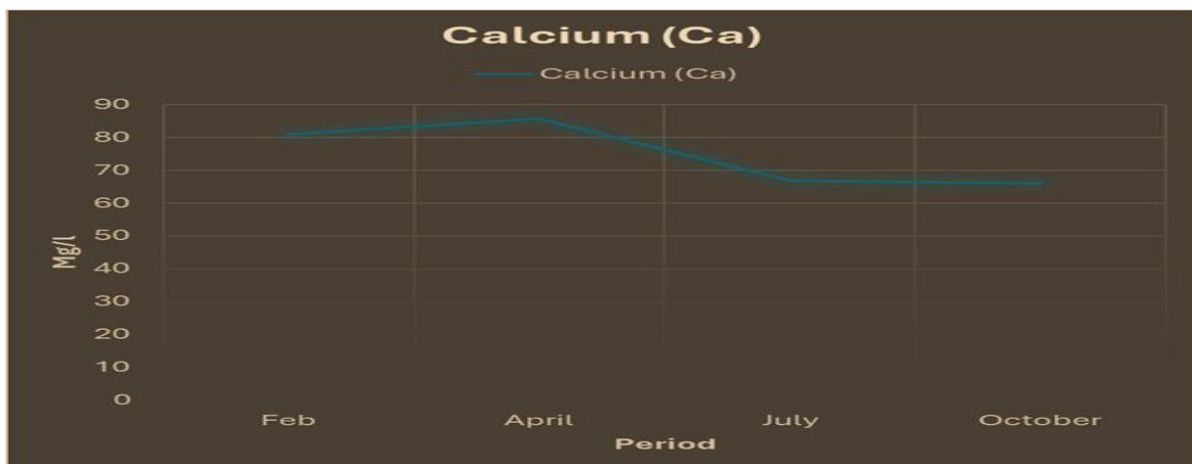
According to the data presented in Figure 4.1, lead concentrations at BH1 were below the detection limit (<0.004 mg/L) for all four sampling periods. This indicates that lead was not detected in the groundwater at this borehole during the study period. The maximum allowable concentration for lead in drinking water is 0.01 mg/L according to both SANS 241-1:2015 and WHO guidelines. As the measured concentrations were consistently below this limit, lead does not pose a concern for groundwater quality at BH1. The absence of detectable lead suggests limited mobilisation of lead-bearing minerals within the local hydrogeological setting or effective containment of mining-related waste materials. Similar findings have been reported in mining areas where lead remains geochemically stable under prevailing groundwater conditions (Fashola et al., 2016; Yusoff et al., 2022).



**Figure 4.1:** BH1 Concentrations of Lead over the sampling periods.

#### 4.3.1.2 Calcium (Ca)

Calcium concentrations at BH1 ranged from 54.1 mg/L to 81.1 mg/L across the sampling periods, with an average concentration of approximately 67.5 mg/L (Figure 4.2). Neither SANS 241-1:2015 nor WHO guidelines specify a health-based limit for calcium in drinking water. However, elevated calcium concentrations contribute to water hardness and may result in scaling of pipes and household appliances (Akram & Rehman, 2018). The observed variation in calcium concentrations over time suggests the influence of natural geochemical processes, such as mineral dissolution and water–rock interactions within the aquifer. Seasonal fluctuations in calcium concentrations are commonly observed in groundwater systems, particularly in arid and semi-arid regions where recharge and evaporation influence groundwater chemistry (Johnson et al., 2020).

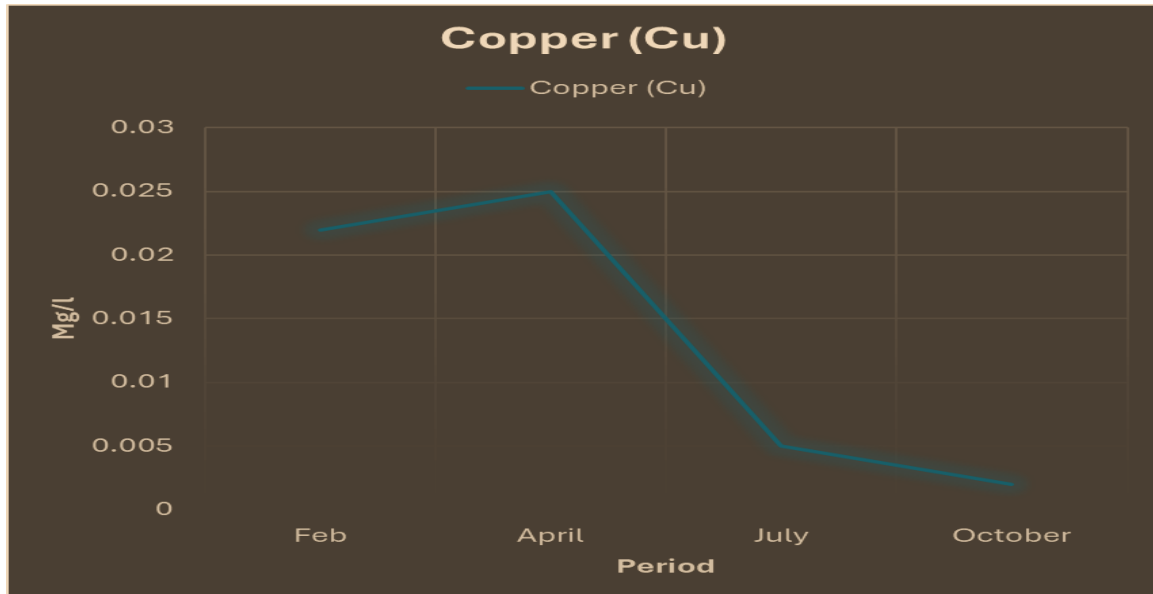


**Figure 4.2:** BH1 Concentration of Calcium over the sampling periods.

#### 4.3.1.3 Copper (Cu)

Copper concentrations measured at BH1 were consistently low across all sampling periods and remained within the permissible limits set by SANS 241-1:2015 and WHO drinking water guidelines (Figure 4.3). Copper is an essential trace element, but elevated concentrations may cause aesthetic issues and potential health concerns. The low and relatively stable copper concentrations observed at BH1 suggest limited mobilisation of copper-bearing minerals and minimal influence from mining-related activities during the study period. Comparable copper patterns have been reported in

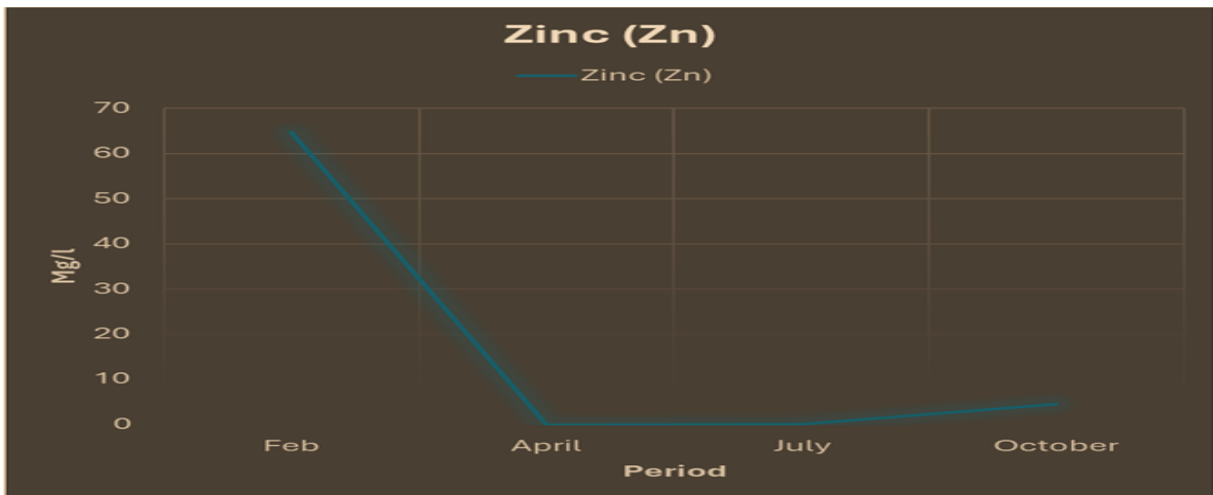
groundwater systems surrounding iron-ore mining operations, where copper typically occurs at background levels rather than as a dominant contaminant (Ettazarini et al., 2021).



**Figure 4.3:** BH1 Concentration of copper over the sampling period.

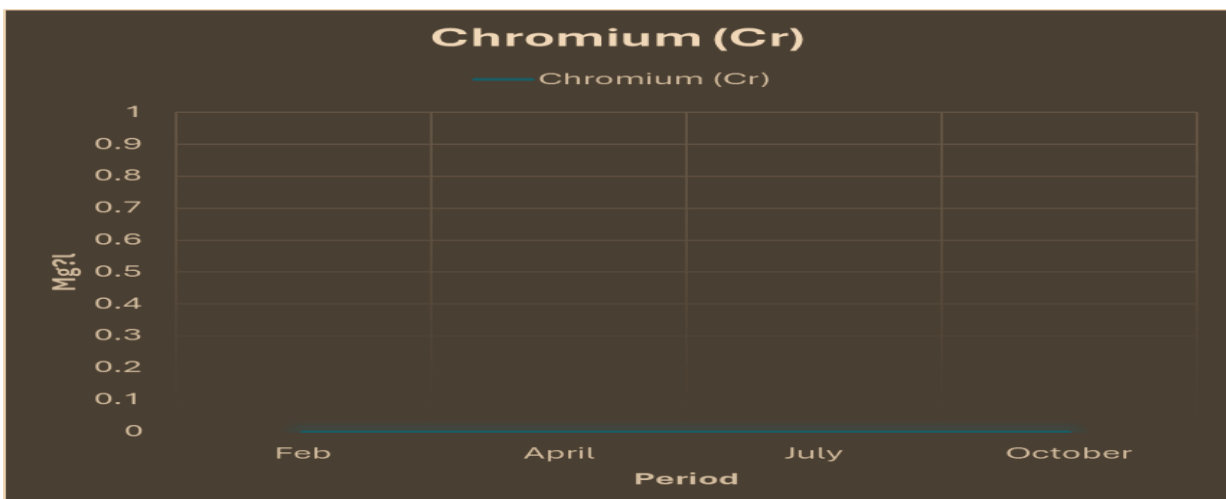
#### 4.3.1.4 Zinc (Zn):

Zinc concentrations at BH1 were low across all sampling periods and remained within acceptable drinking water guideline limits (Figure 4.4). Zinc commonly occurs in groundwater as a result of natural mineral weathering and is typically present at low concentrations in mining-affected aquifers where it is not a primary contaminant (Wang et al., 2020). Identifying and addressing any sources of potential contaminations is crucial to prevent further environmental degradation and protect surrounding ecosystems (Barrett et al., 2019).



**Figure 4.4:** BH1 Concentrations of Zinc over the sampling period.

The data in Figure 4.5 shows Chromium concentrations measured at BH1 remained below the maximum permissible limit of 0.05 mg/L as prescribed by SANS 241-1:2015 and WHO guidelines throughout the sampling period. Minor temporal variations were observed between sampling events, which may be attributed to seasonal changes in groundwater recharge and redox conditions. Chromium mobility in groundwater is known to be influenced by pH, oxidation state and geochemical conditions within the aquifer (Rautio et al., 2022). Although chromium concentrations at BH1 complied with regulatory standards, its presence remains environmentally relevant, particularly in mining environments, and continued monitoring is therefore recommended.

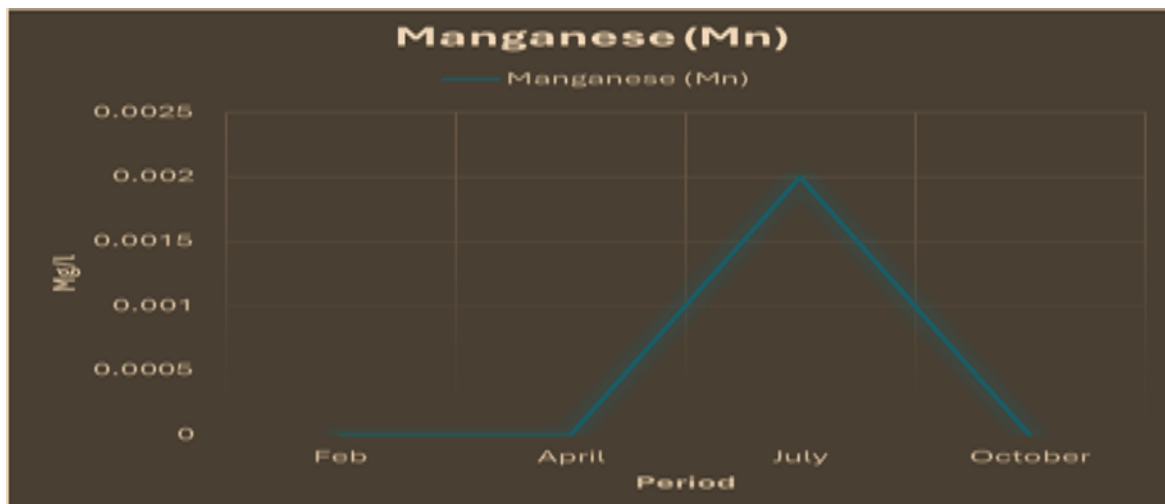


**Figure 4.5:** BH1 Concentrations of Chromium over the sampling period.

#### 4.3.1.6 Manganese (Mn)

Magnesium concentrations at BH1 were moderate and followed a similar pattern to calcium, reflecting the mineralogical composition of the aquifer (Figure 4.6). Magnesium

is commonly associated with groundwater hardness and dolomitic rock interactions. No guideline exceedances were observed, and the measured concentrations are consistent with values reported for groundwater in mining regions (Johnson et al., 2020).



**Figure 4.6:** BH1 Concentrations of Manganese over the sampling period.

#### 4.3.2. Discussion of the findings from BH1

The interpretation of the data for BH1 at Kolomela Mine provides insights into groundwater quality and heavy metal concentrations, particularly in relation to South African National Standards (SANS) 241-1:2015 and IRMA Drinking Water Quality Criteria. The absence of detectable lead concentrations in all sampling events indicates compliance with both SANS and IRMA standards. This suggests that lead contamination is not a concern in BH1's groundwater, mitigating potential health risks associated with lead exposure. Calcium levels fall within the observed range, indicating variability but generally acceptable concentrations. While there are no specific guidelines for calcium in drinking water according to SANS and IRMA, excessive calcium can contribute to water hardness and scale build-up in pipes and appliances. According to Baguma et al. (2017), with such findings, monitoring may be necessary to assess any potential impacts on infrastructure and palatability. According to the findings from BH1, although one sample slightly exceeded the IRMA guideline (0.05 mg/L), the overall mean and standard deviation suggests that copper levels are not a significant concern in BH1's groundwater quality. However, continued monitoring is advisable to ensure compliance with regulatory standards and to identify any emerging trends or localised sources of contamination.

While one sample in July 2023 exceeded both SANS (0.01 mg/L) and IRMA standards (0.05 mg/L), excluding this outlier, zinc levels generally fall within acceptable limits. In terms of the findings, further investigation is required to understand the cause of the outlier and its potential implications for groundwater quality. Overall, the findings suggest that zinc contamination is not widespread in BH1. Like lead, chromium was not detected in any of the sampling events, indicating compliance with regulatory standards. This eliminates concerns regarding chromium contamination in BH1's groundwater and reduces potential health risks associated with chromium exposure. Manganese levels were consistently below both SANS and IRMA standards, indicating no significant manganese contamination in BH1's groundwater. This is reassuring as excessive manganese intake can have adverse health effects, with Barrett et al. (2019) mentioning some of such effects as being tremors, muscle spasms, difficulty walking, impaired speech and cognitive decline. In severe cases, manganese poisoning can lead to a Parkinson's-like disease called manganese. However, the findings suggest that manganese is not a concern for drinking water quality in BH1.

In summary, the interpretation of the data for BH1 indicates that while there may be variability in certain heavy metal concentrations, overall groundwater quality remains within acceptable limits according to regulatory standards. Continued monitoring and assessment are recommended to ensure the ongoing sustainability and safety of groundwater resources at Kolomela Mine.

#### **4.4. Sampling Site: BH2**

This section presents the descriptive results of heavy metal concentrations measured in groundwater samples collected from borehole BH2 during the four sampling periods. Results are evaluated against South African National Standards (SANS 241-1:2015) and WHO drinking water guideline values.

##### **4.4.1. Interpretation of the data**

An analysis and interpretation of the data has a focus on heavy metal concentrations and groundwater quality in BH2 at Kolomela Mine (February - October 2023). This is in line with the South African National Standards (SANS) 241-1:2015 and IRMA Drinking Water Quality Criteria.

#### 4.1.1.1 Lead (Pb)

Lead concentrations at BH2 were consistently below the analytical detection limit (<0.004 mg/L) across all sampling periods (Figure 4.7). This indicates that lead contamination was not detected in groundwater at this borehole during the study period. These findings comply with the maximum permissible limit of 0.01 mg/L stipulated by SANS 241-1:2015 and WHO guidelines.

The absence of detectable lead is consistent with findings from recent groundwater studies in mining-affected regions, which indicate that lead often remains relatively immobile under stable hydrogeochemical conditions, particularly in neutral to slightly alkaline pH environments where sorption and precipitation processes limit its mobilisation (Chukwura & Hursthouse 2020; Zhang et al., 2024).



Figure 4.7: BH2 Concentrations of Manganese over the sampling period.

#### 4.4.1.2 Calcium (Ca):

In Figure 4.8, the data indicate that the concentrations range from 66.1 to 94.3 mg/L, with a mean of 80.5 mg/L. This falls within the acceptable range of SANS 241-1:2015 (30 - 200 mg/L) but exceeds the IRMA recommended range (75 - 150 mg/L). While it is not an immediate health concern, exceeding the International Risk Management Association (IRMA) recommended range suggests that the calcium level might impact palatability and infrastructure. According to DWAF (2017), higher calcium can alter the water taste. This can reduce consumer acceptability while also contributing to scale formation in pipes and appliances, leading to increased maintenance requirements and potential infrastructure damage. The observed temporal variation in calcium

concentrations is consistent with hydrogeochemical studies showing that seasonal recharge and evaporation influence calcium mobilisation in semi-arid mining environments (Karroum et al., 2017; Erdogan et al., 2020).

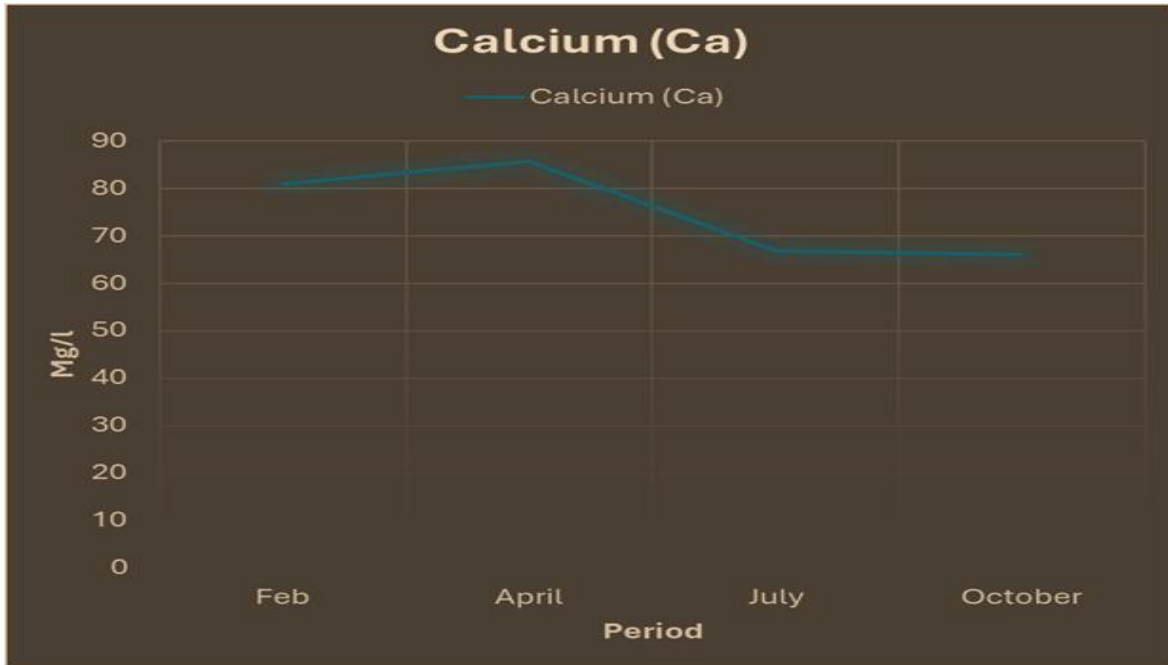
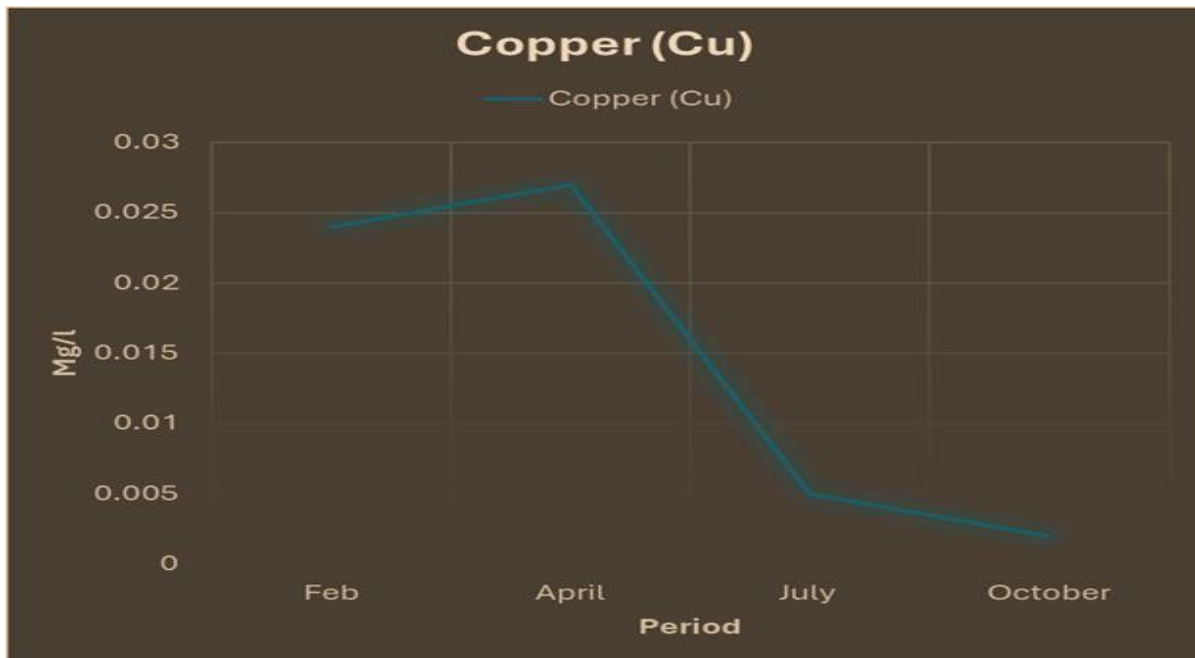


Figure 4.8: BH2 Concentrations of Calcium over the sampling period.

#### 4.4.1.3 Copper (Cu)

Figure 4.9 shows that copper concentrations fall well below both the South African National Standard (SANS 241-1:2015) guideline of 2 mg/L and the International Risk Management Association (IRMA) recommended limit of 1 mg/L. This indicates that copper is not a concern for drinking water quality in BH2. Excessive copper intake can lead to various health problems. Since the levels are significantly lower than the established limits, the risk of negative health impacts associated with copper contamination in BH2 groundwater is very low. While copper levels are low, understanding the source(s) contributing to copper in the groundwater is crucial. This differentiation helps determine if it originates naturally from geological formations or if it is due to human activities like mining or industrial processes. Fashola et al. (2016) argued that knowing the source is vital for implementing preventive or mitigation measures, where necessary. Additionally, low copper concentrations similar to those observed at BH2 have been reported in iron-ore mining regions where copper is not a

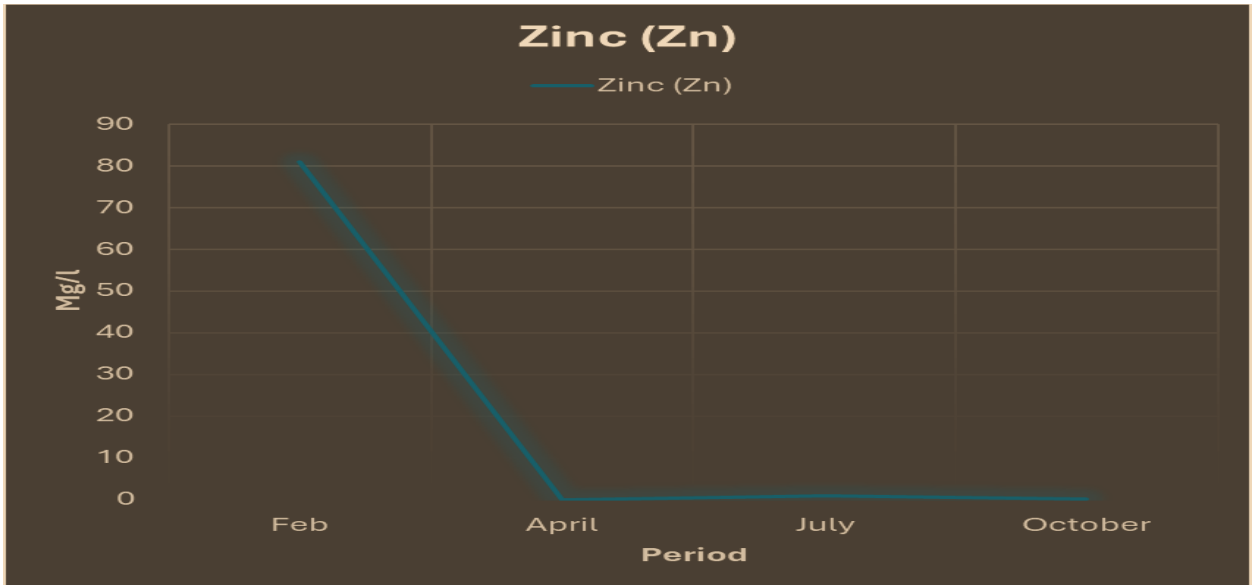
primary contaminant and groundwater chemistry is dominated by natural processes rather than anthropogenic inputs (Kumar et al., 2025).



**Figure 4.9:** BH2 Concentrations of copper over the sampling period.

#### 4.4.1.4 Zinc (Zn)

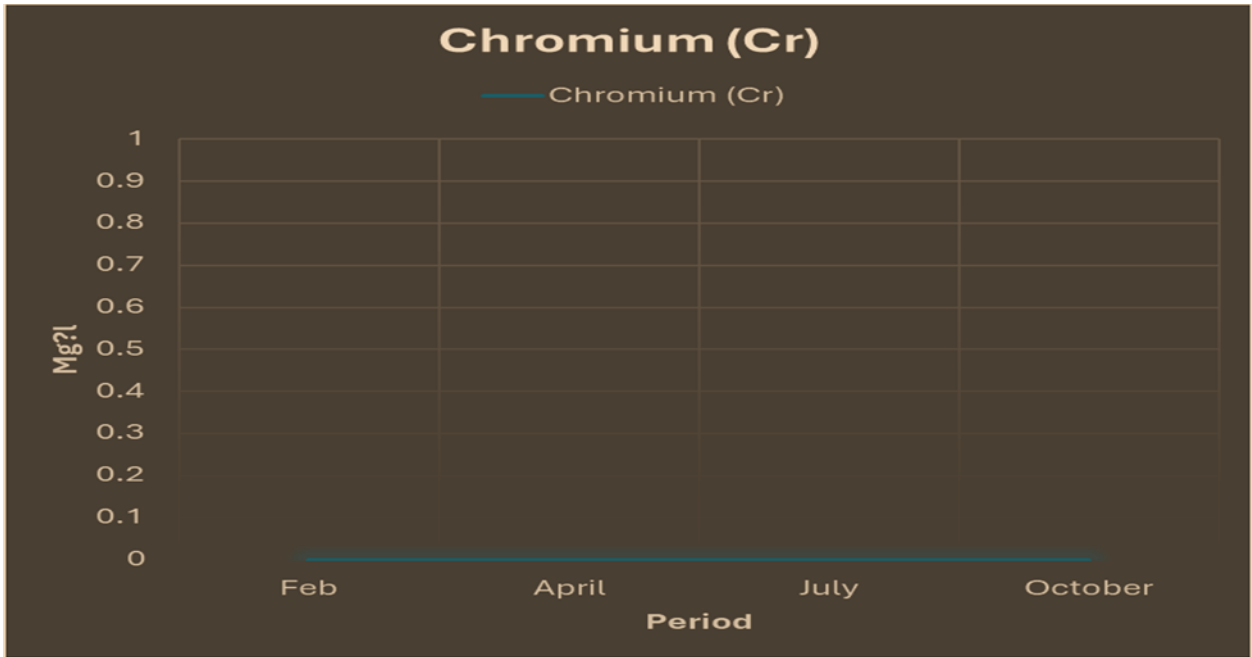
Zinc concentrations at BH2 were consistently low and exhibited minimal temporal variation (Figure 4.10). Zinc is frequently detected at background levels in groundwater and is generally not considered problematic unless elevated by industrial or mining discharges. The observed zinc levels align with recent groundwater assessments indicating stable zinc concentrations in mining-affected aquifers where waste containment systems are effective (O'Connor et al., 2022; Bondu et al., 2023).



**Figure 4.10:** BH2 Concentrations of Zinc over the sampling period.

#### 4.4.1.5 Chromium (Cr)

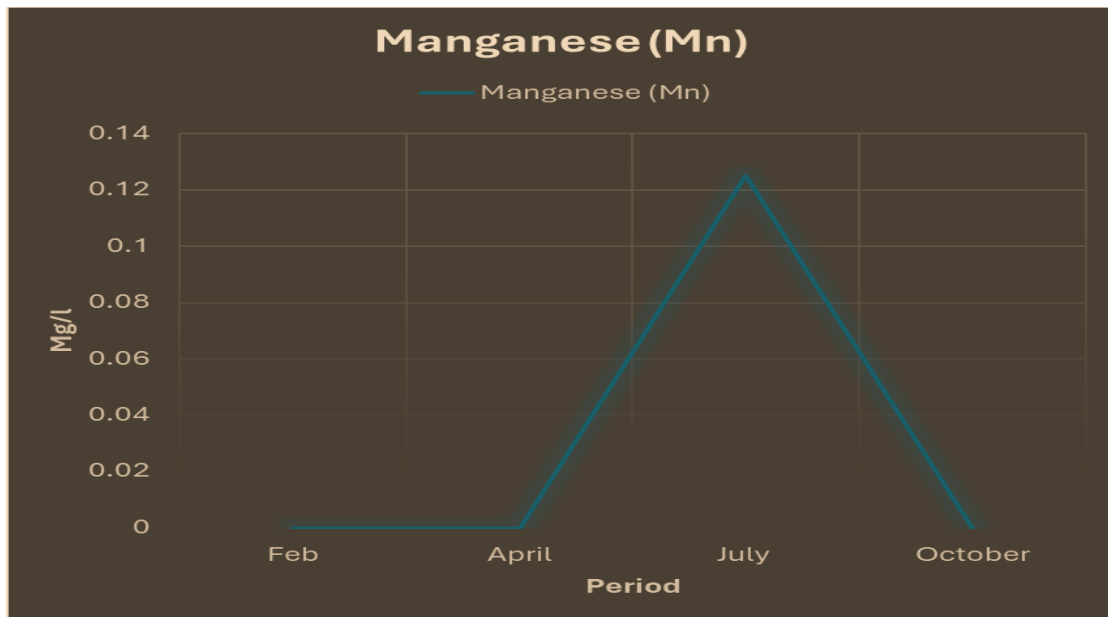
Chromium concentrations at BH2 remained below the maximum permissible limit of 0.05 mg/L throughout the study period (Figure 4.11). Minor temporal fluctuations were observed, which may be attributed to seasonal changes in groundwater redox conditions. Recent studies indicate that chromium mobility in groundwater is strongly influenced by oxidation–reduction conditions and pH, with seasonal recharge playing a key role in observed variability (Rautio et al., 2022; Bu et al., 2024).



**Figure 4.11:** BH2 Concentrations of Chromium over the sampling period.

#### **4.4.1.6 Manganese (Mn):**

The data displayed in Figure 4.12 show that the concentrations ranged from <0.001 to 0.125 mg/L, with a mean of 0.031 mg/L. This falls within the acceptable range of SANS 241-1:2015 (0.1 mg/L) but exceeds the IRMA recommended limit (0.05 mg/L). While it is not an immediate health concern at these levels, Fosso-Kankeu et al. (2017) point out that monitoring remains a crucial strategic aspect when dealing with potential heavy metals contamination of ground water. While the highest value remains below the SANS limit, manganese exposure can affect sensitive individuals, especially children, causing neurological and movement disorders (Bjørklund et al., 2017). Assessing local vulnerability and potential risks is crucial, and monitoring over a longer period and across different seasons can reveal potential fluctuations and inform mitigation strategies.



**Figure 4.12:** BH2 Concentrations of Manganese over the sampling period.

#### 4.4.2 Discussion of the findings from BH2

The implications of the findings on ground water quality and heavy metals concentrations indicate that the consistent detection of lead concentrations below the permissible limits shows that lead contamination is not a current concern for drinking water quality in BH2. This is a positive finding, as lead exposure can have severe health effects. As pointed out by Liu et al. (2022), lead exposure presents a significant public health threat, particularly for children and pregnant women. While naturally occurring in rocks and soil, human activities like mining, industrial waste disposal, and even the use of leaded gasoline have contributed to increased lead levels in some water sources. However, according to this study, the absence of detectable lead levels suggests that the risk of negative health impacts associated with lead contamination in BH2 groundwater is significantly reduced. While calcium concentrations fall within the acceptable range according to SANS guidelines, they exceed the recommended limits set by IRMA. Elevated calcium levels can affect water taste and contribute to scaling in pipes and appliances, potentially impacting infrastructure and consumer satisfaction. Therefore, although not posing an immediate health concern, monitoring and management strategies may be necessary to address potential palatability issues and infrastructure maintenance.

The low copper concentrations indicate compliance with both SANS and IRMA guidelines, suggesting that copper is not a concern for drinking water quality in BH2.

However, understanding the sources contributing to copper in groundwater is essential for long-term management. A study by Mativenga and Marnewick (2018) noted that differentiating between natural geological sources and anthropogenic inputs is crucial in implementing appropriate mitigation measures where necessary. According to the findings of this study, the absence of detectable levels of zinc and chromium indicates compliance with both SANS and IRMA standards, alleviating concerns about contamination from these metals in BH2 groundwater. While manganese concentrations fall within SANS guidelines, they exceed the recommended limits set by IRMA. Although not an immediate health concern, prolonged exposure to elevated manganese levels can pose risks, particularly for sensitive individuals such as children. Continued monitoring and assessment are essential to understand potential fluctuations and inform mitigation strategies.

The findings suggest that while BH2 groundwater meets regulatory standards for most heavy metals, ongoing monitoring and management efforts are necessary to ensure the long-term sustainability and safety of water resources in the area. As Netshiongolwe (2018a) posited, understanding the sources and dynamics of heavy metal contamination is crucial for implementing targeted mitigation strategies and protecting both environmental quality and human health.

#### **4.5 Sampling Site: BH3**

This section presents the descriptive results of heavy metal concentrations measured in groundwater from borehole BH3 across the four sampling periods.

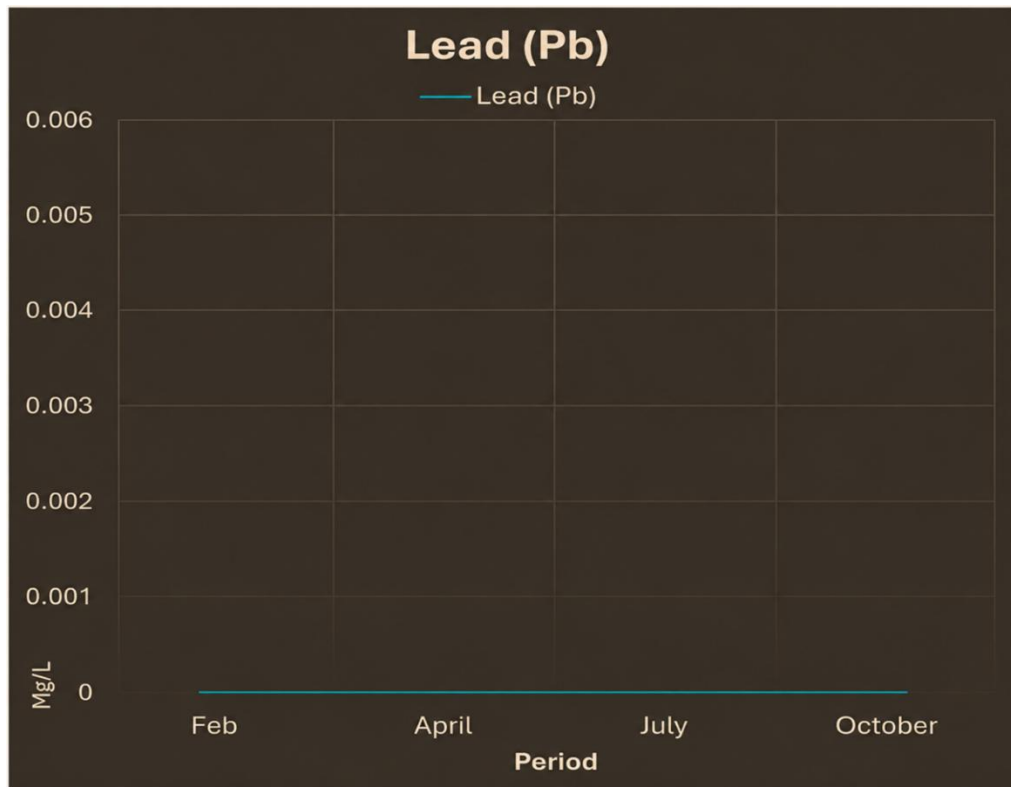
##### **4.5.1 Interpretation of the data**

The data on the BH3 groundwater quality and heavy metals concentrations around Kolomela Mine are interpreted as below.

###### **4.5.1.1 Lead (Pb)**

According to Figure 4.13, lead concentrations at BH3 were below detection limits across all sampling periods. This indicates no detectable lead contamination and compliance with national and international drinking water standards. Similar findings

have been reported in recent groundwater assessments in mining areas where lead remains largely immobile unless acidic conditions prevail (Drapeau et al., 2021).



**Figure 4.13:** BH2 Concentrations of Lead over the sampling period.

#### 4.5.1.2 Calcium (Ca)

In Figure 4.14, findings show that the calcium levels fluctuated between 54.1 mg/L and 94.3 mg/L, with a mean concentration of 72.8 mg/L. This variability suggests some fluctuations in the natural mineral content of the groundwater. As explained by Ndam and Madzimbamuto (2023), the geology of the region plays a role in naturally occurring calcium levels. As such, knowing the rock types and their calcium content helps assess if the observed fluctuations are primarily influenced by mining activities or natural variability. According to Wu et al. (2023), if significantly exceeding the natural range, high calcium levels can increase water hardness, potentially impacting aquatic life sensitive to specific hardness ranges, contribute to scaling in pipes and fixtures, causing maintenance issues. While less concerning than high levels, very low calcium might not provide sufficient calcium intake for some organisms. Seasonal variation in calcium concentration has been widely documented in groundwater studies conducted in semi-arid mining regions (Manimaran et al., 2025).

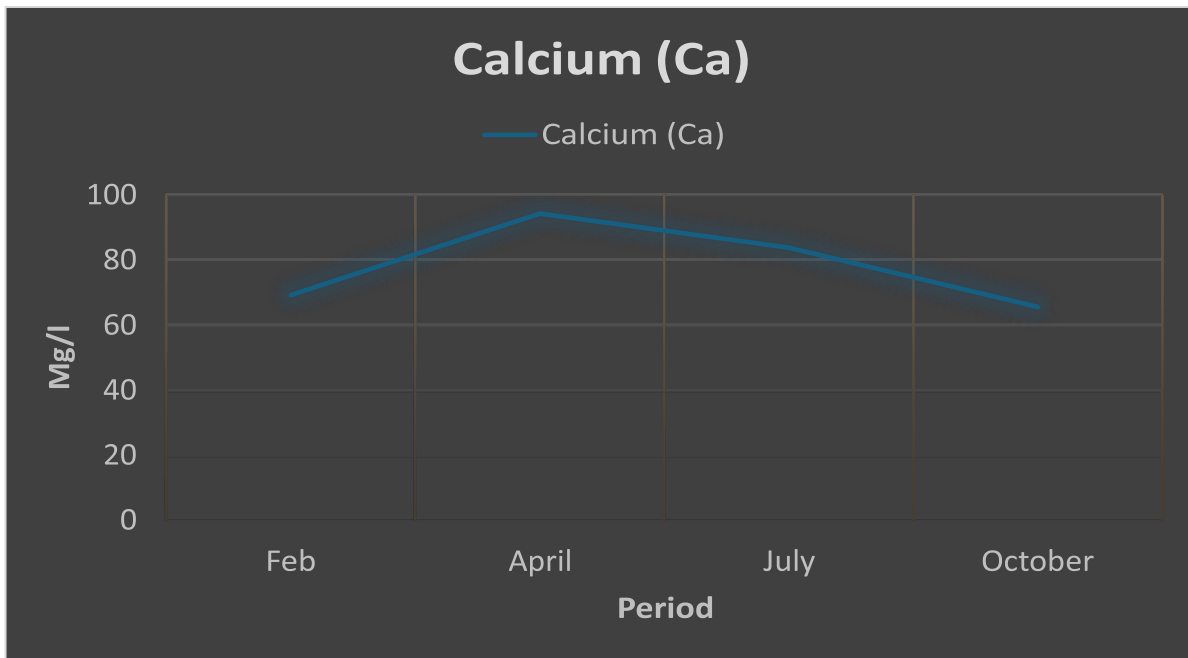


Figure 4.14: BH2 Concentrations of Calcium over the sampling period.

#### 4.5.1.3 Copper (Cu)

As in Figure 4.15, Copper concentrations at BH3 remained low and within guideline limits throughout the study period. These results suggest limited mobilisation of copper-bearing minerals and minimal mining-related influence. Comparable low copper concentrations have been reported in groundwater surrounding iron-ore mining operations, particularly where host lithology is not copper-rich and groundwater conditions are neutral to slightly alkaline, limiting copper mobilisation (Henne et al., 2020).

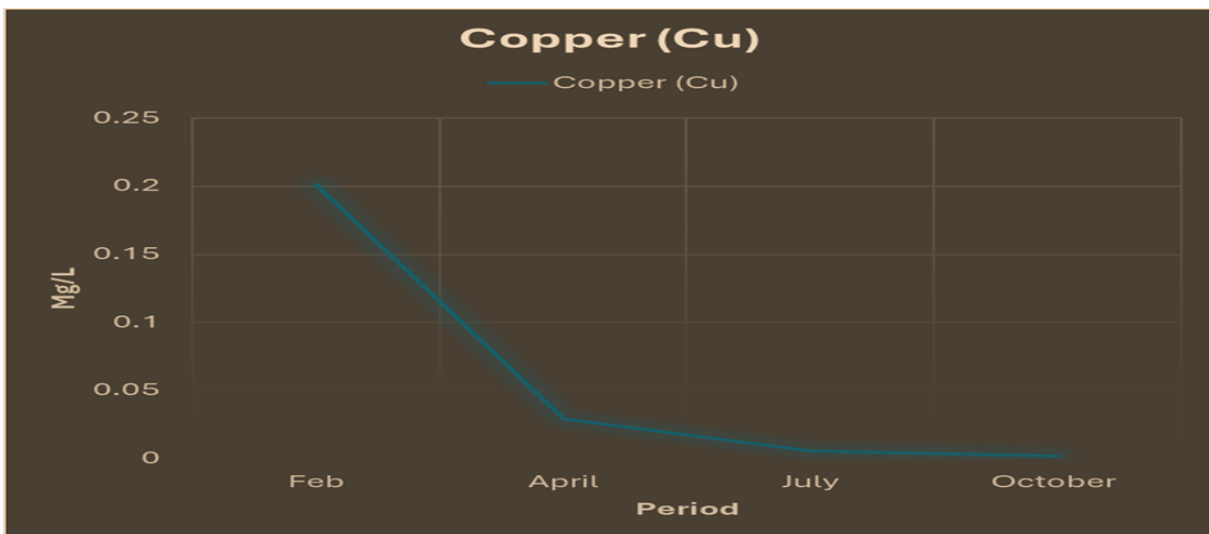


Figure 4.15: BH3 Concentrations of copper over the sampling period.

#### 4.5.1.4 Zinc (Zn)

According to the data (Figure 4.16), Zinc concentrations at BH3 were low and stable across all sampling periods. Such concentrations are characteristic of background groundwater levels and do not indicate contamination.

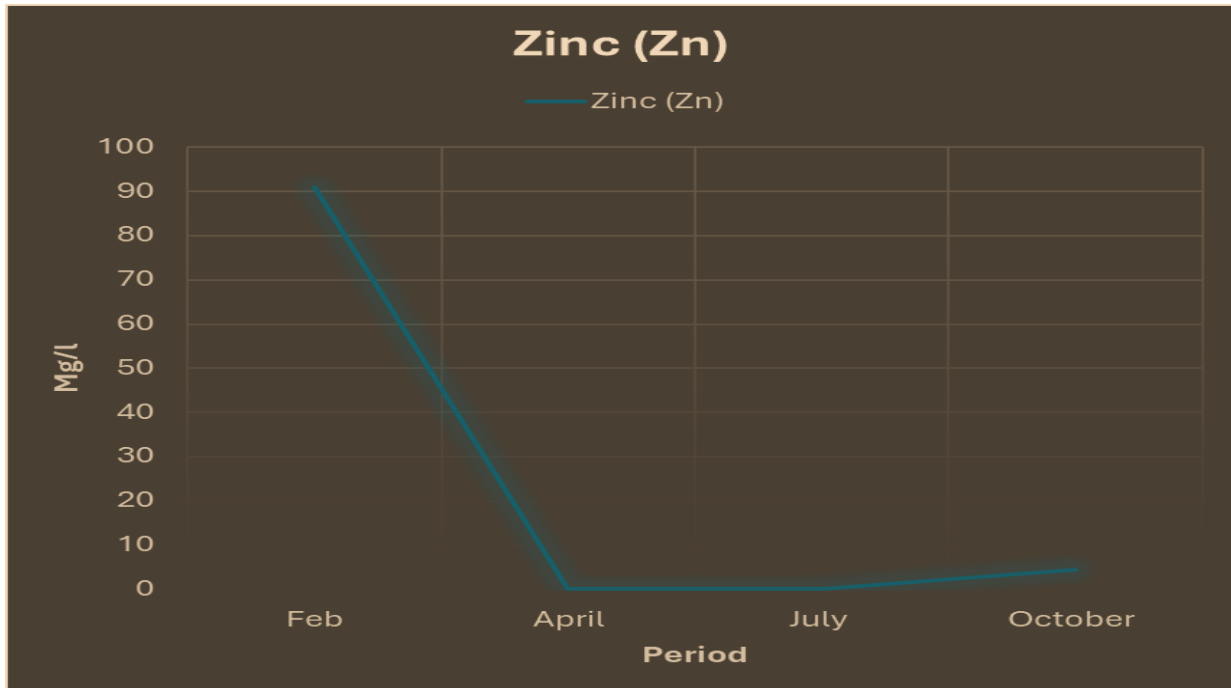


Figure 4. 16: BH3 Concentrations of Zinc over the sampling period.

#### 4.5.1.5 Manganese (Mn)

Figure 4.17 indicates that while the median manganese concentration (0.001 mg/L) remains below both the South African National Standard (SANS 241-1:2015) and the International Reference for Mine Water Assessment (IRMA) guideline values, individual measurements exceed the IRMA recommended limit of 0.05 mg/L. This variability highlights the importance of ongoing groundwater monitoring, as episodic elevations in manganese concentrations may pose potential health concerns under prolonged exposure scenarios. Manganese is an essential trace element; however, chronic exposure to elevated levels in drinking water has been associated with adverse neurological effects, particularly in sensitive populations such as infants, children and pregnant women (WHO, 2017; Bouchard et al., 2018). Continued monitoring is therefore warranted to assess temporal trends and to ensure that episodic exceedances do not translate into long-term health risks.

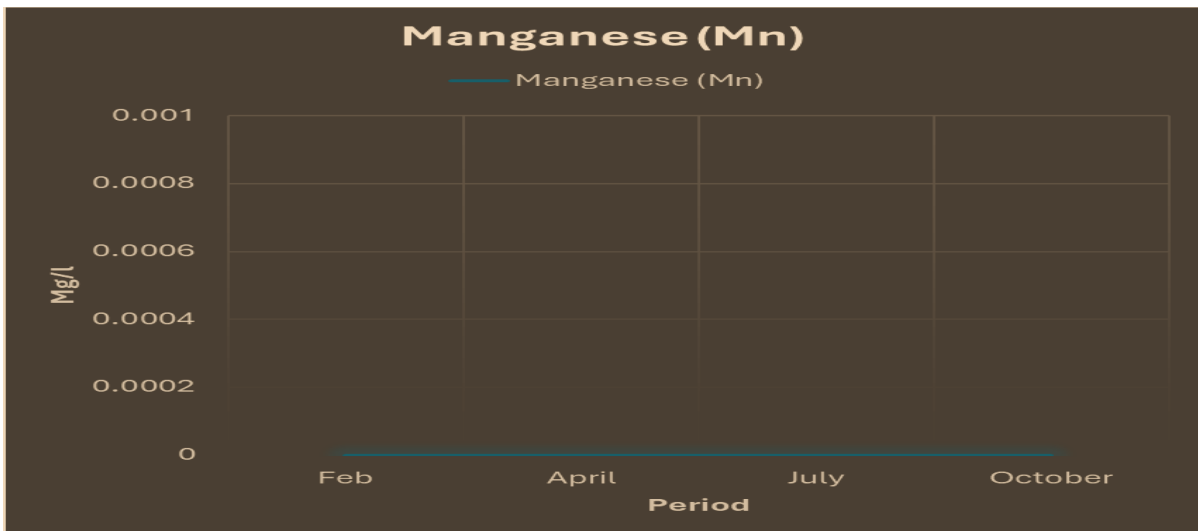


Figure 4.17: BH3 Concentrations of Manganese over the sampling period.

#### 4.5.1.6 Thallium (Tl) and Chromium (Cr)

Thallium and chromium concentrations at BH3 remained consistently below (Figure 4.18 and Figure 4.19) the analytical detection limits throughout the sampling period, indicating the absence of measurable contamination by these elements in the groundwater at this site. This finding suggests limited mobilisation of thallium- and chromium-bearing minerals under the prevailing hydrogeochemical conditions. Similar observations have been reported in groundwater studies where stable pH and redox conditions restrict the release of these metals into solution, particularly in mining environments without active acid mine drainage (WHO, 2017; Rautio et al., 2022).



Figure 4.18: BH3 Concentrations of Chromium over the sampling period.

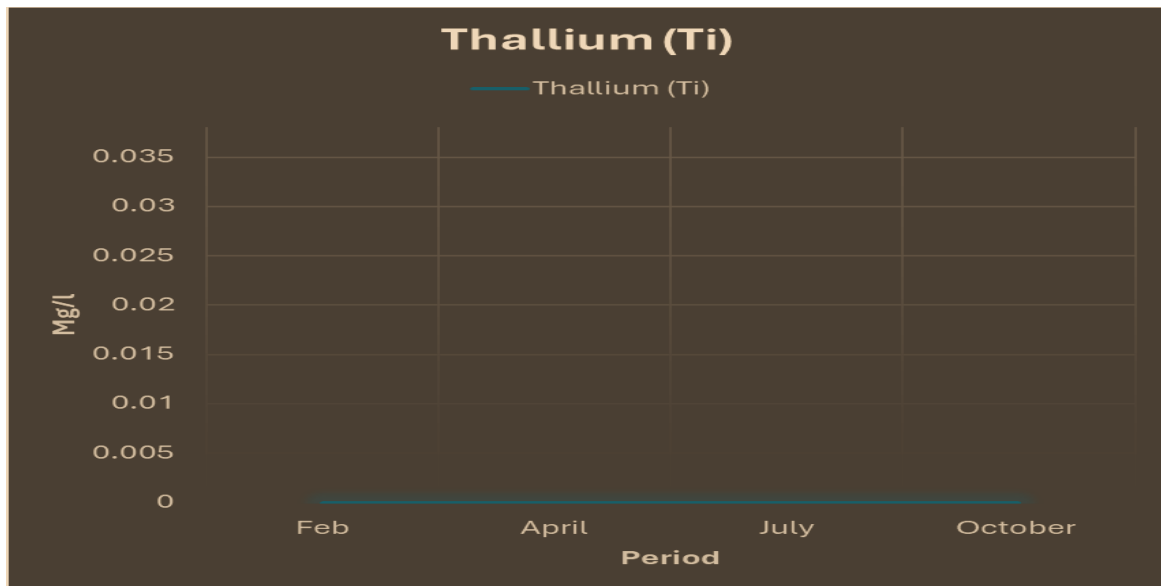


Figure 4.19: BH3 Concentrations of Thallium over the sampling period.

#### 4.5.1.7 Nickel (Ni)

Nickel concentrations at BH3 remained below the analytical detection limit (<0.002 mg/L) throughout the sampling period, indicating the absence of measurable nickel contamination in the groundwater at this site (Figure 4.20). This pattern suggests limited mobilisation of nickel-bearing minerals under the prevailing hydrogeochemical conditions. Similar findings have been reported in groundwater studies where neutral pH conditions and the absence of acid mine drainage restrict nickel solubility and transport in aquifer systems (WHO, 2017; Alloway, 2013).

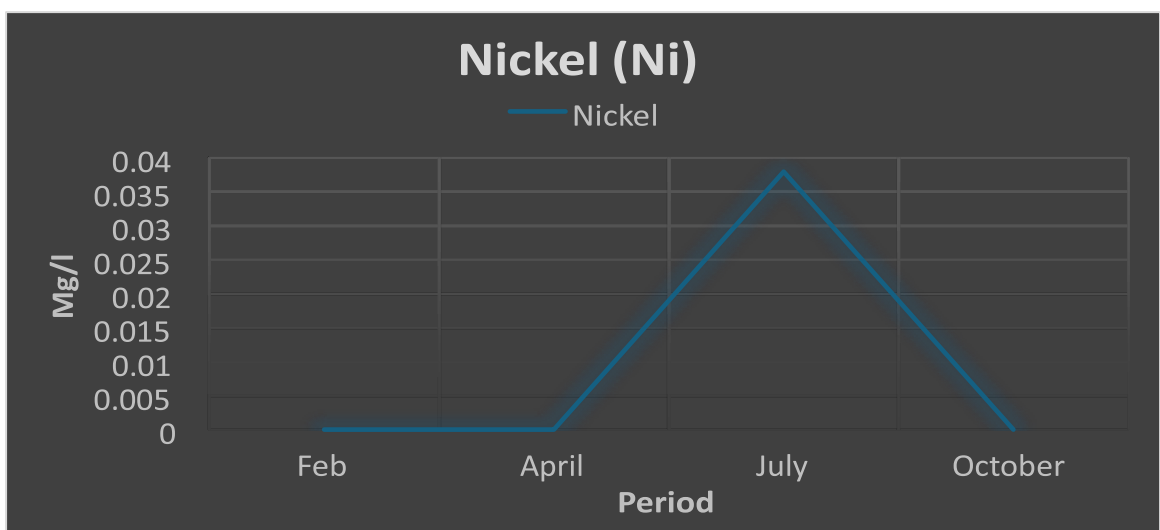


Figure 4.20: BH3 Concentrations of Nickel over the sampling period.

#### **4.5.2 Discussion of the findings from BH3**

The interpretation of groundwater quality at BH3 in Kolomela Mine provides valuable insights into potential heavy metal contamination and concentration trends. The consistent detection of lead concentrations below the limit of detection (LOD) of 0.004 mg/L indicates that lead contamination is not a significant concern in the groundwater at BH3. Lead is a highly toxic heavy metal that can cause severe health effects, especially in children. While the fluctuation in calcium concentrations recommends variations in the natural mineral content of the groundwater, calcium is an essential mineral for human health and is commonly found in geological formations. However, extreme concentrations can affect water hardness and may indicate potential interactions with other contaminants.

The variability in copper concentrations highlights potential sources of contamination, with the proximity to the Kolomela mining area raising concerns about mining activities as a potential source of copper contamination. According to Yusoff et al. (2022), mining processes can mobilise copper from rocks and release it into the environment through various pathways, including acid mine drainage, waste rock leaching and spills. Yusoff argues that low levels of copper can be toxic to aquatic life, impacting sensitive species and disrupting ecosystems. The variability in copper concentrations could pose an ecological risk if it fluctuates above tolerable levels for certain organisms. Although the current levels are unlikely to pose immediate health risks through drinking water, chronic exposure to elevated copper can lead to various health problems in humans, including liver damage, gastrointestinal issues and neurological disorders. Long-term monitoring is crucial to ensure safe drinking water quality.

Like copper, the fluctuation in zinc concentrations indicates potential sources of contamination. Zinc is commonly used in industrial processes and can leach into groundwater from various sources, including mining activities and urban runoff. The fluctuation in zinc concentrations around Kolomela mining site indicates potential sources of contamination for groundwater, and this can have significant implications for both the groundwater itself and the surrounding ecosystem. A study by Nkono et al. (2020) demonstrated that Zinc, a naturally occurring element, can pose significant environmental and health concerns when it leaches into groundwater from

anthropogenic sources such as mine waste runoff, tailings storage and accidental spills. These contaminations, in turn, elevate zinc concentration in water beyond safe drinking standards, leading to detrimental effects on both ecosystems and human health. As Njiru et al. (2019) explained, elevated zinc levels in groundwater can alter its pH and chemical composition, rendering it unsuitable for various purposes. High zinc concentrations can pose a direct threat to human health through consumption, causing gastrointestinal distress (cramps, vomiting, diarrhea) and even neurological issues in severe cases (Schoofs et al., 2024).

The findings show that Manganese concentrations fluctuated within the noticed range, from <0.001 to 0.125 mg/L, with a mean of 0.031 mg/L., suggesting natural variations or potential anthropogenic inputs. While manganese is an essential nutrient, elevated levels can have adverse health effects and aesthetic impacts, such as staining of plumbing fixtures. Continued monitoring is essential to detect any emerging trends or issues. There is also the consistent absence of detectable levels of thallium and chromium, indicating minimal contamination of BH3 groundwater with these elements. According to Njiru et al. (2019), thallium and chromium are highly toxic heavy metals, often associated with industrial activities and mining operations. Their absence suggests effective containment measures or low anthropogenic inputs in the vicinity of BH3. Although the consistent absence of detectable levels of nickel suggests minimal contamination of groundwater at BH3, it is commonly used in various industrial processes and can leach into groundwater from contaminated sites. The absence of detectable levels is a positive indication but warrants continued monitoring to ensure continued water quality.

In summary, the interpretation of groundwater quality at BH3 in Kolomela Mine highlights the importance of comprehensive monitoring and management practices to safeguard water resources from heavy metal contamination.

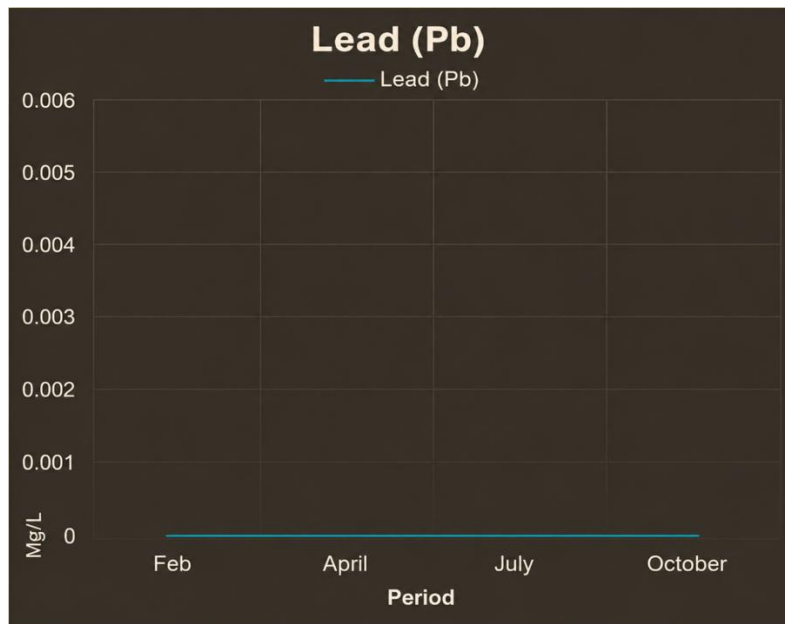
#### **4.6 Sampling Site: BH4**

This section presents the descriptive results of heavy metal concentrations measured in groundwater samples from borehole BH4.

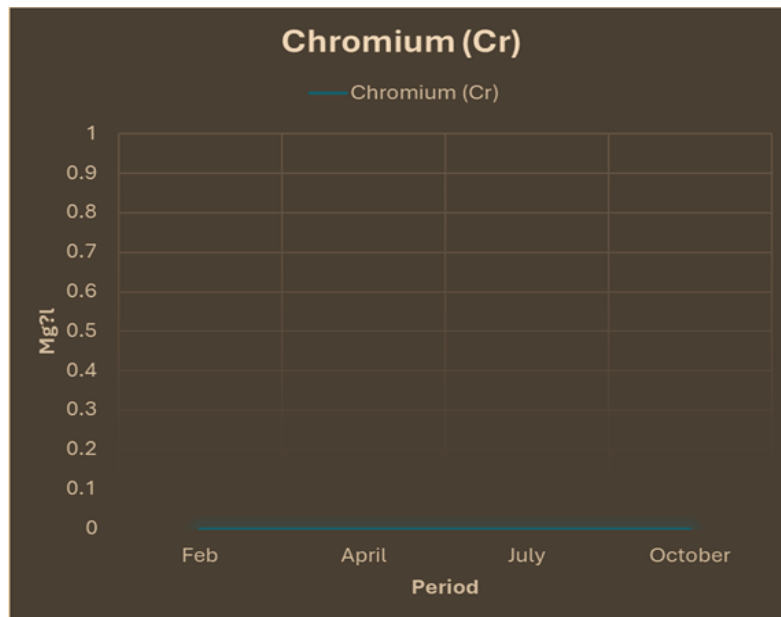
#### 4.6.1. Interpretation of the data

##### 4.6.1.1 Lead, Chromium, Thallium and Nickel

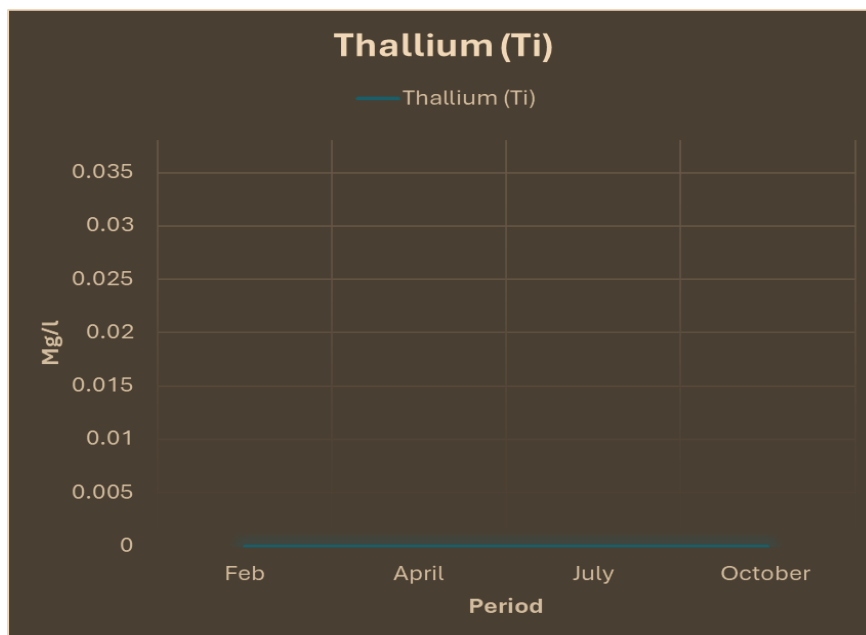
Data presented in Figures 4.21, 4.22, 4.23 and 4.24 show that lead, chromium, thallium and nickel concentrations in groundwater at BH4 remained consistently below their respective analytical detection limits across all sampling dates. These results indicate compliance with relevant drinking water standards, including SANS 241-1:2015 and World Health Organization guideline values. The absence of detectable concentrations suggests no immediate concern associated with these specific heavy metals at this sampling site during the study period. Similar findings have been reported in groundwater studies where stable hydrogeochemical conditions limit the mobilisation of trace metals in mining-influenced aquifers (WHO, 2017; Rautio et al., 2022; Alloway, 2013).



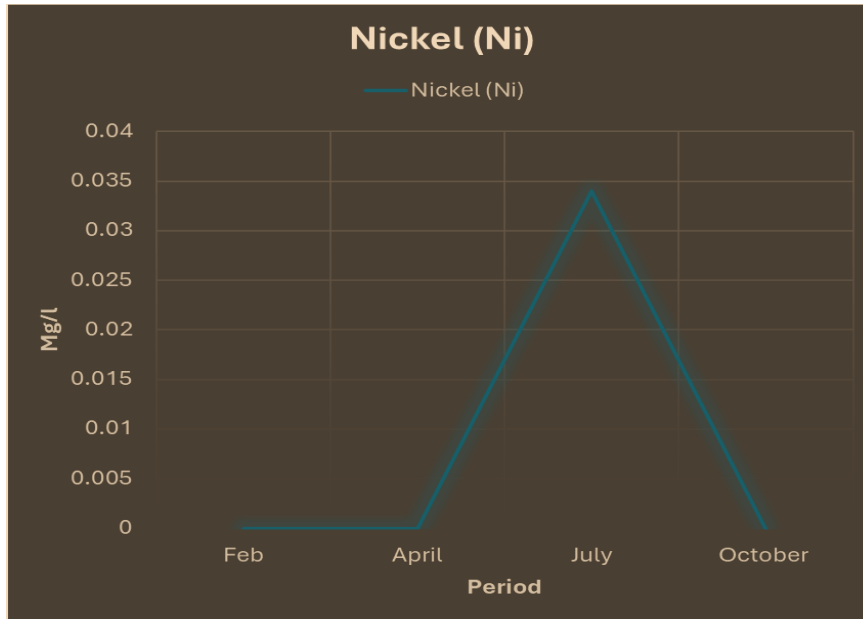
**Figure 4.21:** BH4 Concentrations of Lead over the sampling period



**Figure 4.22:** BH4 Concentrations of Chromium over the sampling period



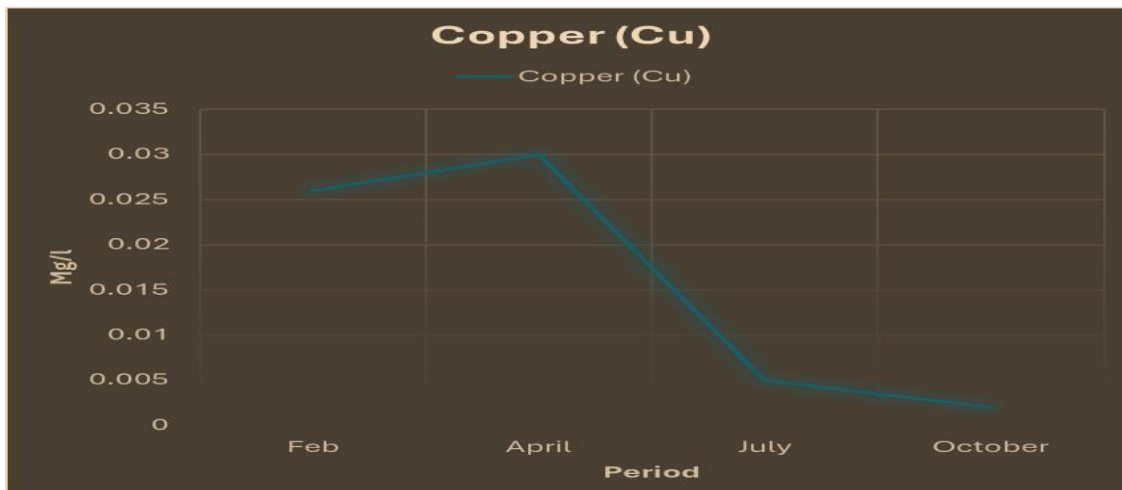
**Figure 4.23:** BH4 Concentrations of Thallium over the sampling period.



**Figure 4.24:** BH4 Concentrations of Nickel over the sampling period.

#### 4.6.1.2 Copper

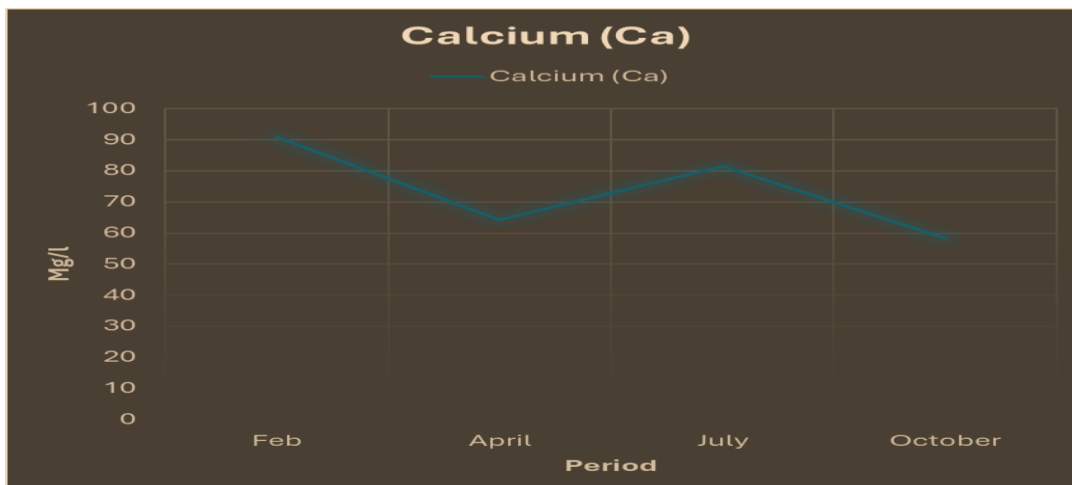
Figure 4.25 shows that copper concentrations in groundwater at BH4 consistently remained within the permissible limits set by the South African National Standard (SANS 241-1:2015; 2 mg/L) and the International Reference for Mine Water Assessment (IRMA; 1 mg/L) across all sampling dates. These findings indicate compliance with applicable drinking water guidelines and suggest a minimal risk associated with copper contamination at this sampling site during the study period. Similar patterns have been reported in groundwater studies where copper occurs predominantly at background concentrations and remains geochemically stable under neutral to mildly alkaline conditions, particularly in the absence of significant acid mine drainage or industrial inputs that would otherwise enhance copper mobilisation. (WHO, 2017; Derkowska et al., 2023).



**Figure 4.25:** BH4 Concentrations of copper over the sampling period.

#### 4.6.1.3 Calcium

According to Figure 4.26, calcium concentrations in groundwater at BH4 consistently fell within the acceptable range specified by the South African National Standard (SANS 241-1:2015; 30–200 mg/L). However, some samples exceeded the International Reference for Mine Water Assessment (IRMA) recommended range of 75–150 mg/L. Although such exceedances do not pose a direct health risk, elevated calcium concentrations may influence the aesthetic quality of drinking water, particularly taste, and contribute to scaling in pipes and household appliances. Similar effects associated with increased calcium and water hardness have been documented in groundwater studies, highlighting the need for continued monitoring to manage potential aesthetic and infrastructure-related impacts (WHO, 2017; Akram & Rehman, 2018).



**Figure 4.26:** BH4 Concentrations of Calcium over the sampling period.

#### 4.6.1.4 Manganese

As shown in Figure 4.27, manganese concentrations in groundwater at BH4 were consistently below the South African National Standard (SANS 241-1:2015) limit of 0.1 mg/L across all sampling dates. However, some measurements exceeded the International Reference for Mine Water Assessment (IRMA) guideline value of 0.05 mg/L. Although these concentrations remain within national drinking water standards, episodic exceedances of the IRMA guideline warrant continued monitoring. Prolonged exposure to elevated manganese in drinking water has been associated with neurological and motor function effects, particularly among vulnerable populations such as infants, children and

pregnant women, underscoring the importance of tracking temporal trends to manage potential long-term risks (WHO, 2017; Bouchard et al., 2018).

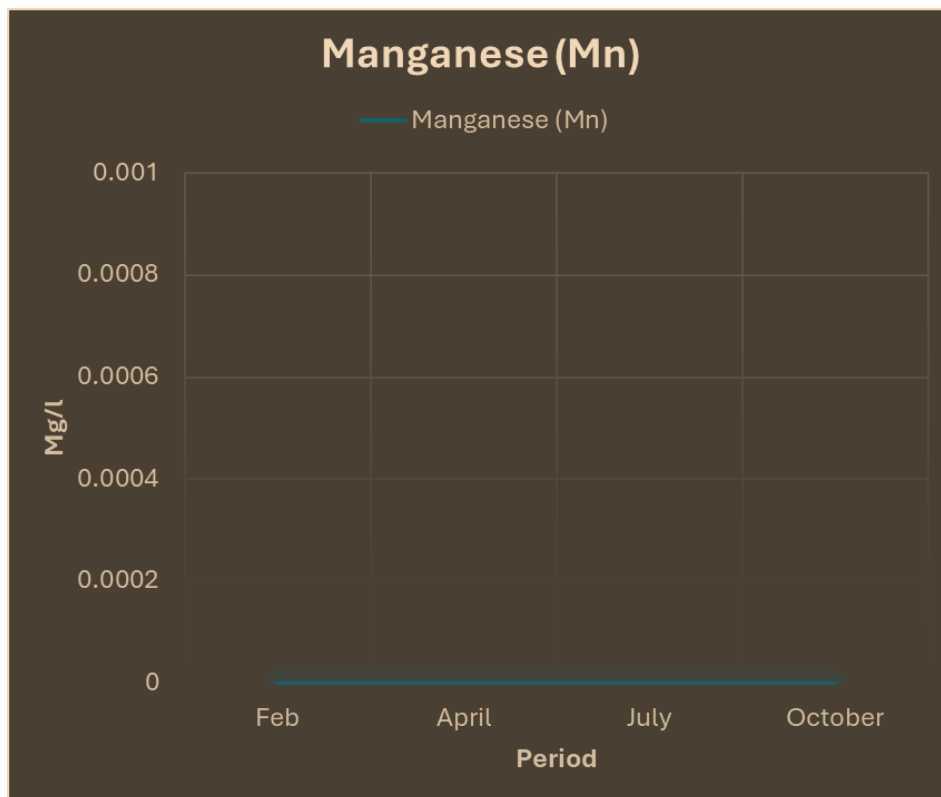
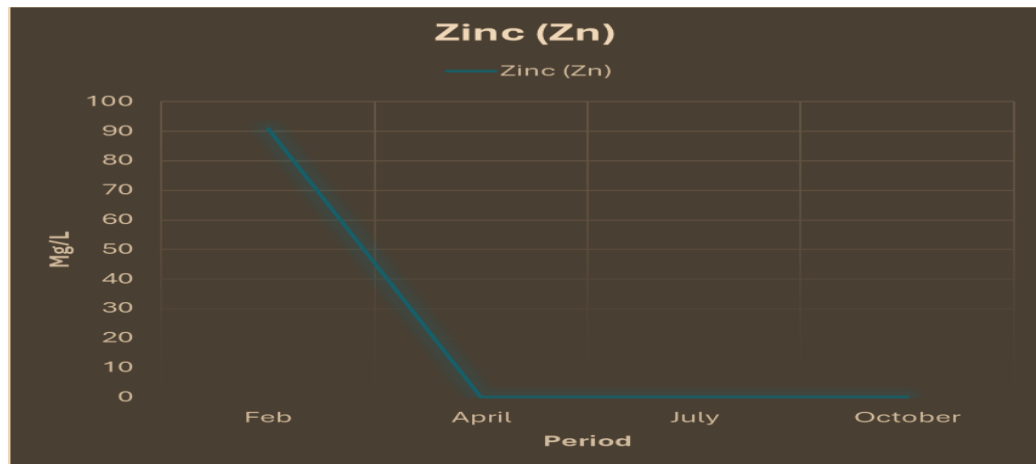


Figure 4.27: BH4 Concentrations of Manganese over the sampling period.

#### 4.6.1.5 Zinc

According to Figure 4.28, the presence of an isolated high zinc concentration (0.91 mg/L) in groundwater at BH4 represents a clear outlier relative to the remaining measurements. Such an anomalous value raises questions regarding analytical accuracy or potential sample-specific contamination rather than indicating a consistent groundwater quality trend. Verification through repeat sampling, duplicate analysis, or confirmation using an alternative analytical technique is therefore essential to ensure the reliability of the zinc dataset. The identification and verification of outliers are widely recommended in groundwater quality assessments to distinguish true environmental signals from analytical or procedural artefacts (APHA, 2018; WHO, 2017; Peterson et al., 2018).



**Figure 4. 28:** BH4 Concentrations of Zinc over the sampling period.

#### 4.6.2 Discussion of the findings from BH4

The results offer insights into the groundwater quality and heavy metal concentrations at Kolomela Mine, as they are focusing on metal species such as Lead (Pb), Calcium (Ca), Copper (Cu), Zinc (Zn), Manganese (Mn), Thallium (TI), Chromium (Cr) and Nickel (Ni). The data on BH4 showed that lead concentrations were consistently below the detection limit of <0.004 mg/L across all sampling dates. This suggests that lead contamination is not a concern in the groundwater at Kolomela Mine during the assessed period.

Compliance with both the South African National Standards (SANS) 241-1:2015 and IRMA Drinking Water Quality Criteria indicated satisfactory levels of lead, which is crucial for preventing adverse health effects associated with lead exposure. Calcium levels in BH4 varied between 54.1 mg/L and 94.3 mg/L, with a mean of 72.8 mg/L. These concentrations fell within acceptable ranges, indicating that calcium is not a significant concern for groundwater quality. However, the standard deviation of 13.0 mg/L suggests some variability in calcium concentrations, potentially causing temporary spikes in water hardness. According to Mativenga & Marnewick (2018), such a deviation could impact various aspects. For instance, hard water can cause scaling in pipes, fixtures and appliances, leading to maintenance issues and reduced efficiency. While generally not acutely toxic, fluctuating calcium levels could disrupt aquatic ecosystems if they reach extremes outside the tolerance range of sensitive species. This could negatively affect biodiversity and overall ecosystem health.

Copper concentrations in BH4 ranged from 0.002 mg/L to 0.029 mg/L, with a mean of 0.009 mg/L. While most samples met regulatory standards, there was some variability in copper levels. Exceedances of the guideline values could indicate potential sources of contamination or natural variations in copper concentrations. Monitoring and further investigation may be necessary to ensure consistent compliance with drinking water standards. Zinc concentrations ranged from 0.002 mg/L to 0.91 mg/L, with a mean of 0.020 mg/L and a high standard deviation of 0.248 mg/L. The wide variability in zinc concentrations suggests potential sources of contamination or geological factors influencing groundwater quality. Elevated zinc levels, particularly the outlier at 0.91 mg/L warrant further investigation to identify the source and mitigate any adverse effects on water quality.

The interpretation of the data also indicates that manganese concentrations of BH4 varied between <0.001 mg/L and 0.125 mg/L, with a mean of 0.013 mg/L. While most samples fell within acceptable limits, manganese levels may pose a concern, especially considering the high standard deviation of 0.033 mg/L.

Manganese contamination can affect water taste and colour and may have health implications at higher concentrations. Continuous monitoring and mitigation measures are essential to ensure water quality compliance. The thallium, chromium and nickel concentrations were consistently below the detection limits, indicating minimal to no presence of these heavy metals in the groundwater samples. This suggests that thallium, chromium and nickel contamination is not a significant concern based on the data provided. While most manganese samples from BH4 were within acceptable limits, the high standard deviation of 0.033 mg/L indicates significant variability, thus raising concerns for potential implications on groundwater quality and associated risks. Elevated manganese levels, according to Mativenga & Marnewick (2018), could lead to spikes exceeding safe limits, and this can adversely impact aquatic ecosystems. Manganese toxicity can harm sensitive species like fish, invertebrates and algae, disrupting food webs and biodiversity. Chronic exposure to elevated manganese can alter water chemistry, affecting other parameters like pH and oxygen levels, further stressing aquatic life and potentially creating anoxic zones. Although most samples seem safe, variability means some might exceed recommended limits. Consuming

water with high manganese can lead to adverse health effects, including neurological disorders, impaired cognitive function, and developmental problems in children.

The results of the BH4 sampling study showed that although the majority of the BH4 heavy metal concentrations in the groundwater at Kolomela Mine are within allowable bounds, there are some variances and outliers that need more research. To preserve groundwater quality and safeguard the environment and public health, it is imperative to identify the source, conduct ongoing monitoring, and put suitable mitigating measures into place.

#### **4.7. Summary**

The study findings offer key insights into groundwater quality and heavy metal concentrations in four boreholes (BH1, 2, 3, and 4) at the Kolomela Mine while they also bring up issues that need more research and varied management approaches. Lead concentrations consistently were below detection limits across all boreholes, indicating minimal risks of contamination and compliance with regulations. This alleviates concerns about associated health risks. However, the constant lack of detectable chromium in every drilling point to either little anthropogenic inputs or successful containment methods allays worries about this extremely hazardous element. With manganese levels in BH1 and 3 consistently complying with both SANS and IRMA standards, it poses no immediate health concerns. Excluding the outlier in BH1, zinc concentrations generally fell within acceptable limits across all boreholes, thus suggesting minimal widespread contamination.

While within acceptable ranges according to SANS in most boreholes, calcium levels exceeded IRMA recommendations in BH2 and 4. This could impact water taste and infrastructure, necessitating monitoring and potential management strategies, and although complying with regulations in BH2 and 3, some copper concentrations in BH4 exceed guidelines. This suggests potential contamination sources that require further investigation to understand their origin and implement appropriate management measures. While falling within SANS guidelines in BH2 and 4, manganese concentrations fluctuate and exceed IRMA limits in some samples. This raises concerns about potential health risks, particularly for sensitive populations, and necessitates further investigation to identify sources, understand variability, and

implement mitigation strategies. The outlier exceeding both SANS and IRMA standards in BH1 warrants further investigation to understand its cause and potential implications for localised groundwater quality.

The findings emphasise the importance of comprehensive and ongoing monitoring across all boreholes, along with targeted management strategies to ensure the long-term sustainability and safety of groundwater resources at the Kolomela Mine. While positive aspects exist, concerns regarding calcium, copper, manganese, and the zinc outlier necessitate further investigation and proactive measures like pollution prevention, remediation efforts, and adherence to regulatory standards. Implementing such measures is crucial for safeguarding both human health and the surrounding ecosystem. With such findings, Liu, Zhou and Wang (2022) are of the view that continued observation and proactive measures, including pollution prevention, remediation efforts and adherence to regulatory standards are essential to ensure the long-term sustainability and safety of groundwater for both human consumption and environmental integrity.

## **CHAPTER 5:**

### **SUMMARY OF KEY FINDINGS, CONCLUSIONS AND RECOMMENDATIONS**

#### **5.1. Introduction**

This chapter is based on conclusions drawn from the groundwater quality assessment conducted around Kolomela Mine, with specific emphasis on the occurrence and distribution of heavy metals in groundwater. The conclusions are based on the descriptive analysis of data collected from four boreholes over multiple sampling periods and interpreted in relation to applicable South African and international drinking water standards. The chapter synthesises the key findings discussed in Chapter Four, highlights their implications for groundwater users and mine management, and provides recommendations aimed at supporting ongoing groundwater protection and monitoring efforts.

#### **5.2. Summary and Interpretation of Key Findings**

##### **5.2.1 Generally low heavy metal levels**

The findings of this study indicate that, during the monitoring period, groundwater around Kolomela Mine generally exhibited low to moderate levels of heavy metal contamination. All measured heavy metal concentrations complied with South African drinking water standards (SANS 241-1:2015), with the exception of a single zinc outlier. This overall compliance suggests that, at present, mining activities have not resulted in widespread heavy metal pollution of the local groundwater system.

Notably, lead, chromium and mercury were not detected in any groundwater samples across all boreholes and sampling periods. This outcome is consistent with expectations based on the mineralogical characteristics of Kolomela's iron ore deposit and the absence of known industrial sources of lead or mercury at the site. The lack of detectable concentrations of these toxic metals is a reassuring finding for local groundwater users, as these elements are commonly associated with significant human health risks when present in drinking water (WHO, 2017).

### **5.2.2 Identification and interpretation of anomalies**

While overall groundwater quality was acceptable, the study identified a small number of anomalous observations that warrant careful consideration. These included a single elevated zinc concentration observed during the July sampling at BH1, as well as occasional exceedances of the International Reference for Mine Water Assessment (IRMA) guideline for manganese at certain boreholes.

The isolated zinc spike at BH1 did not recur in subsequent sampling events and was not observed in other boreholes. This suggests that the elevated value may be associated with a transient event, such as localised runoff, short-term geochemical mobilisation, or a sampling or analytical artefact, rather than an ongoing contamination source. Similar single-event anomalies have been reported in groundwater monitoring studies and are often resolved through confirmatory sampling and quality control checks (APHA, 2018; Peterson et al., 2018). It is therefore recommended that targeted resampling and site-specific investigations be conducted in the vicinity of BH1 to verify zinc concentrations and identify any potential zinc-bearing materials.

Manganese concentrations, while remaining below national drinking water limits, occasionally exceeded IRMA guideline values. Although manganese is an essential trace element, prolonged exposure to elevated concentrations has been associated with neurological effects, particularly in vulnerable populations such as children and pregnant women (WHO, 2017; Bouchard et al., 2018). These findings do not indicate an immediate health risk but highlight the importance of continued monitoring to track temporal trends and prevent potential long-term exposure concerns.

### **5.2.3 Spatial patterns and potential sources**

Analysis of spatial patterns across the four boreholes revealed no consistent elevation of heavy metal concentrations at any single sampling location. Importantly, boreholes situated closer to mining infrastructure, including BH2 near the tailing's facility, did not exhibit higher metal concentrations relative to more distant boreholes. This suggests that the tailings storage facility and associated waste management systems are currently functioning effectively, with minimal evidence of seepage or groundwater contamination.

This outcome contrasts with findings from other mining regions where inadequate tailings management has resulted in elevated groundwater metal concentrations downstream of

waste storage areas (Nguyen et al., 2019; Bu et al., 2024). The absence of a clear contamination gradient at Kolomela Mine therefore places the site on the more favourable end of outcomes reported in the literature and reflects positively on existing environmental management practices.

#### **5.2.4 Temporal variability and seasonal influences**

The study further found that temporal variability in heavy metal concentrations was generally limited, with no pronounced differences observed between wet and dry sampling periods. This subdued seasonal response may be attributed to the arid climatic conditions of the study area and the depth of the groundwater system. In such settings, rainfall infiltration may be insufficient to rapidly mobilise metals into the aquifer, or groundwater residence times may be long enough to buffer short-term changes in surface conditions.

These findings are consistent with groundwater studies conducted in semi-arid environments, where seasonal effects on metal concentrations are often less pronounced than in humid regions with shallow aquifers (Nguyen et al., 2019; Gantayat & Elumalai, 2024). The lack of strong seasonal variation further supports the interpretation that groundwater quality at Kolomela Mine is currently stable.

#### **5.2.5 Implications for stakeholders**

From a stakeholder perspective, the findings indicate that local groundwater resources remain suitable for use with respect to heavy metal contamination. This is particularly important for nearby communities that depend on groundwater for domestic and agricultural purposes, as the results suggest no immediate health risks associated with metals such as lead, chromium, nickel or mercury.

At the same time, the identification of isolated anomalies, including the zinc outlier and occasional manganese guideline exceedances, underscores the need for continued vigilance. Even single exceedances serve as a reminder that groundwater quality can change over time, particularly as mining operations continue and potentially expand. Ongoing monitoring, coupled with periodic data verification and transparent reporting, will be essential to ensure the long-term protection of groundwater resources and to maintain stakeholder confidence.

### **5.3 Conclusions**

In conclusion, the groundwater quality assessment around Kolomela Mine indicates that heavy metal contamination is generally low and remains within acceptable regulatory limits for drinking water. Most metals of concern, including lead, chromium, nickel and mercury, were consistently below detection limits, while metals such as copper, calcium and magnesium reflected natural hydrogeochemical conditions rather than mining-related contamination. Although isolated anomalies, including a single zinc outlier and occasional manganese guideline exceedances, were observed, these did not represent persistent trends across boreholes or sampling periods.

From a stakeholder perspective, these findings are reassuring for local communities and other groundwater users, as they indicate no immediate health risks associated with heavy metal exposure under current conditions. For mine management, the results suggest that existing water and waste management practices are effective in limiting groundwater contamination, particularly in areas proximal to mining infrastructure such as tailings facilities. However, the identification of isolated exceedances underscores the need for continued groundwater monitoring and periodic data verification to ensure early detection of potential changes. For regulators and environmental authorities, the findings provide baseline evidence to support informed oversight and long-term groundwater protection as mining activities continue.

### **5.4 Recommendations**

Based on the findings of this study, it is recommended that Kolomela Mine strengthens its environmental management and sustainability practices through a coordinated and proactive groundwater management approach. Consistent and comprehensive monitoring of all boreholes should be maintained for key heavy metals, including lead, copper, zinc, manganese and calcium, to enable early detection of changes in groundwater quality and to support informed decision-making. Where elevated metal concentrations have been identified, targeted investigations should be undertaken to determine their sources, particularly for copper and zinc at BH1 and BH4 and manganese across all boreholes. Understanding the origin of these metals will result in the development of appropriate mitigation measures, such as improved waste handling practices, infrastructure upgrades or site-specific remediation, where necessary. In parallel, sustainable water use practices

should be promoted to minimise water consumption and protect the long-term availability of groundwater resources.

In terms of water management, continued compliance with South African National Standards and IRMA drinking water criteria is essential to ensure the protection of groundwater users. The potential need for water treatment interventions should be evaluated, particularly in boreholes where calcium concentrations exceed IRMA guideline ranges, given the implications for water palatability and infrastructure scaling. Additional precautionary measures should also be considered to protect vulnerable populations from potential health risks associated with prolonged manganese exposure. These may include the use of alternative water sources, household or point-of-use filtration systems, and targeted public health awareness initiatives. Regular maintenance of water infrastructure is further recommended to address scaling-related issues and to ensure efficient and reliable water delivery.

From an environmental and public health perspective, periodic environmental impact assessments should be conducted to evaluate the potential effects of groundwater contamination on surrounding ecosystems and human health. Where specific sources of contamination are identified, appropriate remediation measures should be implemented to minimise environmental impacts and safeguard ecological integrity. Active engagement with local communities is also critical, both to raise awareness of groundwater quality issues and to incorporate local knowledge into water resource management practices.

To support the credibility and effectiveness of groundwater monitoring, strict adherence to standardised sampling protocols, analytical methods and quality control procedures is essential. Establishing a long-term monitoring programme will enable the assessment of seasonal variability, the identification of emerging contaminants and the evaluation of the effectiveness of implemented mitigation strategies. Routine analysis and interpretation of monitoring data should be undertaken to identify trends, assess potential risks and guide adaptive management.

Finally, transparent communication and collaboration among Kolomela Mine, regulatory authorities, local communities and other stakeholders are vital for sustainable groundwater management. Open sharing of water quality data, monitoring outcomes and management

actions will promote trust and accountability. Through collaborative efforts and responsible stewardship, Kolomela Mine can continue to protect groundwater resources, minimise environmental risks and safeguard the health and well-being of surrounding communities.

### **5.5 Future Research Directions**

Future research at Kolomela Mine should prioritise policy-relevant investigations that support evidence-based groundwater governance and the long-term protection of water resources. In particular, detailed studies aimed at identifying the specific sources of elevated metals, especially copper, zinc and manganese, are necessary to strengthen regulatory oversight and improve environmental decision-making. Such research would provide a clearer scientific basis for targeted mitigation and remediation strategies, support compliance with national and international water quality standards, and inform mine planning and operational controls aimed at preventing future groundwater contamination.

In addition, future groundwater monitoring programmes would benefit from the incorporation of inferential statistical analyses and predictive modelling approaches, building on the descriptive baseline established in this study. The application of statistical trend analysis, spatial modelling and risk-based assessment tools would allow for more robust evaluation of temporal and spatial variations in groundwater quality. These approaches would enhance early-warning capabilities, improve the identification of emerging risks, and support adaptive management strategies that are responsive to changing environmental and operational conditions.

Finally, long-term and integrative research is required to assess the cumulative impacts of mining activities on groundwater quality and availability, particularly in the context of climate variability and increasing water demand. Expanding future studies to include emerging contaminants would further strengthen groundwater protection frameworks. Equally important is the promotion of collaborative research involving mine management, regulatory authorities, researchers and local communities. Such collaboration would enhance transparency, support regulatory compliance, incorporate local knowledge into policy development, and ensure that groundwater management strategies remain socially acceptable and environmentally sustainable over the long term.

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APPENDIX A: Ethical Clearance Letter

College of Agriculture and Environmental Sciences\_Health REC

Date: 12/07/2023

NHREC Registration # : REC-170616-051  
Ref # : 2023/CAES\_HREC/1096  
Name: Ms Goitseone Mokoisi  
Student # : 43398146

Dear: Ms Goitseone Mokoisi

**Decision: Ethics Approval from  
06/07/2023 to 30/06/2026  
Subject to submission of yearly  
progress reports Due date for  
first progress report: 30 June  
2024**

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**Researcher:** Ms Goitseone Mokoisi

43398146@mylife.unisa.ac.za; 0737249887

**Supervisor:** Professor Isaac Rampedi: isaacr@uj.ac.za

**Assessing the degree of pollution of groundwater by heavy metals around the Mine at Kolomela mine, in Postmasburg in the Northern Cape Province**

**Qualification:** MSC in Environmental Management

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Thank you for the application for research ethics clearance by the College of Agriculture and Environmental Sciences\_Health REC for the above mentioned research study. Ethics approval is granted for three years, **subject to submission of yearly progress reports. Failure to submit the progress report will lead to withdrawal of the ethics clearance until the report has been submitted.**

**Due date for progress report: 30 June 2024**

The progress report is available on the college ethics webpage: <https://www.unisa.ac.za/sites/corporate/default/Colleges/Agriculture-&-Environmental-Sciences/Research/Research-Ethics>

The **low risk application** was **reviewed** by College of Agriculture and Environmental Sciences\_Health REC on 06 July 2023 in compliance with the Unisa Policy on Research Ethics and the Standard Operating Procedure on Research Ethics Risk Assessment.

The proposed research may now commence with the provisions that:

1. The researcher(s) will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics.
2. Any adverse circumstance arising in the undertaking of the research project that is relevant to the ethicality of the study should be communicated in writing to the College of Agriculture and Environmental Sciences\_HealthREC .

3. The researcher(s) will conduct the study according to the methods and procedures set out in the approved application.
4. Any changes that can affect the study-related risks for the research participants, particularly in terms of assurances made with regards to the protection of participants' privacy and the confidentiality of the data, should be reported to the Committee in writing, accompanied by a progress report.

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5. The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study. Adherence to the following South African legislation is important, if applicable: Protection of Personal Information Act, no 4 of 2013; Children's act no 38 of 2005 and the National Health Act, no 61 of 2003.
6. Only de-identified research data may be used for secondary research purposes in future on condition that the research objectives are similar to those of the original research. Secondary use of identifiable human research data requires additional ethics clearance.
7. No field work activities may continue after the expiry date (30/06/2024) until a progress report has been submitted and approved. Submission of a completed research ethics progress report will constitute an application for renewal, for Ethics Research Committee approval.

**Additional Conditions**

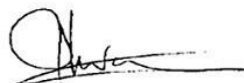
1. Disclosure of data to third parties is prohibited without explicit consent from Unisa.
2. De-identified data must be safely stored on password protected PCs.
3. Care should be taken by the researcher when publishing the results to protect the confidentiality and privacy of the university.
4. Adherence to the National Statement on Ethical Research and Publication practices, principle 7 referring to Social awareness, must be ensured: "Researchers and institutions must be sensitive to the potential impact of their research on society, marginal groups or individuals, and must consider these when weighing the benefits of the research against any harmful effects, with a view to minimising or avoiding the latter where possible." Unisa will not be liable for any failure to comply with this principle. Note

The reference number 2023/CAES\_HREC/1096 should be clearly indicated on all forms of communication with the intended research participants, as well as with the Committee.

Kind regards,



Prof MA Antwi  
Chair of College of Agriculture and Environmental Sciences\_Health REC E-  
mail: antwima@unisa.ac.za



Professor Monde Ntwasa

Executive Dean / By delegation from the Executive Dean of College of Agriculture and Environmental  
Sciences\_Health REC E-mail: ntwasmm@unisa.ac.za

