Assessing the effectiveness of wetlands in the Krugersdorp Game Reserve in attenuating pollution from mines on the West Rand, South Africa

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DECLARATION

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

N. Sawyko (Signature of candidate) 13th of November 2023

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ABSTRACT

In South Africa, 48% of the country's wetlands are critically endangered because of anthropogenic activities. Wetlands are an important part of the landscape and play a critical role including but not limited to improving water quality, habitat provision, and water storage. This research aimed to assess the effectiveness of wetland systemsin attenuating pollution from water discharged from abandoned gold mines in the Krugersdorp Game Reserve (KGR), West Rand. Eight (8) water samples were collected in the study site. Physico-chemical parameters were measured in situ, and chemical parameters were measured in the lab.

The measured physico–chemical parameters from the majority of the sampled wetlands exceeded at least one of the stipulated water quality legislations, which included the General Authorization Limit Section 21f and h, 2013; Unit for TWQGR; Mine Health and Safety Act; and WUL wastewater in terms of the recorded pH, total dissolved solids, and salinity variables. Overall, a decreasing trend in pH level was observed from wetlands sampled upstream of the KGR to wetlands sampled downstream of the KGR, with the highest recorded pH level (Alkalinity: 8.9) obtained from the sampled wetland that was closest to the adjacent mining site upstream of theKGR whilst the lowest recorded pH level (Acidity: 3.9) obtained from a wetland sampling point that was further from the adjoining mine and downstream in the KGR. A weak and positive correlation (r=0.040) was obtained between the measured total dissolved solids and pH levels from the sampled wetlands, indicating minimal spatial variability. However, a strong positive correlation (r=0.999, Correlation is significant at the 0.01 level) was obtained between the measured total dissolved solids and salinity from the sampled wetlands.

At least one of the limits stipulated by the water quality legislation was exceeded in terms of the analysed inorganic constituents from the sampled wetlands. The dominant ions recorded in the wetlands in increasing order are F, K, Cl, Mg, Na, Ca, and SO_4. Mn and Si were the dominant metal concentrations recorded in most wetlands, with the former also showing exceedances when compared to the stipulated water quality guidelines.

The recorded data from the measured physico–chemical parameters and analysed chemical variables indicated poor water quality in wetlands sampled downstream of the KGR and upstream of the KGR. Stringent measures in water quality monitoring need to be implemented to mitigate the environmental impacts associated with wastewater discharge into the receiving environment.

Keywords: Wetlands, Pollution Attenuation, Physico-chemical Parameters, Metal Concentration

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ACRONYMS

AMD – Acid Mine DrainageCC – Climate Change

CW – Constructed Wetlands

EPA – Environmental Protection Agency

FTW – Floating Treatment Wetlands

GDWQR – Guideline for Drinking Water Quality

GHG – Greenhouse Gases

HGM – Hydrogeomorphic

JMP – Joint Monitoring Programme

KGR – Krugersdorp Game Reserve

MCLM – Mogale City Local Municipality

MHS – Mine Health and Safety

NWA – National Water Act

SANAS – South African Accreditation System

SANS 241: 2015 – South African National Standard Drinking Water

SDGs – Sustainable Development Goals

TWQR – Targeted Water Quality RangeUN – United Nations

UNICEF – United Nations International Children's FundWHO – World Health Organization

CHAPTER 1 INTRODUCTION

1.1 The global water problem: pollution from various sources

The status of the water resources occurring on planet Earth has been described as aglobal water crisis, because of the overexploitation, pollution, and negligence of waterresources such as freshwater ecosystems (Garrick *et* al., 2020). The degradation of hydrological systems has resulted in cascading effects of various subcomponents of these systems, for example, global hydrological trends have identified that freshwater biodiversity in ecosystems tends to decline twice as fast compared to marine and terrestrial biodiversity (Tickner *et al*., 2020). The increasing loss in biodiversity demonstrates that the human population as well as other species will be directly affected by this because biodiversity functions in providing, regulating, and supporting ecological goods and services that are needed by the above-mentioned groups to survive on earth (Romanelli *et al*., 2015).

Many factors have and are still contributing to the global issues relating to water quality. Water resources are increasingly being polluted by various sectors such as agricultural practices, mining activities, industries, poor water sanitation, and domestic interaction with water resources - direct pollution of water resources for example dumping of waste into streams, rivers, lakes, and dams (Koronkevich *et al*., 2019). All these sectors significantly contribute to water resources being poor or having compromised water quality (Seiyaboh and Izah, 2017).

Chemical pollution by synthetic or geogenic chemical elements poses a serious threat to freshwater resources. An overload of inorganic constituents or metal concentrations (coupled with ideal physico-chemical conditions) in a water resource such as a wetland can degrade a hydrological system. This is because the introduction of micropollutants such as nitrogen (N) and phosphorus (P) into a water channel often facilitates the process of primary production of biomass which (when occurring at an accelerated rate) can result in oxygen depletion in the water channel and dire growth of organisms such as algae (Schindler, 2006). This process is known as eutrophication and has the potential to significantly compromise the quality of freshwater resources when occurring at various places in an area can cause a lack of available water resources and compromise aquatic life species.

Acid Mine Drainage (AMD) is one of the many phenomena that threaten the environment as a by-product of mining activity releasing chemical pollutants into water channels. AMD occurs when minerals such as iron disulfide are exposed to oxygenated water resulting in elevated levels of runoff with elevated acidic water levels (Simate and Ndlovu, 2014; Kefeni *et al*., 2017). The effect of AMD is exacerbated due to trace metals and heavy metals being soluble in the presence of AMD runoff resulting in elevated levels of metals in environments associated with AMD (Naicker *et al*., 2003; Macingo and Luptakova, 2012). AMD can decant into hydrological systems like wetlands subsequently disrupting the whole system (RoyChowdhury *et al*., 2015). An assessment was conducted (of watersheds from an abandoned mine in the Randfontein region in West Rand, Gauteng) by Lusilao-Makiese *et al*. (2013) to quantify the impact of mercury use during historical gold mining. The results from the study revealed that the Krugersdorp Game Reserve watersheds were directly affectedby the heavy metal pollution from the abandoned mines. Evidence of this was based on the sampled boreholes in the nature reserve having elevated levels of mercury which suggests that there was contamination of groundwater.

Heavy metals are a major source of pollution in wetland areas associated with mining activities (Macingova and Luptakova, 2012). In low concentrations, heavy metals suchas zinc (Zn), nickel (Ni), iron (Fe), manganese (Mn), copper (Cu), magnesium (Mg), selenium (Se), chromium (Cr), and molybdenum (Mo) have an important role in maintaining physiological and biochemical functions of living organisms (Tchounwou *et al*., 2012). However, when heavy metals occur in elevated concentration in the environment and food chain, they pose a significant risk to human health and the ecology (Tchounwou *et al*., 2012). Table 1 is a summary detailing someof the health impacts that heavy metals can have on the human body and its function.

Table 1: Examples of heavy metals, their relative permissible levels, and potential impacts on human health when acceptable concentrations are exceeded (Alluri *et al*., 2007).

Heavy metal	Effect on human health	Acceptable tolerance range of exposure
Arsenic	Absorption of arsenic through the skin can be poisoning and result in damage to peripheral nerves, skin lesions, and even gastrointestinal symptoms.	0,01-0,05 mg/l
Cadmium	Acute health effects caused by exposure to Cadmium include pain in bones and kidney damage.	0,005-0,020 mg/l
Lead	Children that are conceived in areas that have high levels of lead can be born with mental retardation Damage to gastrointestinal organs, liver, and kidney.	0.1 ppm
Manganese	Damage to the central nervous system causes diseases resembling Parkinsonism.	0.1-1.0 mg/l
Mercury	Poisoning of the protoplasm Damage to the nervous system.	0.01 ppm

Chemical pollutants are just one type of pollutant that affects water resources. In addition to these are other concerning pollutants that affect freshwater resources such as organic pollutants and pathogens including viruses and diseases that can be transported to animals and humans as waterborne diseases. The COVID-19 pandemic has highlighted global concerns about water and sanitation issues (Barbier and Burgess, 2020; World Health Organization, 2020; Sivakumar, 2021). Water was and remains a significant resource in overcoming the pandemic as people have to maintain good hygienic standards by continually washing of hands (vander Voorn *et al., 2020).* With that said, it is a concern to observe the degradation of hydrological systems (due to anthropogenic activities) such as wetlands which purify our water resources and compensate (by providing water) for the shortage of water resources as a result of factors like global warming (Patni and Jindal, 2020). Therefore, there needs to be a better approach to combating the global water crisis and it begins by identifying the causes of the problem such as the excessive pollution due to mining activities in water resources like wetlands (Neal, 2020).

1.2 Wetlands used as mechanisms for improving water quality

Wetlands are systems that are considered transitional zones between aquatic and terrestrial zones (Joshi *et al*., 2021). Functional wetlands have a diverse community of flora and fauna species that contribute to the ability of wetlands to improve the water quality of the water that flows through them (Moshiri, 2020). Water that flows into a wetland enters an area of slow-flowing water which then allows for sediments to settle on the bottom of the system and for processes such as Carbon sequestration to occur (El- Sheikh, *et al*., 2010; Deemy and Rasmussen, 2017). In addition, wetlands can improve the water quality of surface water by detoxifying chemicals or retaining elements suchas Nitrogen (N) and Phosphorous (P) in the wetland channel (Ackerman *et al*., 2015).

Wetlands play an important role as systems that purify water resources because wetlands provide a nature-based approach to a filtration mechanism that can be very expensive compared to man-made filtration systems.

1.3 Mining in and around the Krugersdorp Game Reserve (KGR)

The West Rand and its surrounding areas are synonymous with abandoned gold mining sites located in areas such as the Mogale City Local Municipality (MCLM) which encompasses locations like Kagiso and Krugersdorp (Moshupya *et al*., 2019). The inability of mining companies to implement effective strategies to rehabilitate or regenerate mining sites has resulted in a plethora of environmental hazards and impacts around MCLM (Moshupya *et al*., 2019). This is because the elements that are mined in

Krugersdorp and surrounding areas include heavy metals such as iron, asbestos, manganese, gold, and lime (Shapi *et al*., 2021) which have devastating implications when exposed to the environment without being properly monitored and managed. Also, exposed radioactive dust material such as cyanide and uranium can be transported to various places extending further from the mine dumpsite and cause further environmental complications (US EPA, 2022).

There are several concerns when considering the water affairs associated with mine pollution. For example, there is still active pumping of mine effluent into water catchments like the ones flowing into the Krugersdorp Game Reserve (KGR) (Figure 1). The release of polluted water into a natural ecosystem like the KGR is alarming because the reserve houses wildlife species that feed (browsers and grazers) off the vegetation in the landscape and consume the water to survive (Shapi *et al*., 2021). These animals can incur sicknesses and diseases, furthermore, bioaccumulation of pollutants within the organisms can be transported to other organisms at various trophic levels which can ultimately result in a corrupted ecosystem (Ajima *et al*., 2015). Contaminated or treated water can be detrimental to the flora in the game reserve as the elements found in the water resources that supportthe growth of the plants tend to inhibit the healthy growth of plant species (Sardar *et al*., 2013).

Inorganic pollutants pose serious threats to biotic and abiotic (i.e., plants and water resources) in nature reserves that are in areas close to mines because these pollutants adopt different behaviors when exposed to reducing and oxidizing (Redox) conditions (Macingova and Luptakova, 2012). In an oxidizing environment, metals such as Manganese (Mn) and iron (Fe) are formed into oxide particles (fine) that are readily dispersed and can adsorb metalloids and heavy metals; under a reducing environment- depletion of oxygen - these metals release the toxic adsorbed load of metalloids and heavy metals (Macingova and Luptakova, 2012). Through processes such as dissolution and precipitation, the natural environment becomes the recipient of these toxic reactive metal constituents. Visual observation of old mine sites in the Krugersdorp Game Reserve is the presenceof polluted water pockets including artificial wetlands that support a diverse ecosystem of flora and fauna. These water bodies are surrounded by rocks and soils that have abright orange color. Figure 1 is an image that illustrates a portion of a stream flowing in a wetland area where the water inlet is from a mine site upstream. The water flows into the Krugersdorp Game Reserve.

Figure 1: A water body from the mine source upstream being channeled in a wetland area outside of the Krugersdorp Game Reserve (Photo: Noluthando Sawuka).

1.4 Aim

To assess the effectiveness of wetlands in and around the Krugersdorp GameReserve in attenuating chemical pollution of water resources from adjacent mining sites.

1.5 Objectives

A chemical analysis will be conducted to assess the effectiveness of wetlands in attenuating pollution by following these objectives:

1. To determine the heavy metals and inorganic constituents in the inlet water from the mine site.
2. To determine the heavy metals and inorganic constituents of the outlet water from the wetland.
3. To determine the water quality parameters of the sampled wetlands in and outside the KGR.

1.6 Rationale

The assessment of how effective wetlands are in attenuating pollution from mine reserves has not been conducted in the Krugersdorp Game Reserve. This research is important because it approaches the environmental pollution problem at hand by quantifying various ecological components (soil, water, plants) and how these components are affected by the pollution from adjacent mining sites subsequently, how these components affect other communities that they support, for example, the local community or animals in and around the KGR.

1.7 Research Outline

The research that is conducted consists of seven (7) chapters that entail the following:chapter 1 firstly presents the global and regional (South African context) water problemdue to pollution sources from various sectors. Secondly, it introduces the concept of how wetlands can be used as a pollution attenuation system, lastly, the aims, objectives, rationale, and research outline are presented. Chapter 2 presents a detailed literature review of wetland systems. The chapter starts by presenting the environmental impacts that anthropogenic activities have on wetland systems are described - with a focus set on the impacts of mining on South Africa’s aquatic systems; and examples of local, regional, and global approaches taken to mitigate the environmental impacts of wetlands are then explored. Wetlands are then explored as pollution attenuation systems and their role in the environment, this is achieved by describing the functions of wetlands, for example, what ecosystem goods and services can they provide or perform. Additionally, literature on wetland classification systems and types of wetlands is explored.

Chapter 3 describes the study site of the Krugersdorp Game Reserve. The geographic location, climatic conditions, hydrological regimes, geology, vegetation type, land use, and animals found in the KGR are described. Additionally, study site maps have been included. The methods and materials used to achieve the set objects are presented in Chapter 4. This chapter is divided into three sections: desktop study, fieldwork, and laboratory analysis. Additionally, the approaches used for data analysis are mentioned.

The obtained physico - chemical and chemical results from field-based work and laboratory analyses are presented in Chapter 5 with the aid of statistical and graphical approaches. To assess the effectiveness of the sampled wetlands in the KGR in attenuating pollution from adjacent mines, the discussion section presents an investigation of the measured physico – chemical parameters as well as the analsyed chemical constituents. Additionally, the hydrogeomorphic (HGM) classification approach is used to provide insight into how the sampled wetland type(s) aid or hinder the sampled wetlands in attenuating pollution. This section constitutes Chapter 6. Chapter 7 presents the overall conclusion of the study based on the observations and findings from Chapters 1 to 6. The identified limitations that are associated with this study are also presented as well as recommendations.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The world's largest gold mining areas are found in South Africa located in the Witwatersrand Basin and have produced various commodities including over 46 000 tonsof gold (Dankert and Hein, 2010). However, the scale at which mining activities are occurring has significantly reduced since the 1900s (Dankert and Hein, 2010; Ledwaba and Nhlengetwa, 2016).

Acid Mine Drainage (AMD) amongst other detrimental environmental impacts caused by mining activities has resulted in the need for environmental protection practices, and implementations to try to monitor and mitigate problems that have resulted due to mining activities (Feris and Kotze, 2014; Masindi et al., 2018). Companies such as PT. Bukit Asam has invested in constructing wetland systems (in mining sites where wetlands do not naturally occur) to treat mine effluent (Prabowo *et al*., 2019). This is because wetlands have been identified as suitable ecological systems that can lessen the potential environmental impacts that untreated mine waste can have on the immediate and surrounding natural environment. Although wetland systems can function as pollution attenuation systems, Abiye (2014); and Hobbs (2011) argue that exposing high levels of decanting acidic effluent from mine shafts into wetlands can exceed the ability of the wetland to treat the waste material.

2.2 Water quality in the context of South Africa and the status of water pollutionin the country

In South Africa, the biggest threat to water resources arises from the excessive contamination of both domestic and industrial waste into surface waters such as rivers, lakes, and dams (Ramessar and Olaniran, 2019). A case study conducted by Tran (2020) on water pollution from acid drainage due to coalmining activities in Carolina, Mpumalanga illustrated that activities associated with coal mining in Carolina have resulted in detrimental environmental impacts such as biodiversity loss, which has had a direct negative impact to the local community. The study further revealed that spillages from mine tailings into surface and groundwater resources further exacerbate the current poor state of the surrounding water bodies. Furthermore, the issues associated with poor water quality are also exacerbated by the lack of the necessary infrastructure and management strategies governing South Africa’s wastewater treatment plants (Godfrey and Oelofse, 2017).

The Vaal and Klip Rivers (which is a tributary of the Vaal River) are two major systems in South Africa that provide visible evidence of the consequences that may arise due to poor management of water resources that results in poor water quality (Humphries *et al*., 2017). The Vaal River is characterized as a highly eutrophic system while the Klip River is classified as a heavily impacted system (Janse van Rensburg *et al*., 2019; Marara and Palamuleni, 2020). Heavy loading of pollution in the Vaal River and the Klip River systems is a concern because the rivers provide habitat for aquatic species; and many parts of South Africa like the City of Johannesburg receive most of its water for domestic and agricultural use from these river systems (Makumbe, 2018).

2.3 The Impacts of Mining in South Africa

The mining sector has heavily sustained South Africa’s economy since the mid-1800s. The extensive exploitation of the country's diverse and rich mineral wealth has unfortunately caused detrimental environmental impacts (Humphries *et al*., 2017). The two major negative consequences of mining in South Africa’s coal and gold mines are the adverse impacts of AMD which have negatively compromised the water quality of most parts of the country unfortunately - South Africa is a water-scarce country and mining of minerals produce dust, for example, the mining of gold may produce silica-bearing dust which when the dust is exposed to humans affects the respiratory functions of humans (Katz, 1994; Laney and Weissman, 2014). The former impact of AMD poses a threat to the country’s future available water resources (Hedden and Cilliers, 2014). Table 1 presented in Chapter 1 discusses other heavy metals and how they affect humanhealth.

2.3.1 The environmental impacts of mining

The operation of anthropogenic activities such as mining infrastructure construction or any excavations that occur at a large scale may result in the exposure of sulfide minerals, which when exposed to oxidizing conditions create acid mine drainage (Akcil and Koldas,2006). The extraction phase that occurs in mining activities is the main contributor to contamination in the mining operation. This is because chemical reactions such as the oxidation of sulfidic (sulfur-containing) rocks occur in operating effluents, exposed dumps,open pits, and deposits of tailings (Simate and Ndlovu, 2014). A study conducted by Pat-Espadas *et al*. (2018) gives examples of the volume of mineral waste that is produced during the extraction phases which contributes to the formation of AMD: 97-99.5% of porphyry rock is discarded when copper is being extracted; 60-80% of sulfide-rich rocks are discarded as waste when lead or zinc minerals are extracted; and in the case of gold extraction, almost 99% of sulfide containing rock is discarded.

The discarded porphyry - and sulfide - containing mineral residues form sulfides when exposed to microbial activity while water and oxygen chemical reactions occur that transform the input elements to metals such as sulphites. Pyrite (FeS_2) is the most abundant mineral found in the oxidation of sulfides (Macingova and Luptakova, 2012; Dold, 2014. Oxidization of pyrite creates an acidic metallic environment of a very low pH level which can facilitate other sulphuric minerals to be oxidized exacerbating the environmental impacts especially, in water resources (Pat-Espadas *et al*., 2018).

The two major processes that mediate the formation of AMD are microbiological activitiesand complex geochemical processes (Calabrese *et al*., 2006). However, these processescan only occur in mining environments based on site-specific conditions. For example, four major controls have to be at play for the potential of mine waste to generate AMD in an area, these are: (1) physical factors (2) generation factors, (3) chemical control factors,and geological factors (Akcil and Koldas, 2006; Calabrese *et al*., 2006; Skousen *et al*., 2017; Pat-Espada *et al*., 2018; see also Table 2).

Table 2: The four controls and their characteristics that enable the acid generation and contamination release in a mining environment (Skousen *et al*., 2017; Pat-Espadas *et al*., 2018).

Control	Characteristics
1. Physical factors	Physical weathering Particle size Hydrology Permeability
2. Generation factors	Bacteria Oxygen Water
3. Chemical control factors	Receiving water or rock has to have the ability to either add metallic ionsthat have been mobilized by residual acid or to neutralize the acid
4. Geological factors	Rock types – the presence of quartz, calcite, or sulfite enriched rocks

AMD has been identified as the most polluting pollutant in water courses due to its nature,the challenge in resolution, and the extent of its impact (Simate and Ndlovu 2014; Naidu*et al*., 2019). Rivers, aquifers, wetlands, and other hydrological ecosystems that have been affected by AMD are characterized as having high sulfide contents in water resources and sediment and elevated acidic levels (Strosnider *et al*., 2014; Chen *et al*., 2015). AMD has been and still is a persistent issue in mining sites that are in operation and abandoned mining sites (Hatar *et al*., 2013). However, treatment of this problem can be implemented to improve the state of impacted systems. There are broadly two approaches to treating mine-polluted water, namely passive and active. The use of strictly natural available sources of energy such as microbial metabolicenergy, gravity, and photosynthesis energy to improve the water quality of ecological systems that only need regular to infrequent maintenance for their entire life span is known as passive techniques (Younger *et al*., 2002; Zipper and Skousen, 2014). In contrast, active techniques utilize artificial chemical reagents or sources of energy to improve the water quality of the affected system continuously (Zipper and Skousen, 2014). Constructed and natural wetlands are examples of passive techniques that can be used to improve the water quality from AMD effluent (Johnson and Hallberg, 2002; Kalin, 2004; and O'Connor and Courtney, 2020).

The study conducted by Alvarez *et al*. (2013) suggests that wetlands that are used as passive treatment systems are a viable technology when it comes to removing concentrations of cyanide that have been leached because of gold mine tailings that have been closed in. The research was conducted as a laboratory experiment through the construction of a field-scale passive wetland system in Northern Spain. The results of the study indicated that about 21.6% of dissolved cyanide effluents and 98% of copper, as well as nitrate and nitrite constituents, were detoxified from the compost-based wetland-constructed system. The study conducted by Hogsden and Harding (2012) on "consequences of acid mine drainage for the structure and function of benthic stream communities" found that untreated AMD from mining sites that leaches into groundwater basins causes a huge problem in hydrological systems associated with the mine. In this instance, wetland systems that are around these decanting zones are a concern because wetlands are ecological systems that have multiple functions including the provision of ecosystem goods and services so their limitations in treated mine effluent do not only have implications for the hydrological systems but for other subsystems such as the plants and animals that are dependent on the wetland system (Clarkson *et al*., 2013). This literature review will be a discussion about wetlands in the context of assessing their effectiveness in attenuating mine pollution.

2.3.2 The potential environmental impacts that metal concentrations may havewhen they occur in exceeding concentrations in the receiving environment.

In ecological systems such as wetlands, metal concentrations that occur in exceeding concentrations may have detrimental impacts on the immediate and surrounding natural system. The following subheadings describe some of the environmental impacts – specifically on aquatic ecosystems - that some metal concentrations may have when they occur in exceeding and toxic concentrations.

Chloride – Cl

The United States Geological Survey (USGS, 2019) research survey on water resourcesstates that high levels of chloride in streams are toxic to aquatic life. Furthermore, there are different ways that chloride enters into streams, mainly from groundwater discharge, naturally through oceans and atmospheric deposition, and through anthropogenic ways such as farming, wastewater, and water treatment plants (Xia, 2021). Xia (2021) identifies chronic toxicity, which results from having a high concentration of chloride in surface water, thus harming aquatic organisms in the environment by impeding these organisms' balance of body fluids. Verlicchi and Grillini (2020) support this statement by suggesting that the high concentrations of chloride in water are attributed to the dysfunctional methods of treating domestic wastewater and the improper use of fertilizersin farms surrounding streams.

Sulphate – SO_4

Sulphates aid the acidification of soil and surface water due to the formation of acid rain,thus damaging ecosystems, plants, and forests (California Air Resources Board, 2022). This acidification of surface water affects the environment as it inhibits the fertility, development, and growth of aquatic species, it, further, plunders the nutrients available to plants and trees, thus inhibiting their growth. Envirotech Online (2019) reveals that human activities such as mining and textile milling produce large quantities of sulphate in industrial waste and as a result, this gets into groundwater and streams (Envirotech Online, 2019).Zak *et al.* (2021) support the above statement as they reveal that "aquatic flora and fauna can be severely impaired by sulphate pollution" and this is a direct consequence of the anthropogenic sulphate pollution of freshwater systems.

Fluoride – F

Fluoride is a chemical found in minerals, air, soils, and water. Unfortunately, fluoride pollution occurs in the environment because of the synthesized use of it in consumer items such as dental products and the use of water fluoridation. Moore (2022) revealsthat large sums of fluoride are ejected into streams by industrial wastewater and as a result, fluoride is realized into the environment causing harm to plants and animals that eat food grown in areas that have a high fluoride concentration or drink water from waterbodies with high levels of fluoride concentrations (Moore, 2022).

Sodium – Na

Across Europe and North America, the use of salt for deicing roads and highways has introduced salt pollution of freshwater ecosystems. Namely, Sodium chloride, rock salt, isused during the winter to melt ice on roads, and fertilizers containing salts are dissolved by rain and end up in these freshwater systems (Bosman, 2022). Bosman (2022) states that freshwater systems are delicate and having high levels of salt can, negatively, result in decreasing biodiversity of these ecosystems, for instance, the increasing salt concentration has threatened an entire food web because microscopic animals, such as zooplankton are killed by these high levels of salt in these ecosystems. Furthermore, such high levels of sodium chloride in the environment destroy the ecosystems as it changes the composition of the soil and water, thus affecting the biota and vegetation (Borer *et al*., 2019). The ion exchange caused by the movement of sodium and chloride in the environment alters the soil chemistry, as mentioned above, by changing and introducingnutrients such as calcium, potassium, and magnesium into the groundwater and surface water, therefore causing these systems to have an increased number of nutrients, subsequently impacting the aquatic environment.

Calcium – Ca and Magnesium – Mg

Calcium is an essential component of all organisms, and it is found in soils and water. Rapant *et al.* (2017) highlight the negative impacts of calcium in groundwater as they reveal that calcium, magnesium together with water hardness are “the essential parameters of the chemical composition of groundwater on the health of Slovakia’s population”. Rapant *et al*. 2017) concluded that the health of Slovakia’s population and its life expectancy is greatly influenced by the contents of calcium, magnesium, and water hardness in the groundwater.

2.4 Approaches taken globally to mitigate and minimize impacts on wetlands andwater resources.

It is important to note that wetlands are not just water purifiers, carbon sinks, and energy sources, wetlands also act as natural carbon neutralizer (Cao *et al*., 2017). Unfortunately, over time wetlands in South Africa have also been destroyed through the construction of dams, overgrazing, urban development, and inadequate land management and those that are yet to be destroyed are under threat of also being eliminated, thus leaving the Earth and its people vulnerable to possible dangers of climate change. Fortunately, there is a growing call to restore and safeguard wetlands globally as they are our only weapon that will positively change and prevent climate change. International organisations such as the Ramsar Convention on Wetlands have published guidelines on how wetlands should be managed by using science to monitor the behaviors and changes in wetlands globally which has helped countriesto adopt these guidelines and use them to mitigate the destruction of wetlands (Mauerhofer *et al*., 2015; Geiizendorffer *et al*., 2019).

Moreover, Erwin (2009) suggests the protection and restoration of wetlands such as mangrove habitats, which are mainly found in tropical tidal areas, are important in the mitigation of impacts that come with climate change such as reducing the levels of floods and preventing the possibility of harsh tropical cyclones in India and Colombia (Erwin, 2009). Fortunately, the Wetlands International group provides strategic solutions to help in the mitigation of pollution and the revival of wetlands globally.

Wetlands International has assisted six West African countries in formalisingsolutions and established a Mangrove Charter and Action Plan as a measure to conserve mangroves. Lastly, Wetlands in arid and semi-arid landscapes are important to communities that rely on wetlands such as seasonal lakes and floodplains which help in the prevention of encroaching deserts and also assist in giving people and animals a source of fresh water seasonally (Wetlands International, 2023).

In countries such as Mali and Senegal, the Niger and Senegal River Delta have wetlands that have seasonal oases which assist millions of people, however, the overconsumption of water and its use of it in agriculture has caused these wetlandsto dry out. Now, the Wetlands International group is working with these countries' civil society organisations to assist in guiding these countries to develop new management plans to revive these wetlands and, as a result, the Wetlands International group, together with these countries, has established incentives to help replenish the Niger Delta by providing funds to the local communities in exchange for planting over 20000 trees have been planted and this has restored almost 500 hectares of forests in these floodplains (Wetlands International, 2023).

Globally, some legislations and frameworks have been put in to combat issues relating towater and sanitation, for example, according to the set goals of the United Nations (UN) 2030 Agenda for Sustainable Development, water should be a resource that is available for all and used sustainably (UNESCO/UN-Water, 2020). Sustainable Development Goals (SDGs) recognize that access to safe water is a human right and have therefore set target 6 as ‘clean water and sanitation. Despite the goals and the targets set out by the SDGs, results obtained from the Joint Monitoring Programme (JMP) between the World Health Organization (WHO) and United Nations International Children’s Fund (UNICEF) reveal alarming figures: more than 2 billion people in the worlddo not have safely managed to drink water services -SMDW (Bain, *et al*., 2020).

In Morocco, there has been the implementation of innovative ways to compensate for the lack of available water in the southern regions of the country, for example, nets have been installed in the Mount Boutmezguida area that collects water because of fog condensation as a result, over 800 people living in the nearby villages benefit from the water obtained from this piping system (Chapman, 2019).
In South Africa, the introduction of legislation such as the National Water Act (NWA, Act 36 of 1998) has resulted in minor positive changes being observed in water use within provinces of the country (Tempelhoff, 2017). Although this may be the case, most parts of the world are failing to come up with

effective solutions to combat problems associated with water resources. This failure can be attributed to mismatches that exist when it comes to context-based solutions versus what is happening on the ground (Vollmer and Harrison, 2021). For example, the NWA of South Africa can be seen as an internationally hailed piece of legislation due to its progressive and integrated structure in water resource management (Schreiner, 2013); countries such as China and Zambia have even gone to the extent of using the NWA when revising their water legislations (Schreiner, 2013). However, the implementation of the NWA in South Africa has been poor (Schreiner, 2013).

2.5 Wetlands as Pollution Attenuation Systems

2.5.1 Defining what a wetland is

The widely used definition of wetlands was proposed at the 1971 Ramsar Convention which stated that wetlands are areas of peatland or water, marsh, or fen, irrespective of whether the area is artificial, permanent, or temporary, having water that is flowing or static, brackish, or salt, fresh, including marine waters provided that at low tides the depth of the water does not exceed six meters (Ramsar Convention Secretariat, 2009). Although the proposed definition by the 1971 Ramsar Convention identifies three (3) types of wetlands which include fens - a type of peat-forming wetland that does not receive its source of nutrients from precipitation (Treat *et al*., 2021) -, marshes - a wetland that is characterized by continual inundation of water (Treat *et al*., 2021) -, and peatlands - a wetland system found in terrestrial areas and is characterized by an accumulation of organic matter (Treat *et al*., 2021) - it does not consider that fens, marshes, and peat land types do not occur in other ecological regions. In addition, the definition provided does not provide precise ways to identify wetlands based on their characteristics such as the types of species that should occur in the system or the aquatic vegetation found in and around the system.

Since the 1970s, the Environmental Protection Agency (EPA, 2022) in the United States has defined a wetland as an area that is saturated or inundated by ground or surface water that supports a prevalent community of vegetation at normal circumstances or duration and frequency that is sufficient to support the vegetation that is adapted for life form in saturated soil conditions.

The EPA definition continues by giving examples of some wetlands by stating that wetlands include similar areas to bogs, swamps, and marshes (Hu *et al*., 2017). South Africa's Water Act 36 of 1998 (Act 36 of 1998) will be used which state that a wetland is a transitional land between aquatic and terrestrial systems where the land is periodically covered with shallow water, or the water table is near or at the surface and under normal conditions would support vegetation that is adapted to survivein saturated soils (National Water Act 36 of 1998). Therefore, for this study, the definition of wetlands provided by the EPA and National Water Act (NWA) will be considered, although these definitions provide ways to identify a wetland based on its characteristics (saturated soil conditions), they are limited in defining the type of fauna that can inhabit the system, only the flora component is considered.

2.5.2 Understanding the term effectiveness in the context of this study

The word "effectiveness" can be defined by the specific subject matter at hand across various disciplines such as finance, business, and economics. The IGI Global publisher provides a range of definitions from different authors who have previously covered topics that concern effectiveness and the majority of the authors who have defined effectiveness in the IGI Global publishing platform emphasized the degree of success or the potential for a successful outcome when defining the word effectiveness. It should be noted that the word effectiveness is commonly misused with the word "efficiency". While effectiveness measures the degree of success or of accomplishing a desired or better output, efficiency relates to achieving success or desired outcome provided that minimal input from factors or parameters such as time, competency, and effort is observed (Gager, 2022). With that said, the definition of the word effectiveness that will be adopted for this study is the ability of a system (in this instance a wetland and its abiotic and biotic factors such as plants, soil, and microorganisms) to improve (better make the condition in this instance of inflow water from a polluted mine) from a state of poor quality to a state of better quality.

2.6 The global status of wetlands

Globally wetlands are being lost and reduced at an alarming rate with an estimated 35%of wetlands being lost since 1970 (Hu *et al*., 2017; Gardner and Finlayson, 2018). Also, The Ramsar Convention on Wetlands stipulates that wetlands are the most threatened ecosystem globally and when compared to forests, wetlands are being lost three times faster (Xia *et al*., 2021). Wetlands are specifically impacted by climate change, rising sea levels, and coral bleaching caused by the increase of sea surface temperatures; cases of these wetlands were found in coastal areas in the southeast United States. This reveals the rates at which the world is losing wetlands, and this cannot continue because wetlandsare an integrated ecosystem that helps maintain the livelihoods and health of people who are reliant on wetlands.

Various driving forces have resulted in the escalation that is observed in the loss of wetland systems these include deforestation, climate change (CC) and its associated extreme weather events (flooding and droughts), urbanization which facilitates the need for changes in land use, and the increase in global population numbers which results with a need for the expansion in the agriculture secure to supply the demand for food (Worldwide Fund for Nature, 2018). Turkey is an example of the many countries that have suffered the loss of its wetland systems. Scaramelli (2020) reveals that over 2 million hectares of wetlands have been lost in the country since the mid-twentieth century due to draining the wetland systems to transform the land into urbanized spaces, factories, or agricultural fields.

The coronavirus (COVID-19) outbreak which affected millions of people around the world and economies of various countries, presented evidence that the negative impacts on wetland systems imposed by humans can be lessened provided that anthropogenic activities are not influencing changes to the wetland systems. Aswathy *et al*. (2021), mention that, as a direct result, the environmental conditions in various countries, such as India, improved in terms of a reduction in water and air pollution.

Moreover, the authors revealed that the COVID-19 lockdowns heavily influenced the water quality and brought down the water pollution levels, because of the reduced activities in the tourism and industrial sectors, which play a part in the high level of pollution in the country (Aswathy *et al*., 2021).

2.7 Functions of Wetlands

Wetlands can be described as an ecological system with a value (Gren *et al*., 1994; Barbier *et al*., 2013; Narayan *et al*., 2017; Dechasa *et al*., 2021). This is because wetlandsascribe to multiple purposes that benefit their environments both directly and indirectly (Mitsch *et al*., 2015) for example, wetlands directly provide goods – natural resources thatcan be used - and services - activities that are performed to fulfill a need in the environment. Some of the many goods provided by wetlands include the following: food for humans and animals including aquatic species and vegetation; raw materials such astimber, and clean water (Gunderson *et al*., 2016). Some of the services provided by wetlands include habitat for species, erosion and flood control, water purification, biodiversity protection areas, and water storage areas, wetlands can be used as areas of recreation, and biochemical transformation (Gunderson *et al*., 2016). Furthermore, the Global Wetland Outlook states that wetlands are the most effective ecosystem for addressing climate change (Gardner and Finlayson, 2018). For example, coastal wetlands such as mangroves reduce carbon fifty - five times faster than tropical rainforests, this reveals that wetlands are effective in reducing carbon and important in maintaining the Paris Agreement climate goal of limiting global warming to the temperature of 1.5 degrees Celsius.

A study conducted in South Africa by Abiye *et al*. (2018) to determine the “effectiveness of wetlands in retaining metals from mine water” confirmed that wetlands are efficient systems in attenuating toxic metals that are found in mine water. Findings from the study indicated the importance of wetland vegetation in precipitating metals that were in the system through the facilitation of the circulation of oxygen. Another significant observationfrom the study is the change in pH levels between discharge inlets from abandoned tailingdams into the wetland and outlet discharge from the wetlands (Abiye *et al*., 2018). The pH level in the inlet water was highly acidic but once discharged from the wetland, the pH changed to near neutral. Abiye *et al*. (2018) attribute the changes in pH levels as a result to the water in the wetland facilitating gypsum precipitation which eliminates sulphate constituents found in the mine water. The use of vegetation in the removal of mine effluents is also highlighted in a study conducted by Marrugo-Negrete *et al*. (2017). Compared to the study conducted by Turker *et al* (2014), Marrugo-Negrete *et al*. 2017) examine the plant species Limnocharis Flava in the removal of gold and mercury effluentsin a constructed wetland. The findings from the study agree with the findings from Turker*et al*. (2014*)* and also suggest that aquatic vegetation has great potential for phytoremediation of wastewater from mine effluents (Marrugo-Negrete *et al*., 2017).

2.8 Understanding wetlands in the context of ecosystem goods and services

2.8.1 What are ecosystem goods

Nel and Driver (2012) state that wetlands account for 2.4% of South Africa's surface area,about 65% of these wetlands are threatened and the majority of intact and healthy wetlands systems are mainly found in the northern and interior parts of the country. Ecosystem goods are the energy and materials that are provided by ecosystems such asplants, fish, or wood. The plants that are seen as good such as would provide a socio-economic benefit to the surrounding community. Le Maitre *et al.* (2007) further explain that ecosystems deliver services such as regulation and stabilizing services which people benefit from and often these services are interdependent and interlinked. For instance, the ecosystem services of regenerating soil and maintaining the fertility of the soil are greatly dependent on the creation of goods such as food, medicines from plants, and clean water.

2.8.2 What are ecosystem services and their functions

Abd Elbasit *et al.* (2021) define ecosystem services as groups of conditions and processes that sustain the lives of humans by emphasizing the different types of services that these ecosystems provide. When looking at the different classifications of ecosystemservices there are three types of services we can derive from, namely Regulatory processes, the Production of goods, and, lastly, Life fulfilling functions i.e., Recreational or cultural. Firstly, the category of regulation services entails maintaining soil fertility, regulating the control of erosion and sedimentation, and regulating the flow of water, to name a few. These types of services under this category simply mean the replenishment of fertile soil,the prevention of soil erosion and sedimentation, and flow attenuation through trapping by vegetation cover and wetlands, where groundwater is recharged through infiltration facilitated by vegetation cover (Turpie *et al.,* 2017). Turpie *et al*. (2017) further explain that wetlands and vegetation cover regulate the movement of water in the landscape, thus wetlands can reduce the impact of floods, and vegetation can facilitate infiltration of water to recharge aquifers to help mitigate droughts during dry seasons. Therefore, without these services during high rainfall seasons surface runoff willbe higher the effects of floods will be greater, and, subsequently, water supply systems such as groundwater aquifers will be significantly lower.

Secondly, the provisioning services category is one of the main categories found in the ecosystems of South Africa where services such as the supply of livestock feed and harvesting resources such as medicines, food, and ornaments play a major role in sustaining the lives and livelihoods of South Africans. Turpie *et al*., (2017) highlight that South Africa is mainly rangeland and livestock is mainly found in grasslands which containmore moisture in the east of the country. These range land ecosystems provide livestock farmers feed at a lower cost when compared to costs of replacement feed during drier seasons, thus it is evident that such services are essential to the upkeep of the country’s socio-economy as these production services make a significant contribution to the welfareand livelihoods of urban and rural communities.

Lastly, the life-fulfilling services provided by wetlands in South Africa, such as recreational, cultural and heritage benefits, are services which the country’s economy benefits and thrives from as South Africa has an abundance of cultural sites where citizens of the country and abroad appreciate the serenity and aesthetic beauty that the natural environment has to offer. Turpie *et al*. (2017) further estimate that the attractions brought by cultural services in the country totaled to an amount of approximately R21.3 billion of total foreign and domestic spent on visiting natural attractions such as the Sterkfontein Caves and natural sites in and around South Africa.

2.8.3 How do wetland types fully vegetated and functional wetlands vs poorly vegetated wetlands with no animals or plants influence the provision of ecosystemgoods and services?

Wetland ecosystems are currently under threat as 65% of the wetland ecosystems in the country are threatened and the key services that this ecosystem type provides are flood regulation and water purification services, however, these key services are threatened byseveral pressures, namely, urban development, changes in water flow, invasive alienplant species and illegal mining causing pollution (Nel and Driver, 2012).

The functions of wetlands are affected and influenced by external and internal factors asboth these factors have a role in the functioning of a wetland, which benefits communitiessurrounding these wetlands. As mentioned above, external factors usually take place in the surrounding catchment areas where cultivation and change in the land cover would reduce the amount of water that would reach the wetland; and internal factors that wouldaffect the functionality of wetlands would be the damming or draining of the wetland (Kotze and Marneweck, 1999).

2.9 Types of wetlands used as pollution attenuation medium

Wetlands are not geologically and geographically defined as they occur in a range of terrain planes from coastal flatland to mountain ranges in various locations including in environmentally extreme conditions such as Antarctica and deserts. As a result, wetlands have different compositions and structures because processes that affect wetlands are defined by drivers and factors that are predominantly dominating that specific region for example climatic forces (Kingsford *et al*., 2016). Some of the many wetland types that exist are reed beds, peat bogs, salt marshes, wet woodlands, floodplain wetlands, and constructed wetlands (Acreman and Holden, 2013).

2.9.1 Floating Treatment Wetlands (FTWs): An example of a Constructed Wetlands

The quest for the invention of systems and technologies that will be ecologically friendly in purifying water resources has drawn attention to natural systems such as wetlands andhow they can purify water (Colares *et al*., 2020). Wetlands are capable of attenuating chemical, biological, and physical contaminants in water (Colares *et al*., 2020).

Constructed Wetlands (CW) work by integrating different mechanisms in treating water quality these include physical, biogeochemical, and geochemical processes (Perry and Kleinmann,1991; Vymazal, 2014;). Sheridan *et al* (2018) Conducted a study on “the useof constructed wetlands for the treatment of acid mine drainage” and the results showed that CW mainly surface-constructed wetlands can be used as a medium to treat acid mine drainage (AMD).

In CW, the synergistic interplay between plants and microorganisms is the most important relationship as these two components create a symbiosis relationship and in turn can remove pollutants such as metals in wetlands (Pat-Espadas *et al*., 2018). CW can be limited in the treatment of AMD as the metal constituents that are added to the system can be highly toxic and cause the wetland’s functioning capabilities to be limited. However, careful construction of a wetland based on the characteristics of the AMD can eliminate the wetland from being ineffective (Pat-Espadas *et al*., 2018).

Vymazal (2014) identified two categories of CW classification one is based on the type ofmacrophytic growth of species in the wetlands and the other is based on water flow regimes. CW has been widely used as passive natural systems that improve the water quality of mine effluent because they present a cost-effective alternative to water treatment compared to active technology systems that treat water and can cope with fluctuations within the system that could've been unforeseen (Younger *et al*., 2002). Although CW has been widely used as a water purification system in mining environments, the limitations of their abilities to improve water quality are identified due to the excessive toxicity levels that the wetland is exposed to as a result of AMD. The elevated levels of toxic metals and elements in the system may negatively affect the microorganisms and plants that are in the system which in turn causes these components (plants and microorganisms) to be affected (Pat- Espadas *et al*., 2018). Another aspect that has to be considered about the workings of a CW is the disposal of residual waste inan environmentally safe manner. Pat-Espadas *et al* (2018) suggest that the residual waste can be used as building or construction material after the operation of the CW in treating the mine effluent that was discharged into the system.

Turker *et al*. (2014) conducted a study on "constructed wetlands as green tools for management of boron mine" in a borax production mine plant. The exposure of boric acidto water has the potential to affect a natural ecosystem as it is easily transported by animals and plants within their system when the element is in an aqueous phase. *Phragmites australis* and *Typha latifolia* were plants that were used to uptake the boron (B) from the constructed wetland. The recorded B concentrations of water flowing into the CW were: 2019.1, 232.3, 716.4, 28.2, 10.2, and 84.6 mg ^{1}. Boron concentrations that were absorbed by *Phragmites australis* recorded were 839mg kg^{-1} which amounts to 27.2% of B uptake from the water in the wetland. While *Typha latifolia* B concentrations totaled 1300 mg kg^{-1} which relates to 40.7% of B uptake. The study suggested that CW are not only effective in treating B concentrations from mine wastewater, but they are alsoan eco-friendly and economically viable natural solution (Turker *et al*., 2014).

Floating treatment wetlands (FTW) are also known as "artificial floating islands", integrated floating systems", "constructed floating wetlands", "floating mats", "artificial floating reed beds", etc. (Headley and Tanner, 2012) and are systems that have been identified by Yaun *et al* (2013) to perform four functions: floating treatment wetlands provide habitat for birds and fishes, they act as landscape enhancers, they are water purification systems, and they protect the littoral zone - an area of water body that is nearthe shore - by creating a barrier (Yaun *et al*., 2013; Zhang *et al*., 2018).

FTWs remove contaminants by integrating the interactions between, atmospheric, microorganisms, hydrological, and plant systems in and around the wetland (Headley andTanner *et al*., 2012 also see Figure 2. The interactions at play include biofilm development, metals, nutrient uptake and absorption, releases of enzymes, capturing of solids, and flocculation (Chen *et al*., 2015). Chen *et al* (2016) identify another interaction in which FWTs work to purify water through the establishment of a hydraulic gradient that works between the roots of the plant system network. However, Rehman *et al* (2019) state that to achieve an effective filtration system, the plants; root system should not be on the surface but must be touching the FTW system (Rehman *et al*., 2019). Microorganisms such as bacteria found in the treatment plant can remove and reduce radioactive waste in the soil and water components of FTWs (Khan *et al*., 2013). Bacteriacan destabilize the oxidation states of the radioactive waste which in turn eliminates the element's radionuclides and metals and ultimately causes the element to be dissolved or immobilized (Cheng *et al*., 2019). In addition to the removal of radioactive waste, photosynthetic bacteria can improve the water quality of water that contains elevated levels of organic compounds (Afzal *et al*., 2019).

Water quality can be assessed using parameters (physical, chemical, and biological) that usually have specific and defined limits within which a hydrological system does not dysfunctional (Tyagi *et al.,* 2013); these parameters are determined as in situ measurements in a laboratory or on study site. Some additional pollutants that have beenreported to be removed by bacteria species such as Pseudomonas include petroleum, polycyclic and aromatic hydrocarbons, and halogenated compounds (Ivanova *et al*., 2022).

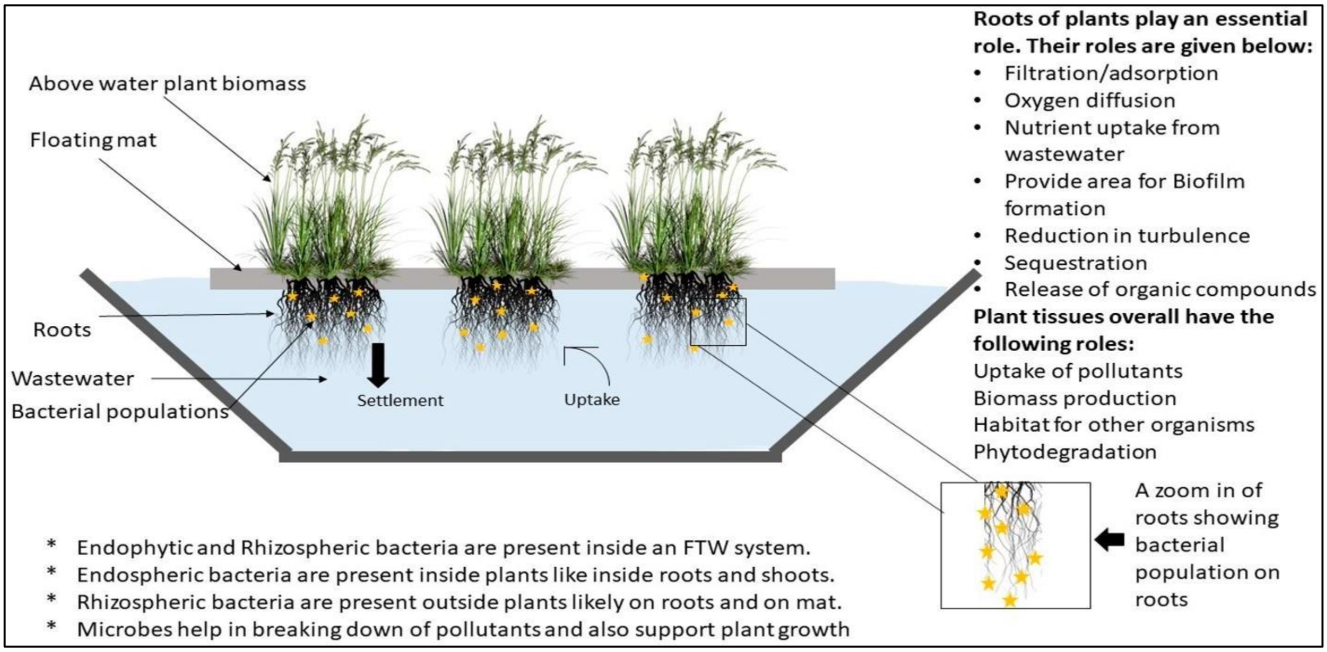


Figure 2: A schematic diagram that illustrates an FTW and its associated components responsiblefor water purification (Wei, 2020, pp8) provides).

2.10 Wetland Classification Systems

Wetland classification based on their hydro and geomorphic dynamics has been a widelyused approach that aids in categorizing wetland types in various landscapes. This type of wetland classification is known as hydrogeomorphic (HGM) classification. The hydrological dynamics refers to the characteristics of the water that govern the wetland for example, the direction of the movement of water in the wetland and the amount of energy the water has (Ollis *et al*., 2015). The geomorphic dynamics refer to a wetland’s topographical setting, geological structure, geological evolution, as well as the wetland’s landform (Smith *et al*., 1995; Ollis *et al*., 2015). A summary of some of the various scholarsthat have used the HGM approach to classify wetland types is presented as well as the HGM approaches they considered. It should be noted that an overlap may exist between some of the described hydrological and geomorphic dynamics because these processes may be simultaneously at play.

Table 3: HGM classification of wetlands and aquatic ecosystems (Ollis *et al*., 2015pp 730).

Author	**Hydrological dynamics determiningwetland type**	**Geomorphic dynamics determiningwetland type**	**Co-occurrence of hydrological and geomorphic dynamics determining wetland type**
Kotze (1999)	-Water channel	- Valley bottom type: channeled or unchanneled - Hill slope -Depression	-Flow concentration area
Kotze *et al.* (2008)		- Valley bottom type: channeled or unchanneled -Depressions	-Hillslope seepage:linked to a stream or is isolated Floodplain area
Sieben *et al.* (2011)	-River margin and vegetated channel deposits. -Groundwater -Water rest level -Isolated or geothermal spring	-Valley bottom: with a channel or without a channel -Depression -Dolomite cave - Raised bog	- Hillslope seepage: feeding a stream or not feeding a stream -Floodplain area
Rountree and Batchelor (DWAF,2007b)	-River -Lake -Meandering flood	- Valley bottom type: channeled or unchanneled	-Meandering floodplain - Slope seepage: isolated or connected -Crest seepage: connected or pans and depressions
Ewart Smith *et al.* (2006)	Non: isolated -River channel Isolated	Non: isolated -Valley bottom -Depressions linked to a channel Isolated -Isolated depressions	Non: isolated -Floodplain -Seep with channeled outflow Isolated -Seep without channeled outflow
Ollis *et al.* (2009a)	Valley floor/Slope/Plain/Bench: -River channel	Valley floor/Slope/Plain/Bench: -Valley bottom: with a channel or without a channel -Depression -Flat	Valley floor/Slope/Plain/Bench: -Floodplain -Hillslope seep -Valley head seep

A study conducted by Oliis *et al* (2015) about the development of a classification system for inland aquatic ecosystems in South Africa, provides six (6) primary levels of classifyingSouth Africa's inland wetlands and aquatic systems based on the HGM – classification approach. According to Ollis *et al.* (2015), it is important to note the time of year before adopting this HGM approach in classifying South Africa's aquatic system due to seasonal variability that may affect the hydrological processing taking place in that aquatic systemduring that time of the year. Ollis *et al*. (2015) describe what each system level entails as follows:

System level 1

Classification of aquatic systems based on their degree of connectivity to the ocean for example the type of water which is found in the aquatic system: Marine, Estuarine, or terrestrial aquatic system.

System level 2: Regionalsetting

Classification based on spatial homogeneity of the region for example, classifying aquatic systemsbased on their ecological regions.

System level 3: LandscapeUnits

Classification based on the topographic characteristics that govern the location of theaquatic system. Four (4) primary topographical units are distinguished: Slope, Valley floor, Bench and Plain.

System level 4: Hydrogeomorphic Units

Classification based on hydrological, landform, and hydrodynamic units governing the aquatic system. There are seven types of hydrogeomorphic units which entail: Floodplain wetland, Channeled Valley-bottom Wetland, Unchanneled Valley-bottom, River, Depression, Wetland flat,and Seep.

System level 5: Hydrological Regime

This level allows for the classification of aquatic systems based on the behaviour and the type of water that is found in that aquatic system. The units that are used to categorize the aquatic system include: Seasonal variations of waterchannel (perennial or non-perennial), Inundation of aquatic system, and Soil saturation.

System level 6: Descriptors

Although descriptors are an optional inclusion when using Ollis *et al* (2015), they providedetails pertaining to the biological, chemical and structural characteristics of an inland aquatic system. The 6 descriptors are: Salinity, pH, Vegetation cover, Substratum type, Geology, and Natural vs Artificial aquatic system.

CHAPTER 3 STUDY SITE DESCRIPTION

3.1 Introduction

In this section, a study site description is provided which details the geographical location of the Krugersdorp Game Reserve (KGR), climatic conditions that govern and influence the game reserve, the geology of the immediate and surrounding landscape, the local and regional hydrological system of the study area, the geology of the game reserve, the flora and fauna found In and around the reserve, and the land use of the immediate and surrounding areas.

3.2 Geographic location of the KGR

The Krugersdorp Game Reserve (26°05′11″S, 27°42′35″ E) is located in Krugersdorp City (26°6′0″ S; 27°46′0″ E) which is also referred to as the Mogale City is found in the West Rand region of the Gauteng province in South Africa (Shapi *et al*., 2020). Two (2) large-scale mining sites juxtapose the reserve mainly Rand Uranium and Mintails Mogale Gold. Both of these mining outfits have been recent–mined of their gold dumps and tailings after being abandoned over the years (Shapi *et al* 2021). Additionally, small holdings are also found adjacent to the KGR. The size of the KGR has been estimated to occupy approximately 1400 – ha of land (Van Niekerk, 2010).

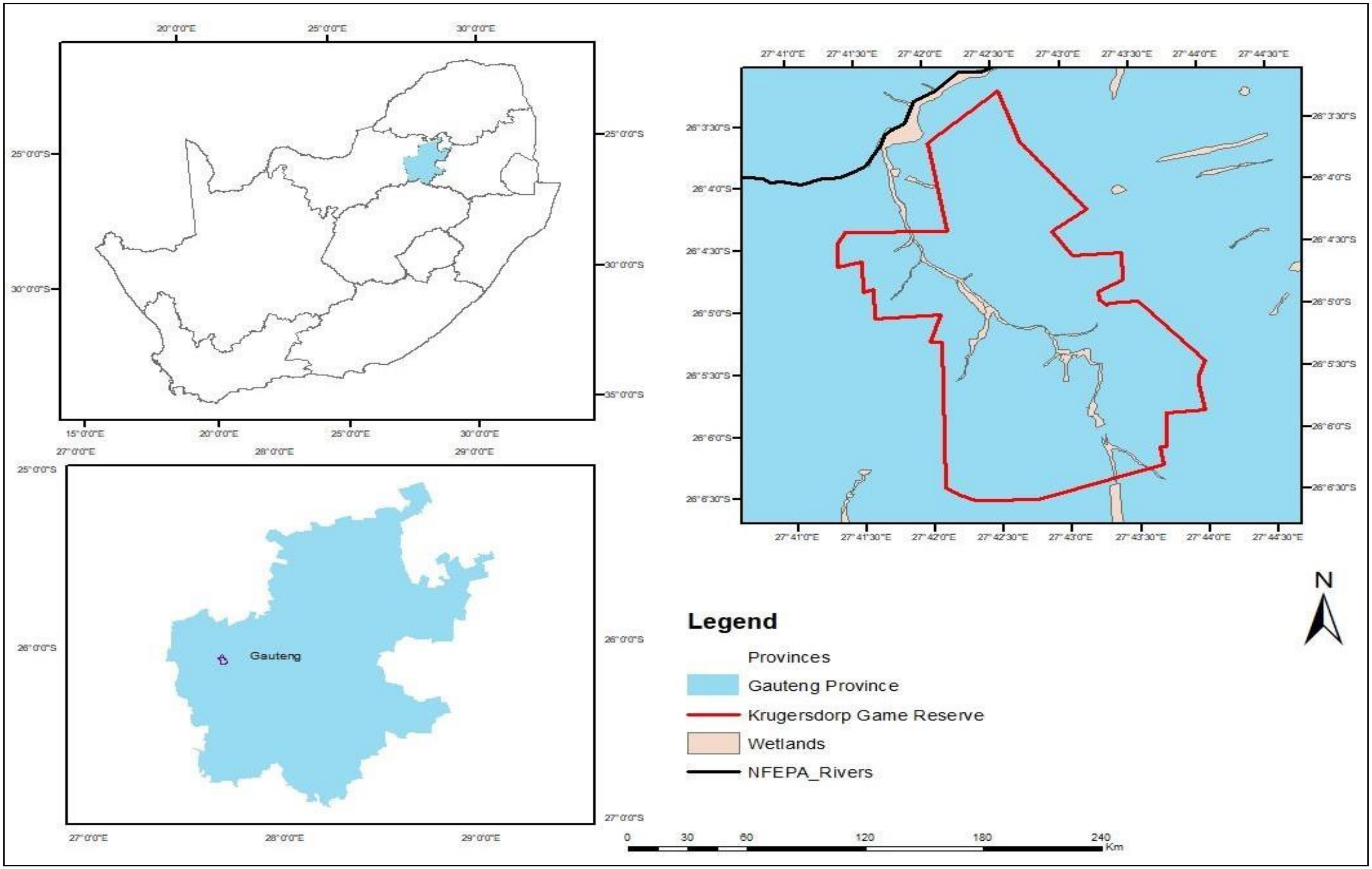


Figure 3: A map delineating the Krugersdorp Game Reserve.

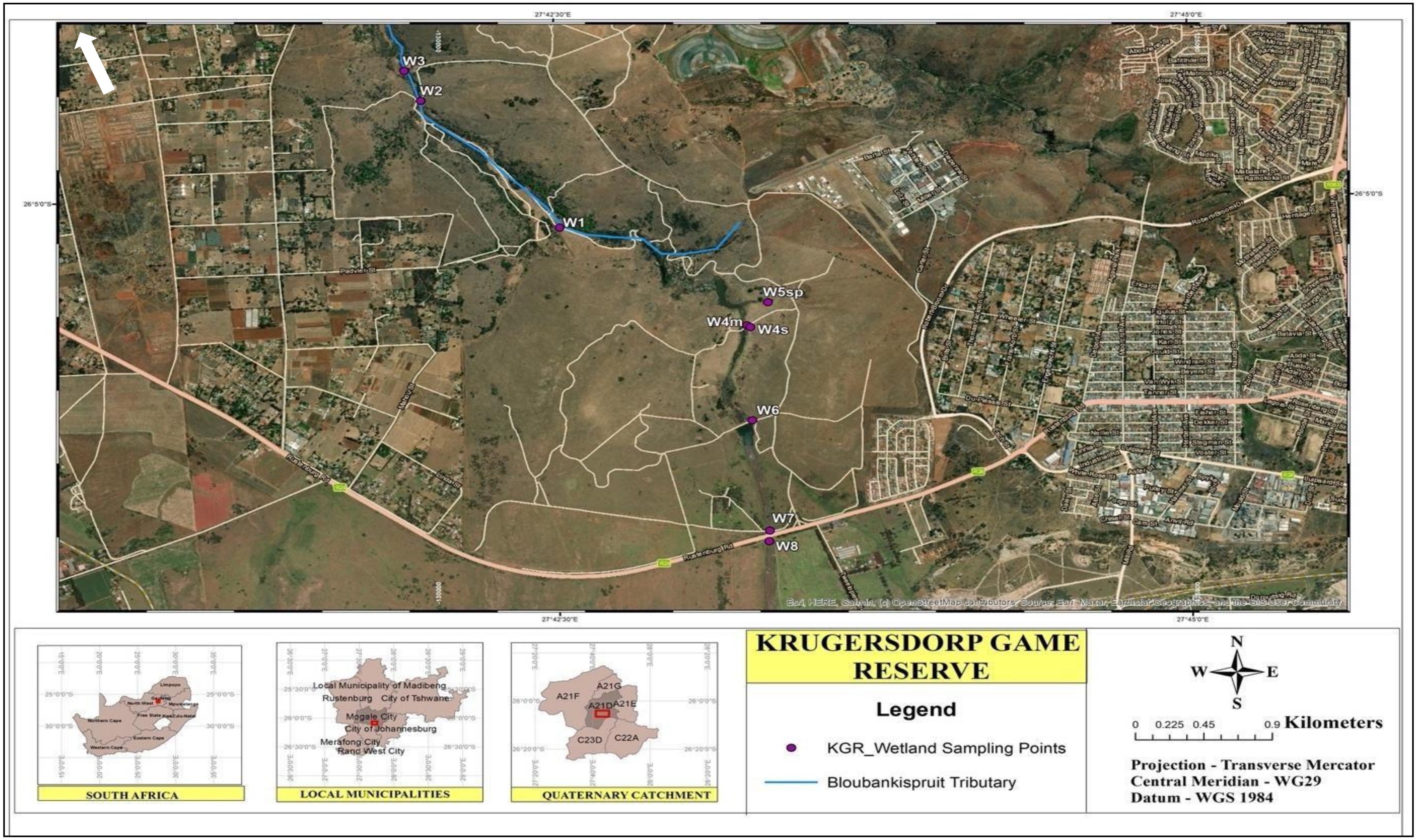


Figure 4: Map illustrating the localities where the water samples were collected inside and outside of the KGR. Locality W8 represents the wetland that was sampled outside of the KGR. Flow direction: South-westerly. The location of the mining sites that are adjacent to the KGR is depicted in Figure 5.

Figure 5: Mining sites adjacent to the KGR.

3.3 Climatic Conditions Governing the Game Reserve

The climatic condition that dominates the KGR is mainly temperate, warm, and sub-humid. In Krugersdorp, January is the warmest month of the year with an average recorded temperature of 20.1°C while June is the coldest month of the year with an average recorded temperature of 9.1°C. The average annual temperature of the town is 15.6 °C (Shapi *et al*., 2021). In terms of precipitation, Krugersdorp receives annual precipitation of about 759 mm which is mainly contributed from the summer season when compared to the dry winter season (Shapi *et al*., 2021). August is the driest month in Krugersdorp and receives an average precipitation of 7 mm while January is the wettest month and receives an average precipitation of 142 mm (Shapi *et al*., 2021).

3.4 Hydrological system of the KGR

The KGR is characterized by different aquifers that constitute the area's hydrogeological network system (Winde, 2012). For example, the north of the KGR is bisected by the Tweelopies Spruit which was once characterized as a non-perennial stream (Shapi *et al*., 2021). The fracturing and weathering of the sedimentary rocks of the Witwatersrand Supergroup has given rise to the groundwater flow of the Tweelopies Spruit (Shapi *et al*., 2021). According to Hobbs and Cobbing (2002), the groundwater of the Tweelopies Spruit has been flowing since 2002 due to mine water decant discharging Acid Mine Drainage (AMD) into the stream. Additionally, the KGR is scattered with springs, non-perennial drainage lines, and seeps (Shapi *et al*., 2021).

3.5 Geology of the KGR

The Witwatersrand Basin is the underground geological formation that underlines the Krugersdorp region (Shapi *et al*., 2021), northwest of Johannesburg. This basin is characterized as a large gold-producing area that extends to about 400 km. Krugersdorp is found on the western ridge margin of this basin at an elevation of about 1740 m (Minerals Council of South Africa, 2020). Additionally, the Witwatersrand Reef has an extensive range of mineralization which constitutes about 70 ore minerals, diamonds included (Minerals Council of South Africa, 2020).

In terms of geology, Government Reef quartzites and Black Reef Formation as an escarpment that separates the KGR into two main subgroups namely the northern plateau which is characterized as being steep, low – lying and underlain by dolomite; and the southern plateau which is characterized by Malmani Subgroup dolomite outcrops and is underlain by arenite of the Black Reef Formation (Minerals Council of South Africa, 2020; Hobbs and Cobbing, 2002).

The soils found in Krugersdorp belong to the Hutton form which is characterized by orthictopsoil that is found on red apedal subsoil (Shapi *et al.*, 2020). The soil type that dominates in the KGR is mainly brown to red in color and ranges in texture depending on the depth of the soil horizon from clayey silt to silty clay to loam (Shapi *et al*., 2020; also see Figure 6). Additionally, sandy clay has also been identified in various areas ofthe landscape, however, the sand content tends to be less.

Figure 6: An image displaying a section of the sampled wetland at W7, and thecolor of the soil found in the wetland.

3.6 Flora and Fauna found in the KGR

The vegetation in the KGR is classified under the Rand Highveld Grassland type (Mucinaand Rutherford, 2006). Intensive vegetable production used to be the former land – use of the reserve before it was established in 1963 (Van Niekerk, 2011). With the establishment of the reserve and halting of gardening weeds such as the creeping thistle Cirsium *arvense,* the common thorn-apple Datura *stramonium,* and other Cyperaceae spp invaded the landscape (Van Niekerk, 2011). In 1980, 60% of the reserve was covered with weeds while other areas of the reserve had flora such as tall grasses including common thatching grass Hyparrhenia *hirta*, Kikuyu Pennnisetum *clandestinum*, and many more Eragrostis spp (Van Niekerk, 2011). Poplar tree plantations and indigenous forests were used to border the old vegetable gardens with shrubs also found on the landscape (Van Niekerk, 2011). Currently, the vegetation on the landscape is characterized by slightly undulating or flat grassland with trees (including shrubs) scattered around. On hilly grounds where there has been no disturbance from anthropogenic activities such as mining activities, vegetation clearance, or urbanization; there are still remnants of native vegetation which comprises thorn and shrubby vegetation species (Nadasan *et al*., 2014). Additionally, densely wooded valley exists on the vast open grassland in the KGR (Shapi *et al*., 2021). The KGR landscape allows for a diverse community of fauna species (both aquatic and terrestrial) to occupy it. For example, in Krugersdorp; the Game reserve is known for its diverse community of mammal species such as giraffes, zebras, gemsbok, and hippopotamus (Sessel, 2021). These animals inhabit the grassland, forests, and rocky outcrops that are on the KGR landscape. Lions are also present in the reserve and are kept in closed enclosures. Additionally, over 200 bushveld bird species have also been recorded in the reserve (Sessel, 2021).

3.7 Land use of immediate and surrounding areas on the landscape

Krugersdorp – known as a mining town - is approximately 247.22 km^2 in size and has a population of approximately 378,821 people (Shapi *et al* 2021). Krugersdorp can be classified as a mixed settlement type with both urban and rural areas occupying various parts of the landscape. Several abandoned mines (gold, asbestos, lime, iron,and manganese mines) surround the area (Shapi *et al*., 2020). Due to soil factors, agricultural development remains low in Krugersdorp even though the town has also been designated as an agricultural hub in the Gauteng province (Shapi, 2020). Krugersdorp has contemporary business and small businesses which are inclusive of malls and shopping centers, schools, hospitals, and local government facilities are also presentin town in addition to the KGR, other heritage sites constitute tourist attraction sites in Krugersdorp which include Sterkfontein, Wonder Caves, and Cradle of Humankind (Leonard and Langton, 2016). There are also sports facilities such as golf courses and leisure parks like the Coronation Park.

CHAPTER 4 METHODS AND MATERIALS

4.1 Introduction

In chapter two, the literature about the effectiveness of wetlands in attenuating mine-polluted water was described. In this chapter, the materials and approaches that we used to achieve the objectives of the study are described so that they are reproducible by related studies with similar aims and objectives. The main of the current study is to assessthe effectiveness of wetlands in improving the water quality of mine polluted entering the Krugersdorp Game Reserve (KGR) from an abandoned gold mine.

The approach that was followed is comprised of four steps, which are presented in the subsequent sub-sections desktop study, fieldwork, laboratory analysis (Table 5), and data analysis.

The identified limitations that are associated with this study include:

1. This study only focused on sampling one type of natural element which was water,because the evolution of the water chemistry along the flow path can provide insights into the effectiveness of wetlands in attenuating pollutants, particularly metals.
2. A potential limitation of the methodological approach is the lack of soil profile data on metal distribution in the study area, which provides information on the effectiveness of wetlands in retaining metals.
3. No analysis of metal enrichment in wetland tissue plants nor their roots in accordance with the maturity was undertaken due to limited accessibility and time constraints. The inclusion of other natural elements such as soil and plants would have provided richer information as to howthe wetlands are attenuating the pollution and which specific metals are contributing to the observed environmental impacts.

4. Due to safety reasons, the sampling of wetlands outside of the Krugersdorp NatureReserve (KGR) was only limited to the wetland system that was closest to the entrance of the KGR.

4.2 Desktop study

The purpose of the desktop study was to gain insights into previous work conducted in the study area and the design and planning of the fieldwork campaign. The focus of the fieldwork campaign was on collecting water samples in the wetland channels. As mentioned in section 4.1 only water samples were collected to assess the efficacy of the wetland in the KGR. Only sampling sites that were accessible and safe were selected as water collection and physio - chemical measurement points. Methods deployed for this study are an amendment and a replication of similar research that was conducted by Bateganya *et al* (2015). The study is about the Masaka municipality in Uganda which buffered municipal wastewater pollution using urban wetlands (Bateganya *et al*., 2015).

4.3 Fieldwork

The fieldwork campaign was conducted at the end of the summer on the 31st of March 2022. Sampling sites were selected based on their location in relation to the wetland along the stream path and ease of accessibility to the stream. A geographical position systems (GPS) device was used to record the geographical coordinates of the water sampling sites, and data recorded in the notebook. In addition, a smartphone GPS App device was also used to capture the geographical coordinates for backup.

One-time water samples were collected in multiple locations in the middle of the stream at the study site. Seven (7) water samples were collected inside of the Krugersdorp Game Reserve (KGR) and one (1) water sample was collected outside the KGR along the R24 (road name), which decants mine water to the KGR. Table 4 illustrates the sampled wetland sites and field observations of the wetland recorded on the day of sampling.

Table 4: Description of the water samples collected.

Wetland site name	The name of the sample collected	Description of wetland location
Moviehouse	W1	Wetland has a dense green vegetation cover which is mostly dominated by flora alien invasion species.
Lion enclosure exit	W2	The wetland is situated in an area where lions dominate the habitat.
Flippie se gat	W3	Cobra and Puff adder snakes were initially identified on this site. Green vegetation including grasses and trees found on site (Figure 7).
Graveyard side (Rooi-belt)	W4s	There was a malodorous smell of rotten eggs which may be due to the high Sulphur containing water that is flowing in the site.
Graveyard site (also known as Rooibeld)	W4m	An algae-dominated wetland point.
Spring	W5sp	The near–pristine water was observed flowing through the wetland.
Hippo dam	W6	The wetland was rich in organic matter.
Picnic area	W7	The soil in the wetland location was red which may be an indication of Iron (Fe) precipitation. Weeds dominate the wetland vegetation.
The name is unknown. The wetland point that was sampled outside of the KGR along the R24.	W8	A very ‘crusty’ environment which may bea result of mineral precipitation over time.

Figure 7: Location of the Flippie se gat wetland that is found inside of the KGRwhere W3 locality was sampled (photo: Noluthando Sawuka).

A YSI ProQuatro Multi-Parameter handheld water quality instrument was used to measure physico-chemical parameters such as pH, total dissolved solids (TDS), electricalconductivity (EC), dissolved oxygen (DO), and salinity on site. The YSI ProQuatro Multi-Parameter handheld water quality instrument is calibrated all the time before use to improve the accuracy and reliability of measuring capacity.

Water samples were collected using 1-liter bottles (Figure 8). The bottles were rinsed at least five times with the sample water. Thereafter, the bottle was filled to the top and tightly closed. The bottles were marked with a pen for easy identification and immediately stored in a cooler box to slow down the rate of chemical reactions that could potentially occur before the samples were transported to the lab. The water samples were transported to a commercial lab on the same day for analysis of major ions and trace metals in the water samples.

Figure 8: A sample of the water bottles that were used to collect water samples from the sampled wetlands photo: Noluthando Sawuka).

4.4 Laboratory analysis

Table 5 is presented below with a list of methodologies followed for the laboratory analysis of the submitted water samples.

Table 5: A list of various methods used for physico – chemical measurements and chemical analyses.

Method Name	Method Number	Method Type	Original Method
pH	WLAB/001/pH/Method	Potentiometric	4500-H^+ pH Value: *Standard Methods for Examination of Waterand Wastewater; 20th Edition*, Instrument manual
Electrical Conductivity	WLAB/002/E.C./Method	Conductometric	2510 Conductivity: *Standard Methods for Examination of Waterand Wastewater; 20th Edition*, Instrument manual
Total Dissolved Solids	WLAB/003/T.D.S./Method	Gravimetric	2540 Solids; Total DissolvedSolids Dried at 180°C: *Standard Methods for Examination of Water and Wastewater; 20th Edition*
Chloride	WLAB/046/Discrete analyser/Method	Colorimetric / Spectrophotometric	
Sulphate	WLAB/046/Discrete analyser/Method	Colorimetric / Spectrophotometric	

Table 5: A list of various methods used for physico – chemical measurements and chemical analyses (continued).

Method Name	Method Number	Method Type	Original Method
Fluoride	WLAB/014/F/Method	Ion Selective Electrode (ISE)	4500-F^- Fluoride; Ion-Selective Electrode Method: *Standard Methods for Examination of Waterand Wastewater; 20th Edition*, Instrument manual
ICP Spectrometertrace metals	WLAB/015/ICP/Method	Spectrophotometric	3125 Metals by InductivelyCoupled Plasma/Mass Spectrometry (ICP): *Standard Methods for Examination of Waterand Wastewater; 20th Edition*, SANS/ISO 11885:1996 Water quality – Determination of 33elements by inductively coupledplasma atomic emission spectroscopy, Instrument manual

4.4.1 Data analysis

Chemical analysis and physico-chemical data collected were analysed using statistical and graphical tools. The statistical approach applied is descriptive statistics of the data and two-tailed Pearson correlation. The descriptive statistics provide information about the mean, minimum, and maximum of the chemistry data for the chemical parameters. The two-tailed Pearson correlation matrix was used to understand the correlation between two water chemistry variables to discern possible processes leading to the observed relationships.

The graphs were useful in displaying how chemical parameters are changing for each sampling site, which gives a pictorial view of the evolution of water chemistry from the decant point to the KGR.

The HGM (Hydrogeomorphic) classification provided by Ollis *et al.* (2015) can be used toclassify the sampled wetlands in and around the KGR based on the 6 systems level as illustrated in section 6. The use of the HGM approach as presented by Ollis *et al*. (2015) is important in interpreting the observed and recorded physico – chemical and chemical results because the effectiveness of the sampled wetlands in attenuating pollution from the adjacent mines is dependent (but not limited) to the 6 system categorizations as described by Ollis *et al*. (2015) and various authors.

CHAPTER 5 RESULTS

5.1 Introduction

The results chapter presents the results of the obtained physico – chemical parameters, inorganic constituents as well as the analysed metal constituents. Graphical representation of data is presented using scatter plots to illustrate relationships between variables. Additionally, bar graphs are used to illustrate variable distribution in the analysed water samples from the sampled wetlands. Tables have also been included which present data including of variable exceedances of specified water guidelines and Pearson's correlation matrices.

5.2 Field measurements of physico - chemical parameters

The measured pH, Electrical Conductivity (EC), and Total Dissolved Solids (TDS) variables are presented in Table 6. The physico - chemical variables that are represented in Table 6 illustrate that the lowest pH values were recorded for wetlands that were downstream (from W1 to W4s water) while neutral to alkaline pH values were recorded from wetlands that were sampled upstream (W5sp to W8).

Table 6 The measured pH, Electrical Conductivity (EC), and Total Dissolved Solids (TDS) variables.

Sample ID	Sample Number	Latitude	Longitude	pH	Electrical Conductivity in(mS/m)	Total Dissolved Solids (mg/l)
W1	157906	-26.0853	27.70862	3.9	320	3200
W2	157907	-26.0762	27.69958	4.3	308	3064
W3	157899	-26.0741	27.6985	4.3	308	3076
W4m	157900	-26.0924	27.72088	4.5	342	3500
W4s	157901	-26.0925	27.72111	4.4	342	3534
W5sp	157902	-26.0907	27.72227	6.2	12.1	74
W6	157903	-26.0991	27.72116	7.5	356	3614
W7	157904	-26.1070	27.72224	7.1	327	3340
W8	157905	-26.1077	27.7222	8.9	360	3744

An exceedance table (Table 7) for the physico – chemical variables has been used tocompare the water quality of the eight (8) water samples to the stipulated water quality standards for South Africa's water bodies. The water standard legislations that have been used as guidelines to compare the water quality of the samples are:

(a) General authorization limit section 21f and h, 2013

(b) Target Water Quality Range (TWQR)

(c) Mine, Health, and Safety Act (MHSA)

(d) Water Use License (WUL) for wastewater

The measured values in Table 7 that are highlighted in red represent an exceedance of at least one of the stipulated guidelines.

*It should be noted that although some of the recorded results are not highlighted in red, it does not necessarily mean that the measured parameters are within the acceptable limits, however, the provided legislation does not stipulate a threshold variable for that specific parameter. Additionally, for this study, pH values that fall within the threshold limits stipulated in Table 7 will be considered as neutral; values that are lower than the threshold values will be considered acidic, while pH values that are higher than the threshold limits will be considered alkaline.

Table 7: An exceedance table for the analsyed physico – chemical parameters.

Physico-chemical variables	UNITS	General Authorisation Limit,Section 21f and h, 2013	Unfit for any TWQGR	RPM Mine Health and Safety act	RPM WUL Wastewater	W1	W2	W3	W4m
Temperature	°C					18	18.1	18.1	21.3
Dissolved Oxygen	%					78.3	80.5	81.5	80.3
Dissolved Oxygen	ppm					7.33	7.53	7.62	7.04
Conductivity	ms/m	70-150	>520	300	31	320	308	308	342
Total Dissolved Solids	mg/l		>3000		191	3200	3064	3076	3500
Salinity	ppt					1.7	1.62	1.62	1.82
pH		5.5-9.5	<3/>11	5.5/9.5	6.0 /9.0	3.9	4.3	4.3	4.5

Table 7: An exceedance table for the analsyed physico – chemical parameters (continued).

Physico-chemical variables	UNITS	General Authorisation Limit,Section 21f and h, 2013	Unfit for anyTWQGR	RPM Mine health and safety act	RPM WUL Wastewater	W4s	W5sp	W6	W7	W8
Temperature	°C					20.8	19.5	21	24.4	23.7
Dissolved Oxygen	%					41.1	55.5	56.3	70.1	73.9
Dissolved Oxygen	ppm					3.64	5.09	4.96	5.8	6.19
Conductivity	ms/m	70-150	>520	300	31	342	12.1	356	327	360
Total Dissolved Solids	mg/l		>3000		191	3534	74	3614	3340	3744
Salinity	ppt					1.78	0.06	1.89	1.72	1.91
pH		5.5-9.5	<3/>11	5.5/9.5	6.0 /9.0	4.4	6.2	7.5	7.1	8.9

The physico - chemical parameters in Table 7 that exceeded the stipulated legislations are measured for conductivity, total dissolved solids (TDS), and pH values. All the water samples (except for W5sp) that were sampled had two (2) or more exceedances for the analyzed physico - chemical parameters.

A statistical summary of the physico – chemical parameters measured which details the minimum, maximum, mean, standard deviation, and variance of the sampled wetlands in the KGR is presented in Table 8.

Table 8: Summary Statistics of physico - chemical water samples from the eight (8) sampled wetlands.

Variables	**Minimum**	**Maximum**	**Mean**		**Std. Deviation**	**Variance**
			Statistic	Std. Error		
pH - Value	3.9	8.9	5.678	.6006	1.8019	3.247
EC in mS/m	12.1	360.0	297.233	36.1975	108.5924	11792.315
TDS in mg/l	74	3744	3016.22	376.207	1128.620	1273783.444

The pH graph depicted on Figure 9 indicates an acidic to alkaline characteristic of the water samples from the wetlands that are located downstream (north westerly direction) of the reserve to wetlands that are located upstream in the KGR.

The water samples that were collected from the W5sp and W6 localities had neutral pH values of 6.2 and 7.5, respectively. Water samples that were collected from wetlands located downstream (W1 to W4m) had slightly acidic pH values (pH<5.5) whilst water samples that were collected from wetlands located upstream (W7 and W8) had neutral (pH 6 - 7) to slightly alkaline (>7 pH<10) values, respectively. A graphical representation of the measured TDS values from the sampled wetlands is presented in Figure 10.

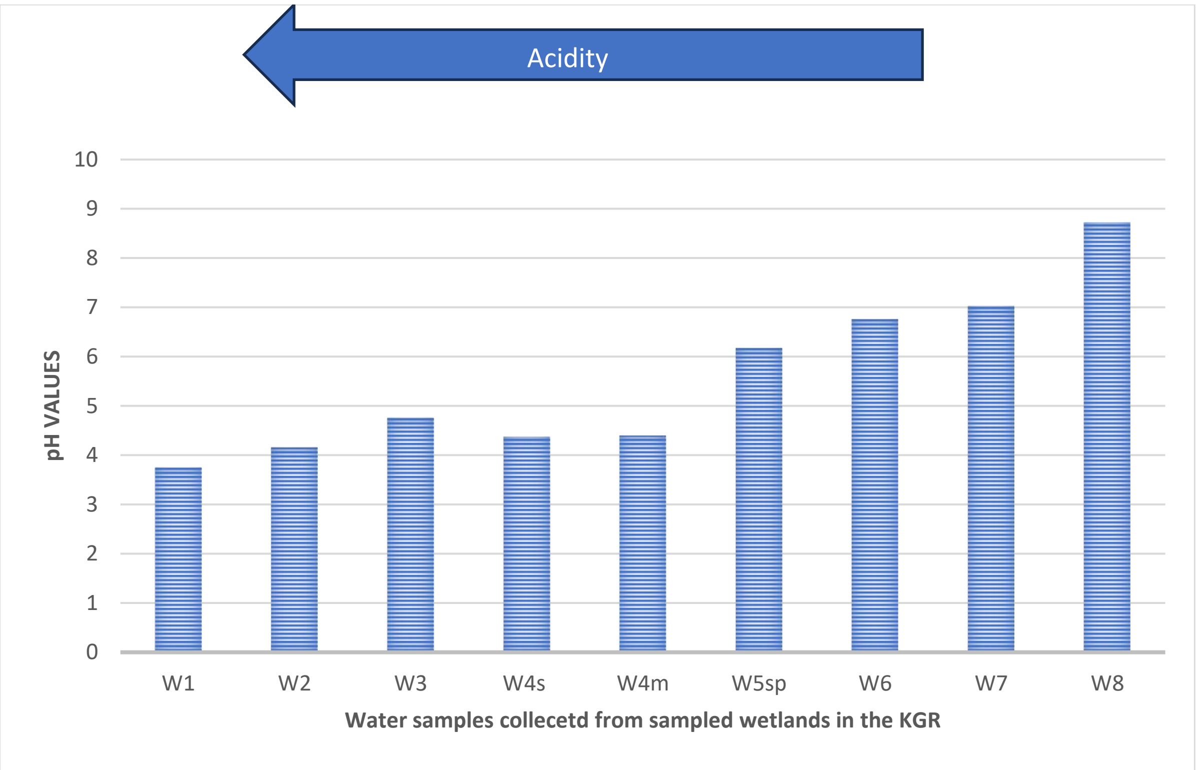


Figure 9: pH values of water samples collected from various wetlands located downstream (W1 to W4m) and upstream (W6 to W8) of the KGR.

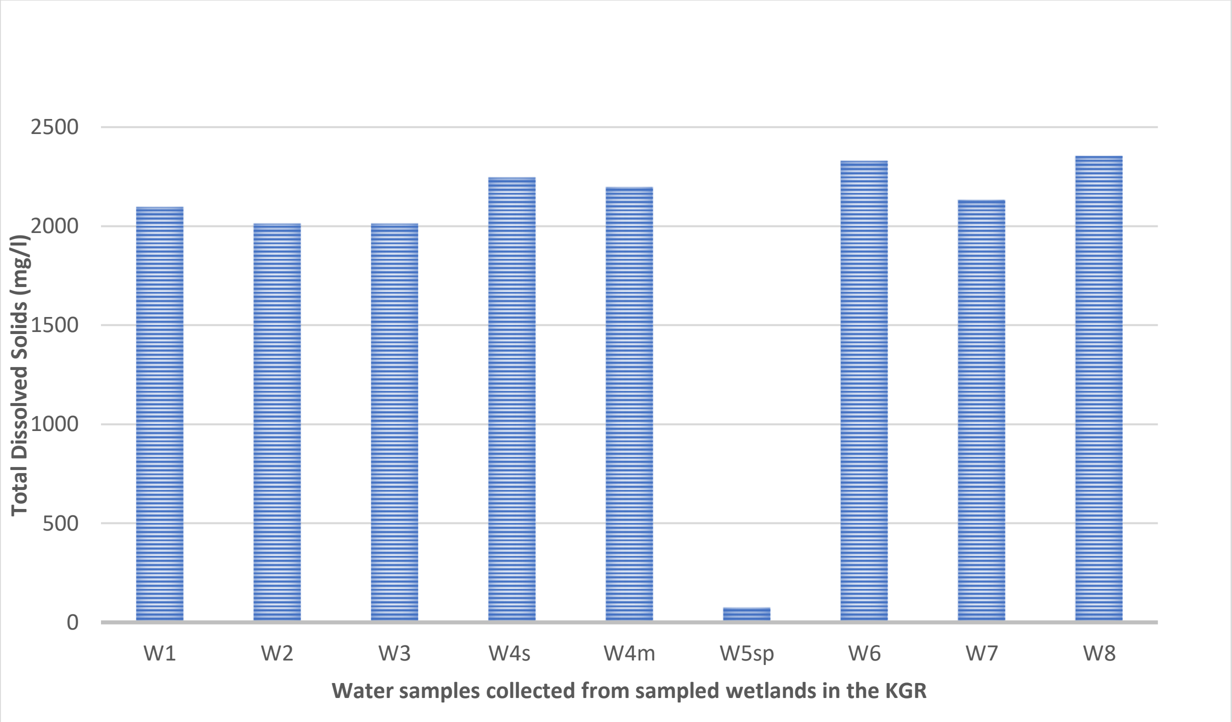


Figure 10: Measured Total Dissolved Solids (TDS) values of water samples collected along the sampled wetlands of the KGR.

5.3 Graphical representations and data analysis of the obtained results of therelationships between the physico - chemical variables

The correlations and relationships between two physico - chemical variables have been presented in Figure 11 to Figure 12. Scatter plots and correlation matrices have been used to illustrate the various types of possible relationships or correlations that exist between the physico - chemical parameters from the eight (8) sampled wetlands.

5.3.1 TDS versus Salinity

The obtained Total Dissolved Solids (TDS) and salinity values for water samples thatwere collected inside and outside of the KGR are represented in Figure 11 below.

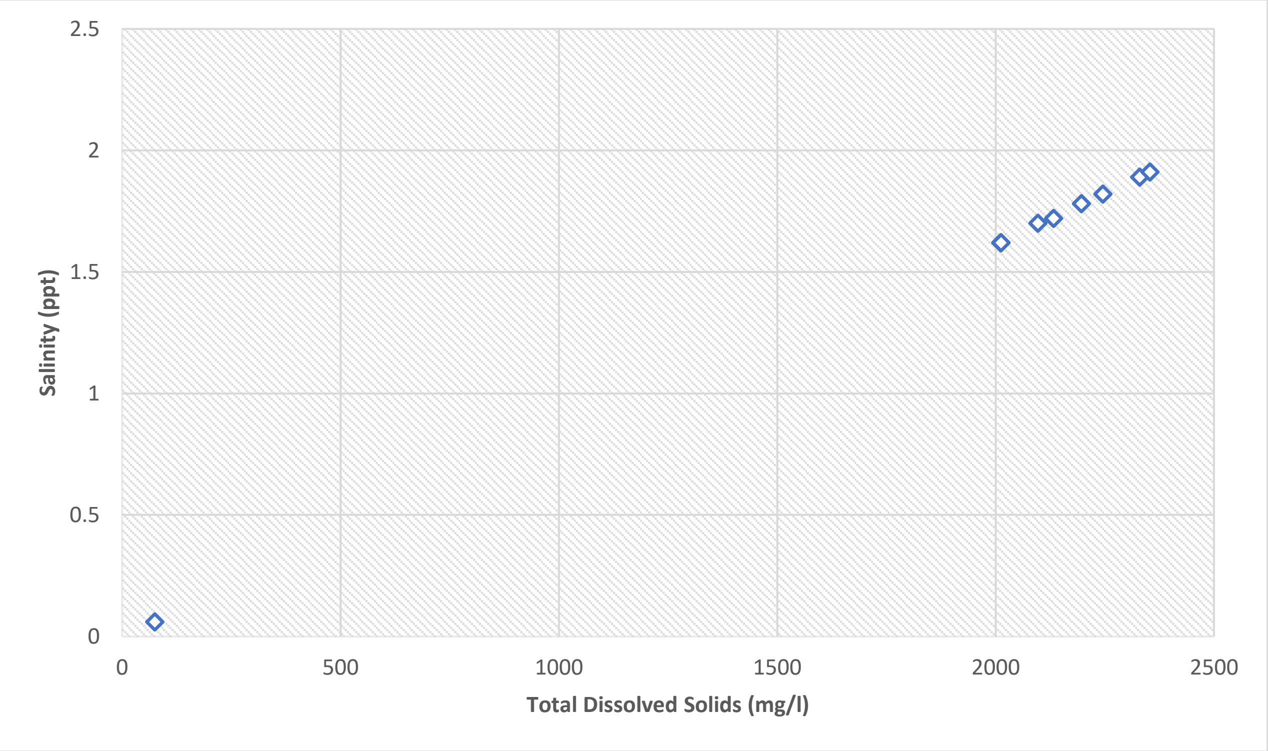


Figure 11: Scatter plot illustrating a TDS versus salinity (EC) relationship. All thesampled points fall within the trendline (shown as the dotted blue line), which shows that there is a continuous increase in salinity values when TDS concentrations are also increasing.

A strong positive correlation of 0.999 is shown in Table 9 when comparing the measured TDS and salinity (EC) values. This correlation translates to an increase in the TDS concentrations measured from the sampled wetlands in KGR is directly proportional to an increase in the salinity (EC) of the sampled water points. The waterthat was sampled at the spring (W5sp) locality had the lowest TDS concentration andconsequently a low salinity value (Table 9).

Table 9: Pearson's correlation matrix of the analysed physico – chemical parameters as well as of the analysed inorganic constituents from the sampled wetlands in the KGR.

		pH	EC in mS/m	TDS in mg/l
pH	Pearson Correlation	1	0.014	0.040
EC in mS/m	Pearson Correlation	0.014	1	.999**
TDS in mg/l	Pearson Correlation	0.040	.999**	1

*. Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

5.3.2 Total Dissolved Solids (TDS) versus pH

The overall trend between TDS concentration and pH values of the sampled wetlandsof the KGR represented by the scatter plot in Figure 12 shows that the majority of thepoints represent a linear, weak, and positive (but not directly proportional) relationship. When TDS is plotted against the respective pH values. At a significant level of 0.459 the Pearson correlation obtained between the measured TDS and pH values is 0.040 (Table 9). The majority of the sampled wetlands in the KGR indicated that pH values ranged from acidic values to alkaline values when TDS concentrations were above 2000 mg/l. An outlier point (W5sp) was also recorded (as illustrated in Figure 12) that illustrates a TDS concentration of less than 100 mg/l but with a slightly acidic pH value.

The scatter plot in Figure 12 illustrates that pH is highly variable (acidic - basic) for the water samples but the TDS is relatively high for all samples except the spring water sample (W5sp). The relationship between TDS and pH is somewhat weak. Ideally, low pH which is associated with acidic conditions which allows for metal mobilization and that increases the concentration of metals dissolved in water subsequently the salinity.However, in this instance, the pH recorded at W8 was high as well as the measured TDS and salinity. A possible reason for this outcome would be that water bodies adjacent to the mines get dozed with an alkaline constituent such as lime which increase the pH, however, does not remove sulphate dissolved in the water channel.

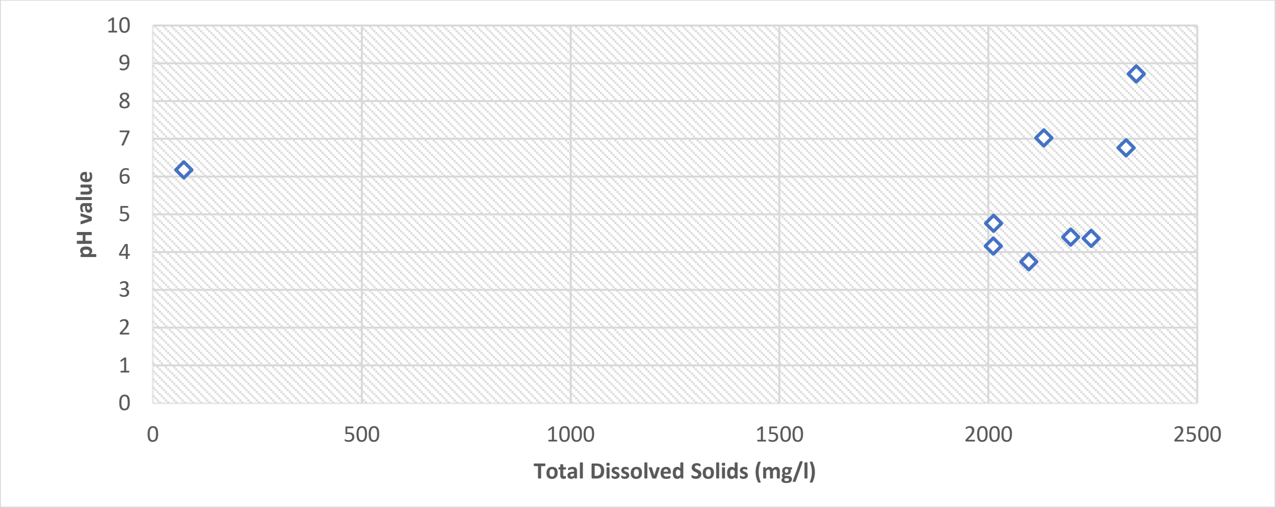


Figure 12: Scatter plot illustrating a TDS versus pH correlation.

5.4 Chemical analysis of analysed inorganic constituents

The results analysed from the WaterLab of the chemical constituents of metals, non-metals, and metalloid elements (above the detection limits) detected from the sampled wetlands in KGR have been presented in Table 10.

Table 10: Analysed inorganic constituents that were above the detection limits.

Sample ID	SampleNumber	Latitude	Longitude	Chlorideas Cl	Sulphateas SO_4	Fluoride as F	Sodium as Na	Potassiumas K	Calcium as Ca	Magnesium as Mg
W3	157899	-26.074167	27.698333	54	1923	0.2	142	13.2	540	97
W4m	157900	-26.092778	27.720556	62	2191	0.2	160	15	596	110
W4s	157901	-26.0925	27.721111	63	2162	0.2	160	14.3	608	113
W5sp	157902	-26.085	27.722778	22	2	0.2	11	0.5	4	4
W6	157903	-26.099143	27.721134	65	2246	0.2	161	15.3	634	104
W7	157904	-26.099111	27.721134	53	2123	0.3	129	10.3	566	130
W8	157905	-26.1075	27.755556	72	2363	0.3	163	15.9	739	81
W1	157906	-26.085278	27.708889	57	2131	0.2	144	13.6	552	99
W2	157907	-26.076111	27.699444	56	1985	0.3	134	12.2	534	95

The above – mentioned water quality legislations have been used as standards to compare the water quality of the inorganic constituents from the eight (8) sampled wetlands with respect to the water quality legislations. An exceedance table illustrating how the analsyed variables (Cl, SO_4, F, Na, K, Ca, and Mg) compare with the water quality legislation is presented in Table 11.

Table 11: An exceedance table of the analysed inorganic constituents.

Analysed metals,non-metals, and metalloid elements	**UNITS**	**General Authorisation Limit, Section 21f and h, 2013**	**Unfit for any TWQGR**	**RPM Mine health and safety act**	**RPM WUL Wastewater**	**W1**	**W2**	**W3**	**W4m**
Chloride as Cl	mg/l		>3000	600	7	57	56	54	62
Sulphate as SO_4	mg/l		>1000	600	10	2131	1985	1923	2191
Fluoride as F	mg/l	1	>3.5	1.5	0.2	0.2	0.3	<0.2	<0.2
Sodium as Na	mg/l		>2000	400	21	144	134	142	160
Potassium as K	mg/l		>500		6	13.6	12.2	13.2	15
Calcium as Ca	mg/l		>100		21	552	534	540	596
Magnesium as Mg	mg/l		>500	100	13	99	95	97	110

*Values written in red exceeded at least one of the water quality legislations.

Table 11: An exceedance table of the analysed inorganic constituents (continued).

Analysed metals, non-metals, and metalloid elements	**UNITS**	**General Authorisation Limit, Section 21f and h, 2013**	**Unfit for any TWQGR**	**RPM Mine health and safety act**	**RPM WUL Wastewater**	**W4s**	**W5sp**	**W6**	**W7**	**W8**
Chloride as Cl	mg/l		>3000	600	7	63	22	65	53	72
Sulphate as SO_4	mg/l		>1000	600	10	2162	<2	2246	2123	2363
Fluoride as F	mg/l	1	>3.5	1.5	0.2	<0.2	0.2	0.2	0.3	0.3
Sodium as Na	mg/l		>2000	400	21	160	11	161	129	163
Potassium as K	mg/l		>500		6	14.3	<0.5	15.3	10.3	15.9
Calcium as Ca	mg/l		>100		21	608	4	634	566	739
Magnesium as Mg	mg/l		>500	100	13	113	4	104	130	81

*Values written in red exceeded at least one of the water quality legislations.

A statistical summary of the inorganic constituents analysed which details the minimum, maximum, mean, standard deviation, and variance of the sampled wetlands in the KGR is presented in Table 12.

Table 12: A statistical summary of the analysed inorganic constituents.

Variables in mg/l	Minimum	Maximum	Mean		Std. Deviation	Variance
	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic
Cl	22	72	56.00	4.702	14.107	199.000
SO_4	2	2363	1902.89	241.540	724.619	525072.861
F	.2	.3	.233	.0167	.0500	.002
Na	11	163	133.78	15.916	47.749	2279.944
K	.5	15.9	12.256	1.5767	4.7300	22.373
Ca	4	739	530.33	69.072	207.216	42938.500
Mg	4	130	92.56	11.960	35.879	1287.278

5.4.1 The analysis of chloride (Cl) concentrations obtained from the water samples

All the analyzed water samples from localities that were inside (W1 to W7) and outside (W8) of the KGR did not exceed the stipulated guidelines for Cl concentrations in water provided by the TWQGR, and the MHSA (>3000 mg/l, 600 mg/l respectively). However, exceedances are observed for all the localities when comparing theirobtained value for the concentration of Cl in the water to the stipulated value providedby the WUL wastewater (7 mg/l).

The locality that was outside of the KGR (W8) had the highest value of recorded Cl inits water when compared to the W5sp which is the locality that has been set as the control due to it having little disturbances. W8 had 72 mg/l of Cl dissolved in the water sample while W5sp had almost 3 times less amount of Cl dissolved in its water sample (Table 10).

5.4.2 The analysis of sulphate (SO_4) concentrations obtained from the water samples

All the analyzed water samples (except for W5sp) from localities that were inside and outside of the KGR showed exceedances in the amount of sulphate concentration forthe stipulated guidelines provided by the TWQGR, MHSA, and WUL wastewater (>1000 mg/l, 600 mg/l, and 10mg/l respectively).

The sampled locality at W5sp had the lowest amount of SO_4 (<2 mg/l) in the sampled water whilst locality W8 had the highest amount of SO_4 (2363 mg/l) in its water sample. The dissolved sulphate concentrations at all the localities (except W5sp) with exceedances were found to be extremely high (> 1000 mg/l).

5.4.3. The analysis of fluoride (F) concentrations obtained from the water samples

The sampled localities: W3, W4m, and W4s water complied with all the guidelines stipulated in Table 11. However, localities W1, W2, W5sp, W6, W7, and W8 exceededthe set limit (0.2 mg/l) provided by the WUL wastewater guideline even though the amount of fluoride in the sampled water points did not exceed the threshold limit stipulated by the General authorization limit (1mg/l), TWQGR (>3.5 mg/ l) and MHSA(1.5 mg/l).

5.4.4 The analysis of sodium (Na) concentrations obtained from the water samples

All of the analysed water samples (except for W5sp) from localities that were inside and outside of the KGR showed exceedances in the amount of sodium concentration in the sampled water for the stipulated guideline provided by the WUL wastewater (21 mg/l). Na Exceedances were not observed for all the localities when comparing the amount of Na concentration in the sampled water localities with the stipulated threshold values for Na concentration in water for TWQGR (> 2000 mg/l), and MHSA (400 mg/l).

The wetland that was sampled upstream (W8) had the highest (163 mg/l) recorded Na concentration value in the sampled water. While the spring locality (W5sp) had the lowest (11mg/l) recorded concentration of Na in its sampled water.

5.4.5 The analysis of potassium (K) concentrations obtained from the water samples

None of the sampled wetlands exceeded the K limit stipulated by TWQGR (> 500 mg/l), however, all the water samples (except for W5sp) that were collected from the wetlands inside and outside of the KGR exceeded the K limit stipulated by WUL wastewater (6 mg/l). W8, W6, and W4 had the highest amount of K concentration in their water samples (15.9 mg/l, 15.3 mg/l, and 15 mg/l respectively). Locality W7 had the lowest (10.3 mg/l) recorded K concentration in its water sample.

5.4.6 The analysis of calcium (Ca) concentrations obtained from the water samples

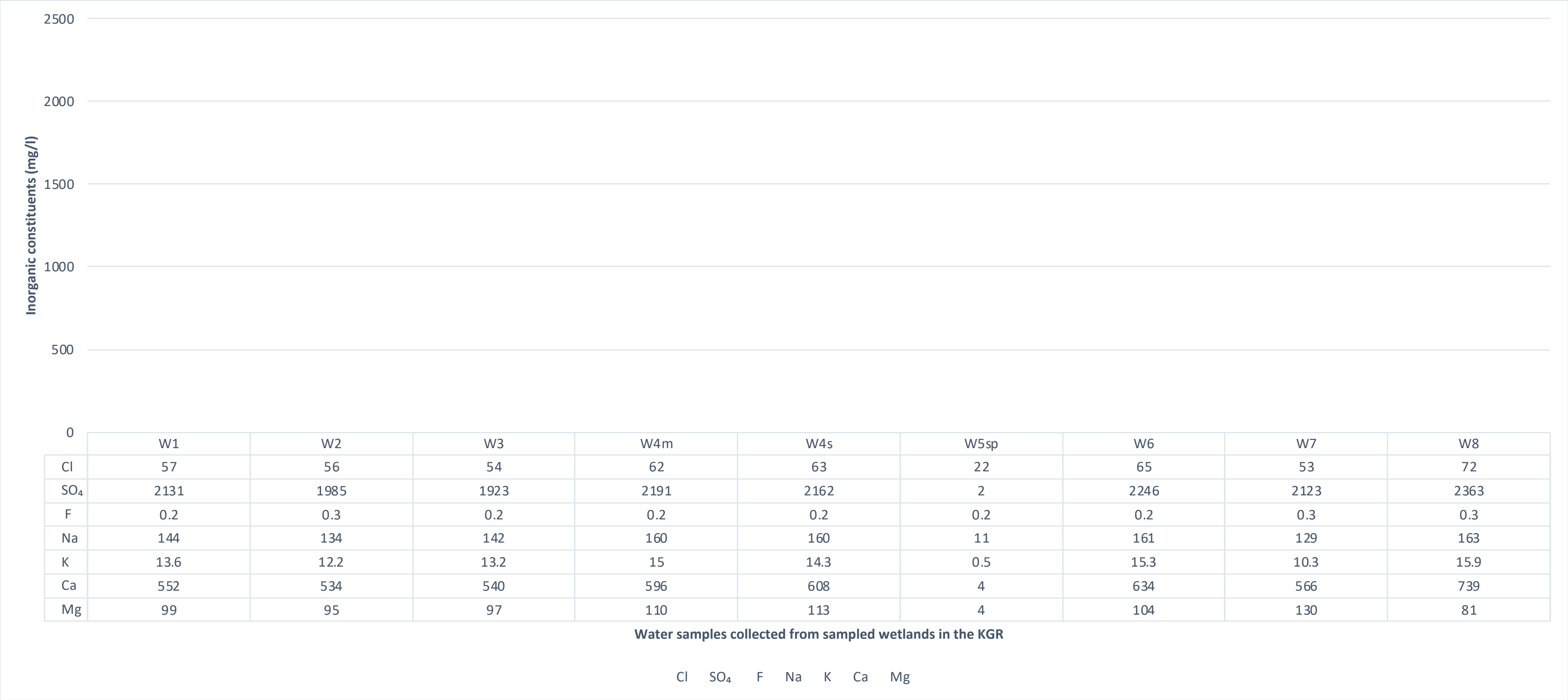
All of the analyzed water samples (except for W5sp) from localities that were inside and outside of the KGR showed exceedances in the amount of Ca concentrations in their sampled water for the stipulated guideline provided by the TWQGR (>100) and WUL wastewater (21 mg/l). W8 had the highest (739 mg/l) recorded concentration of Ca that was found in its water sample. W5sp had the lowest (4 mg/l) recorded concentration of Ca that was found in its water sample. The dissolved Ca concentrations at all the localities with exceedances were found to be extremely high(> 500 mg/l).

5.4.7 The analysis of magnesium (Mg) concentrations obtained from the watersample

All of the analyzed water samples (except for W5sp) from wetland localities that were inside and outside of the KGR showed exceedances in the amount of Mg.

None of the sampled water points exceeded the Mg limit stipulated by the TWQGR (>500 mg/l). The MHSA stipulated value for acceptable levels of Mg is 100 mg/l. W4m, W4s, W6, and W7 all exceeded the limit of Mg stipulated by the MHSA. The wetland that was sampled at locality W7 had the highest (130 mg/l) amount of Mg concentrations in its water sample when compared to the W5sp locality which had thelowest (4mg/l) amount of Mg dissolved in its water sample.

A graphical representation of the analysed inorganic constituents found in the water samples of the sampled wetlands is presented in Figure 13.



	W1	W2	W3	W4m	W4s	W5sp	W6	W7	W8
Cl	57	56	54	62	63	22	65	53	72
SO_4	2131	1985	1923	2191	2162	2	2246	2123	2363
F	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Na	144	134	142	160	160	11	161	129	163
K	13.6	12.2	13.2	15	14.3	0.5	15.3	10.3	15.9
Ca	552	534	540	596	608	4	634	566	739
Mg	99	95	97	110	113	4	104	130	81

Figure 13: Distribution of dissolved elements found in water samples that were collected inside and outside of the KGR.

5.5 Chemical analysis of analysed metal constituents

The analysed results from the WaterLab of the chemical constituents of metals and heavy metal constituents detected from the sampled wetlands in KGR have been presented in Table 13.

Table 13: Analysed metal constituents that were detected.

Sample ID	Sample Number	Latitude	Longitude	Phosphorus as P	Aluminum as Al	Cobalt as Co	Iron as Fe	Manganese as Mn	Nickel as Ni	Silicon as Si	Zinc as Zn
W3	157899	-26.074167	27.698333	0.026	0.257	0.079	0.088	1.6	0.022	9.7	0.001
W4m	157900	-26.092778	27.720556	0.026	0.208	0.09	0.025	1.42	0.02	6.8	0.001
W4s	157901	-26.0925	27.721111	0.011	0.245	0.095	0.154	4.14	0.024	5.3	0.007
W5sp	157902	-26.085	27.722778	0.008	0.1	0.001	0.025	0.025	0.003	5.8	0.001
W6	157903	-26.099143	27.721134	0.026	0.141	0.094	0.025	0.793	0.016	3.3	0.001
W7	157904	-26.099111	27.721134	0.016	0.115	0.097	0.025	20	0.487	7.4	0.148
W8	157905	-26.1075	27.755556	0.001	0.124	0.082	0.025	0.409	0.012	2.5	0.001
W1	157906	-26.085278	27.708889	0.029	0.174	0.087	0.092	1.62	0.025	3.2	0.014
W2	157907	-26.076111	27.699444	0.001	0.172	0.078	0.078	1.56	0.024	3.3	0.001

The majority of the recorded concentrations of heavy metals and trace metals from the water samples of the sampled wetlands were low or below the detection limit as illustrated in Table 14, hence no exceedances were observed when compared to the stipulated guidelines. Additionally, no exceedances were observed where no threshold limits is provided from the stipulated water quality guidelines.

Manganese (Mn) concentrations for all (except for W5sp and W6) of the wetlands that were sampled exceeded the set threshold value for the allowed Mn concentration in water stipulated by the General authorization limit (0.1 mg/l) and MHSA (1 mg/l). The wetland that was sampled upstream (W7) recorded the highest Mn concentration which also exceeded the stipulated Mn limit (>10 mg/l) set out by TWQGR. The recorded value Mn value for this locality was 20 mg/l. There were no exceedances observed for all the other analyzed variables (Table 14).

Table 14: Analyzed chemical variables, and threshold values, and obtained results for each water sample.

Physio-chemical Variable	UNITS	General Authorisation Limit, Section 21f and h, 2013	Unfit for any TWQGR	RPM Mine health and safety act	RPMWUL Wastewater	W1	W2	W3	W4m
Phosphorus as P	mg/l					0.029	<0.001	0.026	0.026
Aluminum as Al	mg/l		>5			0.174	0.172	0.257	0.208
Cobalt as Co	mg/l					0.087	0.078	0.079	0.09
Iron as Fe	mg/l	0.3	>10	1		0.092	0.078	0.088	<0.025
Manganese as Mn	mg/l	0.1	>10	1		1.62	1.56	1.6	1.42
Nickel as Ni	mg/l					0.025	0.024	0.022	0.02
Silicon as Si	mg/l					3.2	3.3	9.7	6.8
Zinc as Zn	mg/l		>5			0.014	<0.001	<0.001	<0.001

*Values written in red exceeded at least one of the water quality legislations.

Table 14: Analyzed chemical variables, and threshold values, and obtained results for each water sample (continued).

Physio-chemical Variable	UNITS	General Authorisation Limit, Section 21f and h, 2013	Unfit for any TWQGR	RPM Mine health and safety act	RPM WUL Wastewater	W4s	W5sp	W6	W7	W8
Phosphorus as P	mg/l					0.011	0.008	0.026	0.016	<0.001
Aluminum as Al	mg/l		>5			0.245	<0.100	0.141	0.115	0.124
Cobalt as Co	mg/l					0.095	<0.001	0.094	0.097	0.082
Iron as Fe	mg/l	0.3	>10	1		0.154	<0.025	<0.025	<0.025	<0.025
Manganese as	mg/l	0.1	>10	1		4.14	<0.025	0.793	20	0.409
Nickel as Ni	mg/l					0.024	0.003	0.016	0.487	0.012
Silicon as Si	mg/l					5.3	5.8	3.3	7.4	2.5
Zinc as Zn	mg/l		>5			0.007	<0.001	<0.001	0.148	<0.001

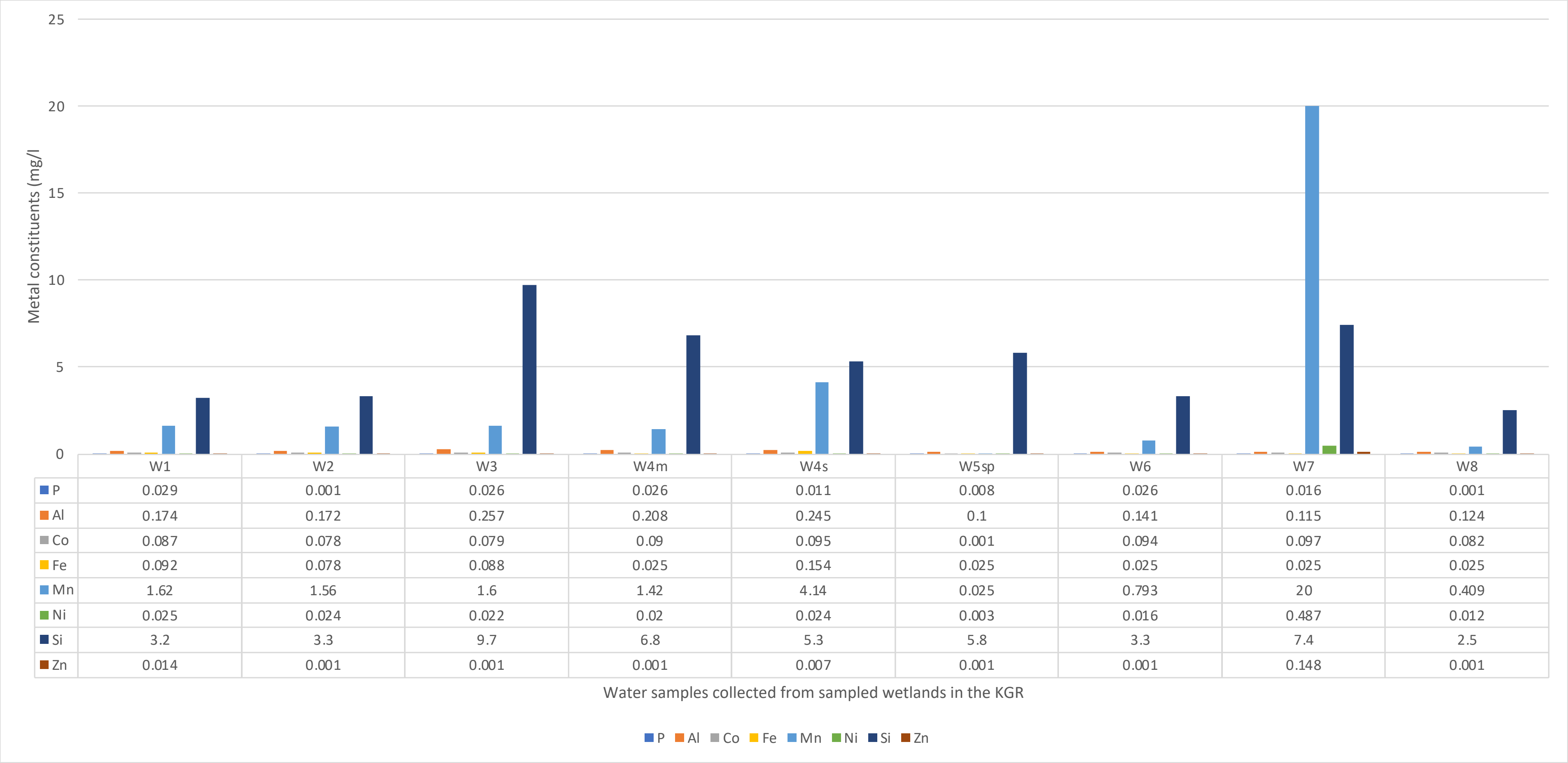
*Values written in red exceeded at least one of the water quality legislations.

A statistical summary of the inorganic constituents analysed which details the minimum, maximum, mean, standard deviation, and variance of the sampled wetlands in the KGR is presented in Table 15.

Table 15: A statistical summary of the analysed metal constituents that were detected.

Variables in mg/l	Minimum	Maximum	Mean		Std. Deviation	Variance
	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic
P	.001	.029	.01600	.003742	.011225	.000
Al	.100	.257	.17067	.018833	.056498	.003
Co	.001	.097	.07811	.009914	.029742	.001
Fe	.025	.154	.05967	.015407	.046222	.002
Mn	.025	20.000	3.50744	2.097787	6.293362	39.606
Ni	.003	.487	.07033	.052137	.156412	.024
Si	2.5	9.7	5.256	.8037	2.4110	5.813
Zn	.001	.148	.01944	.016138	.048415	.002

The distribution of metal concentrations that are dissolved inside of the sampled water points from wetlands located inside and outside of the KGR is represented in Figure 14. Mn had the highest dissolved concentration values for all the sampled water points (except for W5SP which had very little Mn that was dissolved in its water sample). The value of Zn, Ni, and Fe dissolved in the sampled water points were distributed at very low concentrations for all the water samples.



	W1	W2	W3	W4m	W4s	W5sp	W6	W7	W8
P	0.029	0.001	0.026	0.026	0.011	0.008	0.026	0.016	0.001
Al	0.174	0.172	0.257	0.208	0.245	0.1	0.141	0.115	0.124
Co	0.087	0.078	0.079	0.09	0.095	0.001	0.094	0.097	0.082
Fe	0.092	0.078	0.088	0.025	0.154	0.025	0.025	0.025	0.025
Mn	1.62	1.56	1.6	1.42	4.14	0.025	0.793	20	0.409
Ni	0.025	0.024	0.022	0.02	0.024	0.003	0.016	0.487	0.012
Si	3.2	3.3	9.7	6.8	5.3	5.8	3.3	7.4	2.5
Zn	0.014	0.001	0.001	0.001	0.007	0.001	0.001	0.148	0.001

Figure 14: Distribution of dissolved metals found in water samples that were collected inside and outside of the KGR.

5.6 Pearson’s correlation matrices

Table 16 and Table 17 illustrates Pearson correlation matrices of physico – chemical parameters and inorganic constituents as well as Pearson correlation matrix of physico – chemical parameters and metal constituents, respectively. The obtained Pearson’s correlation matrices in Table 16 and Table 17 are synthesized into statistical summary tables for Pearson correlation matrices of physico – chemical parameters and inorganic constituents (Table 18) as well as Pearson correlation matrix of physico – chemical parameters and metal constituents (Table 19).

Table 16: Pearson correlation matrix of physico – chemical parameters and inorganic constituents.

Physical and chemical parameters inmg/l unless specified	**pH**	**EC inmS/m**	**TDS**	**Cl**	**SO_4**	**F**	**N**	**K**	**Ca**	**Mg**	**P**
pH	1										
EC in mS/m	0.014	1									
TDS	0.040	.999**	1								
Cl	0.152	.956**	.963**	1							
SO_4	0.020	.998**	.997**	**.956****	1						
F	0.453	0.238	0.244	0.230	0.263	1					
Na	-0.031	.988**	.988**	**.972****	**.983****	0.129	1				
K	-0.016	.963**	.963**	**.977****	**.958****	0.086	**.990****	1			
Ca	0.135	.985**	.989**	**.984****	**.986****	0.299	**.978****	**.966****	1		
Mg	-0.149	.906**	.900**	**.756***	**.900****	0.197	**.858****	**.783***	.835**	1	
P	-0.345	0.245	0.228	0.111	0.234	**-.668***	0.270	0.270	0.146	0.360	1

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

In terms of the sampled wetlands in and outside the KGR, inorganic constituents dissolved in the water column are weakly dependenton the pH values when considering the obtained average Pearson's correlation value for pH (Table 17). In contrast, the average Pearson correlation values obtained when correlating the EC and TDS physico – chemical variables to the inorganic constituents analysed from the sampled wetlands; show that these physico chemical parameters affect the dissolution of inorganic constituents into the sampled wetland's water channels. In terms of the sampled wetlands in and outside the KGR, metal constituents dissolved in the water column are weakly dependent on the pH values when considering the obtained average Pearson's correlation value for pH (Table 18). Similarly, the average Pearson correlation values obtained when correlating the EC and TDS physico – chemical variables to the metal constituents analysed from the sampled wetlands; show that these physico chemical parameters minimally affect the dissolution of inorganic constituents into the sampled wetland's water channels.

Table 17: Pearson correlation matrix of physico – chemical parameters and metal constituents.

Physical and chemical parameters	pH	EC inmS/m	TDS	Al	As	Co	Fe	Mn	Ni	Si	Zn
pH	1										
EC in mS/m	0.014	1									
TDS	0.040	.999**	1								
Al	-.720*	0.404	0.393	1							
As	.796*	0.384	0.407	-0.503	1						
Co	-0.057	.976**	.974**	0.413	0.356	1					
Fe	-0.666	0.213	0.205	.733*	-0.650	0.257	1				
Mn	0.188	0.179	0.184	-0.229	0.504	0.329	-0.115	1			
Ni	0.266	0.135	0.139	-0.337	0.565	0.273	-0.251	.988**	1		
Si	-0.310	-0.157	-0.162	0.426	-0.098	-0.067	0.050	0.357	0.336	1	
Zn	0.255	0.117	0.121	-0.352	0.547	0.260	-0.230	.986**	.997**	0.309	1

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 18: Statistical summary of the obtained Pearson correlation values from the analysed inorganic constituents.

pH			
Statistical Variables	Pearson's correlation	Inorganic constituent	Correlation between pH variable and analysed inorganic constituent
Minimum	-0.148	Mg	Weak negative correlation
Maximum	0.453	F	Moderate positive correlation
Average	0.08		Weak positive correlation
EC			
Statistical Variables	Pearson's correlation	Inorganic constituent	Correlation between EC variable and analysed inorganic constituent
Minimum	0.098	Na	Weak positive correlation
Maximum	0.998	SO_4	Strong positive correlation
Average	0.734		Strong positive correlation
TDS			
Statistical Variables	Pearson's correlation	Inorganic constituent	Correlation between TDS variable and analysed inorganic constituent
Minimum	0.243	F	Weak positive correlation
Maximum	0.997	SO_4	Strong positive correlation
Average	0.863		Strong positive correlation

Table 19: Statistical summary of the obtained Pearson correlation values from the analysed metal constituents.

pH			
Statistical Variables	Pearson's correlation	Metal constituent	Correlation between pH variable and analysed metal constituent
Minimum	-0.72	Al	Strong negative correlation
Maximum	0.796	As	Strong positive correlation
Average	-0.065		Weak negative correlation
EC			
Statistical Variables	Pearson's correlation	Inorganic constituent	Correlation between EC variable and analysed metal constituent
Minimum	-0.156	Si	Weak negative correlation
Maximum	0.976	Co	Strong positive correlation
Average	0.277		Weak positive correlation
TDS			
Statistical Variables	Pearson's correlation	Inorganic constituent	Correlation between TDS variable and analysed metal constituent
Minimum	-0.161	Si	Weak negative correlation
Maximum	0.974	Co	Strong positive correlation
Average	0.276		Weak positive correlation

CHAPTER 6 DISCUSSION

6.1 Introduction

An analysis of the physico – chemical and chemical parameters from the sampled wetlands in the KGR was conducted by following the set objectives:

1. Comparing the water quality parameters of the sampled wetlands to legislations and standards that stipulate the acceptable water quality limits for surface water bodies in the receiving environment.

2. Identifying wetland sites with the lowest and highest concentrations of major – and minor ions as well as trace and heavy metals.

3. Assessing the changes in physico - chemical and chemical parameters from wetlands that are upstream (closest to the mining site) to the wetlands that are downstream (furthest from the mining site).

6.2 The recorded physico - chemical variables that exceeded one (or more) ofthe stipulated legislation and / or guidelines provided

pH can be defined as the measure of the acidity of a solution, likewise, it is a measure of the amount of hydrogen (H^+) ion concentrations that are in a solution (EnvironmentalProtection Agency, 2022). pH is an important physico - chemical variable that determines the neutrality, alkalinity, or acidity of a water body (Rahmanian *et al*., 2015; Environmental Protection Agency, 2022). The acceptable limits that can be used to define whether water can be classified as neutral, acidic, or alkaline vary because different water bodies have different uses. For example, a more sensitive pH range needs to be observed when measuring the suitable pH for drinking water versus when measuring the suitable pH for industrial use, this is because a pH that is too low (acidic) or too high (alkaline) may have detrimental impacts on animals or people that consume that water. Likewise, using water bodies that do not have a suitable pH for industrial use (machinery operation) may result in the corrosion of machinery and equipment.

Factors that affect the pH of water occurring in a natural environment include effluents that are discharged into the water body, temperature, decay processes, and AMD (Mayes *et al*., 2009; Patil *et al*., 2012). pH only has direct adverse health impacts under extreme conditions – extremely acidic or extremely alkaline environments - Water that has a low pH should not be discharged directly into the environment.

The sampled water points from the upstream localities (W6-W8) illustrated an increase in the recorded pH values - from neutral (6.0 to 8.5) to alkaline (>8.5) values. Locality W5sp (control) had a neutral pH whilst the highest pH (8.9) was recorded at locality W8 (outside of the KGR) which was closest to the Mogale Gold mine. All of the sampled localities from wetlands that were inside of the KGR (W1-W4m) had a pH value that was below (pH<6) the stipulated pH range from the provided guidelines and legislations (Table 7). These localities have been identified as the 'downstream localities' because they are furthest away from the mine that is adjacent to the KGR. The lowest pH value (3.9) was recorded at W1 which was the sampling point that was downstream in the KGR furthest away from the mine.

In an ideal environment where there are little to no human perturbations and no significant geological influences in terms of geochemical influences on surface or groundwater, one would expect the pH level from the wetlands that were sampled downstream to have neutral to alkaline pH values (because the waterbodies are furthest away from the pollutant source). On the other hand, the wetlands sampled upstream to have acidic pH values (<6) because of their proximity to the pollutant sources. The obtained pH results from this study revealed an opposite outcome to that of an ideal environment: the recorded pH values decreased downstream.

There are three postulations that can be made regarding the observed trend in decreasing pH values – from the water points that were sampled upstream to the water points that were sampled downstream:

Firstly, the deterioration in the pH condition can be attributed to the low buffering capacity of the wetlands that were inside of the KGR more especially in wetlands that are downstream. The assumption that wetlands that are upstream of the KGR are effectively attenuating pollution from the mine source implies that the abiotic and biotic components of the wetlands system are ecologically suitable for interacting within a dynamic environment that is often exposed to heavy metal exposure. Besides, wetlands and their constituent substrates have the ability to mobilize and remove metals that inflow within the system from mine effluents through several processes, these include adsorption, oxidation and reduction by microorganisms and flora species, sedimentation, and bioremediation (Sheoran and Sheoran, 2006; Gandy *et al*., 2016).

Secondly, the wetlands that are upstream, locality W8 in particular, may be recipients of water treated with lime (Calcium Carbonate - $CaCO_3$) which in turn increases the alkalinity of the water from being acidic to being neutral or alkaline. The water at W8 had a turbid and milky characteristic before the day of sampling with fast - flowing water. However, the water was clear with slow - moving water on the day of sampling. According to Mayes *et al* (2009) mining centers in South Africa are equipped with constructed wetlands as part of the mining's implementation of environmental practices - these wetland systems are used for mine treatment of effluents. With that said, wetland W8 which is closest to the mining site and the abandoned plethora of mining tailings can be identified as a regulated system that is used to treat the mine effluent from adjacent mines hence the vast differences in its water characteristics, temporally.

The regulation of a wetland's pH (especially in a mining environment) that has acidic conditions can be achieved through the implementation of the process called neutralization (Heviankova *et al*., 2013; Yilmaz *et al*., 2019), this process involves the dissolution of an alkaline reagent for example hydrated lime ($Ca (OH)_2$) inside of a water body. $Ca (OH)_2$ reacts with the dissolved Carbon Dioxide (CO_2) in the water body (O_2) and precipitates it out to a calcium carbonate ($CaCO_3$) product which then is responsible to act as a buffer in the wetland system (Heviankova *et al*., 2013). Thereare various types of neutralization treatments that can be implemented for these including: Anoxic limestone drains, limestone diversion wells, and open limestone channels; all these types of neutralization treatments have been used as neutralizationagents in the AMD area, especially in mining environments in the Eastern United

States of America (Kumari *et al*., 2010). The findings from a study based on the evaluation of ground-, surface water and soil that was conducted by Sako *et al* (2018) revealed that an alkaline pH was recorded at the locality (RW8) which was closest to the Abuasi gold mine (upstream) in West Africa when chemical additives such as Sodium Cyanide - NaCN - and Calcium Oxide - CaO are added to acidic water. Water samples from the wetlands that were sampled upstream of the KGR (compared to the downstream wetlands) had a high concentration of Mg, Mn, which may be attributed to the higher (>6) pH values recorded in the water samples while the downstream localities had Fe and Zn concentrations which may be attributed to the lower (<6) pH values when compared to the upstream localities.

Lastly, there may be seepage of groundwater that is contaminated with heavy metal pollution that flows into the majority of the wetlands (except for W5sp) which affects the water quality of the wetlands in terms of heavy metal load.

The findings from Lusilao - Makiese *et al* (2013) based on the author's study about 'the impact of post gold mining on mercury pollution in the West Rand region, Gauteng, South Africa' reveal contrasting results in pH levels when compared to the findings from this study. The pH level that was recorded by the authors within the mining areawas low and ranged from 2.9 to 5.0 whilst their sampled water points that were approximately 10 km inside of the KGR had higher pH levels that had values ranging between 6.9 to 7.8 (Lusilao-Makiese *et al*., 2013 see also Figure 15). Additionally, the heavy metal load and sulphate concentrations in the sampled water points closest to the mine were extremely high - the authors attributed the high rates of heavy metals and sulphate constituents as a result of seepage of groundwater (with acidic pH) into surface water- contrary to the sampled water points that were downstream which had considerably reduced sulphate and heavy metal contents - some metals were even below detection limit - (Lusilao-Makiese *et al*., 2013). The authors suggest that the pH increase can be attribute due to dilution of water bodies inside of the KGR from adjacent tributaries that drain into the reserve or the liming of water bodies that are situated in the boundary area between the KGR and the mine (Lusilao-Makiese *et al*.,2013).

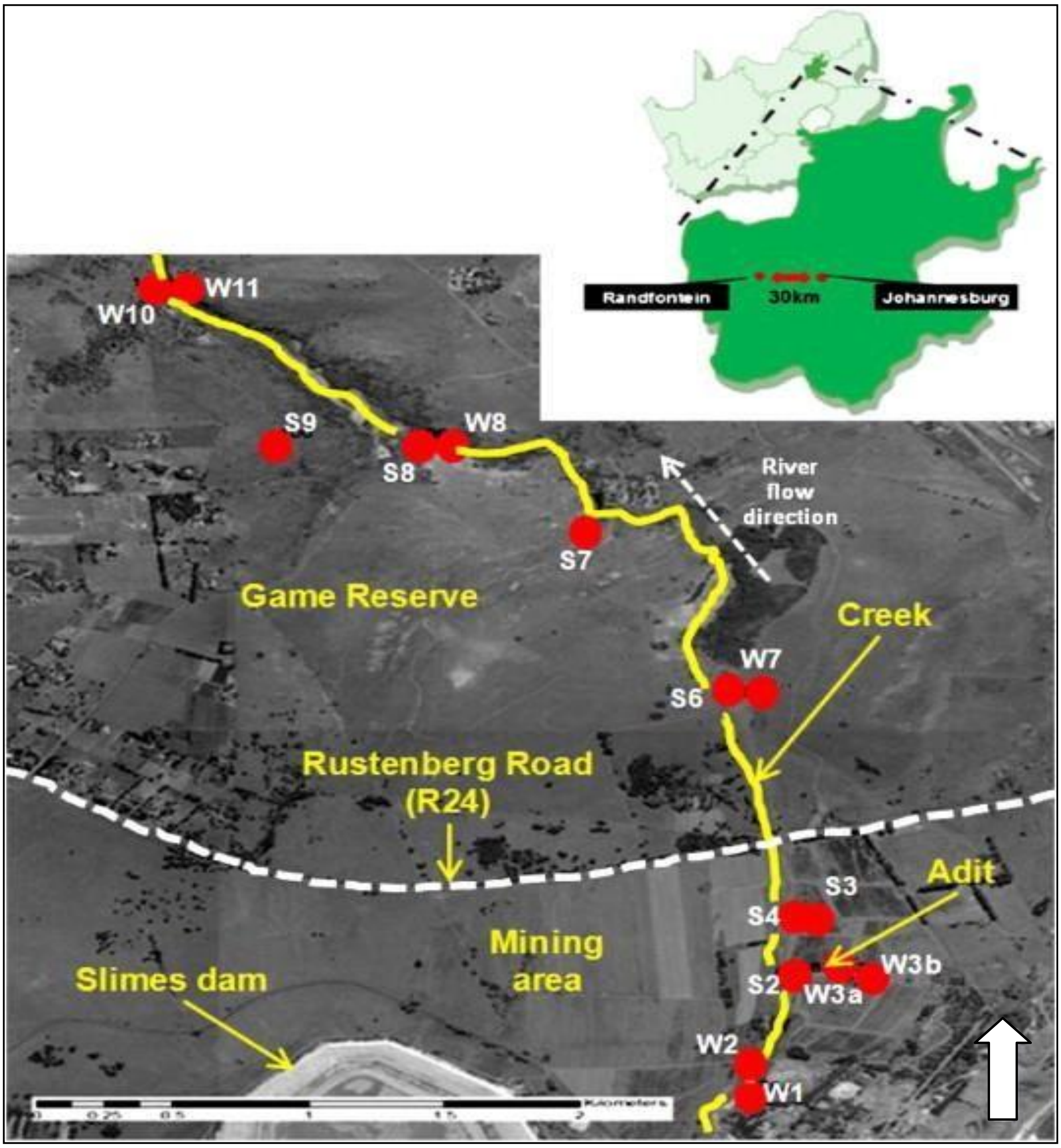


Figure 15 A map illustrating a mining area in the West Rand region in Gauteng,South Africa where the impacts of mercury have been assessed post gold mining. The locality W1 was sampled upstream to the mining area whilst locality W11 was sampled downstream inside of the KGR (Figure by: Lusilao-Makiese *et al*., 2013).

The Electrical conductivity and TDS that have been recorded of various sites along the stream have shown to have values exceeding one or more of the assessment sets. Additionally, saline to extremely saline conditions have been recorded in wetlands that have been sampled inside and outside of the KGR. It is imperative to note that although the pH levels of the sampled wetlands from upstream (W6 – W8) had neutralto alkaline pH conditions, all of the recorded major contributing salt concentrations had EC, TDS, and salinity values that exceeded the permissible salt concentration limits. Additionally, the wetland that was sampled from outside of the KGR (W8) which was close to the mine source had the highest pH value (8.9), however, recorded the highest TDS value (3744 mg/l) and the highest values in salt concentrations (except for Mg) compared to the other sampled wetlands. The recorded high TDS value (compared tothe other sampled wetlands) from the W8 water point indicates that there is a heavy load of TDS from the adjacent mine that is entering into the stream where W8 is a direct recipient of the salts and metal concentrations. This observation further illustrates that there is either alkaline inlet water that flows within the wetland system at W8 or there is a form of dozing (of alkaline chemical additives) into the wetland system that increases the system's pH and its buffer capacity in the wetland that is upstream (W8), however, when the inlet water from W8 comes into contact with the water inside of the KGR (especially the downstream wetland localities) there is soon recontamination of the inlet water by the wetland systems that have high amounts of free protons and fewer hydroxide ions.

The pH of the downstream localities was low; however, the recorded values did not exceed 3.5, therefore, the ferric iron that is found within those wetland systems has been precipitating as ferric iron hydroxide (Tutu *et al*., 2008) hence the wetland substrates both inside of the water channel along the wetland's boundary and outside of the wetland has a bright yellow to orange color (Abiye *et al*., 2018).

6.2.1 Total Dissolved Solids (TDS) and Electrical Conductivity (EC)

TDS has been used as an indicator that measures the amounts of organic or inorganic constituents that are in solution in a medium for example a water body, whilst EC is ameasure of the ability of a medium such as water body to conduct an electric current (Rusydi, 2018). TDS is directly proportional to the EC, that is, an elevated TDS value results in an elevated EC value (Rusydi, 2018). In a naturally occurring hydrological system with little to no human perturbations, the TDS that is in solution in water is a result of other environmental components including the geology of where the water flows in or is in contact (Kumari *et al*., 2010). In addition, TDS concentrations in such environments can be affected by the atmospheric processes that govern the geographic location, for instance, an area that is hot and receives little rainfall can have naturally occurring water bodies that have high TDS values due to the elevated rate of evaporation that occurs within the area with little precipitation (Luo *et al*., 2013).

The W5sp locality is an example of a system with little to no human perturbation nor extreme environmental factors such as a high evaporation rate affecting the TDS, hence its EC and TDS values are significantly lower compared to the other sampled wetlands which have extremely elevated TDS and EC values. The wetland at W5sp is located in an area where there is a diverse ecology of vegetation species inside and around the wetland's channel. The state of the ecological components at W5sp provides an indication that this is a functional wetland with abiotic and biotic factors that support the system's functions such as filtration of water hence the recorded lowerTDS and EC values at this locality when compared to the other sampled wetlands.

Most of the sampled wetlands had exceeding salt concentrations, with the major contributing metal concentrations in the sampled wetlands from inside and outside ofthe KGR including sulphates (SO_4), calcium (Ca), sodium (Na), magnesium (Mg), chloride (Cl) and potassium (K). Additionally, Fluoride (F) concentrations were observed in most of the sampled wetlands, however, at low concentrations.

6.3 pH, EC, and TDS spatial assessments of the upstream and downstream localities

To identify whether the wetlands inside and outside of the KGR are effective in attenuating pollution from adjacent mines, a comparison of the exceeding physico - chemical variables (TDS, EC, and pH) from wetlands that are located upstream to wetlands that are located downstream is made. The spring (W5sp) has been used as the baseline to illustrate the differences between the exceeding physico - chemical variables from the downstream and upstream wetlands. The spatial changes in the amount of exceeding physico - chemical variables have been illustrated in Table 20 for the upstream (inland wetlands: W6 to W8), whilst the spatial changes in the amountof exceeding physico - chemical variables for the downstream localities (wetlands: W1to W4m) have been illustrated in Table 21. Table 22 represents a direct comparison between the upstream and downstream average pH, EC and TDS results.

Values highlighted in blue do not necessarily mean that the variable has deteriorated in water quality, however, a decrease in the amount of that variable has been observed, spatially. Likewise, values that have been highlighted in yellow does not imply that the water quality has improved, however, an increase in the amount of that variable has been observed spatially.

Table 20: Spatial analysis of the variation of the exceeding physico – chemical variables from the upstream wetlands.

Description	Average pH Difference	Average EC (ms/m) difference	Average TDS (mg/l) difference
Inlet: wetland points that were sampled upstream	7.31	229.2933	1520.533
W5sp	6.18	10.28	74.6
Difference	1.13	219.0133	1445.933
Percentage change (%)	15.46	95.52	95.09

Table 21: Spatial analysis of the variation of the exceeding physico – chemical variables from the downstream wetlands.

Description	**Average pH Difference**	**Average EC (ms/m) difference**	**Average TDS (mg/l) difference**
Outlet: wetland points thatwere sampled downstream	4.288	793.44	2113
W5sp	6.18	10.28	74.6
Difference	-1.892	783.16	2038.4
Percentage change (%)	44.12	98.7	96.47

The differences obtained in the averages between the pH, EC, and TDS values of downstream and upstream localities from the W5sp's pH, EC, and TDS values all exceed at least one of the stipulated guidelines and legislations that have set thresholds for the physico - chemical variables as illustrated in Table 7. Furthermore, most of the exceeding physico - chemical variables illustrate an increase in their amounts when a difference is calculated between upstream or downstream physico - chemical variables from the W5sp; in this instance, the increasing values also indicated deteriorating water quality as the physico - chemical variables continue to exceed at least one of the stipulated guideline or legislation. Additionally, the presented data inTable 20 Table 21 illustrate that the obtained differences in the average pH, EC, and TDS values of the downstream localities are higher than the obtained differences in the average pH, EC, and TDS values of the upstream localities (Table 22). This illustrates that there are no improvements in water quality of sampled wetlands from the upstream localities which are closest to the AMD discharge point to the sampled wetlands from the downstream localities which have been sampled further from the AMD discharge point, instead, the exceeding physico - chemical parameters of the sampled downstream wetlands localities have a deteriorating water quality when compared to the exceeding physico - chemical parameters of the sampled upstream wetlands.

The aforementioned observation between the differences in the obtained physico - chemical variables of the downstream sampled wetland localities from the sampled upstream wetlands points indicates that there may be a pollutant source(s) that affects the downstream localities hence the water quality further deteriorates even when wetland points are downstream furthest from the upstream localities where there are polluting mining sources. The pollutant source(s) may be a result of polluted groundwater discharge into the KGR due to poor or no liming of tailing – taking into consideration the extent of the number of abandoned mine dumps and tailing facilities that are visible on site- using materials such as reinforced polyethylene (RPE), high - density polyethylene (HDPE), or low-density polyethylene (LDPE) (La Touche and Garrick *et al*., 2020; Tuomela *et al*., 2021). Evidence of the possibility that seepage ofgroundwater is occurring at the downstream localities would be the presence of pockets containing stagnant water, for example, locality W4s is a point along the W4 wetland that had stagnant water with a foul and rotten smell which is indicative of the presence of metal constituents such as SO_4 (Table 10). With that said, the inorganic- and metal constituents (including heavy metal) that are present in the sampled wetlands both inside and outside of the KGR will be discussed in the next section.

Table 22: Spatial analysis comparison of the exceeding physico – chemical variables from the downstream and upstream wetlands.

Description	Average pHDifference	Average EC (ms/m) difference	Average TDS (mg/l) difference
Upstreamdifference	1.13	219.0133	1445.933
Downstreamdifference	-1.892	783.16	2038.4

6.4 The recorded chemical variables that exceeded one (or more) of the stipulated legislation and/or guidelines provided

This section will be discussing the results of the exceeding chemical variables to determine whether the measured exceeding variables were increasing or decreasing from the upstream to the downstream water sampling points.

The majority (except for W5SP- spring) of the sampled wetlands both inside (W1-W7) and outside (W8) of the KGR noted SO_4, Na, K, F Ca, Mn, and Mg concentrations that exceeded at least one of the stipulated guidelines in Table 11. The distribution of SO_4,Na, K, Ca and Mg concentrations in the water samples that were found in the sampled wetlands both inside and outside the KGR is similarly distributed when considering the elementary constituents (of metal concentrations) of the individual wetlands (Figure 13), however, this is not the case for the elementary constituents that were noted for SO_4, Na, Ca, and Mg for the spring (W5sp); which had low Ca but high Cl and Na concentrations relative to the other water bodies that were sampled from the wetlands inside and outside of the KGR.

The highest Mn concentration was detected in the W4s (4.14 mg/l) water sample. This locality was a pocket of foul - smelling and stagnant water found in the downstream localities. Unlike the other water samples inside of the KGR, W4s water did not have evidence of inflowing surface water, however, there seemed to be seepage from groundwater that supplies the locality with the polluted water that is because the surrounding ground was dry and had little vegetation cover while this locality had muddy and wet soil with a population of grass. The metals attached to sediments such as Mn, Co, Ni, phosphorus, Cr, and Pb are derived from mineral weathering and the use of explosives, specifically phosphorus, in gold mines. These metals are present in trace amounts and could have precipitated into more stable forms, which is why they are in trace amounts in water. Some examples of minerals that could contribute to the weathering process and release of metals in the abandoned gold mining include pyrite, arsenopyrite, chalcopyrite, and sphalerite. These minerals often contain high concentrations of metals such as Mn, Co, Ni, and Pb, and when exposed to air and water during mining activities, they can react and release these metals into the environment.

The study conducted by Alexander *et al*. (2017) about assessment of spatial variation of groundwater quality in a mining basin provides context to the extent of impact that groundwater systems in mining basins (including the Krugersdorp) have been affected by decanting mining areas. The study compared nine (9) chemical parameters - including Sulphates (SO_4) and Nitrates (NO_3) – to determine the quality of groundwater (spatially) in a mining basin. The observations made by the authors from their geostatistical findings indicated that the quality of groundwater resources revealed the most impacted water quality was in mining areas that are in the Krugersdorp basin; additionally, SO_4 was one of the most dominating ions in the sampled water. The authors postulate that the observed pollution in Krugersdorp and some areas of Johannesburg emanates from the flow of groundwater through decanting mines.

The findings on the deterioration of groundwater quality resources in mining basins revealed in the study conducted by Alexander *et al*. (2017) can be used as a reference in understanding the obtained water quality results from this study being conducted based on the principles of groundwater and surface water interactions. The variable concentrations of the analysed chemical parameters (more especially the exceeding variables) indicate that there is very little spatial variation between the metals that arefound in the upstream water points to the metals that are found in the downstream water points (except for the W5sp locality). Instead, the concentration of metal constituents in the sampled water points does not improve from the upstream water points to the downstream water points. The similarity in the distribution of metal concentrations from wetlands that were sampled upstream to the wetlands that were sampled downstream indicates that there is still active groundwater seepage of polluted wastewater from surrounding mining areas into the downstream wetlands hence the wetlands sampled downstream of the KGR still have Acid Mine Drainage (AMD) characteristics and poor water quality.

Based on the findings of this study, one can deduce that there is metal contamination of the sampled wetlands. The W5sp locality is the only water point that had good water quality, all of the other sampled wetlands had poor water quality.

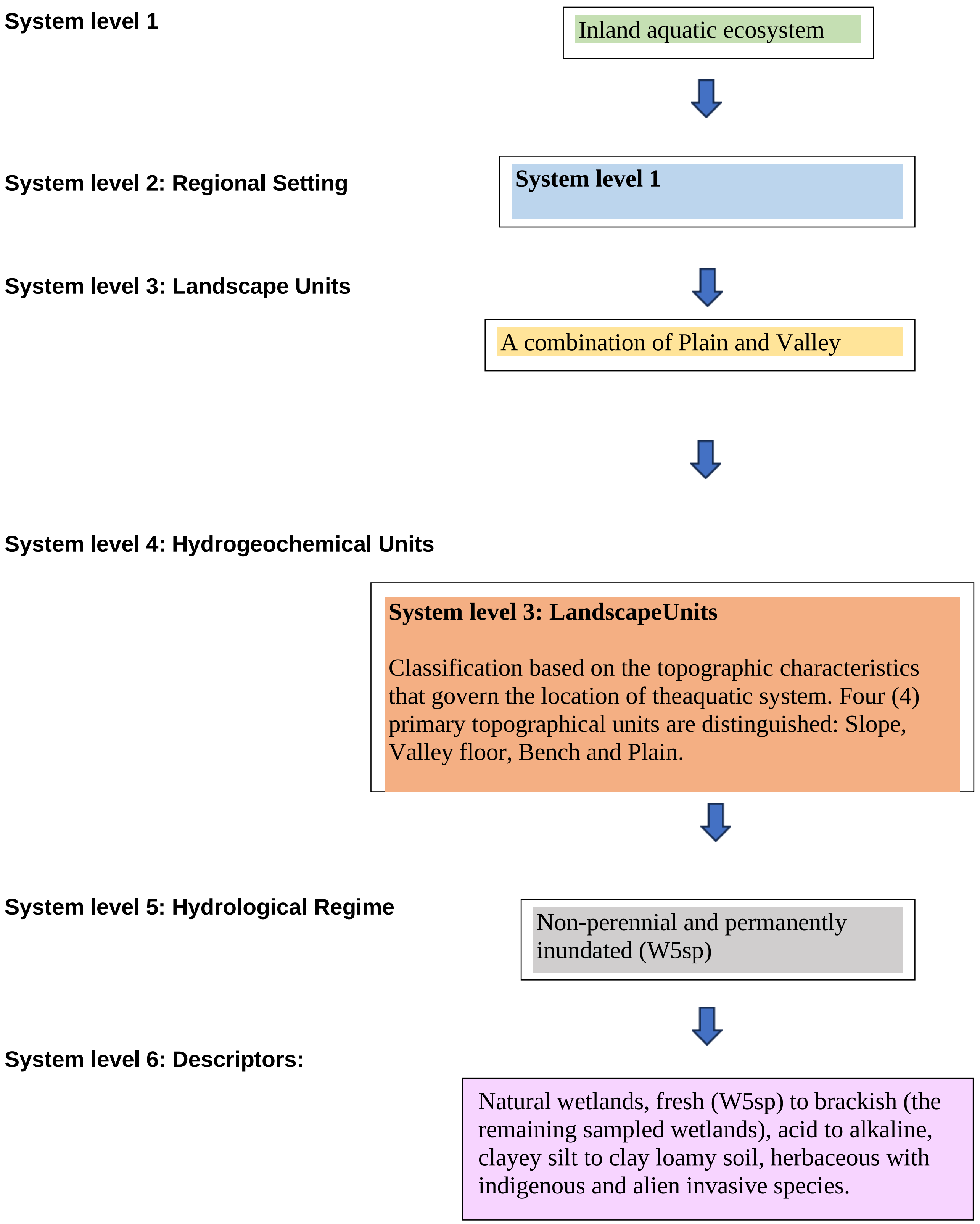
The metal dispersal that has been found in the wetlands that were sampled inside and outside of the KGR support the postulated outcomes from a study that was conductedby Fosso-Kankeu *et al*.

(2015). Firstly, the authors postulated the characteristics of the mineralogical structure the bottom layers of tailing dumps were dominated by sulphide containing minerals while the top layers of the tailing dumps were dominated by oxidecontaining minerals - of the tailing dumps in the Krugersdorp mines have a significant impact on the mobility of heavy metals within the tailing dump (Fosso-Kankeu *et al*., 2015). This is because the concentrations of heavy metals that was found in the labile and mobile phases (top layer of tailing dumps) was higher than the concentrations of heavy metals that were found in the immobile fraction (bottom layer of tailing dumps), therefore, the metals in the top layers of tailing dumps were more susceptible to mobilize versus the metal constituents that were in the bottom layers (Fosso-Kankeu *et al*., 2015). Secondly, the authors postulated that the heavy metals in the mobile phases have the potential to being leached out of the tailing dumps and to being seeped into the natural environment in large amounts which in turn will pollute and have significant impacts on both ground and surface water resources in environmentsthat are adjacent to mines in the Krugersdorp (Fosso-Kankeu *et al*., 2015).

The following section provides a discussion of the obtained metal and inorganic constituent results in relation to wetlands as pollution attenuation systems.

6.5 Assessing the role of Vegetation, Geology, Hydrogeology, Climate, and Wetland type in KGR in contributing to the effectiveness of the sampled wetlands in removing pollution mine pollution from adjacent mines.

A flow diagram was used to classify the sampled wetland types in the KGR based on their (Hydrogeomorphic) HGM classification. The flow level was constructed based onthe March 2023 sampling run which was towards the end of the summer months in Krugersdorp. It should be noted that due to the spatial variability of the KGR, there may be two or more classifications for a level.



System level 1

Inland aquatic ecosystem

System level 2: Regional Setting

System level 1

System level 3: Landscape Units

A combination of Plain and Valley

System level 4: Hydrogeochemical Units

System level 3: LandscapeUnits

Classification based on the topographic characteristics that govern the location of theaquatic system. Four (4) primary topographical units are distinguished: Slope, Valley floor, Bench and Plain.

System level 5: Hydrological Regime

Non-perennial and permanently inundated (W5sp)

System level 6: Descriptors:

Natural wetlands, fresh (W5sp) to brackish (the remaining sampled wetlands), acid to alkaline, clayey silt to clay loamy soil, herbaceous with indigenous and alien invasive species.

The sampled wetlands in the KGR are characterized by clayey silt to clayey loam soils which may be contributing factors to the metal concentration found in the sampled wetlands. Clay soils have a high surface tension due to their particle size being small therefore, metals do not easily mobilize between the soil particles (Dixon, 1991; Rieuwerts, 2007). Additionally, clay soils have a strong affinity to retain and adsorb metal ions (Rieuwerts, 2007). With that said, a wetland characterized by clay soils (provided that other contributing factors such as pH are in neutral and tolerable concentrations) may attenuate metal concentrations such as Ca, Mg, and K which then reduces the amount of metal distribution within the water channel. Such a wetland may be seen as one which is able to effectively attenuate pollution from adjacent pollutant sources such as a mine through the aid of its soil composition. Contrary to clay soils, silt soils do not have a high adsorption capacity (Chakraborty and Mistri, 2015) therefore, metal ions are able to mobilize through the soil and into the wetland'swater channel which then may result with an increase in the concentration of metal constituents within the water channel. The W5sp wetland locality was the only sampled wetland that had cation ions that complied with the stipulated water quality guidelines; the wetland sampled downstream of the KGR and upstream of the KGR all recorded two or more exceedances in terms of the analysed cation – including Ca, Mg, and K constituents (Table 11). Although the KGR is characterized by both soil types, the results gathered results from the metal constituents support that the prevailing soil type from the sampled wetlands (except for W5sp) may be silty soil or loam (combination of both soil types).

Vegetation in a wetland system plays a crucial role in the removal of toxicants both inthe water and soil channel of that system. This is achieved through process such as phytoremediation where vegetation (through the aid of its biological, physical, and chemical processes) is able to actively uptake pollutants, store sediments as well as support symbiotic relationships with microbiological species that degrade toxicants within a wetland (Leguizmo *et al*., 2017).

The Farmer's Weekly Report (2022) identified three wetland plant species found in South Africa which assist in treating polluted water bodies. These three plants includethe leafy juncus (Juncus l*omatophyllus*), flat sedge (Cyperus *texttilis*) and the palmiet (Prionium *serratum*). It is well documented that polluted water bodies usually contain harmful nutrients and chemicals such as nitrogen and phosphorus, therefore the introduction of the three above mentioned plant species in polluted waters will assist in removing such chemicals since these plant species thrive in environments which are rich in nitrogen and phosphorus, thus resulting in the improvement of the water quality. Although the KGR is populated with a diverse community of vegetation, invasive species such as the Cyperaceae spp are wide – spread one the landscape which compromise the processes of phytop – remediation (Leguizmo *et al*., 2017).

A moderate amount of precipitation (annual rainfall of approximately 759 mm) is received in KGR annually. Additionally, there is variation in seasonality which influences the annual temperatures and precipitation conditions within the KGR (Shapi*et al*., 2021). These climatic conditions have an influence on the wetland's potential inattenuating toxins found in the water channels. For example, a wetland system which receives a sufficient and constant recharge of precipitation (coupled with geological conditions that allow for water flow) may be enriched with dissolved oxygen content which may affect the redox conditions occurring in the wetland system (Baker *et al*., 2000). Anaerobic conditions in a wetland may facilitate for the immobilization of metals for example, sulfide ions may precipitate out of the water channel under anaerobic conditions (Baker *et al*., 2000). Additionally, redox conditions may also cause metals to be readily soluble in the water column, this then enables for biotic organisms such as plants and microbes to assimilate the ions – reducing the metal concentration in the wetland's water channel. On the contrary, anoxic conditions due to poorly recharged wetland systems which then aids the prevalence of anerobic bacteria whichare also agents of AMD facilitation in a wetland Pat-Espadas *et al*., 2018). A wetland system dominated by anoxic conditions becomes unhealthy and non – functional.

According to Ollis *et al*. (2015) the hydrological regime - listed under level 5 - of the sampled wetlands in the KGR is characterized by non-perennial and inundated (W5sp) water. Additionally, diffuse flow has been observed in some of the aquatic water bodieson the Game Reserve. In relation to this study, on the day of sampling; the W4m sampled wetland had stagnant water.

Diffuse flow aids in the removal of metal constituents or dissolved solids in the water column through various ways (Tanner and Kadlec, 2013). For example, diffuse flow increases the retention time of water movement within the wetland this then enables for microbiological organisms and plants to assimilate constituents dissolved in the water column; sediments within the water channel are able to adsorb metal ions and mobilize them out of the water channel as well as settlement of sediments (which mainly have metal constituents attached on them) to the bottom of the wetland (Tanner and Kadlec, 2013). Consequently, metals are mobilized from the wetland water channel.

Contrary to the removal of dissolved constituents in the wetland's water channel; diffuse flow may hinder metal removal in a wetland's water channel (Kill *et al*., 2018).On the day of sampling, all of the sampled wetlands in and outside the KGR were characterized with diffuse flow except for the W5sp locality which had fast moving water (also see Figure 6). The observed diffuse flow in the presence of a compromised wetland system (for example poorly vegetated with plants that can absorb metal ions from the water) as well as groundwater seepage - characterized by AMD - in mentioned wetlands enables for metal accumulation within the wetland's water channel therefore, metal constituents accumulate in the wetland's water channel (Tanner and Kadlec, 2013).

CHAPTER 7 CONCLUSION

The importance of having a wetland system in the natural environmental is highlighted particularly when the wetland system is no longer functioning or has been destroyed. This is the case of the sampled wetland systems both inside and outside of the Krugersdorp Game Reserve.

The study conducted aimed at assessing the effectiveness of wetlands in the KrugersdorpGame Reserve (KGR) in attenuating pollution from adjacent mines, results from the spatial analysis illustrated very little to no variation in average physico - chemical values (TDS and Salinity) when comparing the wetlands upstream (closest to the mine) to wetlands that were sampled downstream (furthest away from the mine). Similarly, the recorded chemical variables illustrated similar elementary compositions and constituents (in terms of metal and salt concentrations) within the water samples that were collected from wetlands that were upstream and downstream of the KGR. Additionally, exceedances in terms of physico - chemical and chemical variables that were analysed for were observed from the sampled wetlands.

The hydrogeomorphic (HGM) approach to classify wetland types in the KGR has revealed that various ecological components of the wetland system have to be considered beforea definite deduction can be made in terms of whether the sampled wetlands are effectiveor ineffective in attenuating metal concentrations or inorganic constitutes that may be polluting the system. The classification of the sampled wetlands into wetland types (based on HGM approach) revealed that factors such as sedimentation and water flow may contribute to a wetland having an elevated metal concentration and not necessarily the functionality of the wetland.

The environmental impacts that are associated with polluted (in this case by mine pollutants) hydrological systems such as wetlands have had detrimental consequences to both terrestrial and aquatic life. This is of concern due to other external factors such as climate change that impose even more stringent pressures to these ecological systems, therefore, there needs to be proactive

measures that are implemented to combat the identified problems.
The obtained results from this study about metal and inorganic constituents in the water body of the wetlands that were sampled inside and outside of the KGR reveal that there is chemical contamination of the sampled wetlands. Additionally, it is evident that very little to no remediation was being implemented throughout the mining life cycle of the mines that were in operation adjacent to the KGR hence the heavy dispersal of metals into the environment from areas such as tailing facilities.

The results obtained from this study revealed that there is evidence of water pollution of wetlands that were sampled inside and outside the Krugers Game Reserve (KGR). The following measures can be put in place to manage and mitigate the impacts of AMD on water resources in the KGR:
The KGR houses a diverse community of world life species such as lions, snakes hippopotamus, and giraffes that are freely roaming in the game reserve. These animals are susceptible to ingesting polluted and impacted water from some of the wetlands. Therefore, there has to be physical structures such as barricades or fencing that delineates the impacted wetlands to keep the wildlife away from drinking water from the impacted water sources. Alternatively, these animals need to be relocated to adjacent national parks where they will have access to suitable water resources.

Mining companies that are still operating in and around the KGR should be compelled toimplement stringent measures of wastewater discharge into the environment. Water that does not comply to specific wastewater standards either set out by the mines water use licenses or the general standards stipulated by guidelines such as the MHSA should notbe allowed to be discharged into the receiving environment.

Upon re-opening of the KGR, there needs to be more stakeholder involvement which alsoincludes community-based engagement in the management and facilitation of the park and its activities to avoid re-closure due to poor management of the park.
A similar study can be conducted which incorporates soil analysis and how sedimentation affects the

effectiveness of wetlands in attenuating pollution.

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