GEOSPATIAL CHARACTERISATION AND DETERMINATION OF LANDFILL SITES IMPACTS ON GROUNDWATER RESOURCES IN BUFFALO CITY METROPOLITAN MUNICIPALITY IN THE EASTERN CAPE, SOUTH AFRICA

by

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DECLARATION

I, Ayaka Tase, student number 46951903 declare that the dissertation titled "Geospatial Characterization and Determination of Landfill Sites Impacts on Groundwater Resources in Buffalo City Metropolitan Municipality in the Eastern Cape, South Africa" is my original work and has not been submitted for any degree or examination at any other university. This research project was conducted in accordance with the requirements for the degree of Master of Science in Environmental Management within the Department of Environmental Sciences in the College of Agriculture & Environmental Sciences, University of South Africa.

This study was carried out under the guidance and supervision of Prof. Munyaradzi Mujuru and the co-supervision of Prof. Linda Lunga Sibali, whose invaluable support and expertise have significantly contributed to the successful completion of this study. I am solely responsible for the data collection, analysis, and interpretation presented in this dissertation, ensuring the accuracy and reliability of the findings.

All sources of information used in this research, including books, articles, and websites, have been acknowledged and referenced according to the required citation style. Contributions from other researchers and institutions have been explicitly stated.

I have adhered to the ethical standards and procedures required for conducting this research, obtaining necessary permission from relevant authorities and study participants.

This study complies with the ethical guidelines of the University of South Africa and upholds the principles of research integrity and academic honesty. I have also received the necessary financial and administrative support from the University of South Africa's Student Bursary Funding to undertake this research.

Ayaka Tase

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ABSTRACT

Globally, waste management challenges persist, especially in developing regions like South Africa where landfilling remains the key strategy for waste disposal. However, landfilling is a major concern because of the possible health and environmental impacts it poses. This research study examines the level of leachate contamination of adjacent water sources from the Roundhill and King William's Town (KWT) landfills in the Buffalo City Metropolitan Municipality situated in the Eastern Cape Province, South Africa and the environmental implications of such landfill leachate on surface water and ground water near the two landfill sites. In addressing these aims, the physicochemical properties of leachate, surface water, and groundwater were assessed to identify potential contamination risks to water quality. Primary data gathering through water sample analysis and secondary data analysis from past monitoring reports were both considered in this study. Samples were collected during both dry and wet seasons and were tested for pH, electrical conductivity (EC), anions (chloride, nitrate, nitrite, sulphate, ammonia), and heavy metals (cadmium, chromium, arsenic, lead). The research also involved geospatial profiling to detect pollutant distribution patterns and correlations between the physicochemical properties of water. The results indicated a significant impairment of water quality in the vicinity of landfills. Nitrate concentrations in surface-water samples varied from 0 to 63.3 mg/L and reached maximum historical peak values at NR1 of 168–337 mg/L, which exceeded WHO and SANS limits of 50 mg/L. Nitrite levels generally ranged between 0 and 1.44 mg/L; however, experimental results revealed high nitrite values that further exceeded up to 6.89 mg/L at certain sites. There was a high variability in chloride concentrations, with the highest levels recorded in surface water (1 719.8 mg/L) that is well above the SANS guideline of 300 mg/L. Ammonia in the leachate from landfills was extremely high, with mean values of 614.3 ± 105.1 mg/L (Roundhill landfill) and 11.0 ± 51.4 mg/L (KWT landfill). The concentrations of ammonia were observed from 36.0 to 159.0 ± 207.8 mg/L in polluted water samples and from 10.5 to 23.1 m/L BPA with its contamination levels above WHO guidelines. Heavy metal analysis indicated that lead concentrations were highly elevated and leachate 94.2 µg/L (Roundhill), 56.7 µg/L (KWT) while surface water varies between 28.5-326. u g/L and reaches a groundwater concentration of 486;2 u g /L, well above WHO guide value of loug/1. Spatial profiling revealed that contamination from landfill leachate generally spreads from the landfill sites, with pollutants such as chloride, nitrite and ammonia showing negative concentration gradients as they moved further from the landfill site. It was concluded in this research that there are major problems related to leachate that require improved waste management practices and better landfill regulation compliance in the Buffalo City region.

Keywords: landfilling, leachate contamination, groundwater, water quality, environmental impacts

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ACRONYMS AND ABBREVIATION

ADM: Amathole District Municipality

BCMM: Buffalo City Metropolitan Municipality

BOD: Biological Oxygen Demand

COD: Chemical Oxygen Demand

DBE: Department of Basic Education

DO: Dissolved Oxygen

EC: Electrical Conductivity

EPA: Environmental Protection Agency

FET: Further Education and Training

GDP: Gross Domestic Product

GIS: Geographic Information System

HSRC: Human Sciences Research Council

ICT: Information and Communication Technology

IRP: Integrated Resource Plan

NGO: Non-Governmental Organization

NQF: National Qualifications Framework

OECD: Organisation for Economic Co-operation and Development

pH: Potential of Hydrogen

PISA: Programme for International Student Assessment

R&D: Research and Development

SANS: South African National Standards

SAQA: South African Qualifications Authority

SDG: Sustainable Development Goals

SME: Small and Medium Enterprises

TDS: Total Dissolved Solids

UNICEF: United Nations International Children's Emergency Fund

VRIO: Value, Rarity, Imitability, Organization framework

WHO: World Health Organization

CHAPTER 1: INTRODUCTION

This chapter introduces the background to this study of waste management in South Africa. It presents the problems currently being faced by municipalities in South Africa in terms of waste management, moves to focus on the municipal landfill sites which are the subject of this study that are impacted by illegal dumping of hazardous wastes, poor management of transfer stations and landfill licensing challenges. The research questions, the research objectives and the justification for carrying out the study are also presented.

1.1 Background

Rapid urbanisation and an associated increase in population in urban cities are responsible for massive economic growth and industrial expansion, especially in developing countries like South Africa (Mercandalli et al., 2023). While the resulting economic development is largely positive for the country, urbanisation has generally come at a cost especially to the environment because of increased waste generation (Vergara & Tchobanoglous, 2012; Liu et al., 2015a). Globally, people are discarding increasing quantities of waste whose composition is becoming more complex as varying technological substances and equipment diffuse the markets (Vergara & Tchobanoglous, 2012; Liu et al., 2015a). As a result of increasing waste volumes, waste management, especially solid waste management, has gained much attention and has become a major global environmental concern. According to the World Bank Group report on solid waste management World Bank (2021), the world's cities generated as much as 2.24 billion tonnes of solid waste in 2020. This report estimates that considering the rate at which the population is growing and the pace of urbanisation in countries around the world, annual waste generation is expected to increase by 73% from 2020 levels to 3.88 billion tonnes in 2050.

In 2017, South Africa was estimated to have generated 54.2 million tonnes of general waste and 52 million tonnes of hazardous waste (Department of Environmental Affairs, 2018; Mbazima et al., 2022). The contents of these millions of tonnes of waste include various types of waste materials including medical waste, plastics, electronic waste, food waste, brines, etc. Most of these waste products have serious public health and environmental impacts and have become a major global issue (Noiki et al., 2021). As a result, environmental conservation is one of the key issues on the agenda of the Millennium Development Goals 2030 (MDGs) and the Sustainable Development Goals 2030 (SDGs) (UN Report: Transforming our world: The 2030 Agenda for sustainable development). Unfortunately, of all this waste generated in South Africa, only 10% is recovered or recycled (Stats SA, 2018).

Waste that is not disposed properly has so many consequences for public health, environmental preservation, sustainability, and the circular economy (Jayasinghe et al., 2023). Environmental problems such as loss of biodiversity and habitat destruction, depletion and degradation of forest resources, degradation of marine resources, as well as air and groundwater pollution are some of the most important consequences related to improper disposal of waste (Ololade et al., 2019). While waste is found in different forms, of interest in this research is solid waste (Coker et al., 2016).

Solid wastes are generally classified based on sources of origin (i.e. industrial, hospital and municipal solid waste) (Ugwu et al., 2021). It is also classified into hazardous and non-hazardous categories, a classification that is based on the toxicity of materials in the waste (Vergara & Tchobanoglous, 2012). While other classes of waste are important, a large portion of waste management practices mainly deals with municipal solid waste that is generally defined as all solid or semi-solid waste generated by residential, commercial, industrial, institutional, construction and demolition processes and is collected by the municipality or is disposed of at municipal waste disposal sites (Saleh & Koller, 2019). This definition is, however, not strictly followed and has been used in some of studies to include other wastes which are not typically regarded as municipal solid waste. For instance, wastes generated by industrial, construction demolition, and municipal services are sometimes excluded from the definition, while in some countries, certain contaminated medical wastes and hazardous industrial wastes are part of the municipal waste stream (Chisholm et al., 2021).

As the concept of urban sustainability gained international rhetorical ground, in Europe and other parts of the world, countries have had to come up with sustainable ways of managing solid waste (Danthurebandara et al., 2012; Robinson, 2018). Just as with other countries around the world, South Africa has made huge strides in addressing growing quantities of municipal solid waste but, unlike most developing countries, South Africa has serious solid waste management challenges. The government has been under constant pressure to efficiently handle the surging amounts of solid waste, especially with an ever-growing population. According to the World Bank collection of development indicators (United Nations, Department of Economic and Social Affairs, Population Division, 2019), South Africa has seen about a 10% increase, to 66% in 2018, in the population living in urban areas and cities in the last 20 years and is expected to reach approximately 71% by 2030. A huge part of this populace lives in slums or locations where waste management is generally a major problem. According to the South African Department of Environment, Fisheries and Forestry report (2020), only 65.9% of households had access to collection services at least once a week in 2017, with the other 34.1% having to use their own means of waste disposal or make use of communal rubbish dumps.

In most countries, waste management methods consist of recycling, disposal in landfills, incineration, and composting (Liu et al., 2015a; Vaverkova, 2019). Comparative studies of these various waste management methods in different parts of the world show that among these municipal solid waste treatment and disposal technological options, landfilling or open dumping remains the most popular wate disposal method and is indispensable in most countries because of the relatively low cost and low-technical requirement (Gonzalez-Valencia et al., 2016; Jovanov et al., 2018a; Feng et al., 2018, Kaza et al., 2018). According to a World Bank report compiled by Kaza et al. (2018), landfilling and open dumping constitute about 70% of waste treatment and disposal around the globe (Figure 1.1). Landfilling is the only management technique that is both necessary and sufficient because some wastes are simply not recyclable and will eventually reach a point at which their intrinsic value is dissipated completely, and recycling itself also produces residuals. However, according to the same report (Kaza et al., 2018), open dumping, which is not an environmentally safe method to manage waste, constitutes at least 33% (Figure 1.1) of all global waste management methods and is especially common in developing and underdeveloped countries. In South Africa, as much as 90% of the municipal solid waste (MSW) ends up at landfills, a much larger figure compared to that of the developed countries (Stats SA, 2018). Unfortunately, not all these landfills in South Africa are environmentally safe for waste disposal. In developed countries, the realisation that waste could be a useful source of raw materials has led to the development of new disposal technologies and increased recycling capabilities reducing solid waste going to landfills. They have already made significant progress by moving away from landfilling with policymakers working on specific goals of reducing the volume of disposed waste and imposing very strict requirements for landfilling and landfill sites because of serious environmental and public health concerns (Vergara & Tchobanoglous, 2012; Sun et al., 2019). Of the environmental concerns of interest, the contamination of groundwater resources by the landfill leachate, and the release of greenhouse gases (GHG) and other noxious gases are of major public interest (Vergara & Tchobanoglous, 2012; Sun et al., 2019). For instance, in the USA, around 53% of MSW was discarded on landfills (Sun et al., 2019) whereas for several EU countries, landfilling was reported to be as low as 5% (Brennan et al., 2016), while China still reportedly dumps around 79% of MSW into landfills (Havukainen et al., 2017).

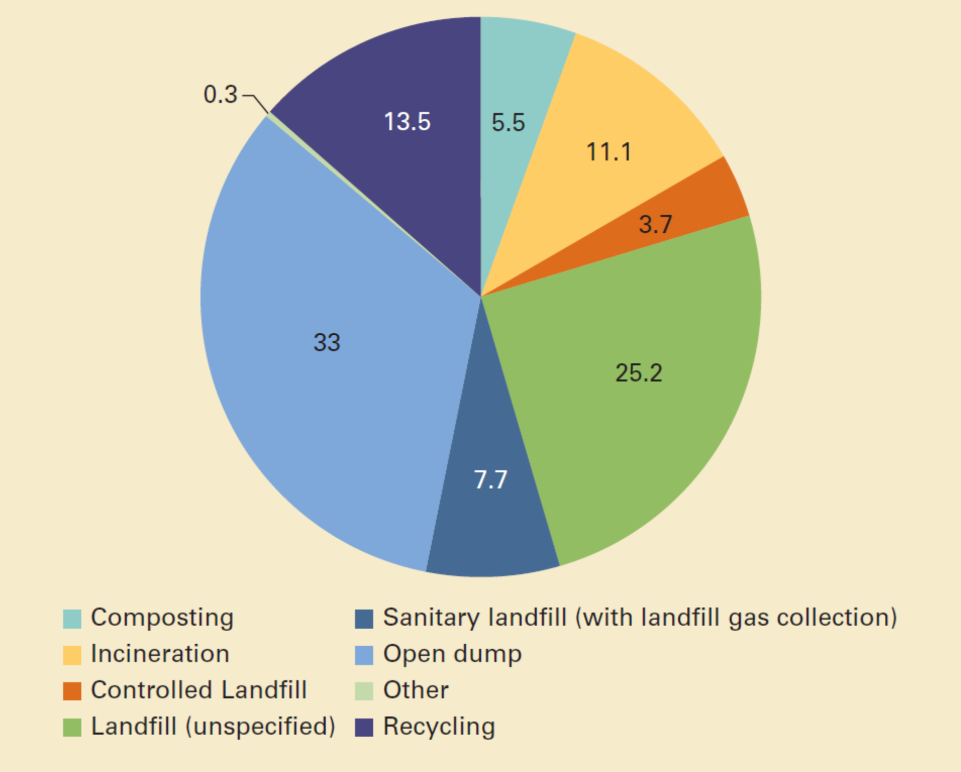


Figure 1.1: Global treatment methods and disposal of waste

Source: https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html *(Accessed: 7 January 2024)*

Landfilling is associated with several environmental impacts. One of the main gases released from landfills, methane, is believed to be about 25 times more harmful to the environment than carbon dioxide and, therefore, is a major concern for environmentalists (He et al., 1997). Research studies by several scholars (Christensen et al., 2005; Negi et al., 2018; Scharff et al., 2023) show that landfill sites contribute around one-fifth of the global anthropogenic methane emissions and are also a source of some of the most toxic gases, although in low concentrations. The scarcity of land for the construction of landfills for effective solid waste disposal is another challenge that results from population growth, thus bringing the residential areas closer and closer to landfill sites (Vergara & Tchobanoglous, 2012; Sun et al., 2019). Consequently, there is a need for a reduction of waste going to the landfills as these sites have a negative impact on the public, especially communities living adjacent to the landfills, and they require management long after the landfill sites are closed, which presents another concern for those communities.

Despite the negative effects associated with landfills, they still play a very critical role in MSW management strategies in South Africa. Landfills are cheaper to operate and are environmentally friendly when properly designed and can be operated as bioreactors for harnessing biogas and leachate (Sekhohola-Dlamini & Tekere, 2019). In general, if MSW is disposed of at properly licensed and regulatory compliant sanitary landfills, this is generally perceived to be a safe and economical option. Thus, site selection and proper design of landfills are critical in reducing the impacts of landfilling on the environment and also the operational costs throughout its lifespan (Elhag & Bahrawi, 2017).

1.2 Problem Statement

While the generation of waste is an unavoidable consequence of urbanisation and population growth, the biggest associated challenges in South Africa are twofold:

1. The licensing and management of the municipal solid waste landfills: This is required by the National Environmental Management Act: Waste Act (No. 59 of 2008) but according to the South Africa State of Waste report of 2018, of the 990 general waste facilities in the country, only 432 were licensed (Department of Environmental Affairs Report, 2018). This means that 56% of the landfills were operating illegally, some of them because they were constructed and started operating before the environmental regulations were instituted, and some because they do not meet the strict requirements of the regulations. Unfortunately, poorly designed and managed landfills can discharge large volumes of leachate into the local groundwater which will have long lasting impacts on the water quality (Danthurebandara et al., 2012; Abiriga et al., 2020; Kamboj et al., 2020; Benaddi et al., 2022).

2. *The second challenge is the ever-increasing volumes and complexity of waste disposed at the landfills:* In South Africa and globally, there is growing quantities and complexity of the solid wastes coming into the landfill sites for disposal, and when combined with the critical need to screen and sort the waste before disposal, solid waste management is increasingly becoming cumbersome. Of interest in this study are the landfill sites in the Amathole District Municipality (ADM) and Buffalo City Metropolitan Municipality (BCMM) in the Eastern Cape, South Africa, where this study was conducted. In a 2013 report on the environmental control plan for ADM that discussed the state of landfills in the municipality, it was highlighted that there was a need for separate disposal of hazardous wastes. This was based on a previous report cited in the 2013 report that pointed out, because of a lack of adequate waste screening at the transfer stations, the possibility of illegal dumping of hazardous wastes such as medical waste by some of the local industries on the municipal solid waste landfills (The Amathole District Municipality Environmental Pollution Control Plan, 2013). According to the report, this suspicion was borne out by the fact that the decision-makers had no information about the disposal of hazardous wastes, and therefore the fears of illegal dumping of hazardous wastes.

The South African Waste Classification and Management regulations that came into effect in 2013 imposed strict norms and standards for waste disposal by landfilling (SA Government Gazette No. 36784, 23 August 2013) (Republic of South Africa, 2013). According to these regulations, hazardous wastes should be disposed of on landfill sites that are licensed to receive such wastes. However, as was highlighted in the report, with transfer centres that are poorly managed or not adequately monitored, the possibility of hazardous wastes being dropped illegally for disposal in the landfills cannot be ignored (The Amathole District Municipality Environmental Pollution Control Plan, 2013). In the sites where waste was accepted and was properly regulated, there is a lot known about the likely composition of this leachate and there is some knowledge of its likely biological and health effects. This is not the case for poorly regulated sites, where the composition of the accepted waste is unknown, thus creating challenges in mitigating the likely impacts of these sites. Recently, another regulation was instituted to minimise the risk to groundwater by the leachate by banning all liquid waste disposal on the landfills as of August 2019 (Ngounou, 2019). Unfortunately, when one considers the fact that a large number of landfills are operating without licences in South Africa, and when coupled with transfer stations that are poorly managed, the likelihood of compliance with this regulation is relatively low.

It is important to declare that the researcher is a resident of BCMM who has been working in the metropolitan area in a nature reserve. Within the reserve, illegal dumping has always been a major challenge. Based on the information that some of the landfill employees informally shared, the researcher is also aware of the challenges with licensing some of the landfill sites in the region. Therefore, while it is worrying enough that some of the landfill sites in the region are operating illegally without waste management licenses as required by the National Environmental Management Act: Waste Act (No. 59 of 2008), the possibility for illegal dumping of hazardous waste on the unlicensed landfills is high. The research question that comes out of these revelations is whether the landfills in BCMM and ADM are polluting freshwater resources in the district, and what is the extent of the problem.

As reported in previous studies (Duse et al., 2003; Blignaut & van Heerden, 2009; Viljoen & van der Walt, 2018; Prins et al., 2023), South Africa suffers major challenges of water scarcity as well as potential deterioration of the surface and groundwater quality as a result of landfill leachate, especially that containing hazardous waste. And these factors combined have far-reaching consequences for one of the major sources of fresh water (Hasan et al., 2020). Leachates from landfill sites contain organic and inorganic compounds, xenobiotics and heavy metals as constituents in waste that are produced physically, chemically and by fermentative processes (Salam & Nilza, 2021). These substances pose a severe water quality problem to groundwater resources and surface water and so for the communities that rely on these water resources, particularly as the polluted aquifers would require longer periods for rehabilitation (Robinson, 2018). With the distinct possibility of illegal disposal of hazardous waste, as highlighted above, landfills, which are potential reservoirs for many pharmaceuticals, provide a conducive habitat for antimicrobial-resistant microbes and resistant gene transfer which could give rise to significant public health problems with possible deadly consequences. In this regard, Borquaye et al. (2019) reported that the waste contained large amounts of some of the three widely used antibiotics, metronidazole, penicillin, and amoxicillin.

Relatively few studies have provided a holistic and compressive summary or findings on the impacts of these landfill sites in the ADM and BCMM of the Eastern Cape Province in South Africa (Negi et al., 2018). Thus, the purpose of this study is to perform chemical characterisation of the leachate and groundwater in and around the landfill sites – by determining the physicochemical parameter of the leachate and water samples, including chemical oxygen demand (COD), total dissolved solids, pH, electrical conductivity, complemented by determining inorganic substances (ammonia, phosphate, chloride), as well as the heavy metal content of the leachate and water. In addition, the study sought to perform geo-spatial characterisation of the physicochemical parameters of the landfills in BCMM to enable spatiotemporal modelling of these impacts on water resources around the landfills as well as predicting impacts on communities nearby.

Although groundwater quality around landfills has been reported for South Africa (e.g., Gauteng, KwaZulu-Natal and Limpopo provinces), previous studies have generally been restricted to physicochemical assessments, with no integration of geospatial modeling or compliance analysis. Outside of the US, other studies conducted in China, India and several European regions have shown the merit of integrating hydrochemical analysis with GIS-based spatial profiling to map contaminant plumes and measure risk associated with exposure. Nevertheless, similar comprehensive studies are scarce in the Eastern Cape, especially relating to the ADM and BCMM settings. This deficiency hampers the evidence-based process necessary for landfill regulation and groundwater protection in Ontario.

1.3 Research Questions

The following research questions were used to guide this study. The main research question that this study was interested in answering was whether the landfill sites in the ADM and BCMM were contributing negatively towards water quality around the landfill sites.

The consideration of this question is directed by the following sub-questions:

1.3.1 Are the landfill sites in ADM and BCMM compliant with environmental regulations?

1.3.2 Are the landfill sites an environmental and public health risk to the local communities?

1.3.3 What are the water quality levels of the groundwater around the landfill sites within the BCMM, South Africa?

1.3.4 What is the link between groundwater pollution and leachates from the selected landfill sites within the BCMM, South Africa?

1.4 Research Objectives

The research objectives that were developed from the research questions are separated into primary and specific objectives as listed below.

1.4.1 Primary objective

To perform physicochemical characterisation of the leachate and groundwater in and around the Roundhill Landfill Site and King William’s Town (KWT) Landfill Site in BCMM in the Eastern Cape to determine if water quality deterioration around the landfills could be linked to the landfills, and therefore predict possible impact on similar waste disposal sites in the ADM region.

1.4.2 Specific objectives

i. To determine the chemical properties (selected heavy metal content and anions) in the landfill leachate and groundwater in and around the Roundhill and King William’s Town landfill sites.

ii. To determine the physical properties (pH, electrical conductivity, turbidity) of the landfill leachate and groundwater in and around the Roundhill and King William’s Town landfill sites

iii. To assess the differences in the levels of measured physicochemical properties in the leachate and groundwater in and around the landfill sites to assess possible leachate pollution of groundwater with heavy metals and other salts.

iv. To perform geo-spatial characterisation (examining, assessing, evaluating, and modelling spatial data) of the measured physicochemical parameters to assess and predict the possible distribution of the waste plumes and assessment of possible environmental and public health risks to the local communities.
v. To investigate the compliance of the Komga and Peddie Waste Disposal sites in the ADM region as well as the Roundhill and King William's Town landfill sites in the BCMM with existing legislations/regulations for disposal of different classes of wastes and the measures the landfills are taking to mitigate effects of illegal dumping of wastes.

1.5 Significance of the Study

Water is a critically important natural resource that sustains life and the environment in general (Halmaghi & Moşteanu, 2019). Therefore, it is imperative that monitoring and evaluation of the chemical and physicochemical parameters of water in the areas surrounding landfill sites is carried out regularly to mitigate the impacts of landfill sites on the water resources. According to Kibena et al. (2014), water resources, be it surface water or groundwater, are crucial for economic development. In South Africa, most communities have poor access to potable water and in some instances, communities rely on unpurified groundwater. Thus, the possibility is high of public health crises due to the contamination of ground water with pharmaceuticals, heavy metals, and other hazardous substances with the potential to cause various conditions such as cancers, or drug resistant microbial infections, leaching from landfills into freshwater sources is of major concern (Danthurebandara et al., 2012). Unfortunately, these problems will hit the most vulnerable communities more and are exacerbated by the fact that the same communities do not have access to proper healthcare (Chiriboga et al., 2020). In addition, remediation of polluted groundwater is a very costly process that will result in the diversion of millions of funds that could be used for poverty reduction and job creation in struggling communities. The results of this project will help in predicting and mitigating the possible impacts of landfills on groundwater resources and public health and will raise awareness of the need for more stringent checks for compliance for the landfills around the country.

This information would be key in devising a robust and effective waste management framework suitable for disadvantaged countries and municipalities. Landfilling remains a requirement to deal with solid waste, but it must be performed in a way that maintains sustainable development. With a large number of other landfills in the country being unlicensed, the results of this study will help environmentalists and managers in modelling, mitigating and predicting possible impacts associated with other sites operating without licences and monitoring, and possible insights into the costs to the environment, as well as the remediation of polluted water. Continuous monitoring, characterisation and determination of the effects of landfill sites on the natural environment are an important step towards effective management of these pollution hotspots. This can also serve as a follow up to ensure that landfill sites remain monitored before they become a serious health hazard, especially for the poor communities in the areas close to the landfill sites. This will help minimise the stress on water resources and the threat to biodiversity as well as air quality (Negi et al., 2018).

1.6 Definition of Terms

This study is an environmental science study that is focused on the solid waste management in South Africa. Any term or variable that is used in this study is therefore presented in an environmental science context. For most of these variables, different definitions exist in the literature. However, presented below are the definitions that have been adopted for this research.

BCMM: is a metropolitan municipality situated on the east coast of the Eastern Cape province of South Africa

Disposal: means the burial, deposit, discharge, abandoning, dumping, placing or release of any waste into, or onto, any land (European Parliament, 2008).

Hazardous Waste: is a waste that contains organic or inorganic elements or compounds that may, owing to the inherent physical, chemical or toxicological properties of that waste, have a detrimental impact on health or the environment (European Parliament, 2008).

Incineration: means any method, technique or process to convert waste to flue gases and residues by means of oxidation (European Parliament, 2008).

Landfill: A landfill is a designated site for the disposal of solid wastes that cannot be reused or recycled. Modern types of landfills are well-engineered and managed facilities and are designed operated and monitored to ensure compliance with environmental regulations developed to mitigate their impacts on the environment and public health.

Leachate: Leachate refers to landfill leachate, which is a very offensive dark liquid composed of a complex matrix of various chemicals including organic matter, inorganic salts, organic trace pollutants, heavy metals, suspended solids, as well as other products of solid waste disposal in an aerobic environment (Moody & Townsend, 2017; Abdel-Shafy et al., 2024).

Liquid Waste: Liquid waste can be defined as wastes consisting of liquids that are hazardous or potentially harmful to human health or the environment such as sewage and domestic wastewater, sludges, fats, used oils, grease or other hazardous liquids produced by industrial activities (https://www.ewastedisposal.net/liquid-waste/).

Municipal solid waste: Municipal solid waste is defined as waste that is collected by the municipality or is disposed of at the municipal waste disposal sites. The waste includes residential or general waste, industrial waste, institutional, commercial, municipal, and construction and demolition waste (Hoornweg et al., 2015).

Recover: Recover in this study is a term to describe the process of recovering resources, which entails recovery of material or energy from solid waste (United States of America, 1976)

Recycling: Recycling refers to the process of converting waste materials into new materials and objects.

Solid Waste: Solid waste means any garbage, refuse, sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities (United States of America, 1976).

Transfer Station: A depot for the reception and aggregation of waste streams prior to their transport to another depot or location for further sorting, resource recovery or disposal.

ADM: The Amathole District Municipality is a Category C municipality in the Eastern Cape province of South Africa. The municipality is comprised of six local municipalities: Mbhashe, Mnquma, Great Kei, Amahlathi, Ngqushwa and Raymond Mhlaba.

Waste: waste as any substance, whether a liquid, solid, gas or radioactive which when discharged or emitted or deposited in the environment in such a volume, constituency or manner may be harmful to human health or cause alteration of the environment (Oelofse & Godfrey, 2008:244).

Waste Management: means the streamlined processes consisting of comprehensive strategies that are employed to effectively and efficiently dispose of wastes, from the collection until final disposal (Robinson, 2018).

1.7 Organisation of the Study

This study is broken down into five chapters that are presented below:

Chapter 1: Introduction

This chapter introduces the background of this research involving waste management in South Africa. It presents the current problems faced by municipalities in South Africa in terms of waste management, focuses in on the ADM and BCMM landfill sites which are the subject of this study and which are impacted by illegal dumping of hazardous wastes, poor management of transfer stations and by landfill licensing challenges. The research questions, the research objectives and the justification for carrying out the study are also presented.

Chapter 2: Literature Review

This chapter focuses on the literature review. The chapter describes waste management practices around the world and in South Africa with special focus on landfilling, its challenges and the methods used to monitor the landfill sites to reduce the impacts on the groundwater.

Chapter 3: Research Methodology and Design

The third chapter presents the overall research methodology and justification of the research approaches that were used to collect the data. The chapter also presents a description of the data analysis techniques used to interpret the collected data, measures taken to ensure reliability and validity of the data, as well as ethical considerations for the study.

Chapter 4: Results & Discussions

Chapter 4 focuses on the analysis, interpretation and presentation of the collected data. The chapter presents and discusses the findings of this study dealing with the water quality of the groundwater around the landfills in ADM and BCMM in South Africa.

Chapter 5: Conclusion and Recommendations

The fifth chapter provides the conclusion to the study, it presents the lessons learnt from the key findings of this study and concludes the study by offering recommendations for future study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter focuses on waste management practices around the world, and also assesses the practices in South Africa with special focus on landfilling as the most popular solid waste management practice in the country. The chapter also discusses the impacts of landfilling and the methods used to monitor the landfill sites to reduce the impacts on the groundwater.

2.2 Legislative Definition of Waste

This chapter is focused on waste management practices globally, and in South Africa. However, before exploring further into the fundamentals of waste management, it is important to define waste and to explain what waste means for this research. There are generally many definitions of waste which have differing implications for policy development and controls or regulations for waste disposal. Thus, the definition of waste can be vague in certain contexts or countries or may be more complex than is generally portrayed by the term. For instance, some of the legislation on waste management around the globe was developed to combat increasing problems with solid waste generation by all sectors of the economy as a result of expanding industrial and commercial activity, and an associated increase in consumer demand for goods and services. As a result, the respective legislation (e.g. Resource Conservation and Recovery Act (RCRA), 1976) are focused on solid waste, and therefore the respective definitions.

The simplest of the definitions of waste defines this term as any product or substance which is no longer suited for its intended use, is unwanted or unusable. This definition of waste is in line with that of the European Court of Justice (Oelofse & Godfrey, 2008:242) which defined the term 'waste' in the European Union legislation, Directive 2008/98/EC of 19 November 2008 on Waste (the Waste Framework Directive) to mean "any substance or object which the holder discards or intends or is required to discard." This implies that anything that is discarded would be regarded as waste.

The definition by the Waste Minimisation Act 2008 of New Zealand (Ministry for the Environment, 2010) has the same description presented in the previous section. It states that waste means anything disposed of or discarded, and it includes:

"… a type of waste that is defined by its composition or source (for example, organic waste, electronic waste, or construction and demolition waste); and to avoid doubt, includes any component or element of diverted material if the component or element is disposed of or discarded." This New Zealand waste definition recognises, just as was highlighted earlier, that anything becomes waste even if it can be reused, as long as it is discarded or disposed of, to become waste.

The Environment Protection Act 1993 of South Australia (Government of South Australia, 2021) provided a much broader definition in terms of terminology to include additional terms such as "dumped", "rejected", "abandoned", and "unwanted or surplus matter". According to its definition, anything that can be described in these terms, whether or not it was intended for sale, recycling, reprocessing, recovery or purification using a separate process becomes waste irrespective of whether it has value or not. This Act also stipulated that any substance which qualifies as waste according to this definition ceases to be waste if it is declared by regulation or an environment protection policy not to be waste (Government of South Australia, 2021).

According to the Environmental Public Health Act (EPHA) Chapter 95 of 1987 of Singapore (FAOLEX Database, 2021), waste is defined as anything which can be described as "scrap material or an effluent or other unwanted surplus substance" or any substance that requires disposal as a result of "being broken, worn out, contaminated or otherwise spoiled". The definition also further expressed that "anything which is discarded or otherwise dealt with as if it were waste" can be assumed to be waste unless if the producer or generator can provide proof that it is not (Oelofse & Godfrey, 2008:243; FAOLEX Database, 2021).

The South African definition of waste is described in the National Environmental Management: Waste Act 59 of 2008 as "any substance, whether or not that substance can be reduced, reused, recycled and recovered: that is surplus, unwanted, rejected, discarded, abandoned or disposed of; which the generator has no further use of for production; that must be treated or disposed of; or that is identified as a waste by the Minister by notice in the Gazette, and includes waste generated by the mining, medical or other sector, but a by-product is not considered waste; and any portion of waste once re-used, recycled and recovered, ceases to be waste". The legal definition of waste in South Africa is broad, but spells out that once a substance considered as waste is reused, recycled or recovered, it ceases to be waste.

The United States of America gives a distinctive definition of waste focusing on 'solid waste' as spelled out in the (United States of America, 1965) and the Resource Conservation and Recovery Act (RCRA) of 1976 (United States of America, 1976). As was highlighted earlier, waste management practices around the globe are more focused on the management of solid wastes. Furthermore, according to the United States Environmental Protection Agency (USEPA) (https://www.epa.gov/hw/criteria-definition-solid-waste-and-solid-and-hazardous-waste-exclusions), the definition of solid waste is not limited to wastes that are physically solid but also includes some that are liquid, semi-solid, or contained gaseous material. Therefore, it can be concluded that these definitions describe related substances. According to Lown (Oelofse and Godfrey, 2008:244), the United States has differing definitions of waste, the statutory (enacted by the legislative branch of government) and regulatory (regulations or rules written by Agencies e.g. EPA) definition.

The statutory definition as spelled out in the Acts (RCRA of 1976) ‘waste' as:
"any garbage, refuse, sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities, but does not include solid or dissolved material in domestic sewage, or solid or dissolved materials in irrigation return flows or industrial discharges…."

This definition is comprehensive, describing in detail most of the materials encountered in the solid waste management systems of today. This definition is related to one given by Gilpin (Vaverkova, 2019) which describes waste as any substance, whether a liquid, solid, gas or radioactive which when discharged or emitted or deposited in the environment in such a volume, constituency or manner may be harmful to human health or cause alteration of the environment. This description of waste as articulated Gilpin as well as by the United States Congress (United States of America, 1976) is the basis of the definition of waste in this study. Additionally, this literature review will discuss mainly solid waste and solid waste management practices.

2.3 Global Perspectives on Solid Waste Management Challenges

Solid waste management remains one of the major challenges facing both developed and developing countries and continues to worsen because of the continued increase in the volume of waste generation as a consequence of population growth, changes in consumption patterns and uncontrolled urbanisation (Kolekar et al., 2016). It is a critical environmental and public health challenge confronting nations across the globe, though its nature and intensity vary significantly with a country's developmental status. The sheer scale of the problem is staggering as has been alluded to earlier, with global generation of more than 2 billion tonnes of municipal solid waste annually, a figure projected to reach approximately 3.9 billion tonnes by 2050, driven by population growth, rampant urbanization, and evolving consumption patterns (World Bank, 2021; Yatoo et al., 2024). This escalating waste stream poses a significant threat to the environment, economy, and public health, necessitating urgent and context-specific action from urban managers worldwide (Zhang et al., 2024).

The approach to and capacity for managing this waste differ dramatically between the Global North and South. In high-income countries of the Global North like the European countries and the USA, solid waste management strategies and practices typically rely on advanced technologies, robust economic tools, comprehensive regulatory frameworks, and widespread public education and engagement (Awino & Apitz, 2024). These nations have largely moved beyond basic disposal, achieving high collection rates—often exceeding 90%—and focusing on waste-to-energy schemes, sophisticated recycling programs, and the integration of circular economy principles to minimize waste generation and maximize resource recovery (Zhang et al., 2024; Hassan, 2025). For instance, the European Green Deal and similar policy goals are increasingly aligned with circularity, driving innovations in areas like AI-enabled sorting and advanced biological treatments (Hassan, 2025). Consequently, only a tiny fraction (approximately 2%) of waste in high-income nations ends up in uncontrolled dumps (Yatoo et al., 2024).

In Asia, significant disparities in waste management performance are evident among nations. According to the Global Waste Index 2025, Japan has emerged as a world leader in waste management, generating only 326 kg of municipal waste per capita annually, the lowest among OECD nations. Of this, a mere 3 kg per capita (less than 1%) is sent to landfill, with the vast majority being incinerated (245 kg per capita) in waste-to-energy facilities and

63 kg per capita recycled (Sensoneo, 2025). South Korea also demonstrates exemplary performance, ranking second globally with a per capita waste generation of 438 kg. Notably, South Korea achieves the highest recycling rate among all OECD nations at 54%, sending only 56 kg per capita to landfill, while incinerating 91 kg per capita (Sensoneo, 2025). These figures illustrate that high-income Asian countries have successfully decoupled economic growth from landfill dependence through strategic investments in recycling infrastructure and energy recovery technologies.

In stark contrast, developing countries in regions such as Asia and Africa face a confluence of challenges that make effective solid waste management exceptionally difficult (Zhang et al., 2024). Here, the most common waste management strategies are often "end-of-stream" solutions, dominated by open dumping and uncontrolled landfilling (Awino & Apitz, 2024; Hassan, 2025). Studies indicate that approximately 93% of waste in low-income nations is either burned or dumped in unregulated sites, leading to severe environmental degradation and public health risks (Yatoo et al., 2024). The primary drivers of this crisis include inadequate infrastructure, severe financial constraints, weak institutional capacity, and ineffective policy implementation and monitoring (Zhang et al., 2024; Njewa et al., 2025). Furthermore, many governments in the Global South take sole legal responsibility for SWM, often viewing it merely as a public "nuisance" to be eliminated, which can sideline community participation and the innovative potential of the informal sector (Awino & Apitz, 2024). This informal sector, however, plays a crucial role; waste separation and recycling in many developing countries are driven largely by informal economies where individuals retrieve recyclable materials for subsistence (Awino & Apitz, 2024).

The African continent presents a particularly concerning picture. Available data indicates that 125 million tonnes of municipal solid waste were generated in Africa in 2012, of which 81 million tonnes (65%) originated from sub-Saharan Africa (Godfrey et al., 2020). This is projected to grow to 269 million tonnes per year by 2030 (Adedara et al., 2023). However, with an average waste collection rate of only 55% across the continent, approximately 68 million tonnes—nearly half of all MSW generated in Africa—remains within cities and towns, dumped onto sidewalks, open fields, stormwater drains, and rivers (Adedara et al., 2023). Sub-Saharan Africa generated approximately 9% of global waste as of 2016, or 180 million tonnes, with about two-thirds of that deposited in landfills and open dump sites, left to pollute the nearby environment and contribute to climate change (Adedara et al., 2023). The average MSW collection rate in sub-Saharan Africa is particularly low at only 44%, although coverage varies considerably between cities, from less than 20% to well above 90% (Adedara et al., 2023).

Specific country examples from Africa highlight these systemic challenges. Nigeria, as Africa's most populous nation, produces over 32 million tonnes of waste annually, yet less than 20% is properly managed, with the vast majority ending up in uncontrolled dumpsites and landfills (Muhammed, 2025). South Africa, the continent's most industrialized economy, contributes another 54 million tonnes of waste annually, much of which ends up in unregulated landfills (Muhammed, 2025). Ghana, despite progressive strides in waste management policy, struggles to manage its 1.1 million tonnes of plastic waste generated annually, with only 5% being recycled and the remainder accumulating in landfills and the environment (Muhammed, 2025). These figures underscore the scale of the waste crisis facing African nations and the urgent need for transformative solutions.

Specific examples from the developing world beyond Africa further highlight these systemic issues. In Malawi, challenges such as inadequate funding, a lack of disposal infrastructure, weak enforcement of regulations, and the use of inappropriate vehicles for waste collection mean that existing dumpsites are in a poor state and pose significant environmental and health dangers (Njewa et al., 2025). Similarly, in Uganda, low waste collection rates, unsafe disposal practices, and poverty-driven informal recycling are prevalent, hindering progress toward sustainable development goals (Castellani, 2025). Research across Asia and Africa from 2013 to 2023 confirms that socio-economic factors, infrastructural limitations, and cultural considerations are major barriers to optimizing solid waste management systems (Zhang et al., 2024). The growing volume of waste, combined with these entrenched challenges, leads to the common practice of illegal dumping in public spaces, rivers, and drains, which in turn causes flooding, contaminates water sources, and creates breeding grounds for disease vectors (Zhang et al., 2024). These observations underscore a critical point: while a few exceptional countries demonstrate progress, most developing nations struggle, highlighting a pressing need for solutions tailored to local realities rather than a blind adoption of foreign models (Awino & Apitz, 2024; Zhang et al., 2024; Hassan, 2025).

2.4 Overview of Solid Waste Management Challenges in South Africa

Building on the global context outlined above, this section focuses specifically on South Africa, a country whose waste management challenges mirror many of the issues prevalent across the developing world while also exhibiting unique characteristics shaped by its specific socio-political and economic landscape. According to Polasi et al. (2020), solid waste management is one of the major environmental issues of concern that developing countries like South Africa are currently facing, especially given problems such as poor service delivery, illegal dumping of waste, and non-compliance with regulations. The overall goal of solid waste management is to collect, sort, treat and dispose of solid wastes generated by all urban population groups in an environmentally and socially satisfactory manner, using the most economical means available. Unfortunately, in developing countries like South Africa, the most economical, and therefore the most commonly used waste management strategies are dominated by end-of-stream solutions which contribute to material accumulation into landfills on the one hand, and the production of harmful emissions and global overuse of virgin materials on the other (Chioatto, Khan & Sospiro, 2023), both contributing negatively to the environment.

South Africa, like other developing countries around the world, has had its fair share of waste management challenges (Njoku, Edokpayi & Odiyo, 2019). The country has half of its population located in informal settlements or shantytowns with no proper waste management structures in place. Cases of illegal dumping of waste in informal settlements are a common sight because of poor service delivery in those places. According to the South African Constitution (Section 156(1)(a)), solid waste management in the country is the responsibility of the municipalities so that, according to the Municipal Structures Act, Act 117 of 1998, municipalities are responsible for managing solid waste disposal sites in terms of the determination of a waste disposal strategy; the regulation of waste disposal; and the establishment, operation and control of waste disposal sites.

In 2001, the South African government set a target of providing all households with access to refuse removal services by the year 2012 (National Treasury, 2013). Although considerable progress has been made in expanding access to solid waste services mostly in urban centres, waste removal remains a problem in many local municipalities with many residents disposing of their waste in open dumps (Kadama, 2011; Njoku, Edokpayi & Odiyo, 2019). Additionally, when one considers the dysfunction in some of the municipalities in the country, corruption, and other factors, waste management is a real problem and therefore poses a serious risk to public health and the environment and is a major stumbling block for sustainable development (Dagwar & Dutta, 2024a). While most of the municipalities, especially the large metropoles, have properly designated landfill sites, challenges due to lack of funding and poor management persist in those facilities. When coupled with a lack of advanced technologies to monitor waste in these areas, this makes solid waste management a real threat to human health and the environment in the country.

Another major challenge, and most likely the most important that local municipalities are facing in respect of solid waste management, is organisational capacity. Organisational capacity is a multidimensional concept that consists of culture as the core determinant (Marshall & Farahbakhsh, 2013). Organisational capacity consists of leadership, strategy, structure/governance, skills, human capital and accountability as the major pillars. The relative importance of those pillars varies depending on the mission and maturity of the organisation, but they ultimately determine if the organisation will be able to fulfil its mandate. Organisational capacity-building in municipalities on waste management issues has not only involved new technology and strengthening of the financial base, but also involves understanding the administration systems for waste management and related activities (Marshall & Farahbakhsh, 2013). This requires the need for human resource development to achieve better results in waste management service delivery. Organisational capacity building should also focus on building sound institutions and good governance for attaining improved waste management service delivery (Schübeler, Wehrle & Christen, 1996). Unfortunately, this has not been the case in most municipalities where leadership, governance and accountability have been some of the major issues (Mamokhere, 2023; Mabunda & Chauke, 2023).

Also of note in the local government in South Africa is poor institutional practice which entails deficiencies or shortcomings in the way local government institutions operate and fulfill their responsibilities. Poor institutional practice encompasses a range of issues, including governance and decision-making, service delivery, accountability and oversight, transparency, and legal compliance, among others. According to Cointreau-Levine (1994), municipalities in developing countries usually spend between 20% and 50% of municipal expenditure on solid waste management but are unable to effectively provide waste management services because of inefficient institutional structures (Godfrey & Scott, 2011).

In South African municipalities, poor institutional practice is a consequence of poor allocation of the municipal budget, poor equipment management and a shortage of skilled and qualified staff.

The legal framework for waste management has been one of the most effective tools utilised in developed nations to mitigate challenges related to waste management. While legislation has been one of the major challenges for developing countries, South Africa, in contrast, has been very proactive and has some of the best environmental regulations. The major challenge in South Africa, which is common not only for environmental regulations of interest in the study but for all legislative and regulatory policies developed by the Government, is that they are developed on sound programme theories with vague implementation frameworks, and therefore suffer implementation failure. An example of this problem can be seen with the recently reviewed National Development Plan 2030 in which none of the indicators have moved in the desired directions, but instead have only worsened (The Presidency, 2023). Both mismanagement and non-compliance are common in South African municipalities which also lead to this failure and are unfortunately the most prevalent and damaging to the environment and society. These challenges call for a re-evaluation of the current waste management processes employed in the country in order to forge solutions for maintaining environmental quality for present generations, while also endeavouring to meet sustainability goals in the future (Dagwar & Dutta, 2024b).

In conclusion, the waste management challenges faced by South Africa are a microcosm of the larger global crisis, particularly acute in the developing world. While the specific manifestations are shaped by local socio-political and economic contexts, the underlying issues of inadequate infrastructure, financial constraints, weak institutional capacity, and policy implementation failures identified in Section 2.3 are clearly evident in the South African case. Addressing these challenges effectively requires a move away from fragmented, end-of-pipe solutions towards integrated, context-sensitive approaches. As seen in successful pilots globally, this includes investing in appropriate technologies, fostering inclusive governance that leverages the informal sector, building human capital, and securing sustainable financing to enable a just transition towards a more circular and sustainable model of waste management (Awino & Apitz, 2024; Castellani, 2025).

2.5 Waste Management Practices Across the Globe

Waste management practices in industrialised countries around the world have improved over the years as countries attempted to meet new demands as a result of population growth, urbanisation and industrialisation. Legislation that required control of the discharge of human wastes, and the collection of solid wastes in cities, was first introduced as early as the 19th century in the Western industrialised nations to protect public health (Wilson, 2023a). However, according to this author, the disposal of municipal, industrial and hazardous solid wastes remained unregulated until the last quarter of the 20th century when governments in developed countries started developing mechanisms to keep waste under control. According to Wilson (2023b), the responsibility for managing industrial waste at the time lay with the industry generating the waste.

As the challenges related to the disposal of municipal, industrial and hazardous solid wastes grew within the industrialised nations, it became necessary to find ways of addressing wastes. The challenges shaped the modern concepts of solid waste management in the United States which emerged around the 1980s (Dillion, 2023). As reiterated by Louis (2004), the RCRA of 1976 was the defining legislation that propelled the solid waste management practice in the United States today. This legislation forced the nationwide closure of open dumps, enforced requirements for permits for the operation of disposal and treatment facilities, reinforced the need for institutional responsibilities for waste collection and disposal, and the need for inspection of licensed facilities and enforcement of license conditions. This Act was preceded by the European Community (EC) Directive on Waste (75/442/EEC) of 1975, which was motivated by the development of similar regulations in several European countries such as the United Kingdom, France and the Netherlands. For instance, according to Wilson (2023), the United Kingdom developed the Deposit of Poisonous Wastes Act of 1972 and the Control of Pollution Act of 1974 which were focused on controlling disposal of hazardous wastes on the land. In France, the lawmakers voted into law the Extended Producer Responsibility (EPR) in 1975, which was a similar regulation for managing solid wastes in France.

This period in the 1980s saw wider institutionalisation of waste management with the expansion of municipal solid waste collection in smaller urban cities and rural areas (Wilson, 2023). It also saw innovations such as the introduction of trucks, motorised street sweepers, incineration, and sanitary landfills, recycling and composting becoming major components of waste management practices, all regulated by these and other related laws (Wilson, 2023). These regulations also enforced the separation of different classes of waste types, and therefore different facilities for waste disposal for certain wastes. Another important component of waste management in this period was the introduction of independent environmental regulators who were responsible for licensing of the waste disposal facility, inspecting operations and enforcing licensing conditions, and tracking shipments of hazardous wastes among others. In the United States, this role is assigned to the USEPA. Therefore, waste management during this period was driven by legislation (compliance with waste management regulations) and technologies. Some of the waste management approaches are discussed below.

2.5.1 Waste Hierarchy

According to Wilson (2023), the primary focus of the developed legislative framework was technical, aimed at raising the level of control of treatment and disposal facilities. The operationalisation of the developed frameworks, however, required the development of further regulations and either statutory or advisory guidance to operationalise them. Unfortunately, the implementation of these disposal regulations resulted in a rapid increase in waste disposal facility costs. Therefore, the focus of waste management at the time was to comply with the set legislative standards of environmental control at the least cost. As a consequence of the implemented legislation, this resulted in an improvement of the economics for waste reduction, reuse and recycling (the '3Rs'). However, it also presented an opportunity for organised waste crime (Wilson, 2023). The 1990s saw the initial shift in waste management practices towards a more, holistic, interdisciplinary, systems thinking, 'integrated' approach to deal with these challenges (Wilson, 2023). The period saw the explicit development of what is termed "waste hierarchy" today, a conceptual hierarchical sequence of preferred options in waste management, that first appeared in the 1970s (e.g. in the RCRA showing order of preference for managing hazardous wastes).

The waste hierarchy concept appeared in the European Union's Council Directive 91/156/EEC of 18 March 1991 European Union (1991) and in the 1993 Dutch Environmental Management Act (Wilson, 2023). It was not until the Waste Framework Directive

2008/98/EC was introduced in 2008 that the EU context of the concept of a waste hierarchy was realized (Figure 2.1), together with clearly defined priority order for prevention and waste management operations (Zhang et al., 2022a). The Waste Framework Directive 2008/98/EC went further to clarify the basic concepts related to waste management, including definitions of waste, recycling and recovery. The waste hierarchy was introduced as a sustainable way for waste management by ranking waste prevention and management options in order of priority (Eriksson, 2015). It provided a pyramid of priorities for managing waste which acted as a blueprint for other member states in the EU to develop their country-specific programs. This waste framework Directive required that waste be managed without endangering human health and harming the environment. The waste hierarchy approach to waste management became the cornerstone of today's waste management practice for developed countries.

While there is a general acknowledgement of the successes of the waste hierarchy approach, some researchers have however articulated that the waste hierarchy was limiting because it only viewed and recommended better strategies for waste management based solely on the environmental standpoint, and not taking into account the social, economic and logistic considerations. These reservations led to further development of other approaches to waste management.

Figure 2.1: The waste hierarchy approach to waste management. *https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en*

(Accessed: 7 January 2024)

2.5.2 Integrated Solid Waste Management

One approach that is closely linked to the waste hierarchy and which has been applied in waste management is the integrated solid waste management system. Integrated solid waste management systems have been employed to address solid waste management challenges with the objective of minimising waste disposal (Robinson, 2018). An integrated solid waste management system can be understood as a comprehensive strategy involving the four key elements, waste prevention, recycling, composting, and disposal program, which are blended for the same objective, of managing solid wastes. It is a strategic approach to sustainable management of solid wastes which covers all aspects of the solid wastes from the sources, segregation, transporting, sorting, treatment, recovery and finally disposal in an integrated manner, with an emphasis on maximising resource use and efficiency. This approach involves the application of suitable techniques, technologies and management programs covering all types of solid wastes from all sources to achieve the twin objectives of waste reduction and effective management of waste.

This framework was first articulated in the context of developing countries where some of the legislation to curb the production of solid waste, and to manage it, as proposed in the waste hierarchy was either impractical or faced other challenges. For instance, according to Wilson (2023), it was observed that in developing countries, the constraints to extending collection coverage and controlled disposal were identified as institutional and financial rather than technical (Wilson, 2023). This led to the development of a framework that considers handling solid waste challenges from a holistic point of view. The integrated solid waste management concept is built upon four basic principles of equity, effectiveness, efficiency and sustainability. According to Muzenda et al. (2012), the primary goal of integrated solid waste management is to enable each community to handle its solid waste in the most effective, cost-efficient, safe and environmentally beneficial manner that is financially and realistically possible.

The framework applies the waste hierarchy to the local waste management process by evaluating the local needs and conditions, considering all the options and selecting the most effective ways of protecting the people and the environment using the available resources. The integrated solid waste management framework acknowledges that while there are several options for solid waste management as shown in the waste hierarchy (Figure 2.1), no single or simple solution exists to deal with all the challenges of solid waste.

The integrated approach proposes that solid waste management should rather take a holistic approach by combining elements of several strategies instead of focusing on only one, irrespective of which of the options offer improved benefits for the environment and the citizens. Integrated solid waste management became the cornerstone of solid waste management practices around the world because of its ability to consider various other factors for waste management, instead of a focus solely on the environment. Apart from the European Union, other countries such as China, Japan, the USA and Korea employ integrated waste management as the essential principle for waste management policymaking (Zhang et al., 2022a). The framework still pushes for the prevention of waste as the preferred option and sending waste to landfill as the last resort.

2.5.3 Zero Waste Approach as Sustainable Waste Management System

Integrated solid waste management systems and the other approaches used for managing waste around the world have had quite some success in waste minimisation, with many European countries reporting a considerable decrease in waste disposal at landfills (Chioatto et al., 2023). However, there have also been many cases of failures in some parts of the world, e.g. in South Africa where landfilling is still phenomenally high despite enacting integrated solid waste management practices in 2008. Moreover, waste and pollution from municipal and industrial activities, combined with factors like population growth and climate change, are increasing the strain on our finite natural resources (Öztaş, S., & Bektaş, 2022a). However, while much of the discussion surrounding waste management have focused on ways of addressing the challenge of accumulation of waste, another problem that has become a reality is resource scarcity due to unsustainable production and consumption practices. This has led to continued research into other methods that would help deal with the gaps in these approaches and looking into other approaches that can lead to sustainable waste management in line with SDG 11.6.

One of these approaches that has found much interest is the adoption of the circular economy in systematic solid waste management strategies. This approach is aligned to a net-zero waste agenda, therefore promoting a sustainable environment and the economy.

This approach is referred to as the "Zero Waste Approach" in this study (Mapani et al., 2022).

The circular economy model is an approach to economic development that emphasises the importance of sustainability, resource efficiency, and waste reduction (Franco-Garcia et al., 2019). It is a system that is built on the idea of circularisation of productive processes by creating closed cycles of materials and energy flows (Avilés-Palacios et al., 2021). It is believed to be one of the key economic models that can help the world attain the objectives of sustainable development as it is focused on the transformation of waste into resources that can be reintroduced into the economic value system through proper management of the various processes. As a result of this approach to production and resource consumption, the linear and waste-producing value chain problems convert waste into resources and thereby waste generation and waste volumes. This approach has its roots in the triple bottom line framework which indicates that sustainable waste management is a multidisciplinary problem that connects the social, environmental and economic pillars of sustainability, and therefore needs a holistic approach.

The EU has already revised its major waste management directives and incorporated the Circular Economy model into its environmental policy in 2015 with the aim of reducing resource extraction through the implementation of innovative ways of production and consumption (Chioatto et al., 2023). These directives regulate waste management practices in European countries. The Waste Directive 2018/851 reinforced the targets for municipal solid waste recycling and reuse to 55% by 2025, 60% by 2030, 65% by 2035 while and Waste Directive 2018/850 redefined the target on municipal landfilling to less than 10% of the total amount of municipal solid waste generated by 2035.

By considering the Circular Economy model, a new waste hierarchy for zero waste has also been developed (Figure 2.2). The hierarchy promotes the reuse of products as much as possible, and recycling (including composting) where reuse is not possible. European countries have been making significant progress towards zero waste in line with the sustainability goals. According to statistics from 2021, 49.6% of all municipal waste in the EU is recycled or composted - an increase of 3.6% compared with 2017. According to Chioatto et al. (2023), Germany, Bulgaria, Austria and Slovenia have already reached or exceeded this 60% target. According to the European Parliament News (2023), the share of landfills in the European Union decreased from 24% in 2017 to 18% in 2020, which highlights tremendous progress towards zero waste.

This discussion on new waste management strategies highlights the progress that is being made in other parts of the world. Unfortunately landfilling remains the waste disposal of choice in developing countries because of several waste management challenges (Danthurebandara et al., 2012; Vergara & Tchobanoglous, 2012). Due to the lack of sufficient sanitary landfill facilities and other logistics such as waste collection, open dumping remains one of the major challenges faced by developing countries (Kadama, 2011). Globally, the general parlance in urban solid waste management is based on the "polluters pay" principle. In developing countries, the majority of polluters dispose of their waste illegally in open dumps or poorly managed sites to escape charges involved with waste management (Kadama, 2011; Idowu et al., 2019). It can be pointed out that in increasing waste generation, the burden imposed on the municipal budget due to high costs associated with solid waste management, technical constraints, legislation and regulations are the major challenges holding the developing back in terms of their solid waste management goals (Idowu et al., 2019; Njoku et al., 2019).

Figure 2.2: The new zero waste hierarchy.

Source: https://zerowasteeurope.eu/2019/05/a-zero-waste-hierarchy-for-europe/ (Accessed : 7 January 2024)

2.6 Waste Management in South Africa

Europe has played a significant role in shaping the waste management policy and legislation that has emerged in South Africa since the late 1990s (Godfrey & Oelofse, 2017). Waste legislation in South Africa is centred around Section 24 of the Bill of Rights gives all citizens the right to a clean environment (Constitution of SA 1996) which spells out that:

"Everyone has the right –

(a) to an environment that is not harmful to their health or well-being; and

(b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that –

(i) prevent pollution and other degradation;

(ii) promote conservation; and

(iii) secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development."

The overarching legislation dealing with waste management in South Africa includes the two Acts: the National Environmental Management Act (Act 107 of 1998) and the National Environmental Management Act: Waste Act (Act 59 of 2008).

The National Environmental Management Act 107 of 1998 was the first of the Environmental Acts in the new dispensation which were enacted to address environmental issues, including solid waste management in line with this constitutional mandate. According to Zhakata et al. (2016), the National Environmental Management Act 107 of 1998 was responsible for waste management aspects in the country such as waste disposal, recycling or recovery of waste as part of the Act. However, this Act did not even have a separate definition of waste which made it difficult to regulate many recycling and recovery activities. The Act provided hazardous waste guidelines, and protection of the environment when hazardous waste is disposed of. The National Environmental Management Act: Waste Act (Act 59 of 2008) was developed based on the National Environmental Management Act 107 of 1998. The South African Waste Act introduced improved governance mechanisms of waste by introducing matters such as waste planning, performance reporting as well as designation of waste management officers. The National Environmental Management Act: Waste Act operationalised the development of integrated waste management plans by all spheres of government and industry waste management plans for specified waste generators. This Act also introduced an improved system for licensing of waste management activities, in order to control these activities and to ensure that the impacts on the human health and the environment are minimised.

South Africa also enacted several other legislative and regulatory policies to operationalise the two environmental Acts by providing guidance for solid waste management in the country. Some of the policies and regulations include the White Paper on Integrated Pollution and Waste Management (Notice 227 of 2000), the National Norms and Standards for Disposal of Waste Disposal, Waste Classification and Management Regulations of 2013, the National Norms and Standards for the Storage of Waste of 2013, and the National Waste Management Strategy of 2020 (Figure 2.3). While most of these developed policies looked progressive, unfortunately, as highlighted earlier, for most of the government programmes in South Africa, they general suffered implementation failure as a result of a lack of proper planning, unclear and vague implementation framework and/or insufficient waste services (Godfrey & Oelofse, 2017). A case in point is the Polokwane Declaration on Waste Management of 2001 which resulted in a resolution to reduce of waste going to landfills, that was declared with an accompanying 16-point working strategy for dealing with waste. One of the key resolutions of the Polokwane Declaration was the recommendation for prioritisation of waste management, development and the implementation of legislative and regulatory framework to promote waste management, and the provision of efficient and effective collection and disposal facilities. Also in the declaration was the setting of a benchmark of 50% waste to the landfills by 2012, and zero waste to landfills by 2022.

Unfortunately, a South African: State of Waste report of 2018 (Department of Environmental Affairs, 2018) highlighted that little to no progress has been made on these targets. In fact, solid waste management services in South Africa still remain a major problem with as much as 90% of the waste generated in the country ending up on the landfills for disposal (Department of Environmental Affairs, 2018). This problem is further exacerbated by the fact that South Africa is running out of landfill space, and therefore requiring urgent need to curb landfilling.

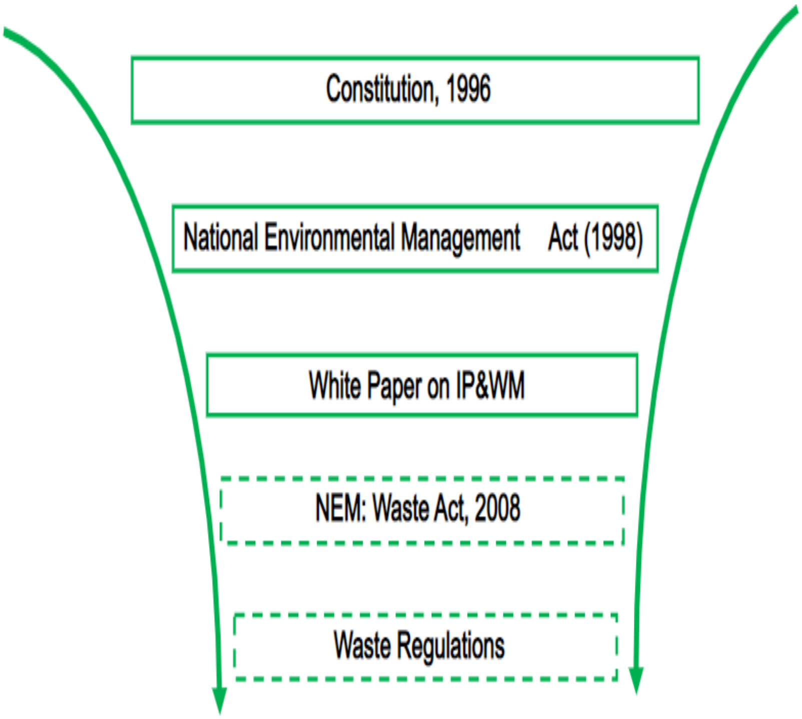


Figure 2.3: Legislative Background. (Source: Ministry of Environmental Affairs)

Source: https://slideplayer.com/slide/6117692/ *(Accessed : 7 January 2024)*

The vision of the South African government is to employ integrated waste management strategies as is included in the National Environmental Management Waste Act of 2008. As was highlighted earlier, integrated solid waste management provides a comprehensive waste prevention, recycling, composting, and disposal program to manage solid waste in ways that most effectively protect human health and the environment. Integrated waste management strategies, which came into effect with the implementation of the National Environmental Management Waste Act of 2008, are focused on decreasing waste going to the landfill, and to move waste up the waste management hierarchy. This key objective has been the focus of all subsequent legislations and regulations that were developed to guide municipal solid waste management in the (Republic of South Africa, 2013). However, to date, landfilling remains the most popular waste management practice of choice in the country, while limited reuse and recycling practices are also practiced, largely driven by the private sector. The informal sector in South Africa collects glass and PET plastic, and most of the recovered paper into the recycling economy. Incineration is also used as a waste management technique but is mainly used for medical wastes (Cairncross & Nicol, 2005).

The National Waste Management Strategy of 2020, which provides the current direction in terms of waste management in South Africa has as its key pillars, waste minimisation with a long-term target of zero waste going to the landfill (Figure 2.4), effective and sustainable waste services and enforcement, compliance and awareness. The two entry points for waste minimisation include waste prevention and stimulating a secondary resource economy based on recycling and recovery of materials and energy from the waste. This policy also advocates for waste separation at the source, which is critical for reuse and recycling. Unfortunately, a lack or absence of recycling infrastructure that would enable the separation of waste at source and diversion of waste streams to material recovery mean that most waste that end up at landfills for disposal are mixed. When considering inefficiencies at the transfer stations where sorting of wastes is performed in the current system, much of the waste that have potential for recycling or reuse are unfortunately disposed of at the landfills.

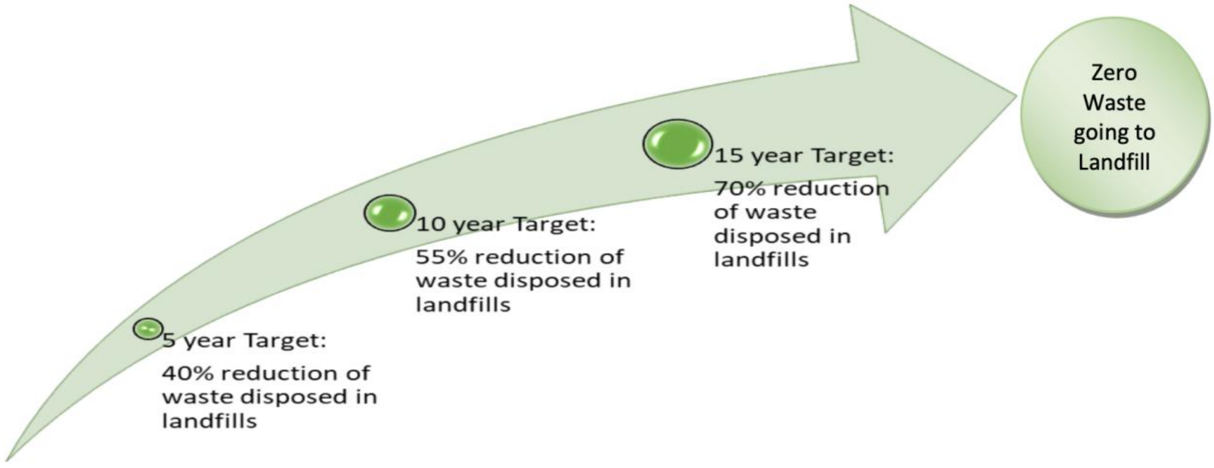


Figure 2.4: Strategic goals of the National Waste Management Strategy 2020. https://www.dffe.gov.za/sites/default/files/docs/nationalwaste_management_strategy.pdf

Source: Department of Forestry, Fisheries and the Environment (DFFE) (2020). *National Waste Management Strategy*. Available at: https://www.dffe.gov.za/sites/default/files/docs/nationalwaste_management_strategy.pdf (*Accessed: 7 January 2024).*

2.7 Landfilling in South Africa

Landfilling has been the most popular waste management technique for decades and remains necessary and the most economical option for the disposal of solid waste. The design and development of landfills have evolved over time as the environmental impacts of these sites became evident (Vergara & Tchobanoglous, 2012).

In the not too distant past when waste streams were simple and land constraint was not a challenge, landfills were called 'dumps' and were located in areas of cheap, poor-quality land which included disused quarries and low-lying marshy ground (Crowley et al., 2003). Their main purpose was to keep waste separated from the populace, hence limiting exposure to disease vectors, as well as odour and other direct effects. Landfill gas was allowed to enter the atmosphere and the leachate seeped into the grounds with no controls or monitoring of the impacts of such dumps.

The lack of adherence to the sanitary landfill principles was attributed as a leading cause of surface and groundwater pollution (Wang and Chen, 2012). One of the main reasons for the implementation of the National Environmental Management Act (No. 59 of 2008) was to address the challenge posed by several badly located, designed and operated landfill sites in the country. The same legislation requires that landfill sites be at a specified distance away from residential areas and ecologically sensitive zones, for the protection, health and safety of residents as well as the environment (IWMSA, 2017). Unfortunately, South Africa has a huge number of landfills that are not licensed and so are non-compliant (Department of Environmental Affairs Report, 2018). South Africa still has several active landfills which could be classified as dumps (Kadama, 2011). The environmental hazards posed to groundwater by 'dumps' have been recognised in recent years and at the turn of the century, efforts to close and sometimes remediate these facilities were undertaken in the country and elsewhere in the world.

Modern landfills, also known as sanitary landfills, are well-engineered and managed facilities for the disposal of solid waste that are operated under very strict environmental regulations, and each are designed and specified for certain types of waste (Idowu et al., 2019). Their design and location go through extensive review and investigation before commencement of their construction. Current practice in landfill design must consider the construction, operation, closure, restoration and aftercare of the facility. Their operation, monitoring and closure are all carried out in a way to ensure compliance with environmental regulations. The Waste Classification and Management Regulations, 2013 (Department of Environmental Affairs, 2013a) which were developed under Section 69 of the Waste Act introduced a new waste classification system and requirements for the disposal of waste to landfill. According to the regulations, waste must be classified by applying the Globally Harmonized System of Classification and Labelling of Chemicals (SANS 10234) (Department of Environmental Affairs, 2013a). This classification was implemented to ensure that different wastes are disposed of in the correct landfill sites. The main objectives of all these processes are to protect the environment from contaminants from the leachate and gaseous emissions and to protect the health and safety of residents by adequately containing the waste.

Landfill operators countrywide have been under enormous pressure to acquire licensing by implementing adequate waste sorting and classification, better landfill design, improving operation and monitoring the surrounding environment for contamination as a requirement for the National Environmental Management Act (No. 59 of 2008) and the subsequent regulations (Waste Classification & Management Regulations, 2013) (Oelofse, ND).

The sanitary landfill has a protected base where a liner, which is usually a combination of high-density polyethylene (HDPE-plastic) and a mineral layer (clay or bentonite), will prevent it from contaminating the groundwater below, with some having the capabilities of harnessing gases produced from the decomposition process (Environmental Protection Agency, 2000). These requirements for construction of the sanitary landfills have drastically increased the cost of landfilling or construction of new ones, hence resulting in significant non-compliance in South Africa (Kadama, 2011; Idowu et al., 2019). Regulations also require regular monitoring of the air and groundwater quality near landfill sites. Without collection of the leachate and proper monitoring of the possible impacts of these non-compliant landfills, the risk they cause to public health and the environment cannot be ignored.

The country has four main types of landfill sites based on the type of waste, size of waste stream and potential for leachate generation, general waste and hazardous waste landfills (Department of Environmental Affairs, 2013). While the landfills in South Africa are the cornerstone of its waste management, there are so many challenges with most of them. As was highlighted earlier, 56% of these landfills in the country are operating illegally (Department of Environmental Affairs, 2018). As was pointed out by Kadama (2011), some of the waste disposal sites in some municipalities around the country are open dumps or are former open dumps which became landfills and are unlicensed because of not meeting qualifying criteria. This also means that some of these sites are not located in suitable places. This is generally the case for landfills in smaller municipalities where service delivery has always been a challenge. A number of the older sites are classed as open dumps, and consequently, these sites have been significant potential points of pollution in the past and some still are because of no collection of leachate which consequently leaches into the ground.

A number of the major cities have seen the growth of informal settlements, with some expanding and encroaching into the buffer zones next to the landfill sites. The challenge that comes with the developments of such communities is the public safety of the residents about the impacts of these poorly managed landfill sites. Indeed, poorly located, designed and managed landfill sites are a major pollution risk, with far-reaching impacts on the public health, environment and water resources (Bialowiec, 2011; Brennan et al., 2016; Koda et al., 2017). The impacts associated with these landfill sites is further exacerbated by the lack of up-to-date information on the effect they have on the communities around, ecosystems and groundwater resources as well as the air quality.

2.8 Environmental Impacts of Landfilling

Well managed and constructed landfill sites are generally environmentally friendly and are believed to have more benefits than associated risks (Danthurebandara et al., 2012; Vergara & Tchobanoglous, 2012). Recycling and reusing are generally more favourable to the environment, so that governments across the world are generally pushing towards those waste management goals because of the economic value waste can have in addition to reduction of pollution challenges (Danthurebandara et al., 2012; Vergara & Tchobanoglous, 2012; Liu et al., 2015a; Nellesa, 2016). When landfills are poorly designed, not managed well and are non-compliant, the damage they can cause to the environment is lasting and may take years to clean up.

Landfills have a number of environmental and public health problems of concern due to emissions emanating from them. Landfills are highly chemically and biologically active bioreactors (Ham, 2005) and the degradation of wastes in the landfill results in the production of leachate and gases. Both the leachate and landfill gases consist of a complex and varying chemical composition depending on what has been disposed of at the landfill. But these are not the only worries for the public health and environment coming from the landfills. Listed below are some of the main emissions of concern that can be released from landfills.

2.8.1 Landfill Gas

Landfill gas is a gas generated in the waste decomposition processes of the waste in the landfill. Gas production within the landfill takes place at elevated temperature and the gas is usually saturated with water (Jafari et al., 2016). The composition of the gas is again influenced by the composition of the waste material on the site. The major components of landfill gas are methane (CH_4) and carbon dioxide (CO_2) (typically in a 3:2 ratio), with a large number of other constituents at low concentrations (Danthurebandara et al., 2012). Both

CH_4 and CO_2 are greenhouse gases, and therefore, their release is a major concern. Both contribute significantly to climate change, with CH_4 reported to be about 25 times more potent than CO_2. Climate issues remain one of the major global areas for discussion, with countries tasked to find ways of minimising GHGs emission (Zhang et al., 2019). Landfills remain one of the major sources of GHGs emission. However, from a human health perspective, some of the constituents found in low concentrations may be as important as the major components. This is because while these gases may never be present in levels that give rise to risks of either fire or asphyxiation, the odour associated with the gases may represent a problem even at very low concentrations, while some of the gases released are highly irritating (Crowley et al., 2003; Danthurebandara et al., 2012).

2.8.2 Wind-blown Litter

This consists of lightweight rubbish from the landfill that is blown by the wind and is easily dispersed into the environment by the wind, and sometimes water as well. This causes visual pollution resulting in injury to animals and sometimes in death due to choking or entanglement (Njoku et al., 2019). Studies show that over one million marine animals and birds are killed across the globe every year due to plastic debris in the ocean (Plastic Pollution in the Ocean, 2018). The recent campaign against the use of plastic straws to save the turtles is one such risk that is related to windblown litter.

2.8.3 Vermin and Pests

Bacteria, pests and vermin thrive on garbage. Pests and vermin are attracted to the landfill by the ready availability of food, after which they may breed, multiply and move away from the landfill. Waste coming from the waste management facilities generally arrives with an already established fly burden (Lole, 2005). High levels of rotting organic waste provide a rich food supply on which flies and their pupae can feed. Most of these pests and vermin find their way into residential areas. Along with the potential to carry pathogens from the sites with them, they are a huge risk to public health, especially the communities staying close to the landfill sites or the dumps (Wanderly et al., 2017). A number of the pests and vermin are known carriers of pathogens that causes diseases. For instance, flies are known to be responsible for the mechanical transport of some gastrointestinal diseases through cross-contamination of exposed food (Olsen, 1998). Badgers are linked with transmission of Bovine Tuberculosis to cattle (Chambers et al., 2005). It is estimated that at the worldwide scale, over five million people die every year due to waste-related diseases (Wanderly et al., 2017).

2.8.4 Leachate

By far the most worrying of all landfill emissions is the leachate. Leachate is defined as a liquid which has percolated through the waste, picking up suspended and soluble materials that originate from or are products of the degradation of the waste (Vergara & Tchobanoglous, 2012; Jadeja et al., 2019). Unmanaged dumping and non-proper segregation of waste are among the leading concerns contributing towards the generation of leachate in landfill sites. The chemical composition of the leachate is very complex and varies depending on what has been disposed of at the landfill, the degree of its decomposition, and the environment at the landfill site e.g. humidity, temperature and precipitation among others (Jadeja and Tiwari, 2019; Wilk et al., 2019).

The composition also gives an indication of the state of the biological processes occurring within the waste body and the solubility of the ions. In the early stages of waste degradation, the leachate is more acidic and is more biologically and chemically active, showing an increased BOD and COD. It has higher concentrations of many chemical species such as calcium, manganese, iron and zinc, but not ammonia, sodium and chloride, compared to latter leachate (Ham 2005; Jafari et al., 2016). As the degradation progresses, ammonia forms and affects both the pH and solubility of some of the chemical species. Many of the products of the degradation process of solid waste that seep together with this liquid are detrimental to the groundwater resources. Furthermore, leachate has hazardous effects on human health and the environment.

The composition of the leachate can be generally classified into the four classes of pollutants (Crowley et al., 2003; Gupta, 2017):

a) Organic pollutants: organic by-products of waste degradation such as
    - BOD: Measures biodegradable organic matter; ranges from 100–30,000 mg/L (higher in young landfills).
    - COD: Indicates total oxidizable organics; typically 500–60,000 mg/L.
    - TOC: Reflects overall organic load; correlates with COD.

    - Phenols and volatile organic organics (VOCs): Benzene, toluene, xylene (BTEX), and chlorinated solvents (e.g., trichloroethylene) from industrial waste.

    This class also includes specialised classes of organic compounds such as POPs, antibiotics, PAHs, dioxins etc.

b) Inorganic compounds: this includes the inorganic salts and compounds
    - Chlorides and sulphates: from salts, construction debris, and gypsum, which contribute to salinity and corrosivity,
    - Ammonia (NH_3/NH_4^+): derived from protein decomposition with concentrations that can exceed 1,000 mg/L, posing toxicity to aquatic life., and
    - Heavy Metals: Includes metals and metalloids such as lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), and mercury (Hg) from batteries, electronics, and industrial sludge.

c) Physical Parameters: includes parameters pH, conductivity, turbidity.
    - pH – Varies from acidic (4–6) in young landfills to neutral/alkaline (7–9) in mature landfills.
    - Conductivity – High values (2,000–20,000 µS/cm) indicate dissolved ions (salts, metals).
    - Turbidity – Measures suspended solids; affects light penetration in water bodies.

d) Nutrients: Nitrates (NO_3^-) and Phosphates (PO_4^{3-}) – Promote eutrophication in surface waters; linked to agricultural and food waste

The constituents of these classes are generally by-products of the degradation process of solid waste materials and all of these emissions constitute a serious threat to both public health and the environment. Economic losses due to clean up or remediation processes caused by pollution, especially to the soil, as well as surface and groundwater are enormous (Vergara & Tchobanoglous, 2012; Varvekova, 2019). In general, the clean-up process takes years to restore the environment to its natural state. One of the major problems with those staying close to landfills is odour and insects, especially flies, as already discussed. Land close to landfill sites loses its value because of the impacts of a landfill being closer to places of residence.

2.9 Leachate Impacts on Groundwater and Surface Water

Surface and groundwater are major natural resources and are the largest sources of freshwater with both ecological and economical value (Vergara & Tchobanoglous, 2012). For this reason, their protection from pollution is of prime importance (Varvekova, 2019; Wilk et al., 2019). Unfortunately, pollution by landfill leachate is one of the main reasons for deterioration of water quality and therefore represents one of the most significant threats to these natural water resources globally.

Leachate is very toxic, and its control is very important in order to reduce its impact on the surface and groundwater (Crowley et al., 2003; Vergara & Tchobanoglous, 2012; Varvekova, 2019; Wilk et al., 2019). The main concern for surface and groundwater pollution is not just the toxicity of the leachate, but also the persistence of the effects of the discharge which still cause damage long after the pollution event (Varvekova, 2019; Wilk et al., 2019). Leachate from landfills may leak into groundwater aquifers due to rainfalls, spread into the adjacent river system by groundwater flow and pollute the surrounding environment. As the liquid percolates through decomposing waste, it accumulates a complex mixture of organic compounds, heavy metals, and other hazardous substances that can migrate into both groundwater aquifers and surface water bodies (Mor et al., 2018). This leaching of landfill leachate continues even after the landfill activities have stopped receiving solid waste and, hence, the need to keep assessing and monitoring the surroundings of decommissioned landfill sites. This section examines the mechanisms of leachate migration, analyses surface water contamination pathways, and discusses the consequent health and ecological impacts, supported by scientific evidence.

2.9.1 Mechanisms of Leachate Migration

Leachate primarily contaminates water systems through subsurface percolation and hydraulic dispersion (Fetter, 2018). When precipitation infiltrates a landfill, it generates leachate that moves downward through the unsaturated zone under gravitational force. Upon reaching the water table, the contaminated liquid spreads horizontally along hydraulic gradients, forming plumes that can extend kilometers from the source (Kumar et al., 2022). The rate and direction of migration depend critically on the hydraulic conductivity of subsurface materials, with sandy soils permitting faster flow than clay layers (Cirpka et al., 2016). Preferential pathways such as bedrock fractures or poorly engineered landfill liners can accelerate this process, enabling rapid contaminant transport to sensitive receptors (Mor et al., 2018).

Empirical evidence from global case studies demonstrates the severe consequences of leachate migration. At India's Ghazipur landfill, groundwater monitoring revealed ammonia concentrations exceeding 100 mg/L, which was 50 times the WHO guideline value - alongside dangerous levels of lead and chromium from co-disposed industrial wastes (Kumar et al., 2022). In the United States, the Love Canal disaster remains a seminal case where VOCs and dioxin leakage from an abandoned landfill caused unprecedented health crises, including clusters of birth defects and cancers, ultimately prompting the creation of the Superfund program (USEPA, 2020). Malaysian researchers similarly documented COD levels surpassing 2000 mg/L and lead concentrations that were five times above safe limits in groundwater adjacent to the Taman Beringin landfill (Aziz et al., 2020). These cases underscore the universal vulnerability of groundwater systems to leachate infiltration, particularly where regulatory controls are inadequate.

2.9.2 Surface Water Contamination Pathways

Surface waters face equally severe risks through three primary contamination pathways. The first one being stormwater runoff, which transports suspended solids, heavy metals, and organic pollutants from landfill surfaces to nearby watercourses. The second one is the direct leaching of leachates which occurs when unlined landfill bases allow continuous contaminant seepage into adjacent water bodies, often introducing nutrient loads that trigger environmental problems such as eutrophication (Nevondo et al., 2019; Siddiqua et al., 2022). The third pathway involves extreme weather events such as floods which can cause catastrophic contaminant dispersal as water flows through the landfill sites (Brand et al., 2018; Nevondo et al., 2019). These pathways demonstrate surface water's susceptibility to both chronic and acute contamination events.

2.9.3 Health and Ecological Consequences of Chemical Contamination of Ground and Surface Water

The human health impacts of leachate-contaminated water are well-documented and severe. For instance, Naujokas et al. (2013) highlights the dangers of chronic exposure to arsenic in groundwater, which causes skin and lung cancers, while benzene induces leukaemia (Snyder, 2012). This section discusses the health and ecological impacts of some of these chemicals and physical parameters.

2.9.3.1 Physical Parameters

The first impacts discussed in this section are the physical parameters. This study investigated the pH, electrical conductivity and turbidity of the water and leachate samples from sources around the landfills and that of the leachates from the landfill sites. The pH is one of the most important water parameters that is monitored regularly to check whether water is safe for disposal, consumption or for monitoring any signs of pollution. The pH of a solution is influenced by its composition. For freshwater systems, the pH is affected by a number of chemical and biological processes in the water which, in turn, impacts other processes. For instance, heavy metals become increasingly mobile and available for uptake by aquatic plants and animals at lower pH values because they are more soluble in water with lower pH values. Therefore, low pH values tend to reflect greater potential for toxicity for aquatic animals and make freshwaters unsuitable for consumption.

The other parameter that is key in contamination monitoring is electrical conductivity (EC). EC is one of the most important parameters of interest in water quality monitoring which measures the ability of water to conduct electricity. While naturally occurring minerals contribute to background EC levels, anthropogenic activities like industrial discharge, agricultural runoff (fertilizers, pesticides), mining effluents, road salt application, and landfill leachate infiltration can significantly elevate conductivity in natural water bodies (rivers, lakes, streams, wetlands). In the presence of high levels of ionic salts and other inorganic substances in water, the value of EC is enhanced (Omer, 2019). Thus, high EC values are associated with the presence of elevated levels of ions in the water. EC is one of the main parameters used to determine the suitability of water for irrigation and other important industrial uses (Omer, 2019). According to the WHO guidelines (Meride & Ayenew, 2016), EC of water should not exceed 400 $mS.m^{-1}$. In comparison, the SANS:241 (2015) guidelines stipulate that the EC for water that may be used for domestic purposes should not exceed 170 $mS.m^{-1}$. High EC is rarely a direct toxicant itself but acts as a surrogate for elevated concentrations of potentially harmful dissolved ions, posing significant risks to human health through multiple exposure pathways

The other physical parameter, is turbidity, a parameter as described as an optical characteristic of water that measures its relative clarity or cloudiness (Omer, 2019; Fahimah et al., 2023). Turbidity has significant impacts on the ability of the light to pass through the water, and therefore has significance influence on aquatic life. This parameter is affected by the levels of total dissolved solids and suspended materials (e.g. clays, organic material and other particulate matter) in the water. According to Fahimah et al. (2023), higher levels of turbidity are often associated with higher levels of disease-causing microorganisms such as viruses, parasites and bacteria. The presence of high amounts of suspended materials can clog or damage fish gills and decrease their resistance to diseases and their growth rates (Omer, 2019). In addition, the suspended particles provide a good adsorption surface for heavy metals and hazardous organic pollutants such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and many pesticides. According to the SANS-241 (2015), the maximum allowable turbidity values for drinking water is 4 NTU (aesthetic risk). Leachate samples are expected to show high values of turbidity (Azougarh et al., 2019), because of excessive amounts of total dissolved solids (TDS) as well as suspended particulate matter in the water. According to Azougarh et al. (2019), the range of turbidity in leachates may lie between 1330 NTU and 2420 NTU. Turbidity of water in natural environments may range from as low as 1 NTU to 2 NTU in fresh water to >30 NTU for river water samples collected from rivers with sediments, especially during the rainy season because of an increase in the suspended sediment load (Azus et al., 2015).

2.9.3.2 Chemical Parameters

The chemical parameters of interest in the water includes anions (e.g. chlorides, sulphates, phosphates etc.), nutrients (e.g. nitrates, phosphates, etc.) and heavy metals (e.g. manganese, lead, mercury, etc.) in the water and leachate samples from sources around the landfills site. The organics, though not covered in this study are also here in the frame of the impacts on the environment.

2.9.3.2.1 Chloride

The final degradation soluble salts in the leachate contain chloride as the major contributor of their ionic strength. Chloride is generally found in all types of natural waters such as rivers, streams, dams and lakes, with levels that are typically less than 20 mg/L. According to (https://ei.lehigh.edu/envirosci/watershed/wq/wqbackground/chloridebg.html), the chloride range of 35-155 mg/L is generally considered normal for surface water bodies while concentrations greater than 250-400 mg/L cause the water to taste salty. Chloride concentrations are typically high in landfill leachates as a result of food waste deterioration at the landfill. Concentrations of chloride in freshwaters above 250 mg/L are usually interpreted as indicative of pollution from anthropogenic activities such as discharge of waste from the chemical industry, contamination from waste leachates, or seawater intrusion in coastal sites. Higher chloride concentration can cause a problem to fish life, and are associated with dehydration, kidney failure, nervous system dysfunction, and death in extreme cases. The SANS-241 (2015) limit for chloride in water is 250 mg/L.

2.9.3.2.2 Sulphate

Sulphate is ubiquitous in wastewater and in natural water systems where its levels are driven by leaching of minerals with soluble sulphates such as gypsum, melanterite, chalcanthite, magnesium sulphate and others (Omer, 2019). Discharge from industrial and domestic waste tends to increase sulphate levels in natural water systems. Sulphate concentrations vary depending on the source of the discharge (Environmental Protection Agency, 2000). Methanogenic leachate generally contains low concentrations (median of 35 mg/l) whereas on average acetogenic leachate contains up to 10-fold higher sulphate concentration. High levels of sulphate in water, though it doesn’t have any significant public health or environmental challenge, causes water to lose taste. Sulphate, if present, are likely to cause a problem due to reduction to hydrogen sulphide which gives rise to odour problems at low odour thresholds (Environmental Protection Agency, 2000). According to Zak et al. (2021), typical freshwater levels of sulphate range from 0 to 630 mg/L in rivers, 0 to 250 mg/L in lakes, and from 0 to 230 mg/L in groundwater. The SANS-241 (2015) limit for sulphate in drinking water is 250 mg/L while a limit 500 mg/L is stipulated as an acute health risk. The USEPA (2001) recommended a limit of sulphate in water of 200 mg/L, slightly lower than the limits in South Africa.

2.9.3.2.3 Nitrogen as ammonia, nitrate and nitrite

Nitrogen compounds are one of the most important class compounds of interest in landfill leachates and studies of water quality (Environmental Protection Agency, 2000). Nitrogen exits in natural water systems in three different forms: ammonia (NH_3), nitrate (NO_3^-), and nitrite (NO_2^-). Of these, nitrate is the most important as an essential plant nutrient. The nitrates and nitrites are products of the biological decomposition of ammonia, which is one of the major products of degradation of organic matter. Ammonia formation tends to increase with the age of the leachate. It is a product of the hydrolysis and fermentation of the nitrogenous fraction of the biodegradable substrate. According to Kabdasli et al. (2020), the average amounts of ammonia in leachate are as large as 965 mg/L. Ammonia is particularly toxic to aquatic life and may not be discharged to surface water bodies other than in very low concentrations (Schullehner et al., 2017). For both fresh water and salt water, most research studies show acute toxicity effects for salmonid and non-salmonid fish species between 0.002 mg/land 10 mg/l of un-ionised ammonia (Environmental Protection Agency, 2000; Kabdasli et al., 2020).

Nitrate in natural waters is a common water pollutant originating from agricultural activities (Shigut et al., 2017). In water containing considerable amounts of dissolved oxygen, nitrates are also formed from the nitrification of ammonia, where ammonia is converted into nitrites and finally nitrates (Saleem & Algamal, 2016; Schullehner et al., 2017). However, when the water system is polluted with nitrogen-rich organic matter, the decomposition of the organic matter depletes the dissolved oxygen which, in turn, slows the oxidation of ammonia to nitrate. As a result, monitoring of nitrogen in the water systems usually characterises all three nitrogen species. Nitrate is more mobile than other nutrients like phosphates because of its solubility in water. Therefore, nitrates from anthropogenic sources such as wastewater effluents and agricultural activities end up in rivers and streams more quickly than other nutrients and is therefore a common water pollutant. The typical levels of nitrate and ammonia in natural water systems are generally very low (<1 mg/L). The concentrations are, however, considerably higher in the effluent from wastewater treatment plants where the concentration may exceed 30 mg/L. Nitrate in groundwater is generally driven by the leaching process as the water percolates into the ground (Feng et al., 2020). According to Shigut et al. (2017), while nitrate is common in natural waters, concentrations above 3 mg/L in groundwater generally indicate contamination. For both the WHO (2017) and SANS-241 guidelines, the upper limit for nitrate in water is 50 mg/L while the upper limits for nitrite and ammonia are 3 mg/L and 1.5 mg/L, respectively.

Nitrites and ammonia are considerably more toxic to aquatic life than nitrate (Shigut et al., 2017). Nitrate and nitrite in drinking water can negatively impact human health - nitrates are known to cause an acute condition called methemoglobinemia in infants (Schullehner et al., 2017). Ecologically, ammonia concentrations as low as 2.5 mg/L prove lethal to aquatic organisms (Edwards et al., 2023).

2.9.3.2.4 Heavy Metals

The disposal of excess quantity of heavy metals on landfills causes significant damage to the environment and human health as a result of their mobility, longevity, solubility and their ability to transfer in water or plants (Environmental Protection Agency, 2000; Adel-Salam & Abu-Zuid, 2015). Conditions within the landfill during the acetogenic phase are such that the leachate can aggressively chemically dissolve various inorganics. Due to this process, the resulting leachate may contain high concentrations of iron, manganese, calcium, and magnesium (Environmental Protection Agency, 2000; Chuangcham et al., 2008). On the other hand, conditions during the methanogenic stage reduce solubility of heavy metals and the levels of dissolved metals tend to be low. Heavy metals in leachate include chromium, cadmium, lead, mercury, nickel, copper, zinc, iron, and selenium (Chuangcham et al., 2008).

Heavy metals are some of the most concerning of the pollutants, and some of the important pollutants of interest whenever there is a potential pollution source like landfill leachate. Higher concentrations of metals, especially the heavy metals, are not good for the environment and health. Heavy metals pose long term risks to the earth's ecosystem because of bioaccumulation, sometimes beyond the tolerance thresholds of living organisms (Chuangcham et al., 2008; Vergara & Tchobanoglous, 2012; Varvekova, 2019). In small concentrations, heavy metals are toxic, as such they have the potential to cause cancer. This is attributed to municipal as well as industrial solid waste. In general, the larger part of the metals does not leach with the leachate, thus this process continues for a long time in the life of the landfill (Chuangcham et al., 2008).

Municipal landfill leachates can be major sources of a number of toxic and heavy metals that are of both of environmental and public health concern (Ahmad et al., 2021; Essien et al., 2022; Hosseini Beinabaj et al., 2023). The major problem with heavy metal pollution is that while they end up in that natural waters in the environment, their bioaccumulation in some of the products we consume like mercury in fish creates secondary exposure routes for humans. The major problem is that these impacts persist for decades. The heavy metals of interest in this study included chromium (Cr), manganese (Mn), arsenic (As), cadmium (Cd), and lead (Pb).

Of these heavy metals, cadmium, Pb and arsenic are some of the most toxic even in trace levels. Cadmium is a heavy metal that is available naturally in the environment in trace amounts. However, it is also introduced into water and soil through different anthropogenic activities such as application of fertilisers, and industrial and waste management activities (Genchie et al., 2020). Cadmium is a very toxic heavy metal that is a major health risk for both humans and animals. It is a carcinogen that is associated with several types of cancer such as breast, lung, prostate, nasopharynx, pancreas and kidney cancers (Genchie et al., 2020). Exposure to cadmium is primarily through the ingestion of contaminated food and water. It accumulates in plants and in animals where it stays for an extended period, with a half-life of about 25–30 years. As a control for this toxic metal, the allowed levels of cadmium in water should not exceed 3 μg/L. According to Kubier et al. (2019), cadmium levels in surface water are in the range from 0 μg/L to 5 μg/L in and up to 1 μg/L in groundwater.

Like cadmium, arsenic is increasingly becoming one of the most concerning elements because of a global increase in public health concern surrounding exposure to humans through contaminated groundwater and other human activities (Fatoki & Badmus, 2022). It is linked to a variety of neurologic, cardiovascular, dermatologic and carcinogenic effects (Patel et al., 2023). Its elevated level in the environment is now regarded as a global problem where it is present in various inorganic and organic chemical forms. It is a pollutant that is known to be toxic to both animals and plants. The SANS-241 and WHO limits for arsenic in drinking water are 10 mg/L. According to Shankar et al. (2014), groundwater concentrations of arsenic in the literature were reported in a wide range from less than 0.5 ppb to 5000 ppb. Irnawati et al. (2021) reported arsenic concentrations in river water ranging from 0.80 to 166 mg/L. According to Singh et al. (2010), the baseline concentrations in river waters are generally low with concentrations from 0.1 mg/L to 2 mg/L.

Lead is one of the most toxic heavy metals that has been studied intensively in environmental sciences. It is found in the environment in trace amounts and has seen widespread use in different industries e.g. in batteries, which has resulted in its increase above its natural levels, causing extensive environmental contamination and health problems in many parts of the world. It is an extremely toxic heavy metal that is known to disturb various physiological processes in plants and animals and has no known biological function (Jaishankar et al., 2014). According to Balali-Mood et al. (2021:4), this pollutant is mainly absorbed from the respiratory and digestive systems, where exposure is associated with medical conditions such as "neurological, respiratory, urinary, and cardiovascular disorders due to immune-modulation, oxidative, and inflammatory mechanisms." Because of its toxicity, lead is one of the heavy metals that is constantly monitored. According to Danziger and Mukamal (2022), lead is found in very low amounts in water and is more soluble in water with a lower pH, which means that the uptake and toxicity of lead increase with a decrease in pH. According to the SANS-241 (2015) and WHO guidelines, the standard for lead is 10 mg/L.

The other metals investigated in this study included manganese and chromium. Manganese is an element that is required by all living organisms in trace amounts where it plays critical biological functions in different organisms (Wu et al., 2022). For instance, it is used as a protein transporter in humans and animals. Industrially, it is a key element used in the production of alloys, batteries, electrode materials and catalysts. Unfortunately, overexposure to manganese is also associated with some negative effects regarding environmental and public health. For instance, bioaccumulation of manganese in the central nervous system can result in adverse neurological effects in humans (Wu et al., 2022). It is generally found in low concentrations in water, either as dissolved Mn^{2+} ions or particulate manganese oxides at levels of up to 200 mg/L (Canada Government - Federal-Provincial-Territorial Committee on Drinking Water, 2016). Chromium is a toxic element whose impacts are dependent on oxidation state. According to Ahmad et al. (2023), the most toxic of its forms is Cr(VI) which is highly carcinogenic. According to Zhuo et al. (2023), this is one of the most hazardous environmental heavy metals and is very toxic to living organisms. It causes tissue damage as well as cardiovascular and liver disease and is therefore a major public concern.

2.9.3.2.5 Organic Compounds

Leachate contains a large amount of organic matter. The principal organic content of leachate is formed during the waste breakdown process and its organic strength is normally measured in terms of biological oxygen demand (BOD), chemical oxygen demand (COD), or total organic carbon (TOC). Organic matter, sometimes referenced as organic loading, is a very important factor because of its effect on dissolved oxygen when compounds are broken down aerobically (Jadeja and Tiwari, 2019; Shah & Gami, 2019). This process causes the dissolved oxygen levels in the watercourses to fall and therefore threaten aquatic life, especially fish. When the values of these parameters are measured and compared with those from guidelines, conclusions can be drawn on whether leachate emissions have occurred or not.

Other classes of organic compounds of interest in the leachate samples are xenobiotic organic compounds (XOCs) as well as pharmaceuticals (Paxeus, 2000; Baun et al., 2004; Wilk et al., 2019). The XOC include a variety of compounds such as aromatics, chlorinated aliphatics, phenols, pesticides and others. In this study, antibiotics in the leachate and groundwater are investigated. A number of these XOCs are formed as products of the degradation process or remain in the water because they are not biodegradable. Paxeus (2000) identified hydrocarbons such as the PAHs, aromatics, traces of alkenes, terpenes and a number of others. As many as 35 compounds that were identified are on the list of priority pollutants. In general, some of the compounds are listed as persistent organic pollutants (POPs) with serious potential for both environmental and public health effects. Some are very toxic even in small amounts. Other studies have shown presence of pharmaceuticals in the landfill leachate (Borquaye et al., 2019; Chung et al., 2019). Chung et al. (2019) described research to determine the presence of commonly used human antibiotics: (cephalexin [CLX], chloramphenicol [CAP], ciprofloxacin[CIP], erythromycin [ERY], roxithromycin [ROX], trimethoprim [TMP] and sulfamethoxazole [SMX]), in the leachate from closed and active landfills in Hong Kong, and observed the presence of these antibiotics that differed among leachates of closed and active landfills during wet and dry seasons.

Summary

It can be concluded that leachate needs to be controlled in a landfill to:

- reduce the potential for seepage out of the landfill through the sides or the base by exploiting weaknesses in the liner.
- prevent liquid levels rising to such an extent that they can spill over and cause uncontrolled pollution to ditches, drains, watercourses etc.
- influence the processes leading to the formation of landfill gas, chemical and biological stabilisation of the landfill.
- minimise the interaction between the leachate and the landfill liner.

However, with poorly designed landfills, and with some not even having the structural capabilities to collect the leachate, the possibility of leachate emission into the groundwater resources is a real threat (Jadeja and Tiwari, 2019). Also of importance is the soil around the landfill that may be polluted by the leachate due to surface water runoff from the landfill sites. Several pollutants, such as heavy metals, polyaromatic hydrocarbons (PAHs) and pharmaceuticals, can all accumulate in the soil around the landfill sites due to adsorption of the pollutants on the soil as the leachate seeps into the ground (Crowley et al., 2003; Wilk et al., 2019).

2.10 Methods for Assessing Environmental Impacts of Landfill Sites

The determination of the environmental impact of landfill sites is a critical area of study in science because of the increasing challenges associated with waste management and its implications for public health and the environment. Landfills pose significant environmental risks, including groundwater contamination, air and soil pollution, and ecosystem degradation. As a consequence, it is crucial to develop thorough assessment methodologies to quantify and manage their effects on public health and the environment. To mitigate these risks, leachate and water quality analysis is essential for assessing contamination levels, identifying pollutant sources, and implementing remediation strategies. The evaluation of these impacts are generally carried by employing a combination of field monitoring**,** laboratory analysis, geospatial techniques, and modelling approaches. Modelling and experimental determination of targeted analytes are the most common (Koda et al., 2017; Naveen et al., 2014). Modelling is dependent on successful prediction of the amount of landfill leachate generated and its composition, and this is a highly complex and difficult task. On the other hand, models are important because they help in visualising a bigger picture, especially understanding the extent of the problem, and to provide guidance in cost estimation for remediation purposes (Abdullah et al., 2018). However, experimental determination is usually the most convenient and easier of the two. These different approaches are discussed in the sections below.

2.10.1 Laboratory Analysis

This approach hinges on precise leachate and water quality analysis, which provides critical data on contaminant migration and ecological risks ((Jadeja and Tiwari, 2019; Shah & Gami, 2019). This integrated process combines field sampling protocols with advanced laboratory techniques to characterize pollutants threatening groundwater and surface water resources, enabling rigorous assessment of landfill-derived pollution. This approach reveals the chemical and biological mechanisms driving environmental impacts.

Leachate characterization involves comprehensive testing of the chemical parameters of the different samples for inorganic ions (e.g., chloride, ammonium, heavy metals) using tools such ion chromatography (IC) and inductively coupled plasma mass spectrometry (ICP-MS). Organic pollutants—including benzene, toluene, ethylbenzene, xylenes (BTEX), polycyclic aromatic hydrocarbons (PAHs), and phthalates—are quantified using gas chromatography-mass spectrometry (GC-MS) or high-performance liquid chromatography (HPLC) (Borquaye et al., 2019; Chung et al., 2019). Toxicity testing employs bioassays (e.g., Daphnia magna mortality, Vibrio fischeri bioluminescence inhibition) to evaluate ecological risks.

Soil and groundwater samples undergo sequential extraction to determine metal speciation (e.g., bioavailable vs. residual fractions) and mobility. Isotopic analysis ($\delta^{13}C$, $\delta^{2}H$) traces contaminant origins and degradation pathways (North et al., 2004). Microbiological analyses, including DNA sequencing and enzyme activity assays, assess microbial communities responsible for waste decomposition and methane oxidation in cover soils. Emerging techniques include non-target screening using high-resolution mass spectrometry (HRMS) to identify unknown contaminants and ecotoxicogenomics to link chemical exposure to genetic responses.

A study by Adamcová et al. (2016) highlights the importance of laboratory analysis in the monitoring of landfills containing hazardous materials by analysing the soil and groundwater. Results of such analysis can conclusively determine whether the soil or the groundwater have been contaminated with leachate. In some studies, inorganic trace elements have been used as indicators of leachate contamination of groundwater (Wdowczyk et al., 2020; 2024). The most common analysis performed for such investigations involves determination of a diverse of physicochemical and biological parameters from the soil, the surface and groundwater, and the leachate. Examples of such analysis include:

- determination of physicochemical parameters: (pH, conductivity, total dissolved solids, chloride, total suspended solids, COD, BOD, total nitrogen, ammonia, nitrate-N, nitrite–N, sulphates, phosphates) (Adel Salam & Abu-Zuid, 2015).
- determination of targeted analytes such as heavy metals, pharmaceuticals and pesticides (e.g. Wilk et al., 2019).
- analysis for presence of microbes (e.g. Wilk et al., 2019).

2.10.2 Field Monitoring

Field surveys and monitoring techniques are crucial in evaluating the consequences of landfill sites. This approach involves regular sampling and analysis to detect any changes or pollutants that may indicate environmental impact. This technique provides direct, real-time data on landfill emissions and their migration pathways through physical measurements at the site (Soupios & Ntarlagiannis, 2017). The approach establishes baseline conditions and detects temporal changes in environmental parameters, forming the empirical foundation for impact assessments. Field monitoring typically includes groundwater monitoring, landfill gas monitoring and leachate monitoring.

Groundwater monitoring is critical, typically involving strategically placed wells upgradient, downgradient, and within the landfill footprint. Multi-level samplers track contaminant plumes vertically and horizontally, measuring parameters like pH, electrical conductivity, dissolved oxygen, and contaminant concentrations (Zhao et al., 2023). Automated sensors enable continuous tracking of hydraulic head fluctuations and contaminant breakthrough, revealing leachate migration patterns. This approach has been used for much longer periods to monitor groundwater contamination using electrical earth resistivity surveys (Cartwright & Sherman, 1972). Ground penetrating radar and reflectance spectroscopy can characterize landfill structure and leachate distribution, aiding in risk-based management (Ferrier et al., 2009).

Landfill gas (LFG) monitoring employs static chambers, flux boxes, and tunable diode lasers to quantify methane (CH_4), carbon dioxide (CO_2), and trace volatile organic compounds (VOCs) at the surface. Subsurface gas probes measure gas composition and pressure gradients within the waste mass (Scheutz et al., 2009). Surface emissions surveys using flame ionization detectors (FIDs) identify fugitive emission hotspots, essential for greenhouse gas inventories and explosion risk mitigation.

Leachate monitoring involves collecting samples from drainage systems, sumps, and perimeter ditches. Field parameters like temperature, turbidity, and oxidation-reduction potential (ORP) are measured on-site. Lysimeters installed below liners directly assess liner integrity and contaminant migration (Elmaghnougi et al., 2022). Soil gas probes around the landfill perimeter detect lateral VOC migration, while surface water sampling in adjacent streams assesses runoff impacts. Field monitoring faces challenges including spatial heterogeneity, accessibility limitations, and high operational costs. As a result, geospatial approaches (remote sensing and GIS-based spatial analysis) which are discussed separately in Section 2.9.3, are often used to complement and validate field observations through synoptic spatial coverage. Despite limitations, it remains indispensable for regulatory compliance and validating other assessment methods.

2.10.3 Geospatial Techniques

The Geographic Information Systems (GIS) has major application in decision-making in various fields. A GIS is a system designed to capture, store, manipulate, analyse and manage geographical data. The main advantage of a GIS-based approach is its simplicity while saving time and cost. Geospatial methods play a crucial role in assessing the environmental impacts of landfill sites. The GIS technique is a very useful tool for zone mapping and hazard evaluation on natural environmental issues (Abdulla et al, 2018).

Landfill leachate, the liquid that drains from waste, poses a significant threat to the quality of groundwater if not properly managed. Geospatial methods play a crucial role to:

- develop models that predict the migration pathways of leachate and identify potential areas of contamination,
- analyze patterns of groundwater flow and assess the susceptibility of these areas to pollution,
- conduct spatial analyses of groundwater quality data obtained from monitoring wells.

The GIS and geospatial techniques play a crucial role in the effective assessment of leachate contamination from landfills. These tools can be used to create spatial distribution maps of contaminants and water quality indices (WQI), as well as to determine safe drinking water zones and assess groundwater vulnerability to leachate (Jaseela Chonattu et al., 2016; Alhassan Sulemana & Hogarh, 2018). The integration of the DRASTIC method (a standardized system used to assess groundwater vulnerability to pollution), geophysical techniques, and GIS can generate thematic maps for landfill site suitability and groundwater vulnerability assessment (Onwe et al., 2019). Electroresistivity, a geophysical method, can be used to define leachate plumes and guide the placement of groundwater monitoring wells (Lopes et al., 2012). By combining these techniques with physicochemical analysis of groundwater samples, a comprehensive approach can be developed to detect and assess leachate contamination in areas surrounding landfills. This integrated approach enables better management of groundwater resources and landfill site selection. Furthermore, when used in conjunction with remote sensing technologies can be utilized to identify areas of potential leachate seepage through the use of thermal imaging.

Geospatial techniques leverage satellite, aerial, and drone-based platforms to monitor landfill impacts across large spatial scales, providing synoptic views unattainable through ground-based methods. GIS integrate spatial data for comprehensive analysis. When combined with multi-criteria decision-making (MCDM) methods, GIS is one of the most effective approaches for evaluating the impacts of landfill sites and has been shown to be effective in selecting suitable locations for landfills. These methods integrate spatial analysis with weighted criteria to determine appropriate sites, taking into account environmental, social, and economic factors such as closeness to water sources, population density and current land usage (Alfy et al., 2013; Din, 2010). Weighted linear combination (WLC) and analytical hierarchy process (AHP) are popular MCDM methods for determining the importance weights of criteria like slope, geology, land use, and proximity to urban areas and water sources (Alkaradaghi et al., 2019; Babalola & Busu, 2011). The usual procedure includes screening to remove unsuitable areas first, then a more in-depth analysis of potential sites to fully evaluate environmental impacts and guarantee the best solutions that reduce ecological risks. This method assists in identifying key environmental issues and areas for enhancement in landfill operations. (Alfy & colleagues, 2013; Din, 2010). Research has shown that this method works well in various locations such as Egypt, Malaysia, Iraq, and Nigeria, indicating its ability to be adjusted to different settings (Alfy et al., 2013; Din, 2010; Alkaradaghi et al., 2019; Babalola & Busu, 2011). This comprehensive approach offers a useful tool for decision-makers in the field of solid waste management.

When employed for impacts assessment, this approach uses remote sensors which utilize multispectral (e.g., Landsat, Sentinel-2) and hyperspectral imagery to detect vegetation stress (via NDVI anomalies) indicative of soil or groundwater contamination (Cusworth et al., 2020). Thermal infrared sensors identify landfill surface temperature anomalies associated with subsurface fires or methane hotspots (Jensen et al., 2012). Synthetic Aperture Radar (SAR) interferometry (InSAR) measures millimeter-scale ground deformation from waste settlement or liner failure, with persistent scatterer techniques (PSInSAR) enhancing accuracy in vegetated areas (Ng et al., 2009).

Light Detection and Ranging (LiDAR) generates high-resolution digital elevation models (DEMs) to map landfill topography, volume changes, and erosion patterns. Drone-based surveys equipped with methane sensors (e.g., cavity ring-down spectrometers) quantify point-source emissions and generate flux maps at meter-scale resolution (Shahrokni et al., 2015). GIS platforms integrate raster and vector data—including hydrogeology, land use, soil types, and infrastructure—to model contaminant transport pathways and vulnerability. Spatial statistics (e.g., kriging) interpolate sparse monitoring data, while machine learning algorithms classify landfill expansion trends. Challenges include cloud cover limitations, sensor resolution trade-offs, and data processing complexity. Nevertheless, geospatial techniques are invaluable for site selection, regulatory compliance, and long-term change detection, especially when fused with field data.

One of the areas where geospatial techniques play a key role in relation to landfill is the process of selecting landfill sites. This process is a multifaceted and crucial endeavour that entails the examination of diverse environmental, economic, and social factors. The amalgamation of GIS with MCDM methods has emerged as potent instruments to facilitate this procedure and are extensively utilized for the identification of appropriate landfill site locations while mitigating environmental hazards. The GIS serve as a technological apparatus that enables the organization, scrutiny, and depiction of spatial data. Upon integration with MCDM, it furnishes a sturdy framework for the selection of landfill sites. The integration of GIS with MCDM approaches like the analytical hierarchy process (AHP) and the ordered weighted average (OWA) empowers decision-makers to efficiently manage extensive datasets and reach well-informed conclusions by simultaneously considering multiple criteria. The GIS is employed extensively by environmentalists, managers and researchers the world over for decision-making and research because of the simplicity it provides especially in relation to the geospatial data which provides some very vital information. The process involves:

- Defining criteria based on factors like proximity to water bodies, land use, and population density
- Assigning weights to criteria using methods like Analytical Hierarchy Process (AHP)
- Creating suitability maps in GIS to visualize appropriate areas for landfills
- Validating existing landfill sites against the suitability criteria

This integrated approach allows for systematic evaluation of environmental factors in the site selection process. It has been used for numerous applications including assessment of possible groundwater pollution (Abdullah et al., 2018), land evaluation for per-urban agriculture (Thapa & Murayama, 2008), soil environment, selection of site for landfill (Elhag & Bahrawi, 2017; Mussa & Suryabhagavan, 2019) among others. For instance, in a study by Richter et al. (2019), by applying GIS and remote sensing in Canada, the researchers employed data collected from a number of remote sensing indices which were used together with the normalised difference vegetation index (NDVI) to rank locations for waste disposal site expansion.

Satellite remote sensing has emerged as a valuable tool for landfill monitoring. Satellite image analysis, particularly using platforms such as Landsat and Sentinel, enables the examination of land surface temperature (LST) and vegetation indices including the normalised difference vegetation index (NDVI) and Soil-Adjusted Vegetation Index (SAVI) (Mirtorabi, 2021; Shaker & Yan, 2010). These remote sensing techniques can detect temperature anomalies between landfill sites and surrounding areas, as well as vegetation health changes, potentially indicating pollution movement earlier than traditional ground sampling methods (Mirtorabi, 2021). When satellite image analysis is combined with ground sampling, it can improve landfill site monitoring efficiency and effectiveness (Mirtorabi, 2021; Shaker & Yan, 2010). Monitoring temperature variations can help identify areas of gas emissions or leachate seepage, providing valuable data for environmental assessments

2.10.4 Modelling Approaches

Modelling approaches simulate landfill processes to predict long-term environmental impacts, supporting risk assessment and mitigation planning. These range from conceptual models to sophisticated numerical tools incorporating physical, chemical, and biological dynamics. Hydrological models like the Hydrologic Evaluation of Landfill Performance (HELP) simulate water balance components (precipitation, evapotranspiration, runoff, percolation) to forecast leachate generation rates (Xu et al., 2012). Coupled with subsurface flow models (e.g., MODFLOW/MT3DMS), they predict contaminant transport in aquifers, using advection-dispersion equations and chemical reaction terms (Xu et al., 2012; Chabuk et al., 2018).

Landfill gas models employ first-order decay kinetics (e.g., LandGEM) or microbial process-based approaches to estimate CH_4/CO_2 generation from waste composition, climate, and site management (USEPA, 2005). Atmospheric dispersion models (e.g., AERMOD) predict downwind gas concentrations for odor and health risk assessments. Multi-pathway exposure models integrate leaching, transport, and human intake parameters to quantify health risks from contaminants like heavy metals or VOCs. Life cycle assessment (LCA) models evaluate broader environmental trade-offs, including global warming potential from methane emissions.

The LCA is a useful instrument for assessing the ecological impacts of landfill locations as it can assess various landfill technologies and management choices, taking into account factors like gas and leachate collection, energy recovery, and waste treatment, to offer perspectives on the sustainability and environmental impacts of waste management practices (Manfredi & Christensen, 2009). By examining energy consumption and environmental effects, the technique can pinpoint the most sustainable landfill location (Din, 2009). The LCA is also capable of evaluating the sustainability of utilizing alternative materials, like industrial by-products, in landfill cover systems (Sanoop et al., 2024). When used alongside groundwater transport modeling, LCA can offer a more thorough assessment of site remediation choices, taking into account immediate and long-term environmental effects (Godin et al., 2004). In general, LCA is a successful method for improving landfill location, planning, and operation to reduce environmental harm and enhance sustainability in waste management strategies.

Another example of these models is the EVIAVE methodology, developed by the University of Granada. The EVIAVE methodology is a diagnostic tool for environmental diagnosis and monitoring of landfills (Arrieta et al., 2015). This tool allows for a systematic evaluation of the environmental effects of landfills, aiding in the development of environmental management plans. It quantifies environmental impacts through various indexes, including the environment landfill index, environmental risk index, and probability of contamination index (Arrieta et al., 2015; Paolini et al., 2008). The EVIAVE methodology has been successfully adapted and applied in several countries including Colombia, Venezuela, and Iran, by modifying it to fit local legal, socio-economic and ecosystem contexts (Arrieta et al., 2015; Zamorano et al., 2009). The methodology assesses environmental descriptors, considering vulnerability and potential impacts on elements such as surface water, groundwater, atmosphere, soil and human health (Zamorano et al., 2008). The EVIAVE methodology has proven to be an effective planning and decision-making tool for landfill management, enabling the identification of affected environmental elements and facilitating the development of action plans for improved operation, closure, sealing and recovery of landfills (Zamorano et al., 2009; Paolini et al., 2008).

Model calibration and validation against field/lab data are essential. Uncertainty analysis (e.g., Monte Carlo simulations) addresses parameter variability and data gaps. Emerging trends include machine learning for predictive analytics and integrated digital twins for real-time landfill management. While models simplify complex systems, they remain vital for scenario testing and regulatory decision-making.

2.11 Conclusion

This chapter has provided a comprehensive review of global and South African waste management practices, with a particular focus on landfilling. It explored the legislative definitions of waste, highlighting the varying interpretations across different jurisdictions, and demonstrated how these definitions influence waste policy, regulation, and implementation. The chapter also critically examined the persistent challenges in South Africa’s solid waste management sector, including organisational capacity, institutional weaknesses, poor service delivery, and implementation failures despite an otherwise progressive legislative framework.

While developed countries have successfully adopted integrated solid waste management and circular economy models, South Africa continues to rely heavily on landfilling due to infrastructural, financial, and administrative constraints. The environmental consequences of poorly managed landfill sites, especially the generation of harmful leachate and landfill gases, remain significant threats to public health and natural resources, particularly groundwater. The review concluded by emphasizing the urgent need for more effective implementation of existing policies, investment in infrastructure, and adoption of sustainable waste management strategies aligned with global best practices to achieve long-term environmental and public health protection.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the research methodology section of this study. It further highlights that a research methodology provides a description of the research design and the research methods that were employed to support the study. It describes the processes and the decisions that were taken by the researcher to address the research questions of interest for the research project. This includes clarification and justification of the research process that was employed, including the choices on the research design, data analysis tools, as well as the data collection techniques employed in the collection of primary and/or secondary data. The chapter further presents the scope and research limitations of the study, the processes involved in ensuring the reliability and validity of the results, as well as the ethical considerations for the study. Clarification of these critical components of this research project are presented in detail in the sections below.

3.2 Research Design

The research design is one of the most important components of any research project and so it must be well researched and justified. It shows a plan of how the research will be conducted and provides a plan which includes every detail of the proposed study from the conceptualisation of the problem right through to the dissemination of the findings (Mount (2009) cited in Creswell (2014:78)). Creswell (2014) posits that a good research design increases the probability that the study findings are a true reflection of the reality.

There are two major types of research designs: qualitative and quantitative research. Qualitative research refers to a systematic, holistic, subjective and process-oriented approach used in research associated with words and experiences rather than measurements, statistics and numerical figures (De Vos et al., 2014). Qualitative research attempts to study human action from the perspective of the social actors themselves, by describing the depth, richness, and complexity inherent in the phenomena and involves putting pieces together in order to understand, interpret, explore and describe a setting or phenomenon in its natural settings (Maxwell, 2014). A quantitative research design, on the other hand, is focused on numerical data. A quantitative research design collects numerical data which are then objectively and systematically processed in order to describe the findings, and therefore allows conclusions to be drawn that can be generalised or can be employed to a population of interest from the findings of the study (Creswell & Creswell, 2018:49; Daniel, 2016:93; Khaldi, 2017:17). In much research however, a combination of these two research designs - the mixed method research design - is employed in order to increase the validity and reliability of the results from a given study, and to justify conclusions made in given research.

This study therefore employed a mixed method research approach, consisting of quantitative and qualitative research designs, as well as a descriptive and explorative approach in the characterisation and determination of landfill site impacts on groundwater quality. The researcher employed qualitative research by preparing interview questions and receiving and analysing responses to this questionnaire after interviewing municipal workers at the landfill sites.

Exploratory studies usually lead to insight and understanding rather than the collection of accurate and replicable data (Creswell, 2014). The design is often used as preliminary research to get more information on the topic (Maxwell, 2014). Exploratory actions are done in order to discover something or learn the truth about something contends (De Vos et al., 2014). Exploratory research is aimed at gaining new insights, discover new ideas, and/or increase knowledge of a phenomenon. Exploratory actions are done in order to discover something new or to learn the truth about something. This study was also exploratory as it sought understanding and insight into impact of landfills on water resources in the Buffalo City Metropolitan Municipality and Amathole regions of the Eastern Cape. According to Creswell (2014) descriptive research is the in-depth description used to identify facts, patterns of relationships and trends. The in-depth description may take the shape of a narrative description which describes or defines a subject by creating a side view of a group or problems or events (Barnes-Holmes et al., 2018; Sevilla-Liu, 2023).

3.3 Description of Study Area

The study was conducted within the Amathole District Municipality (ADM) and the Buffalo City Metropolitan Municipality (BCMM) which are both located in the Eastern Cape Province of South Africa. The ADM is one of the six districts found within the province. Within the ADM is the Great Kei and the Ngqushwa local municipalities (Figure 3.1). The population of

ADM is approximately 872 000 people (Stats SA, 2022) and includes predominantly IsiXhosa-speaking communities, located at 32°30′S 27°30′E and 32°30′S 27°30′E. The population of the Great Kei and Ngqushwa local municipalities is 35 990 and 68 300 respectively. The BCMM (Bufallo City in Figure 3.1) is a metropolitan municipality with towns such as East London, Bhisho and King William's Town being part of the metropole, as well as townships of Mdantsane and Zwelitsha. The population of Buffalo City Metro is about 975 000 (Stats SA, 2022).

Both Great Kei and Ngqushwa local municipalities have local landfill sites. The Komga Waste Disposal site serving the Great Kei local municipality was licensed in 2014 (https://sawic.environment.gov.za/sawis-license/) and is due for closure according to the Great Kei IDP of 2020/2021 (Great Kei Local Municipality, 2021). The Peddie Waste Disposal site in Ngqushwa local municipality has no recorded license on the South African Waste Information System database. The BCMM has two landfill sites located near Berlin (Roundhill Landfill Site) and in King William's Town (referred to as the KWT landfill site in this study). Roundhill landfill has been in operation since 2006 and is permitted to take general waste. The landfill site has been reported in previous studies to have run into operational challenges that made the site non-compliant with respect to regulations (Dookhi et al., 2015). The landfill site is located between longitudes 27.394 – 29.3915 and latitudes -32.8525 – -32.8495. The landfill started as an abandoned quarry, and like many landfills in South Africa, it was open dump (a site where solid waste is disposed of in large quantities without proper management or environmental protection measures) which became operationalised for landfilling from 1983 (Mepaiyeda et al., 2019). Service delivery remains one of the major challenges within the region. For instance, access to clean water and pollution due to the presence of undesignated dumping sites is among one of the key problems facing the region and the province (Figure 3.2).

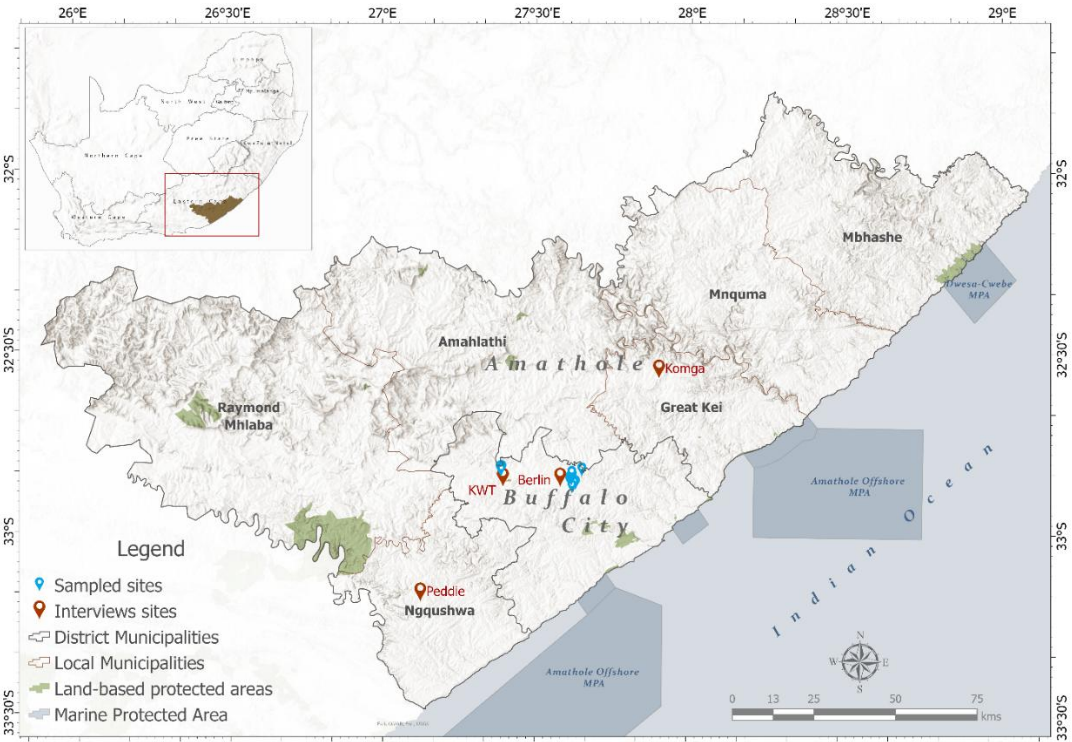


Figure 3.1: Location of BCMM and ADM regions as well as the local municipalities that are covered in this study. *Source: Developed from GIS software programme.*

Figure 3.2: Challenges resulting from illegal dumping in the Buffalo City Metropolitan. Source: Photographed by the researcher.

3.4 Research Methods and Field Data Collection

In order to address the key research questions for this study, the research utilised a combination of qualitative and quantitative research methods using both primary and secondary data. Primary qualitative data were collected using interviews and requesting responses to a questionnaire. Primary quantitative involved analysis of the chemical and physicochemical parameters of the groundwater, surface water and leachate samples from the landfill sites using instrumental methods. Furthermore, secondary data were collected from historical records on chemical and physicochemical analysis of the leachate, surface and groundwater near the study landfill sites. Data for Komga and Peddie Wate Disposal Sites were limited to interviews with staff working at the landfill sites since there is no water quality monitoring at those facilities. The descriptions of the data collection methods and the process of data collection are presented below.

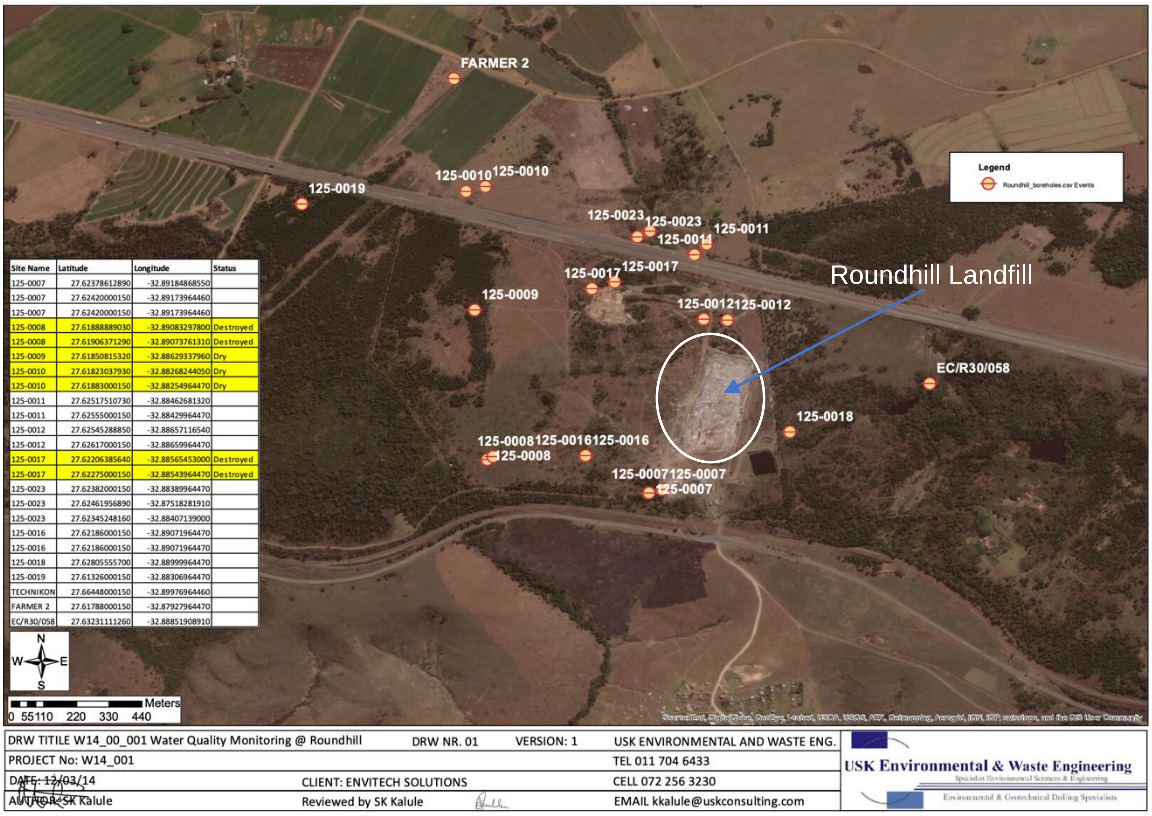
3.4.1 Surface water, Groundwater, and Leachate Sampling

Leachate samples from the sampling points on the two landfill sites, Roundhill Landfill Site in Berlin and the KWT Landfill Site, both under Buffalo City Metropolitan Municipality, and surface and groundwater samples from specified sampling points (Table 3.1) within and around the landfill sites were collected and used for water quality or contaminant assessment. As highlighted before, no samples were collected from Komga and Peddie Wate Disposal Sites because of unavailability of infrastructure for leachate and groundwater collection. The selection of sampling sites for groundwater samples for the two landfill sites was based on the location of water monitoring boreholes as well as nearby water sources groundwater was extracting. Surface water sampling sites consisted of streams close to the landfill site to the landfill sites or dams fed by the streams coming from the vicinity of the landfills.

For each sampling site, a 2.50 L volume of either water (surface or groundwater) or leachate sample was collected in pre-washed and acetone-rinsed amber bottles in each of the wet (January 2022) and dry (August 2021) season. The grab method was used to collect both leachate and the water samples for the respective sampling sites (leachate ponds for leachate samples, and boreholes, dam and river water for surface and groundwater samples). The sample containers were rinsed three times each with the sample prior to collection of the sample. The GPS coordinates of each sampling location were recorded and documented in the field book. The description each sampling site and the types of collected samples is shown in Table 3.1. The collection of leachates was performed at about 5 cm below the surface of the leachate pool. The samples were covered immediately after sampling, stored in cooler boxes, and transported to the laboratory where they were kept at 4ºC in a cold room overnight prior to analysis.

3.4.2 Assessment of spatial distribution of chemical and physicochemical parameters of the groundwater around the landfill Sites based on remote sensing and GIS Techniques

To evaluate the spatial distribution of the chemical and physicochemical parameters of the groundwater, samples from various sampling sites - listed in Tables 3.1 and 3.2 - were collected from groundwater monitoring boreholes around the landfills. Seventeen sampling points were utilised for the Roundhill landfill in Berlin (Figure 3.3). Six sampling points at the Roundhill Landfill could not be used because of either the boreholes being dry, or the sampling point was no longer in use (Table 3.1).



Site Name	Latitude	Longitude	Status
125-0007	27.62378612890	-32.89184868550	
125-0007	27.62420000150	-32.89173964460	
125-0007	27.62420000150	-32.89173964460	
125-0008	27.61888889030	-32.89083297800	Destroyed
125-0008	27.61906371290	-32.89073761310	Destroyed
125-0009	27.61850815320	-32.88629337960	Dry
125-0010	27.61823037930	-32.88268244050	Dry
125-0010	27.61883000150	-32.88254964470	Dry
125-0011	27.62517510730	-32.88462681320	
125-0011	27.62555000150	-32.88429964470	
125-0012	27.62545288850	-32.88657116540	
125-0012	27.62617000150	-32.88659964470	
125-0017	27.62206385640	-32.88565453000	Destroyed
125-0017	27.62275000150	-32.88543964470	Destroyed
125-0023	27.62382000150	-32.88389964470	
125-0023	27.62461956890	-32.87518281910	
125-0023	27.62345248160	-32.88407139000	
125-0016	27.62186000150	-32.89071964470	
125-0016	27.62186000150	-32.89071964470	
125-0018	27.62805555700	-32.88999964470	
125-0019	27.61326000150	-32.88306964470	
TECHNIKON	27.66448000150	-32.89976964460	
FARMER 2	27.61788000150	-32.87927964470	
EC/R30/058	27.63231111260	-32.88851908910	

DRW TITILE W14_00_001 Water Quality Monitoring @ Roundhill	DRW NR. 01	VERSION: 1	USK ENVIRONMENTAL AND WASTE ENG.	
PROJECT No: W14_001			TEL 011 704 6433	
DATE: 12/03/14	CLIENT: ENVITECH SOLUTIONS		CELL 072 256 3230	
AUTHOR: SK Kalule	Reviewed by SK Kalule		EMAIL kkalule@uskconsulting.com	

Figure 3.3: Location of the sampling sites around the Roundhill landfill in Berlin

For additional samples collected from a dam and the river, precautions were taken to ensure that the sample sites were within the vicinity of the landfill area. A handheld GPS was used to code sampled points or sites. The X,Y coordinates of each sampling site were collected and imported into an Excel spreadsheet and then displayed in ArcGIS for further analysis. Geospatial characterisation of the chemical and physicochemical parameters was performed in a GIS environment to map their distribution using spatial analyst tools. Unfortunately, the same could not be performed for the KWT landfill because it only has one working borehole for groundwater monitoring.

3.5 Determination of Physicochemical Parameters of Groundwater and Leachates

3.5.1 Determination of Physical Parameters

After the groundwater and leachate sampling, the collected samples were immediately taken to the Amatola Water Laboratory for analysis of the two physical parameters (the pH and electrical conductivity) while the rest of the samples were stored in a fridge at 4°C for further analysis. The two physical parameters for both the leachates and groundwater samples were analysed using a pH meter (Inolab, Xylem Analytics, Germany, model PHM220) and a conductivity meter (Inolab, Xylem Analytics, Germany, model COND7310). The parameters (pH and electrical conductivity) were measured for all the samples within 24 hours of sampling. The samples were kept in cooler boxes with ice for the period between sampling while being transported for analysis at the laboratory.

3.5.2 Preparation of the Groundwater and Leachates Samples for chemical analysis

In the preparation of leachate and groundwater samples, 20 mL aliquots of each sample (leachate or groundwater samples) were pre-treated by digestion with 6 mL HNO_3 (65% HNO_3) and 3 mL of hydrogen peroxide (30% H_2O_2) before being boiled for 60 minutes in a beaker. The solutions were cooled to room temperature before being filtered through Whatman filter paper (Grade 1) into a 50 mL volumetric flask. The filtrate was then diluted to 50 mL with deionised water and was thoroughly mixed by swirling vigorously for about five (5) times. All reagents were of analytical grade.

Table 3.1: Description of the sampling sites at Roundhill landfill that were used in this study for collection of leachate, surface water and groundwater samples.

NAME: Water Sampling Site	LONGITUDE	LATITUDE	DESCRIPTION	
EC-R30-058	27.63223	-32.88891	Groundwater monitoring borehole outside the Roundhill Landfill fence close to the N2 highway.	Borehole Water Samples
125-0018	27.62764	-32.88996	Groundwater monitoring borehole just outside the Roundhill Landfill fence (125-0018)	
EC-R30-196 (P2)	27.62420	-32.89174	Groundwater monitoring borehole inside the Roundhill Landfill (125-0007).	
EC-R30-196 (P1)	27.62421	-32.89176	Groundwater monitoring borehole inside the Roundhill Landfill (125-0007).	
125-0019	27.61319	-32.88308	Groundwater monitoring borehole outside landfill in farm next to the bridge.	
125-0011 (P1)	27.62551	-32.88434	Borehole (outside landfill next to the N2 freeway)	
125-0011 (P2)	27.62551	-32.88434	Borehole (outside landfill next to the N2 freeway)	
Farmer 2	27.61491	-32.87563	Water sample from a farm reservoir (water extracted directly from the borehole).	
Stormwater Pond	27.62756	-32.89058	Pond in the landfill contaminated with leachate.	Surface Water Samples
MH1	27.62756	-32.89058	Manhole in the landfill site. It contains contaminated with leachate	
MH2	27.62672	-32.89020	Manhole in the landfill site. It contains contaminated with leachate.	
NR1 (Stream)	27.62029	-32.89977	Stream outside landfill, next to an agricultural farm.	
NX4 (Dam)	27.61815	-32.87864	Dam (farm with cows) The site is a dam in the middle of the livestock farm that is fed from a stream on the north of Roundhill Landfill.	
NX5 (Dam)	27.62107	-32.86952	Dam (outside landfill)	
NX4a (Stream)	27.61958	-32.86264	Stream (outside landfill, little running under the bridge)	
NX3 (Stream)	27.65236	-32.85299	The stream outside of a landfill and is near a livestock and agricultural farm. It originates upstream near the Roundhill Landfill.	
Leachate Pumps & Collection Pit	27.62716	-32.89019	Inside landfill	Leachate Samples

Table 3.2: Description of the sampling sites at KWT landfill that were used for collection of leachates, surface water and groundwater samples.

NAME: Water Sampling Site	LONGITUDE	LATITUDE	DESCRIPTION
KWT Stream	27.38671	-32.85314	A stream close to KWT landfill.
KWT Landfill Borehole	27.38781	-32.85278	Groundwater monitoring borehole used for monitoring groundwater at KWT landfill
KWT Landfill Leachate	27.38908	-32.85236	Leachate collected at KWT landfill.

3.5.3 Determination of metals in the groundwater and leachate samples

The prepared samples were analysed using the inductively coupled plasma optical emission spectrometer (ICP-OES) (Thermo Scientific Jarrell Ash, Model ICAP 7000 Series, and Waltham MA, USA) to determine the concentration of the various metals of interest in the groundwater and leachate. The list of metals that were analysed in the study included arsenic (As), cadmium (Cd), chromium (Cr), manganese (Mn), nickel (Ni), and lead (Pb). Merck standard stock solutions (1000 mg L^{-1}) were prepared from the standard solutions of the elements in 0.5% (v/v) nitric acid. All samples were analysed in triplicate.

3.5.4 Determination of Anions and Ammonia

The inorganic anions, sulphate (SO_4^{2-}), nitrate (NO_3^-), nitrite (NO_2^-) and chloride (Cl^-), and ammonia (NH_3) were determined using Ion Chromatography (IC) (Metrohm 761 Compact IC System). Prior to undertaking any analysis of the prepared leachate and groundwater samples, the ion chromatography system was calibrated using standard solutions for each species of interest. The calibration standards were prepared for every analyte at a minimum of three concentration levels in the ranges 1-150 ppm for SO_4^{2-}, 1-100 ppm for NO_3^-, NO_2^- and Cl^- and 0.5-30 ppm for NH_3. The standard stock solutions were prepared from the sodium salts of the anions and NH_4Cl (all analytical grade chemicals). All the leachate and groundwater samples were filtered through a 0.45-μm IC syringe filter to remove sediments and particles before each filtrate was diluted into the ranges of the standards prior to analysis using the IC System.

3.6 Mapping of the Perceptions of the Landfill Managers on the Challenges Related to the Management of Landfill Sites

In addition to the analysis of various physicochemical parameters, this study also employed interviews as a method of qualitative data collection. The primary purpose of the interviews was to explore the challenges faced by landfill sites, particularly in relation to illegal dumping and compliance with national legislation governing landfill management and operations. The interviews also aimed to understand the strategies that landfill staff are implementing to mitigate the impact of illegal waste dumping.

Interviews are a widely used method of qualitative data collection (Blanche et al., 2006:287). They involve a conversation between a researcher and a participant, where the researcher guides the discussion to gain insight into the participant's experiences, perspectives, and knowledge of the topic under investigation.

There are three main types of interviews commonly used in research: **unstructured**, **semi-structured**, and **structured**.

- **Unstructured interviews** are highly flexible and exploratory, with no predetermined questions or answers. They allow the conversation to develop naturally during the interaction (Royce, 2005:222).
- **Structured interviews**, on the other hand, follow a fixed set of questions presented in the same order to all participants. This approach is typically used in quantitative research where consistency and comparability of responses are essential.
- **Semi-structured interviews** offer a balance between the two. In this format, the researcher prepares a set of guiding questions in advance but remains open to exploring new topics that emerge during the conversation. This flexibility allows for deeper insight while maintaining some structure (De Vos et al., 2005:296).

For this study, semi-structured interviews were chosen, as they are particularly well-suited for qualitative research. They enable the researcher to explore the participants' views in depth while allowing space for participants to elaborate on their responses. This approach helped uncover rich, context-specific information about the operational challenges of landfill sites and the adaptive measures taken by staff to address issues related to illegal dumping.

The interview questions were developed by the researcher. Semi-structured interviews were used as a guide for the researcher to obtain more information from the participants and to pose structured questions on issues pertinent to the investigation. The qualitative interview outline (Appendix A) consisted of 11 questions (4 biographical and 7 landfill site operations-related questions). A non-probability sampling procedure using the purposive sampling technique was employed to select a sample for the interview study. A purposive sampling plan is used for the selection of the participants based on whether they meet the purpose of the study or fit the purpose of the research. The purposive sampling technique has the advantage that it allows the researcher to select participants with different characteristics to gain rich data (Creswell, 2014). The choice of the participants for this study was based on their perceived knowledge of managing the landfills due to their experience working at the landfills in question in operations or senior positions. Therefore, the target for the interviews was the personnel in supervisory or management roles at the three landfill sites. According to Hennink and Kaiser (2022), in qualitative research, the size of sample is generally controlled by saturation, which indicates whether more data collection may be necessary or not. In this study however, the sample size was limited by availability of the participants. The data collected from the interviews with the selected participants were used to gain insights on the operations of the landfill sites in question, their compliance with relevant environmental and waste management legislation, and the challenges related to illegal dumping.

The interviews were carried out and recorded via Microsoft Teams platform and also by phone when the conversation was recorded. The researcher requested for consent of the interviewees before going ahead with recording. The details for the interviews and the schedules are shown in Table 3.3 below. The links for the Microsoft Teams interviews, the schedule and an electronic copy of the interview questions guide (Appendix A) were shared with the participants prior to the interview via email. Unfortunately, because of circumstances beyond the control of the researcher, the researcher was able to interview only two participants each from the Roundhill and KWT landfills and one participant each for Peddie and Komga Waste Disposal sites. The interviews were carried out between January 2022 and January 2024.

Table 3.3: Table showing the details of the participants for the interviews for the study.

Landfill Site Name	Participant ID & Position	Date of Interview	Length of Interview
Roundhill Landfill (Berlin)	Participant 1:	12/01/2022	34m:19 s
	Participant 2	26/01/2022	11m:56 s
KWT Landfill (King William's Town)	Participant 3	25/01/2022	25m.34 s
	Participant 4	25/01/2022	12m:52 s
Peddie Waste Disposal Site (Ngqushwa)	Participant 5	19/01/2024	56m:01 s
Komga Waste Disposal Site (Great Kei)	Participant 6	20/01/2024	28m:06 s

3.7 Collection of Secondary Physicochemical Data for Leachate and Groundwater Analysis for the Respective Landfills Sites

The study also collected secondary physiochemical data for the leachate and groundwater analysis for the landfill sites from the Industrial Effluent Compliance Monitoring reports of the BCMM for the period between 2016 and 2021. The sampling points for the monitoring of leachate, groundwater and surface water in the recorded secondary data were the same as the points reported in Figure 3.3 for Roundhill landfill. However, the retrieved secondary data were inconsistent and contained gaps for most of the parameters, and did not include all the sampling points that were used in the study. The KWT landfill site had no record of groundwater monitoring data. The site, however, has only one borehole for groundwater monitoring and so was the only groundwater sampling site used for collection of water samples. Sampling points for surface water sample analysis results recorded in the historical data included rivers/streams and dams that are in the vicinity of the landfill sites.

3.8 Data Analysis

Data analysis is an important component of a research study. According to De Vos et al. (2014), it is the process of breaking down the raw data collected in research, and transforming it to bring order, structure and meaning to the collected data. The data analysis process organises the collected data to produce useable data that can be interpreted by the researcher. In this research study, both qualitative and quantitative data were collected.

Therefore, the data analysis techniques used for this research involved both qualitative and quantitative data analysis methodologies.

For quantitative data analysis, because of the nature of the data collected in quantitative research designs which is numeric, the techniques employed involve the evaluation of descriptive statistics such as percentages, frequencies, means, and standard deviations as well as inferential statistics. For qualitative data which consists of non-numeric information such as interviews, notes, video and audio recordings, text documents and others, the data analysis techniques involve organising the data into themes and providing some level of understanding, explanation, and interpretation of patterns and themes in textual data.

Data analysis for the primary and secondary quantitative data employed descriptive and inferential statistics using the IBM SPSS Statistics Software Version 25.0. The first part of the analysis of the data involved the processing of numerical primary and secondary data to organise and validate the collected data. After completion of the data processing, univariate analyses were conducted to describe the temporal profiles (monthly, seasonal and yearly trends for the secondary quantitative data and seasonally for the primary quantitative data) for the selected physicochemical parameters of interest in the study using data from various monitoring sites at the Buffalo City Metro’s landfills. The monthly data for the period between 2016 and 2021 from the records were averaged for each parameter to obtain yearly mean concentrations, which were subsequently used to calculate the overall mean values of the physicochemical parameters for each monitoring station. In addition, inferential statistics were evaluated for each parameter. Temporal profiles were also developed for selected parameters that had sufficient data for such analysis for a given monitoring site. No data records were found for Komga and Peddie Waste Disposal sites. The results from secondary data analysis were compared with the primary data that was collected by the researcher in this study. The values of the parameters investigated in the study were analysed to determine their alignment to the recommended water quality standards of according to the World Health Organisation (WHO) and the water quality guidelines by Department of Water and Sanitations (DWS) (SAN 241, 2015).

Using the various locations of the sample collection points and the evaluated levels for selected physicochemical parameters, the GIS spatial profiles for the groundwater quality were developed using Surfer Data Mapping and Modelling Software Version 18.1 and was thereafter used to estimate the variables at the unmeasured location. Surfer Data Mapping and Modelling Software is a strong contouring, gridding, and 3D surface mapping software that is used by scientists, engineers, educators, and other professionals who require a robust platform for generating maps and models with precision and ease (Ali, 2024). It is a powerful surface analysis and contour mapping software that allows users to visualize and interpret spatial variations in data. The grid-based mapping tool Surfer interpolates randomly spaced XYZ data into a regularly spaced grid. The software has different options for gridding and interpolation capabilities to ensure that the employed datasets are accurately represented, enhancing the reliability of the resulting maps and analyses. In this study, kriging, which is a geostatistical interpolation technique, and is the default gridding method in Surfer, was used to map the spatial distribution of the physicochemical parameters. The technique considers both the distance and the degree of variation between known data points when estimating values in unknown areas (Kitanidis & Kitanidis, 1997; Bohling & Wilson, 2005). Kriging interpolation was chosen for the study because it assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. Kriging is effective for most data sets because of its capability to compensate for clustered data by giving less weight to the cluster in the overall prediction. The Kriging tool fits a mathematical function to a specified number of points, or all points within a specified radius, to determine the output value for each location (Kitanidis & Kitanidis, 1997; Bohling & Wilson, 2005). The developed spatial profiles were used applied to evaluate the water quality trends around the landfills and to investigate whether leachate leaks are a driver for water quality deterioration in the areas around these landfills. Data from both spatial and temporal profiles were compared with national and international standards (Table 3.4) to evaluate compliance with the water quality standards.

For the qualitative data collected through interviews, qualitative data analysis methods were used. Of the various qualitative analysis techniques, the most popular and best-known are grounded theory analysis, content analysis, narrative analysis, discourse analysis, and framework analysis. The data analysis technique that was used for this study was framework analysis. According to Gale et al. (2013), framework analysis is part of the broad family of qualitative analysis techniques often termed thematic analysis or qualitative content analysis. Framework analysis allows a researcher to identify commonalities and differences in the collected qualitative data, before focusing on relationships between different parts of the data, and thereby identifying, analysing, and interpreting patterns (themes) within the data from which descriptive and/or explanatory conclusions can be drawn. Framework analysis makes it possible to obtain a holistic, descriptive overview of the entire data set, and therefore the production of highly structured outputs of summarised data (Gale et al., 2013). The key purposes of the interviews were to find out important information on compliance with waste management regulations for the respective landfill sites, monitoring of leachate, surface and groundwater, and the strategies employed by the respective landfill sites to mitigate the challenges related to illegal dumping. The transcripts of the interviews were summarised and analysed according to these key themes. By following Braun and Clarke's (2006) six-step process, the analysis started with familiarization with the data, generating initial codes, identifying and reviewing themes, and producing the final thematic narrative. An inductive approach was adopted, allowing themes to emerge from the data without the constraints of a pre-existing coding framework. Themes were identified at a semantic level and supported by direct quotations from participants. To ensure trustworthiness, coding decisions were recorded, and an audit trail was kept throughout the process.

3.8.1 The Pearson's correlation-physicochemical parameters of surface water needs discussion

Descriptive statistics, Pearson's correlation analysis, one-way ANOVA (used to test differences between upstream and downstream samples), and spatial interpolation techniques were employed. One-way ANOVA was specifically used to determine statistically significant differences ($p < 0.05$) in pH and EC values between sampling locations.

Table 3.4: Water Quality Limits for the Investigated Water Quality Parameters According to the National (SANS 241 (2015a) Limits) and WHO (2017) Standards.

Parameter Name	Standard Limits/ mg.L^{-1}		Additional Information
	SANS 241 (2015a) Limits	WHO (2017)	
As	0.01	0.01	Value for chronic health risk limit according to SANS 241
Cd	0.003	0.003	Value for chronic health risk limit according to SANS 241
Cr	0.05	0.05	Value for chronic health risk limit according to SANS 241
Mn	0.4	0.08	Value for chronic health risk limit according to SANS 241aesthetic value of 0.1.
Ni	0.07	0.07	Value for chronic health risk limit according to SANS 241
Pb	0.01	0.01	Value for chronic health risk limit according to SANS 241
SO_4^{2-}	250		Aesthetic risk value according to SANS 241, Acute health risk value of 500 mg/L.
NO_3^-	50	50	Acute health risk limit for SANS 241
NO_2^-	3	3	Acute health risk limit for SANS 241
Cl^-	250		Aesthetic risk value according to SANS 241
NH_3	1.5		Aesthetic risk value according to SANS 241. The operational risk limit is 0.3.
Electrical Conductivity	150	400	Aesthetic risk value according to SANS 241
pH	5-9.7	6.5-8.5	Operational risk limit
Turbidity (NTU)	4		Aesthetic risk value according to SANS 241. The operational risk limit is 1.

Acute Health Risk:	Determinant that poses an immediate unacceptable health risk, if present, at concentration values exceeding the numerical limits specified in this part of SANS 241.

Chronic Health Risk:	Determinant that poses an unacceptable health risk if ingested over an extended period if present at concentration values exceeding the numerical limits specified in SANS 241.
Operational Risk:	Determinant that is essential for assessing the efficient operation of treatment systems and risks to infrastructure.
Aesthetic Risk:	Determinant that taints water with respect to taste, odour and colour and that does not pose an unacceptable health risk if present at concentration values exceeding the numerical limits specified in SANS 241.

3.9 Validity and Reliability of the Collected Data

Validity and reliability of collected data are key issues importance in research. The key aspects associated with the validity and reliability of the data are trustworthiness and credibility of the research results. When results are credible and trustworthy, it means that the conclusions that are drawn from the collected data are a true reflection of the investigated population. According to Adler and Clark (2011), reliability of a research tool provides a measure of the degree to which the tool can produce consistent results. On the other hand, validity provides a measure of how accurate and truthful the research findings from an investigation are.

As part of a quality assurance and quality control process to ensure the validity and reliability of the results before performing data analysis, the collected primary and secondary data were assessed for validity, completeness, uniqueness and consistency. Completeness was evaluated on the measured secondary data to verify if the available data were sufficient to be summarised. A validity evaluation was undertaken to verify whether the collected secondary data conformed to the specific logging format, syntax and range, to ensure that it was usable. Measurements below 0 were deemed to be incorrectly measured data, ND was deemed to show values below the detection limit and the values were replaced with 0 for processing of the mean, significant figures for mean values were processed according to the rules of significance.

3.10 Scope and Limitations of the Study

The primary objective of this study was to investigate the geospatial and temporal variations of selected physiochemical parameters of the groundwater to investigate possible pollution of the groundwater by leachate from the landfill sites in Buffalo City Municipality and ADM region. The study employed both historical (secondary) and primary physicochemical data to make conclusions about the study. While there are many parameters that are monitored in landfill sites, the study was limited to selected metals, anions and physical parameters because of availability of secondary data. The secondary data that were employed were also limited, had gaps with some periods in which there was insufficient data to make reliable comparative analysis against the primary data. The research also observed that the Peddie and Komga waste disposal landfills do not have monitoring boreholes or systems for monitoring the landfill effluents and have no record of secondary data. Therefore, no samples were collected for analysis from the two sites, and primary data collection was limited to the interviews that were carried out to confirm compliance with the national standards for waste disposal.

3.11 Ethical Considerations

In this research study, the researcher observed all the ethical considerations as stipulated by the institution's research ethics policy such as informed consent during the interview respondents. The guidelines for the research were explained to every participant. All participants were briefed as to the aim and objectives of the study and their consent requested before taking part in the interviews. Participant's confidentiality was emphasized and maintained; it was expressly explained that the study was sorely for academic purposes. All confidential data such as personal identifying information of the participants was removed from the final report. The recordings of the interviews were kept in a secure location by the researcher and will be destroyed upon completion of the report.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

In this study, secondary data from the historical water quality records for the leachate and ground water monitoring boreholes around the Roundhill and KWT Landfill sites and surface water bodies (ponds/dams and streams) in the vicinity of the landfills were used to investigate the water quality trends around the BCMM landfill sites. By providing a focus on important factors associated with land use and waste activities, this secondary data analysis of background data contributed to practical aspects of the study. This was achieved by comparing a summary of the obtained secondary water quality records for the period between 2016 and 2021 with collected primary research data for the given sampling points identified in the secondary data.

The significant findings of the study were:

- The current water quality monitoring plan for Roundhill and KWT Landfill sites was limited, mainly focusing on the measurement of physical parameters such as pH and electrical conductivity. In addition, the Komga and Peddie landfill sites have no facilities for collection of leachates, and have no groundwater monitoring boreholes, and therefore cannot monitor water quality.
- The physical parameters (pH, EC and temperature) were generally within the WHO (2017) and SANS-241 (2015b) guidelines for both surface and groundwater samples, while the values for the groundwater samples close to the landfill site exceeded the SANS-241 guideline limits.

The concentrations of heavy metals (Pb, Mn, Cr, Ni, Cd and As) and the anions (Cl^-, NO_2^- and NO_3^-) in the surface and groundwater around the landfill were high and exceeded the ranges of the WHO and SANS-241 guidelines. The results are discussed in detail in the sections below.

4.2 Thematic Analysis of Compliance and Waste Management Practices at Selected Landfill Sites in the ADM and BCMM in Eastern Cape

4.2.1 Introduction

This section presents a thematic analysis of interview data collected from personnel at four landfill sites, Komga, Peddie, KWT, and Roundhill, to assess their compliance with existing waste management legislation and their efforts to mitigate illegal dumping. Compliance with the South African Minimum Requirements for Waste Disposal by Landfill of 1998 and the subsequent regulations requires that the sites must have operating license, and that they must have both surface and groundwater monitoring near to a landfill site. Routine analysis of surface and groundwater monitoring is necessary to manage and mitigate, where necessary, the negative impacts of solid waste on the environment (Department of Water Affairs and Forestry DWAF, 1998). For general waste landfill sites, the requirement for groundwater monitoring and the minimum number of boreholes for the landfill, as well as leachate collection are stipulated in the regulations and is dependent on the size of the landfill site. Roundhill Landfill site is classified as a Class C landfill site for general waste (G:L:B+) and should have a containment barrier designed for collection of leachates. It is required by law to record waste streams, perform water quality and gas monitoring, conduct air quality monitoring as well as perform external audits twice a year. The KWT Landfill site is also a general waste landfill classed as a G:M:B-, and by law should have records of waste streams, and water quality monitoring and external audits must be conducted. The results of the analysis of the limited records that were obtained for both Roundhill and KWT landfill sites showed that they are complying with the existing waste management legislation. No secondary data were obtained for Komga and Peddie Waste Disposal Sites as they have no facilities for collection of groundwater and leachate samples. The classification of the two disposal sites could not be obtained, and therefore could not verify their compliance with water quality monitoring requirement.

The themes that were drawn from the content of semi-structured interviews, observation notes, and license verification checks include:

- Regulatory Compliance and Licensing,
- Waste Classification and Handling,
- Illegal Dumping and Access Control, and
- Infrastructure and Operational Challenges.

The findings are contextualised within South Africa’s broader waste governance framework.

4.2.1.1 Regulatory Compliance and Licensing

A recurring theme across all four sites is the issue of licensing compliance, a fundamental requirement under the National Environmental Management: Waste Act (Act No. 59 of 2008). Three of the four landfills, KWT, Roundhill, and Komga were confirmed to have valid licenses for accepting general waste, as verified either through personnel statements or the South African Waste Information Centre (SAWIC) records (https://sawic.environment.gov.za/sawis-license/).

However, Roundhill’s licensing details could not be independently corroborated online, as personnel failed to provide a copy of the license. In contrast, the Peddie Waste Disposal Site was reported to be operating without a valid license, which directly contravenes the Waste Act and reflects ongoing challenges in bringing former informal dumps into compliance (Godfrey & Oelofse, 2017). These findings underscore broader issues in South Africa, where despite robust policy frameworks, enforcement and consistent implementation are often lacking (Nyika et al., 2020). The transition from unlicensed dumps to regulated landfills remains incomplete in many municipalities, particularly in under-resourced regions such as the ADM.

4.2.1.2 Waste Classification and Handling

All four sites were reported to accept only general waste, with some variation in what is classified as general waste. For instance, KWT and Roundhill landfill sites sometimes receive animal carcasses and tyres, which can be environmentally problematic if not properly managed. According to landfill personnel at Roundhill landfill sites, there was a prior attempt to include medical waste in their operations via a permit amendment, but it was later retracted due to unspecified complications. This raises concern about inconsistent application of waste classifications and potential regulatory loopholes.

In South Africa, the correct classification of waste is governed by the Waste Classification and Management Regulations (2013), which set strict criteria for the handling and disposal of various waste streams. Deviations from these standards, even at general waste sites, pose environmental risks and may lead to contamination.

4.2.1.3 Illegal Dumping and Access Control

Another dominant theme across all sites was the challenge of illegal dumping, often attributed to poor access control. Personnel at Komga and Peddie waste disposal sites specifically noted insufficient fencing and enforcement, resulting in frequent unauthorised waste disposal. At Roundhill and KWT landfill sites, scavengers were frequently mentioned, not only as a cause of fires but also as contributors to disorderly waste dispersal, especially near entry points and transfer stations.

The issue of illegal dumping highlights systemic challenges in the governance of municipal solid waste, particularly in peri-urban and rural contexts. Poor access control enables unsanctioned disposal of tyres, rubbers, and other potentially hazardous materials. As noted by Nhamo and Inyang (2011), such practices exacerbate public health risks and degrade community trust in waste management institutions.

4.2.1.4 Infrastructure and Operational Challenges

Operational capacity and infrastructure deficits were evident across all sites. While Roundhill and KWT have transfer stations, they were described as non-functional or poorly managed, echoing national critiques of municipal waste services (Polasi et al., 2020). Komga and Peddie waste disposal sites lacked basic infrastructure for leachate management, such as boreholes for monitoring groundwater contamination. This infrastructural gap directly undermines environmental monitoring obligations under South Africa’s Norms and Standards for Disposal of Waste to Landfill (DEA, 2013).

Additionally, fire outbreaks were cited frequently, especially in connection to scavenger activity. Fires not only pose safety hazards but can also increase emissions of hazardous gases, such as dioxins and furans (Pathak et al., 2024). Without proactive fire management systems, such emissions compromise both human health and air quality in surrounding areas.

Thematic analysis of the interview data reveals that while progress has been made in licensing and regulatory alignment at some Eastern Cape landfills, significant challenges remain, particularly at under-resourced sites like Peddie and Komga waste disposal sites. Issues such as inadequate infrastructure, misclassification of waste, illegal dumping, and insufficient monitoring reflect broader governance deficits in South Africa's waste management sector. Bridging the gap between policy and practice will require targeted investment in infrastructure, stronger oversight, and community engagement strategies to combat illegal dumping and support compliance with national waste regulations.

4.3 Monitoring of Physicochemical Parameters near to the Landfill Sites

The physicochemical parameters that were analysed in this study included the pH, turbidity, electrical conductivity and the levels of the anions (Cl^-, SO_4^{2-}, NO_3^-, NH_3), compounds (NH_3) and heavy metals (Mn, Cr, Cd, As and Pb) from both primary and secondary data resulting from the analysis of the leachate and water samples collected at the various sampling sites. The secondary data collected from the historical records of interest in the study were limited in terms of scope of measured parameters, sampling sites and the frequency of the measurements. For instance, while some sites contained weekly data for a given period, some of those records were limited to the measurement of the physical parameters: pH and electrical conductivity, and at times a selected few chemical parameter. Therefore, the pH and electrical conductivity were the only physical parameters that appeared in each collected record while limited secondary records were available for turbidity (no records at all) and chemical parameters such as heavy metals. Details of anion analysis appeared in very limited records (e.g. once to thrice in a year or over the entire period analysed). The experimental results for the study were collected for the winter and summer periods and were summarised and compared with the secondary records. The parameters are discussed separately below in the context of the obtained results**.**

4.3.1 Results of pH analysis of the groundwater, surface water and leachate samples from Roundhill and KWT landfills

This study investigated the pH profiles of the surface and groundwater from sources around the landfills and that of the leachates from the landfill sites. Primary data were collected and analysed in this study and compared to secondary data. The pH of a solution is influenced by its composition so that for freshwater systems, the pH is affected by a number of chemical and biological processes in the water which, in turn, impacts other processes. In this study, primary and secondary pH data of the leachate and water samples from within the landfills and those from freshwater sources in the vicinity of the landfill sites (described in Tables 3.1 and 3.2) were collected and analysed to develop pH profiles of the different sampling sites.

The results are presented in Table 4.1 (leachate samples) and Table 4.2 (freshwater sources).

4.3.1.1 Results of leachate pH analysis

With the exception of a mean pH value (pH 9.8) recorded in 2019, the average pH of the leachates was all within the acceptable range according to the WHO (Meride & Ayenew, 2016) and the SANS:241 (2015) guidelines. For the leachates collected at Roundhill and KWT Landfills, all of the recorded values were alkaline, above pH 7.0 and below pH 9.8, which is consistent with leachate production from mature landfills. The average pH values for the Roundhill Landfill leachate samples (pH 8.57) were lower than the average pH value determined for leachate sample collected at the KWT Landfill site.

The results are consistent with observations from literature. Omofunmi et al. (2020), in their study of landfill leachate impacts on water quality in Ilokun, Nigeria, a tropical region with distinct wet and dry seasons, demonstrated that leachate pH is strongly influenced by landfill age. They reported that leachate from recently established landfills (within 5 years) exhibited acidic pH values (3.5-6.5) due to volatile fatty acid production and high partial pressure of carbon dioxide, while mature landfills like Roundhill (18 years) and KWT (40+ years) produce alkaline leachate (pH >7.5) as methanogenic conditions stabilize. According to Wdowczyk and Szymańska-Pulikowska (2020), the pH of leachate originating in mature landfills operating for more than 10 years may reaches values higher than pH 7.5 as volatile fatty acids are converted into methane and carbon dioxide. Therefore, depending on the composition and level of pollution, surface and groundwater are prone to pollution by leachates, resulting in an overall reduction in the pH of the fresh water.

Table 4.1: Table of mean data for the physical parameters of the leachate samples from collected secondary data.

pH (Threshold pH range: 5 - 9.7)									
Sampling Site	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**x̄**	**SD**	**Experimental Data**
Roundhill Landfill Leachate	8,0	8,2	8,1	8,2	8,3	8,1	**8,2**	**0,1**	**8.57**
KWT Landfill Leachate	-	-	-	9.8	8.5	8.5	**8.8**	**0.7**	**9.16**

Understanding the pH profile of the surface and groundwater is very important because heavy metals become increasingly mobile and available for uptake by aquatic plants and animals at lower pH values because they are more soluble in water with lower pH values. As a consequence, low pH values tend to reflect greater potential for toxicity for aquatic animals and make freshwaters unsuitable for consumption. The KWT Landfill leachates showed the highest pH values of all the collected records, with about 20% of the collected data over the upper limit of pH 9.7 and a maximum recorded value of pH 10.1 (Figure 4.1). The summarised monthly data for KWT leachates show that the majority of these high values were recorded in 2019, and possibly earlier (Figure 4.1).

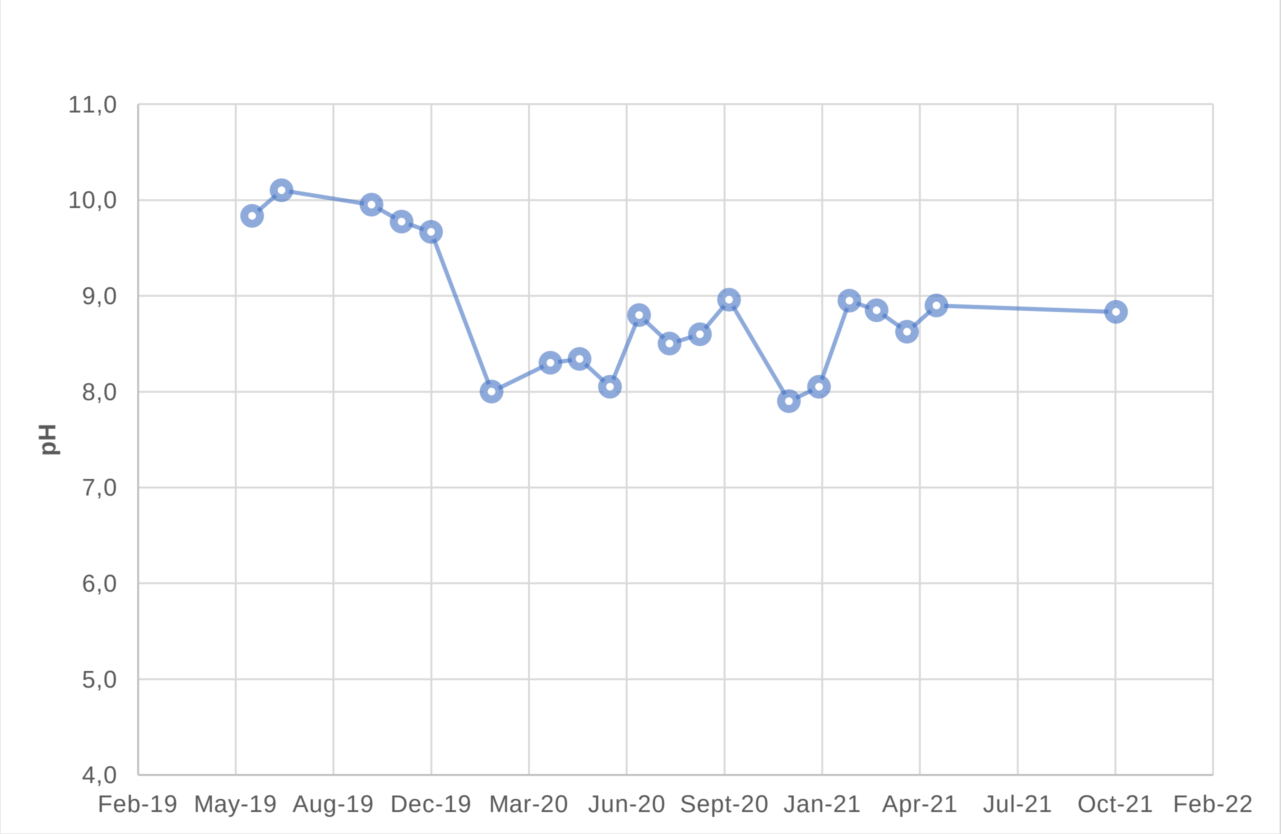


Figure 4.1: Historical monthly average pH values for KWT landfill leachates between 2019 and 2021

Temporal leachate data for Roundhill Landfill site from 2016 to 2021 were all within the acceptable range. The results collected from the secondary data were consistent with the experimental results which showed the KWT Landfill leachates with relatively higher pH values compared to Roundhill Landfill leachates. Both Berlin and KWT Landfill sites have been in operation for more than 10 years, with KWT Landfill being in operation for a much longer period (over 40 years compared to about 18 years for Roundhill Landfill). The KWT Landfill began operations as an open dump in 1976 before it was converted at a later stage into a fully operational landfill. According to interview data obtained during the study, the landfill site has no base lining for leachate collection and can therefore be considered a high risk for water contamination.

4.3.1.2 Results of Freshwater pH analysis

The pH data analysis for freshwater sources included results for both surface and groundwater with samples being collected from dams, rivers or streams, boreholes, as well as a polluted stormwater pond as well as manhole samples (MH1 and MH2) at the landfill site (Table 4.2). Both the historical data as well as experiments were used to develop a profile for each sampling site. The results showed that the pH of both surface and groundwater water were within the range of pH 6.6 and pH 8.4. According to Al-Badaii et al. (2013), the pH range of pH 6.5 to pH 8.0 is generally regarded as more conducive for the physiological systems of most organisms. According to SANS-241 (2015a), the threshold pH for potable water is in the range of pH 5 to pH 9.7. The measured pH values for the freshwater systems in the vicinity of the two landfills all had pH values above 7.0 and were generally within the range that is considered safe for aquatic life (Table 4.2).

Of all the freshwater sources, the secondary data showed that the stormwater pond, NX4, NX4a and NX5 had considerably higher pH values (pH = 8.1-8.4) which were very close to those reported for the leachates in Table 4.1. According to the results collected from interviews, the stormwater pond, together with MH1 and MH2, are all surface samples that are contaminated with leachate. According to the one of the interview participants who stated:

> *".. the stormwater pond is contaminated by the leachate that trickles from the landfill and is monitored all the time".*

Of the collected stormwater pond records, 39% of the pH values were between 8.5-8.8, thereby highlighting the considerable impact of the leachate on the physical properties of this water source. Water from the stormwater pond may be regarded as a risk for aquatic life, and therefore so this water may need treatment before being discharged into the environment. According to the interview participants, the water from this pond is reused at the landfill site to extinguish landfill fires.

The pH values of the other surface water systems that are monitored by the city were all in the accepted pH range (Table 4.2). As indicated, the pH for water samples from NX4 and NX4a from secondary data showed average pH values above pH 8.0 and these were more comparable to the pH of samples from the stormwater pond, which may indicate possible anthropogenic pollution in those water bodies. The secondary data collected for the surface and groundwater samples were very limited, with other sampling sites of interest showing no historical record (e.g., KWT stream and KWT Landfill Borehole), while others had fewer than five records for the entire period of six years that was analysed. As a result, no temporal profiles could be developed from the secondary data.

Comparison of the secondary and primary data presented in Table 4.2 showed close agreement between the two data sets. While the pH difference between the secondary data and experimental results was significant for MH1, MH2, NX3 and NX5, NX3 was the only surface water sample that was slightly acidic (pH 6.67), just above the normal range for surface water bodies (pH 6.5 to pH 8.5). Few conclusions could be drawn from these data because of limited secondary records for the site. However, this was noted for further analysis to verify its impact on other physicochemical parameters. The samples NX4a, and NX4 recorded relatively high pH values which are comparable to the polluted storm water pond (Figure 4.2), with pHs above 8.0, which are generally not conducive for aquatic life, and therefore may be a risk to some of the aquatic organisms.

According to a study by Mepaiyeda et al. (2020), the waterbodies are on the downstream side of the landfill site. It can be inferred from this that there may be a possibility of landfill leachate more readily impacting these water sources. The spatial profile that was developed from the surface water data show that the pH values around Roundhill Landfill site are generally higher than pH 7.8 (Figure 4.3) and decrease in the direction of flow of the surface and groundwater. Thus, NX4, which is a dam in a farm with cattle is clearly highlighted in Figure 4.3 as a location of concern on the map, with pH generally >8.1.

Table 4.2: Means of data for the physical parameters of surface and groundwater samples from collected secondary data.

pH (Threshold pH range: 5-9.7)				
	Site Name	**N**	**Secondary Data**	**Experimental Results**
Surface Water Data	Stormwater Pond	28	8.4(0.3)	8.17
	Farmer 2	5	7.6(0.3)	7.57
	MH1	23	7.4(0.1)	8.17
	MH2	26	7.6(0.2)	7.10
	NR1	22	7.9(0.5)	7.89
	NX3	3	7.9(0.7)	6.67
	NX4a	6	8.1(0.6)	8.13
	NX4	3	8.1(0.6)	8.40
	NX5	4	8.4(0.3)	7.91
	KWT Stream		No Record	7.13
Groundwater Data (Boreholes)	ECR-30-196 (P1)	3	7.0(0.2)	8.01
	ECR-30-196 (P2)	3	7.3(0.3)	7.29
	P125-0011 (P1)	2	7.8(0.3)	7.45
	P125-0011 (P2)	-	No Record	6.66
	P125-0018	3	7.2(0.5)	7.86
	P125-0019	7	7.3(0.3)	8.03
	EC-R30-058	3	7.3(0.3)	7.04
	KWT Landfill Borehole	-	No Record	6.81

The available secondary data showed that all the groundwater records were in the pH range 7.0-8.0, with pH values generally lower than those of surface water sources (Table 4.2). However, experimental pH data for KWT borehole and P125-0011 samples, as with the NX3 water samples, were slightly acidic. Normal groundwater pH values are generally lower, falling in the range of 6.0-8.5. Therefore, while the samples for KWT and P125-0011 are below pH 7.0, they fall within the normal range for groundwater.

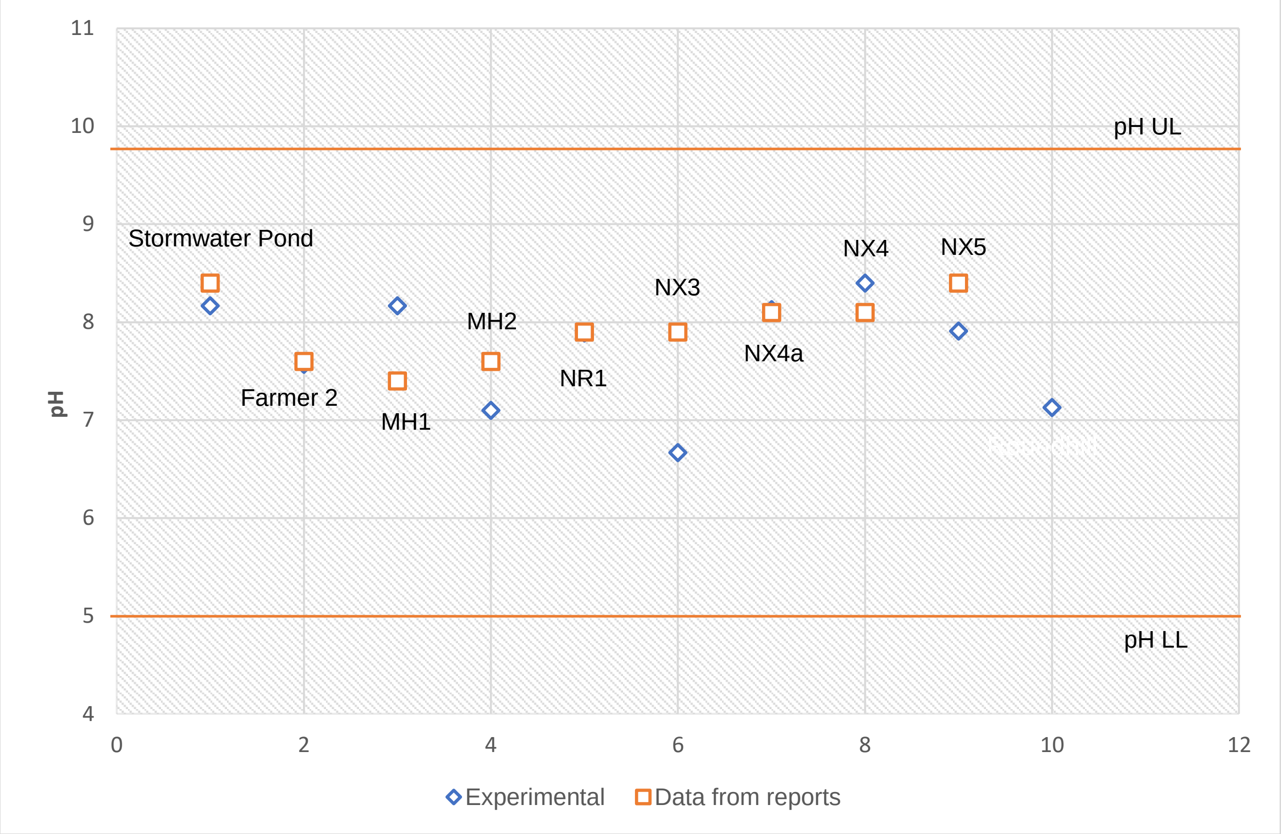


Figure 4.2: Measured pH values for the surface water samples in relation to the normal pH range for surface water systems

Boreholes ECR-30-196 (P1) and P125-0018, closer to the landfill (Figure 4.3), presented highest pH values in groundwater sampling. On the other hand, the only groundwater monitoring borehole located within the KWT Landfill site (KWT borehole) had lower pH values compared to those of landfill leachate (the highest ph of all measured samples).

Figure 4.4 Spatial patterns of pH for groundwater in the vicinity of the Roundhill Landfill pH is elevated near to land-fill on bearing radials in south-west direction from it. In addition, spatial profile also reveals that the groundwater samples taken from downstream have relatively lower pH values than those taken from upstream. Statistical significance for differences in pH measured between upstream and downstream sample locations was tested for using a one-way analysis of variance (ANOVA). The ANOVA showed that the pH values MAD between groundwater wells upstream and downstream were significantly different ($p < 0.05$), which confirms that site-related activities and hydrogeological flow orientation exert an influence on spatial variation of pH in groundwater.

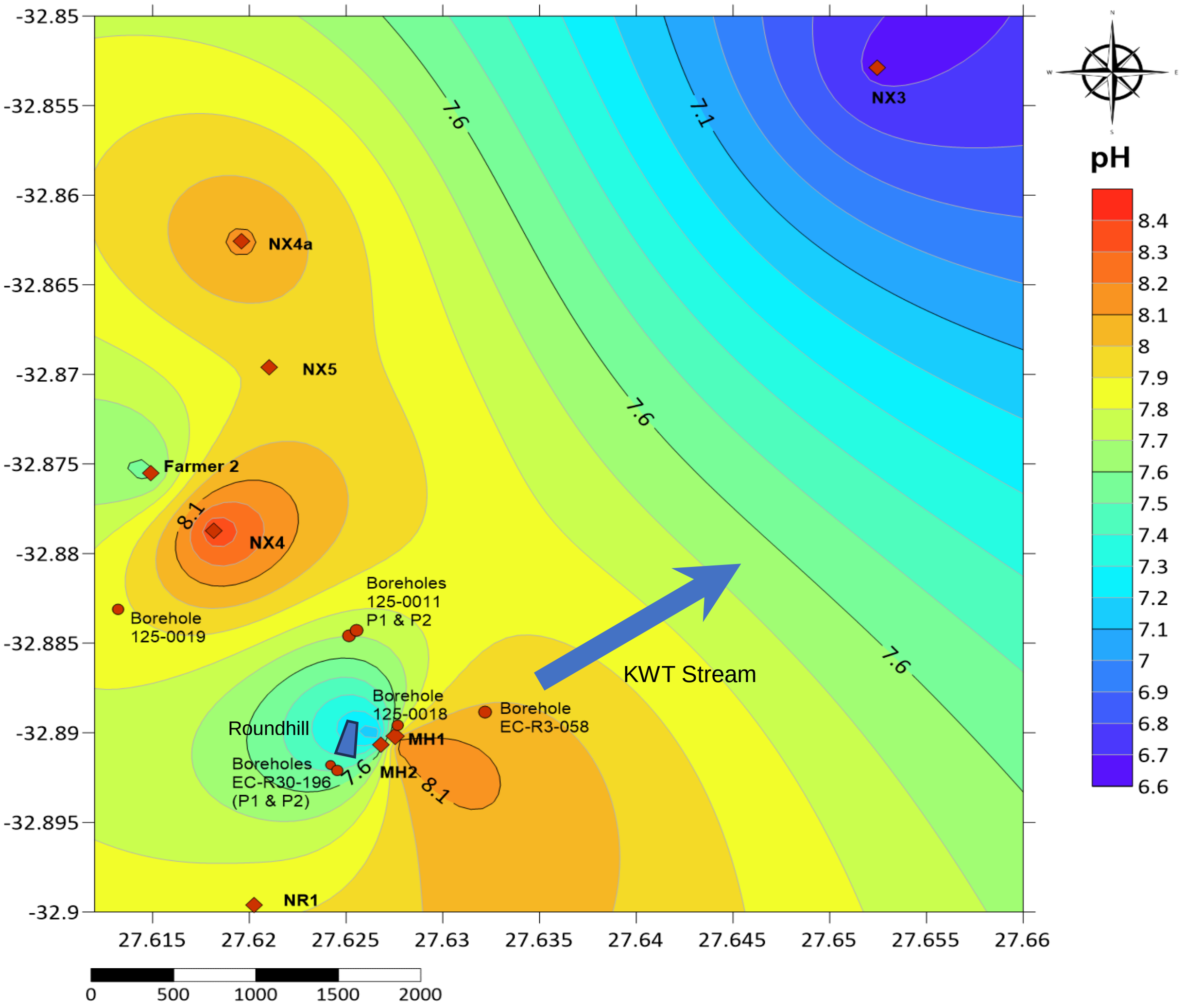


Figure 4.3: Spatial profiles of pH for surface water sites in and around the Roundhill Landfill site

The observed spatial profile for groundwater is in agreement with that which was developed for the surface water (Figure 4.3) showing that the water pH values became lower on the downstream side away from the landfill. It can be concluded that while the measured pH for most of the collected samples of the freshwater systems included in the study are within the accepted range for aquatic life, the spatial profiles developed from the study showed a pH distribution that decreased away from the landfill sites. This may indicate the possibility of considerable impacts of the Roundhill Landfill site on the freshwater sources in its vicinity. The sampled borehole and river water from the KWT landfill site were within acceptable

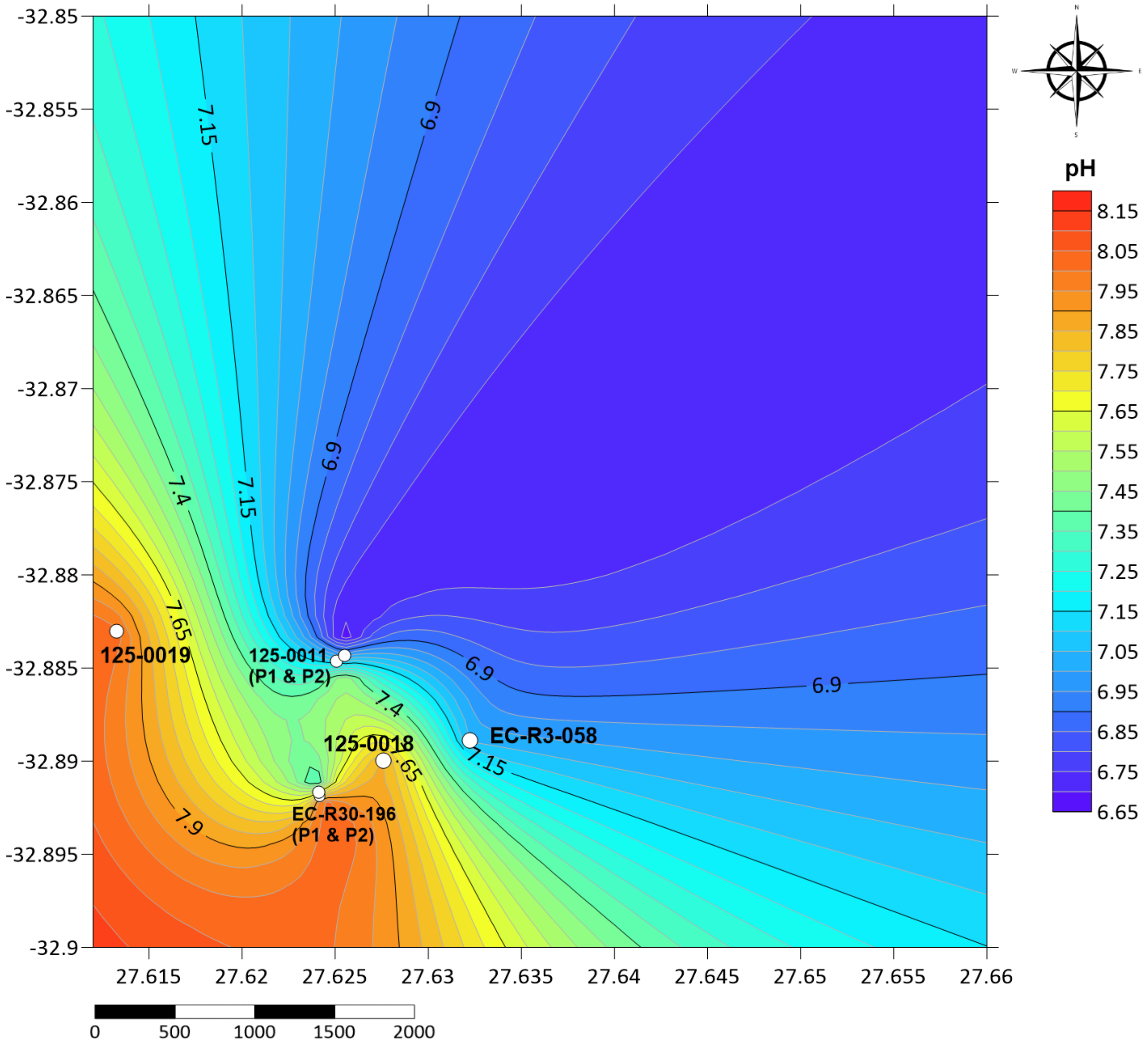


Figure 4.4: Spatial profiles of pH for surface water sites within and around the Roundhill Landfill site

levels, and therefore no conclusion could be made in relation to the impacts of the landfill based with regard to the pH analysis.

4.3.2 Electrical Conductivity

The results for the analysis of the EC of the landfill leachates and the respective freshwater sources in the vicinity of the landfill sites summarised in Tables 4.3 and 4.4 involved the use of both secondary and primary data. Together with the pH, data for this physical parameter appeared consistently in every record that was available from the collected secondary data. The EC measures the ability of water to conduct electricity, which is enhanced by the presence of ionic salts and other inorganic substances in water (Omer, 2019). Thus, high electrical conductivity values are associated with the presence of elevated levels of ions in the water.

Water quality guidelines for electrical conductivity vary by jurisdiction. The World Health Organization (WHO) guidelines, as applied by Meride & Ayenew (2016) in their assessment of drinking water quality in Ethiopia (a developing country context with similar water quality challenges to South Africa), recommend that EC should not exceed 400 $mS.m^{-1}$ for palatable drinking water. In comparison, the South African National Standard (SANS:241, 2015) sets a more stringent limit of 170 $mS.m^{-1}$, reflecting local water quality management priorities. Tables 4.3 and 4.4 below indicate the results from the collected primary and secondary data for electrical conductivity measurements of.

4.3.2.1 Results of Leachate EC analysis

The values for electrical conductivity for the leachate samples from the secondary data were relatively high, with both Roundhill and KWT landfill leachates about 10 times higher than those for surface and groundwater samples (Table 4.3 and Table 4.4). Regarding EC figures, the KWT landfill leachates showed much larger variation ($\bar{x}$ = 1277.1; SD = 878.8) compared to Roundhill Landfill leachates ($\bar{x}$ = 1375.1; SD = 91.9). Electrical conductivity values for KWT landfill ranged from 225 to 5420 $mS.m^{-1}$ for the three-year period from 2019 to 2021 with the latter figure being the highest EC value (5420 $mS.m^{-1}$) recorded in December 2019. The experimental results for both the Roundhill and KWT Landfill sites were consistent with the summarised secondary data for the sampling sites. The electrical conductivity for Roundhill landfill site was found to be 1356.5 $mS.m^{-1}$ while it was 922.2 $mS.m^{-1}$ for the KWT landfill site.

Table 4.3: Secondary yearly mean electrical conductivity data for leachate samples.

Electrical Conductivity/ mS·m^{-1} (Threshold 400 mS·m^{-1})									
Sampling Site	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**$\bar{x}$**	**SD**	**Experimental Results**
Roundhill Landfill Leachate	1367.7	1351.9	1531.5	1257.1	1370.0	1492.3	**1375.6**	**91.9**	**1356.5**
KWT Landfill Leachate	-	-	-	1608.6	1285.1	901.4	**1277.1**	**874.8**	**922.2**

4.3.2.2 Results of Freshwater EC analysis

The electrical conductivities for the surface and groundwater samples collected from within the Roundhill Landfill site and from various sources in the vicinity of the landfill area are shown in Table 4.4 below. The freshwater electrical conductivity values from the collected secondary data were much lower than those for the leachate samples. The average value for the storm water pond from secondary data was raised (858.6 mS.m^{-1}), comparable to leachate data. As discussed, water that collects in the storm water pond is polluted with leachate that contributes to the high EC values in the pond water (Table 4.4). With the exception of MH2 which, as indicated above is also contaminated with leachate, all the other surface water data were within the acceptable range for SANS-241 (2015) guidelines for drinking water. The mean values were in the range 71.5 mS.m^{-1} for NX3 to 157.8 mS.m^{-1} for NX5. Comparison of experimental and secondary data for the surface water sources presented in Table 4.4 and Figure 4.5 show that the majority of data from experimental the recorded data mean, and outside the confidence intervals of the recorded mean.

The stormwater pond sample was the only sample with an experimentally determined electrical conductivity value that was lower than that obtained from the records. The EC values for MH1 and MH2 aligned with equivalent secondary data and standard deviation of the secondary records. The experimental data (123.3 and 219.0 mS.m^{-1}, for MH1 and MH2 respectively, were also within the WHO guidelines (Omer, 2019a) even though the EC value obtained for MH2 exceeded the SANS-241 (2015a) standard limit. Samples from Farm 2, NR1, NX3 and NX5 were all above the SANS-241 (2015a) limit for domestic water and the limits set by the WHO (Omer, 2019a) with electrical conductivities ranging from 436.1 to 4840.3 mS.m^{-1}. Of these results, the most concerning is a significantly raised value of 4840.3 mS.m^{-1} that was obtained from sampling site NR1, a figure that is around 12 times higher than the WHO guideline limit. According to a BCMM Proposed Water Quality Monitoring Report of 2017, NR1 is one of the sites that is used specifically for early detection of leachate pollution of the freshwaters. Based on this result, this site seems to show evidence of pollution by plumes from the landfill site and may therefore signal potential pollution of the surrounding waterbodies by landfill leachate.

Table 4.4: Electrical conductivity data from collected surface and groundwater samples.

	Site Name	**N**	**EC/mS.m^{-1} (Secondary Data)**	**EC/mS.m^{-1} Experimental Results**
Surface Water Samples	Storm water Pond	28	858.6(307.8)	123.0
	Farmer 2	5	110.8(13.3)	757.2
	MH1	25	136.8(30.0)	123.3
	MH2	25	202.1(108.8)	219.0
	NR1	22	118.0(62.1)	4840.3
	NX3	3	71.5(72.9)	1063.2
	NX4a	6	99.5(69.9)	277.8
	NX4	3	99.5(69.9)	970.3
	NX5	4	157.8(69.6)	436.1
	KWT Stream		No Record	105.7
Groundwater Samples (Boreholes)	ECR-30-196 (P1)	3	79.5(20.8)	94.7
	ECR-30-196 (P2)	3	92.6 (15.3)	106.7
	P125-0011 (P1)	2	88.6(0.0)	121.8
	P125-0011 (P2)	-	No Record	86.9
	P125-0018	3	65.3(2.5)	98.2
	P125-0019	7	64.6(1.6)	272.5
	EC-R30-058	3	156.1(44.6)	194.4
	KWT Landfill Borehole	-	No Record	651.8

The spatial profiles developed from the study surface data source results (Figure 4.6) appear to agree with this conclusion, with the south-western side of the Figure showing higher electrical conductivity values that appear to spread away from the landfill area, decreasing in the direction of flow of surface and ground water. The extrapolated profile

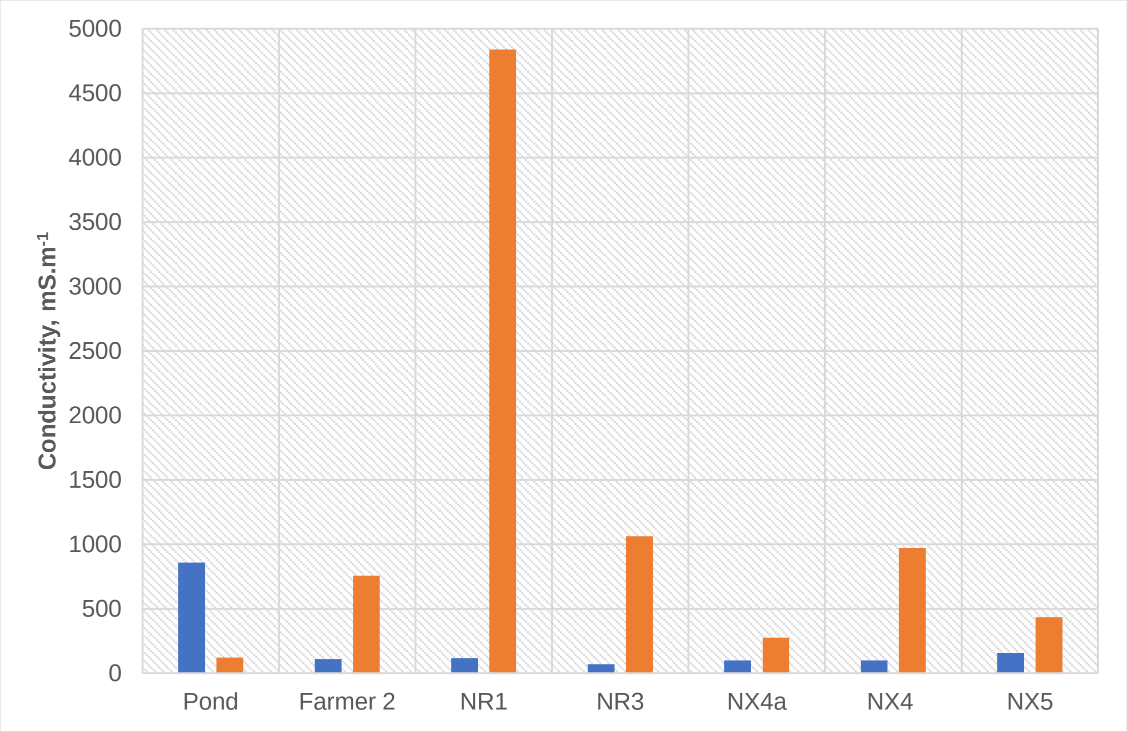


Figure 4.5: Comparison of electrical conductivities (primary data (brown bars) vs secondary data (blue bars)) for the listed surface water samples.

shows that more than 70% of the studied area may have surface water above the SANS-241 and WHO guidelines.

The groundwater electrical conductivity values for samples collected from the boreholes surrounding the Roundhill Landfill are presented in Table 4.4. These values were all within the WHO guideline limits, even though P125-0019 and EC-R30-058 were above the SANS-241 (2015) limits. The experimental value for electrical conductivity of borehole P125-0019 (272.5 mS.m^{-1}) was about four times larger than the mean from the secondary data, while the results for P125-0023 were consistent with the secondary data. The sample from the borehole at KWT Landfill showed the highest electrical conductivity of all the boreholes records (651.8 mS.m^{-1}) for both primary and secondary data. This could be interpreted as evidence of the significant impact of the KWT Landfill leachate on underground water quality. Unfortunately, this could not be explored further because of limited underground water sampling points around the KWT landfill site.

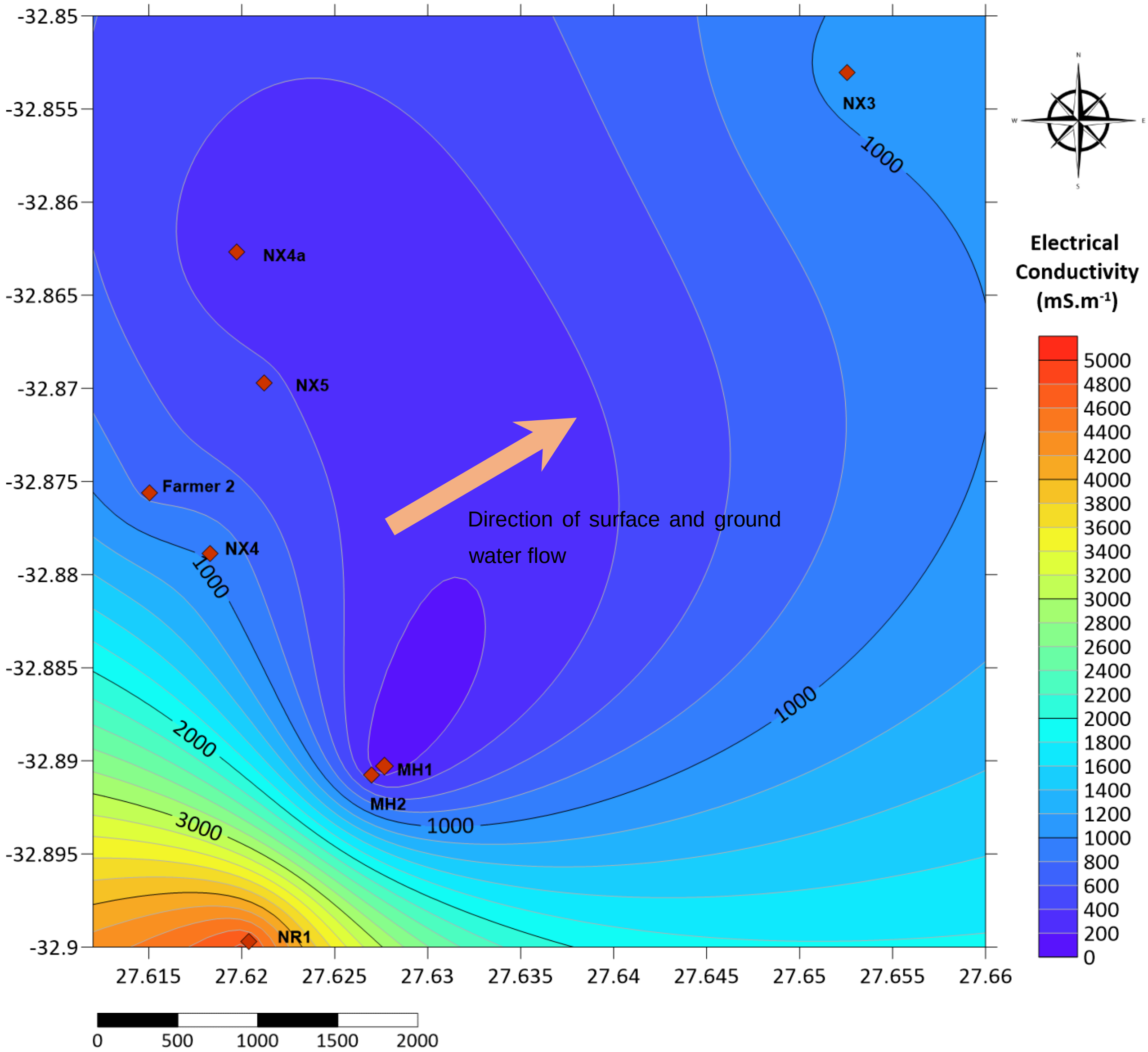


Figure 4.6: Spatial profiles of electrical conductivities for surface water sites within and around the Roundhill Landfill site

The spatial profile for electrical conductivity for groundwater sources (Figure 4.7) contrasts with that of the surface water sources. The profile shows increasing values of electrical conductivity in the direction of flow of the groundwater that fall within the WHO guidelines, even though over 70% of the EC values from the groundwater samples exceed the SANS-241 (2015b) limits.

The spatial profile for electrical conductivity for groundwater sources (Figure 4.7) contrasts with that of the surface water sources. The profile shows increasing values of electrical

conductivity in the direction of flow of the groundwater. The values of these EC results fall within the WHO guidelines, even though over 70% of the EC values from the groundwater samples exceeded the SANS-241 (2015a) limits.

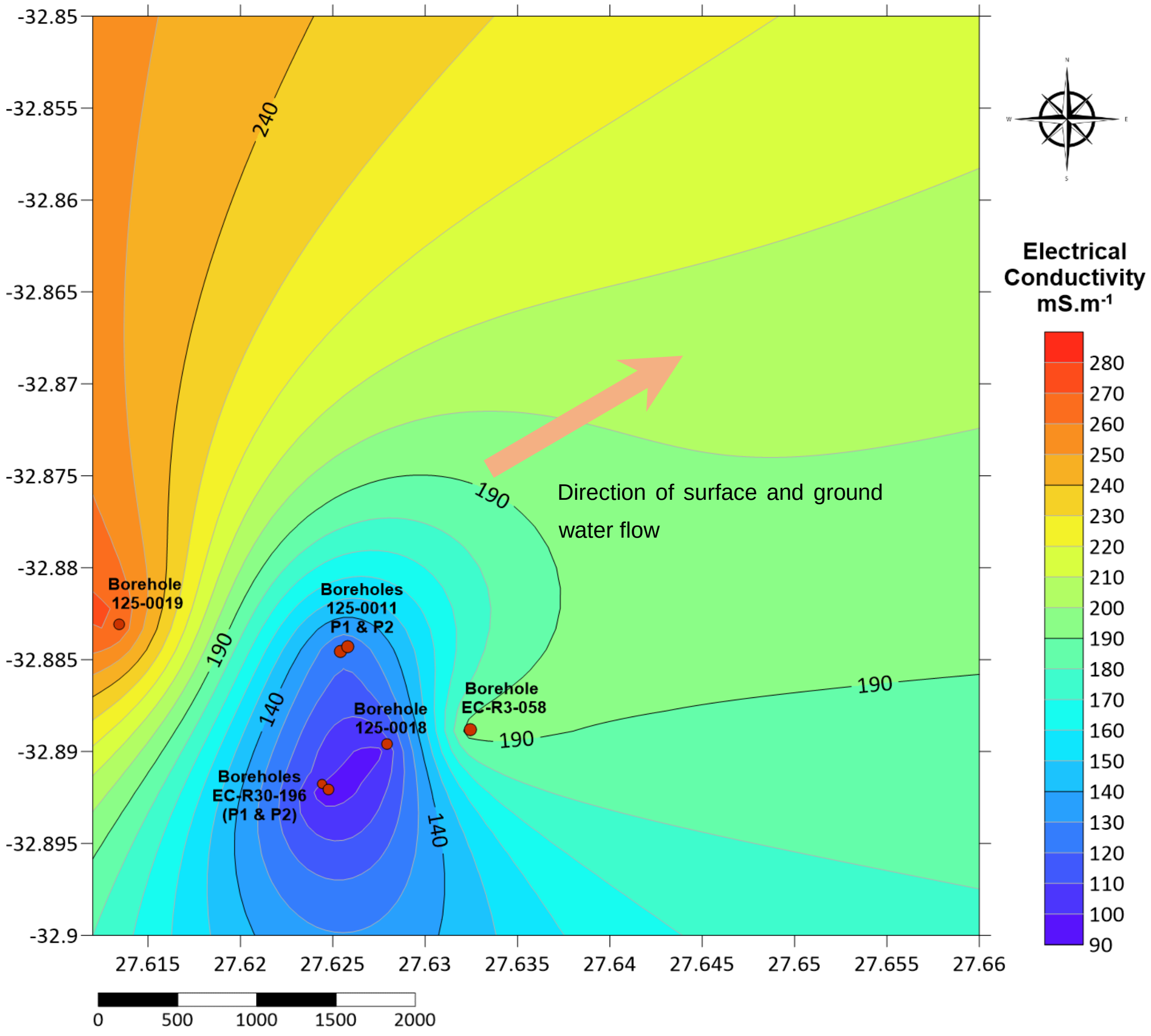


Figure 4.7: Spatial profiles of electrical conductivities for ground water sites within and around the Roundhill Landfill site

4.3.3 Turbidity and Temperature

Turbidity and temperature are the remaining physical parameters affecting water quality that were measured in this study. Turbidity is an optical characteristic of water that measures its relative clarity or cloudiness (Omer, 2019a; Fahimah et al., 2023). It has significant impacts on the ability of the light to pass through the water, and therefore has significance influence on aquatic life. As was discussed earlier, this parameter is affected by the levels of total dissolved solids and suspended materials in the water.

4.3.3.1 Results of Leachate Turbidity Analysis

There was no record of turbidity measurements from the secondary data that were collected for all the sites of interest in this study. However, the parameter was measured to provide additional insights into the study physicochemical parameter results that are discussed from section 4.5 below. The results of the analysis of turbidity and water temperature are shown in Table 4.5 below. According to the SANS-241 (2015a), the maximum allowable turbidity values for drinking water is 4 NTU (aesthetic risk). Leachate samples were expected to show high values of turbidity (Azougarh et al., 2019), because of excessive amounts of total dissolved solids (TDS) as well as suspended particulate matter in the water. According to Azougarh et al. (2019), the range of turbidity in leachates may lie between 1330 NTU and 2420 NTU. The observed turbidity values for the leachates were much lower than those recorded in literature, giving a reading 26.1 NTU for Roundhill Landfill leachate and 7.2 NTU for KWT Landfill leachate.

4.3.3.2 Results of Water Turbidity Analysis

The results for turbidity analysis for the surface and groundwater samples (Table 4.5) ranged from 0.9 to 489.1 NTU. According to Azus et al. (2015), turbidity of water in natural environments may range from as low as 1 NTU to 2 NTU in fresh water to >30 NTU for river water samples collected from rivers with sediments, especially during the rainy season because of an increase in the suspended sediment load (Azus et al., 2015). The record turbidity value for NX5 with a value of 489.1 NTU, was highest, and way over the values predicted in literature for freshwater sources (Azus et al., 2015). This result can be interpreted to show presents excessive amounts of dissolved organic (decaying plant or animal material) and/or inorganic compounds, or a considerably high amount of suspended sediment in the water (e.g. clay soil). Samples from the NX3 and NX4 also showed elevated turbidity values in a range between 15 NTU and 25 NTU. According to Azus et al. (2015) this range may be described as fairly turbid. Five of the surface water sources had turbidity values below the SANS-241, (2015a) threshold for drinking water (< 4 NTU).

Table 4.5: Primary mean temperature and turbidity data for leachate as well as surface and groundwater samples.

	Site Name	Temperature (ºC)	Turbidity (NTU)
Threshold Values			**4.0**
Leachate Data	Roundhill Landfill Leachate	18.1	26.1
	KWT Landfill Leachate	21.7	7.2
Surface Water Samples	Storm water Pond	18.7	0.9
	Farmer 2	21.8	3.7
	MH1	18.7	0.9
	MH2	18.3	7.5
	NR1	17.3	1.7
	NX3	18.2	16.2
	NX4a	21.0	1.1
	NX4	21.9	17.5
	NX5	18.0	489.1
	KWT Stream	20.6	1.2
Groundwater Samples (Boreholes)	ECR-30-196 (P1)	19.5	6.3
	ECR-30-196 (P2)	18.3	42.8
	P125-0011 (P1)	17.2	1.1
	P125-0011 (P2)	17.4	110
	P125-0018	18.4	2.0
	P125-0019	18.7	4.6
	EC-R30-058	18.3	27.7
	KWT Landfill Borehole	21.5	1.6

The spatial profile for the turbidity of surface water samples collected within and around the Roundhill landfill site shows that NX5 is a hotspot with excessively high turbidity values (Figure 4.8). The NX5 sample collection site is much further from the landfill compared to NX4 and the Farmer 2 water reservoir. Given that it is dam/pond, its relatively high turbidity values may not be solely related to pollution from the landfill site.

The turbidity values for groundwater samples from boreholes ECR-30-196 (P2), P125-0011 (P2) and EC-R30-058 were relatively high, ranging from 27.7 NTU for EC-R30-058 to 110 for P125-0011), compared to the reported results for the majority of surface water samples, and much larger than the SANS-241 (2015a) threshold of 5 NTU for drinking water. In general, groundwater samples have low turbidity values because of the natural process that occurs as the water penetrates soil (Omer, 2019b). High turbidity values in groundwater are usually attributed to high clay content, high levels of decaying organic matter, large amounts of dissolved salts from the chemical process on the rocks beneath or may point to signs of pollution of the groundwater.

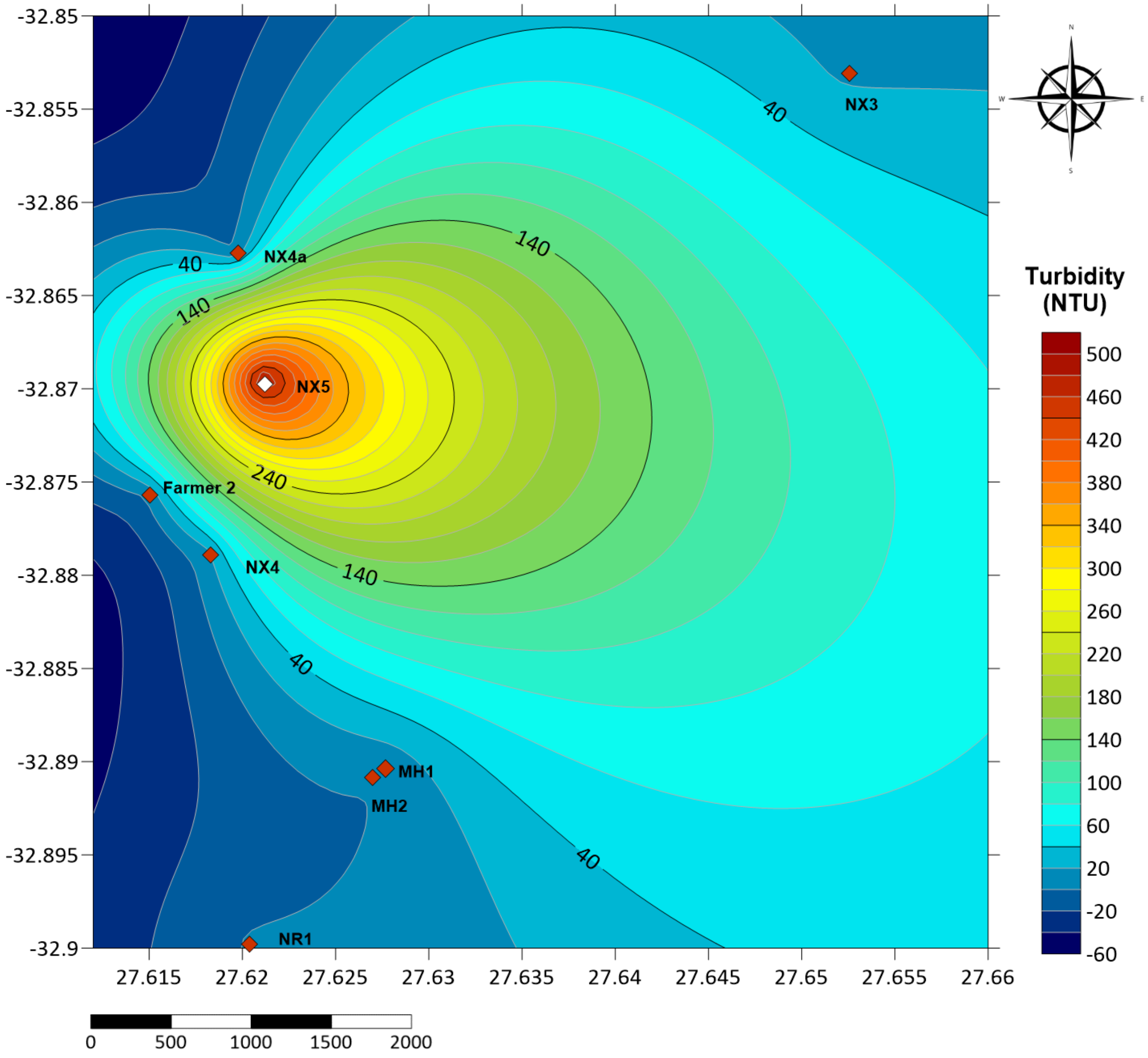


Figure 4.8: Spatial turbidity profile for surface water samples collected at Roundhill Landfill

All the highlighted boreholes with significantly high turbidity values are close to the landfill, and therefore may point to contamination of the groundwater by the leachate. This will be further explored later in relation to the results of chemical analysis. However, it was also noted that some of the boreholes next to each other had significantly different turbidity values (e.g. ECR-30-196 (P1 and P2 with values 6.3 and 42.8 respectively) and P125-0011 (P1 and P2 with values 1.1 and 110 respectively). The same was observed earlier for pH and electrical conductivity for the same boreholes. This difference in the turbidity for adjacent groundwater samples may be explained by some geological factors which are not included within the scope of this study.

The results for the measured water temperatures for all the collected samples presented in Table 4.5 show that the recorded values were all in a range between 5-25^{o}C that is optimal for aquatic life. This temperature range corresponds to the results of the study conducted by (Dallas, 2008). According to Omer (2019b), surface water sources with higher turbidity are generally characterised by high water temperatures which has an impact on dissolved oxygen. A relatively high turbidity value for NX5 did not correlate with the water temperature (18^{o}C), which could mean that the high turbidity value that was reported for the river source could have been a disturbance which was temporary, and therefore didn’t have long lasting impacts on the water quality.

4.4 Assessment of Chemical Parameters

The results for the analysis of the chemical parameters involved the use of both secondary (Tables 4.6 and 4.8) and primary data (Tables 4.7 and 4.9) for the inorganic anions (Cl^-, NO_3^-, NO_2^- and SO_4^{2-}) and ammonia, as well as the heavy metals (As, Cd, Cr, Mn and Pb). Secondary data for the chemical parameters was relatively limited, particularly regarding the heavy metals, with some chemicals having no data recorded for the period while other data were limited to as few as two measurements for the period considered in this study (2016-2021). As a result of these incomplete data records, the researcher was unable to make conclusive findings about some of the analytes, for instance those with data for only one year of the six years considered. The results for the analysis of the chemical parameters are presented below.

4.4.1 Assessment of Chloride Contamination

The results for secondary data analysis show mean data for the period between 2016 and 2021 (Table 4.6). Concentrations of leachate chloride were high for both Berlin and KWT landfills (2220.4±740.9 mg/L and 2517.7±982.4 mg/L, respectively). The levels of chloride for water samples from the contaminated stormwater pond were comparable to the values obtained for the leachates (Table 4.6). With the exception of MH1 (292.4±106.7 mg/L) and NX5 (286.5±146.4 mg/L), all the other surface water sources were within the accepted range stipulated by SANS-241 (2015) limit for chloride in water of 250 mg/L. Groundwater secondary data were available for only three boreholes, with only ECR-30-196 (P2) having chloride concentration of 280.5±285.0 mg/L, which exceeded the SANS-241 (2015b) limit.

The primary data for chloride levels in the leachate samples from Roundhill (993.9 mg/L) and KWT (2811.2 mg/L) landfills are shown in Table 4.7. These were consistent with results from the secondary data, indicating high chloride concentrations in the leachate. Unlike the secondary data in Table 4.6, the results for six of the 10 surface water sources in the vicinity of the landfill showed severe chloride contamination with the highest levels reported for MH2 (4070.8 mg/L) and from NR1, NX3, NX4a, NX4 and NX5 showing values ranging from 254.3 mg/L to 2523.8 mg/L (Table 4.7). As was highlighted earlier, MH2 is a surface water source with water that is contaminated with leachate, which could explain the high values for chloride concentration. However, for the other analysed samples, the results appear to indicate the possibility of wastewater contamination of the respective freshwaters sources. The results of the analysis of groundwater samples showed high chloride concentrations that exceeded the SANS-241 (2015b) limits for boreholes P125-0019, EC- R30-058 and the KWT landfill borehole. These observed chloride concentrations were considerably higher than typical background levels reported for unpolluted groundwater in South Africa. For comparative context, Edokpayi et al. (2018), investigating groundwater quality in the Muledane area of Limpopo Province, a rural region with similar geological characteristics to the Eastern Cape reported chloride levels ranging from 10 to 45 mg/L in unpolluted boreholes. Similarly, Maliehe and Moropeng (2024), in their study of groundwater around landfill sites in Mankweng, Limpopo (a semi-arid region with comparable hydrogeological conditions), obtained chloride concentrations ranging from 36.1 to 184.55 mg/L in samples influenced by leachate contamination. The substantially higher values observed in the present study (particularly at MH2, NR1, and NX4a) indicate severe contamination beyond typical landfill impacts reported elsewhere in South Africa.

The spatial profile shows a high concentration level of chloride around MH2, which is in the landfill, and spreading around the landfill at a decreasing concentration gradient. The map (Figure 4.9) shows the landfill as a hotspot for chloride contamination in the area. The profile for the groundwater sources seems to show an opposite profile (Figure 4.10), with the boreholes in the landfill area showing lower concentration of chloride, and the chloride levels increasing in the direction of the flow of surface and groundwater.

Table 4.6: Mean concentrations of Cl^-, SO_4^{2-}, NO_3^-, NO_2^- and NH_3 (mg/L) calculated from secondary data of the water samples collected from sites located within and around the Roundhill and KWT landfills.

	Site Name	**Cl^- (mg.L^{-1})**	**SO_4^{2-} (mg.L^{-1})**	**NO_3^- (mg.L^{-1})**	**NO_2^- (mg.L^{-1})**	**NH_3 (mg.L^{-1})**
Threshold Levels		**250 mg.L^{-1}**	**250 mg.L^{-1}**	**50 mg.L^{-1}**	**3 mg.L^{-1}**	**1.5 mg.L^{-1}**
Leachate Samples	Roundhill Landfill	2220.4(740.9)	67.0(31.0)	2.15(0.99)	0.11(0.02)	614.3(105.1)
	KWT Landfill	2517.7(982.4)	100.0(19.1)			11.0(51.4)
Surface Water Samples	Storm water Pond	2049.0(1171.1)	88.5(58.7)			159.0(207.8)
	Farmer 2	201,8(40.4)	42,5(7,0)	1.90(1.70)	0.02	0.7(0.5)
	Farm 2 Pond	18.7				5.6
	MH1	292.4(106.7)	38.0(28.3)	0.90(2.20)	0,91(1.14)	3.2(6.5)
	MH2	435.1(204.2)	30.6(14.4)	4.84(13.02)	1.44(2.18)	34.1(128.4)
	NR1	189.1(51.0)	226.58(684.5)	63.27(112.6)	1.18(1.67)	0.5(0.4)
	NX3	178,5(211.4)	35,5(40.3)		0.02	0.6(0.1)
	NX4a	128.0(100.4)	30.3(35.8)		1.0	0.6(0.1)
	NX4	131.2(99.2)	26.2(12.0)	0.03	0.03	0.8(0.1)
	NX5	286.5(146.4)	24.7(22.1)	0.38(0.26)		2.4(3.0)
	KWT Stream					
Groundwater Samples (Boreholes)	ECR-30-196 (P1)	214.3(153.8)	15.0(20.9)	0.10(0.14)		10.5(7.3)
	ECR-30-196 (P2)	280.5(285.0)	25.2(28.6)	1.61(2.24)		23.1(19.87)
	P125-0011 (P1)					
	P125-0011 (P2)					
	P125-0018	71	21.7(24.2)	2.85(4.12)		16.5
	P125-0019	9.5(6.4)	1.17(1.11)		1.19(1.38)	11.5(6.4)
	EC-R30-058					
	KWT Landfill Borehole					

Table 4.7: Mean concentrations of the Cl^-, SO_4^{2-}, NO_3^-, NO_2^- and NH_3 (mg/L) calculated from primary data of the water samples collected during the summer and winter period from sites located within and in the vicinity of the Roundhill and KWT landfills.

	Site Name	**Cl^- (mg.L^{-1})**	**SO_4^{2-} (mg.L^{-1})**	**NO_3^- (mg.L^{-1})**	**NO_2^- (mg.L^{-1})**	**NH_3 (mg.L^{-1})**
Threshold Levels		**250 mg.L^{-1}**	**250 mg.L^{-1}**	**50 mg.L^{-1}**	**3 mg.L^{-1}**	**1.5 mg.L^{-1}**
Leachate Samples	Roundhill Landfill	993.86	34.42	1.55	1.53	0.44
	KWT Landfill	2811.22	84.84	3.86	2.67	3.44
Surface Water Samples	Storm water Pond	175.77	34.09	3.99	0.23	0.16
	Farmer 2	121.04	30.58	6.39	0.37	0.9
	MH1	175.77	34.09	3.99	0.23	0.16
	MH2	4070.81	78.93	2.12	5.08	0.27
	NR1	1022.57	8446.67	2.47	3323.4	1.23
	NX3	768.65	48.12	0.94	0.11	0.29
	NX4a	2523.48	105.75	6.89	3.17	0.05
	NX4	875.64	521.62	51.78	9.80	0.13
	NX5	254.25	53.50	0.57	0.04	0.11
	KWT Stream	148.65	25.55	0.36	0.19	0.44
	ECR-30-196 (P1)	141.47	4.92	0.82	0.20	0.00
Groundwater Samples (Boreholes)	ECR-30-196 (P2)	83.43	6.01	2.41	0.27	66.2
	P125-0011 (P1)	138.64	61.73	2.12	0.11	0.65
	P125-0011 (P2)	115.23	2.71	0.03	0.08	15.22
	P125-0018	142.80	31.24	1.72	0.70	0.8
	P125-0019	527.75	5.19	0.06	0.37	10.3
	EC-R30-058	438.50	31.38	4.56	1.76	2.39
	KWT Landfill Borehole	1719.83	86.15	1.43	0.00	11.14

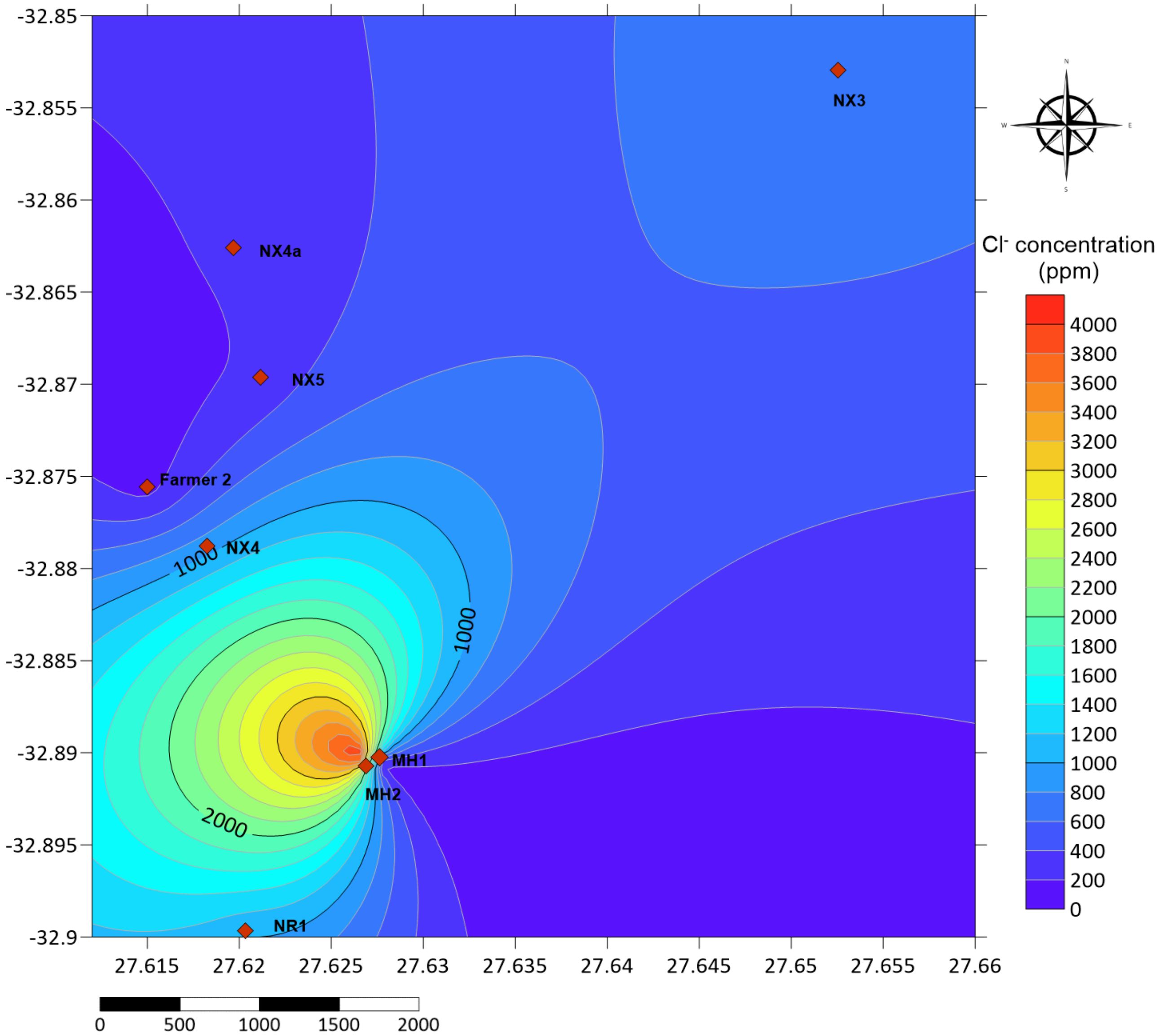


Figure 4.9: Spatial profile for chloride levels (mg/L) for the surface water samples in the vicinity of Roundhill Landfill

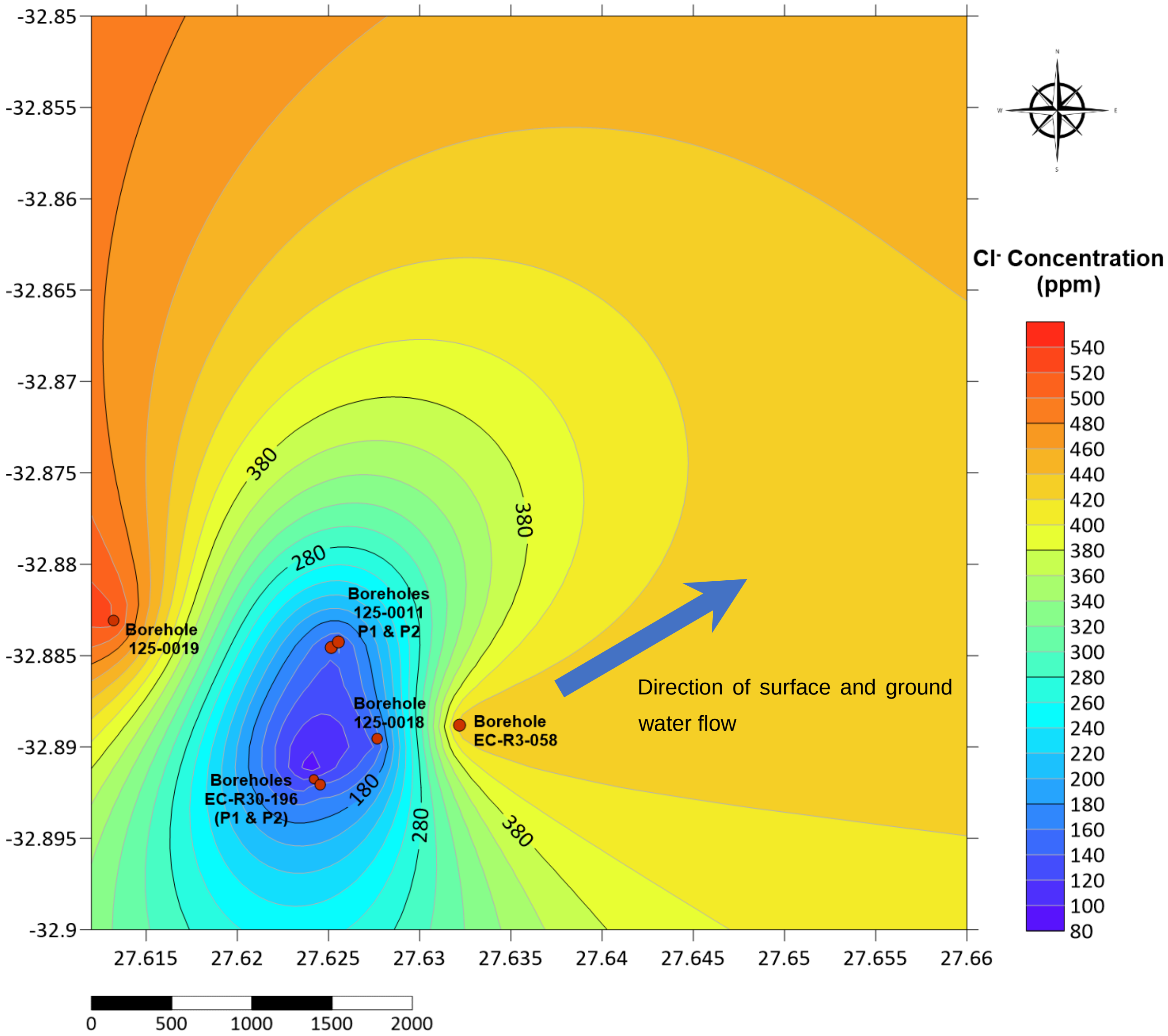


Figure 4.10: Spatial profile for chloride levels (mg/L) for the groundwater samples in the vicinity of Roundhill Landfill

4.4.2 Assessment of Sulphate Contamination

Secondary data for sulphate concentrations in surface water, groundwater and leachate samples are presented in Table 4.6 above and primary sulphate data are presented in Table 4.7. The SANS-241 (2015a) limit for sulphate in drinking water (250 mg/L) is also shown in the Table. The results calculated from the secondary data show that the mean concentration for sulphate for all the sites were within the accepted range according to the SANS-241 (2015a) guidelines. The values for both surface and groundwater sources were in the range 1.12 mg/L to 226.6 mg/L (Table 4.6). Though all results were within the SANS 241 (2015) limits, one sample (NR1) was above a more stringent USEPA limit of 200 mg/L. Leachate samples were considerably lower (67.0 and 100.0 mg/L for Roundhill and KWT landfills, respectively). It should be noted however that for the limited results that the researcher was able to access mean that sulphate levels in NR1 showed significantly high variation (226.58±684.5), which can be indicative of the susceptibility of the stream NR1 to sulphate contamination.

This assertion was confirmed by results from the analysis of primary data (Table 4.7) which recorded a concentration of 8446.7 mg/L of sulphate for NR1, which is about 33 times larger than the accepted threshold limit. As was observed with the secondary data in Table 4.6, the values of sulphate in leachate samples were much lower (34.4 and 84.8 mg/L) for Berlin and KWT landfill sites, respectively. Considering that the concentrations in both primary and secondary data for leachate sulphate were low, it may be inferred that the contamination in NR1 may result from a source other than the landfill site. Besides NR1, experimental results also showed that NX4 (521.6 mg/L) exceeded the upper SANS-241 (2015a) limit of 500 mg/L. The sulphate levels in NX4, which is a farm dam and is used as a source of drinking water for cattle, may be influenced by nearby agricultural chemicals, and therefore is most likely also not related to landfill waste pollution. The groundwater samples were all within the limits, ranging from 2.7 to 86.2 mg/L (Table 4.7). The results were consistent results from a study of groundwater samples by Mutileni et al. (2023) who reported sulphate in the ranges of 1.92-16.62 mg/L and Masindi and Foteinis (2021) with reported data of concentration.

4.4.3 Assessment of Nitrate, Nitrite and Ammonia Contamination

Data collected from the historical records for nitrate content were limited (Table 4.6), with records for only six out of the eleven sampling points for surface water data, and three out of the eight sites for groundwater data. The same was observed for nitrite data which also contained data for only six surface water sampling sites and only one for groundwater samples. Ammonia data was available for 10 of the 11 surface water sampling sites and was limited to only four sites for groundwater data (Table 4.6).

The mean nitrate levels for the surface water sources from the six sampling points were in the range of 0 mg/L to 63.3 mg/L. Of the six surface water records, only one record had nitrate level above the SANS-241 and WHO limits (NR1, 63.3±112.6 mg/L) (Table 4.6). The mean concentration of nitrate on site NR1 showed variability, with high values of nitrate in

2021 in the range of 168 mg/L to 337 mg/L. The remaining records showed much lower nitrate levels (< 3 mg/L), within the recommended limits according to the WHO and SANS-241. The records for nitrate were consistent with those reported by Masindi et al. (2021) in a study of borehole water in Limpopo (mean of 15.2 mg/L). The reported values for mean nitrite concentration in both surface and groundwater were below the SANS-241 (2015) limit of 3 mg/L, with all results ranging between 0 to 1.44 mg/L (Table 4.6). Based on the available records, the NR1 site was the only one that had historical records where high nitrite levels were recorded. There were no records for nitrate and nitrite concentrations for the KWT landfill site leachates. Both nitrate and nitrite levels for Roundhill Landfill sites were in the accepted range according to the SANS-241 (2015) guidelines.

Research has indicated that ammonia concentrations in leachate can exceed 1000 mg/L under certain conditions (Saleem & Algamal, 2016; Schullehner et al., 2017; Feng et al., 2020). Feng et al. (2020), in their investigation of groundwater contamination in rural areas of northern China, a region with continental climate and intensive agricultural activity reported that elevated ammonia levels in groundwater were strongly correlated with proximity to unlined waste disposal sites and fertilizer application. Their findings highlight the global relevance of ammonia as an indicator of anthropogenic pollution, though the dominant sources may vary by region (waste disposal in China, agricultural runoff in Saudi Arabia, and landfill leachate in the present study. The mean concentration of ammonia as obtained from historical data in the leachate samples from Roundhill Landfill site was in line with typical values for landfill leachates (Table 4.6). The average concentration was high (614.3 mg/L) and characterised by high variability (SD = 105.1 mg/L). Therefore, while the observed concentration exceeded the standard according to the WHO and SANS-241 guidelines, the results are normal and typical because of the nature of the sample.

In contrast, the ammonia concentration for KWT landfill leachate (11.0±51.4 mg/L), though at levels exceeding the SANS-241 standard, was lower than those determined in Roundhill Landfill leachate. The contaminated stormwater pond also exhibited significantly high mean ammonia levels which is indicative of leachate pollution (159.0±207.8 mg/L). As was indicated earlier, the stormwater pond at Roundhill Landfill site is contaminated with leachate. This may therefore explain the high ammonia content in that sampling site. The other surface water records showed evidence of pollution with four sites showing high levels of ammonia in excess of the SANS-241 limits, within a range of 2.4 mg/L to 34.1 mg/L. All the groundwater records for the available sites (four sampling points) showed a high concentration of ammonia, with the data showing levels in the range of 10.5 mg/L to 23.1 mg/L.

The experimental results for the analysis of nitrite in samples collected from the two landfill sites (Table 4.7) showed that samples from all sites, with the exception of NX4, were significantly within the SANS-241 (2015a) limit and within a range of 0 mg/L to 6.89 mg/L. The nitrite concentration in samples collected from NX4 just exceeded the SANS-241 (2015) limit (51.8 mg/L), which is an unhealthy level for nitrate in water. As was observed with results for nitrates, experimental data for nitrite in the various samples showed that with the exception of results for NX4, NX4a, MH2 and NR1, all the other samples had nitrite concentration within the accepted SANS-241 guideline limits, ranging from 0 mg/L to 2.7 mg/L. Samples collected from NX4 (9.8 mg/L), NX4a (3.2 mg/L) and MH2 (5.1 mg/L) showed high levels of nitrite (Table 4.7), which can be described as toxic. The levels in NR1 are the most worrying, with a concentration that is over 1000 times in excess of the limit (Table 4.7). High levels of nitrite in drinking water have been associated with methemoglobinemia and hypotension in humans. For instance, Saleem & Algamal (2016) , in their study of groundwater quality in the Khulais Province of Saudi Arabia — a semi-arid region with limited recharge — reported elevated nitrite levels attributed to agricultural runoff and wastewater infiltration. Similarly, Schullehner et al. (2017), analysing drinking water distribution systems in Denmark under temperate climatic conditions, demonstrated that prolonged exposure to nitrite concentrations exceeding 3 mg/L poses significant health risks, particularly for infants. According to Schullehner et al. (2017), high levels of nitrite can produce hypotension in humans as a result of its action as a smooth muscle relaxer, especially in the vascular system. These findings underscore the global relevance of nitrite contamination, though the dominant sources (agricultural in Saudi Arabia, wastewater in Denmark, and landfill leachate in the present study) may differ by region. While their study focused on public water distribution systems in a developed country context, the underlying physiological mechanism applies universally to humans and other mammals. Therefore, the extremely high nitrite concentration (3,323.4 mg/L) detected in NR1, a surface water stream in the temperate coastal region of the Eastern Cape, represents a genuine environmental and public health concern for local communities and livestock that may rely on this water source.

The plotted spatial profile for nitrite levels (Figure 4.11) in surface water shows the point around NR1 as the hotspot for nitrite pollution. It should be pointed out that as was highlighted earlier, in oxygenated water systems, ammonia is converted to nitrite, and finally into nitrate. It can be postulated that there may be contamination of NR1 with leachate containing high levels of ammonia, which is oxidised to nitrite, hence the extremely high levels of the pollutant in the stream. The direction of flow for surface and groundwater according to Mepaiyeda et al. (2020) suggest a flow of the water from the landfill moving away from NR1. However, as was highlighted earlier, NR1 is used as a site for early detection of leachate pollution. It can be concluded that from the landfill site, NR1 is in such a position that it receives considerable amounts of the leachate plume when it is spilled. Therefore, it can be concluded that the site may receive considerable volumes of contaminated plumes from Roundhill Landfill, hence the high values of nitrite concentration.

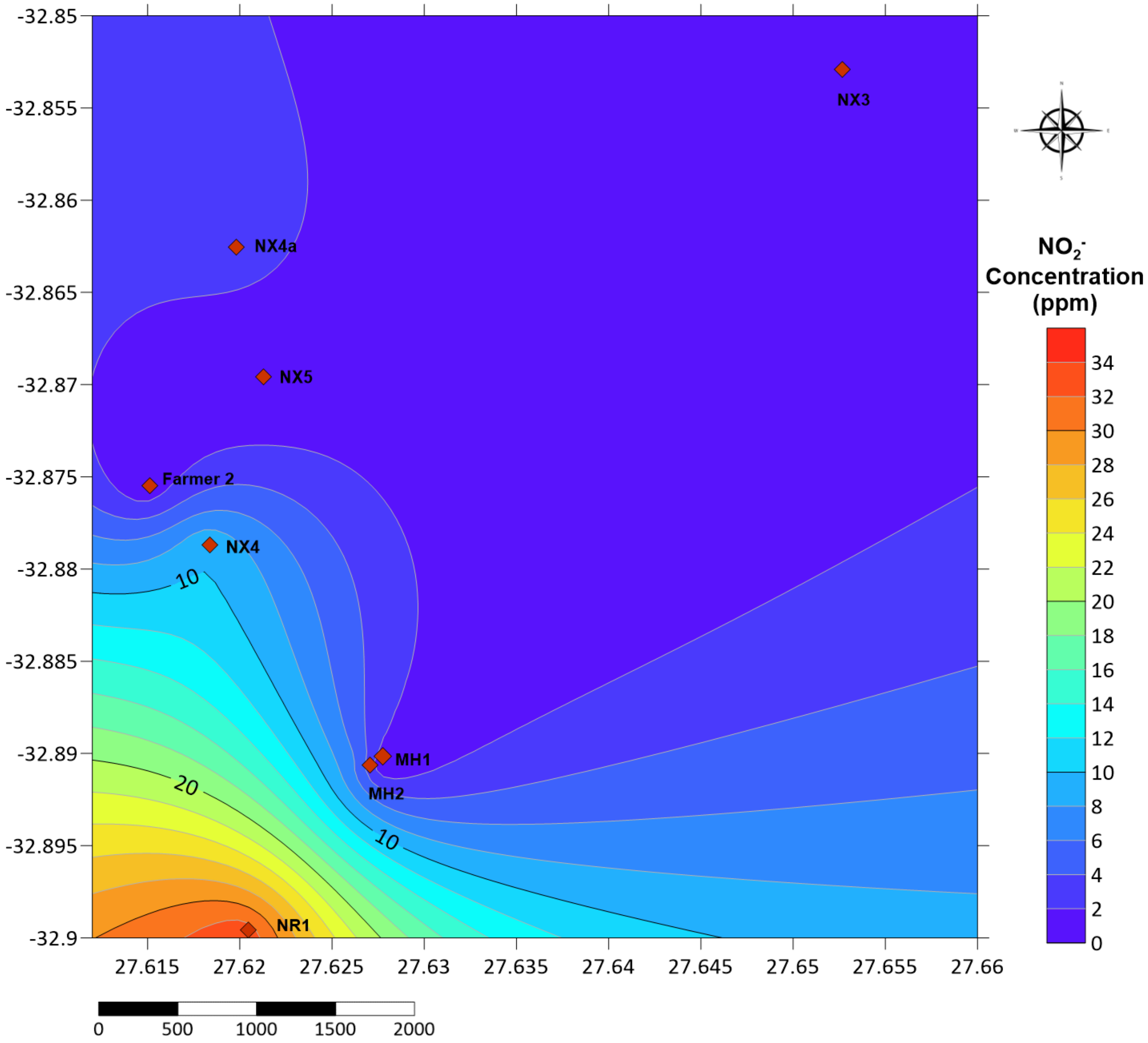


Figure 4.11: Spatial profile for nitrite levels (mg/L) for the surface water samples in the vicinity of Roundhill Landfill

Unlike the secondary data which showed extremely high levels of ammonia at some sites, the primary data for ammonia gave a different picture, with all the collected surface water and the leachates samples having concentrations less than the threshold of 1.5 mg/L (Table 4.7). The concentrations were in the range 0 mg/L to 1.23 mg/L. The KWT landfill leachate recorded high levels of ammonia (3.44 mg/L), above the SANS-241 limit. However, for typical leachate samples, the ammonia concentration was low. The groundwater samples, as observed in the secondary data, exhibited high ammonia concentrations with boreholes ECR-30-196 (P2) (66.2 mg/L), P125-0011 (P2) (15.2 mg/L), P125-0019 (13.3 mg/L) and

KWT Borehole (11.1 mg/L) all having dangerously high levels of ammonia. Borehole ECR-30-058 was also above the threshold, with an ammonia concentration of 2.4 mg/L.

The spatial profiles for ammonia levels in surface water (Figure 4.12) around Roundhill Landfill show high levels of ammonia increasing towards NR1 from the landfill, a profile similar to the nitrite distribution (Figure 4.11) and also as observed for sulphate. The spatial profiles for the concentration of ammonia in the groundwater (Figure 4.13) shows high levels of ammonia in groundwater around the landfill. The concentrations are highest around the landfill site and spreading towards the north-eastern side of the landfill of the map, which are reported as the direction of flow of the ground water. Figures 4.11, 4.12 and 4.13 are similar and highlight a hotspot around the landfill and decreasing in the direction of flow of the surface water and groundwater. The decrease in levels can be understood as spread of the pollutants as they become diluted. These results show that there may be a leachate leak at Roundhill Landfill. These conclusions could be supported by results from KWT that is not an engineered landfill but is a very old landfill that started as a dumpsite and therefore has no leachate collection capacity. Thus, leachate flows into the ground. The KWT landfill borehole’s levels of ammonia, which would be most likely linked to pollution by the landfill is in the same ranges as those observed for Roundhill Landfill boreholes.

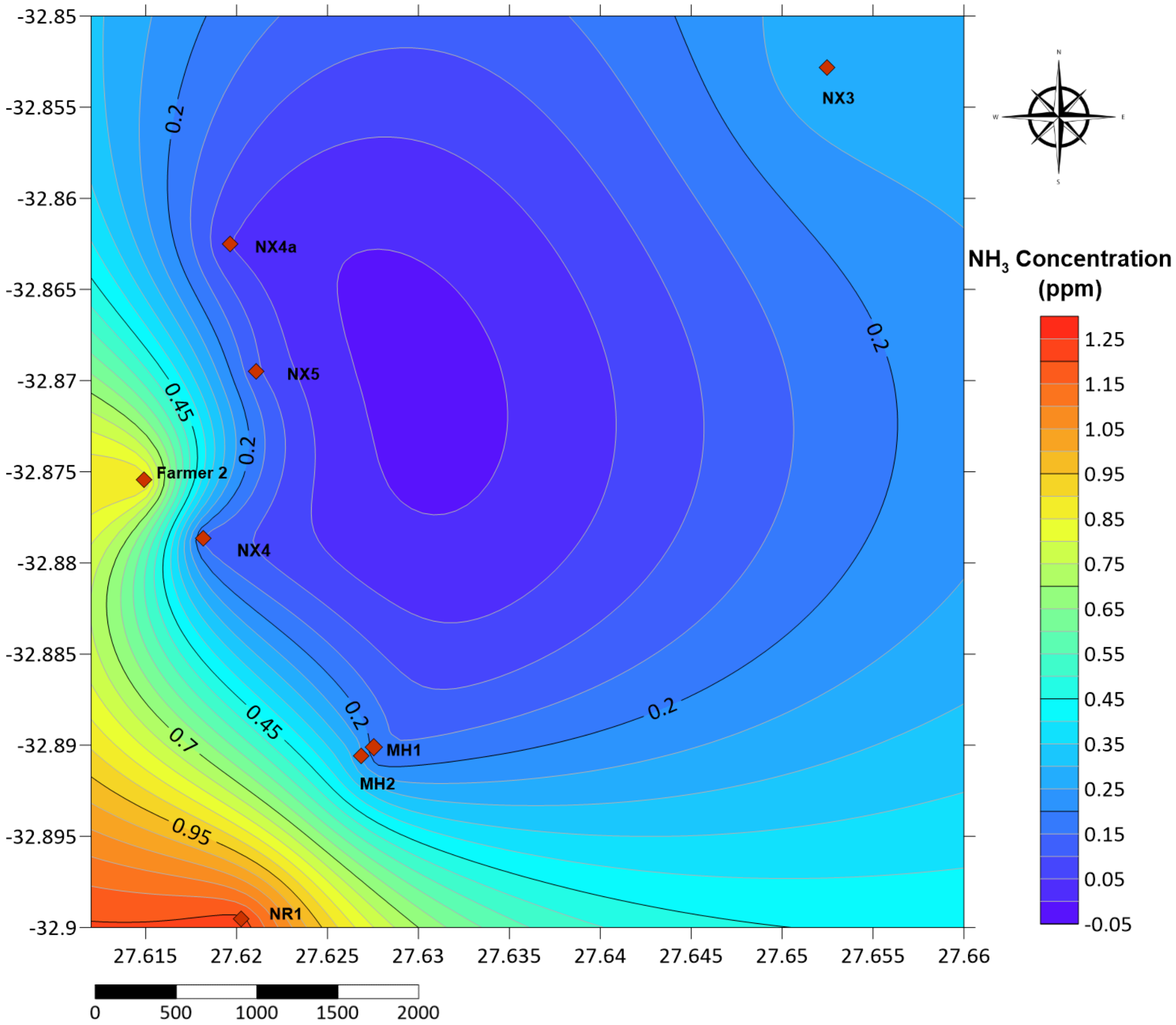


Figure 4.12: Spatial profile for ammonia levels (mg/L) for the surface water samples in the vicinity of Roundhill Landfill

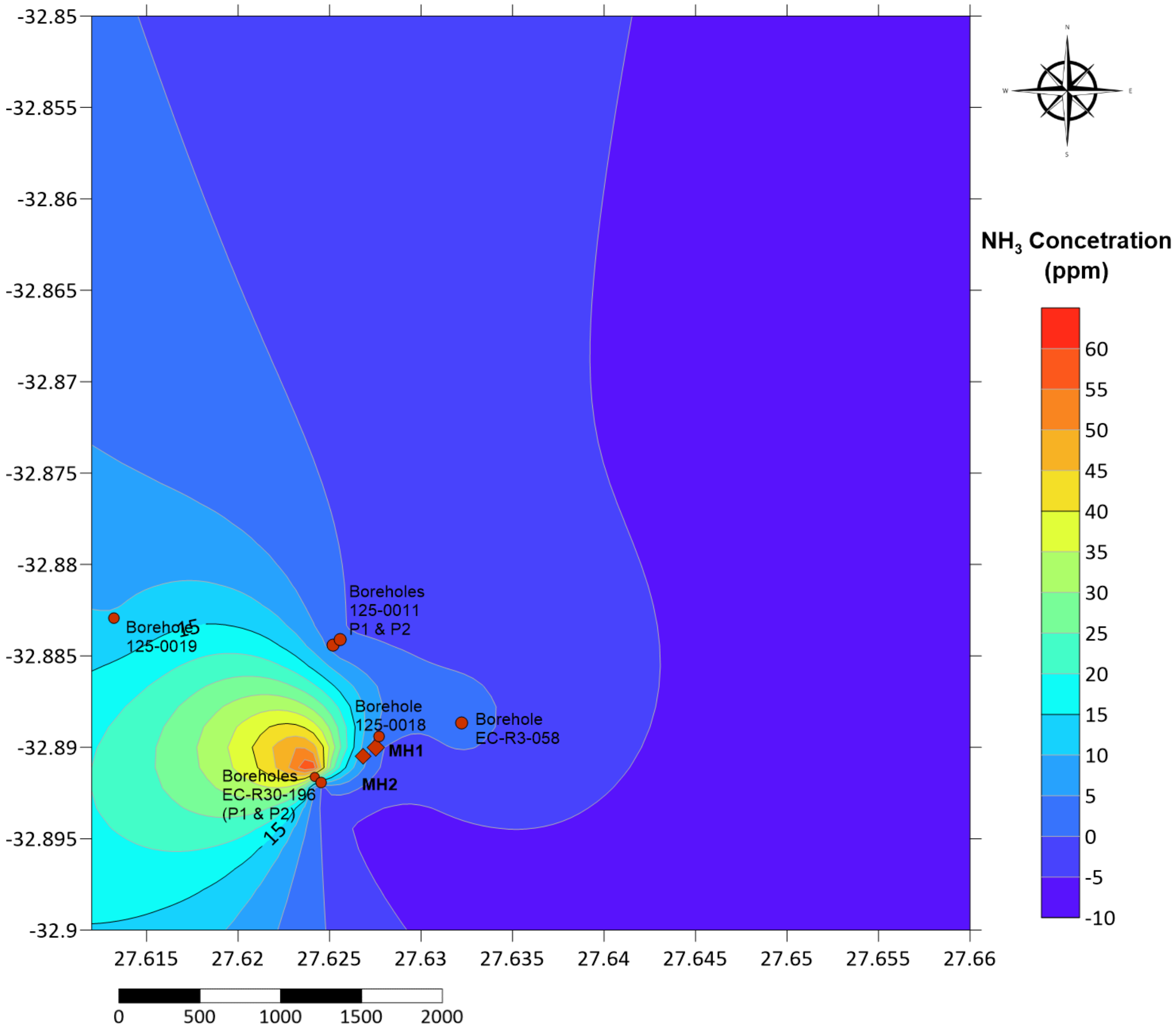


Figure 4.13: Spatial profile for ammonia levels (mg/L) for the groundwater samples in the vicinity of Roundhill Landfill

4.4.4 Assessment of Heavy Metal Contamination

Heavy metals are some of the most concerning of the pollutants, and some of the important pollutants of interest whenever there is a potential pollution source like landfill leachate. One of the primary objectives of this study was to assess heavy metal (Cr, Mn, Ni, As, Cd, Pb) contamination as a result of the leachates for the two landfill sites using historical and experimental data. Both secondary and primary data was used to draw conclusions on the profiles of the heavy metals around the landfill. The results for the different sites from secondary data analysis was very limited as very few heavy metal measurements were performed for the heavy metals in the period 2016-2021, particularly as there were limited sampling sites. For instance, the results seem to show a focus mainly on the sampling sites within the landfill (stormwater pond, MH1, MH2), and NR1 which is used for early detection of contamination. The results of the investigation are presented in Tables 4.8 and 4.9 below.

4.4.4.1 Cadmium

Cadmium is a heavy metal that is available naturally in the environment in trace amounts. According to the SANS-241 guidelines (2015), the levels of cadmium in water should not exceed 3 μg/L. According to Kubier et al. (2019), cadmium levels in surface water are in the range from 0 μg/L to 5 μg/L in and up to 1 μg/L in groundwater. Secondary data presented in Table 4.8 show that for all the samples that were analysed, cadmium concentrations exceed the standard limit, ranging from 4.0 μg/L to 12.0 μg/L. These reported levels were higher than those by Edokpayi et al. (2018) for groundwater samples in Berlin. Both Berlin and KWT leachates showed high levels of cadmium (12.0 μg/L and 4.0 μg/L, respectively). The range for the reported surface water sites was between 4.3 μg/L and 4.8 μg/L. There were no records for boreholes measurements. The experimental results (Table 4.9) show that cadmium was not detected in all the samples. It can therefore be concluded that there is currently no problem related to cadmium contamination as a result of the landfill.

4.4.4.2 Chromium

Chromium is one of the most toxic heavy metals, with the Cr(VI) form of the element highly carcinogenic (Ahmad et al., 2023). According to Zhuo et al. (2023), this is one of the most hazardous environmental heavy metals and is very toxic to living organisms. According to the SANS-241 (2015a), its levels in water should not exceed 50 μg/L. Results from the secondary data, though available only from a limited number of sites, show that chromium is a problem in the surface and groundwater around the landfills (Table 4.8). For comparative context, Tripathi and Chaurasia (2020), in their study of chromium contamination in surface and groundwater in Uttar Pradesh, India — a region with intensive industrial activity — reported that chromium concentrations in unpolluted surface water typically range up to 80 μg/L, while groundwater levels are generally below 1 μg/L in the absence of anthropogenic contamination.

Table 4.8: Secondary heavy metal data (μg/L) showing mean concentrations in landfill leachates, surface and groundwater samples in the vicinity of the Roundhill and KWT landfill sites.

	Site Name	Cd (μg.L^{-1})	Cr (μg.L^{-1})	Pb (μg.L^{-1})	Mn (μg.L^{-1})	As (μg.L^{-1})
Threshold Levels		**3 μg.L^{-1}**	**50 μg.L^{-1}**	**10 μg.L^{-1}**	**400 μg.L^{-1}**	**10 μg.L^{-1}**
Leachate Samples	Roundhill Landfill	12±6	400±30	31±8	1038±138	No Available Secondary Data
	KWT Landfill	4	58		30	
Surface Water Samples	Storm water Pond	4.8±6.2	147±38	290±391	1387±460	No Available Secondary Data
	Farmer 2		6.5	13.00		
	MH1	4.5	11.0±8.4	ND	571±656	
	MH2	4.5	375±981	ND	1777±2725	
	NR1	4.3	13.5±13.2	3.0	22.0	
	NX3	-	6.7	-	-	
	NX4a	-	-	800	-	
	NX4	-	30.5±30.4	-	-	
	NX5	-	35.0	-	-	
	KWT Stream	-	-	-	-	
Groundwater Samples (Boreholes)	ECR-30-196 (P1)	-	-	70000	51100	No Available Secondary Data
	ECR-30-196 (P2)	-	41000	84000	52000	
	P125-0011 (P1)	-	-	-	-	
	P125-0011 (P2)	-	-	-	-	
	P125-0018	-	-	-	-	
	EC-R3-058	-	-	-	-	
	P125-0019	-	-	1190±1380	9500±6400	

The values observed in the present study (103.5-538.7 µg/L in surface water; 141.2-1,212.3 µg/L in groundwater) far exceed these baseline levels, indicating significant pollution."

According to the historical data collected (Table 4.8), the leachates from the two landfill sites showed high values of chromium (400 μg/L and 58 μg/L for Berlin and KWT landfill sites, respectively), exceeding the SANS-241 and WHO limits. The presence of chromium is typical of landfill leachates where various types of waste are being dumped. The contaminated stormwater pond and MH2, both which are contaminated by the leachate from Roundhill Landfill, showed extremely high levels of chromium (147 and 375 μg/L). Of these,

Table 4.9 Experimental results for the measurement of the concentrations of heavy metals (μg.L^{-1}) in the landfill leachates, surface and groundwater samples in the vicinity Roundhill and KWT landfill site.

Type of Sample	Site Name	As (μg.L^{-1})	Cd (μg.L^{-1})	Cr (μg.L^{-1})	Mn (μg.L^{-1})	Pb (μg.L^{-1})
Leachate Samples	Roundhill Landfill	ND	ND	192.1	7370.7	94.2
	KWT Landfill	5.0	ND	245.3	5538.5	58.7
Surface Water Samples	Storm water Pond	84.1	ND	538.7	ND	70.2
	Farmer 2	28.6	ND	282.0	4267.6	74.3
	MH1	84.1	ND	538.7	4707.1	70.2
	MH2	15.8	ND	1.5	0.1	4.9
	NR1	16.4	ND	103.5	14578.7	28.5
	NX3	ND	ND	479.1	18377.7	326.2
	NX4a	15.4	ND	0.8	5.1	4.2
	NX4	25.6	ND	231.1	12809.3	89.2
	NX5	ND	ND	431.7	6474.1	162.7
	KWT Stream	35.0	ND	273.7	3400.0	210.7
Groundwater Samples (Boreholes)	ECR-30-196 (P1)	3.1	ND	141.2	0.8	17.4
	ECR-30-196 (P2)	ND	ND	401.6	9988.2	101.5
	P125-0011 (P1)	ND	ND	258.9	21694.5	486.2
	P125-0011 (P2)	6.7	ND	287.5	13729.8	150.2
	P125-0018	8.5	ND	ND	0.8	14.9
	P125-0019	8.7	ND	1.6	5.4	0.0
	EC-R3-058	19.0	ND	440.5	6312.9	136.3
	KWT Landfill Borehole	ND	ND	1212.3	10336.5	119.0

MH2 showed variability with the highest concentration of 2800 μg/L being recorded. Unfortunately, the records for most of these sites were very limited. The only borehole with a record (only one measurement) showed extremely high levels of chromium (41 000 μg/L). The chromium concentrations observed in this study are substantially higher than those reported elsewhere in South Africa. Edokpayi et al. (2018), investigating groundwater quality in the Muledane area of Limpopo Province (a region with similar rural characteristics to the Eastern Cape), reported chromium levels ranging from 5-150 μg/L in boreholes near waste disposal sites, with values exceeding SANS-241 guidelines but lower than those found at Roundhill and KWT. Similarly, Masindi and Foteinis (2021), in their assessment of groundwater in Limpopo Province's mining-affected areas, reported mean chromium concentrations of 12 μg/L in unpolluted groundwater, rising to 45 μg/L near industrial sites.

The experimental results in Table 4.9. show leachates from both landfill sites having significantly high concentrations of chromium (192.1 μg/L and 245.3 μg/L for Roundhill and KWT landfill sites, respectively). Both the KWT stream and the borehole showed extremely high levels of chromium, with the KWT borehole having the largest concentration of all the samples (1212.3 μg/L). The substantially higher values at KWT borehole suggest exceptional contamination, likely related to the landfill's unlined status and long operational history. Seven of the nine sampling sites for surface water around the Roundhill Landfill all showed high levels of chromium in excess of the SANS-241 and WHO standards and above typical ranges in natural water, ranging from 103.5 μg/L around NR1 to 538.7 μg/L for the stormwater pond and MH2 which are located in the landfill site. This was also observed for the boreholes which all contained high levels of chromium (ranging from 141.2 to 440.5 μg/L) with the exception of P125-0018 and P125-0019. Besides the KWT reading of 1212.3 μg/L, the other results are consistent with those of rivers and dams in Cape Town with ranges of 9.27 to 327.29 μg/L, which show significant pollution (Olujimi et al., 2014).

The spatial profiles for chromium distribution in the surface water samples (Figure 4.14) and groundwater samples (Figure 4.15) show related profiles with concentration diverging eastwards from the landfill. Both profiles seem to highlight the landfill site as a hotspot for chromium contamination.

4.4.4.3 Arsenic

Arsenic is one of the most concerning elements because of a global increase in public health concern surrounding exposure to humans through contaminated groundwater and other human activities (Fatoki & Badmus, 2022). The SANS-241 and WHO limits for arsenic in drinking water are 10 mg/L. Arsenic concentrations in groundwater vary widely depending on geological and anthropogenic factors. A global review by Shankar et al. (2014), synthesizing data from over 200 studies across Asia, South America, and Europe, reported that groundwater arsenic concentrations range from <0.5 μg/L in pristine aquifers to over 5,000 μg/L in geogenically enriched areas of Bangladesh and West Bengal, India, where naturally occurring arsenic in alluvial sediments is mobilised under reducing conditions.

The historical data for the two landfill sites did not contain records of the levels of arsenic in the leachates or in the freshwater. This means that based on the data available to the researcher, the element was never monitored for the period analysed in this work.

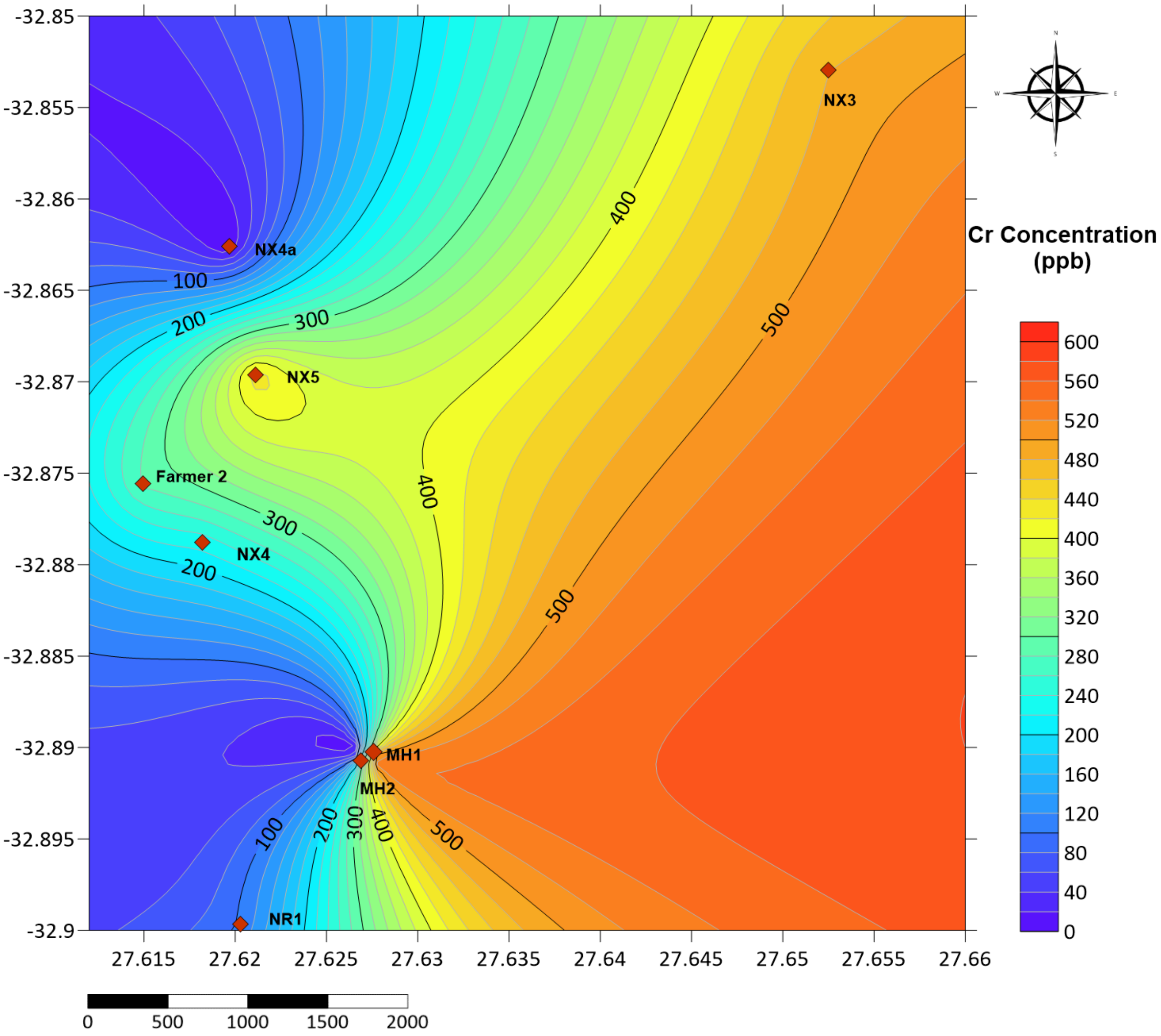


Figure 4.14: Spatial profile for chromium levels (µg/L) for the surface water samples in the vicinity of Roundhill Landfill

Experimental results showed the concentrations of arsenic in the leachate samples in an acceptable range, within the WHO and SANS-241 (2015) limits. With the exception of NX3 and NX5, all other surface water samples showed high concentrations of As, above the standard limit and the baseline concentrations in natural waters (Singh et al., 2010). The arsenic concentrations observed in surface water at Roundhill (15.4-84.1 µg/L) are consistent with values reported for polluted rivers in other regions. Irnawati et al. (2021), studying river water quality in Aceh Province, Indonesia, a tropical region affected by both natural geological sources and anthropogenic mining activities — reported arsenic concentrations ranging from 0.80 to 166 µg/L in rivers receiving industrial effluent. This range encompasses the values observed at NR1 and MH1, suggesting comparable pollution levels.

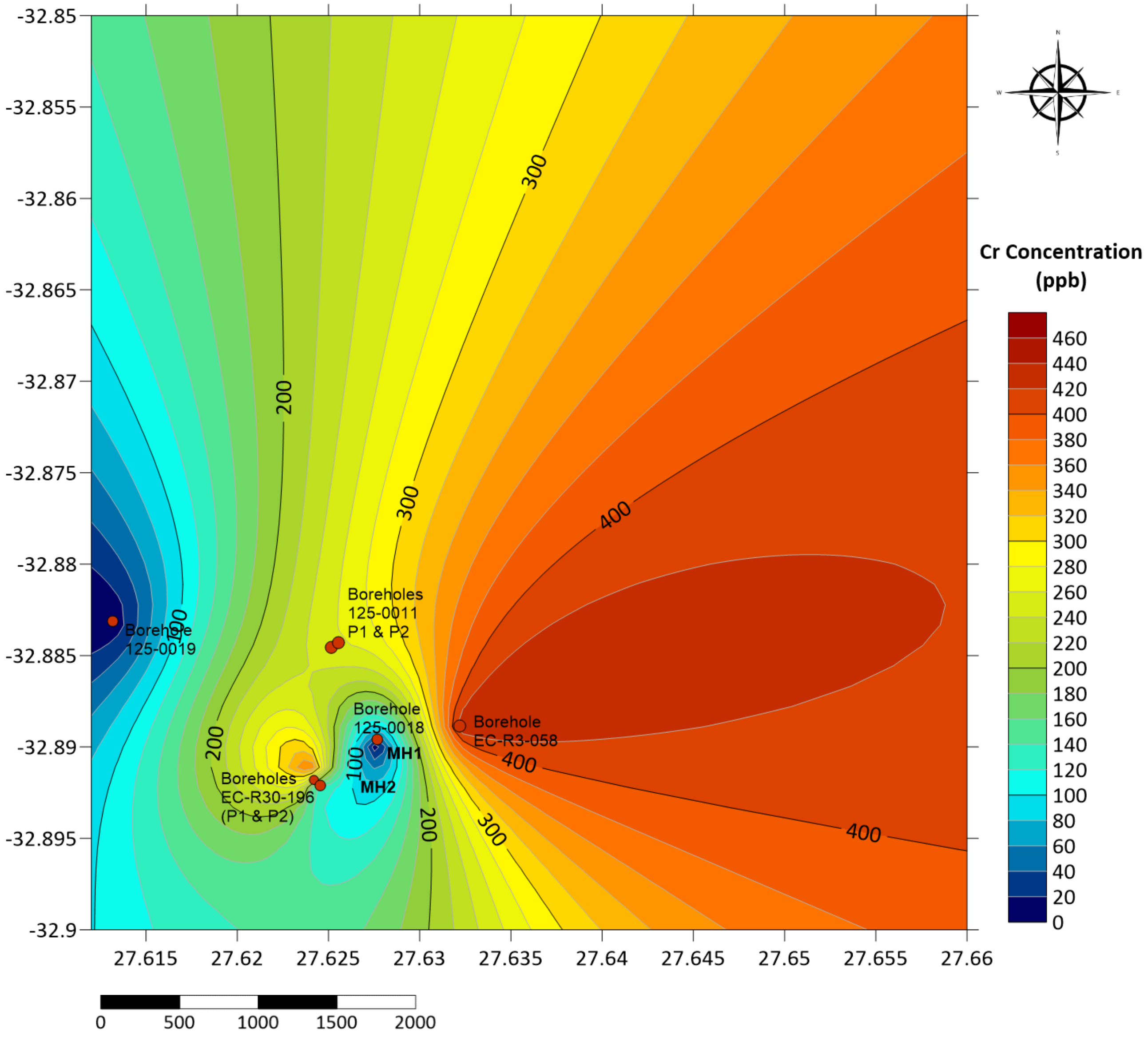


Figure 4.15: Spatial profile for chromium levels (µg/L) for the groundwater samples in the vicinity of Roundhill Landfill

For baseline comparison, Singh et al. (2010), in their extensive study of the Ganga River basin in northern India — one of the world's most intensively studied river systems —

reported that unpolluted river waters typically contain arsenic concentrations between 0.1 and 2 μg/L, with values above this range indicating anthropogenic or geogenic enrichment. The concentrations observed in the present study (15.4-84.1 μg/L) are 8-40 times higher than these baseline values, confirming significant contamination. Arsenic also exceeded the limit for the KWT Landfill stream (35.4 μg/L), a concentration higher than that of the respective leachate. The groundwater samples from the boreholes around Roundhill Landfill showed low levels of arsenic compared to the surface water samples, within the limits of arsenic according to the SANS-241 and WHO guidelines. The only exception for groundwater was borehole EC-R3-058 which showed a concentration of 19.0 μg/L, about twice as high as the SANS-241 and WHO limits. These results were all more than five times the mean reported by Masindi and Foteinis (2021) for groundwater in Limpopo, while those from the river samples were consistent those reported by (Olujimi et al., 2014).

The spatial profile (Figure 4.16) for arsenic concentrations in surface water around Roundhill Landfill site shows the landfill site as a hotspot for arsenic contamination. It can therefore be concluded that there is evidence of contamination of groundwater and surface water sources.

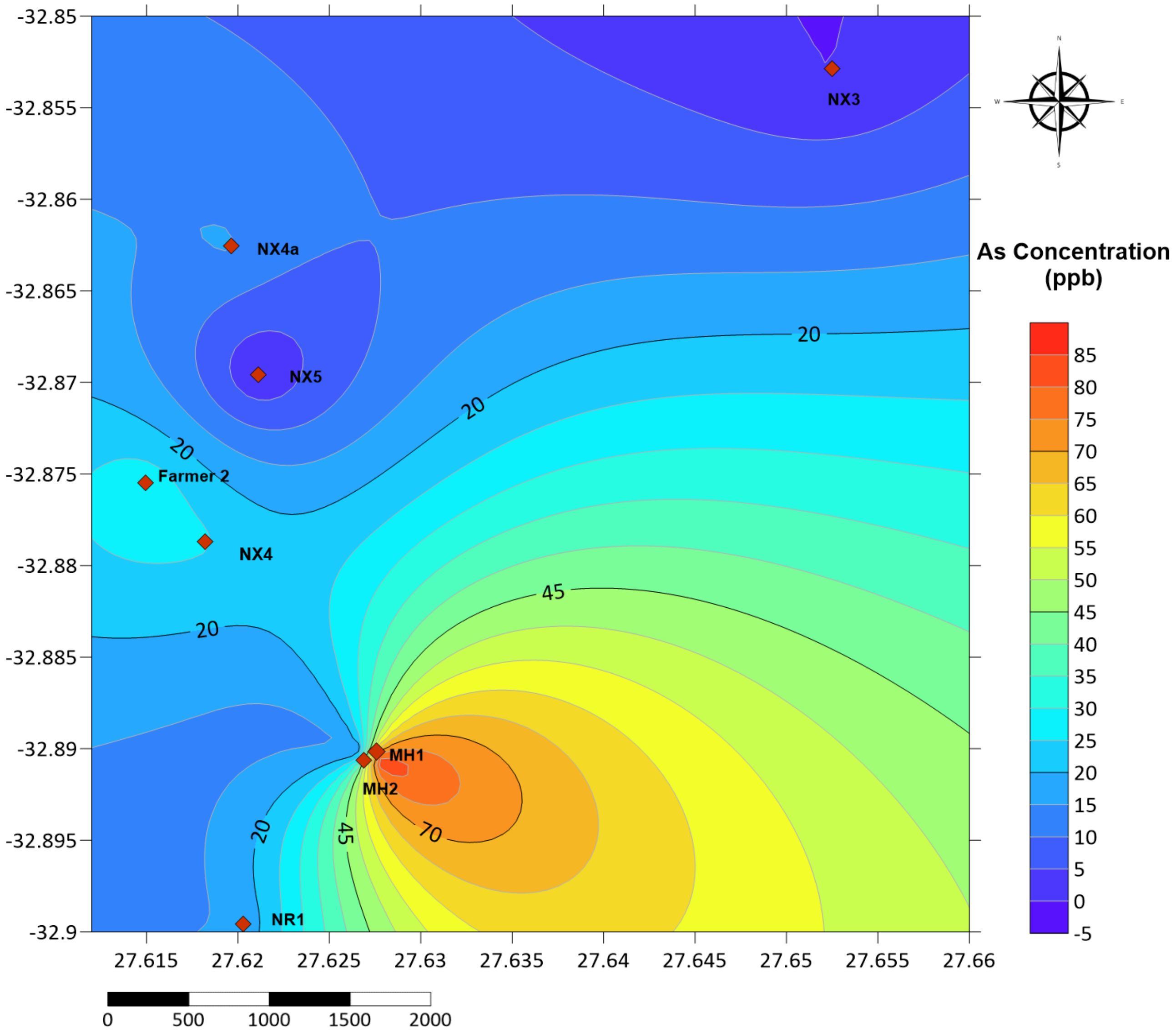


Figure 4.16: Spatial profile for arsenic levels (μg/L) for the surface water samples in the vicinity of Roundhill Landfill

4.4.4.4 Manganese

Analysis of manganese pollution of surface and groundwater associated with landfill sites was investigated by use of both secondary and primary data. The limit for manganese in drinking water according to the SANS-241 (2015a) is 400 μg/L while the limit for the WHO is 80 μg/L. The mean data from the results of the analysis of leachate samples at Roundhill Landfill site were excessively high (about 2.5 times over the SANS limit) with a concentration of 1038 μg/L while the concentration for KWT Landfill leachates was within the SANS 241 (2015a) and WHO (2017) limits (Table 4.8). Analysis of surface water and ground water samples both recorded high levels of manganese in excess of both standards. For instance, groundwater samples had the highest mean data ranging from a minimum manganese concentration of 9500 μg/L to a maximum of 52 000 μg/L (Table 4.8). For surface water, the levels were lower, with the lowest manganese mean concentration of 22.2 μg/L at NR1 to a maximum of 1777 μg/L at MH2. The stormwater pond and MH2, both of which are contaminated with leachate, contained significantly higher levels of manganese (mean concentrations of 1387 μg/L and 1777 μg/L, respectively).

The mean concentration of manganese derived from secondary data was corroborated with experimental data which showed that both landfill leachates contained high concentrations of manganese up to 13-18 times in excess of the SANS-241 limit (Table 4.9). With the exception of NX4 and MH2, all the surface water samples exceeded both the WHO and SANS-241 (2015) standards, with concentrations ranging from 3400 μg/L to 18377 μg/L. Similar results were obtained for groundwater samples where the levels ranged from 0.8 μg/L to 21695 μg/L, including the KWT landfill borehole that showed a manganese concentration of 10337 μg/L. It can therefore be concluded that manganese pollution of the freshwaters around the landfill is a major problem. The manganese concentrations observed in this study (up to 21,694.5 μg/L in groundwater) are exceptionally high and warrant serious concern. For comparative context, Masindi and Foteinis (2021), investigating groundwater quality in the Limpopo Province of South Africa — a semi-arid region with similar basement geology to the Eastern Cape reported mean manganese concentrations of only 8 μg/L in unpolluted boreholes, with values rarely exceeding 50 μg/L even near mining activities. Similarly, Edokpayi et al. (2018) , in their study of groundwater around the Muledane area of Limpopo Province, reported manganese levels ranging from 10 to 1,220 μg/L in boreholes affected by waste disposal, with the highest values occurring in wells immediately adjacent to unlined dumpsites. Even the maximum value reported by Edokpayi et al. (2018) (1,220 μg/L) is 18 times lower than the highest value recorded in the present study (21,694.5 μg/L at P125-0011 P1), indicating that manganese contamination at Roundhill and KWT is of an unprecedented magnitude compared to previously documented cases in South Africa.

From the experimental data, the spatial profile for the concentrations of manganese in both surface water (Figure 4.17) and groundwater sources (Figure 4.18) around the Roundhill Landfill site showed a similar profile as observed with other heavy metals. This showed a concentration gradient in the direction of flow of the surface and groundwater. For surface water samples (Figure 4.17), the concentrations increase away from the landfill, while a decreasing profile (Figure 4.18) was observed for groundwater data. It can be concluded from the presented results that manganese may be one of the major problems that the two landfills experience. The levels of the manganese observed should drive enquiry as to what is driving its level to such dangerously high concentrations.

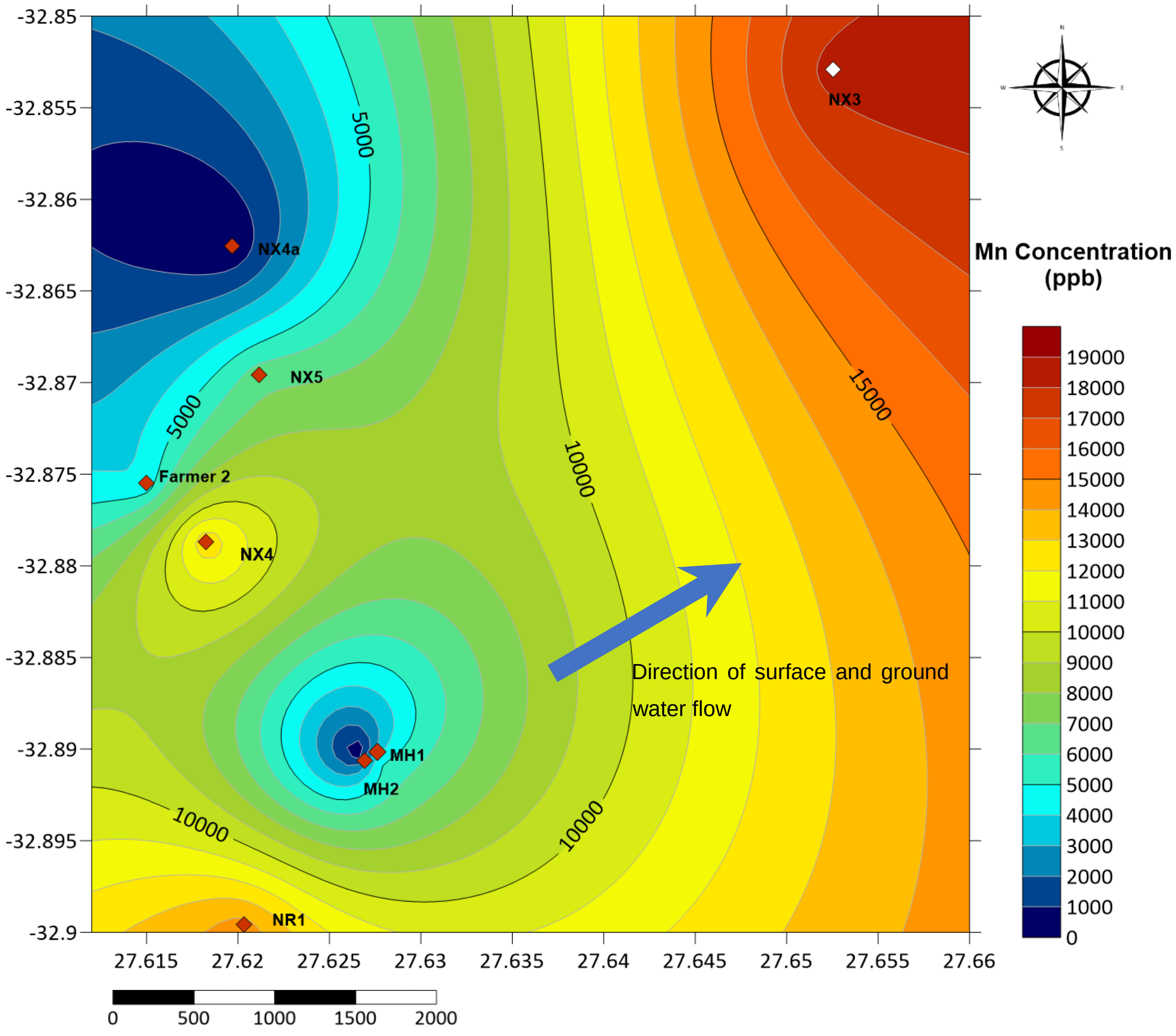


Figure 4.17: Spatial profile for manganese levels (μg/L) for the surface water samples in the vicinity of Roundhill Landfill

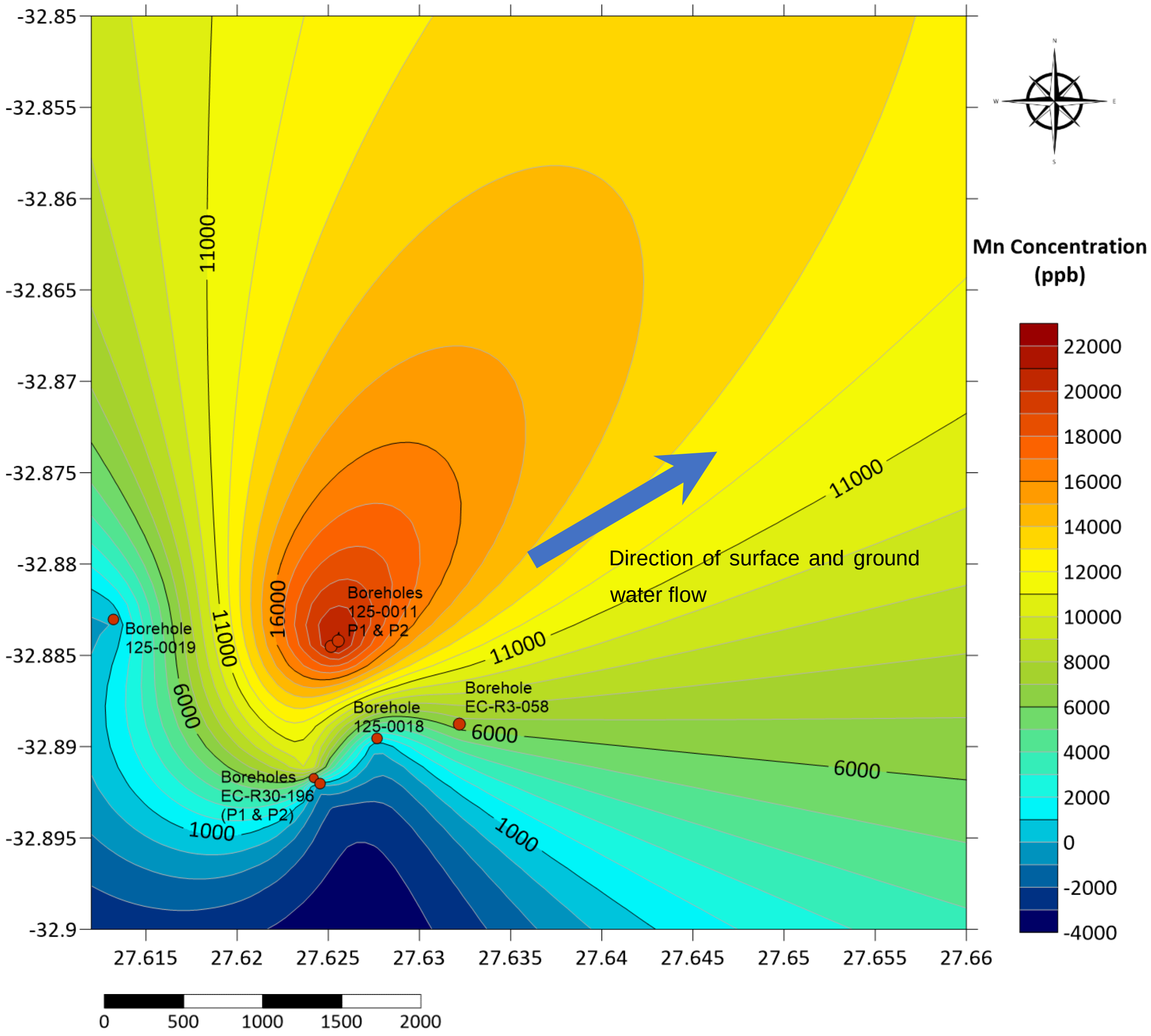


Figure 4.18: Spatial profile for manganese levels (μg/L) for the groundwater samples in the vicinity of Roundhill Landfill

4.4.4.5 Lead

Lead is a very toxic heavy metals that has been subject to many studies in environmental sciences. It is found in the environment in trace amounts and has seen widespread use in different industries e.g. in batteries, which is one of major anthropogenic sources. It is an extremely toxic heavy metal that is known to disturb various physiological processes in plants and animals and has no known biological function (Jaishankar et al., 2014). According to the SANS-241 (2015) and WHO guidelines, lead levels in water should not exceed 10 μg/L.

In order to verify compliance with these guidelines, analysis if primary and secondary was performed. The results for the analysis of secondary is presented in Table 4.8. When compared with the results from the analysis of secondary data, the analysis shows that except for three records, all the other sites had high to extremely high levels of lead, well in excess of both the SANS-241 and WHO limits (Table 4.8). For instance, Roundhill leachate had a mean of 31 μg/L lead content, surface water samples showed a lead content range from 0 μg/L to 800 μg/L, while the groundwater samples showed a maximum reading of 84 000 μg/L for one of the boreholes. Unfortunately, despite the frightening results from the collected records, there were limited data to allow making meaningful inferences.

Experimental results (Table 4.9) were able to verify the lead content for almost all the samples analysed. Both KWT and Roundhill Landfill leachates had levels of lead in excess of both the SANS-241 and WHO guidelines (94.2 μg/L and 56.7 μg/L). Of the surface water sources, only MH2 (4.0 μg/L) and NX4a (4.2 μg/L) had a lead content which would be considered safe according to the standards. The lead concentrations observed in surface water at Roundhill (28.5-326.2 µg/L) (Table 4.9) are consistent with values reported for other polluted South African water bodies. Olujimi et al. (2014), in their comprehensive study of river water quality in the Cape Town metropolitan area a region with Mediterranean climate and significant industrial activity reported lead concentrations ranging from 9.27 to 327.29 µg/L in rivers receiving urban and industrial effluent. The authors attributed these elevated levels to a combination of industrial discharge, stormwater runoff, and historical contamination. The present study's findings are comparable, though the source of contamination (landfill leachate rather than industrial effluent) differs. Notably, the groundwater lead concentration at KWT borehole (119.0 µg/L) and surface water at NX3 (326.2 µg/L) fall within or exceed the upper range reported by Olujimi et al., confirming significant lead pollution in the study area. These results are a major concern, indicating that the freshwater around the landfill is not safe, and is a major threat to the environment and public health in the area.

As with the spatial profiles for manganese observed earlier, the spatial profile for lead in surface water (Figure 4.19) also show increasing levels of lead in the direction of flow of the surface and groundwater. The spatial profile for groundwater (Figure 4.20) shows a decrease in levels of lead away from the landfill in the direction of the flow of the water.

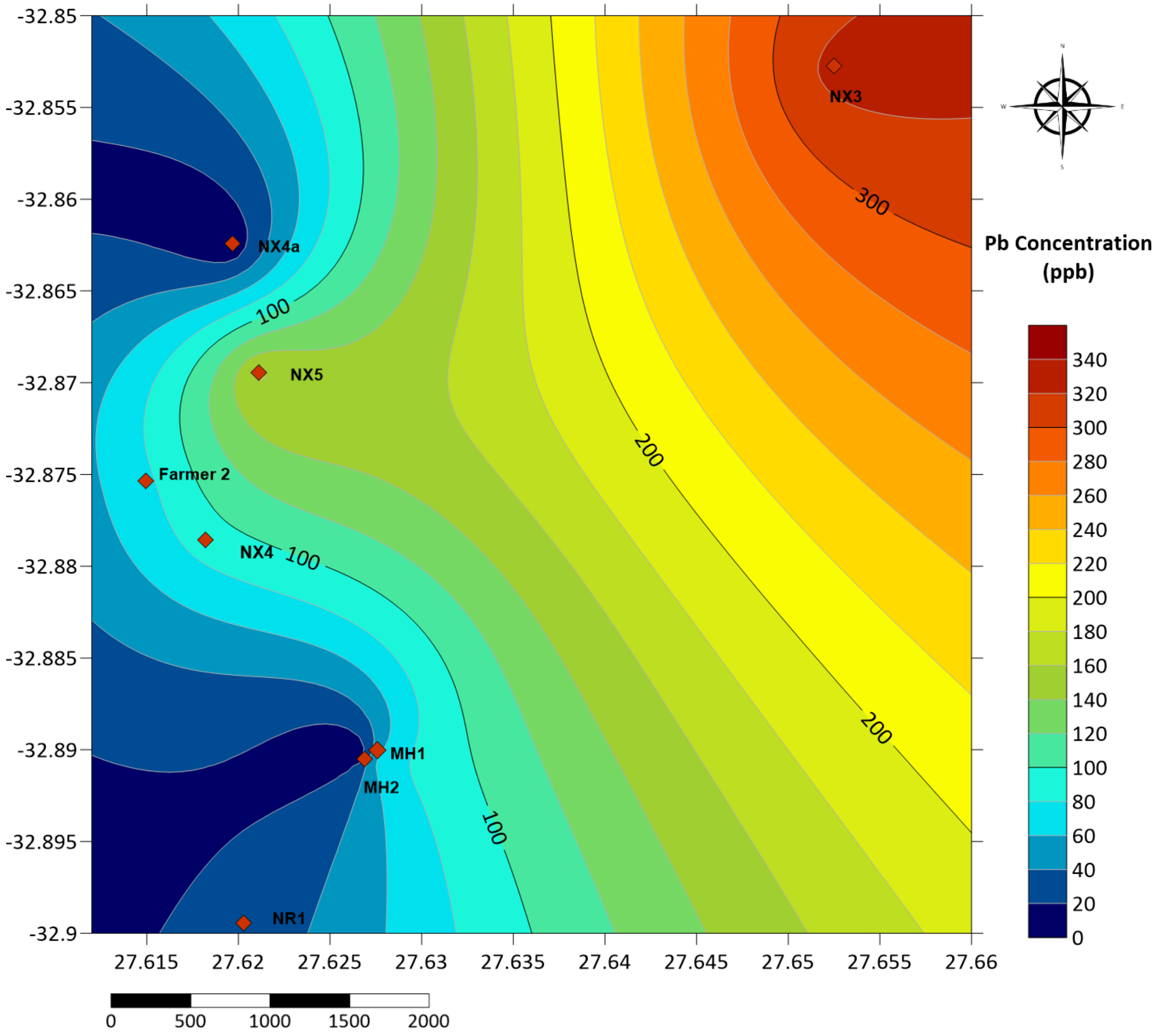


Figure 4.19: Spatial profile for lead levels (μg/L) for the surface water samples in the vicinity of Roundhill Landfill

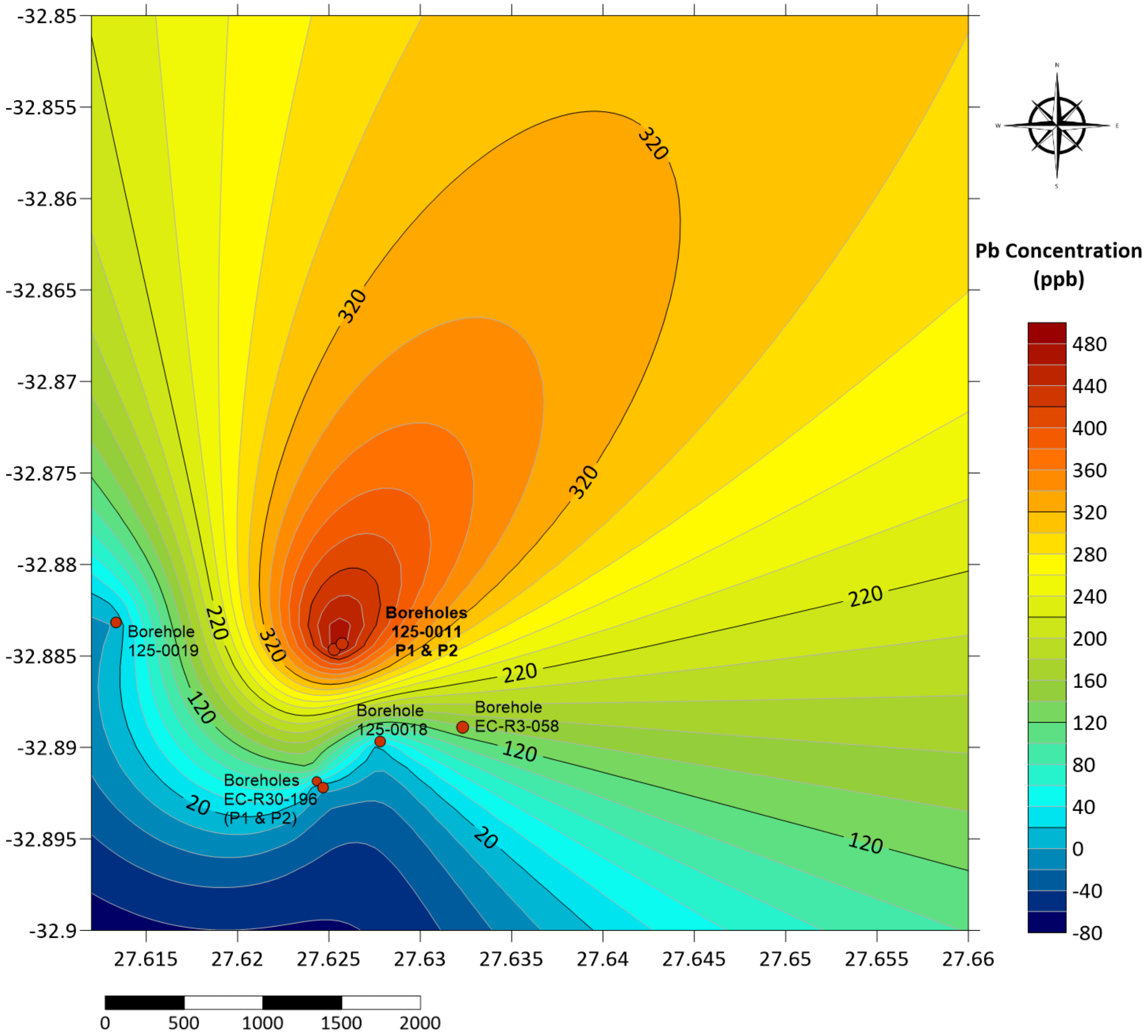


Figure 4.20: Spatial profile for lead levels (μg/L) for groundwater samples in the vicinity of Roundhill Landfill

4.5 Correlations

The results from the experimental analysis of physicochemical parameters were used to develop the Pearson's correlation matrix for the surface (Table 4.10) and groundwater samples (Table 4.10). The results showed a very strong positive correlation between electrical conductivity and sulphate (0.977) as well as with nitrite (0.971) in surface water, both of which are statistically significant at 0.01 significance level. These results mean that the extremely high electrical conductivity values observed at NR1 can be attributed to the sulphate and nitrite. Nitrite and sulphate at NR1 were extremely high (3323.4 mg/L and

8446.67 mg/L respectively). While the sulphate could not be conclusively linked to the landfill site as discussed above, the nitrite is most likely derived from leachate plumes from the landfill. A strong positive correlation of the sulphate with the nitrite (0.999) and ammonia (0.772) could, however, be indicative of similar sources from, therefore, the landfill.

A similar analysis for groundwater showed a strong negative correlation between the pH and the chromium levels in groundwater (-0.779) and turbidity (-0.837), both statistically significant at 0.05 significance levels (Table 4.11). The results also showed that electrical conductivity was mainly impacted by the level of chloride, which showed a strong positive correlation with electrical conductivity (0.964). The results for both surface and groundwater have negative correlations for the metals and the pH, which is expected for metals which are generally more soluble at lower pHs. These observations are in agreement with the profiles which show increased levels of the heavy metals away from the landfill. Therefore, it can be predicted that the landfill leachate plumes raise the pH of the water around the landfill site, therefore reducing the levels of metals in the water around the landfill.

4.6 Summary

The study results have shown that a number of the analytes that were the subject of interest in this study were unsafe and above the typical or baseline values for natural water. This means that there is evidence of pollution of the water sources by the landfill. As indicated earlier, the pH of mature landfills is generally above 7.0. The pH profile presented in the experimental results show that the pH decreases away from the landfill, in the direction of the flow of water. This profile seems to explain the observed trends for the levels of heavy metals in the surface water. As observed in the results, the levels of chromium, manganese and lead in the water were increasing away from the landfill, in the direction of flow of water. The metals are soluble in lower pHs, which may explain the observations. Arsenic behaviour was not clear but seemed more soluble in higher pH. Sampling points NR1 had a high pH, and consequently had lower concentrations of the metals. The electrical conductivity for NR1 which was the highest seems to be driven by sulphate, nitrate and chloride, in addition to other species not covered in the study.

Table 4.10: The Pearson's correlation matrix for physicochemical parameters of surface water from the experimental data.

	pH	Conductivity	Turbidity	Cl-	SO_4^{2-}	NO_3^-	NO_2^-	NH_3	As	Cr	Mn	Pb
pH	--											
Conductivity	.061	--										
Turbidity	.112	-.144	--									
Cl^-	.308	-.046	-.242	--								
SO_4^{2-}	.137	**.977****	-.163	-.110	--							
NO_3^-	.512	-.042	-.184	**.882****	-.108	--						
NO_2^-	.111	**.971****	-.156	-.158	**.999****	-.159	--					
NH_3	-.128	.706	-.277	-.326	**.772***	-.231	**.783***	--				
As	.442	-.207	-.367	-.087	-.105	.086	-.103	-.065	--			
Cr	-.077	-.236	.338	-.413	-.307	-.099	-.297	-.199	.327	--		
Mn	-.214	.589	-.046	.062	.425	.231	.409	.300	-.264	.391	--	
Pb	-.535	-.084	.280	-.236	-.258	-.097	-.253	-.185	-.338	**.708***	.671	--

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

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

Table 4.11: The Pearson's correlation matrix for physicochemical parameters of groundwater from the experimental data.

	pH	Conductivity	Turbidity	Cl^-	SO_4^{2-}	NO_3^-	NO_2^-	NH_3	As(ppb)	Cr (ppb)	Mn(ppm)	Pb(ppb)
pH	--											
Conductivity	.273	--										
Turbidity	**-.837***	-.328	--									
Cl^-	.209	**.964****	-.284	--								
SO_4^{2-}	-.019	-.056	-.452	-.061	--							
NO_3^-	-.282	.054	-.217	.137	.507	--						
NO_2^-	-.166	.383	-.166	.552	.219	**.789***	--					
NH_3	-.266	-.150	.348	-.302	-.417	.063	-.234	--				
As (ppb)	-.197	.503	.039	.697	-.001	.438	**.886****	-.406	--			
Cr (ppb)	**-.779***	-.195	.466	-.162	.101	.641	.316	.443	.097	--		
Mn (ppm)	-.631	-.312	.354	-.397	.521	.159	-.286	.162	-.388	.567	--	
Pb (ppb)	-.378	-.195	.003	-.266	.773*	.264	-.175	-.112	-.326	.411	**.923****	--

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction: Assessing Landfill Impacts on Water Quality and Regulatory Compliance in Eastern Cape

This study comprehensively investigated the physicochemical characteristics of leachate and groundwater around Roundhill and King William's Town (KWT) landfill sites in Buffalo City Metropolitan Municipality (BCMM), while concurrently evaluating regulatory compliance at these sites and the Komga and Peddie waste facilities in Amathole District Municipality (ADM). The findings provide compelling evidence of water quality deterioration linked to landfill operations, with significant implications for environmental management and public health. The conclusions are structured according to the study's specific objectives, supported by empirical evidence from the results.

5.1.1 First Objective: Chemical Properties of Leachate and Groundwater

The chemical analysis revealed severe contamination from anions and heavy metals exceeding regulatory thresholds. Leachate chloride concentrations were alarmingly high at both Roundhill (993.9–2,220.4 mg/L) and KWT (2,811.2–2,517.7 mg/L), far surpassing the SANS 241 (2015) limit of 250 mg/L for drinking water (Table 4.6–4.7). Surface water near landfills showed similar contamination, with MH2 (4,070.8 mg/L) and NR1 (1,022.6 mg/L) demonstrating chloride pollution plumes (Fig. 4.9–4.10). These findings align with studies linking elevated chloride to landfill leachate intrusion, which mobilizes salts into aquifers. For instance, Edokpayi et al. (2018) demonstrated this phenomenon in groundwater near unlined waste sites in Limpopo Province, South Africa, while Maliehe and Moropeng (2024), observed similar chloride enrichment in aquifers down-gradient of landfills in Mankweng, South Africa, both studies conducted in comparable semi-arid South African settings.

Heavy metals posed critical risks:

- Chromium exceeded guidelines (50 µg/L) in leachate (Roundhill: 192.1 µg/L; KWT: 245.3 µg/L) and groundwater (KWT borehole: 1,212.3 µg/L) (Table 4.9). Spatial profiles identified landfills as contamination hotspots (Fig. 4.14–4.15). The chromium levels observed (up to 1,212.3 µg/L at KWT borehole) are consistent with Cr(VI) carcinogenicity concerns documented by Ahmad et al. (2023) in their global review of heavy metal toxicity, and with the findings of Zhuo et al. (2023) who demonstrated the environmental persistence of hexavalent chromium in contaminated water systems.

- Manganese reached 7,370.7 µg/L (Roundhill leachate) and 21,694.5 µg/L (groundwater), exceeding SANS 241 limits (400 µg/L) by 18–54 times (Table 4.8–4.9). These levels dwarf typical groundwater concentrations (8–1,220 µg/L) (Masindi & Foteinis, 2021; Edokpayi et al., 2018).
- Lead violated guidelines (10 µg/L) in leachate (94.2 µg/L at Roundhill) and surface water (326.2 µg/L at NX3) (Table 4.9), corroborating global concerns about Pb neurotoxicity (Jaishankar et al., 2014).
- Nitrite in NR1 (3,323.4 mg/L) exceeded limits (3 mg/L) by >1,000-fold (Table 4.7), posing acute methemoglobinemia risks (Schullehner et al., 2017).
- Anthropogenic sulphate pollution was evident at NR1 (8,446.7 mg/L), though agricultural sources may contribute (Table 4.7). Ammonia spikes in groundwater (ECR-30-196(P2): 66.2 mg/L) signalled organic waste decomposition (Saleem & Algamal, 2016).

5.1.2 Second Objective: Physical Properties of Leachate and Groundwater

The physical parameters—pH, electrical conductivity (EC), and turbidity—were analysed to assess the overall water quality. While pH values mostly remained within the acceptable 6.5–8.5 range, the spatial trends revealed that values decreased downstream, indicating possible acidification due to pollutant migration. This phenomenon is supported by studies suggesting that landfill leachates typically have alkaline pH, and the downstream drop may be due to buffering reactions and metal dissolution (Olujimi et al., 2014). Physical parameters confirmed leachate influence on water systems:

- *pH*: Leachate alkalinity (Roundhill: pH 8.2; KWT: pH 8.8) (Table 4.1) typified mature landfills (Wdowczyk & Szymańska-Pulikowska, 2020). Freshwater near landfills showed elevated pH (stormwater pond: pH 8.4), decreasing downstream (Fig. 4.3–4.4), indicating plume dispersion.
- *Electrical Conductivity (EC)*: Leachate EC was extreme (Roundhill: 1,356.5 mS/m; KWT: 922.2 mS/m) (Table 4.3). Groundwater EC at KWT borehole (651.8 mS/m) and surface water at NR1 (4,840.3 mS/m) exceeded WHO (400 mS/m) and SANS 241

(170 mS/m) limits (Table 4.4), signifying ionic pollution from leachate (Omer, 2019a). Spatial EC profiles revealed contamination spreading along hydraulic gradients (Fig. 4.6–4.7).

- *Turbidity:* Groundwater turbidity at P125-0011(P2) (110 NTU) and surface water at NX5 (489.1 NTU) (Table 4.5) indicated suspended solids from leachate or erosion, violating SANS 241 limits (4 NTU) (Azus et al., 2015).

5.1.3 Third Objective: Leachate Pollution of Groundwater

To examine possible contamination routes, the study conducted comparative analyses between upstream and downstream sites and observed that levels of key parameters—particularly chloride, EC, and heavy metals—increased downstream of the landfill sites. These spatial patterns suggest plume movement in alignment with the hydrological flow. Sites such as NR1 and MH2 consistently showed elevated levels of pollutants. A multivariate correlation matrix showed significant positive relationships between EC and pollutant concentrations (chloride: $r = 0.964$; sulphate: $r = 0.977$). These findings were further supported by thematic analysis of interviews, where landfill personnel acknowledged that the monitoring infrastructure was outdated or non-functional, and there was limited enforcement of pollution mitigation strategies. These observations support the conclusion that the spatial differences in water quality parameters validate the intrusion of leachate into both surface and groundwater systems, successfully fulfilling the third objective.

The following highlighted could be use as key arguments for proposing that leachate was the primary contamination source:

- *Proximity trends*: Contaminant concentrations (Cl^-, Cr, Mn, NH_3) peaked near landfills and decreased downstream (Fig. 4.9, 4.12, 4.17). For example, Cl^- in MH2 (within Roundhill) was 4,070.8 mg/L vs. 254.3 mg/L at distal NX5 (Table 4.7).
- *Chemical signatures*: Leachate-like anion ratios (e.g., $Cl^-/SO_4^{2-} > 20$) in groundwater (e.g., KWT borehole) mirrored landfill leachate (Christensen et al., 2001).
- *Thermal and turbidity anomalies*: Elevated groundwater temperature (21.5°C at KWT borehole) and turbidity near landfills suggested leachate intrusion (Fahimah et al., 2023).
- *Correlations*: In groundwater, EC strongly correlated with Cl^- ($r=0.964$, $p<0.01$) (Table 4.11), confirming ionic pollution from leachate. Negative pH-Cr correlations ($r=-0.779$) indicated metal mobilization in acidic conditions downstream.

Non-engineered landfills (KWT) showed severe impacts due to absent liners, consistent with global findings on unlined sites (El-Fadel et al., 2002).

5.1.4 Fourth Objective: Geo-Spatial Characterisation of Contamination

Though the study faced limitations in spatial modelling due to restricted access to GIS layers, it nonetheless presented spatial profiles of parameters like EC, pH, turbidity, and chloride, helping infer pollution hotspots. The figures presented in Chapter 4 clearly show pollutant dispersion away from landfill sites, with maximum contaminant concentrations aligned with groundwater flow directions. For instance, the hotspot at NR1 for both EC and nitrate confirmed the vulnerability of that region to leachate-induced pollution plumes. While advanced GIS-based risk prediction was not completed, the visual profiles provide compelling evidence that such assessments are critical. These spatial analyses revealed the following systematic contamination patterns:

- *Plume migration*: Contaminants followed groundwater flow paths northeast of Roundhill (Fig. 4.10, 4.13, 4.18, 4.20). For instance, NH_3 and NO_2^- hotspots at NR1 aligned with hydraulic gradients (Mepaiyeda et al., 2020).
- *Risk mapping*: Over 70% of the study area had EC exceeding guidelines (Fig. 4.6–4.7). Chromium and arsenic hotspots (Fig. 4.14–4.16) coincided with residential/agricultural zones, posing ingestion risks (Fatoki & Badmus 2022).
- *Public health implications*: Heavy metals (Cr, As, Pb) in water used for irrigation (NX4) or livestock (Farmer 2) threaten food chains via bioaccumulation (Amiard-Triquet et al., 2013). High NO_2^- at NR1 risks methemoglobinemia in communities (Ward et al., 2018).

Therefore, the geospatial representation of pollution dispersion and hotspot identification affirms the landfill’s influence on water quality, meeting the intent of the fourth objective.

5.1.5 Fifth Objective: Regulatory Compliance

The thematic analysis of interviews revealed discrepancies in compliance across the four sites. While Roundhill, KWT, and Komga were licensed (per SAWIC data), Peddie remained unlicensed and lacked basic monitoring infrastructure. Moreover, the Komga and Peddie

sites started as illegal dumpsites, and although later operationalised, they lacked essential facilities like transfer stations and leachate collection systems.
Thematic analysis exposed critical non-compliance:

- *Regulatory Compliance and Licensing:* Peddie operated without a license, violating the Waste Act (No. 59 of 2008) (Godfrey & Oelofse, 2017). Roundhill's unverified license and KWT/Komga's permits indicated inconsistent enforcement (Nyika et al., 2020).
- *Infrastructure Gaps*: Komga and Peddie lacked leachate collection and groundwater monitoring, breaching Minimum Requirements (DWAF, 1998). Roundhill and KWT had dysfunctional transfer stations, exacerbating illegal dumping.
- *Operational Challenges*: Scavenger-induced fires at all sites increased emissions of dioxins (Pathak et al., 2005). Absent base liners at KWT (a converted dump) explained severe groundwater contamination.
- *Illegal Dumping and Access Control:* Both ADM sites reported widespread illegal dumping, exacerbated by limited site fencing and unregulated public access. This was consistent with findings by Godfrey and Oelofse (2017), who highlighted access control as a critical determinant in landfill efficacy.
- *Monitoring inadequacies:* Heavy metals were rarely tested historically. Komga/Peddie had no monitoring data, preventing impact assessment.

These findings reflect systemic governance challenges in South Africa's waste sector, particularly in resource-limited regions like ADM (Polasi et al., 2020).

5.2 Primary Objective: Water Quality Deterioration Linkages and ADM Implications

The physicochemical and spatial data conclusively link water quality degradation to landfill leachate. Key evidence includes:

- Consistent contaminant plumes: Ionic (Cl^-, SO_4^{2-}) and metal (Cr, Mn, Pb) gradients radiating from landfills.
- Source-specific fingerprints: NH_3 and NO_2^- spikes in leachate-impacted sites (e.g., stormwater pond).
- Age-dependent impacts: Alkaline pH and high EC in mature landfills (KWT: 40+ years) aligned with global leachate evolution models (Kjeldsen et al., 2002).

For ADM's Komga and Peddie sites, the absence of infrastructure predicts severe contamination. Unlined dumps in similar hydrogeological settings typically exhibit Cl^- (>500 mg/L) and heavy metal pollution within 5 years (Rapti-Caputo & Vaccaro, 2006). The poor compliance observed suggests ADM sites may already have undocumented impacts, requiring urgent intervention.

5.3 Overall Conclusions and Implications

- Landfills are contaminating water resources: Roundhill and KWT landfills have significantly degraded groundwater and surface water through leachate seepage, evidenced by the ions (Cl^-, NH_3), heavy metals (Cr, Mn, Pb), and altered physical parameters (pH, EC).
- Compliance is inadequate: Licensing gaps, infrastructure deficits, and poor monitoring at all sites undermine regulatory frameworks. Komga and Peddie's non-compliance poses imminent environmental risks.
- Public health threats are multifaceted: Contaminated water exposes communities to carcinogens (Cr(VI), As), neurotoxins (Pb), and acute hazards (NO_2^-). Agricultural use of polluted water (e.g., NX4) introduces toxins into food chains.
- Spatial tools are critical for management: Contamination maps effectively identify hotspots and plume trajectories, enabling targeted remediation.
-

5.4 Recommendations for Mitigation

From this study, urgent intervention is needed to mitigate current groundwater and surface water pollution due to operating landfill sites in the BCM. It is advisable to prioritize rehabilitation of the landfill facility, especially at KWT, by installing engineered liners and leachate collection and containment systems. Lack of such facilities or its ineffectiveness has been associated with high leachate migration and groundwater pollution in the landfill conditions prevalent in developing countries (Department of Environmental Affairs, 2013; Omer, 2019a). The high levels of chloride, ammonia, nitrate and heavy metal pollution observed in this study reinforce the urgent need to deal with highly polluted sites like NR1 and MH2.

The study also suggests to improve and expand the monitoring program of ground water, surface water at all active and closed landfill sites within the municipality. Monitoring networks should be composed of both up and downstream boreholes as well as surface water sampling points, with samples taken in wet and dry seasons to allow for temporal variations. Parameters to be measured are physico-chemical variables, nutrients and heavy metals attributed to landfill leachate in accordance with WHO (2017) and SANS 241 (2015a; 2015b). The application of GIS-based spatial analysis presented in this study should be institutionalised to facilitate on-going monitoring of pollution plumes, and make evidence-based decision regarding their management (Masindi and Foteinis, 2021; Mutileni et al., 2023).

Regulatory and governance The enforcement of the Minimum Requirements for Waste Disposal by Landfill and related environmental laws should be enhanced. Compulsory heavy metal testing and site compliance audits must be written into law for licensed as well as unlicensed landfills in order to minimize health risk on the environment and HIV general populations (Department of Environmental Affairs, 2013). Unofficial dumping sites, such as those observed in Komga and Peddie must be officially assessed, restored where required and incorporated into municipal waste management planning. Strengthened enforcement and increased compliancy would contribute to sustainable protection of groundwater resources and bring municipal practices in line with national water quality standards (WHO, 2017; SANS 241, 2015a).

5.5 Future Research Direction

Although this work shows unambiguous evidence of the influence of PLLs on GW and SW quality, additional research should be carried on for refining source discrimination, as well as improve knowledge of contaminant migration. Future research should use isotopic tools, in particular stable isotope $\delta^{15}N$ and $\delta^{37}Cl$ analyses to gain a more accurate indication of the source of nutrients (NH 4 +-N) and salts (mainly with concentration peaks following drought periods) found in water supplies. Isotopic approaches have proven useful in discriminating leachate-derived pollution from agricultural and natural geochemical sources in comparable hydrogeological contexts (Saleem and Algamal, 2016; Schullehner et al., 2017; Feng et al., 2020).

Long-wrist monitoring programs are likewise suggested to account for seasonal, and/or interannual variability of contaminant levels and leachate plunge behavior. It would also enhance insight into the impact of rainfall, groundwater recharge and landfill aging on leachate production and migration if collecting periods were extended over several hydrological cycles. Researchers have shown that short-term data may give an under approximation of contamination risk and may disguise longer term patterns (Masindi et al., 2021; Mutileni et al., 2023). Thus, longitudinal datasets would increase statistical power and contribute with better groundwater risk predictions.

Future studies could also benefit from employing state-of-the-art geospatial and data-driven modelling techniques, such as machine learning, for predictions of contaminant plume migration over varying hydrogeological and climatic scenarios. Coupling hydrochemical data with spatial analysis and groundwater flow modelling has been proven to enhance predictability and provides a basis for taking proactive measures in managing groundwater (Omer, 2019b; Masindi & Foteinis, 2021). Comparative studies at multiple landfill sites within the Eastern Cape as well as in other South African provinces are further recommended for these findings to be put into perspective and assist formulation of nationalised guidelines for landfill design, monitoring, and groundwater security.

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