Assessing environmental impacts, community perceptions and management strategies for historical mine wastelands: A case study of Brakpan (Kwa-Thema), South Africa

by

Tobius Mawase Mogale

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Supervisor: Dr KW Maphangwa

Co-supervisor: Prof M Tekere

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Declaration

I, Tobius Mawase Mogale, hereby declare that this dissertation and work presented in it is my own work and that all sources that have been cited and quoted have been indicated and acknowledged by means of complete references in line with the University of South Africa plagiarism policy.

This work has never been submitted for any degree at this institution or any other higher learning institution in South Africa, in fulfilment of the requirements for the Master of Science in Environmental Science degree.

16 February 2026

Signature Date

Dedication

To my beautiful mother, siblings and my late father who always supported and invigorated me to pursue success in everything I do

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Academic outputs

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Abstract

Historical mine wastelands resulting from historical gold and uranium mining are lasting legacies of mining, leaving environmental degradation and social challenges for nearby communities. This study assessed the environmental impacts, community perceptions and management challenges associated with the historical mine wastelands in Brakpan (Kwa-Thema), South Africa, while also identifying appropriate management strategies. An interdisciplinary approach was used to combine community perception surveys, erosion modelling, and water and soil quality laboratory analysis to assess post-mining environmental and community risks.

The community survey involved structured questionnaires administered to purposively identify 90 residents residing in close proximity to the mine wasteland investigated. Respondents of over 18 years of age and various occupations reported health concerns such as respiratory ailments, dust exposure and contaminated water, especially among children. These concerns were supported by qualitative feedback, where nearly half (48%) of the respondents demanded urgent government-led rehabilitation, expressing dissatisfaction with current interventions and a lack of accountability.

Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) results on heavy metals revealed elevated concentrations of uranium (U: 10.731 mg/kg), Chromium (Cr: 156.802 mg/kg) and Nickel (Ni: 129.081 mg/kg) in soil samples collected from mine tailings and exposed surfaces within the Brakpan (Kwa-Thema) mine wastelands, exceeding commonly referenced soil quality guidelines values (U: 1.400 mg/kg, Cr: 6.500 mg/kg, and Ni: 50.000 mg/kg). Surface water samples collected from nearby stagnant ponds and drainage pathways within the same area showed metal concentrations exceeding the South African National Standards for Drinking Water Quality and WHO guidelines (U: 0.030 mg/L, Cr: 0.050 mg/L, and Ni: 0.070 mg/L).

Gamma spectrometry confirmed high uranium-238 decay activity, while thorium-232 levels were lower and its decay progenies were recorded. Radiological hazard indices, including Annual Effective Dose (AED: 1.414 mSv/y) and Excess Life Cancer Risk (ELCR: 0.99×10^{-4}), with AED surpassing regulatory limits of the National Nuclear Regulator and

International Commission of Radiological Protection, indicate significant long-term radiological health risks to exposed populations. RUSLE modelling estimated soil loss at 75.281 tons/ha/year, with erosion hotspots observed within mine wasteland, particularly on loosely compacted tailings and exposed slopes. On-site inspections carried out during field visits assisted in identifying observable human activities, such as illegal dumping and evidence of unregulated past mining operations, which contributed to the environmental conditions observed in the study area.

Findings highlight ongoing environmental and health risks from inadequate rehabilitation and weak regulation. The study recommends erosion control, phytoremediation interventions, targeted health campaigns and stronger enforcement of the “polluter pays” principle. This study provides practical insights into the impacts and rehabilitation of mine wastelands in Brakpan, offering broader relevance for managing post-mining landscapes across South Africa and other regions of the Global South facing similar challenges.

Keywords: Mine wasteland; environmental pollution; heavy metals; radionuclide contamination; surface water contamination; soil erosion; Revised Universal Soil Loss Equation (RUSLE); mine rehabilitation.

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Acronyms

α	Alpha Particle
γ	Gamma ray
β	Beta Particle
µm	micron
%	Percentage
Bq/kg	Becquerel per Kilogram
F_v	Plant transfer factor
H_T	Equivalent dose
mg/kg	milligram per Kilogram
mg/L	milligram per Litre
mSv	micro-Sievert
n	Sample size
AED	Annual Effective Dose
AED_T	Total annual effective dose
AMD	Acid Mine Drainage
BLLs	Blood Lead Levels
BMF	Benchmarks Foundation
CAES	College of Agriculture and Environmental Sciences
CCME	Canadian Council of Ministers of the Environment
CoE	City of Ekurhuleni
CSIRO	Commonwealth Scientific and Industrial Research Organization
DALRRD	Department of Agriculture, Land Reform and Rural Development
DFFE	Department of Forestry, Fisheries and the Environment
DMRE	Department Mineral Resources and Energy

DNRME	Department of Natural Resources, Mines and Energy
DRDMD	Durban Roodepoort Deep Mine Dumps
DWS	Department of Water and Sanitation
EIA	Environmental Impact Assessment
ELCR	Excess Lifetime Cancer Risk
EMM	Ekurhuleni Metropolitan Municipality
EMP	Environmental Management Plan
EMPr	Environmental Management Program
EMS	Environmental Management System
EPA	Environmental Protection Agency
ESG	Environmental, Social and Governance
EU	European Union
FAO	Food and Agriculture Organization
FAO-UN	Food and Agriculture Organization of United Nations
FEP	Full Energy Peak
FRA	Forestry Reclamation Approach
GDP	Gross Domestic Product
GIS	Geographic Information System
GTI	Global Tailings Institute
GPS	Global Positioning System
ha	hectare
HCL	Hydrochloric Acid
HPGe	High Purity Germanium Detector
HRW	Human Right Watch
IAEA	International Atomic Energy Agency
ICMM	International Council on Mining and Metals
ICP-MS	Inductively Coupled Plasma-Mass Spectrometry

ICRP	International Commission of Radiological Protection
IP	Intellectual Property
IMF	International Monetary Fund
ISO	International Standard Organization
keV	Kilo-electron Volt
LRS	Labor Research Service
MCA	Multi-Channel Analyser
MCSA	Mineral Council of South Africa
OMECP	Ontario Ministry of the Environmental Conservation and Parks
MHSA	Mine Health and Safety Act
MHSC	Mine Health and Safety Council
MPRDA	Mineral and Petroleum Resources Development Act
NASA	National Aeronautics and Space Administration
NEMA	National Environmental Management Act
NEM: WA	National Environmental Management: Waste Act
NEPC	National Environment Protection Council
NHO_3	Nitric acid
NNR	National Nuclear Regulatory
NOB	Northern Ontario Business
NORMs	Natural Occurring Radioactive Materials
NRC	Nuclear Regulatory Commission
NWU	North-West University
OALA	Ontario Association of Landscape Architects
OES	One Environmental System
pH	potential of Hydrogen
PGM	Platinum Group Metals
PwC	PricewaterhouseCoopers

QAQC	Quality Assurance and Quality Control
QMENR	Quebec Ministry of Energy and Natural Resources
RSA	Republic of South Africa
RUSLE	Revised Universal Soil Loss Equation
SA	South Africa
SAHPRA	South African Health Products Regulator Authority
SAHRC	South African Human Rights Commission
SAMI	South African Mineral Industry
SD	Standard Deviation
SLO	Social License to Operate
SLPs	Social and Labour Plans
STATS	Statistics
UNISA	University of South Africa
UNEP	United Nations Environment Programme
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation Standards
USEPA	United States of America Environmental Protection Agency
USA	United States of America
WHO	World Health Organization
WRC	Water Research Commission
WPR	World Population Review
ZAR	South African Rand

Chapter 1: Introduction

1.1 Study Background

Mine wastelands are lands that are constituents of by-products of mining activities generated after valuable minerals are separated from the uneconomic fraction of an ore (Laker, 2023). The size and composition of mine wastelands depend on the mining methods used by the mining company for the specific minerals. Most of the by-products of the mining are typically a mud-like material, waste rock, overburden, slags, mine water, Acid Mine Drainage (AMD) and tailings (Lourenco *et al*., 2021; Mabaso *et al*., 2023). These by-products vary in their chemical, physical composition and their potential for environmental pollution (Nwaila *et al*., 2021; Baloyi *et al*., 2024).

Most of the mine wastelands in Brakpan, Gauteng, South Africa (SA) were generated because of gold mine activities that occurred following the discovery and mining of coal and gold from the 1888 to the present day (Ergo-Mining, 2019; Mpanza, 2022; DRDGOLD Limited, 2023). The mining of coal and gold in Brakpan not only boosted the economy of Gauteng Province and South Africa (SA) but also brought massive landscape changes and environmental problems, among which are mine wastelands (Chadi, 2022). Owing to the extensive mining activities over a long period, the activities have evolved and impacted the natural environment of Brakpan, bringing about massive challenges to monitor and implement mitigation strategies for the management and rehabilitation of all mine wastelands in Brakpan region (Cornelissena *et al*., 2019; Du Plessis *et al.,* 2023).

In countries such as Australia, mining has left approximately 50,000 abandoned mines alone and the Australian government has established an abandoned mine lands programme to tackle the problem of mine wastelands (Kragt *et al*., 2021). Department of Natural Resources, Mines and Energy (DNRME) from Australia administered the programme and since 2013, about 400 mines with approximately 134 sites have been remediated (Queensland Government, 2019).

The tailings management framework adopted by DNRME from Australia included the involvement of stakeholders through formal investigations and risk assessments to minimise public health and safety risks. It also requires comprehensive documentation and the integration of tailings management plans into all phases of mine planning, operation and closure (Armstrong *et al*., 2019; Queensland Government, 2019). In contrast, in South Africa, DMRE issues mining rights, ensure that mining companies do not violate the South African Constitution and that mining companies mitigate their impacts (social, environmental and economic) after their operations according to their Environmental Management Plan (EMP) which they submitted to DMRE before mining (Centre for Energy, Petroleum and Mineral Law and Policy, 2021; DMRE, SA, 2023). The DMRE oversees and tackles the mining rehabilitation issues. Currently, approximately 267 derelict and ownerless mines have been rehabilitated, while others are still undergoing rehabilitation (DMRE, SA, 2023; 2024).

Brakpan, located in the East Rand of Gauteng Province, South Africa, has been mining gold since 1888 and visible mine dumps and the transformation of the area are evident. There are on-going activities of recovering and treating the mine wastelands (mine dumps) that are taking place in Brakpan. One of the mining companies that is responsible for re-mining is Ergo/DRDGOLD Mine, which is the prime mine located in the northern part of Gauteng, South Africa (Ergo-Mining, 2019). Due to the re-mining of the mine wastelands (mine dumps), new opportunities for socio-economic and environmental challenges have arisen (MCSA, 2023; Stats-SA, 2024). Ergo/DRDGOLD Mine company re-mines the old tailings dams by digging them up, turning the sand into a liquid slurry, then pumping the liquid slurry along a pipeline to a treatment plant outside Geluksdal (Ergo-Mining, 2019; BMF, 2023; CoE, 2025). As the mining methods used back then were not efficient enough to recover the total amount of gold, some gold was wasted in mine tailings (Araya *et al*., 2021; Chetty *et al*., 2021).

Against this background, this study assessed the environmental impacts, community perceptions and management challenges associated with historical mine wastelands in Brakpan (Kwa-Thema), South Africa, while also identifying practical management strategies for rehabilitation and environmental management. It further reviewed current measures used to manage contamination and explored approaches to improve environmental rehabilitation. The goal was to understand the impacts of mine wastelands, assess ongoing rehabilitation efforts and provide recommendations for authorities and community-led mitigation initiatives.

1.2 Problem statement

There are numerous abandoned mine wastelands (mine dumps) in mine areas of South Africa, such as Giyani Greenstone Belt in Limpopo Province and Geluksdal (Brakpan) in

Gauteng Province (Ergo-Mining, 2019; Mangwaya *et al*., 2021). These mine wastelands pose a significant danger to nearby communities and occupy important space in towns that could be used productively (Mhlongo *et al*., 2020). Some people have begun to settle on top of this mine wasteland. For example, the Tudor Shaft area near Krugersdorp in Gauteng, South Africa, is one of those areas where humans have moved and settled in owing to a lack of space for settlement in Johannesburg (Rotimi *et al*., 2021; Moshupya *et al*., 2022). The Tudor Shaft area is one of the highly radioactive and contaminated areas in Gauteng, which poses human health risks to the residents of the mine wasteland (Kaninga *et al*., 2020; WRC, 2020; Moshupya *et al*., 2022).

The mine wastelands that have been abandoned need to be maintained and managed appropriately as they produce and distribute heavy metals such as uranium, copper, arsenic, iron and lead that tend to pose the biggest health risk threats towards the surrounding communities and environment (Iyaloo, 2020; Sibuyi *et al*., 2023). In the Brakpan (Kwa-Thema) area, these mine wastelands are primarily associated with historical gold mining within the Witwatersrand Basin, where uranium occurs as a co-occurring element in gold-bearing ores, providing a geological basis for the observed contamination. As heavy metals are ingested or inhaled, they can lead to cancer, asthma, and reproductive defects, to the natural environment, heavy metals reduce microbial diversity in soil and result in poor soil quality, which encourage poor growth of tolerant plants leaving the environment devoid of vegetation and intensify the soil erosion (Asare *et al*., 2021; van Wyk *et al*., 2022; Jomova *et al*., 2024).

Despite the economic importance of mines, such as the creation of employment and providing minerals, they have massive challenges of posing negative impacts on the environment and the communities at large, and one of the challenges is the enormous waste they produce daily (Siyongwana *et al*., 2019; BMF, 2023). To evaluate effective mitigation strategies for the environmental impacts and management challenges of historical mine wastelands in Brakpan, this study also considered community perceptions and assessed the current measures being implemented to address these impacts.

1.3 Research Aim and Objectives

The main aim of the research was to assess the environmental impacts, community perceptions and management strategies of historical mine wastelands in Brakpan (Kwa-Thema), South Africa.

1.3.1 Research objectives

- To evaluate the impacts of mine wastelands on the surrounding environments by quantifying soil erosion rates, heavy metal and Natural Occurring Radioactive Materials (NORMs) concentrations in soil and water from historical mine wastelands
- To examine the community perception on how mine wastelands impact their quality of life (health and economics).
- To assess the challenges and effectiveness of measures that are being implemented to address the impacts of mine wastelands in Brakpan.
- To evaluate and identify suitable methods for the decommissioning, assessment and management of mine wastelands based on the findings of the study.

1.4 Research questions

- What are the environmental impacts exacerbated by mine wastelands in Brakpan?
- What are the community's perceptions on how mine wastelands impact their quality of life (health and economics)?
- What are the challenges and effectiveness of measures that are being implemented to address the impacts of mine wastelands in Brakpan?
- What methods can be used to decommission, assess and manage the mine wastelands by local authorities and communities?

1.5 Justification of the study

Owing to the legacy of mining in South Africa and the central role the industry continues to play in the economy, the rehabilitation of mine wastelands remains a critical environmental and social priority. Historical gold and uranium mining in Brakpan (Kwa-Thema) has left behind extensive tailings, degraded landscapes and potential health risks to surrounding communities. Understanding these environmental impacts and how local residents perceive and respond to them is essential for designing effective rehabilitation strategies and promoting sustainable land-use planning.

Studies conducted elsewhere demonstrate the significance of integrating environmental assessments with community perspectives. For instance, research in Zambia's Copperbelt region has shown that the poor rehabilitation of mine wastelands leads to persistent soil and water contamination, with communities reporting increased health problems and reduced agricultural productivity (Festin *et al*., 2019; Banda *et al*., 2023). In Australia, long-term monitoring of gold mine tailings indicated that successful rehabilitation depends not only on technical interventions but also on gaining social acceptance and involving local stakeholders in decision-making processes (Kragt *et al*., 2021; Taylor *et al*., 2023). Similarly, in Canada's Sudbury mining region, large-scale ecological restoration through soil amendments and tree planting helped to restore biodiversity and improved community confidence in land reuse (OMECP, 2020; OALA, 2021).

Assessing Brakpan's mine wastelands within the Ekurhuleni region is therefore critical in the interest of designing sustainable rehabilitation approaches. Unlike regions where rehabilitation frameworks are more advanced, South Africa faces the dual challenge of widespread historical legacies and ongoing socio-economic inequalities which exacerbate community vulnerability. This study assessed the environmental impacts, community perceptions and management challenges of historical mine wastelands in Brakpan, offering evidence-based insights that can inform local and national policy.

The research provides value to local authorities by supporting environmental planning efforts, while contributing to broader scientific understanding of how to mitigate mine wastelands in urbanised, resource-dependent settings. By linking environmental data, radiological assessments and community perspectives, the study establishes a foundation for sustainable rehabilitation framework (Environmental Management System: EMS). This framework can be applied across South Africa and similar mining regions globally.

1.6 Dissertation chapter breakdown

The dissertation is compiled and presented in 6 chapters as follows:

Chapter 1: Introduction

Introduction and background to the description and history of mine wastelands, mine reclamation and rehabilitation, are provided and discussed in this chapter. The problem statement, justification of the study, research aim, and objectives related to the study are also outlined.

Chapter 2: Literature review

In this chapter, literature related to the study is discussed with a detailed emphasis on case studies of incidents involving mine wastelands and rehabilitation. First, the researcher describes the overview of mine wastelands, the importance of mining in South Africa and the impacts of mining on the environment and mitigation. Secondly, the researcher detailed methods to rehabilitate the mine wastelands, threats posed by the distribution of heavy metals and NORMs, accumulation and detection of heavy metals and NORMS. Lastly, the researcher details the socioeconomic benefits of re-mining mine wastelands, the cost of rehabilitation and the financial provision of environmental rehabilitation.

Chapter 3: Research design and methodology

This chapter presents the research design and methodology adopted in the study. Details of the mixed-methods approach followed are given, with the qualitative aspect focusing on community participation to capture local community knowledge and experiences, while quantitative components include laboratory analysis of soil and water samples. The Revised Universal Soil Loss Equation (RUSLE) model used to assess erosion risks, sampling procedures, data collection tools and analysis techniques used to ensure credibility, reliability and objectivity of the findings are described. The ethical considerations and limitations of the study are detailed in the final section of this chapter.

Chapter 4: Results and data analysis

This chapter details the findings of the study in a clear, rational and structured way. The presentation includes results from participants, surveys, fieldwork, experiments and laboratory results. There are two categories of data presentation in this chapter, namely qualitative and quantitative results. Qualitative presentation focuses on participants' responses and surveyed data acquired in the research, while the quantitative presentation focuses on experimental and laboratory data results obtained.

Chapter 5: Discussion

This chapter presents a comprehensive interpretation of the research findings related to the environmental impacts, community perceptions and management challenges associated with historical mine wastelands in Brakpan (Kwa-Thema), South Africa, while also examining appropriate management strategies. It discusses the broader implications and significance of the results, reflecting on how the study's aims and objectives were achieved. Key findings are compared with existing literature to highlight consistencies and discrepancies and to provide explanations for unexpected results. Furthermore, the chapter explores the theoretical contributions of the study and its practical implications for mine wasteland management and community wellbeing.

Chapter 6: Summary, Conclusions and Recommendations

This chapter summarises the significant findings, provides conclusions derived from the main findings of the study, makes practical recommendations, and concludes the whole study.

The references and annexures are provided at the end of the study.

Chapter 2: Literature review

2.1 Introduction

The literature review gives a clear overview of mine-wastelands, impacts of mining on the environment, assessment of potential and predicted environmental impacts of re-mining mine-wastelands, evaluating proposed mitigation measures and contingency plans for decommissioning mine-wastelands. The chapter also discusses the reclamation and rehabilitation of mine wastelands and the socio-economic benefits of re-mining mine wastelands in Brakpan.

2.2 Conceptual and global perspectives on Mine wastelands

Environmental degradation caused by mine wastelands from developed countries (Canada, Sudbury Basin) to developing countries (South Africa, Witwatersrand Basin) highlights a global pattern of neglect (Cole *et al*., 2022; Reuters, 2024). Years of intense mining activities have led to the severe degradation of these landscapes, typically marked by toxic metal pollutants, mine tailings, acid-generating materials and persistent environmental degradation (Cole *et al*., 2024). Management practices for mine wastelands are diverse, vary globally and are shaped by each country's laws, environmental conditions and available technologies.

In the Witwatersrand region in Gauteng Province, South Africa, historical gold and uranium tailings have been identified as radioactive contamination hotspots, underlying the urgent need for site-specific reclamation (Mpanza, 2022). In addition, Haddaway *et al*. (2019) proposed a mixture of ecological restoration models that can be applied to local environments, while recent frameworks emphasise the role of community engagement and bioindicators in promoting social acceptance and sustainability in the rehabilitation processes. To illustrate differences in rehabilitation approaches and identify lessons applicable to local contexts, Table 2.1 presents a comparative assessment of mine wastelands characteristics, rehabilitation strategies and policy responses among these four countries: South Africa, Canada, Zambia and Australia. This comparison serves as a basis for evaluating the adaptability of global rehabilitation approaches to the South African mining landscape.

Table 2.1: Comparative assessments of mine wastelands rehabilitation strategies: Case studies from Canada, Australia, Zambia and South Africa

Country and location	Mine wasteland type	Core challenges	Remediation strategies	Observed outcomes / Environmental impacts	Reference
Canada, Sudbury	Copper/ Nickel mine	Acidified soils and vegetation loss	Soil conditioning with biosolids and vegetation restoration	Planted about 100 000 trees for ecosystem recovery is observed	CCME, 2021; OALA, 2021
Australia Mount, McClure	Gold mine	Tailings with acid-producing materials	Decommissioning of tailings	Risks minimized with secure and stable closure framework	Truong *et al*., 2020; Taylor *et al*., 2023
Zambia, Kitwe	Copper mine	Massive overburden with metallurgical slags	Limited data of site-specific interventions	Significant biodiversity loss due to mining activities	Festin *et al*., 2019; Mutelo, 2023
SA, Brakpan	Gold and Uranium mine	Tailings with elevated radionuclides contents	Re-mining and secured containment system (DRDGOLD)	Partial remediation yet exposure risks are still evident	DFFE, SA, 2023

2.3 Overview of mine wastelands

Mine wastelands are by-products of mining operations that are deemed uneconomically viable (Nwaila *et al*., 2021). These by-products are a combination of fine-grained solid materials generated after minerals and metals were extracted (Laker, 2023). To understand the mine wastelands, it is essential to examine the history of mining. Over time, mining operations have led to widespread environmental damage, harming local plants and animals (Mabaso, 2023).

Mine wastelands often cause environmental damage that is interconnected with degraded soil, vegetation loss and water pollution. These impacts tend to reinforce each other. Such areas typically have abnormal levels of power of hydrogen (pH), degraded soils, elevated concentration levels of heavy metals and NORMs and scattered or sparse vegetation cover (Banda, 2023; Raji *et al*., 2023). Additionally, these areas are mostly exposed to sedimentation, transportation and soil erosion. Moreover, these conditions tend to hinder the processes of natural ecological recovery, biodiversity and pose significant environmental health risk to communities residing nearby through environmental degradation, groundwater contamination and air pollution pathways (Belle *et al*., 2021; Khan *et al*., 2022; Hong *et al*., 2024).

From a socio-economic perspective, mine wastelands can have prolonged impacts on surrounding communities, particularly where land has been degraded and unsuitable for agricultural practices, settlements and/or other productive activities (Shackleton, 2020; Sibuyi *et al*., 2023). In developing countries such as South Africa, Zambia and Ukraine, abandoned mine sites remained neglected owing to weak regulatory enforcement, limited financial resources and the absence of comprehensible policy frameworks for effective post-mining rehabilitation (Siyongwana *et al*., 2019; Mulenga, 2022; Dychkovskyi *et al*., 2024).

Developed countries such as Australia and Canada have addressed the negative impacts that have been brought by mining operations (gold, copper and nickel mining) in their environment (Truong *et al*., 2020; Reuters, 2024). One of the companies that has addressed this is the mining company called Mount McClure Mine, which is located in Western Australia in the Leinster Goldfields region. It had two storage facilities whereby tailings were placed. The tailings were identified as acid-generating, posing serious risks to both the surrounding environment and groundwater resources (McCullough, 2024; Lacy *et al*., 2005). Discharged tailings were decommissioned, which led to the design of an appropriate final closure plan. Risk mitigation strategies included physical methods such as capping the tailings and reshaping the embankment into a concave profile. Biological methods were also used, including seeding the topsoil with indigenous plants such as *Acacia pulchella* and *Eucalyptus marginata* to prevent further environmental degradation (Van Wyk, 2019; Priya *et al*., 2023; Mlalazi, 2024).

On the contrary, in Sudbury, Ontario, Canada, Copper Cliff Central Tailings areas of nickel and copper smelting operations were found to be generating acidic, nutrient-poor soils, resulting in unfertile landscapes (CCME, 2021; LaRowe *et al*., 2023; Wang *et al*., 2023). Mining companies such as Vale and Glencore, in collaboration with Terrapature Environmental through the Sudbury Regreening Program, have implemented a range of mitigation strategies to rehabilitate mining-impacted areas in Sudburry, Ontario (OALA, 2021; NOB, 2025). These strategies include chemical methods, the application of biosolids (municipal waste) and biological methods. As part of the revegetation efforts, over 100, 000 seedling trees, primarily jack pine, white spruce and white pine, were planted to improve soil conditions and restore ecological function in the affected landscapes (Glencore Canada, 2021; OALA, 2021).

In the Far West Rand (Carletonville), South Africa, watercourses (wetlands, rivers and aquifers) were impacted by AMD and radionuclides leaching from uranium bearing tailings and radionuclides levels in sediments were found to reach 10 000 Bq/kg above recommended acceptable limits of both national (< 500 Bq/kg) and international (<1000 Bq/kg) standards (NNR, 2021; Moshupya *et al*., 2022; Mashamaite, 2023). Then multi-prolonged remediation strategies (physical, chemical and biological techniques) together with public awareness were suggested by experts (Mintek, North -West University (NWU) and University of Witwatersrand, South Africa) (Raji *et al*., 2021; Ndlovu *et al*., 2023). The uranium mine in Carletonville, was upgraded in 2011 to treat 30 million litres of mine water a day to resolve the issue of AMD in the Witwatersrand area. As the mine contaminated water continues to pose severe public and environmental health risks in the Witwatersrand area, the cost of addressing AMD is estimated between R900 million and R1 billion (Baloyi *et al*., 2023). However, the government allocated only R433 million to the project, meaning additional funds still had to be secured to ensure its completion (DMRE, SA, 2021).

With the South African mining industry struggling with mine wastelands management, one of the companies that has capitalised on mine wastelands is DRDGOLD Mine. It is re-mining the old mine dumps that were generated since the discovery of a diamond on the banks of the Orange River in 1867 in South Africa (DRDGOLD Limited, 2023). One of the other mine dumps that the DRDGOLD Mine is re-mining is Brakpan tailing, which is situated in Brakpan (Geluksdal) and is one of the largest man-made structures in Africa with a total of 200 million tons of mine waste (Ergo-Mining, 2019; DRDGOLD Limited, 2023).

In the 21st century, the global mining industry, through mining bodies such as the International Council on Mining and Metals (ICMM) and national bodies, the Mineral Council of South Africa (MCSA), is pursuing the augmentation of mining practices to achieve sustainable development imperatives. This was implemented through regulatory reform frameworks and environmental accountability by integrating various investments that include social responsibility, environmentally friendly practices, financially feasible, and technical appropriate (Cole *et al*., 2022). These efforts assist mining companies that operate in South Africa and internationally with alignment and compliance with both the South African and international mining operational standards (MCSA, 2023).

2.4 The mining sector and economic contributions in SA

Mining continues to drive South Africa's economic growth, maintaining its position as one of the country's most important industries, accounting for 10.5 percent (10%) of global gold reserves (Stats-SA, 2024). With a well-developed and vibrant exploration sector, the country has the potential to supply a large share of global demand for many commodities. In 2023, the mining sector alone contributed ZAR444.2 billion, down from ZAR494 billion in 2021, which is about six (6) percent of South Africa's Gross Domestic Product (GDP) (Ecofin Agency, 2023). This was achieved regardless of the slow growth of the global economy, low commodity prices, as well as labour, strikes, especially from the mining sector (SAMI, 2017; SAMI, 2018; Zulu *et al*., 2022).

South Africa remains a global leader in terms of production of variety and quantity of mineral resources (BCG, 2023). It houses most of the deepest mines in the world and has the largest reserves of gold, manganese, chrome, vanadium and platinum group metals (PGM's) (DMRE, SA, 2023; PwC SA, 2023). South Africa is one of the leading producers of nearly all mineral resources in Africa except uranium (Niger), copper and cobalt (Zambia and the Democratic Republic of the Congo), diamonds (Botswana and the Democratic Republic of the Congo) and phosphates (Morocco) (Stats-SA, 2018; IMF, 2024).

2.5 Impacts of mining on the environment

Mining operations are well known as a major source of environmental degradation, particularly in regions where weak regulatory oversight and inadequate mine closure practices prevail (DRBMP, 2021; Du Plessis *et al*., 2023). The environmental consequences of mining affect land, air and water. These effects often remain even after mining operations have ended. They include changes in landforms, contamination of natural resources and damage to ecological systems (Mangwaya *et al.,* 2021). Key areas of concern include the deterioration of soil quality and land stability, the pollution of water bodies through AMD and the mobilisation of toxic heavy metals (such as arsenic, cadmium, lead and uranium) as well as the release of airborne pollutants (particulate matter, sulphur dioxide and nitrogen oxides) that compromise the air quality and public health (Raji *et al*., 2021; Baloyi *et al*., 2024). The alteration of these aspects (air, land, water and biodiversity quality) is discussed in following sections.

2.5.1 Air

Mining activities involve vegetation clearing and eventually exposing the soil to different weather patterns, causing the particles to become airborne through wind, erosion and road traffic (Mononen *et al.*, 2022; Raji *et al*., 2023). This makes the communities residing near mine dumps exposed to air pollution, causing detrimental impacts on their health and well-being (Iyaloo, 2020). Most of these communities complain about the increased levels of dust and deteriorating health (Siyongwana *et al*., 2019; SAHRC, 2022).

Unrehabilitated tailing dumps often worsen air pollution in surrounding areas, which triggers respiratory diseases such as asthma, pneumonia and emphysema in the near surrounding communities situated about 5km (BMF, 2023). This was witnessed in communities such as Welkom in Free State, South Africa and Fort Chipewyan, Alberta, Canada. Residents there have reported serious health issues, including asthma and bronchitis. These problems were linked to decades of exposure to dust from gold mining tailings dumps that released uranium particles into nearby areas (Andraos *et al*., 2018; Nkosi *et al.,* 2020). Moreover, long-term residence of Alberta, Canada had elevated autoimmune disease, cancer risks and other health concerns owing to tailing pond leaks from the imperial oil site of Oil sands development (Imperial Oil, 2023; Reuters, 2024).

The dust from the tailing dumps is usually fine-grained and contains toxic heavy metals (e.g., cadmium, lead, and arsenic), which can be inhaled or ingested through food consumed there daily (Nkosi *et al.,* 2020). Witwatersrand has about 320 mine dumps which contain significant levels of arsenic, cobalt, uranium and cadmium (WRC, 2020). For instance, when exposed to excessive uranium, it could lead to lung cancer. Recent studies conducted between 2020 and 2024 have highlighted the health risks associated with exposure to uranium and radon in communities near gold mine tailings such as Soweto's Snake Park and Bramfisher. Zupunski *et al*. (2023) found elevated uranium concentrations in hair samples from residents living close to mine tailings, indicating significant exposure. Similarly, Nkosi *et al*. (2020) and Mphaga (2024) reported increased indoor radon levels in households situated near these sites, further emphasising the potential health hazards, such as respiratory illnesses.

2.5.2 Land

Mining alters natural landscapes, leaving environmental scars such as open pits, mine dumps and sinkholes (Mabaso, 2023). Such disturbances can harm plants, animals and natural features in the surrounding mining area. After mining, vegetation is usually cleared, and the land's aesthetics change because of large-scale waste disposal. Ground movements on the surface of the earth owing to crumbling overlaying sheets, e.g., sinkholes, can cause damage to buildings and roads (Strzałkowski *et al*., 2021). Some of the sinkholes were seen in Lyttelton quarry, Centurion and Waterkloof whereby some of the sinkholes have damaged houses in Lyttelton Manor in 2008 (Ferentinou *et al*., 2020).

In Poland, from the old copper district of Lubków Municipality in 2017 to 2018, the sinkholes started to appear after mining operations had ceased. The sinkhole, though, was secured and sealed with no human casualty (Mirek *et al*., 2019; Strzałkowski *et al*., 2021), owing to the exploitation of mineral deposits underground, which resulted in discontinuous deformation of the earth. These discontinuous deformations manifest as sinkholes later, after mining operations have ceased for 25 years (Mirek *et al*., 2019; Ferentinou *et al*., 2020; Strzałkowski *et al*., 2021).

2.5.3 Water

About 120km of the Witwatersrand is affected by mining tailings owing to the legacy of gold mining operations that took place. Many of these dumps have been reprocessed and are being reprocessed by companies such as MINTAIL and Ergo/DRDGOLD Mine Company, but the dumps are continuing to cause pollution (WRC, 2020). Tailing mines in Hokkaido (Japan) were reported to continuously generate AMD containing Cu, Zn, and Fe and pollute the local environment even though these tailings were disposed of 40 years ago **(**Khoeurn *et al*., 2019; Islam *et al*., 2023**)**. Some of the areas that are more vulnerable and exposed are groundwater, which is easily polluted by tailing mines (Baloyi *et al*., 2024). Because tailing materials are fine-grained depending on the parent rock, they often have low infiltrates, high bulk densities and lead to compaction, which makes it easier for the groundwater to be polluted (Lourenco *et al*., 2021).

Most of these mine tailings are near human settlements, especially in the Witwatersrand region (West Rand) (Chetty *et al*., 2021). Consequently, proximity and uncontrolled access to these tailing mines provide opportunities for usage such as sand mining for construction by the community and brick manufacturing, which exacerbate material dispersal (Kanda *et al*., 2021; Nwaila *et al*., 2021). Water erosion and aeolian dispersion are major factors that contribute to soil contamination by heavy metals around mine wastelands from mine wastes in Hunan province China, Klip River Catchment, Johannesburg and Witwatersrand, SA (Yun *et al*., 2020; Chetty *et al*., 2021). Soil contamination is typically accompanied by reduced diversity and activity of microbial communities (LaRowe *et al*., 2023), resulting in poor soil quality and elevated metal concentrations that restrict plant growth as observed in Linfen (China) and Norilsk (Russia) (Wang *et al*., 2022; Bellona, 2023; Zverev, 2023; Mlalazi, 2024). The other substance that is likely to form is AMD and is mostly released from underground and tailing mines when the sulphide minerals are exposed to oxygen and water, resulting in oxidation. This oxidation process leads to the production of sulphuric acid, which in turn dissolves heavy metals, making the drainage water both acidic and toxic (Baloyi *et al*., 2024). Tailing mines are man-made structures with young, unstable soils that do not hold together well. Their walls are usually barren and often lie next to floodplains. This combination makes the dump surfaces very prone to erosion, especially during the rainy season (Hefft *et al*., 2022; van Wyk *et al*., 2022).

2.5.4 Biodiversity

Most impacts of mining activities on the environment are seen after the mining operations have stopped. For instance, about 350 tons of waste is generated, and 147 tons of the waste is tailings when producing one ton of copper at Nkana Slag dump (Black Mountain), Kitwe (Zambia) (Festin *et al*., 2019; Mulwanda *et al*., 2024). In Zambia's Copperbelt Province, 20,646 hectares (ha) of land was covered by 1899 million tons of overburden, 9125 ha by 791 million tons of tailings, and 279 ha by 40 million tons of slag (Festin *et al*., 2019; Mulenga, 2022; Mulenga *et al*., 2023; Mutelo, 2023). Mining, therefore, significantly impacts biodiversity through vegetation clearing and large-scale waste disposal across regions such as the eastern Democratic Republic of Congo (Mononen *et al*., 2022; Ladewig *et al*., 2024).

Mining causes significant habitat loss, making it challenging for plants and animals to survive as their natural ecological conditions are disrupted (Mononen *et al*., 2022). The slightest disturbance or disruption of fauna and flora occupying wetlands, including animals that inhabit trees in mining areas, can result in annihilation or put them at high risk of extinction (Rehmana *et al*., 2021; Hefft *et al*., 2022). The level of concentration, distribution and nature of contaminants dictate the degree to which mining affects biodiversity around mining sites. This relationship was documented in the districts of Mardan and Mohmand Khyber Pakhtunkhwa in Pakistan (Rehmana *et al*., 2021; Khan *et al*., 2022). The assessment study was conducted to see how mining adversely affects wildlife, especially species of mammals (*Capra aegagrus*), birds (*Passer domesticus*) and reptiles (*Saara hardwickii*) (Rehman *et al*., 2021). Furthermore, Rehman *et al*. (2021) documented that species such as *Capra aegagrus*, *Passer domesticus*, and *Saara hardwickii* virtually disappeared from mining areas but remained abundant in unaffected zones, while *Passer domesticus* and *Canis aureus* showed relative resistance to such disturbances (Rehman *et al*., 2021; Filice *et al*., 2023).

Conservation and biodiversity rehabilitation has two essential objectives, namely "to develop practical approaches to prevent the extinction of species and maintain the integrity of ecosystems and to evaluate human impacts on biological diversity" (Pathe *et al*., 2021; Rehmana *et al*., 2021). South Africa has policies and legislation to protect and conserve its biodiversity, namely the National Environmental Management: Biodiversity Act of 2004, which "provides a regulatory framework to protect South Africa's valuable species, ecosystems and its entire biological wealth" and the National Environmental Management Act 107 of 1998.

2.6 Socio-economic impacts and community perception of mine wastelands

Regions that were previously heavily mined, such as Brakpan, tend to face both socio-economic and environmental impacts. Current literature concerning communities residing near mine wastelands has demonstrated that they often have limited land-use, infrastructure deterioration, property declining in commercial value and constant exposure to environmental pollution (Grobler *et al*., 2024). Socio-economic profiling study conducted in West Rand shows deteriorating infrastructure, diminishing employment and weakening economic activity as mining becomes less central, reinforcing the pattern of environmental and social decline near mining wastelands (Grobler *et al*., 2024).

Similar socio-economic and environmental patterns have also been reported in other mining regions globally, including the Copperbelt Province in Zambia and the Jharkhand mining region in India, where abandoned mine lands contribute to reduced agricultural productivity, land degradation and increased community vulnerability due to soil and water contamination (Banda *et al*., 2023; Ghosh *et al*., 2023; Giri *et al*., 2023). In developed countries such as the Sudbury Basin in Canada and the Hunter Valley region in Australia, legacy mine wastelands continue to present long-term challenges related to land rehabilitation costs, environmental monitoring and land-use constraints. Additionally, all these agglomeration issues can have adverse effects on the quality of life and public health (Nkosi *et al*., 2020; Baloyi *et al*., 2024).

These impacts are often intensified by prolonged exposure to contaminated soil, dust and water sources, which increases health risks while simultaneously limiting economic opportunities for affected communities. With the continuation of environmental contamination and the lack of rehabilitation initiatives by the local and national governments, the impacts keep threatening the provision of food security through agricultural practices, development opportunities and marginalisation of local communities (Priya *et al*., 2023; Tibanea *et al*., 2023).

Understanding how local communities perceive mining rehabilitation is critical to sustaining mitigation initiatives and building trust. In many mining-affected areas, local residents have raised concerns about limited engagement and poor communication with authorities and mining companies (Kaonda *et al*., 2024). These concerns often result in reduced community participation in rehabilitation initiatives and can weaken the effectiveness of implemented mitigation strategies. Therefore, evaluating mitigation strategies must involve local communities, governance bodies and economic stakeholders to strengthen the social license to operate (SLO) and ensure sustainable long-term rehabilitation (Nguyen *et al*., 2023; Smith *et al*., 2023). Incorporating participatory approaches in decision-making processes can improve transparency, accountability and the overall success of mine wasteland rehabilitation efforts.

2.7 Soil erosion in Mine wastelands and the role of RUSLE

Soil erosion is one of the most perceptible and damaging consequences of mine wastelands. The removal of vegetation during mining exposes unstable, fine-grained soils and tailings to wind and water, making them highly susceptible to displacement. In gold and uranium mining regions, steep slopes created by overburden piles and tailings accelerate surface runoff, the rate at which topsoil is lost, and the spread of contaminants (MacEwan *et al*., 2023; Yu *et al*., 2024). Without vegetation cover to stabilize the surface, rainfall events trigger sheet, rill and gully erosion, while winds disperse fine dust-like particles over long distances. This not only reduces revegetation success but also facilitates the spread of heavy metals and radionuclides into residential areas, agricultural lands and water bodies (EPA, 2020; Nkosi *et al*., 2020; Van Wyk *et al*., 2022).

Historical mining regions such as the Witwatersrand Basin (South Africa) and Mount McClure (Australia) have experienced severe erosion for decades, largely owing to inadequate erosion control measures (Laker, 2023; MacEwan *et al*., 2023). Similar erosion challenges have been documented in other mining-affected regions, including the Loess Plateau in China and the Iberian Pyrite Belt in Spain and Portugal, where high erosion rates are associated with exposed mine tailings, steep slopes and limited vegetation cover (Duan *et al*., 2024; Zhang *et al*., 2024; Sánchez-Donoso *et al*., 2024). In these regions, erosion processes have contributed to significant sediment transport and the mobilisation of contaminants into surrounding ecosystems. These conditions have caused extensive land degradation and environmental hazards (Mourinha *et al*., 2022; Sánchez-Donoso *et al*., 2024).

The RUSLE is widely used to estimate erosion rates and guide measures such as slope stabilisation and revegetation. The model integrates key factors such as rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C) and conservation practices (P), making it suitable for assessing erosion dynamics in disturbed mine landscapes (Getachew *et al*., 2021; Kumar *et al*., 2022). By identifying erosion hotspots and providing a practical framework for limiting sediment movement and contamination, RUSLE serves as a crucial tool for mine rehabilitation planning, as demonstrated in Australia's post-mining landform design (McCullough, 2024).

In addition, applications of RUSLE in regions such as the Loess Plateau in China have demonstrated its effectiveness in quantifying soil loss and informing large-scale erosion control strategies, while in Mediterranean mining regions it has been used to prioritise rehabilitation interventions and optimise land management practices.

2.8 Overview of rehabilitation methods of mine wastelands

Mine rehabilitation can be described as the process of restoring mined land to its natural form and/or to sustainable and beneficial use conditions after mining operations. It involves biological, physical and chemical methods to address environmental issues such as acid mine drainage (AMD), radionuclides (uranium, thorium, radium), and heavy metals (lead, arsenic, cadmium, chromium, nickel, zinc) build-up, as well as erosion and land degradation (Akoto *et al*., 2019; Lourenco *et al*., 2021; Li *et al*., 2023; Miller *et al*., 2023). In the case of mine wasteland, particularly gold and uranium mine wastelands, rehabilitation is complex and crucial owing to lasting risks posed by toxic and radioactive materials often arising from them. Consequently, the materials may impact the surrounding environments and communities (human health) if not properly managed for decades to come. Widely adopted approaches for mine rehabilitation are as follows:

2.8.1 Biological methods

These methods are increasingly being adopted globally in mine wasteland rehabilitation efforts as they offer long-term sustainable solutions. They involve using plants and microorganisms to manage heavy metals contamination, AMD and ecological decline to restore impacted mining areas (Priya *et al*., 2023; Wang *et al*., 2023). Biological approaches include phytoremediation, revegetation and bioremediation strategies, which are methods well adopted to achieve environmental sustainability. Phytoremediation and revegetation include using tolerant indigenous and/or hyperaccumulator plant species, particularly in mine wastelands (Jansen van Vuuren *et al*., 2024; Mlalazi, 2024). Phytoremediation of mine wastes includes two primary methods, namely phyto-stabilisation and phytoextraction. In phyto-stabilisation plants, such as *Chrysopogon zizaniodes*, *Cenchrus ciliaris* and *Cynodon dactylon* are planted to reduce dust and erosion while immobilising contaminants. These plants, once established, are not removed. In phytoextraction, other species such as *Helianthus annuus*, *Medicago sativa* and *Berkheya coddii* are used to absorb heavy metals like uranium, thorium, cadmium, and arsenic. These plants are later harvested and removed together with contaminants absorbed (Omoregie *et al*., 2023; Mlalazi, 2024). Additionally, the use of constructed wetlands in conjunction with microbial consortia has proven effective in the passive treatment of AMD and radionuclides leachate, especially at abandoned or poorly managed sites. Bioremediation involves using microorganisms (e.g., *Acidithiobacillus* *ferrooxidans*, *Thermus scotoductus* and *Comamonas testosterone*) to reduce, degrade and transform contaminants into less harmful forms (Wang *et al*., 2023; Jansen van Vuuren *et al*., 2024). In South Africa, private and parastatals like Mintails, Council for Geoscience and Mintek have experimented with such techniques (phytoremediation and revegetation) in historical mining sites in areas like Witwatersrand Basin (Mining Weekly, 2022).

Beyond South Africa, biological rehabilitation has shown varied success across different regions. In the Loess Plateau in China, large-scale revegetation programmes have significantly reduced soil erosion and improved soil stability (Bai *et al*., 2024; Wang *et al*., 2024), demonstrating the effectiveness of vegetation-based rehabilitation in highly degraded landscapes. Similarly, in the Appalachian coal mining region in the United State of America (USA), reforestation initiatives under the Forestry Reclamation Approach (FRA) have successfully restored native vegetation and improved ecosystem functionality (Bower *et al*., 2024; Sherman *et al*., 2024). In contrast, in the Copperbelt Province, phytoremediation efforts have shown mixed results due to high contamination levels of heavy metals such as copper (Cu), cobalt (Co), lead (Pb), zinc (Zn), and cadmium (Cd) associated with long-term mining and smelting activities, as well as limited long-term maintenance, highlighting the importance of site-specific adaptation and sustained management (Kříbek *et al*., 2023; Matakala *et al*., 2023).

2.8.2 Chemical methods

Chemical methods play a crucial role in restoring mine-impacted environments. These methods include application of lime, clay and/or phosphate and industrial by-products such as biochar and fly ash to counter soil acidity and stabilise NORMs and heavy metals, which are often present in gold and uranium mine wastelands (Baloyi *et al*., 2024). Layered containment structures, often referred to as multi-barrier systems, consist of engineered layers of clay, geomembranes, compacted soil, and cover materials designed to limit water infiltration and prevent the movement of contaminants through soil profile. These structures are used to enclose radioactive or toxic waste while creating a stable cover that support vegetation. This approach was implemented at Mount Morgan and Broken Hill (Australia) by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to immobilise heavy metals, leading to improved soil fertility and vegetation cover (Truong *et al*., 2020; Meiers *et al*., 2023). Similar chemical stabilisation approaches have been applied in the Iberian Pyrite Belt in Spain and Portugal, where liming and alkaline amendments have been used to neutralise AMD and improve soil conditions for vegetation establishment (Paniagua-López *et al*., 2024; Sánchez-Donoso *et al*., 2024). In addition, in mining regions of Peru, particularly in La Oroya and Cerro de Pasco, chemical treatments have been implemented to manage heavy metal contamination; however, their effectiveness has varied depending on soil composition, scale of contamination and ongoing pollutant sources (Crisostomo *et al*., 2023; Quispe-Ccanto *et al*., 2023).

Although these methods reduce environmental risks, there have several advantages and limitations. Their main strengths lie in the rapid stabilisation of contaminants, relatively low installation costs, and the ability to target specific pollutants. Composite liners offer strong containment performance by limiting leachate movement and safeguarding groundwater. However, their effectiveness can be constrained by long-term maintenance needs, potential liner degradation over time, and the risk of secondary pollution when materials such as lime are applied excessively. In addition, while chemical amendments can improve soil chemistry, they do not automatically translate into broader ecological recovery. This limits their long-term sustainability when compared to biological approaches, which support natural soil processes and promote ecosystem regeneration (Lourenco *et al*., 2021; Baloyi *et al*., 2023).

2.8.3 Physical methods

Physical methods primarily focus on recontouring the land, securing the surface and confining contaminants to reduce environmental degradation and enhance site safety. In cases of gold and uranium mine wastelands, these measures are essential owing to the threat posed by tailings instabilities, radioactive residues, heavy metals and potential AMD formation. Most widely used method is mine wastelands restructuring and installing sealing layers to attenuate dust and water infiltration that could potentially trigger formation of AMD (Cole *et al*., 2022). As noted by van Wyk *et al*. (2022), this method is typically employed as an initial step prior revegetation or installation of cover systems. Slopes are usually reduced to gradients, commonly less than 18 degrees ($<18°$) to avoid instability and gully erosion. This method was used at Ridgeway Gold Mine, South Caroline, USA by Rio Tinto to cover tailings with clay and grass to construct artificial hills that minimise water infiltration and erosion (Meiers *et al*., 2023). In addition to the United States, physical rehabilitation methods have been widely implemented in Europe, particularly in the Ruhr region in Germany, where land recontouring and engineered capping systems have successfully transformed post-mining landscapes into industrial and recreational areas (Stumpe *et al*., 2024; Zeqiri *et al*., 2024). Similarly, in India, slope stabilisation and land reshaping have been applied in coal mining regions such as Jharkhand; however, their long-term effectiveness is often limited by insufficient maintenance and financial constraints (Ahirwal *et al*., 2021; Bandyopadhyay *et al*., 2022).

However, the long-term success of these rehabilitation methods depends on consistent oversight, post-rehabilitation of land use planning and socio-economic setting of the affected communities. In addition, the reinforcements of legislations (Mineral and Petroleum Resources Development Act (MPRDA, Act No. 28 of 2002) and National Environmental Management Act (NEMA, Act No. 107 of 1998) that govern mining licensing and operations is commendable. Table 2.2 presents the comparison of biological, chemical, and physical methods, their strengths, limitations and their applicability.

These examples highlight that while biological, chemical and physical rehabilitation methods can be effective, their success is highly dependent on site-specific environmental conditions, regulatory frameworks and long-term management strategies. Therefore, integrated approaches that combine multiple rehabilitation methods are often required to achieve sustainable mine wasteland restoration.

Table 2.2: Summary of the comparison of mine wasteland mitigation strategies

Methods	Positive attributes	Limitations	Best suited for	Reference
Biological	Environmentally friendly Low cost and more sustainable	Site-specific and requires considerable time Seasonal dependency	Treatment of AMD and uptake of heavy metals	OALA, 2021
Chemical	Predictable and controllable	Can be expensive due to the area size May need follow-up treatment	Treating acidic soils and stabilization of radionuclides	DFFE, 2023; Wang *et al*., 2023

Methods	Positive attributes	Limitations	Best suited for	Reference
	Faster response time	Risk of secondary pollution		
Physical	Immediate response and containment Support infrastructure	Engineering-dependent and capital-intensive Requires long-term monitoring	Stabilization of large-scale mine waste dumps	Festin *et al*., 2019

2.9 Human and environmental health threats of heavy metals

Heavy metals pose significant threats to human health, particularly when ingested even in low concentrations. In some cases, levels below 1 part per million (ppm) can be harmful. For instance, 0.3 ppm of mercury (Hg) in the body of humans can have serious health effects (WHO, 2024). Minerals that are needed in small amounts may become toxic when consumed in excess (Kanda *et al*., 2021). Some of these heavy metals are Lead (Pb), Copper (Cu), Chromium (Cr), Nickel (Ni), Cadmium (Cd), Cobalt (Co), Barium (Ba), Zinc (Zn), Arsenic (As), Vanadium (V) and Uranium (U) (Akoto *et al*., 2019; Radfard *et al*., 2023; WHO, 2024).

Both mining activities and natural forces like rainfall and wind accelerate the spread of heavy metals from one location to another, (Phuong *et al*., 2023) causing critical concern to public health and the environment worldwide. In the Witwatersrand Basin (South Africa), Zamfara State (Nigeria), and Zhuzhou in Hunan Province (China), studies have reported elevated concentrations of heavy metals such as U, Cd, As, Pb and Hg. These contaminants, arising from gold mining, artisanal mining and industrial park activities, were found to exceed the respective national safety standards, with sources including AMD, artisanal gold extraction and industrial discharges (Ndlovu *et al*., 2023; Raji *et al*., 2023; Li *et al*., 2024). The toxicity of these heavy metals not only affects human health but also has effects on the environment and ecology.

2.9.1 Impacts of heavy metals on human health

When humans are exposed to elevated levels of heavy metals, their health may be compromised in renal, neurological, cognitive development, cancer and carcinogenic disease. Toxic metals tend to substitute nutrient minerals at enzyme binding sites often substituting for metals like calcium (Ca^{2+}), magnesium (Mg^{2+}) and/or zinc (Zn^{2+}) (Imlay, 2021; Valko *et al*., 2021). This interference disrupts nutrient flow and accumulation in the body by altering the function of thousands of enzymes. As a result, a variety of health conditions can arise in humans and other organisms (Jaikhankar *et al*., 2019; Jomova *et al*., 2024). Toxic metals such as uranium, cadmium and lead impair bodily functions by displacing essential elements within tissues. They can substitute for vital substances in structures such as cartilage, bones, muscles and joints, thereby weakening them and disrupting their normal physiological functioning (Akoto *et al*., 2019; Tchounwou *et al*., 2019; Jomova *et al*., 2024).

In Japan, a study conducted in Toyama Prefecture confirmed that Cd-induced proximal tubular injury leads to renal osteomalacia, a key feature of Itai-Itai disease, which has been historically associated with prolonged Cd exposure through contaminated water and rice cultivation (Imura *et al*., 2019). In Zambia, a 2017 study conducted in Kabwe, a region near a former lead mine, revealed that over 95% of the children had elevated Blood Lead Levels (BLLs), with nearly half requiring urgent chelation therapy, a medical intervention that uses chelating agents to bind and remove lead from the bloodstream (Yabe *et al*., 2020). Such elevated BLLs are strongly associated with impaired communication, motor coordination, problem-solving abilities and social behaviour, underscoring the neurodevelopmental impact of lead exposure (Yabe *et al*., 2020; HRW, 2025). Similarly, in South Africa, studies conducted in communities near Robinson Lake (Krugersdorp) and the Tudor Shaft informal settlements found high uranium levels in residents' hair and nail samples, indicating significant exposure to radioactive tailings from nearby gold mines (Rotimi *et al*., 2021).

2.9.2 Impacts of heavy metals on the natural environments

Elevated levels of heavy metals disrupt the well-functioning of the environment as they upset microbial biodiversity, reduce soil fertility, stagnate the growth of plants, pollute water bodies and affect terrestrial animals (Raji *et al*., 2023). They disturb microbial communities, as these microbial communities (*Nitrosomas Europaea*, *Azospirillum Brasilense* and *Acidobacterium Capsulatum*) are essential in nutrient cycling of the soil and result in poor soil fertility (LaRowe *et al*., 2023; Ndlovu *et al*., 2023). In water bodies, they can harm aquatic life and drinking water for animals and humans, causing death across water bodies and the terrestrial environment (Mamba *et al*., 2022). As for plants, photosynthesis can be affected, leading to the development of yellow leaves, disturbance of nutrient uptake, and root damage, causing a reduction of vegetation and/or elimination of plants in the environment (Witwatersrand Basin, Iberia Pyrite Belt, Sudbury Basin) (Kracmarova-Farren *et al*., 2023; Neethling *et al*., 2023).

Heavy metals can bioaccumulate in prey organisms over time and spread through the food chain. Predators then ingest these metals, which affects their health. Over time, this leads to ecosystem imbalances as sensitive species perish, and ecological functions are disrupted. In the Magdalena River Basin, Colombia, and the Phongolo River Floodplain, South Africa, macroinvertebrates and fish within the river have bioaccumulated high levels of Hg, and their predator species, such as *Hydrocynus vittatus*, have shown the highest concentration of Hg, depicting biomagnification (Phaenark *et al*., 2024). Moreover, in the Magdalena River Basin, birds (Platalea ajaja) have shown a high level of heavy metals in their blood, the same as their prey (fish and invertebrates) from polluted wetlands (Filice *et al*., 2023; Phaenark *et al*., 2024). This shows the biomagnification of heavy metals and their effects on ecology. The different essential and toxic elements, as well as their functions and toxicities, are presented in Annexure A**.**

2.10 Radiation and its distribution in mine wastelands

Mining, especially gold and uranium extraction, introduces large quantities of naturally occurring radioactive materials (NORMs) into the environment (Ibrayeva et al., 2024). During ore processing, isotopes such as uranium-238 (^{238}U) and thorium-232 (^{232}Th), along with their decay progeny, become elevated in mine wastelands. Over time, these materials increase gamma radiation levels in the surrounding environments. Elevated radiation and heavy-metal concentrations have been reported in soil and groundwater across the Far West Rand, Carletonville and Westonaria (South Africa) (Moshupya *et al*., 2022; SAHRC, 2022).

Radiation in the mine is not spread evenly across the mine wastelands. Its variability is influenced by several factors, including ore type and grade, waste management practices, natural weathering, and the topography of the landscape. This uneven distribution can complicate monitoring and clean-up efforts (Ntsohi, 2019; Rotimi *et al*., 2021; Vandromme *et al*., 2023). The ore and grade characteristics influence the baseline radionuclide levels, while waste containment and erosion processes determine how radionuclides are distributed. Terrain and drainage patterns further affect their migration into terrestrial and aquatic environments (Ibrayeva *et al*., 2024; Sombo *et al*., 2024).

Studies conducted in areas such as Witwatersrand Basin, South Africa, and Sudbury Basin, Canada have exhibited elevated ambient gamma radiation levels from abandoned mine sites, especially areas that were not or not properly rehabilitated (WRC, 2020; OALA, 2021). Similarly, radiological assessments at Tudor Shaft in Krugersdorp, which is a legacy mine site, have demonstrated how radiation hotspots persist in and adjacent to informal settlements, resulting in long-term, low-level ionizing radiation among exposure to nearby communities, raising the issue of environmental injustice and radiological risk (Sibuyi *et al*., 2023). Understanding how radiation spreads across mine wastelands helps guide decisions on which areas to prioritise for rehabilitation.

2.11 Radiation detection and measurements

Radioactive contamination represents a significant environmental and public health concern within mine wastelands, particularly in historically mined regions such as Brakpan, where extensive gold and uranium mining activities have taken place (Mashamaite, 2023; Nkosi *et al.,* 2023). NORMs, such as uranium-238 and thorium-232, often remain embedded in soil and water, contributing to prolonged low-dose radiation exposure to surrounding communities. Therefore, measurements of radiation play an integral part in the assessment, environmental management and remediation of mine wastelands, particularly those impacted by NORMs. As legacy mining activities (gold, uranium, phosphate and rare earth elements) have and continue to contribute to the accumulation and elevation levels of radioactive isotopes in environmental media (soil, surface water, and mine tailings). With inadequate monitoring and mitigation, these residues can pose significant long-term ecological risks and cumulative impacts over time (Rotimi *et al*., 2021).

Accurate measurement of ionizing radiation type and intensity is essential for evaluating environmental risks in mine wastelands. These measurements help to identify the dangers these sites pose and provide a basis for improved monitoring and mitigation strategies (Michael, 2020). There are several types of radiation instruments that are used to measure radiation in both field and laboratory settings, namely High Purity Germanium Detector: HPGe (gamma spectrometry), Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), portable Alpha-Beta proportional counter and Thermoluminescent dosimeters)

(Michael, 2020; Alharbi *et al*., 2021). Furthermore, the include risk evaluation standardised models such as Annual Effective Dose (AED) and Excess Lifetime Cancer Risk (ELCR) (ICRP, 2020; Banik *et al*., 2021). However, for clarity and conciseness, comprehensive technical evaluations and dose calculations are elaborated in Chapter 4 and detailed in Annexure B.

2.12 Uptake and retention of elements and radionuclides by flora

For the past four decades, mining operations have unearthed and distributed radionuclides across the environments, and some of those environments include Witwatersrand Basin and Sudbury Basin (Ali *et al*., 2023). These radionuclides move through ecosystems and food chains either by uptake through plant roots or by settling on external plant surfaces. The soil-to-plant transfer (F_v) is one of the key parameters used in environmental assessments to estimate human radiation dose through ingestion pathways, as stated in equation 1 (Thien *et al*., 2020; Van Duong *et al*., 2020).

$$F_v = \frac{activity\ of\ radionuclide\ in\ plant\ (Bqkg{-}1\ dry\ weight)}{Activity\ of\ radionuclide\ in\ soil\ (Bq\ kg{-}1\ dry\ weight)} \qquad 1$$

Airborne radionuclides carried by wind can also settle on leaves, especially in areas with high contamination like mine wastelands, where they accumulate mainly on the waterproof cuticle surface. They enter the food chain when animals feed on the leaves, while gaseous radionuclides such as radon enter through stomata (Ratnayake, 2021; Phuong *et al*., 2023).

Once deposited in soil through precipitation or gravity, radionuclides move from areas of high concentration, such as mine dumps, to nearby residential areas and farmlands via runoff and wind (Ali *et al*., 2023; Sombo *et al*., 2024). Plants take them up at their roots and from there they enter the food chain when consumed by animals and humans. Uptake depends on several factors, including climate, vegetation type, soil pH, exchangeable potassium, the chemical form of the radionuclide, length of exposure, and crop management practices such as irrigation, liming and fertilization (Banik *et al*., 2021). Seasonal and climatic variations also affect their movement in the soil and the rate at which they are transferred to plants (Phuong *et al*., 2023).

2.13 Overarching Policies and regulatory framework governing the environmental management and mining industry

Successful mine wastelands rehabilitation depends on strong regulatory frameworks and consistent enforcement that were enacted to govern mining and the environmental practices altogether. These legal instruments not only govern active mine operations to encompass environmental compliance but also post-mining closure operations and responsibilities. Notably, they support perpetual reduction targets developed to restore degraded mining environments, such as those found in Brakpan.

2.13.1 National Environmental Management Act (NEMA), Act No. 107 of 1998)

In South Africa, NEMA provides the legislative basis for environmental management. It requires that any activity likely to have a significant environmental impact undergo an Environmental Impact Assessment (EIA) and stress that environmental degradations must be avoided, minimised, or remedied (South Africa, 1998; DFFE, SA, 2022; 2023). In the context of mining, NEMA, mining companies need to design and submit an Environmental Management Programme (EMPr) that holds them accountable for any environmental damage incurred during mining activities and post-mining activities. This Act is critical because it helps address the historical mine sites, especially in areas that were severely impacted by the failure of mining companies to hold themselves accountable after mine closure (Mineral Law in Africa, 2022).

2.13.2 Mineral and Petroleum Resources Development Act (MPRDA), Act No. 28 of 2002)

The Act oversees the prospecting, mining and mineral resources in South Africa. It obligates mining rights holders to incorporate their detailed mine closure and rehabilitation plans as part of their application process. Furthermore, the Act requires the submission of financial provisions to ensure that the adequate resources for environmental rehabilitation are available. However, the challenges of oversight and enforcement continue with little impediments (South Africa, 2002; South Africa, 2024a). This Act, for areas such as Brakpan, serves as the important fighting instrument for assessment and long-term credibility of mitigation strategies and financial resources warranty (South Africa, 2024a).

2.13.3 National Environmental Management: Waste Act (NEM: WA), 2008

Part of the policy oversees the management of mine wastes from handling, treating and disposal of wastes with the intention of reducing waste generation, re-using and safety disposal. The mine residues and/or by-products of mine are classified as waste under South African law are placed under the scope of NEM: WA (RSA, 2023a). The Act encourages development and implementation of site-specific remediation strategies, which are applicable in regions such as Brakpan, struggling with minimisation, assessment and management of mine dumps and tailing. Under NEM: WA, both mining companies and government authorities have defined responsibilities in relation to mine waste:

- Mining companies are required to ensure the safe storage, handling, transport, and disposal of residues. They must prevent pollution, undertake ongoing monitoring, implement approved waste management plans, and rehabilitate affected areas. Their responsibility extends to managing environmental impacts during operations as well as post-closure.
- Government authorities: The Department of Forestry, Fisheries and the Environment (DEFF), together with provincial and municipal structures, is responsible for enforcing compliance with the Act. This includes reviewing and issuing waste management licenses, monitoring environmental performance, and overseeing the rehabilitation of derelict or ownerless mine sites. Government also carries obligation to protect surrounding communities from hazardous waste exposure and to address legacy pollution where no accountable operator exists.

This framework ensures accountability and provides a legal basis for addressing legacy mine wastes, including those present in Brakpan.

2.13.4 Mine Health and Safety Act (MHSA), Act No 29 of 1996

Although MHSA mainly focuses on occupational health and safety, it also indirectly implicates environmental management particularly in mitigating hazardous exposure linked to abandon and poorly managed mine sites (RSA, 2023a). In areas such as Brakpan, where communities are residing near old mine wastelands, health risks posed by airborne dust, contaminated water sources and unstable land highlight the important policy consideration in addressing the broader health and environmental impacts of historical mining activities (MHSC, 2023). Therefore, the Act compliments environmental legislations mentioned above by reinforcing the responsibility of mining companies to ensure that mine areas whether active or derelict do not pose unacceptable risks to human health. This aligns with broader national efforts to address the environmental and public health impacts associated with historical mining activities.

2.13.5 One Environmental System (OES) (2014 Amendment)

This interdepartmental framework integrates key environmental and mining legislation (NEMA, MPRDA and NEM: WA) to streamline regulatory processes of mining-related activities. Under this integrated framework, the DMRE serves as the competent authority accountable for issuing environmental authorisations in accordance with NEMA for mining operations, while the Department of Forestry, Fisheries and the Environment (DFFE) hold appealing authority (Bowmans, 2017). While the overall system of OES was to encompass NEMA, MPRDA and NEM: WA regulation, it has been criticised for its inefficiencies and effectiveness when it comes to enforcement of regulations. Many feel that for historically hit hard mining areas such as Brakpan, the OES only worsen the persistence of environmental risks posed by mine wastelands while mining companies are left scot-free.

2.13.6 The Mining Charter and Social and Labour Plans (SLPs)

The Mining Charter and SLPs are some of the key frameworks developed to champion the inclusion of affected parties while encouraging socially responsible mining practices across the environment and communities. This policy is instrumental for community development and stakeholders' involvement in mine rehabilitation efforts (Otto *et al.*, 2022; Maphosa, 2023). However, local communities in Brakpan are still marginalised when it comes to issues of mine rehabilitation and that contributes to broken trust between mining companies, government and local communities. Moreover, this hinders the process of long-term of mine rehabilitation. Notably, current literature highlights the need to integrate local knowledge systems, which can be extracted from local communities and community-driven rehabilitation models (UNEP, 2018). This enhances and enforces the social legitimacy and long-term rehabilitation efforts among local communities and authorities.

2.13.7 Local government frameworks and municipal by-laws

They were both instituted under the Constitution of South Africa in 1999 and are overseen by the Municipal Structures Act (No. 117 of 1998) and Municipal Systems Act (Act No.

32 of 2000). One local government that governs the municipality (e.g., Ekurhuleni Metropolitan Municipality (EMM)) assume office, it is automatically mandated to promote sustainable environmental development and management under the frameworks (EMM, 2024). These frameworks ensure that service delivery within municipality level concerning environmental services, are within reach and feasible. Brakpan area which falls under EMM jurisdiction, the EMM is authorised to impose environmental compliances in Brakpan. However, existing literature highlighted the challenges the EMM faces in relation to overseeing, monitoring and management of mine wastelands. Some of the challenges include technical expertise, financial resources and political endorsement to implement long-term mitigation strategies for mine wastelands (CoE, 2025). Moreover, the municipal by-laws governing land use, waste management and environmental health can either support or impede sustainable reclamation efforts, depending on the degree to which they are implemented and enforced.

2.14 Implications arising from policy review

The policies analysed show that while the regulatory framework covers many areas, it remains fragmented in practices. South Africa has instituted one of the most robust framework tools that helps in addressing the environmental mitigation. However, weakness in the enforcement of these frameworks, particularly in tackling the issues of historical mine wastelands in Brakpan, undermine the efforts of these frameworks (Bowmans, 2017; Mabaso, 2023; EMM, 2024). The critical loopholes are found within the long-term efforts of mine wastelands management. Moreover, limited info has been shared in successfully addressing the issue of mine wastelands in a sustainable way. This highlights the need to revisit and improve current rehabilitation practices through a policy lens, directly supporting this study's objective of evaluating the effectiveness of existing mitigation frameworks (Cole, 2024; GTI, 2025).

2.15 Framework for evaluating sustainable mine wastelands mitigation

Successful and sustainable rehabilitation of mine wastelands particularly regions that are impacted by gold and uranium mining requires a comprehensive assessments framework that encompasses environmental, technical and social outcomes. The effectiveness of mitigation can be assessed through interrelated components such as measurable rehabilitation outcomes, a vigorous monitoring and evaluation system and an active involvement of both local communities and stakeholder engagement.

2.15.1 Key indicators of effective mine site rehabilitation

The effectiveness of rehabilitation efforts should be measured using well-defined scientifically validated indicators that display improvements in environmental health and functionality. Common environmental indicators often include enhanced soil stability, reduced soil erosion, the re-establishments of vegetation cover and biodiversity, and significant reduction in contamination level, particularly heavy metals and NORMs (Winde *et al*., 2022; Miller *et al*., 2023; Singh *et al*., 2023). Heavy metals and NORMs serve as essential indicators and markers in both water bodies sources near mine sites for rehabilitation programmes. With their improvements in their activity concentration levels, they provide better understanding in the direction of rehabilitation process. So, these indicators can be contextualised in alignment with environmental conditions and long-term sustainable environmental restoration and land-use.

2.15.2 Monitoring and evaluation of Mine rehabilitation initiatives

Well-structured monitoring and evaluation systems are vital for assessing the progress of mine rehabilitation projects overtime. It should outline the timing and methodologies for data collection, analytical tools to be used and establish a vigorous benchmark for assessing the advancements towards the perpetual remediation targets (Johnson *et al*., 2023). Integrating adaptive management principles is essential, allowing interventions to be continuously improved based on data-driven awareness and observed outcomes (Brown *et al*., 2023). Likewise, the framework should include risk analysis and contingency planning to proactively address emerging and/or unexpected rehabilitation challenges.

2.15.3 Role of community participation and stakeholder engagement in sustainable mine rehabilitation

Achieving long-term sustainable mitigation requires more than technical solutions. It also depends on meaningful community participation and coherent well-aligned policies. Active involvement of local communities and stakeholders provides SLO, which is essential for the legitimacy of the rehabilitation processes. For example, in Zambia's Copperbelt, community-led monitoring programmes were integrated into rehabilitation projects, which improved transparency and built trust between mining companies and residents (Chipangamate *et al*., 2023). Similarly, in Canada's Sudbury region, successful revegetation and soil restoration projects incorporated community input on land-use priorities, resulting in the recovery of between 80 to 100 hectares and creating spaces that benefited both ecosystems and residents (Smith *et al*., 2023). In Australia, participatory approaches in mine closure planning have demonstrated how integrating traditional ecological knowledge from indigenous communities not only enhanced restoration outcomes but also secured long-term stewardship of rehabilitated land (Nguyen *et al*., 2023). These examples highlight that open communication, inclusive decision-making and integration of local knowledge significantly enhance the sustainability and socio-economic benefits of rehabilitation. For Brakpan, adopting similar participatory frameworks can ensure that restoration strategies are socially acceptable, economically beneficial and ecologically viable.

2.16 Challenges to effective implementation of mitigation strategies

Although there is increasing interest in addressing historical environmental injustices that were brought by mining operations such as mine wastelands and to achieve sustainable development through rehabilitation, the implementation of mitigation strategies continues to face several challenges from practical, technical and socio-economic aspects (LRS, 2023). These challenges slow down progress in achieving long-term environmental restoration and reducing the impacts of mine wastelands. This is particularly true in South Africa, where about 6000 abandoned and derelict mines still need rehabilitation (DMRE, 2023; 2024).

2.16.1 Limitations of financial provisions, resources and socio-economic aspects in effective mitigation

One of the main barriers is financial provisions in implementing and maintaining effective mitigation measures. Many legacy mine sites do not have rightful owners and designed funds for rehabilitation, especially those abandoned and derelict mines prior to the enforcement of modern environmental policies and regulations. These abandoned and derelict mine wastelands in South Africa (e.g., Mintails Mining area, Witbank Coalfields) led to the shortfall in available funds for rehabilitation and now falls under the State's responsibilities. Inadequate financial resources can only sustain short-term fixes rather than long-term sustainable interventions (WRC, 2020; Azinheira *et al*., 2023; LRS; 2023). Furthermore, some of these mine wastelands are in proximity to human settlements (e.g. Durban Roodepoort Deep Mine Dumps (DRDMD), Vlakfontein Mine Dump and

Ribinson Dam Tailings) and investment in research and innovation that could help in resolving and optimising cost-effective rehabilitation are limited.

2.16.2 Technical limitations and environmental complexities

Mine wastelands such as gold and uranium tailings (e.g., DRDMD) often present extreme radiological hazards, chemical toxicity and physical instability to the environment and neighbouring communities (Mhlongo *et al.*, 2020; OALA, 2021; Baloyi *et al.*, 2024). These conditions further make it difficult to apply conventional remediation methods effectively such as revegetation, soil modifications and passive AMD treatment and need integrated, multidisciplinary resolutions (Peco *et al.*, 2021; Rathnayaka *et al.*, 2023). Additionally, a lack of comprehensive site profiling and long-term monitoring overshadow the accuracy of risk assessment and custom-made remediation planning.

2.16.3 Regulatory and institutional overlaps and coordination challenges

Poor coordination and weak enforcement among regulatory agencies such as National Nuclear Regulatory (NNR) often slow down the progress and effectiveness of mine rehabilitation in South Africa. Inconsistent and overlapping mining laws and environmental policies create gaps that some mining companies and other interested groups can exploit (Du Plessis *et al.*, 2023; Kuipa *et al.*, 2024). These regulatory issues also discourage private-sector involvement in post-mining remediation efforts, largely because of uncertainty around compliance requirements and long-term commitments.

2.16.4 Inadequate stakeholder integration in rehabilitation processes

When local communities and directly affected stakeholders are marginalised from decision-making processes, it often results in resistance, diminished trust and potential conflicts. Too often, community engagement is often treated as a formality rather than substantive and inclusive process, limiting the relevance and social acceptance of selected rehabilitation strategies (Mensah, *et al.*, 2023; Kaonda *et al.*, 2024). In the absence of SLO to operate, such efforts are unlikely to gain legitimacy and long-term support required to achieve sustainable success (Chipangamate *et al.*, 2023).

2.17 Identified knowledge gaps and research opportunities

Despite ongoing initiatives of mitigating the environmental impacts of mine wastelands, implementation remains a key challenging aspect owing to poor coordination among stakeholders, including insufficient funding, weakness in institutional coordination, inadequate data availability and fragmented enforcement of regulatory frameworks. While many studies focus mostly on technical and environmental parts of rehabilitation, such as AMD treatment and chemical stabilisation, they often overlook broader economic and governance factors that also matter for lasting results. There is still little research that combines environmental assessments with community views and efforts to rebuild local livelihoods (Du Plessis *et al*., 2023; Kaonda *et al*., 2024; Yu *et al*., 2024).

Brakpan, located within the Witwatersrand Basin and historically mined for gold and uranium, provides an important opportunity to fill critical gaps in mine wastelands research by offering a case study that integrates multiple dimensions of assessment. While environmental issues such as radioactive residue, soil contamination and groundwater pollution are well-documented, few studies have combined field-based environmental measurements with community perceptions and institutional capacity analysis to evaluate long-term management options (Bowmans, 2017; Mkandawire, 2019; CoE, 2025). By addressing these aspects together, the Brakpan case can contribute a more comprehensive understanding of the socio-environmental dynamics of mine wastelands and inform sustainable rehabilitation strategies in South Africa and beyond.

This research addresses these gaps through four integrated objectives, namely:

- establishing the extent of environmental damage on soil and water caused by mine wastelands;
- examining the community perception on how mine wastelands impact their quality of life;
- assessing the effectiveness of measures that are being implemented to address the impacts of mine wastelands; and
- how surrounding communities can benefit from mine wastelands and reclamation and develop methods of assessing and managing mine wastelands based on data obtained in the study.

Through this multi-dimensional approach, the research not only contribute to empirical knowledge of mine wastelands but also lays sustainable and inclusive rehabilitation policies and practices.

2.17.1 Research significance and expected contributions

The significance of this research lies in its ability to address the complex legacy of mine wastelands in Brakpan by combining environmental assessments, community perceptions and management practices into a single, integrated study. Unlike previous work that focused on either contamination levels or socio-economic effects in isolation (Akinola, 2018; Ugo, 2019; Nkosi *et al*., 2023), this study generates site-specific evidence while also capturing the lived realities of affected communities. The findings are expected to inform sustainable rehabilitation policies, strengthen institutional responses and provide practical strategies that can be adapted to similar post-mining landscapes. The expected contributions of this research are as follows:

- New data and site-specific evidence - detailing the environmental degradation patterns specific to Brakpan's mine wastelands.
- Community centred viewpoints – offering an understanding of local communities' lived experiences, perception and socio-environmental concerns associated with mine wastelands.
- Assessments of current mitigation measures to identify gaps and areas for improvements in existing mitigation strategies.
- Framework for sustainable reclamation to promote social inclusive and ecological rehabilitation approaches.
- An integrated assessment guidelines to inform future mine rehabilitation initiative in South African mine wastelands and similar post-mining landscapes.

2.17.2 Literature review synthesis

This review explored the layered challenges of mine wastelands, especially those arising from legacy gold and uranium mining in South Africa, with Brakpan serving as a case study. It began by analysing the environmental, social and health impacts linked to mine residue deposits and AMD, as well as highlighting the pervasive contamination of soil and water systems by heavy metals and NORMs. The review also assessed core legislative and policy frameworks such as the NEM: WA of 2008 to position mine wastelands governance within South African broader environmental regulatory guidelines. However, the existence of comprehensive legal tools and poor enforcement coordination among stakeholders were identified as persistent challenges for effective mine wastelands rehabilitations.

Next, the review looks at biological, chemical and physical mitigation methods applied in the rehabilitation of mining-impacted areas, highlighting their applicability and limitations in addressing gold and uranium mine residue. Comparative global case studies from Canada (e.g., Sudbury Basin), Australia (e.g., Mount Morgan and Broke Hill) and South Africa (e.g., Witwatersrand Basin) were studied to display the effectiveness of integrated remediation approaches that combine stakeholder engagement, passive treatment systems and revegetation. Furthermore, the review discussed evaluation criteria for robust sustainable mitigation involving monitoring and evaluation guidelines and stakeholder participation, and creation of socio-economic benefits. The chapter ended by pointing out the significant knowledge gaps particularly lack of integrated community-driven and site-specific assessments. These gaps underscore the justification for this study focus on Brakpan area mine wasteland. It provides a foundation for the study objectives and methods, while highlighting the practical and academic contributions required for better long-term management of mine wastelands.

Figure 2.1 presents a framework linking environmental, technical and social aspects of mine rehabilitation that will evaluate the effectiveness of mine wastelands rehabilitation initiatives.

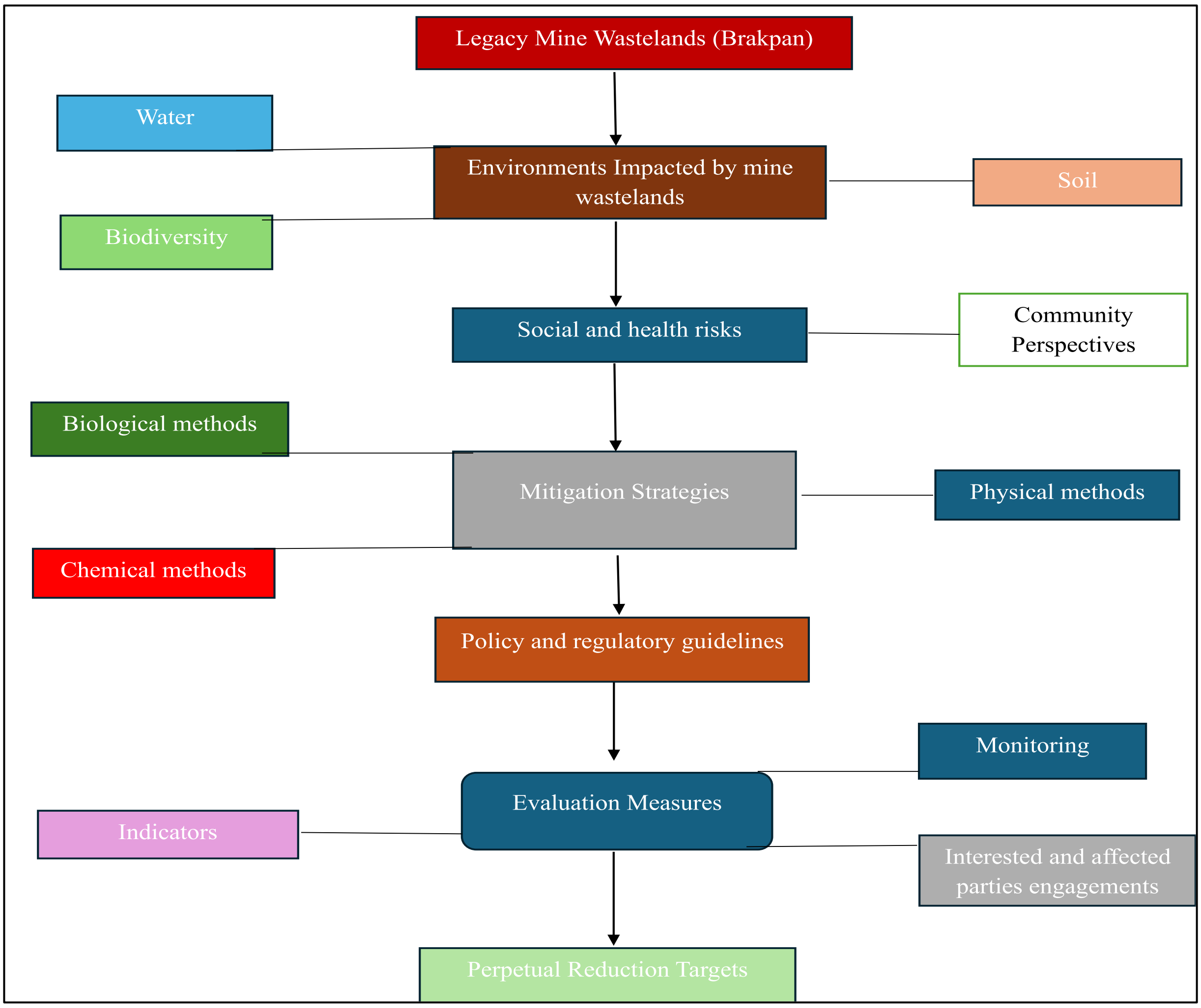

Figure 2.1: Conceptual framework for evaluating mitigation strategies of mine wastelands

Chapter 3: Research design and Methodology

3.1 Introduction

This chapter outlines the research design, describes the study area and details the data collection techniques (including both qualitative and quantitative approaches). It also covers laboratory procedures, analytical methods and the ethical considerations applied in the study.

3.2 Study design

This study adopted a convergent mixed-methods research design to assess the impacts and management of mine wastelands in Brakpan (Kwa-Thema). The study combined qualitative and quantitative approaches because it involved both environmental measurements and community perceptions regarding the socio-economic and health impacts associated with mine wastelands. Quantitative methods were applied in soil and water analysis, erosion modelling and radiometric assessment, while qualitative methods were used to understand community experiences and concerns regarding the mine wastelands.

The case study design enabled an in-depth, site-specific investigation of the Brakpan (Kwa-Thema) mine wastelands, a site with a long-standing history of gold and uranium mining. This design allowed the researcher to unpack complex environmental challenges, examine the efficacy /effectiveness of existing policy interventions and explore long-term mitigation strategies through a combination of field-based data collection and community engagement.

The qualitative aspects include open-ended questionnaire components, images and maps taken during field surveys, and document reviews to capture local community perspectives and understand the regulatory frameworks surrounding the rehabilitation of mine wastelands. Quantitative dimensions encompassed field sampling, laboratory analyses using instruments such as ICP-MS and gamma spectrometry, as well as statistical risk modelling techniques, including AED, ELCR and RUSLE.

By integrating both data types drawn from the community responses, environmental sampling and statistical models, the study initiates a comprehensive analytical approach to evaluate the range in which the existing mitigation strategies contribute towards achieving the objectives of perpetual reduction of mine wastelands in Brakpan, with the broader aim of reducing environmental and human health risks associated with these areas.

3.3 Study area

The study was conducted in Brakpan, which falls under the Ekurhuleni Metropolitan Municipality (EMM), South Africa, situated at 26°19′41.67″ S, 28°25′02.41″ E and 1616 metres (5300 feet) elevation above the sea level, in the south part of Kempton Park between Springs and Benoni as shown in Figure 3.1. Brakpan has a temperate climate with warm, cool and wet summers and dry winters. The total area of Brakpan is 182.81 km^2 (70.58 sq. mi). The population is diverse and compromises major racial groups as classified in South Africa, namely Black African, White, Coloured, Indian and Asian (Stats-SA, 2018; 2024). These racial categories differ from ethnic group classifications, which are typically based on language, culture, and heritage.

Brakpan was named after the small pan on a farm called Weltevreden, which is filled with brackish water, and it is famously known as a uranium and gold mining town in Gauteng owing to the discovery of gold and coal in 1888 and 1905. The town has approximately 305 692 population, which includes Kwa-Thema with a total population of 103 727 and emerging as an urban hub in sub-Saharan Africa (WPR, 2025). Its biome is grassland, typically of the highveld. The soils vary from clay to sandy, frequently predisposed by urban development and mining (Khumalo *et al*., 2024).

Brakpan presents a distinctive urban landscape characterised by the coexistence of diverse industries and extensive mine wastelands. The town sustains a broad industrial base, ranging from extractive mining operations to construction enterprises that support significant economic activities in the Ekurhuleni region, particularly in mining, retail, transportation and tourism. Consequently, the Brakpan area makes a substantial contribution to the GDP of the Ekurhuleni region (Stats-SA, 2018; CoE, 2023).

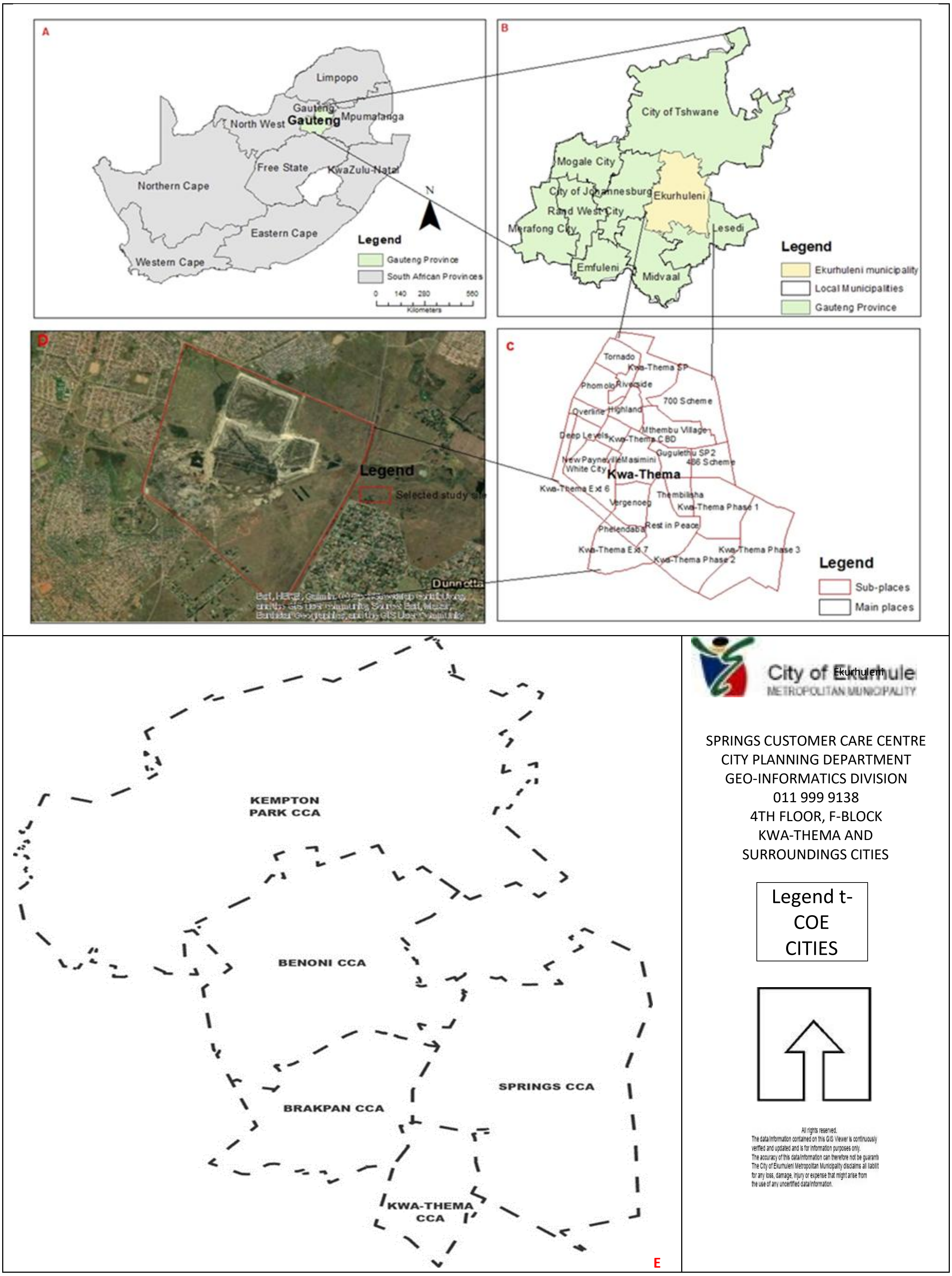

Figure 3.1: Brakpan map (Tailing mine).

3.4 Data collection approaches

This study which covers the Brakpan mine wastelands was conducted from April 2023 to May 2025. The methodology outlines each phase of the research including sampling protocols, laboratory sample preparation and analytical procedures.

3.4.1 Qualitative data collection

For qualitative data collection, open-ended questionnaire components, secondary data and direct field observations were used. Structured (closed-ended) questionnaire components were used as part of the quantitative data collection, as they allow responses to be standardised and statistically analysed.

Structured questionnaires were designed to evaluate the impact of mine wastelands on nearby communities, both socioeconomically and environmentally. The questionnaires captured information on the loss of economic benefits, public health concerns, land-use restrictions and access to clean air and water, reflecting the lived experiences of communities in Brakpan. Secondary data from existing literature further supported the analysis, particularly studies that emphasised community engagement in rehabilitation processes and risk management (Otto *et al*., 2022; Pretorius *et al*., 2023). Field observations focused on documenting visible environmental conditions, including soil erosion features (e.g. rills and gullies), vegetation cover, dust dispersion, proximity of mine waste to residential areas and signs of water contamination. These observations were aligned with the study objectives to assess environmental degradation and its potential impact on surrounding communities.

Field observations, supplemented by images, maps and descriptive statistics, were applied to assess the environmental setting over time and to outline patterns of environmental change. The integration of mixed-methods enhanced the study’s ability to triangulate findings and present both objective and perception-based evidence of mine wastelands' impacts.

3.4.1.1 Structured questionnaires

Structured questionnaires are documents consisting of well-prepared questions intended to collect information that can be analysed by the researcher. In mixed-methods research, questionnaires may consist of both closed-ended (quantitative) and open-ended (qualitative) questions, depending on the research design (Creswell *et al*., 2018).

This study used a questionnaire consisting of both closed-ended and open-ended questions (Annexure C). Closed-ended questions allow participants to choose predefined responses and are easier to administer (Mashuri *et al*., 2022; SmartSurvey, 2022). Closed-ended questions were used to generate quantitative data that could be statistically analysed, while open-ended questions were included to capture qualitative insights and provide deeper understanding of community perceptions. All the questions were asked in simple and broad terms, and participants were asked to select the option that best matched their knowledge and experience of living next to mine wastelands. The questionnaire was shared with target participants in Brakpan (Kwa-Thema) through face-to-face interaction.

A total of 90 participants were purposively selected based on their proximity to the mine wastelands of Brakpan. The inclusion criterion was that participants had to be 18 years old and above, and live within the mine wastelands of Brakpan at a distance of 0 km to 15 km.

The sample size of 90 participants was determined to ensure sufficient representation of the study population and to allow for meaningful statistical analysis. This sample size is consistent with similar environmental perception studies conducted in mining-affected communities, where sample sizes typically range between 50 and 150 respondents (Seloa *et al*., 2022; Taiwo *et al*., 2024). It was considered adequate to capture variability in community responses while remaining feasible within the study constraints. Since the Brakpan group shared similar backgrounds and experiences, a total of 90 participants was sufficient to capture the main perspectives while maintaining sufficient variation in responses.

The questionnaire was administered using a researcher-assisted approach, where the researcher guided participants through the questions and recorded responses in their presence. All questionnaires distributed were identical. This approach was adopted to minimise misinterpretation of questions and to ensure consistency, particularly where participants required clarification.

The participants were then grouped according to their distance from the mine wastelands and their willingness to participate in the study. The intended distribution included 30 participants residing within 0-5 km, 30 within 5-10 km, and 30 within 10-15 km. However, the final distribution was 35, 30 and 25 participants respectively, indicating a minor deviation from the planned sampling distribution. This limitation is acknowledged as a shortcoming in the study design. Each participant was individually engaged by the researcher, who explained the purpose of the study and encouraged participants to ask questions for clarity and informed participation. The questionnaires were then collected for collation and analysis to provide an understanding of participants' perceptions and experiences of living next to mine wastelands.

3.4.1.2 Secondary data acquisition

In this study, both hard and soft copies of key administrative and regulatory documents relevant to the Brakpan mine wasteland were accessed. These included both government and municipal annual reports, environmental impact assessments reports, mine rehabilitation and closure reports, and corporate compliance documents from mining companies and regulatory agencies. The provided materials offered information on the history of the wasteland, environmental contamination, rehabilitation efforts, and associated risks, enabling the study to establish a background context, verify compliance processes and supplement primary qualitative data. As noted by Morgan (2022), documents can reveal insights beyond their explicit content, including their style, scope and emphasis, which helped to contextualise findings within local governance and community engagement frameworks. Administrative materials such as permission letters were considered ethical documentation but were not included as data sources for the methodology.

3.5 Maps and images acquisition, and erosion modelling

Images were acquired during the field survey using a mobile phone camera (12 Megapixel) to capture site-specific features such as soil erosion scars, vegetation cover and waterlogged areas. Additionally, satellite imagery was obtained from Google Earth Pro (high-resolution, 0.5-1 m spatial resolution) to analyse cumulative land-use and land-cover changes over time in Brakpan. Together, these data sets provided both ground-based observations and synoptic views, offering a cost-effective and non-destructive approach to environmental monitoring. Similar approaches have been used in mine wasteland studies to evaluate vegetation recovery, soil erosion patterns and land degradation (Xulu *et al*., 2021; O'Donnell *et al*., 2024). In this study, the acquired images were integrated into the RUSLE model to estimate soil loss rates, with comparative analysis between disturbed and undisturbed sites in the Brakpan mine wasteland. This integration allowed for the detection of visible land cover changes while quantitatively estimating soil erosion, which is difficult to determine manually.

3.6 RUSLE modelling for soil loss estimation

RUSLE was applied to estimate the annual soil loss rate in the study area. This model was chosen because it provides a consistent approach to quantifying erosion risk in disturbed areas (Getachew *et al*., 2021). It uses five empirical parameters, namely rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and support practices (P) to calculate potential erosion rates. The model is expressed as:

$$A = R \times K \times LS \times C \times P \qquad 2$$

Whereby

A - annual soil loss (tons ha^{-1} yr^{-1})

R - rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1})

K - soil erodibility factor (tons. ha. h. ha^{-1} MJ^{-1} mm^{-1})

LS - slope length-steepness factor (dimensionless)

C - cover-management factor (dimensionless)

P - support practice factor (dimensionless)

3.6.1 Estimation parameters

The estimation process was guided by field surveys, images, and maps collected during the sampling period. Each parameter was determined as follows:

Rainfall Erosivity Factor (R) was calculated using monthly rainfall data obtained from the National Aeronautics and Space Administration (NASA) POWER database for Brakpan (latitude -26.320, longitude 28.461) for the period of 2018-2023 (Knight *et al*., 2024; NASA, 2024; DALRD, SA 2024; 2025**)**. The R value was estimated at 401.5 MJ.mm/ha. h. yr using the Arnoldus (1980) method, suitable for regions with limited high-intensity rainfall data:

$$R = \sum_{1}^{12}(1.735 \times 10\hat{}(1.5\log_{10}\left(\frac{P_i^{2}}{P}\right) - 0.08188)) \qquad 3$$

Where p_i is the monthly rainfall (mm) and p is the annual rainfall (mm)

This approach is widely recommended for South African conditions. The Soil Erodibility Factor (K) was quantified based on soil texture assessments conducted through field observations and manual soil texturing. A K value of 0.25 t ha h ha^{-1} MJ^{-1} mm^{-1} was assigned based on the observed sandy-loam texture and low organic matter content, consistent with USDA Handbook 703 (Renard *et al*., 1997). The homogeneous nature of the mine waste material supports a representative single value of K.

The Slope Length-Steepness Factor (LS) represents the effect of topography on soil erosion. For this study, the LS factor was set at a value of 3.0.

This value is consistent with established RUSLE reference values for a slope length (L) of 10 m and slope steepness of 12% (Renard *et al*., 1997). As shown in Table 3.1, adapted from Ramirez *et al*. (2023), an LS factor of 3.0 is a standard and conservative estimate for slopes between 10% and 15%, aligning perfectly with the study site's conditions.

Table 3.1: LS factor values different slopes adopted from Ramirez *et al*., (2023).

Slope (%)	**LS Factor (Approximate)**
0.5	0.03 – 0.1
1	0.1 – 0.2
2	0.2 – 0.5
5	0.5 – 1.5
10	1.5 – 3.0
15	3.0 – 5.0
20	5.0 – 7.0
30	7.0 – 12.0
40	12 – 20.0

Note: These fixed values were chosen to maintain consistency with previous erosion studies and to provide a conservative estimate appropriate for slopes between 10% and 15%. The focus of this is on assessing soil erosion related to land cover, vegetation loss and management practices, rather than detailed topographic parameterisation.

The Cover Management factor (C) was quantified at a value of 0.5 based on both field observations and satellite imagery obtained from Google Earth Pro. Estimates of the relative proportion of the bare soil and vegetative cover were made across several representative sampling units within the site. Results indicated that bare soil accounted for more than 50% of the surface area which aligns with a C value of 0.5 as classified for sparsely vegetated, disturbed lands (Bussiere *et al*., 2021; Bredenhand *et al*., 2023).

Support Practice Factor (P) was determined through field observations and the site investigated presented limited erosion control measures in place. Therefore, the P value was set at 0.5 indicating a site with limited support for erosion control practices (Asare *et al*., 2021; Ramirez *et al*., 2023). All the calculations were performed manually using Microsoft Excel. The specific parameter values and estimated soil loss rates are presented in Chapter 4.

3.7 Inferential statistics

To test the study's hypotheses, a Chi-square test was used to check the pattern of responses from participants. This test helped to determine if there was a meaningful link between the ways people answered. A p-value of less than 0.05 ($p<0.05$) was used to decide if the results were statistically significant.

Spearman's rank correlation was also used to examine the relationship between key variables as the data did not follow a normal distribution. The test helped to check how strongly the variables were linked and in which direction. Just like with the Chi-square test, results were seen as important (statistically significant) if the p-value was less than 0.05 ($p<0.05$) and not important (statistically insignificant) if the p-value was greater than 0.05 ($p>0.05$). Checking the p-values was useful for testing the null hypothesis. In this study, it was helpful to determine whether the community's perceptions, particularly regarding their proximity to the mine wastelands, occurred by chance or reflected a genuine pattern (Abdul-Motaal, 2023).

Notably, Spearman's correlation was preferred over Pearson's correlation owing to the non-parametric nature of the data. The null hypothesis was rejected when $p < 0.05$, suggesting a significant correlation. Conversely, if p exceeded 0.05, the null hypothesis was retained, implying no substantive link between variables (Yu *et al*., 2022). A two-tailed test was employed rather than a one-tailed alternative to account for potential effects in both positive and negative directions. This method is more conservative and aligns with standard practice in social science research (Mida, 2024).

3.8 Quantitative methodologies (survey, sample collection and experiments)

Soil and water samples were collected for analysis of heavy metals and NORMs in the laboratory. Sampling locations were determined using a computer-generated random number system applied to a GIS-based grid overlay of the study area. This randomised grid approach ensured unbiased site selection, adequate spatial coverage of both the mine wastelands and nearby communities, allowing all sites an equal chance of selection.

3.8.1 Sample collection

3.8.1.1 Soil

A simple sampling strategy aided by Geographic Information System (GIS) tools was applied to sampling sites. A grid was overlaid onto recent satellite imagery of the study area, with each grid cell assigned a unique identifier. Sampling locations were then randomly selected using a computer-generated random number system, so that all sites had an equal chance of being selected. This procedure was designed to enhance spatial coverage and minimise potential systematic errors during data collection. This method enabled an unbiased spatial representation of soil conditions in and around the Brakpan mine wastelands. Soil samples were dug out using a spade and stored in clean one (1)-litre plastic bottles. Sampling points were randomly distributed across the site (see Figure 3.2). To avoid bias from disturbed surface soil, the top 15 centimetres (15 cm) were removed before sampling. This provided a more accurate measure of subsurface contamination by heavy metals and radionuclides (Grinand *et al*., 2019; Nwaila *et al*., 2021). About 500 g to 1 kg of soil sample was collected from each selected sampling point. The Global Positioning System (GPS) was used to capture the coordinates of where individual soil samples were acquired. Specifically, sampling was conducted at the locations listed in Table 3.2, with all samples collected once off during November 2024. All the samples were labelled using BKS, L, and differentiated by subscripts, i.e., BKS1, BKS2, L1, L2, except the control soil sample named BP1. BKS stands for Brakpan samples and L stands for samples that were collected 3-5 km from the Mine wasteland (see Figure 3.3 and Figure 3.4). The collected soil samples were transported to the laboratory for analysis.

Figure 3.2: Site collection of soil samples illustration.

Figure 3.3: Image of Brakpan (Kwa-Thema) indicating the GPS coordinates of locations where additional soil samples were collected (Google maps, 2024).

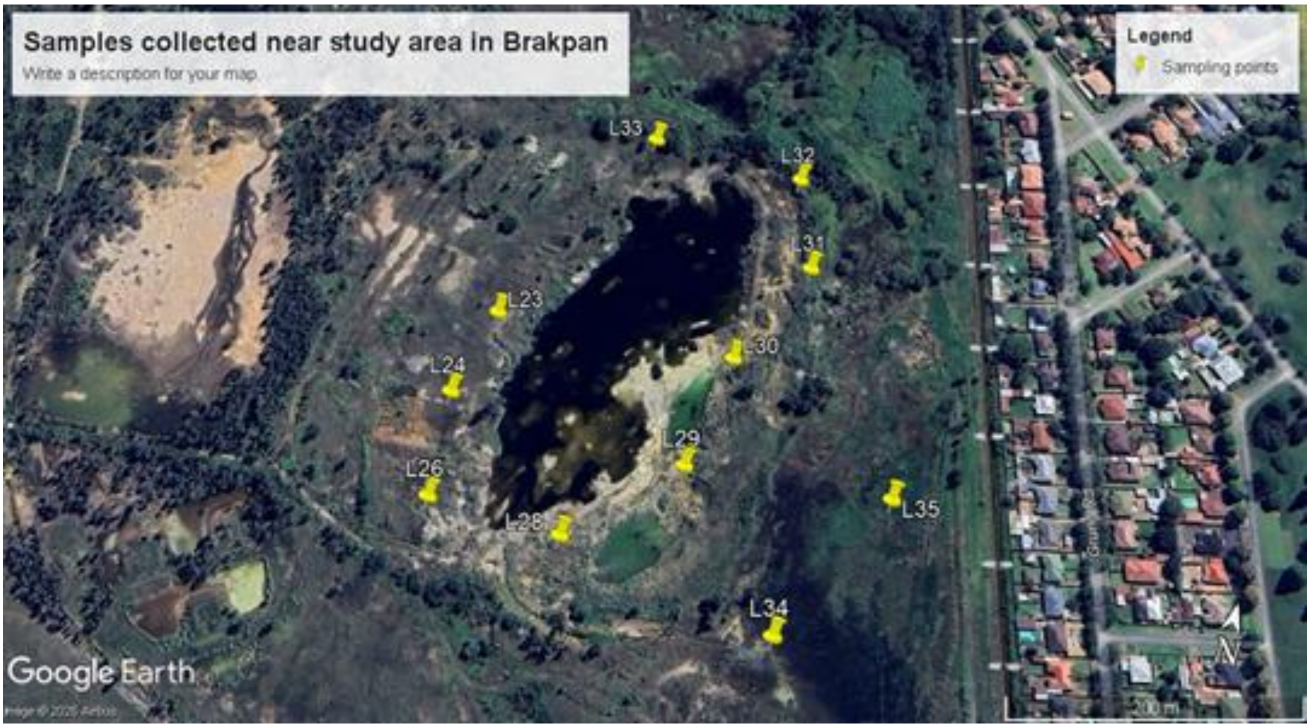

Figure 3.4: Image of Brakpan (Kwa-Thema) indicating the GPS coordinates of locations where additional soil samples were collected (Google maps, 2024).

Table 3.2: The GPS coordinates for collected soil samples from mine wasteland.

Sampling point	Location		Description of sampling points
	Latitude	Longitude	
BP1(Control Sample)	-25.735206	28.455628	Located at Mamelodi East Ext 18 about 50 km away from the study area
BKS3	-26.323781	28.416044	Located at the near tip of the mine wastelands near Kwa-Thema phase 2, along the road that connects to Tonk Meter Rd
BKS4	-26.328019	28.416531	
BKS5	-26.322144	28.410856	
BKS6	-26.323783	28.416028	
BKS7	-26.328367	28.416058	
BKS8	-26.420469	28.53155	Located at the near tip of the mine wasteland near Langaville township along the Vlakfotein road via (Masibeni street)
BKS11	-26.277425	28.428542	
BKS12	-26.323781	28.416044	
BKS13	-26.322156	28.410847	
BKS14	-26.307625	28.391417	
BKS16	-26.326011	28.40565	

Sampling point	Location		Description of sampling points
	Latitude	Longitude	
BKS9	-26.420461	28.531828	Located at the near tip back corner of the mine wasteland near Langaville township along the Vlakfotein road
BKS10	-26.314772	28.4719	
BKS20	-26.336494	28.428542	
BKS15	-26.307628	28.428511	Located at the middle or near the middle of the mine wasteland
BKS17P	-26.331033	28.407931	
BKS18	-26.334769	28.399094	Located at the front part of the mine wasteland along the Tonk Meter Rd of Sharon Park and Dunnottar communities
BKS19	-26.330247	28.330258	
BKS21	-26.334442	28.411147	
BKS28	-26.326139	28.440589	Located at the tip point of Kwa-Thema phase 2, away from the mine wasteland
L22	-26.272858	28.435417	Located about 3-5 km from Brakpan (Kwa-Thema) mine wasteland along the Tonk Meter Rd
L23	-26.273336	28.435164	
L24	-26.273978	28.435031	
L25	-26.274589	28.4341	
L26	-26.274686	28.435147	
L28	-26.274664	28.436144	
L29	-26.274067	28.436858	
L30	-26.273258	28.437	
L31	-26.272489	28.437369	
L32	-26.271706	28.437156	
L33	-26.271739	28.436461	
L34	-26.274906	28.437761	
L35	-26.273792	28.438433	

3.8.1.2 Water

Surface water samples were collected from open surface water bodies (including stagnant ponds and drainage pathways) using 330 mL plastic bottles which had been pre-rinsed with 10% ultrapure nitric acid (HNO_3). A random sampling approach was employed by dividing the sampling area into several segments and then selecting sampling sites within these segments using a random number generator to ensure unbiased coverage in and around mine wasteland. Each sampling bottle was dipped to a depth of approximately 5 cm below the water surface and rinsed twice with water from the sampling location before approximately 150 mL of water was collected. Then 2 mL of ultrapure concentrated Nitric acid (NHO_3, 65%) was added once each water sample was collected to lower the pH and preserve both radionuclides and heavy metals. All samples were labelled using the BKW code and differentiated by numbers (i.e., BKW1, BKW2, BKW3) (Figure 3.5), except for the control water sample named BPW1 which was collected approximately 50 km away from the mine wasteland near the former sand mine site (Figure 3.6). GPS was used to record where each water sample was collected as shown in Table 3.3. The collected water and soil samples were transported to the laboratory for analysis.

Figure 3.5: Image of Brakpan (Kwa-Thema) showing locations where water was collected (Google maps, 2024).

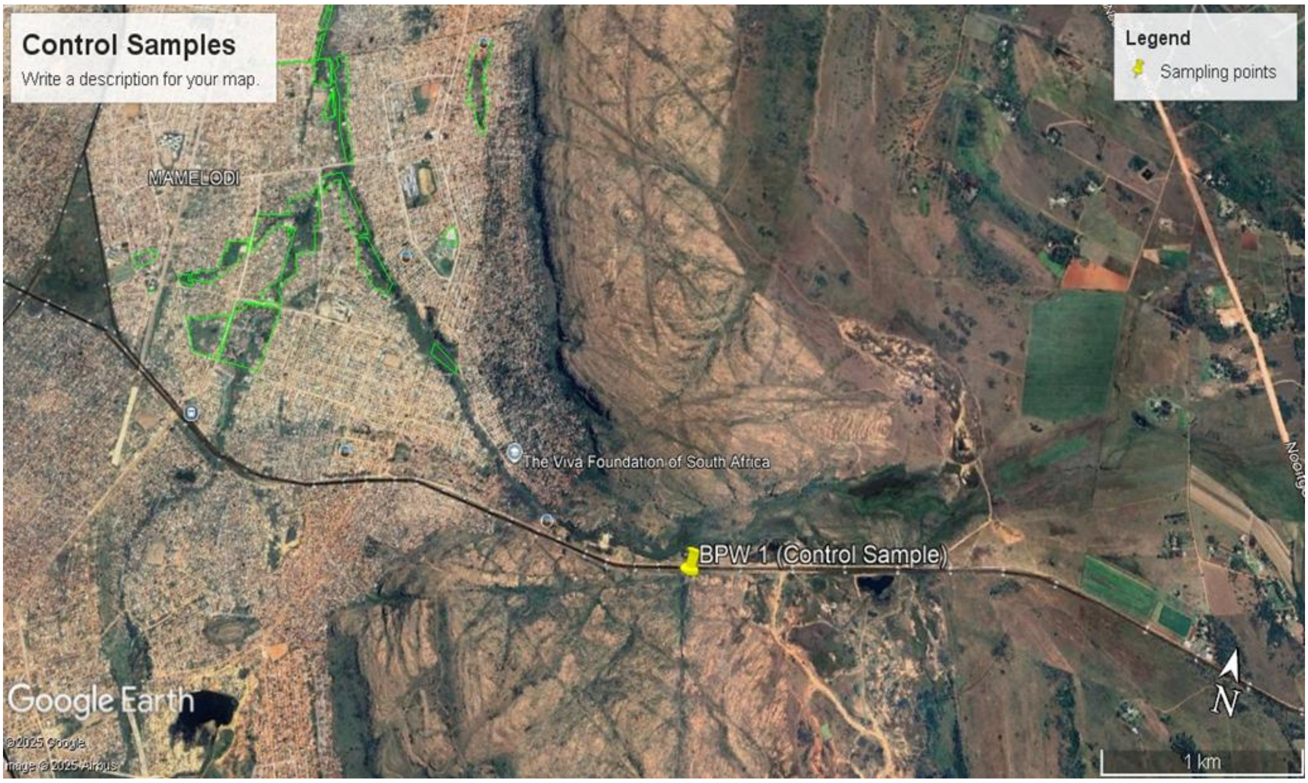

Figure 3.6: Image of Mamelodi-East Ext 18 showing location where both control soil and water samples were collected (Google map, 2024).

Table 3.3: The GPS coordinates for collected water samples from within the mine wasteland

Sampling point	Location		Description of sampling points
	Latitude	Longitude	
BPW1(Control sample)	-25.735219	28.455642	Located at Mamelodi East Ext 18 about 50 km away from the study area
BKW2	-26.336828	28.409414	Located at the back of mine wasteland near Langaville and Dunnottar communities
BKW4	-26.336411	28.408569	
BKW5	-26.331906	28.417842	Located at the front part of the mine wasteland along the Tonk Meter Rd of Sharon Park and Dunnottar communities
BKW6	-26.332628	28.406842	

3.9 Soil and water samples preparation for analysis

ICP-MS and Gamma Spectroscopy instruments were used to measure the presence and concentrations of heavy metals and radionuclides respectively, under laboratory environments. Sample preparation was conducted following both International Standard Organization (ISO) 11466: 1995 and ISO 5667-3:2018 guidelines for sample handling, digestion and extraction to ensure consistent and accurate analysis of contaminants.

3.9.1 Soil samples preparation for ICP-MS heavy metal analysis

Aqua regia was used to digest soil samples for the extraction of metal contaminants. For each sample, approximately 1 g of soil was mixed with 9 mL of diluted hydrochloric acid (HCL) and 3 mL of diluted nitric acid (HNO_3). These acids act together to oxidize the matrix and preserve the target metal solutions. The mixtures were heated in a microwave digestion system to promote thorough dissolution of the solids. After cooling, the digested samples were filtered through 25 mm nylon syringe filters with a 0.45 µm pore size to remove any remaining particulates before analysis. The filtration process was followed by dilution of the sample to 100 mL in de-ionized water, with subsequent ICP-MS analysis of an aliquot.

3.9.2 Water sample analysis for heavy metals

Acid-cleaned containers were used to collect water samples for analysis of heavy metals. Each 50 mL of water sample was filtered through 0.45 µm membrane, 3 mL of diluted hydrochloric acid (HCL, 10%) and 2 mL of concentrated nitric acid (HNO3, 65%) were added to preserve the samples and prepare them for digestion. The aqua regia digestion method was used for appropriate digestion of water samples and were filtered through 25 mm nylon syringe filters with 0.45-micron pore size, non-sterile. After filtration, the samples were diluted to a final volume of 100 mL with de-ionized water, ready for ICP-MS analysis as an aliquot.

3.9.3 Quantification of heavy metals using ICP-MS

Following sample preparation, ICP-MS was used to quantify heavy metals in both soil and water samples. The analysis was performed with an auto-sampler interfaced with the ICP-MS system, which was managed through Syngistix software. This setup ensured consistent sample introduction, automated instrument calibration and continuous quality control throughout the analytical process.

The instrument was operated in Total Quant mode, using the optimised parameters listed in Table 3.4, which enabled the simultaneous quantification of multiple trace elements across a wide range. External calibration standards covering the expected analyte concentrations were utilised. Moreover, blank solution and quality control standards were introduced periodically to validate the instrument's precision and accuracy.

The Syngistix software streamlined the workflow by overseeing method setup, auto-sampler coordination, real-time data collection and post-acquisition data processing. This ensured accurate determination of elemental concentrations for each sample. Target heavy metals for analysis included heavy metals such as Pb, As, Cd, Zn, Cu, Cr, Ni and U, among others, depending on the sample matrix. The adopted procedure is consistent with established protocols commonly used in environmental pollution studies (Akoto *et al*., 2019; Raji *et al*., 2023).

Table 3.4: ICP-MS, Perkin Elmer (2023), NexION 2000C optimised operating parameters.

Parameter	**Value**
Nebulizer	Glass concentric
Spray Chamber	glass cyclonic
Cones (Sampler, Skimmer, super-skimmer)	Nickel
Sample Uptake Rate	300 µL/min
Auxiliary gas flow	1.2 L/min
Plasma gas flow	18.0 L/min
Nebulizer Gas Flow	0.98 L/min (Optimized for 2% CeO/Ce)
RF Power	1600W
Sweeps/Reading	200
Cell Gas	Argon
Readings/Replicate	10
Detector Type	Dual mode
Replicates per sample	2
Internal Standard	$^{107}Ag/^{109}Ag$ using a 25 µg/L solution
Mode / Universal Cell Technology™	Isotope Ratio/Collision mode
Total integration time	3.4s

The concentration of selected heavy metals and naturally occurring radionuclides, including Pb, As, Cd, U, Cr, Cu, and others in both soil and water samples was quantified after acid digestion. The resulting instrument readings (µg/L) were converted to dry-weight concentrations (µg/g) using equation (4), which standardises results based on sample mass, solid content and dilution factor (ICRP, 2020; PerkinElmer, 2023).

$$\text{Concentration (dry weight)} \left(\frac{\mu g}{g}\right) = C X \frac{V_f}{W x S} X \frac{\text{DF}}{1000} \quad (4)$$

Whereby:

C= Instrument reading in µg/L (the mean from all repeat integrations).

V_f= Volume of final digestion (mL)

W= Preliminary volume of aliquot (g)

S= % solids/100

DF= Factor of Dilution

This formula ensures precise conversion of concentration values from the liquid phase to their corresponding dry weight equivalents. It allows for meaningful comparison between different matrices and sample types.

3.10 Sample preparation for Gamma Spectroscopy analysis

3.10.1 Soil

Each soil sample was air dried for two weeks to ensure the samples are free of water, then sieved with a 2 mm sieve size to keep the size of soil particles homogenous and transferred and sealed into a Marinelli beaker using masking tape for 26 days following IAEA 1989 method for soil sample preparation for gamma spectrometry analysis (Solomon, 2021). This was done to allow and ensure ^{226}Ra to be in equilibrium with all its daughters for gamma analysis of NORMS.

3.10.2 Radionuclides quantification

For gamma spectrometry for naturally occurring radionuclides, the system (equipped with High-Purity Germanium detector) was operated with Genie 2000 software (version 3.3), with automated spectral processing, peak area calculation, efficiency corrections and background subtraction. To minimise interference, the nuclide confidence index and energy tolerance threshold were set to 3.00 and 0.30 keV, respectively. Additionally, radionuclide quantification was performed for key naturally occurring radionuclides with specific gamma energies and nuclear data used for identification and calculation provided in Table 3.5. Specifically, ^{226}Ra: activity was determined from the average of its decay products (^{214}Pb and ^{214}Bi) measured at gamma peaks of 351.93, 295.22, 609.31, 1120.28 and 1764.49 keV. This method assumes secular equilibrium, requiring radon gas retention in sealed containers for 25 days. Radon leakage disrupts the equilibrium, invalidating results. ^{238}U calculated using emissions at 63.20, 92.60 and 1001.03 keV, ^{232}Th quantified via peaks at 338.32, 911.204 and 238.63 keV, and ^{40}K measured at 1460.63 keV. Finally, the activity concentrations were manually computed into Microsoft Excel spreadsheet.

Table 3.5: Key naturally occurring radionuclides, gamma energies, and nuclear data from the ^{238}U and ^{232}Th decay series used for identification and activity calculation (adopted from Nasser, 2022).

Nuclide to be determined		**Nuclide**	**Energy in Kev**	**Probability in %**	**Half-life time**
^{238}U		^{234}Th	63.28	4.1	
			92.37	2.42	24 d
			92.60	2.39	
		^{234m}Pa	766.37	0.316	
			1001.03	0.839	1.17 m
		^{226}Ra	186.1	3.51	1600 y
^{226}Ra			295.22	18.15	
		^{214}Pb	351.93	35.1	26.8 m
		^{214}Bi	609.31	44.6	
			1120.29	14.7	19.9 m
			1764.49	15.1	
			2204	5	
	^{228}Th	^{228}Ac	209.25	3.89	
^{232}Th			338.32	11.27	6.13 h
			911.2	25.8	
			968.97	15.1	
	^{228}Ra	^{224}Ra	240.99	4.1	3.66 d
		^{212}Pb	238.63	3.28	10.64 h

Nuclide to be determined		Nuclide	Energy in Kev	Probability in %	Half-life time
			300.09		
		^{212}Bi	727.3	6.67	60.5 m
		^{208}Ti	277.36 583.19 860.56 2614.83	2.27 30.4 4.47 35.64	3.03 m
^{40}K		^{40}K	1460.83	10.67	1.28×10^9 y
^{137}Cs		^{137}Cs	661.9	85.1	30.07 y

m; metastable state of radionuclide

3.11 Gamma spectrometry and ICP-MS calibrations

3.11.1 Calibration of ICP-MS

Calibration was performed using a multiple-element calibration solution containing 5% Nitric acid for total quantitative analysis (TotalQuant). The solution consists of 10 mg/L concentrations of multiple elements, including arsenic (As), aluminium (Al), silver (Ag), chromium (Cr), barium (Ba), and others. Calibration prepares analytical instruments for estimated quantities. A standard and blank check were run every ten sample intervals for each measurement. The targeted heavy metals were of uranium series, actinium series, thorium series, potassium-40 series and other heavy metals (Cu, Cr, Ni, Cd, Co, As, Zn, V) that might pose a threat to humans' health (Solomon, 2021; Russell *et al.*, 2021; Indongo, 2022).

Quality control was done by running a blank sample, calibration standard check and duplicates to check for contamination, traceability of measurements and accuracy of the instrument and for the adjustment of the instrument for calibration. The report was generated, showing the errors in measurements and the mode of analysis being considered. Helium gas for kinetic energy circulation (KED) was employed for collisions on the cells. Daily optimisation was performed on [KED] QID, [Helium KED] Cell Entrance Voltage, [Helium KED] Cell Exit Voltage, [Helium KED] CRO, and [Helium KED] Performance Check of the ICP-MS.

3.11.2 Efficiency calibration

For the system calibration, three known reference powdered sources (RGU-1, RGTH-1and RGK-1), which were obtained from International Atomic Energy Agency (IAEA) for K, U and Th activity measurement, were used (IAEA, 1987). The Uranium calibration standard is U-ore diluted with silica having 400 parts per million (ppm) and a negligible amount of potassium (K) less than 20 ppm with some traces of Thorium (Th) less than 1 ppm. The Thorium calibration standard (RGTH-1) is Th-ore diluted with silica having 800 ppm and contains U of 6.3 ppm and K of 0.02 %. Potassium calibration standard is extra-pure potassium sulphate with 44.8 % of K, and Th and U contents of lower than 0.01 and 0.001 ppm, respectively. The calibration standards were sealed for 26 days and counted for 12 hours, same as the research samples that were collected from the field for the experiment. The gamma emission lines that were considered include ^{234}Th (63.200 and 92.600 keV), ^{234}Pa (1001.03 keV), ^{214}Pb (295.224, 351.932, 609.312, 1120.287 and 1764.494 keV), ^{210}Pb (46.54 keV), 228Ac (338.320 and 911.204 keV), ^{212}Pb (238.632) and ^{40}K (1460.630 keV). The ratio of the calculated activity was calculated into the actual activity $\frac{Actual}{Calculated}$ for each gamma line and plotted against the gamma energy. Figure 3.7 shows the gamma spectrometry efficiency calibration curve.

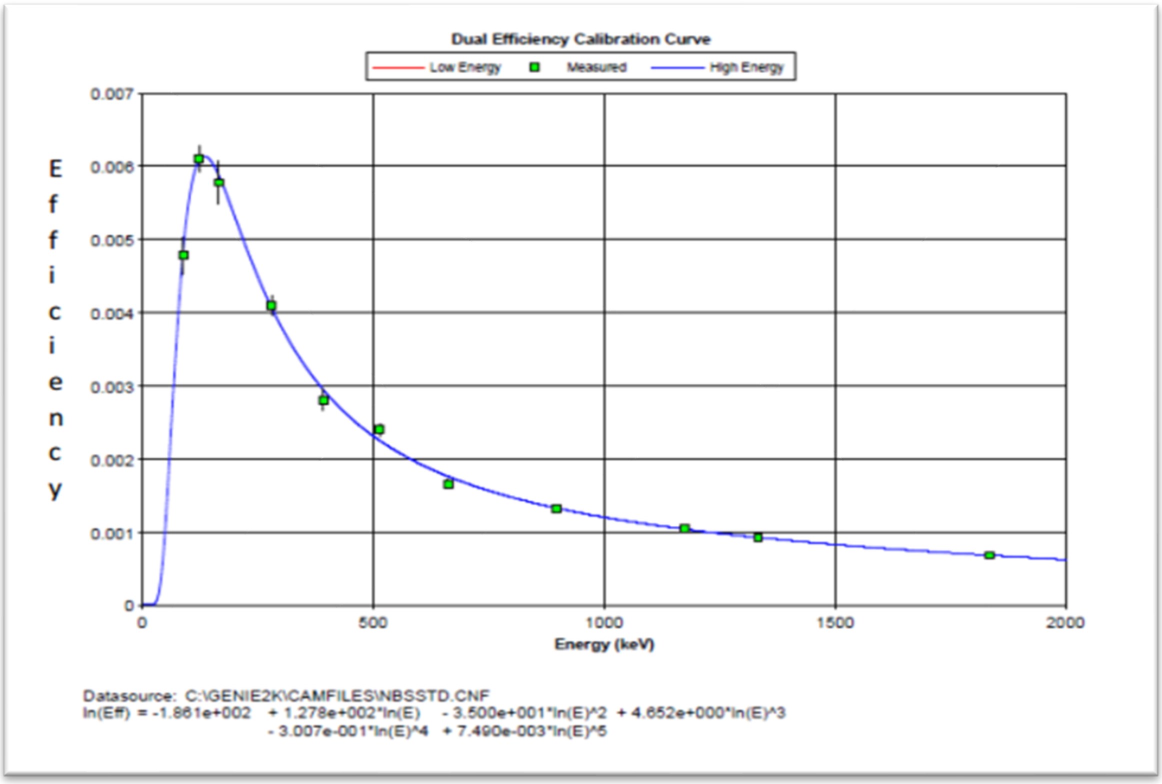

Figure 3.7: Gamma spectrometry efficiency calibration curve.

3.11.3 Energy calibration

Energy calibration was carried out to establish a correlation between the energy deposited in the detector (E, keV) and the pulse height recorded by the multichannel analyser. In this process, each pulse is assigned to a specific channel (k), resulting in a linear relationship that can be used to accurately determine the energy of detected events during spectral analysis (UNSCEAR, 2020; 2021). The equation is given below:

$$\mathrm{E} = m.k + C \qquad 2$$

Whereby m represents the linear scale (keV per channel) of the Multi-Channel Analyser (MCA), and C is the intercept, typically set near zero. Accurate values for m and C were determined empirically using the following procedure:

Barium-133 (Ba-133) and Europium-152 (Eu-152) were selected as calibration sources owing to the close match between their emission energies and those of the target radionuclides (^{234}Th, ^{241}Pb, ^{241}Bi and ^{40}K). The calibration covered a gamma-ray energy range of 63.8, 295.224, 609.312 and 1460.13 keV. As Ba-133) and Eu-152 emit enough number of photons (UNSCEAR, 2020; 2021; Almeqbali, 2022). The standard sources were run long enough (ten minutes) to produce well-defined photo-peaks and the channel number that matches the centre of each full energy peak on the Full Energy Peak (FEP) on the MCA was recorded and plotted on logarithmic paper on the X-axis versus the gamma ray energy on the Y-axis. Then the determined values of C (Intercepts) and m (the linear energy scale (keV/ Channel) of the MCA from the slope energy calibration line. Computerised systems are normally equipped to perform their slope and intercept calculations automatically during the calibration routine. Figure 3.8 shows the gamma spectrometry detector energy calibration curve obtained.

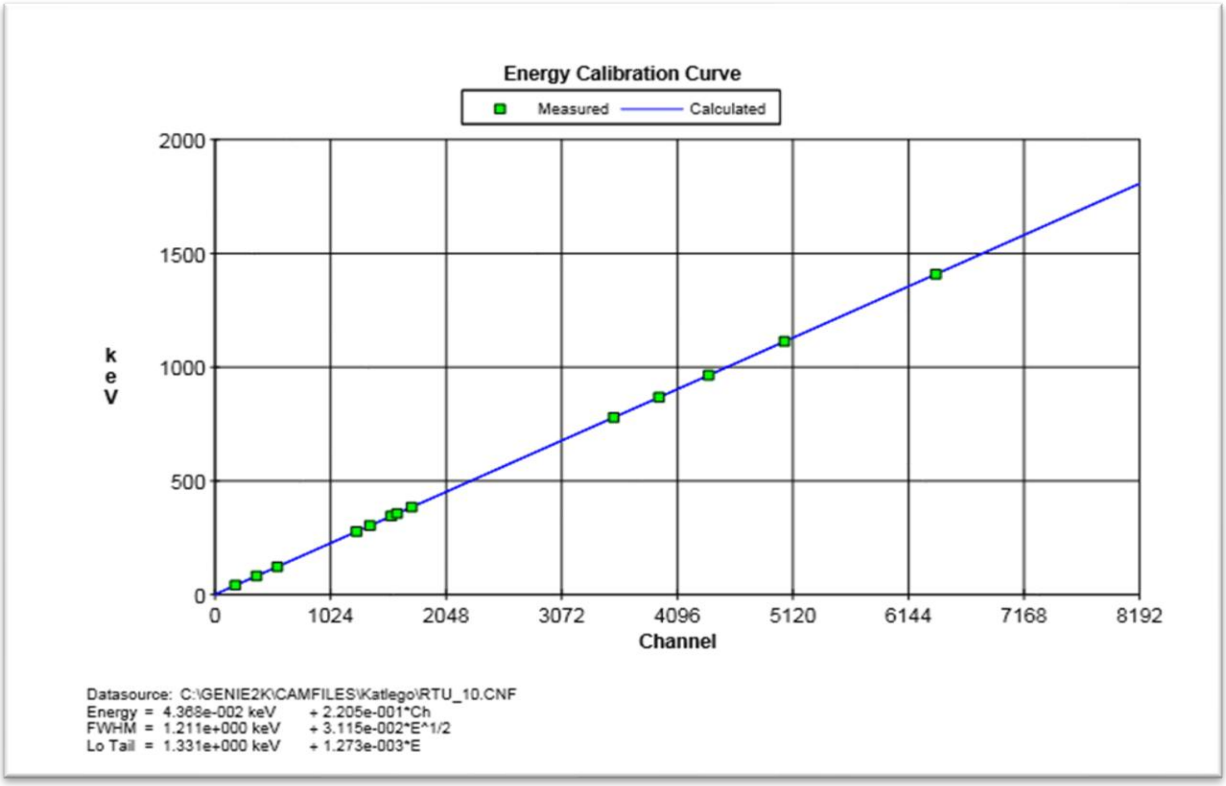

Figure 3.8: Gamma spectrometry detector energy calibration curve.

3.11.4 Quality test and analysis

Laboratory testing and analysis were undertaken to ensure accurate measurement of contaminants and radiological activity. ICP-MS and gamma spectroscopy were employed as the primary analytical instruments, enabling precise detection of heavy metal concentrations and naturally occurring radionuclides under controlled laboratory conditions.

3.11.4.1 Background measurements

The background of the system has a significant impact on the lower limits of the detector and the accuracy of measurements of low levels of activity. The counting system must have a background that is lower than the sample that may be presented in the system component, such as the detector itself, the manufactured material of the detector shielding or laboratory equipment (John *et al.*, 2019; Abt *et al.*, 2021). Natural radionuclides originating from the surrounding research facility, such as building material and cosmetic radiation, also need to be lower in activity compared to the counting sample (NNR, 2021; Ratnayaka, 2021). Quality Assurance and Quality Control (QAQC) need to be conducted to ensure that various methods/techniques have been employed to reduce and correct background values (ISO, 2024).

- Firstly, use pure non-radioactive construction materials for the detector, shielding any counting system equipment from cosmic radiation and exterior natural and man-made radionuclides.
- Secondly, vacuum the shield to eliminate dust particles and maintain a dust-free environment in the counting room, and ensure that there is no presence of samples or radioactive sources in the counting room.
- Thirdly, counting and/or measuring the background radiation for a period of 48 hours before counting any sample, and after every sample was counted.

Each counted sample is ensured to be moved from the counting room to the storage room. To ensure that background radiation does not spoil or interfere with the real results obtained. In this study, both techniques were employed, and background radiation activities were measured before and after the experiment was carried out. Then, after the experiment, the background radiation activities (Bq/s) were subtracted from all measured samples.

3.11.4.2 Activity measurements

Gamma-ray spectrometry was used to quantify environmental radioactivity by detecting and measuring gamma emissions from radioactive nuclei present in the samples. This technique identifies radionuclides through their characteristic full-energy peaks observed in the spectrum, enabling both qualitative and quantitative assessment of radioactive contaminants. After 26 days of sealing samples, to allow ^{226}Ra to be in equilibrium with all its daughters for gamma analysis for NORMS. Each sample was first placed in the detector, close to the sensitive volume of the detector and gamma-ray spectrum and counted for approximately 12 hours (43200 seconds) (counting time), many gamma-emitting nuclides can be measured simultaneously. Once the counting was done, the counted soil spectrum for each sample was saved for NORMs analysis.

The calculations of activity concentrations of radionuclides of interest were attained from results of daughter products under the presumptions that secular equilibrium has been achieved.

3.11.4.3 Data acquisition for gamma spectrometry

Data acquisition was done using Winspec for automation, and each soil sample spectrum obtained was analyzed using the software (Gamma acquisition analysis) with the help of efficient and energy calibration files, which were created early on.

3.12 Data analysis

Data analysis was conducted to organise, interpret and synthesise research findings. Employing a mixed-methods approach, this study integrated qualitative and quantitative data collection and respective analysis.

3.12.1 Qualitative data and statistical analyses

The qualitative data from structured questionnaires and document reviews were coded and analysed. This process combined thematic content analysis with descriptive statistics. Responses from open-ended questions were organized according to key themes derived from the literature review, including environmental risk perceptions, socio-economic impacts and mitigation strategies.

Microsoft Excel was used to capture and organise raw responses for descriptive analysis and visualisation. This included the development of bar charts and tables to summarise participant demographics and frequency distributions of common response patterns. GraphPad Prism version 8.0.1 was utilised to test the normality of data distribution, with statistical significance assessed at $p<0.05$ (GraphPad Software, 2020, Microsoft Corporation, 2021; Wang *et al*., 2023).

Content analysis followed a deductive approach, guided by pre-existing categories identified in the literature. This was supplemented by inductive coding where new themes emerged from the data. The analysis was informed by the framework proposed by Nowell *et al*. (2017) which emphasises transparency, trustworthiness and methodological rigour in thematic analysis for qualitative research. The goal was to identify patterns in local community perceptions, particularly in relation to their proximity to mine wastelands, awareness of association health risks and engagement with current or proposed mitigation strategies.

The integration of qualitative themes with simple descriptive statistics enhanced the interpretive power of the analysis, ensuring that the findings remained grounded in both the lived experiences of participants and broader theoretical frameworks.

3.12.2 Quantitative data analysis

Heavy metals in both soil and water samples were quantified using ICP-MS and for NORMs in soil samples by gamma spectrometry. Gamma spectrometry detectors manufactured by Canberra Industries (Meriden, CT, USA) and ICP-MS from Perkin Elmer, CT, USA were employed for analyses. The laboratory analysis helped with the provision of numerical data from collected samples, measuring variables, identifying patterns and relationships, performing statistical analysis, and assessing potential environmental and health risks connected to mine wasteland.

3.12.3 Radiological assessments of naturally occurring radionuclides

To evaluate environmental radiation levels and potential health risks (Annexure D), several radiological hazard indices were calculated in accordance with guidelines from the NNR, IAEA, ICRP and other regulatory agencies (IAEA, 2019; Ademoh *et al*., 2022; El-Afandy *et al*., 2022).

3.12.3.1 Absorbed Dose Rate (*DR*)

The absorbed dose rate in air at 1 m above the ground was first measured using gamma spectrometry. This *DR* serves as the basis for subsequent dose and risk calculations (Indongo, 2022; El-Taher *et al*., 2023). The *DR* was calculated using the following equation:

$$DR = 0.0417A_K + 0.0462A_U + 0.604A_{Th} \qquad 5$$

Where:

- A_K, A_U and A_{Th} = activity concentrations for potassium, uranium and thorium.
- The factors 0.0417, 0.462 and 0.604 are dose conversion factors for A_K, A_U and A_{Th}

3.12.3.2 Annual Effective Dose (AED)

The AED was calculated to estimate the radiation dose received by individuals annually, accounting for:

- Internal exposure: via inhalation and ingestion.
- External exposure: from environmental gamma radiation.

The AED was calculated using Equation 4 (El-Afandy *et al*., 2022; Esi *et al*., 2024):

AED (mSv.y^{-1}) = $DR \times DCF \times F_2 \times T$ 6

Where:

- DR = absorbed dose rate in nGy·h^{-1}
- DCF = dose conversion factor (0.7, 0.8, 0.9 Sv·Gy^{-1} for infants, children, adults, respectively)
- F_2 = occupancy factor (0.8 indoors, 0.2 outdoors)
- T = time in hours per year (8760 h·y^{-1})

Indoor (AED_{in}) and outdoor (AED_{out}) doses were calculated separately as follows:

AED_{in} $(\frac{mSv}{yr}) = D_R(\frac{nGy}{h}) \times 8760(\frac{h}{yrs}) \times DCF(\frac{SV}{Gy}) \times 0.8 \times 10^{-6}$ 7

AED_{out} $(\frac{mSv}{yr}) = D_R(\frac{nGy}{h}) \times 8760(\frac{h}{yrs}) \times DCF(\frac{SV}{Gy}) \times 0.2 \times 10^{-6}$ 8

These calculations assume that individuals spend 80% of their time indoors and 20% of their time outdoors (Shah *et al*., 2023; Omogunloye *et al*., 2024).

3.12.3.3 Total Annual Effective Dose (AED_T)

The AED_T represents the cumulative dose from both indoor and outdoor exposures for all age groups residing in the area (El-Taher *et al*., 2023):

3.12.3.4 Excess Lifetime Cancer Risk (ELCR)

The ELCR quantifies the probability of developing cancer over a lifetime owing to prolonged radiation exposure (El-Afandy *et al*., 2022; Nasser, 2022). ELCR is calculated using Equation 9:

$ELCR = AED \quad \times HLD_A \times CRF$ 9

Where:

- AED_T = total annual effective dose (mSv·y^{-1})
- HLDA = average human lifetime (70 years)
- CRF = fatal cancer risk factor (Sv^{-1}). Recommended value for public exposure is 0.05 Sv^{-1} per ICRP (ICRP, 2020). The world average CRF is 0.29×10^{-3} Sv^{-1} (IAEA, 2014; Baghani *et al*., 2019).

Thus, ELCR is estimated as:

$$ELRC = AED_{tot}(mSv^{-1}) \times 70y \times 0.05S^{-1} \quad 10$$

3.13 Integration of the Environmental Management System framework

In this study, the radioactive EMS was used as a high-level framework to organize and interpret findings from the laboratory, field and spatial analyses. As the EMS is a proprietary, IP-protected system developed by the researcher, its internal structure is not disclosed. Only its non-confidential guidance function was applied, serving as an interpretive lens without influencing the core analytical procedures.

3.14 Ethical considerations

Ethical clearance was granted by the University of South Africa (Unisa) through the College of Agriculture and Environmental Sciences (CAES) Research Ethics Review Committee with reference number: 2023/CAES_HREC/057 (Annexure E). Permission to conduct the study was granted by the Ergo /DRDGOLD Mine Company (Annexure F). The permission for sample analysis at the laboratory was granted by North-West University (Annexure G), and the work was done in compliance with lab waste and safety standards.

The researcher provided a comprehensive explanation of the study to all participants prior to their involvement, ensuring they obtained informed consent to participate. The names of participants were kept confidential and were not mentioned in this study.

3.15 Limitations of the study

The study encountered several limitations that are worth acknowledging. The limited accessibility to historical maps of the study area and pre-mining environmental data reduced the potential for long-term land use trend analysis of the research. Furthermore, local community engagement was successful, but in consideration of perception bias, some community responses might not be entirely accurate, as people were asked about the lived experiences that could influence their answer. However, triangulation with scientific results helped to mitigate this issue.

For the fact that the study included only community members not government and mine, limited collaboration of the results.

The sample size and budget constraints only allowed 38 soil and 5 water samples to be analysed owing to financial limitations, which restricted the number of samples. As a result, the findings might not fully represent how contamination spreads across the area. Additionally, this may not capture seasonal fluctuations in contaminant distribution, and the field data only reflect a snapshot in time. While the study cannot comment on long-term trends, conclusions are based on the conditions observed during the study. Furthermore, while RUSLE is effective in identifying potential erosion areas, it does not account for gully formation, chemical transport and wind erosion of which all are relevant in this context. Finally, delays in laboratory analysis, particularly gamma spectrometry, impacted the timeline for data interpretation and integration.

3.16 Conclusion

A mixed-method case study approach was used in this research, combining qualitative and quantitative techniques to strengthen the depth and breadth of the analysis. Community perception assessment, soil and water analysis for heavy and NORMs were conducted using ICP-MS and gamma spectrometry following standard laboratory procedures and internationally recognised analytical protocols. Despite some limitations, the researcher was able to utilise diverse data sources to ensure the credibility and reliability of the overall analysis, particularly in areas with similar post-mining conditions in South Africa. This helped to provide a strong basis for assessing environmental impacts, community perceptions and management strategies associated with historical mine wastelands, with the aim of achieving perpetual reduction targets of mine wastelands in Brakpan.

Chapter 4: Results and data analysis

4.1 Introduction

This chapter presents findings from interviews with the local community, field surveys, analyses of maps and images and laboratory assessments using ICP-MS and gamma spectrometry. The analysis integrated both qualitative approach which covers the participants' demographic profiles, community awareness, land-use and degradation, environmental risks, knowledge of reclamation, and quantitative, which is composed of soil and water samples analysis. The results are structured into thematic areas covering demographic profiles, community awareness, land-use and degradation, environmental risks, knowledge of reclamation, and contamination analysis. Each section draws on field and laboratory data as applicable. The questionnaire consisted of both closed-ended and open-ended questions. Closed-ended responses are presented in percentages, while open-ended responses were used to support the results where relevant.

4.2 Socio-demographic information of respondents

The demographic profile of participants shows that 73% (n= 66) were male and 27% (24) were female. A higher number of male respondents, therefore, contributed more responses to this study done in Brakpan.

In terms of race/ethnicity, the racial makeup was primarily Black (77%), with minor representation from White and Coloured (10% each) and Indian (3%). Educational attainment varied, with 46% having completed Grade 8 to 12, and 19% holding undergraduate degree, and 13% having no formal education. While minor representation has grades 1 to 7 (12%) and postgraduate (10%). A subset of the respondents identified as mine workers within the study area. Within this subgroup, 21% (n= 19) of the total sample were male mine workers, while 9% (n= 8) were female mine workers.

Employment status showed that 34% of respondents were employed, 29% were unemployed, and 20% were self-employed. While a small proportion (9%) were students and (8%) retired. Among the respondents, 30% are general workers in the mining sector. In terms of settlement type, 53% of participants reported living in permanent housing, 39% resided in informal settlements, and 8% lived in mobile housing.

Finally, in terms of duration of residence, 49% of participants lived in the area for more than seven years, 24% lived there for 6 and 7 years. Then 9% indicated that they had lived for 1 to 11 months and 12% indicated 3 to 5 years. Fewer participants (6%) reported living in the area for only 1 to 2 years.

These six variables gender, race/ethnicity, qualifications, employment status, type of settlement, and duration of residence are presented in Table 4.1, which also reflects the overall sample size (n = 90).

Table 4.1: The socio-demographic characteristics of the study respondents in Brakpan (Kwa-Thema) based on gender, race/ethnicity, qualifications, employment status, type of settlement, and duration of residence.

Variables	**Description**	**Number of respondents**	**Respondents Percentage(s) (%)**
Gender	Female	24	27
	Male	66	73
	Black	69	77
Race/ethnicity	White	9	10
	Coloured	9	10
	Indian	3	3
	No formal education	12	13
	Grade 1 to 7	11	12
Qualifications	Grade 8 to 12	41	46
	Undergraduate	17	19
	Post-graduate	9	10
Employment status	Unemployed	26	29
	Scholar/ Student	8	9
	Employed	31	34
	Self-employed	18	20
	Retired/ Pensioner	7	8
Type of settlements	Permanent Settlement	48	53
	Informal Settlement	35	39
	Mobile Settlement	7	8
	1 to 11 Month	8	9
	1 to 2 Years	5	6

Variables	Description	Number of respondents	Respondents Percentage(s) (%)
Duration of residence in the area	3 to 5 Years	11	12
	6 to 7 Years	22	24
	7 Years and above	44	49

4.3 Mapping of mine wastelands and examination of socio – economic benefits of mining in Brakpan

This section focuses on mapping mine wastelands in Brakpan and includes questions such as "Do you know what mine wastelands are?", "How far do you reside away from mine wastelands?" and "Do mining companies provide employment to local people?"

4.3.1 Knowledge, employment and management of mine wastelands

Table 4.2 deals with whether local communities of Brakpan (Kwa-Thema) know what mine wastelands are and whether local communities are associated with environmental conservation, and whether local communities should be allowed to extract resources from mine wastelands. The participants' responses for each choice variable are provided in percentages as indicated in Table 4.2.

From the results presented in Table 4.2, it was found that 73% of participants indicated they know what mine wastelands are and that they are considered dangerous. In addition, most respondents (72%) reported that they have free access to these sites without any hindrances, whereas a small number of participants, 27% each has both indicated that they do not know what mine wastelands are, and do not think mine wastelands are dangerous and 28% indicated that they do not have free access to mine wastelands, respectively. Most participants, 56%, have indicated that mining operations in Brakpan do not provide employment to local people, followed by 30% participants who indicated that mining operations in Brakpan do provide employment to local people. In contrast, 14% of participants have indicated that they do not know if mining operations in Brakpan provide employment for local people. However, 76% of participants indicated that they do not participate in the decision-making of mining operations in Brakpan. Only 24% of participants indicated participation in decision-making related to mining operations in Brakpan (Kwa-Thema).

Table 4.2 reveals that most of the participants (80%) indicated that they are not members of their close family, nor do they associate with environmental conservation organisations. Conversely, few of the participants, 20%, indicated that they are, or a member of their close family associated with environmental conservation organisations. Then 71% of participants indicated that no local people should be allowed to extract resources from mine wastelands and 29% of participants indicated that local people should be allowed to extract resources from mine wastelands.

Table 4.2: Knowledge, accessibility, provision of employment and involvement of community in the management of mine wastelands.

Variables	Description	Respondents percentage (s) (%)
a. Knowledge, accessibility and danger of mine wastelands	i. Do you know what mine wastelands are?	
	No	27
	Yes	73
	ii. Do you think mine wastelands are dangerous?	
	No	27
	Yes	73
	iii. Do you have access to mine wastelands?	
	No	28
	Yes	72
b. Involvement of local communities in mining operations in Brakpan	i. Do mining operations in Brakpan provide employment to local people	
	No	56
	Yes	30
	Don't know	14

Variables	Description	Respondents percentage (s) (%)
	ii. Does the local community participate in decision-making of mining operations in Brakpan	
	No	76
	Yes	24
c. Should local communities manage they mine wastelands in their vicinity	i. Are you or a member of your close family, associated with environmental conservation organization	
	No	80
	Yes	20
	ii. Should local people be allowed to extract resources in mine wastelands	
	No	71
	Yes	29

4.3.2 The distance of residence from mine wastelands

The study examined the distance between participants' residences and the mine wasteland under investigation, and their responses are displayed in percentages as indicated in Figure 4.1. In assessing the distance away from mine wasteland under the study, the results indicate that 39% of participants reside between 0-5km, whereas 34% of participants indicated that they reside between 5-10 km, and 27% reside 10-15km away from mine wastelands.

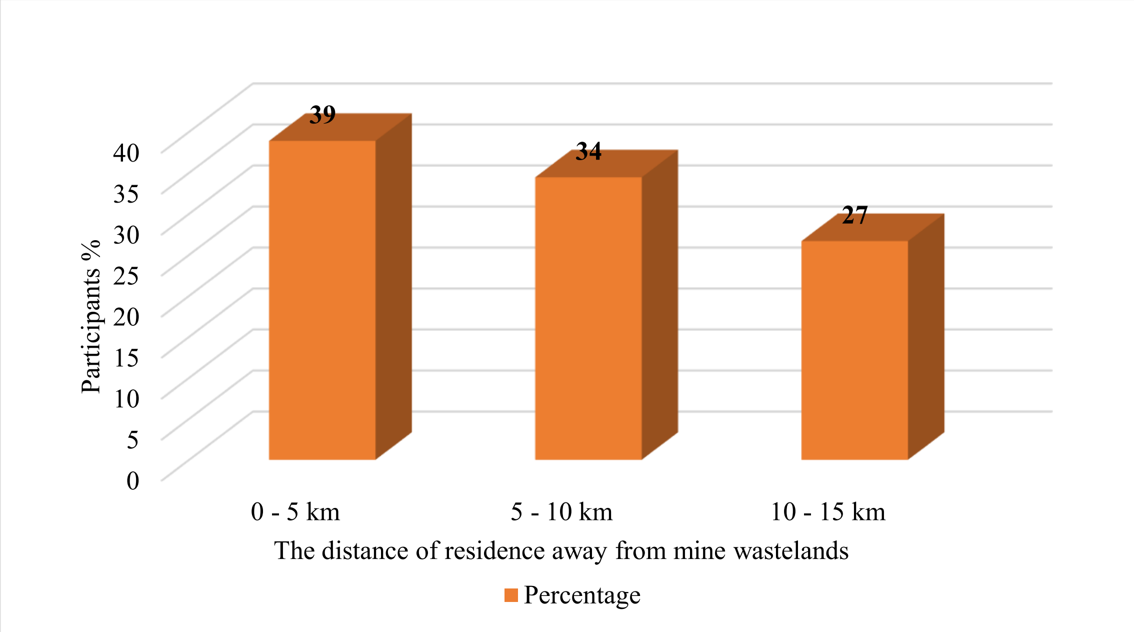

Figure 4.1: The distance of residence away from mine wasteland.

4.3.3 Mining operations in Brakpan

The purpose of this investigation was to identify which mining operations have previously operated or are currently operating in Brakpan, with the aim of understanding the types of mine wastelands present. The total number of participants based on the response is provided in percentages as indicated in Figure 4.2.

Since the inception of mining in South Africa, the mining industry has been the economic backbone of South Africa and plays a significant role in the development of South Africa. The results in Figure 4.2 indicate that 62% of participants identified gold mining as the dominant historical and/or current mining operation in the area. Moreover, 18% indicated that the dominant operations are those of uranium mining, while another 17% believed it involves the extraction of other minerals, and a minor percentage indicated it is coal (3%). About 17% of respondents work as miners in the mining sector in Brakpan.

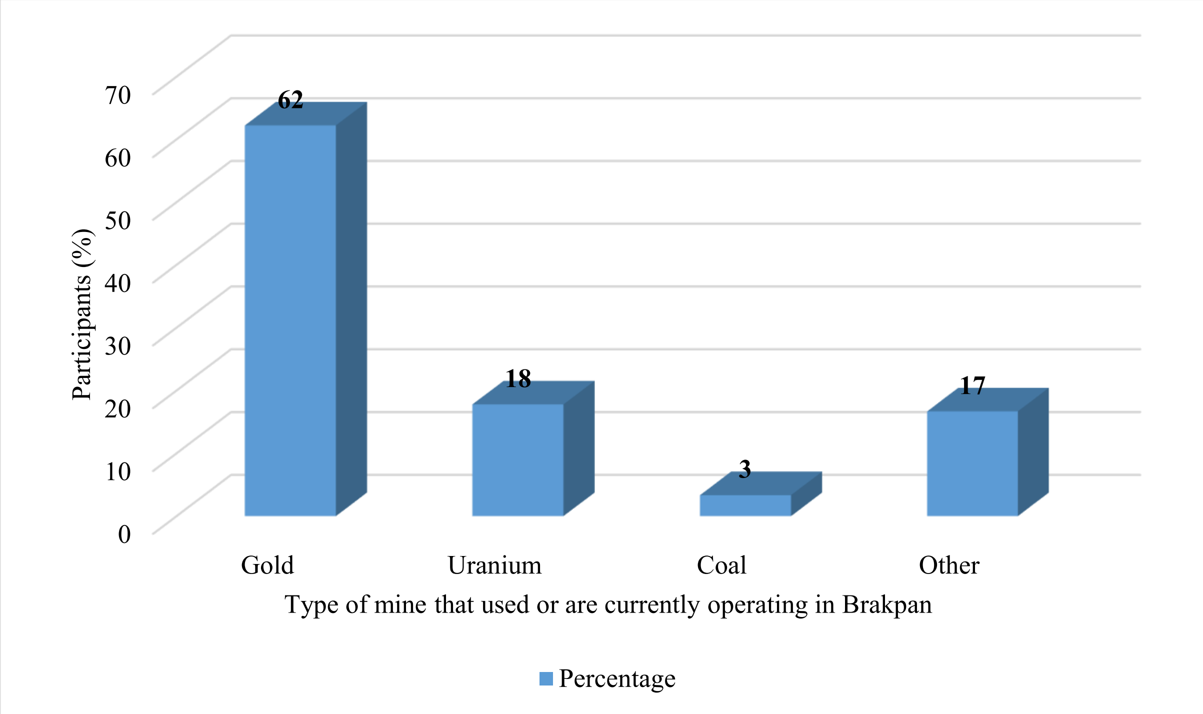

Figure 4.2: Responses on Mining operations that used to operate or are currently operating in Brakpan.

4.4 Land use, land cover and human activities in the degradation of the environment in Brakpan

The principal drivers of land-use change and anthropogenic activities contributing to environmental degradation in Brakpan were analysed, with respondents allowed to choose more than one answer. The respondents' perspectives are illustrated in Figure 4.3, Figure 4.4, Figure 4.5, Figure 4.6, Figure 4.7 and Figure 4.8, and Table 4.3.

4.4.1 Main land uses in Brakpan

The number of responses for each choice variable is provided in percentages, as shown in Figure 4.3. Moreover, a high number of respondents 44% and 30% indicated that the main land uses in Brakpan are residential and mine wastelands, respectively. Though 17% and 9% of respondents indicated that commercial/businesses and agricultural practices are the main land uses in Brakpan. According to the results in Figure 4.3, residential and mining wastelands are the two primary land uses in the Brakpan area.

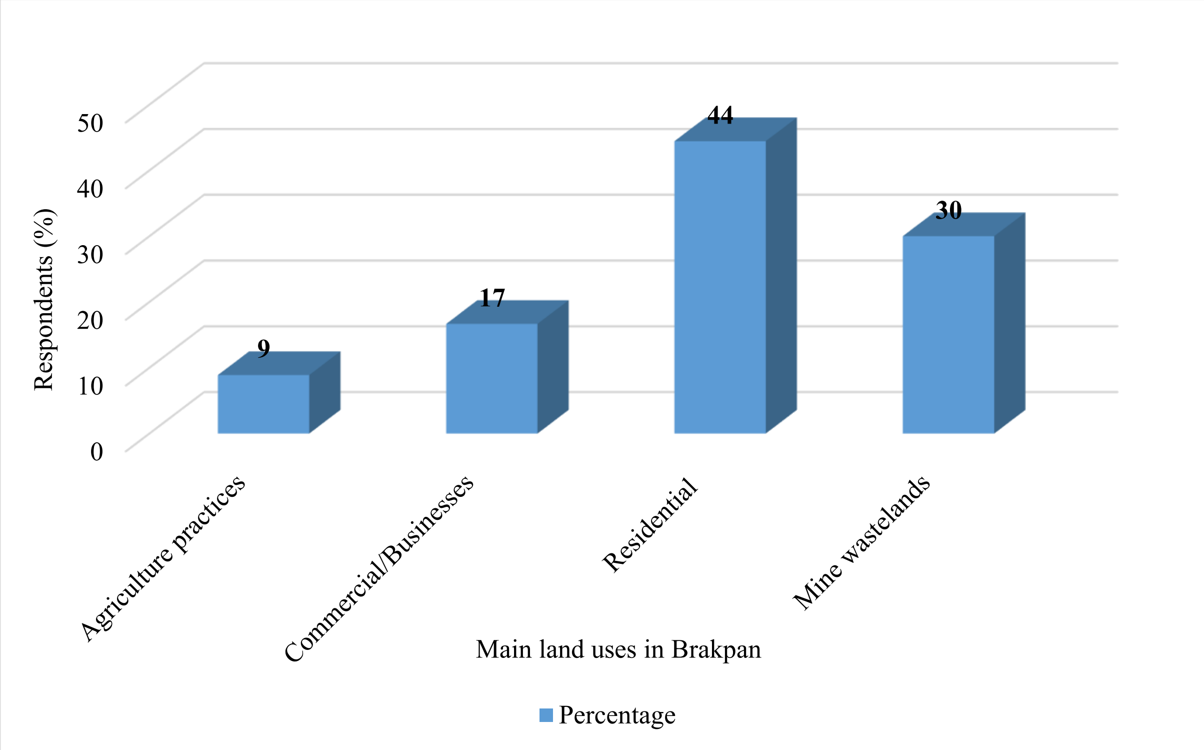

Figure 4.3: Main land uses indicated for Brakpan.

4.4.2 Environmental degradation in Brakpan

The causes of environmental degradation in Brakpan are summarised in Figure 4.4. The participants responded by ticking one or more options for this closed-ended question to indicate whether they agreed with the statement or not. The number of responses for each variable is provided in percentages as presented in Figure 4.4.

From the results obtained in Figure 4.4, most of the participants indicated that pollution (32%), human settlements (31%) and mine wasteland (26%), respectively are the core causes of environmental degradation in Brakpan. A small number of participants believe that overpopulation (11%) is a central cause of environmental degradation in Brakpan, while none identified deforestation or landfills as contributing factors.

Pollution contributes to environmental degradation through the release of contaminants into soil and water systems. Human settlements increase pressure on land through waste generation and land clearing. Mine wastelands contribute through exposed contaminated soils and dust dispersion, while overpopulation increases pressure on available resources and environmental systems.

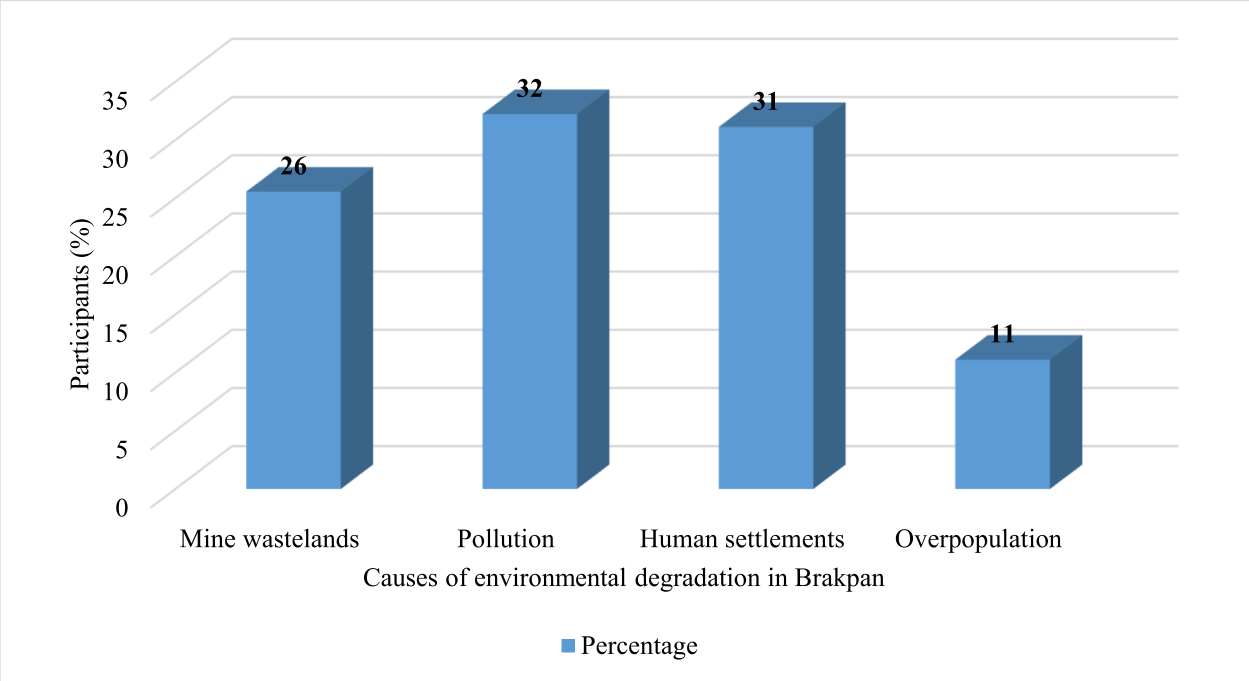

Figure 4.4: Causes of environmental degradation in Brakpan.

4.4.3 Factors driving land changes in Brakpan

Understanding what drives land use change in Brakpan is essential for effective planning and environmental management. The participants responded to this closed-ended question by indicating whether they accepted the statement or not. The number of responses for each variable is provided in percentages as highlighted in Figure 4.5.

Figure 4.5 shows that 42% of respondents indicated that population growth is the chief factor that is the driving force of land change in Brakpan and 27% indicated urbanisation. However, 16% of respondents indicated that construction (mining) and others are the main factors and none of respondents believe that agricultural practices are the driving forces of land changes in the Brakpan area.

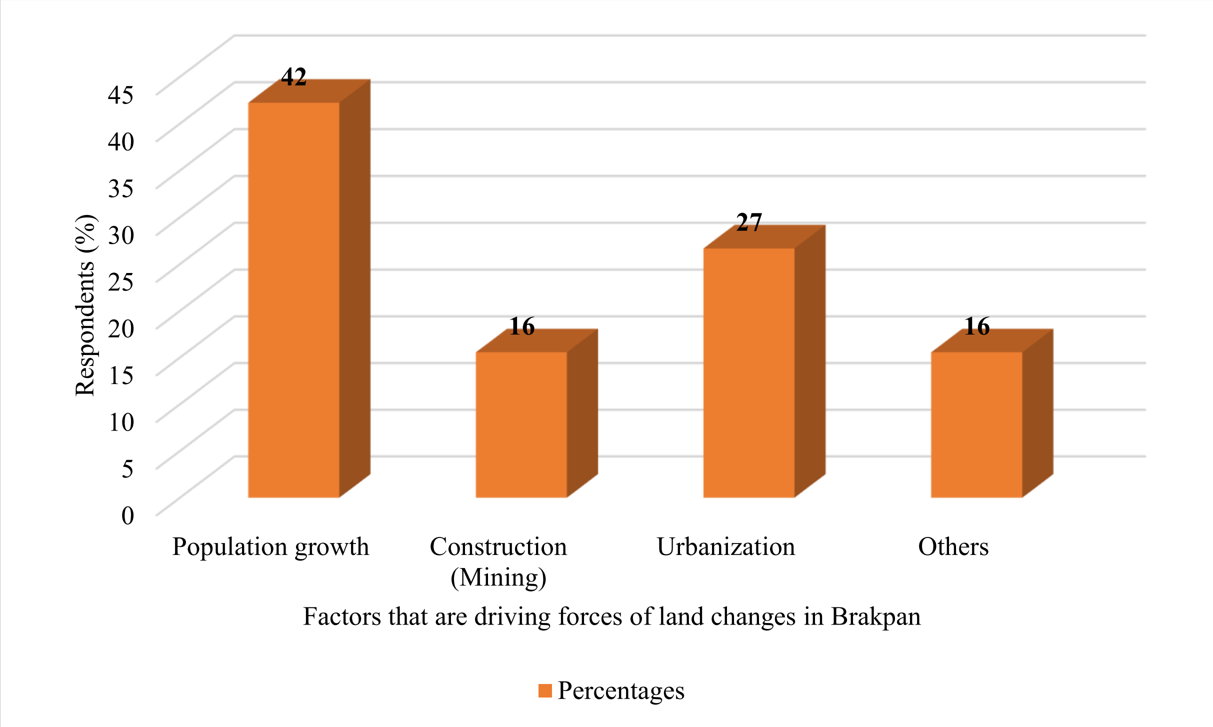

Figure 4.5: Factors driving land changes in Brakpan.

4.4.4 Negative experiences and/or problems of living next to the mine wastelands?

The overall purpose of the questions asked in Figure 4.6 was to determine the negative impacts that local communities face on a regular basis when living next to mine wastelands. The number of responses for each variable is provided in percentages as highlighted in Figure 4.6.

Based on the data presented in Figure 4.6, most participants, 38%, indicated that dust is the main problem experienced when living near mine wasteland. This is consistent with open-ended responses, where participants reported exposure to dust from mine dumps and surrounding areas. Another 31% reported loss of land and livelihood is a key issue. In addition, 18% identified restricted access to resources as a problem, while 14% indicated that hostility and harassment by authorities were significant concerns.

Figure 4.6: Negative experiences and/or problems living next to the mine wastelands.

4.4.5 Benefits of mine wastelands to the community of Brakpan

Table 4.3 deals with the benefits of mine wastelands towards the participants' community. The participants indicated the relative importance of each variable on a six-point Likert scale depending on the corresponding level of benefits. The number of responses for each choice variable is provided in frequencies and percentages as depicted in Table 4.3.

In Table 4.3, 36% of participants indicated that the mine wastelands around Brakpan are neither good nor bad, which accounts of the n = 32 of participants, followed by 21% of the n = 19, who indicated that mine wastelands are very bad, 18% of the n = 16 indicated that mine wastelands are good and whereas n = 12 of participants indicated that mine wastelands are bad which accounts 13% of participants and 12% of the n = 11 indicated that mine wastelands are very good.

Table 4.3: Benefits of mine wastelands towards the local communities of Brakpan.

Variables	Description	Number of participants	Percentage(s) (%)
a. How would you describe the benefits of mine wastelands towards the community of Brakpan?	Very good	11	12
	Good	16	18
	Neither good nor	32	36
	Bad	12	13
	Very bad	19	21
	Good and bad	0	0

4.4.6 Which of the following poses threats to land conservation in Brakpan

Figure 4.7 provides results on what poses threats to land conservation in Brakpan, and the number of responses for each variable is provided in percentages.

The results from Figure 4.7 show that most participants (38%) indicated that pollution is the leading cause posing threats to land conservation in Brakpan, followed by illegal encroachment by local communities (29%), then the expansion of land development (e.g. Construction, Mining) (23%) and other factors (10%).

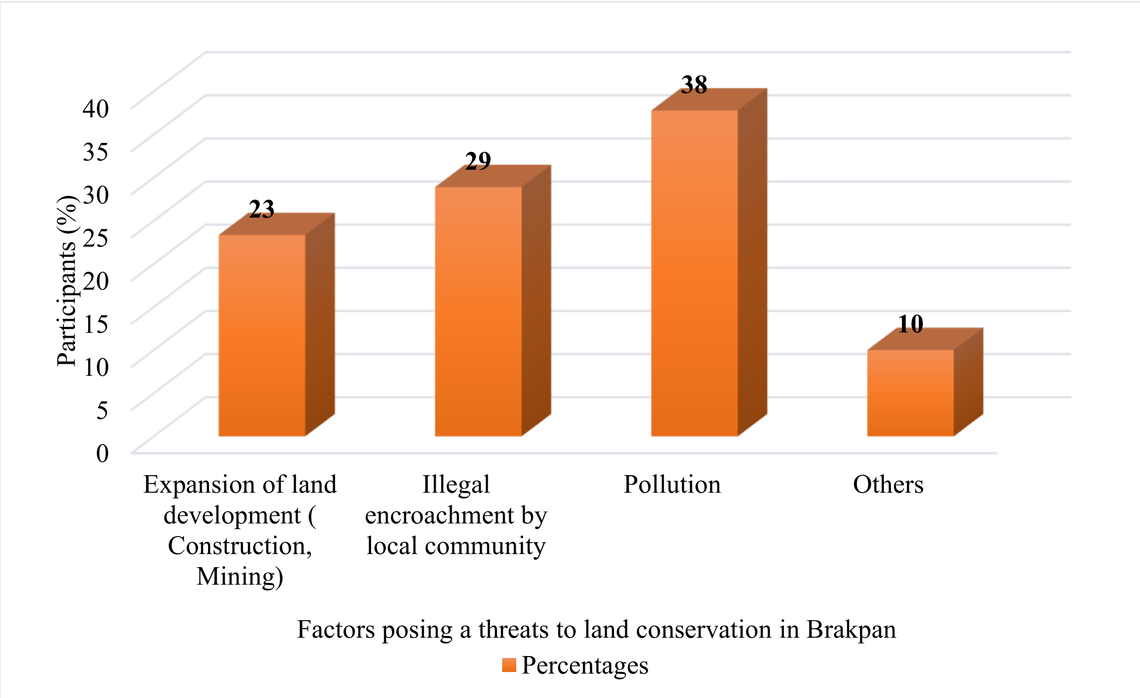

Figure 4.7: Indicated threats to land conservation in Brakpan.

4.5 Mine wastelands reclamation

Table 4.4, Figure 4.8, Figure 4.9 and Figure 4.10 present the responses for each selected variable on mine reclamation as provided by participants.

4.5.1 Mine reclamation and contribution of the local community to mine wastelands in Brakpan

Table 4.4 summarises the community contribution and the scope of participation noted across the study area. The number of responses for each choice variable is provided in frequencies and percentages, as depicted in Table 4.4.

Table 4.4 reveals that 68% of participants reported not knowing what mine reclamation is, and 32% of participants indicated that they know what mine reclamation is. Moreover, 63% of participants indicated that local communities would not contribute towards funding reclamation of mine wastelands if asked, followed by participants 21% who indicated that they were "not sure who" and 16%, who indicated that the local community would contribute towards funding reclamation of mine wastelands if asked, respectively.

Table 4.4: Mine reclamation and contribution of the local community towards the reclamation of mine wastelands in Brakpan.

Variables	Description	Number of participants	Percentage(s) (%)
a. Mine wastelands reclamation	i. Do you know what mine reclamation is?		
	No	61	68
	Yes	29	32
	ii. In your opinion, would the local community be willing to contribute towards funding the reclamation of mine wastelands	57	63
	No	14	16
	Yes	19	21
	Not sure who		

4.5.2 How much would you say you know about mine wasteland's reclamation?

Participants rated their knowledge of mine wasteland reclamation through re-mining using a 5-point Likert-scale ranging from 1= no knowledge to 5 very knowledgeable. Figure 4.8 presents the response in percentages for each scale point.

The purpose of asking this question was to assess the extent to which the participants understand mine reclamation in Brakpan on a scale of 1 to 5, especially in relation to the importance of secondary mining and/ re-mining. From data in Figure 4.8, a high number of participants 54% do not know about mine reclamation, followed by 12% who know little about mine reclamation and 16% of participants who moderately know about mine reclamation, respectively. However, 18% of participants demonstrated that they have sufficient knowledge about mine reclamation.

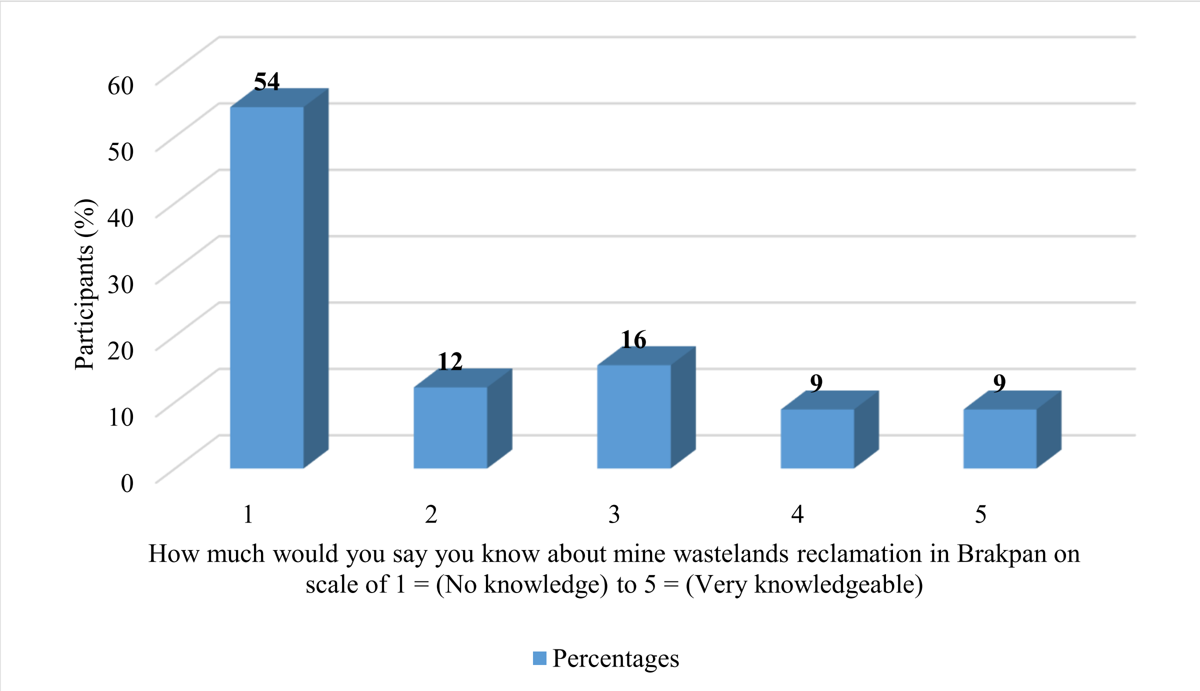

Figure 4.8: Knowledge of mine wasteland reclamation.

4.5.3 Have you observed or heard of any mine reclamation activities taking place around Brakpan or nearby areas?

Figure 4.9 shows that 68% of participants reported not having observed or heard of any mine reclamation activities taking place around Brakpan, while 18% were uncertain. In contrast, only 16% of participants reported having observed or heard about such activities in the area.

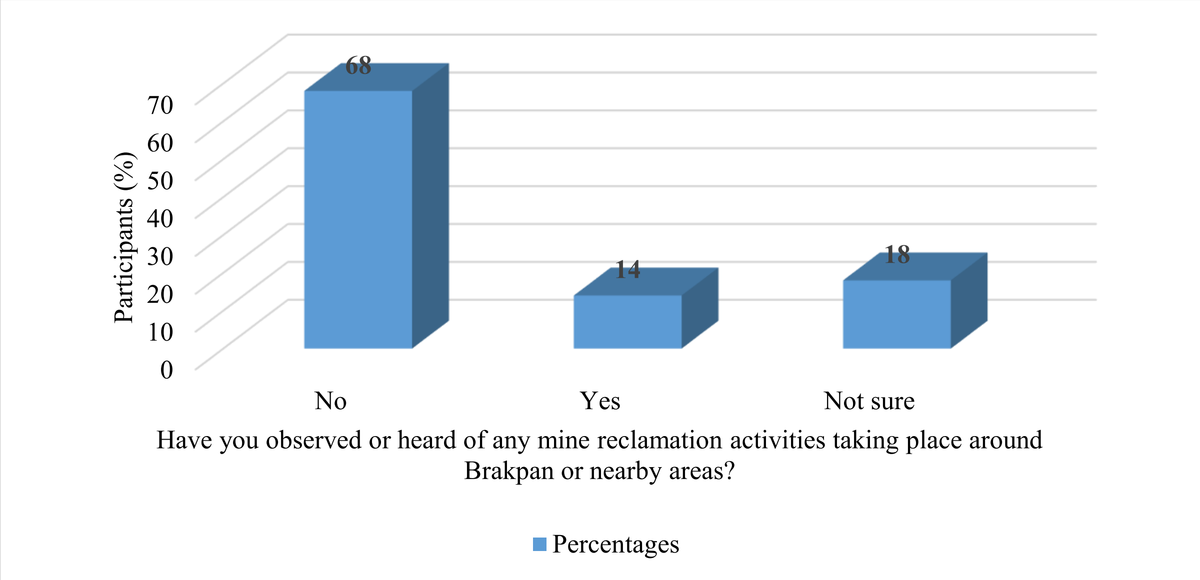

Figure 4.9: Have you observed or heard of any mine reclamation activities taking place around Brakpan or nearby areas?

4.5.4 DMRE, and other associated government departments handling mine wasteland in Brakpan

Proper management of mine wastelands is critically important for the environment and community health as there might be commercial use and/or pose threats to the health and security of the local communities. Figure 4.10 addresses whether local communities approve or disapprove of how DMRE and other associated government departments handle mine wastelands in Brakpan. The total number of respondents based on the responses is provided in percentages as indicated in Figure 4.10.

Figure 4.10 illustrates that most respondents (76%) disapprove and 24% approve of how mine wastelands are handled by DMRE and other associated government departments.

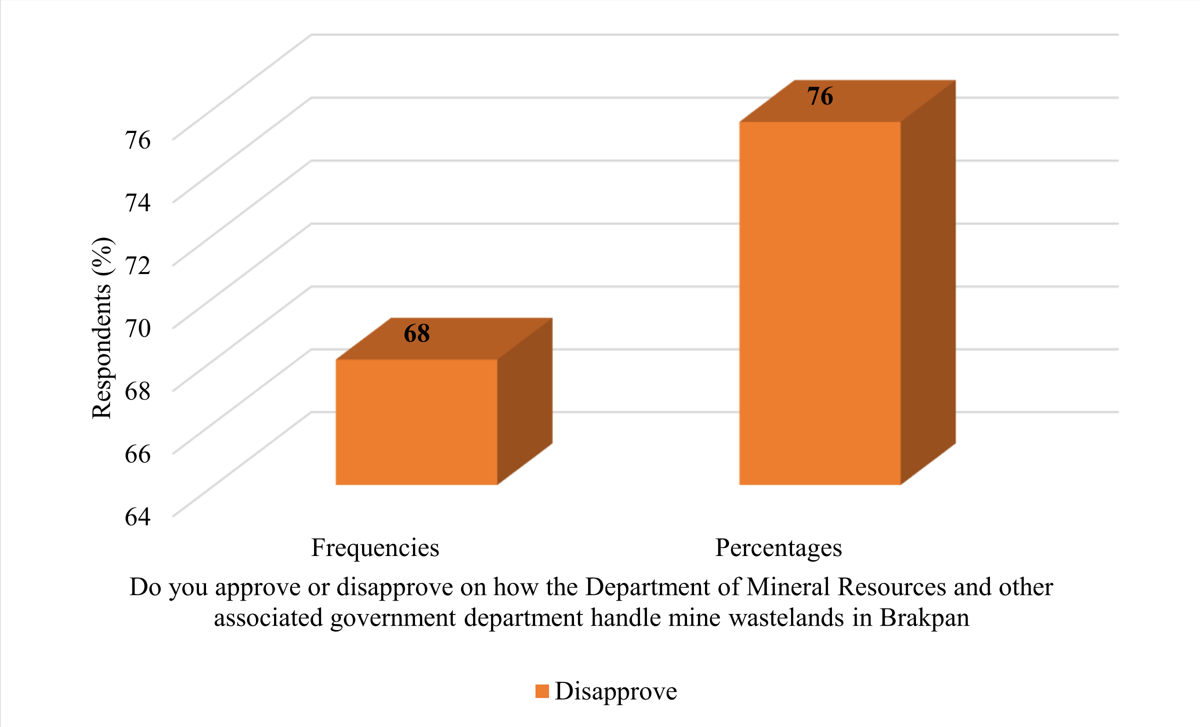

Figure 4.10: Do you approve or disapprove of how the DMRE, and other associated government departments handle mine wastelands in Brakpan?

4.5.5 What changes would you recommend improving the management of Mine wasteland and/ or management practices for environmental protection around Brakpan?

Mitigating ongoing environmental degradation requires the implementation of targeted management practices. Figure 4.11 examines the best management practices that local communities in Brakpan indicated they can adopt. From Figure 4.11, most of the participants (68%) indicated that environmental education is the best management practice that needs to be undertaken to protect the environment around Brakpan. In contrast, 22% believe that fencing the environment is the best management practice, and only 10% indicated that nothing should be done, and everything should be left the way it is.

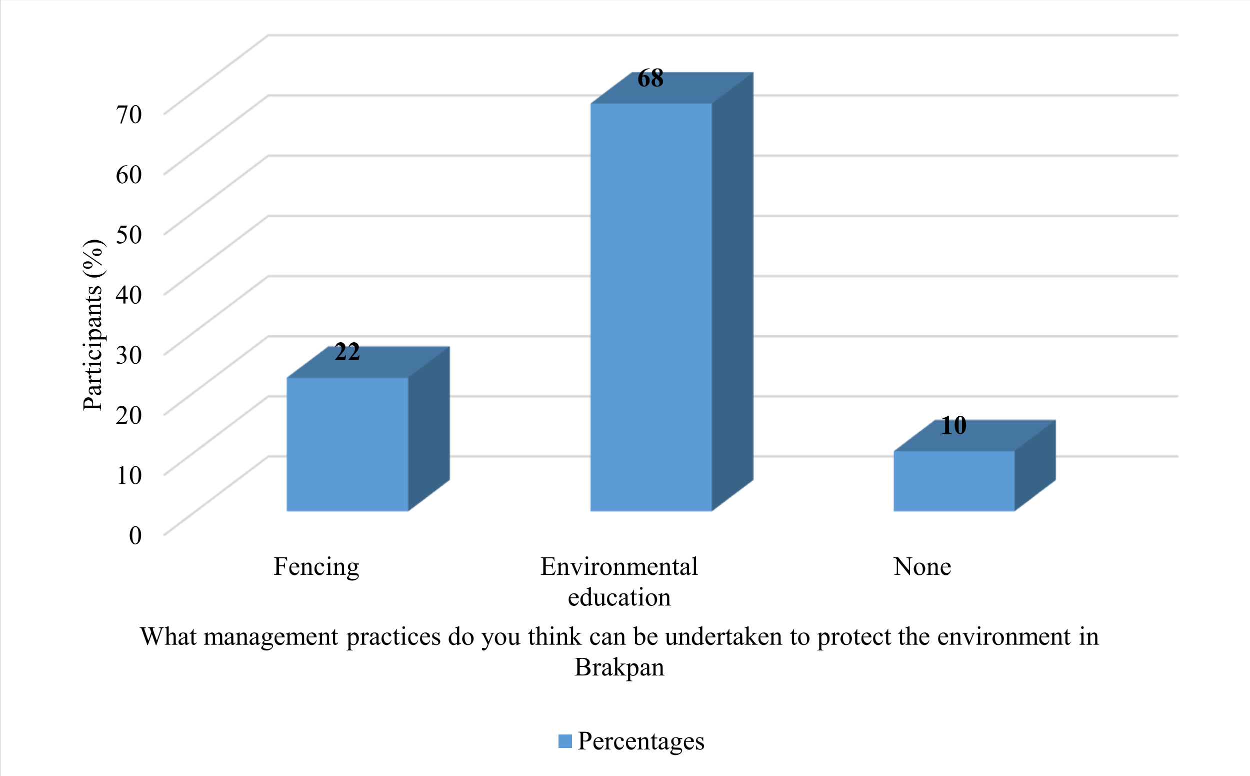

Figure 4.11: Management practices to be undertaken to protect the environment around Brakpan.

4.5.6 Responsibility for the rehabilitation of Mine wastelands in Brakpan

Through the respondents, the study determined who is or should be truly responsible for handling the issue of rehabilitating the mine wastelands, as this might/affect and influence policies around mining, settlements, pollution and the environment. The total number of participants' responses is provided in percentages as indicated in Figure 4.12.

The results in Figure 4.12 indicated that 48% of the respondents felt that the government is the one that should be responsible for the rehabilitation of mine wastelands, and 32% believe that mining companies should be the ones responsible for rehabilitating the mine wastelands in Brakpan. In contrast, 20% of the respondents indicated that the local community should be the ones responsible for rehabilitating the mine wastelands.

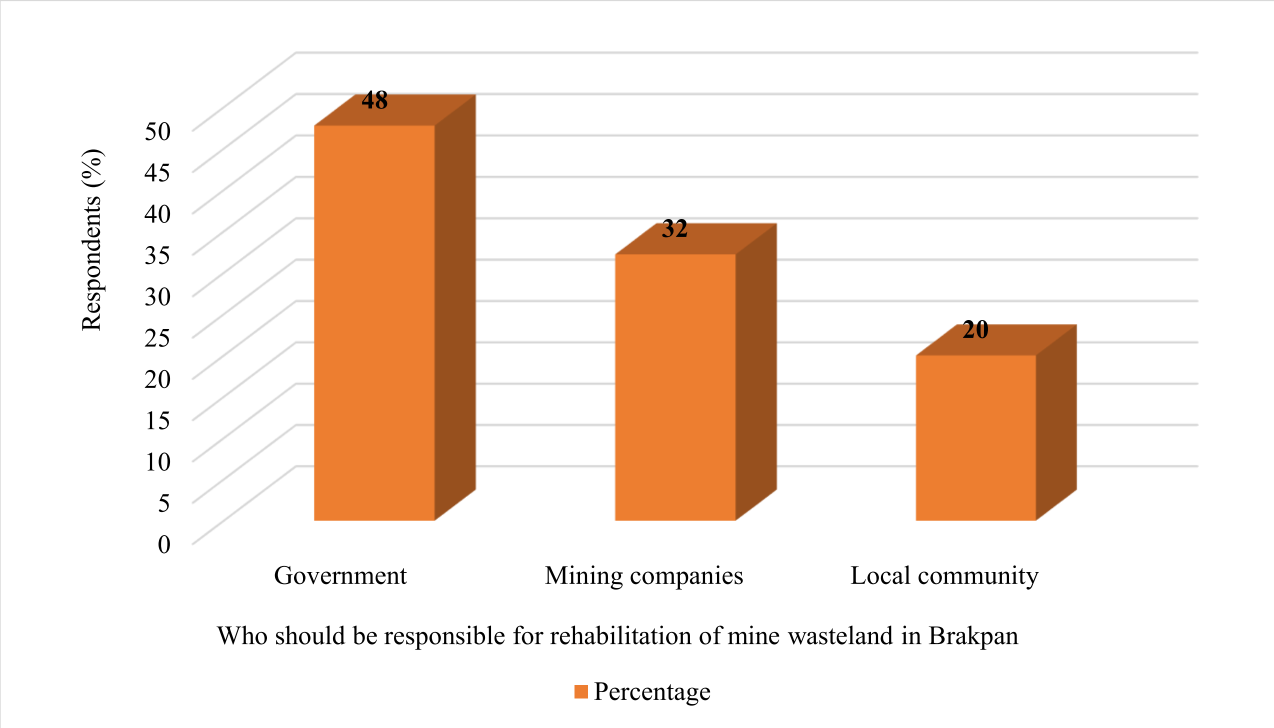

Figure 4.12: Responsibility for the rehabilitation of Mine wastelands in Brakpan, the government, mining companies, and/ local communities.

4.6 Inferential statistics analysis on community perceptions

The inferential statistics were adopted to draw conclusions about the sample data collected from the participants in the study area. While descriptive statistics were used to summarise the key features of the data set, Spearman's rank-order correlation was used for testing hypotheses and the identification of possible relationships between variables. By using hypothesis testing and confidence interval valuations, the study was able to simplify the findings from sampled data to a wider socioeconomic and environmental conditions distressing the communities residing near mine wastelands. This approach helped to interpret the random variation and supported the dependability and uncertainty of the assumptions made based on the observed data. Given the small sample size ($n = 90$) and the ordinal nature of most survey variables (e.g., Likert-scale responses and binary categorical responses), Spearman's correlation (ρ) was deemed the most applicable non-parametric test.

The significant threshold of $p < 0.05$ was adopted to identify statistically significant relationships between variables. The analysis aimed to determine which factors influence environmental knowledge, risk perception and behavioural intent (e.g., contribution to reclamation funding).

4.6.1 Variables used in correlation analysis

The variables tested in this analysis are summarised in Table 4.5 and Table 4.7. Their selection was guided by both theoretical and practical relevance to the research objectives, and Table 4.5 depicts the survey codes (V1-V17) that were used.

Table 4.5: Variable codes and descriptions used in correlation testing.

Variable code	Description
V1	Gender
V2	Race/Ethnicity
V3	Qualifications
V4	Employment status
V5	Type of settlements (formal/informal/mobile)
V6	Duration of residence in Brakpan
V7	Do you know what mine wastelands are
V8	Do you think mine wastelands are dangerous
V9	Do you have access to mine wastelands
V10	Do mining operations in Brakpan provide employment to local people
V11	Does the local community participate in decision-making of mining operations in Brakpan
V12	Are you or a member of your close family, associated with environmental conservation organization
V13	Should local people be allowed to extract resources in mine wastelands
V14	How would you describe the benefits of mine wastelands towards the community of Brakpan
V15	Do you know what mine reclamation is
V16	In your opinion, would the local community willing to contribute towards funding reclamation of mine wastelands
V17	How much would you say you know about Mine wasteland's reclamation in Brakpan on scale of 1 to 5
V18	Who should be responsible for rehabilitation of mine wastelands

4.6.2 Statistically significant relationships

Table 4.6 presents the statistically significant correlations ($p < 0.05$) identified between selected variable pairs. These results reveal notable associations, particularly qualifications, duration of residence, awareness levels and willingness to contribute to reclamation strategies.

Based on Table 4.6, a strong positive correlation between knowledge of mine wastelands (V7) and free access to mine wastelands (9) (ρ = 0.972, p = 0.000) was observed. Similarly, gender (V1) is more likely to perceive mine wasteland as dangerous (V8). Furthermore, moderate but significant correlations were identified between qualifications (V3) and knowledge of mine reclamation (V15), and knowledge of mine reclamation (V15) and knowledge of mine wasteland's reclamation in Brakpan on a scale of 1 to 5 (V17). Weak positive correlation was identified between knowledge of mine wastelands (V7) and knowledge of mine reclamation (V15). Employment status (V4) displayed a weak but significant negative correlation with extracting resources from mine wasteland.

Table 4.6: Statistically significant Spearman's rank-order correlations.

Variable pair	Spearman's (ρ)	p-value
V7:V9	0.972	0.000
V3:V15	0.633	0.000
V4:V13	-0.296	0.007
V1: V8	0.972	0.000
V7:V15	0.351	0.001
V8: V16	-0.439	0.000
V11:V17	0.285	0,007
V14:V16	0.315	0.003
V15:V17	0.577	0.000

4.6.3 Statistically insignificant relationships

Table 4.7 displays the statistically insignificant correlations ($p > 0.05$) identified between selected variable pairs. These results indicate notable associations, race/ethnicity, type of settlements (formal/informal/mobile), access to mine wasteland, and who is responsible for the rehabilitation of mine wastelands.

As shown in Table 4.7, the relationships between variables were statistically insignificant at p > 0.005. For instance, race/ethnicity (V2) does not significantly predict a person's knowledge of mine reclamation (V15), nor does living in formal settlement or an informal settlement (V5) predict willingness to contribute towards funding the reclamation of mine wastelands (16). Similarly, the association with the environmental conservation organisation (V12) does not significantly support local extraction of resources from mine wastelands (V13). The allowance of extraction of resources from mine wastelands (13) and benefiting from mine wastelands (V14), and duration of residency (V6) and participation in decision making (V11) weak negative correlation was identified.

Table 4.7: Statistical insignificance Spearman's rank-order correlations.

Variable pair	Spearman's (ρ)	p-value
V2:V15	-0.022	0.833
V5: V16	0.000	1.000
V6: V8	0.092	0.545
V13:V14	-0.203	0.055
V6:V16	-0.285	0.055
V6:V11	-0.225	0.134
V10:V15	0.005	0.962
V12:V13	-0.135	0.205
V18:V16	0.036	0.733

The statistical relationships presented in Table 4.6 and Table 4.7 were analysed using Spearman's correlation to identify the variables that influence local community awareness, perception and participation in mine wasteland rehabilitation. Some of the variable pairs demonstrated statistically significant correlations ($p < 0.005$), leading to the rejection of the null hypothesis, while others were statistically insignificant ($p > 0.005$), thereby supporting the null hypothesis.

Notably, qualifications, duration of residence in Brakpan and knowledge of mine wastelands were strongly associated with core behavioural outcomes such as willingness to contribute towards funding reclamation of mine wastelands. In contrast, demographic variables such as race/ethnicity, employment status, and type of settlements (formal/informal/mobile) showed no statistically significant influence.

These findings identify key social factors that inform the development of targeted mitigation strategies. The next section presents the results of quantitative data to complement qualitative findings.

4.7 Mine wasteland field analysis and observations

This section presents the assessments of soil erosion from mine wasteland in Brakpan (Kwa-Thema) using the RUSLE model. Field surveys, maps and satellite images were used to derive input parameters for the RUSLE model. The soil erosion risk was estimated and compared with both national and international acceptable tolerable soil loss limits. The images are presented in Figures 4.13 to 4.17.

4.7.1 Field observations from GPS and satellite imagery

Figure 4.13: Brakpan (Kwa-Thema) settlement adjacent to Mine wasteland (GPS coordinates, -26.323708, 28.409075).

Figure 4.13 illustrates the proximity of the mine wasteland to the nearby community of Kwa-Thema Phase 2, with only a road separating them. This road links to Tonk Meter

Road, which further connects to two other nearby communities: Sharon Park and Dunnottar.

Figure 4.14(a): Slope edge front side of Mine wasteland (GPS; -26.330451, 28.413819)

Figure 4.14(b): Slope edge of the Mine wasteland area in Brakpan (Kwa-Thema) (GPS; -26.330461, 28.413839)

Figure 4.14: Shows the steep slope on the front side of the Mine wasteland and evidence of environmental degradation in the surrounding environment.

Figure 4.14 displays the steep slope on the front side of the Mine wasteland and evidence of environmental degradation in the surrounding environment. The images reveal little or sparse vegetation, likely owing to contamination, and indicate that local communities have and/ are using the front site of the mine wasteland as an informal dumping site.

Figure 4.15(a): Overhead view section of Mine wasteland , illustrating how the area is laid out (GPS coordinates; -26.330744, 28.412897)

Figure 4.15(b): Overhead view of the Mine wasteland and adjacent Brakpan settlements (GPS coordinates; -26.330744, 28.412897)

Figure 4.15: Top section of the mine wasteland and on how this area is structured.

Figure 4.15 presents the top section of the mine wasteland and illustrates the structural layout of this area. The images reveal that vegetation cover is scarce, leaving the surface largely exposed and, therefore, highly vulnerable to soil erosion.

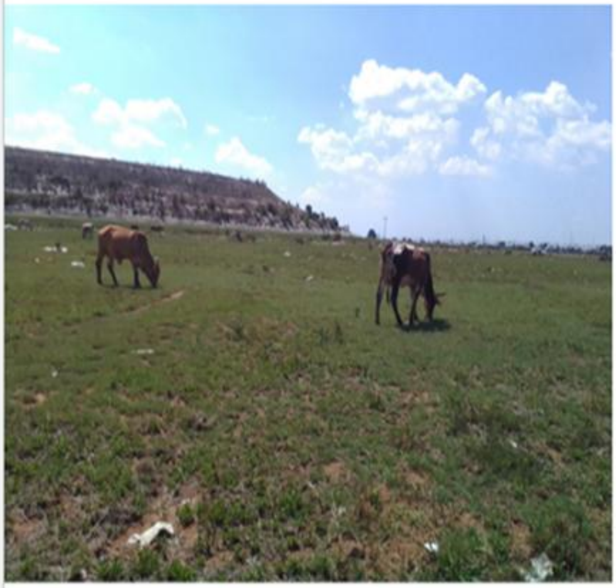

Figure 4.16(a): Depicts livestock grazing next to Mine wasteland (GPS Coordinates; -26.331431, 28.417325)

Figure 4.16(b): Cattle grazing adjacent to the Mine wasteland in Brakpan (GPS Coordinates; -26.331431, 28.417325)

Figure 4.16: Livestock grazing and accessing water near the Brakpan (Kwa-Thema) mine wasteland.

Figure 4.16 shows livestock grazing next to the mine wasteland in Brakpan (Kwa-Thema). The animals were observed feeding on grass and drinking from water sources in and around the degraded area.

Figure 4.17: Elevated view of the mine wasteland study area with Brakpan (Kwa-Thema) visible in the background.

Figure 4.17 shows the proximity of the mine wasteland to a Brakpan (Kwa-Thema) shopping complex, with the upper waste section clearly visible from the commercial area.

4.7.2 Soil erosion estimation using RUSLE model-based

The RUSLE was used to estimate the rate of soil loss per unit from Brakpan mine wasteland. The assessment of the images from Figure 4.13 to Figure 4.16 helped in deriving some of the values of K and LS, which were part of the empirical parameters for RUSLE. Likewise, both the C and P were also determined, and all derived values are presented in Table 4.8.

The prevalence of soil erosion in the mine wasteland is limited to moderate, based on the images above. The rainfall erosivity (R) was calculated at 401.5 MJ.mm/ha. h. yr from 2018 to 2023. The soil quality of mine wasteland is both sandy and loamy, putting the soil erodibility factor (K) at 0.25 tons. ha. h. ha^{-1} MJ^{-1} mm^{-1}, and slope length and steepness factor (LS) at 3 owing to its steepness (refer to Table 3.1). The mine wasteland Cover management factor (C) is 0.5 owing to dispersed vegetation and Support practice factor (P) is 0.5 because of tolerable control measures in place in mine wasteland. All the parameters are presented in Table 4.8.

Table 4.8: The parameter values used in the RUSLE estimation

Parameter	Description	Value
R	Rainfall erosivity	401.5 MJ.mm/ha. h. yr
K	Soil erodibility	0.25 tons. ha. h. ha^{-1} MJ^{-1} mm^{-1}
LS	Slope length and steepness factor	3
C	Cover management	0.5
P	Support practice	0.5

Therefore, the soil loss per unit area (A) of the Brakpan mine wasteland is calculated as follows.

A = $R\ x\ K\ x\ LS\ x\ C\ x\ P$

= A = $R\ x\ K\ x\ LS\ x\ C\ x\ P$

= 401.5 x 0.25 x 3 x 0.5 x 0.5

= 75.281 tons/ha/year

The rate of soil erosion in Brakpan (Kwa-Thema) mine wasteland is 75.281 tons/ha/year

Table 4.9: Tolerable soil loss limits nationally and internationally

Region	**Acceptable erosion rate (tons/ha/year)**	**Notes**	**Reference**
Present study	75.281		
South Africa	< 5 (General) and < (Sensitive)	Based on EIA, mine closure guidelines	DFFE, SA, 2021; DWS, SA, 2024
Canada	<10-20	Post mine reclamation	OMECP, 2020
European Union (EU)	< 1	Aim for natural background erosion	EU, 2024
Australia	<2 – 5	Based on post mining land use	MacEwan *et al*., 2023

Region	Acceptable erosion rate (tons/ha/year)	Notes	Reference
Food and Agriculture Organization of United Nations (FAO-UN)	<1	Not to exceed soil regeneration	FAO, 2023

The results obtained from the RUSLE model estimates indicate severe soil erosion in the Brakpan (Kwa-Thema) mine wasteland, with rates approaching 75.281 tons/ha/year. The estimated rate of soil erosion in Brakpan (Kwa-Thema) mine wasteland exceeds that of the acceptable erosion rate (tons/ha/year) of South Africa, the European Union, Australia, Canada, and the FAO (UN) as per Table 4.9 and Figure 4.6.

4.8 Heavy metals and radionuclides in the soil and water

This section presents the results of heavy metals and radionuclides identified in the soil and water samples obtained from the study area. Analysis included the radioactivity concentrations, Annual Effective Dose, and Excess Life Cancer Risk of samples collected from the study area. The measured results were compared with national, world-accepted set standards and public and occupational exposure levels recognized by national and international organizations (UNSCEAR, 2020; 2021; SAHPRA, 2022; WHO, 2022; DWS, SA, 2023).

The ICP-MS results for heavy metal concentrations in soil and water samples are presented in Table 4.10 and Table 4.13. The results obtained from measured activity concentrations (mg/kg and mg/L) of various elements in soil and water samples were compared and discussed with those of South Africa and international guidelines for acceptable limits.

4.8.1 Heavy metal concentrations in soil samples

The ICP-MS results of heavy metal concentrations (mg/kg) in soil samples collected around and away from Brakpan (Kwa-Thema) mine wasteland are presented in Table 4.10. The analysis detected several heavy metals, including Vanadium (V), Chromium (Cr), Cobalt (Co), Nickel (Ni), Copper (Cu), Zinc (Zn), Arsenic (As), Cadmium (Cd), Lead (Pb) and Uranium (U). Across the study area, concentrations ranged from <0.00115 to 129.0808 mg/kg. In contrast, the control soil sample (BP1) recorded significantly lower levels, with values ranging between <0.00002 and <0.00050 mg/kg (refer to Annexure H).

Table 4.10: ICP-MS results of heavy metal concentrations in soil samples collected around and away from the Brakpan (Kwa-Thema) mine wasteland.

Soil samples						
Sample	**BP1 (Control Sample)**	**BKS10**	**BKS16**	**BKS21**	**BKS28**	**Standard Deviation (SD)**
	mg/kg	***mg/kg***	***mg/kg***	***mg/kg***	***mg/kg***	
Be 9	<0.22500	0.341	0.326	0.320	0.3372	0.010
B 11	<0.05000	<0.05000	<0.05000	<0.05000	<0.05000	<0.05000
Na 23	18.373	79.870	192.589	39.5892	1076.6874	449.622
Mg 24	242.610	3845.862	2742.004	6045.0053	2662.1276	2104.380
Al 27	7760.371	9507.351	8335.408	13489.5033	8780.6580	2279.713
P 31	138.150	123.832	100.077	164.0879	156.6710	25.777
K 39	409.915	1257.215	2942.099	1469.9940	2269.4607	971.570
Ca 43	218.379	652.380	1952.380	1224.2159	15366.8424	6452,546
V 51	10.630	18.161	17.270	25.2789	16.1547	5.244
Cr 53	31.654	109.822	122.190	156.8019	99.4464	45,846
Mn 55	33.692	140.552	84.400	237.9763	147.6704	76.535
Fe 57	3177.388	22246.821	22924.875	34812.7560	22635.1620	11360.503
Co 59	1.806	8.934	18.493	27.8395	11.9864	9,874
Ni 60	9.799	58.083	78.462	129.0808	78.6180	43.010
Cu 63	5.009	26.737	47.193	33.9660	51.0565	18.377
Zn 66	17.678	34.720	17.658	46.3107	19.0286	12.944
As 75	1.005	58.299	71.102	56.1284	52.2226	27.074
Se 78	0.644	1.255	1.404	1.4296	1.8496	0.436
Mo 95	<0.00115	0.337	1.225	<0.00115	11.2414	6.056
Cd 111	<0.00208	0.012	0.005	0.0209	<0.00208	0.008
Sn 118	0.462	1.200	0.357	0.6308	0.4629	0.337

Soil samples						
Sample	**BP1 (Control Sample)**	**BKS10**	**BKS16**	**BKS21**	**BKS28**	**Standard Deviation (SD)**
	mg/kg	***mg/kg***	***mg/kg***	***mg/kg***	***mg/kg***	
Sb 121	0.107	0.748	0.797	0.5479	0.5300	0.273
Ba 137	31.993	25.307	35.818	32.7192	22.2455	5.627
Hg 201	0.011	0.237	0.109	0.1663	0.0359	0.093
Pb 208	9.125	16.885	7.742	11.3679	7.6351	3.847
U 238	0.367	7.765	10.731	7.6646	9.1599	3.985

Values reported as <0.01 mg/kg suggest that the isotope concentration was too low to be detected by ICP-MS.

The concentrations of selected heavy metals (As, Pb, Cd, Cr, Cu, Ni, Zn, Co and U) in soil samples (BKS10, BKS16, BKS21, BKS28 and BP1) were analysed using ICP-MS, and the statistical summary of minimum, maximum, average, and SD values is shown in Table 4.11. Overall, the concentrations varied considerably across the sampling sites. Pb measured from 7.635 mg/kg in BKS28 to 16.885 mg/kg in BKS10, with BKS21 peaked at 11.368 mg/kg and BP1 recording 9.125 mg/kg. Cu levels varied between 26.737 mg/kg in BKS10, 33.966 mg/kg in BKS21, 47.193 mg/kg in BKS16, and 51.057 mg/kg in BKS28, while BP1 measured 26.737 mg/kg. Cr concentrations ranged from 31.654 mg/kg in BP1 to 156.802 mg/kg in BKS21. Cd was below detection (<0.002 mg/kg) in BP1 and BKS28 but detected in BKS10 (0.012 mg/kg), BKS16 (0.005 mg/kg), and BKS21 (0.021 mg/kg). Ni ranged from 9.799 mg/kg in BP1 to 129.081 mg/kg in BKS21. Co concentrations varied from 1.806 mg/kg in BP1 to 27.840 mg/kg in BKS21. Zn ranged from 17.658 mg/kg in BKS16 to 46.311 mg/kg in BKS21. As concentrations ranged from 1.005 mg/kg in BP1 to 71.102 mg/kg in BKS16. V varied from 10.630 mg/kg in BP1 to 25.280 mg/kg in BKS21, while U ranged from 0.367 mg/kg in BP1 to 10.731 mg/kg in BKS16.

Table 4.11: Minimum, maximum, and average concentrations of selected heavy metals in soil samples collected from the Mine wasteland.

Heavy metals	**BP1**	**BKS10**	**BKS16**	**BKS21**	**BKS28**	**Min**	**Max**	**Average**	**SD**
Pb	9.125	16.885	7.742	11.3679	7.6351	7.6351	16.885	10.551	3.847
Cu	5.009	26.737	47.193	33.966	51.057	5.009	51.057	32.7924	18.377
Cr	31.654	109.822	122.19	156.802	99.446	31.654	156.802	103.9828	45.846
Ni	9.799	58.083	78.462	129.081	78.618	9.799	129.081	70.8086	43.010
Cd	<0.002	0.012	0.005	0.021	<0.002	0.005	0.021	0.0127	0.008
Co	1.806	8.934	18.493	27.840	11.986	1.806	27.84	13.8118	9.874
Zn	17.678	34.720	17.658	46.311	19.029	17.658	46.311	27.0792	12.944
As	1.005	58.299	71.102	56.128	52.223	1.005	71.102	47.7514	27.074
V	10.630	18.161	17.270	25.280	16.155	10.63	25.28	17.4992	5.244
U	0.367	7.765	10.731	7.665	9.160	0.367	10.731	7.1376	3.985

Values reported as <0.01 mg/kg suggests that the isotope concentration was too low to be detected by the ICP- MS (PerkinElmer, 2023).

The average concentrations of heavy metals in soil samples gathered from mine wasteland (study area) were compared with South African and international regulatory standards for soil quality, as summarised in Table 4.12. The results exhibit that most selected heavy metals (As, Pb, Cd, Cr, Cu, Ni, Zn, Co, and U) exhibit variable concentrations across the study area. Specifically, As, Cr, Cu, and U were measured at 47.75 mg/kg, 103.983 mg/kg, 32.792 mg/kg, and 7.137 mg/kg, respectively. These values exceed or approach the upper limits of acceptable standards set by South Africa and other countries. For instance, the permissible ranges for As, Cr, Cu, and U in soils are 5.800-60.000 mg/kg, 50.000-100.000 mg/kg, 16.000-100.000 mg/kg, and 1.400-4.1.00 mg/kg, respectively. These comparisons indicate that As, Cr, Cu, and U concentrations in the study area exceed national guidelines, and both Cr and U surpass those of international and national regulatory limits.

Table 4.12: Comparison of heavy metal concentrations in soil samples from current study area and regulatory standards from South Africa and other countries.

Study Country	Acceptable set standards and guidelines for heavy metals from different countries (mg/kg)									Reference
	As	**Pb**	**Cd**	**Cr**	**Cu**	**Ni**	**Zn**	**Co**	**U**	
Current study	47.751	10.551	0.013	103.983	32.792	70.809	27.079	13.812	7.137	
Germany	50.000	70.000	1.000	60.000	40.000	50.000	150.000	-	-	Solomon, 2021
Poland	-	100.000	3.000	100.000	100.000	100.000	300.000	50.000	2.080	
Australia	20.000	270.000	3.000	50.000	120.000	170.000	500.000	120.000	2.200	NEPC, 2013; Taylor *et al.*, 2023
Zambia	20.000	300.000	3.000	100.000	100.000	75.000	200.000	50.000	3.000	Banda, 2023; Solomon, 2021; ZEMA, 2020
Bulgaria	10.000	26.000	0.400	65.000	345.000	46.000	88.000	20.000	3.200	
Canada	12.000	140.000	10.000	64.000	63.000	50.000	200.000	300.000	4.100	CCME, 2021; Palmer, 2023
China	30.000	80.000	0.500	200.000	100.000	50.000	250.000	-	-	DFFE, SA, 2014; Solomon, 2021
Tanzania	12.000	200.000	1.000	100.000	200.000	100.000	150.000	-	-	
South Africa	5.800	20.000	7.500	6.500	16.000	91.000	240.000	91.000	2.290	
World average	30.000	140.000	2.800	120.000	139.000	-	275.000	125.000	2.670	Solomon, 2021; WHO, 2022
FAO/ WHO (World Health Organization) Guidelines	20.000	100.000	3.000	100.000	100.000	50.000	300.000	50.000	1.400	WHO, 2022

Acceptable set standards recorded as "-" means that no standard or guideline was available for that metal in the reference source.

4.8.2 Heavy metal concentrations in water samples

The concentrations (mg/L) of heavy metals measured in water samples from the Brakpan mine wasteland, analyzed by ICP-MS, are presented in Table 4.13. Elevated levels of V, Cr, Co, Ni, Cu, Zn, As, Cd, Pb and U were observed in the water samples (BPW1, BKW2, BKW4, BKW5 and BKW6), with concentrations ranging from below detection limits (<0.00002 mg/L) to 16.7988 mg/L across the mine-affected sites. In contrast, the control water sample (BPW1) recorded significantly lower concentrations, between <0.00002 and <0.00050 mg/L (See annexure H). Compared to soil samples from the same locations, the concentrations of heavy metals in water were generally much lower, reflecting the difference in medium, although the same metals were present in both matrices.

Table 4.13: ICP-MS results of heavy metal concentrations in water samples collected around and away from Mine wasteland in Brakpan.

Sample	**BPW1**	**BKW2**	**BKW4**	**BKW5**	**BKW6**	**SD**
Heavy metals	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	
Be 9	<0.009	<0.009	<0.009	<0. 009	0.0201	0
B 11	<0.00200	0.214	<0.00200	<0.00200	<0.00200	0
Na 23	6.139	57.292	204.281	97.9037	159.1603	78.883
Mg 24	1.159	18.261	132.271	97.7930	175.8976	74.404
Al 27	0.083	0.021	60.665	62.4824	113.4202	43.002
P 31	<0.27149	1.547	<0.27149	<0.27149	<0.27149	0
K 39	0.106	12.835	22.824	3.1199	2.8052	9.429
Ca 43	<4.51990	52.233	267.619	218.3550	230.4258	95.611
V 51	<0.00050	<0.00050	<0.00050	<0.00050	<0.00050	0
Cr 53	<0.00060	<0.00060	<0.00060	<0.00060	<0.00060	0
Mn 55	<0.00043	<0.00043	25.806	11.9380	22.6854	7.275
Fe 57	<0.00292	<0.00292	0.115	<0.00292	<0.00292	0
Fe 57	<0.00292	<0.00292	0.115	<0.00292	<0.00292	2.181
Co 59	<0.00002	0.00022	3.811	2.8119	5.1419	2.181
Ni 60	<0.00012	<0.00012	12.416	9.1270	16.7988	3.849
Cu 63	<0.00019	<0.00019	1.033	1.2930	2.2645	0.649
Zn 66	<0.00029	<0.00029	3.434	2.4241	4.4234	1.000

Sample	BPW1	BKW2	BKW4	BKW5	BKW6	SD
As 75	<0.00006	0.006	0.008	0.0105	0.0150	0.004
Se 78	<0.00114	<0.00114	0.032	0.0369	0.0432	0.005
Mo 95	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	0
Cd 111	<0.00008	<0.00008	0.004	0.0025	0.0048	0.001
Sn 118	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004	0
Sb 121	<0.00002	<0.00002	<0.00002	<0.00002	<0.00002	0
Ba 137	<0.00009	<0.00009	<0.00009	<0.00009	<0.00009	0
Hg 201	<0.00011	<0.00011	<0.00011	<0.00011	<0.00011	0
Pb 208	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004	0
U 238	<0.00006	<0.00006	1.163	1.1442	2.6249	0.849

Values reported as <0.01 mg/kg suggests that the isotope concentration was too low to be detected by the instrument (PerkinElmer, 2023).

Selected heavy metals (As, Pb, Cd, Cr, Cu, Ni, Zn, Co and U) in water samples from the study area (BPW1, BKW2, BKW4, BKW5, and BKW6) were analysed using ICP-MS. A statistical summary of minimum, maximum, average and SD values is presented in Table 4.14. Pb concentrations were consistently <0.00004 mg/L across all samples. V was <0.00050 mg/L and Cr <0.00060 mg/L in all samples. Cu measured <0.00019 mg/L in BPW1 and BKW2, while BKW4, BKW5 and BKW6 recorded 1.033, 1.293, and 2.265 mg/L, respectively. Ni concentrations were <0.00012 mg/L in BPW1 and BKW2, increasing to 12.416, 9.127, and 16.799 mg/L in BKW4, BKW5, and BKW6. Cd was <0.00008 mg/L in BPW1 and BKW2, and 0.004, 0.003, and 0.005 mg/L in BKW4, BKW5, and BKW6. Co ranged from <0.00002 mg/L in BPW1 to 5.142 mg/L in BKW6. Zn was <0.00029 mg/L in BPW1 and BKW2, and 2.424-4.423 mg/L in BKW4, BKW5, and BKW6. As was <0.00006 mg/L in BPW1, 0.00618 mg/L in BKW2, and 0.0081-0.0105 mg/L in BKW4-BKW6. U concentrations were <0.00006 mg/L in BPW1 and BKW2, and 1.1634, 1.144, and 2.625 mg/L in BKW4, BKW5 and BKW6. When compared with the soil concentrations (Table 4.11), most metals, such as As, Pb, V and

Cr showed relatively lower levels in water, while Ni, Co, Cu, Zn, and U were notably higher in water samples.

Table 4.14: Minimum, maximum and average concentrations of selected heavy metals in water samples collected from the Mine wasteland.

Heavy metals	**BPW1**	**BKW2**	**BKW4**	**BKW5**	**BKW6**	**Min**	**Max**	**Average**	**SD**
Pb	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004	0	0	0	0
Cu	<0.00019	<0.00019	1.033	1.293	2.265	1.033	2.265	1.530	0.649
Cr	<0.00060	<0.00060	<0.00060	<0.00060	<0.00060	0	0	0	0
Ni	<0.00012	<0.00012	12.416	9.127	16.799	9.127	16.799	12.781	3.849
Cd	<0.00008	<0.00008	0.004	0.003	0.005	0.003	0.005	0.004	0.001
Co	<0.00002	0.00022	3.811	2.812	5.142	0.0002	5.141	2.941	2.181
Zn	<0.00029	<0.00029	3.434	2.424	4.423	2.424	4.423	3.427	1.000
As	<0.00006	0.00618	0.0081	0.0105	0.015	0.0062	0.015	0.010	0.004
V	<0.00050	<0.00050	<0.00050	<0.00050	<0.00050	0	0	0	0
U	<0.00006	<0.00006	1.1634	1.144	2.625	1.144	2.625	1.644	0.849

Values reported as <0.01 mg/L suggest that the isotope concentration was too low to be detected by ICP-MS (PerkinElmer, 2023).

The average concentrations of heavy metals in water samples collected from mine wasteland (study area) are compared with South African, USEPA and FAO/WHO guideline values for heavy metals in Table 4.15. The measured average concentrations of heavy metals for this study were: As (0.010 mg/L), Pb (0.000 mg/L), Cd (0.004 mg/L), Cr (0.000 mg/L), Cu (1.530 mg/L), Ni (12.781 mg/L), Zn (3.427 mg/L), Co (2.941 mg/L) and U (1.644 mg/L). In comparison, the permissible limits set by South Africa, USEPA, and FAO/WHO are: As (0.010 mg/L), Pb (0.015-0.019 mg/L), Hg (0.00-0.006 mg/L), Cd (0.003-0.005 mg/L), Cr (0.050-0.100 mg/L), Cu (1.000-2.000 mg/L), Zn (0.500 mg/L), Co (0.100 mg/L), Ni (0.070 mg/L), and U (0.03 mg/L).

Table 4.15: Permissible thresholds for heavy metals in drinking water and measured concentrations in water samples from the Brakpan (Kwa-Thema) mine wasteland.

Country/ Organization	**Acceptable set standards and guidelines for heavy metals from different countries (mg/L)**										
	As	**Pb**	**Hg**	**Cd**	**Cr**	**Cu**	**Zn**	**Co**	**Ni**	**U**	
United States of America Environmental Protection Agency (USEPA)	0.010	0.015	0.002	0.005	0.100	1.300	0.500	0.100	n/a	0.030	USEPA. 2018; WHO, 2022
FAO/WHO	0.010	0.010	0.006	0.003	0.050	2.000	n/a	n/a	0.070	0.030	Drechsel *et al.*, 2023; WHO, 2022
Canada	0.010	0.010	0.001	0.007	0.050	2.000	1.170	n/a	n/a	0.030	CCME, 2019
Australia	0.010	0.005	0.001	0.002	0.050	2.000	3.000	2.000	0.020	0.030	NEPC, 2013; Taylor *et al.*, 2023
South Africa	0.010	0.010	0.000	0.003	n/a	1.000	5.000	n/a	n/a	0.030	DWS, SA 2021; DWS, SA 2023
Current study	0.010	0.000	0.000	0.004	0.000	1.530	3.427	2.941	12.781	1.644	

Values reported as <0.01 mg/L suggest that the isotope concentration was too low to be detected by ICP-MS (PerkinElmer, 2023).

4.8.3 Naturally occurring radionuclides in soil samples

Gamma spectrometry was conducted on 33 soil samples to assess activity concentrations of ^{238}U, ^{232}Th and ^{40}K. These included 20 samples from the Brakpan (Kwa-Thema) mine wasteland (main study area), 12 from adjacent mine wasteland sites and 1 control sample collected approximately 50 km away near an old sand mine area. The overall results obtained using the energy line method are presented in Table 3.5 and Annexure B. These measurements were also used to calculate the AED and ELCR, with the completed results provided in Tables 4.16 and Table 4.17.

Table 4.16 summarises the minimum, maximum, median, mean, and SD values of activity concentrations (Bq/kg) of the naturally occurring radionuclides across the main study area and control site. ^{238}U concentrations ranged from 12.780 to 409.730 Bq/kg, ^{232}Th from 3.980 to 74.140 Bq/kg, and ^{40}K exhibited the highest variability, spanning from 13.170 to 814.500 Bq/kg.

Table 4.16: Activity concentrations of naturally occurring radionuclides (^{238}U, ^{232}Th and ^{40}K) in soil samples collected from the Brakpan (Kwa-Thema) mine wasteland.

Sample no	Activity concentrations (Bq/kg)		
	^{238}U	^{232}Th	^{40}K
BP1 (Control Sample)	12.780	9.283	13.170
BKS3	131.880	19.341	378.500
BKS4	64.780	18.221	704.510
BKS5	89.080	21.783	814.500
BKS6	251.970	21.014	552.780
BKS7	136.070	8.243	373.740
BKS8	20.800	3.983	465.500
BKS9	47.300	74.139	327.100
BKS10	289.340	19.107	288.500
BKS11	111.070	5.200	164.500
BKS12	77.630	15.710	470.900
BKS13	264.270	18.694	345.100
BKS14	216.030	20.186	357.800
BKS15	59.600	15.625	465.800

Sample no	Activity concentrations (Bq/kg)		
	^{238}U	^{232}Th	^{40}K
BKS16	200.080	16.740	517.700
BKS17P	78.690	10.244	305.800
BKS18	229.100	12.851	475.00
BKS 19	169.130	24.855	493.600
BKS20	409.730	20.399	696.00
BKS21	172.600	20.951	402.00
BKS28	146.300	16.326	402.900
SD	94.080	11.070	207.670
Median	131.880	18.690	402.00
Min	12.780	3.980	13.170
Max	409.730	74.140	814.500
Mean	137.630	18.630	432.220

Table 4.17 depicts the statistical summary of minimum, maximum, median, mean and SD values of activity concentrations (Bq/kg) of naturally occurring radionuclides (^{238}U, ^{232}Th and ^{40}K) in soil samples collected from sites adjacent to the main study area. ^{238}U exhibited the highest activity concentrations, ranging from 34.300 to 302.680 Bq/kg. ^{40}K concentrations ranged from 20.530 to 144.700 Bq/kg, while ^{232}Th showed the lowest activity, between 7.420 and 36.570 Bq/kg.

Table 4.17: Activity concentrations of naturally occurring radionuclides (^{238}U, ^{232}Th and ^{40}K) in soil samples collected from sites adjacent to the Brakpan (Kwa-Thema) mine wasteland.

Sample ID	Activity concentrations (Bq/kg)		
	^{238}U	^{232}Th	^{40}K
L22	34.300	7.420	20.530
L23	221.920	22.070	64.680
L24	164.380	17.350	43.240
L26	302.680	36.570	144.700
L28	52.460	10.230	30.780
L29	60.630	11.480	29.390

Sample ID	Activity concentrations (Bq/kg)		
	^{238}U	^{232}Th	^{40}K
L30	51.670	10.370	29.600
L31	74.090	15.293	43.870
L32	54.750	10.581	30.740
L33	62.300	12.748	33.940
L34	59.570	11.708	41.960
L35	61.650	11.670	32.910
SD	83.020	6.940	33.350
Median	60.630	11.480	32.910
Min	34.300	7.420	20.530
Max	302.680	36.570	144.700
Mean	100.320	14.080	44.790

4.8.4 Isotopic activity ratios

Secular equilibrium in radioactive series can be indicated by the isotopic activity ratios between parent and daughter radionuclides. For the ^{238}U series, equilibrium is reached when $^{226}Ra/^{214}Pb = 1$ and $^{214}Pb/^{214}Bi = 1$, and for the ^{232}Th series, when $^{228}Ac/^{212}Bi = 1$ and $^{212}Pb/^{212}Bi = 1$ (Trichet, 2022). The isotopic activity ratios for ^{238}U and ^{232}Th series were measured for all samples collected from the main study area, adjacent sites and the control area, and are presented in Table 4.18. In most samples, the ratios were approximately equal to one. The mean values of $^{226}Ra/^{214}Pb$, $^{214}Pb/^{214}Bi$, $^{228}Ac/^{212}Pb$, and $^{212}Pb/^{212}Bi$ were 0.960, 1.370, 2.480 and 1.760, respectively (refer Annexure I).

Table 4.18: Isotopic activity ratios of ^{238}U and ^{232}Th series in soil samples from the Brakpan (Kwa-Thema) mine wasteland and surrounding areas.

Sample code	**Isotopic activity ratios of ^{238}U series**		**Isotopic activity ratios of ^{232}Th series**	
	$^{226}Ra/^{214}Pb$	**$^{214}Pb/^{214}Bi$**	**$^{228}Ac/^{212}Pb$**	**$^{212}Pb/^{212}Bi$**
BP1 (Control Sample)	0.999	1.004	1.652	1.440
BKS3	0.971	1.094	1.541	1.626
BKS4	0.981	1.059	1.466	1.461

Sample code	Isotopic activity ratios of ^{238}U series		Isotopic activity ratios of ^{232}Th series	
	$^{226}Ra/^{214}Pb$	$^{214}Pb/^{214}Bi$	$^{228}Ac/^{212}Pb$	$^{212}Pb/^{212}Bi$
BKS5	0.954	1.149	1.609	1.595
BKS6	0.965	1.093	3.291	3.453
BKS7	0.944	1.195	0.492	1.637
BKS8	0.675	3.579	0.144	1.433
BKS9	1.551	1.361	0.997	0.950
BKS10	0.981	1.084	1.958	2.332
BKS11	0.895	1.707	0.187	2.021
BKS12	0.741	2.196	1.040	1.653
BKS13	0.621	2.140	1.302	2.139
BKS14	0.683	1.564	1.435	1.985
BKS15	0.641	1.997	1.299	1.794
BKS16	0.718	1.706	1.394	2.115
BKS17P	0.863	1.221	1.646	2.305
BKS18	0.652	1.985	1.336	2.008
BKS19	1.005	0.986	11.285	1.645
BKS20	1.005	0.985	1.340	1.000
BKS21	1.015	0.957	1.600	2.008
BKS28	1.006	0.984	0.000	1.235
L22	1.027	1.006	4.485	1.341
L23	1.026	1.009	2.782	1.412
L24	1.029	1.012	3.556	1.289
L25	1.013	1.020	3.070	1.438
L26	1.013	1.006	3.829	1.480
L27	1.021	1.008	4.050	1.465
L28	1.025	1.000	3.652	1.198
L29	1.030	1.014	4.701	1.401
L30	1.024	1.002	3.363	1.425
L31	1.039	0.996	3.808	1.325
L32	1.014	0.978	7.964	1.796

Sample code	Isotopic activity ratios of ^{238}U series		Isotopic activity ratios of ^{232}Th series	
	$^{226}Ra/^{214}Pb$	$^{214}Pb/^{214}Bi$	$^{228}Ac/^{212}Pb$	$^{212}Pb/^{212}Bi$
L33	1.026	1.018	9.913	1.706
L34	0.999	1.004	1.652	1.440
L35	0.971	1.094	1.541	1.6260
SD	0.190	0.640	2.160	0.560
Median	0.980	1.090	1.540	1.640
Min	0.620	0.960	0.140	0.950
Max	1.550	3.580	11.290	3.450
Mean	0.960	1.370	2.480	1.760

4.8.4.1 The correlation between naturally occurring radionuclides (^{238}U. ^{232}Th and ^{40}K) activities for soil samples of mine wasteland

The Correlation Coefficient (R) between the radionuclides (^{226}Ra (as a daughter of ^{238}U). ^{232}Th and ^{40}K activity concentrations for soil samples was calculated. So, to determine if there is any relationship between these radionuclides in change and movement owing to rain and wind on mine wasteland. The Pearson correlation coefficient (R) was used to measure the strength between linear dependence two variables and the equation below used to calculate the Correlation Coefficient (Wang *et al.*, 2023).

$$R^2 = \frac{(\Sigma xy - n\bar{x}\,\bar{y})^2}{(\Sigma x^2 - n\bar{x}^2)\,(\Sigma y^2 - n\bar{y}^2)} \qquad 10$$

Whereby x and y are data points and $\bar{x}$ and $\bar{y}$ are mean of n data points, hence we can classify the type of correlation by considering as one variable increase what happens to the other variable.

- Negative correlation – the other variable has a proclivity to decrease.
- Positive correlation – the other variable has a proclivity to increase.
- No correlation – the other variable does not incline to either decrease or increase.

Correlation is an effect size and therefore, we can vocally label the strength of correlation using the guide that (UNSCEAR, 2020; 2021) recommends for the absolute value of R^2 0.00-0.19 (very weak). 0.20-0.39 (weak). 0.40-0.59 (moderate). 0.60-0.79 (strong) and 0.80-1.0 (very strong), respectively. The correlation between ^{226}Ra. ^{232}Th and ^{40}K were calculated from the results of activity concentrations of radionuclides tabulated in Table

4.16 and Table 4.17. In line with Figure 4.18, the correlation between ^{238}U and ^{232}Th is (R^2 = 0.045), ^{238}U and ^{40}K is (R^2 = 0.132) and ^{232}Th and ^{40}K is (R^2 = 0.0415).

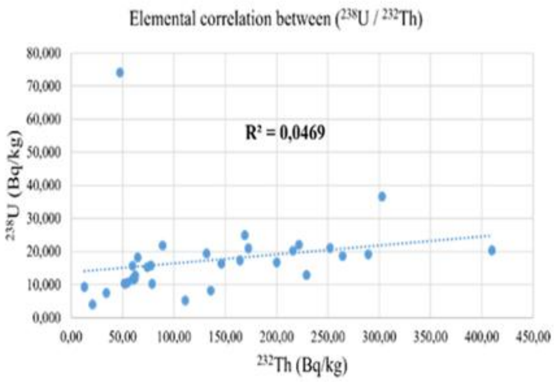

Figure 4.18(a): Correlation between $^{238}U/^{232}Th$ for collected soil samples

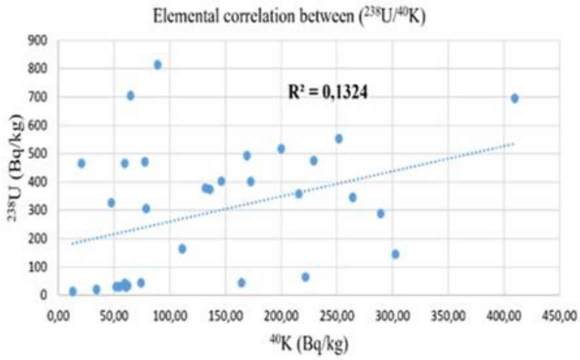

Figure 4.18(b): Correlation between $^{238}U/^{40}K$ for collected soil samples

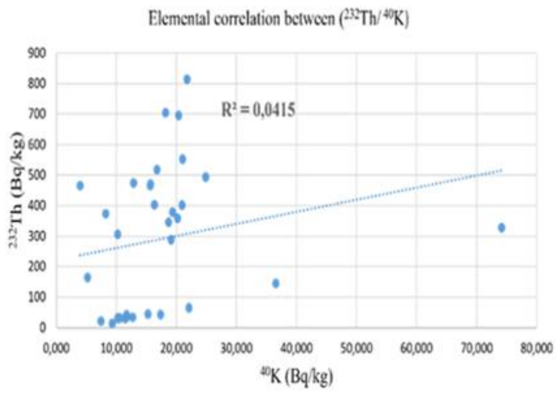

Figure 4.18(c): Correlation between $^{232}Th/^{40}K$ for collected soil samples

Figure 4.18: Correlation between $^{238}U/^{232}Th$, $^{238}U/^{40}K$, $^{232}Th/^{40}K$ for collected soil samples.

4.8.4.2 Comparison of activity concentrations with similar studies

The activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in soil samples from the study area were compared with values from the same region, as well as South African and international guideline limits. As shown in Table 4.19, the mean activity concentrations of ^{238}U (137.630 Bq/kg), ^{232}Th (18.630 Bq/kg), and ^{40}K (432.220 Bq/kg) in soils from the study area exceed the worldwide recommended standards.

Table 4.19: Mean activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in soil samples from the study area were compared with values from South Africa and other countries.

Country		Activity concentration Bq/Kg			
		^{238}U	^{232}Th	^{40}K	
Brakpan. South Africa	Main study area	137.630	18.630	432.220	
	Adjacent sites	89.530	14.790	45.530	
	Control sample	12.780	9.280	13.170	
Zambia. Kitwe		102 ± 76	57	740	Mulwanda *et al*., 2024
Sana'a. Yemen		48.2 ± 4.4	41.7 ± 4.5	939.1 ± 36	Al-Qadhi, 2017
Johannesburg. South Africa		32 ± 7	27 ± 13	208 ± 29	Nkosi *et al*., 2023
Punjap. Pakistan		58.000	83.900	445.200	Muhammad *et al*., 2019
Australia		30.100 ± 3.000	53.400 ± 5.100	504 ± 75.400	Lottermoser, 2004
Nigeria		22.900	17	144	Bello *et al*., 2022
Romania		38 ± 6.200	35.500 ± 3.000	504 ± 38.900	Roman, 2023
China		537 ± 966	130 ± 98	983 ± 382	Li *et al*., 2023
Spain		39.500 ± 1.500	32.400 ± 1.200	479.300 ± 12.500	Moreno *et al*., 2019
Canada		90 ± 43	32 ± 4.500	410 ± 30	QMENR, 2020
USA		36 ± 6	32 ±5	410 ± 15	NRC, 2020
Worldwide average		35	45	420	ICRP, 2020

The radiological health hazards associated with NORMs in soil samples from the Brakpan (Kwa-Thema) mine wasteland were calculated using Equations 5-9 in Chapter 3. The results are presented graphically in Figures 4.19 and 4.20 and are also provided in Annexure B.

The AED was calculated for soil samples from Brakpan (Kwa-Thema) mine wastelands to assess radiological hazards and its values ranged from 0.070 mSv/year to 1.414 mSv/year as depicted in Figure 4.19.

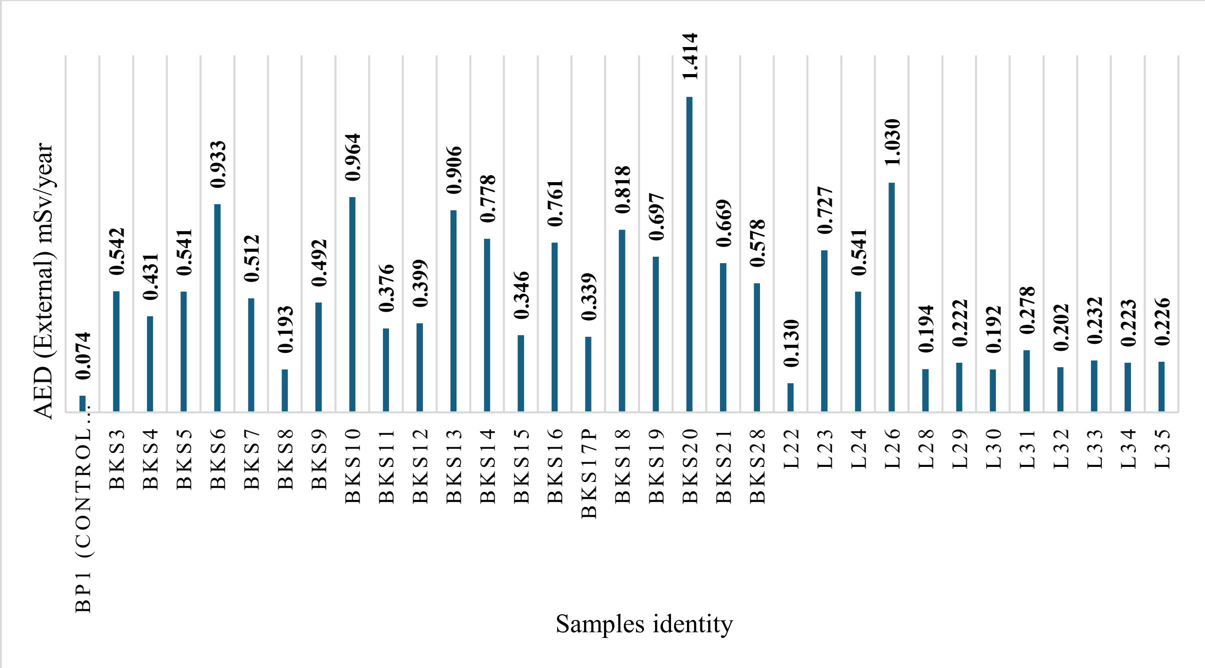

Figure 4.19: The AED determined in the soil samples from Brakpan (Kwa-Thema).

Figure 4.20 presents the ELCR values calculated for soil samples from mine wastelands using equations 8 and 9 from Chapter 3. The observed ELCR values ranged from 0.050 to 0.990.

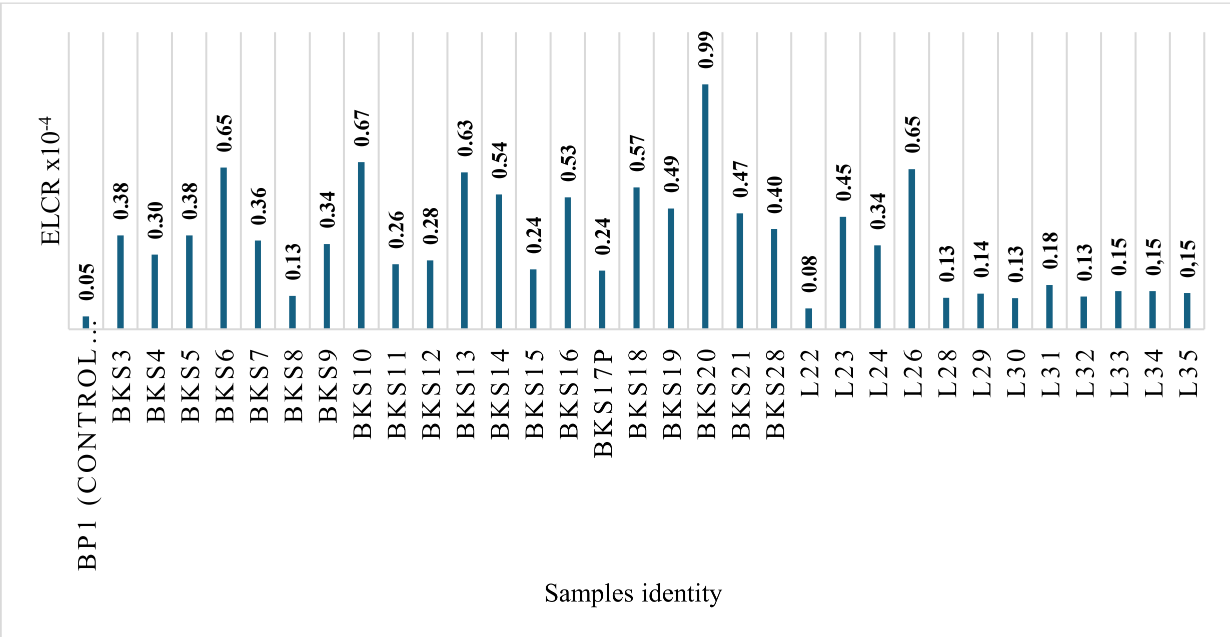

Figure 4.20: ELCR of soil samples from Brakpan (Kwa-Thema).

The radiological health hazards associated with naturally occurring radioactive materials (NORMs) in soil samples from the Brakpan (Kwa-Thema) mine wasteland. The AED and ELCR were calculated for all soil samples and ranged from 0.070 to 1.414 mSv/year, as shown in Figure 4.18 and Figure 4.19. These values were compared with regulatory limits from South Africa and international standards, summarised in Table 4.20. The highest detected AED in this study was 1.414 mSv/year, and the ELCR was 0.99×10^{-4}.

Table 4.20: Regulatory limits for AED and ELCR, and the detected values for AED (1.414 mSv/year) and ELCR (0.99×10^{-4}) in soil samples from the Brakpan mine wasteland.

Country	**Public AED limit (mSv/year)**	**Occupational AED limit (mSv/year)**	**ELCR limit**	
South Africa	1	20 mSv/year and, Over 5 years (≤50 mSv/year in any one year)	$1x10^{-4}$	ICRP, 2020; NNR, 2021
Zambia	1	n/a	$1x10^{-4}$	ICRP, 2020; Mulwanda *et al*., 2024
Australia	1	20 mSv/year (≤50 mSv/year in any one year)	$1x10^{-4}$	ICRP, 2020
Canada	1	20 mSv/year for nuclear energy worker, 50 mSv single year max and 100 mSv/year or max over 5 years	$1x10^{-4}$	ICRP, 2020; Government of Quebec, 2020

Value reported n/a suggests not publicly available data

4.9 Conclusion

The results of the Brakpan (Kwa-Thema) mine wasteland case study confirm significant environmental degradation associated with historical mining activities in the area. Laboratory analysis of soil and water samples revealed elevated concentrations of heavy metals and radionuclides exceeding several national and international environmental quality thresholds. Spatial analysis, erosion modelling, and field observations further indicated extensive contamination, land degradation and unrestricted community access to mine wastelands, which may increase potential environmental and human health risks. Community survey findings also revealed varying levels of environmental awareness and concern regarding the impacts of mine wastelands. Collectively, these findings highlight the need for improved management, rehabilitation, and community engagement strategies in the affected areas. The results provide the empirical basis for the broader interpretation and policy discussion presented in Chapter 5.

Chapter 5: Discussion

5.1 Introduction

This chapter discusses the findings obtained from the study using structured questionnaires, maps, images and two radiometric techniques. The aim of the study was to evaluate the community perceptions, estimate soil erosion using RUSLE modelling and determine the activity concentrations of heavy metals and NORMs in the soil and water samples using ICP-MS and gamma ray spectrometry. These results were compared and assessed for their environmental and health risks associated with the Brakpan (Kwa-Thema) mine wasteland.

5.2 Community participation, socio-demographics and perceptions

The findings reveal strong links between the socio-demographic characteristics, contamination patterns and the physical degradation within the Brakpan (Kwa-Thema) mine wasteland. Participation in the survey was predominantly male (73% male and 27% female), reflecting gender patterns often seen in mining communities across the Far West Rand, Gauteng Province (Cole *et al*., 2022). While the men dominated responses, the views from women still provided valuable insights into how environmental risks are perceived across gender lines.

Opposition to resource extraction from mine wasteland was widespread (71%), underscoring how the attitudes of the local community toward mine wasteland use are influenced by environmental and social concerns. This also reflects the involvement of the local community in rehabilitation efforts and sustainable land-use planning. Similar findings have been observed globally (UNEP, 2018; Maphosa, 2023), where mining-affected communities resist new mining activities unless transparent decision-making and environmental safeguards are in place.

Educational attainment also shaped perceptions. Although most respondents had only grade 8-12 qualifications (46%), this literacy level still played a significant role in shaping their environmental awareness. A positive correlation was observed between qualifications and knowledge of mine reclamation, suggesting that even secondary-level education improves awareness of what mine reclamation entails and why it is important. Nguyen *et al*. (2023) and Reuters (2024) found similar patterns in Zambia and Canada, where education enabled communities to interpret environmental change more critically. In Brakpan, this indicates that awareness campaigns can leverage existing literacy levels to enhance community knowledge about reclamation and environmental management.

Although 73% of participants recognised the dangers posed by mine wastelands, half had lived in the Brakpan area for more than seven years. This suggests that awareness does not necessarily translate into relocation or avoidance. Economic limitations and strong community ties to the area remain barriers. Otto *et al*. (2020) and Azinheira *et al*. (2023) similarly note that financial constraints and social networks are powerful barriers that prevent relocation from hazardous environments, thereby revealing how structural inequalities keep vulnerable communities in contaminated landscapes.

Another recurring theme was the community's exclusion from decision-making processes. Respondents reported limited awareness of reclamation initiatives in Brakpan (Kwa-Thema), suggesting weak communication, insufficient stakeholder involvement and inadequate environmental education. Smith *et al*. (2023) highlight that poor information flow and top-down governance are common barriers in post-mining contexts, eroding trust and reinforcing community marginalization.

Race did not appear to influence reclamation knowledge despite the sample majority being Black (77%). This aligns with Brown *et al*. (2023), who argue that environmental awareness is shaped more by access to information and participation opportunities than by race. Similarly, the type of settlement did not influence willingness to contribute financially to mine reclamation. Instead, 63% of participants rejected financial contributions, reflecting economic hardship and the belief that government and mining companies should carry the primary responsibility for rehabilitation. This finding aligns with Kaonda *et al*. (2024), who noted that post-mining communities often assign responsibility for rehabilitation to governments and mining firms, perceiving them as the primary instigators and facilitators of mining-related impacts.

Free access to mine wasteland was common among community members (72%), showing a lack of control measures and continued reliance on unsafe areas. However, access alone did not shape how residents perceived the mine wasteland, suggesting that familiarity does not equate to benefit. The relationship between resource extraction and perceived benefits was weak and insignificant, showing that those who extract sand or graze animals do so out of necessity rather than economic opportunity. Similar patterns were reported in Carletonville and Krugersdorp where communities used contaminated land for grazing and/or metal collection owing to limited alternatives (Mpanza, 2022; Nkosi *et al*., 2023). Employment in mining (30%) also did not translate into greater awareness of reclamation (54%), possibly because most mining jobs are operational rather than environmental, meaning employees are not exposed to reclamation planning or monitoring (Azinheira *et al*., 2023).

Nearly half of respondents (48%) believed the government is responsible for the rehabilitation of mine wastelands, showing a weak correlation with willingness to contribute financially. This reflects a common norm in environmental governance where institutional responsibility is emphasised over community, especially in disadvantaged contexts (Cole *et al*., 2022; Mensah *et al*., 2023). However, successful reclamation requires joint responsibility, effective communication and inclusive participation to build trust and ensure long-term sustainability in areas like Brakpan (Kwa-Thema).

Health risks were a central concern in shaping the community's perceptions. Dust exposure and delayed rehabilitation were the most cited concerns (38%). Participants shared lived experiences such as children swimming in contaminated ponds next to mine wasteland, skin irritation, the spread of contaminants into nearby homes and houses being blanketed in dust like a second skin. These fears are well-founded. Previous studies have shown that dust from gold mine tailings in Johannesburg and the West Rand contains uranium and heavy metals that pose significant health and environmental risks (Iyaloo, 2020; Nkosi *et al*., 2020). Similar challenges have been documented in Mount, McClure (Australia) and Sudbury (Canada), where prolonged exposure to mine dust from mines and smelters caused community exposure until major interventions reduced risks (OMECP, 2020; MacEwan *et al*., 2023). The Brakpan experience reflects these global patterns and highlights the urgent need for dust suppression and air monitoring as immediate interventions.

Those residing close to mine wasteland also reported loss of land and livelihood (33%), illustrating how erosion and contamination prevent safe land use and hinder farming and/or other income-generating activities. This mirrors findings from the Free State and West Rand, where mine-affected communities experienced reduced agricultural productivity and food security owing to mining-related contamination (Andraos *et al*., 2018; Mpanza, 2022; O'Donnell *et al*., 2024). In Brakpan, livelihood loss deepens poverty and exclusion, showing that rehabilitation should address both environmental risks and the restoration of productive land to support households' resilience.

5.3 Heavy Metal Contamination in Soil and Water (ICP-MS)

Heavy metals and radioactive elements in water and soils within mined areas pose significant risks to both the environment and human health. This study confirmed elevated concentrations of U, As, Cr, Cu and Ni beyond South African and international thresholds (see Table 4.11 and Table 4.12). For instance, U reached 10.731 mg/kg in sample BKS16, exceeding the national limit of 2.290 mg/kg. Such levels are concerning owing to U's dual chemical and radiological toxicity, which can lead to kidney damage, cancer and other chronic health effects upon prolonged exposure. Similarly, As peaked at 71.102 mg/kg in BKS16 (over 12 times the national limit of 5.800 mg/kg), Cr at 156.802 mg/kg in BKS21 (threshold 6.500 mg/kg), Cu at 51.057 mg/kg in BKS28 (threshold 16 mg/kg), and Ni at 129.081 mg/kg in BKS21 (threshold 91 mg/kg). These concentrations indicate that the Brakpan (Kwa-Thema) mine wasteland is heavily burdened by legacy contamination, reflecting both the historical deposition of mining residues and ongoing geochemical mobilisation of metals from waste materials. These contamination patterns are strongly associated with the historical mining of gold in the Brakpan area, where gold-bearing ores of the Witwatersrand Basin are enriched with U as a co-occurring element. U forms part of the mineralised system and was historically recovered as a by-product of gold extraction. As a result, the processing and deposition of mine tailings have contributed to the co-release and long-term accumulation of U (as NORM) alongside associated heavy metals, thereby shaping the observed geochemical signatures in both soil and water.

Comparable contamination patterns have been documented in other parts of the Witwatersrand Basin, where Moshupya *et al*. (2022) report elevated U, As and Ni concentrations linked to historical gold mining and inadequate rehabilitation. Likewise, Mashamaite (2023) and Sibuyi *et al*. (2023) found that soil U and As levels in the Krugersdorp and Carletonville mining belts exceeded global safety thresholds, emphasising the persistence of heavy metals in reclaimed and abandoned mine areas. In the same vein, studies by Ali *et al*. (2023) and OALA (2021) in the Sudbury Basin (Canada) similarly observed that historical mine residues contribute to long-term contamination, often exceeding natural attenuation capacity. The consistency between these findings and the current study underscores the cross-regional nature of heavy metal pollution in mining environments, highlighting the urgent need for active remediation rather than passive recovery.

The magnitude of exceedance in this study designates the Brakpan (Kwa-Thema) site as a hotspot of contamination, with potential long-term persistence owing to the slow natural reduction of heavy metals. Elevated concentrations in both soil and water imply mixed point and non-point pollution sources, consistent with mine tailings seepage, AMD and surface runoff (Baloyi *et al*., 2024). Moshupya *et al*. (2022) and Mabaso (2023) further note that spatial variability in heavy metal concentrations across Witwatersrand Basin is shaped by historical ore extraction intensity, waste management inefficiencies and current land use practices.

Water samples (BKW2, BKW4, BKW5, BKW6) also contained elevated U (2.625 mg/L in BKW6; FAO/WHO limit 0.030 mg/L), Ni (16.799 mg/L), and Co (5.142 mg/L), along with moderate Zn and Cu contamination (Tables 4.14-4.15). These findings mirror those of Banda *et al*. (2023) and Tibanea *et al*. (2023), who attributed similar contaminant profiles in the Gauteng and Copperbelt mining basins to leaching, acid generation and runoff under acidic conditions. The presence of U at nearly 91 times the FAO/WHO limit is particularly alarming for nearby communities reliant on surface and groundwater resources. Chronic exposure to Ni and Co is associated with gastrointestinal, dermatological, cardiovascular, and carcinogenic effects, while moderate levels of Zn and Cu may exacerbate ecological stress through synergistic toxicity (Yabe *et al*., 2020; Ndlovu *et al*., 2023).

The elevated heavy metal concentrations pose both toxicological and radiological risks. U, As, Cr, Ni and Co can bio-accumulate, affecting kidney function, cardiovascular health, fertility and neurological systems. Environmentally, these metals disrupt soil microbial activity, reduce vegetation cover, degrade infrastructure and threaten aquatic ecosystems (LaRowe *et al*., 2023; Ndlovu *et al*., 2023).

The contamination patterns in Brakpan (Kwa-Thema) are consistent with other mining-affected regions internationally. For instance, U and Ni levels are comparable to Mount McClure (Australia), As and Ni to Sudbury Basin (Canada), and Cu and U to Kitwe

(Zambia). Brakpan samples BKS21, BKS28, BKS16, and BKW6 yield similar results to those documented in these regions (CCME, 2021; Mulwanda *et al*., 2024; Taylor *et al*., 2023). This suggests that contamination is part of a broader pattern where abandoned or poorly managed sites continue to release heavy metals and radionuclides into surrounding environments (OALA, 2021; Banda, 2023; Raji *et al*., 2023).

Variations in metal concentrations are influenced by soil chemistry, pH, organic matter, clay content and historical mining activities (Lourenco *et al*., 2021). Site-specific conditions explain why certain locations, such as BKS16 or BKW6, exhibit higher contamination than others. Overall, the high concentrations of U, As, Cr, Ni and Co indicate both immediate environmental hazards and potential long-term public health burdens if mitigation strategies are not implemented.

5.4 Radiological Hazards (Gamma Spectrometry)

Gamma spectrometry results revealed that the ^{238}U activity concentrations averaged 137.630 Bq/kg, which is significantly above the global average of 35.000 Bq/kg, while ^{232}Th (18.630 Bq/kg) was below and ^{40}K (432.220 Bq/kg) was above the world average (Table 4.19). The highest annual AED recorded in the study was 1.414 mSv/year (sample BKS20) (Figure 4.18), exceeding the recommended public limit of 1.000 mSv/year set by both the NNR and ICRP. The corresponding ELCR values ranged from 0.05×10^{-4} to 0.99×10^{-4} (Figure 4.19), which are still below the permissible threshold of 0.0004 (0.04%).

These findings are consistent with previous studies that reported elevated uranium series radionuclides in mine-impacted soils of the Witwatersrand Basin, specifically in Carletonville and Randfontein (Mkandawire, 2019; Nkosi *et al*., 2023). Similarly, Ibrayeva *et al*. (2024) observed that abandoned uranium and gold mines in Kazakhstan exhibited uranium activity concentrations two to four times higher than world averages, comparable to the current study. Lottermoser *et al*. (2004) in Australia and Mulwanda *et al*. (2024) in Zambia also noted that elevated ^{238}U and ^{40}K levels in mine-adjacent soils indicate persistent NORMs enrichment caused by ore weathering and tailings dispersion.

The elevated AED values in this study reinforce the notion that mine wastelands, particularly those associated with historical gold and uranium extraction, act as persistent secondary sources of gamma-emitting radionuclides. This finding aligns with

Mkandawire (2019) and Rotimi *et al*. (2021), who reported AED levels exceeding 1 mSv/year in gold mining areas, indicating potential chronic low-dose exposure risks for nearby residents. When such radiological exposure is compounded by heavy metal contamination, the resultant health risks become both chemical and radiological, warranting integrated risk management approaches (Meiers *et al*., 2023; Nkosi *et al*., 2023; Ibrayeva *et al*., 2024).

Disequilibrium in isotopic ratios, as depicted in Table 4.18, suggests secular equilibrium was not fully achieved across all samples, indicating ongoing environmental disturbance in mine wastelands. The isotopic activity ratios between parent and daughter radionuclides ($^{226}Ra/^{214}Pb$= 0.960) and the weak correlation between radionuclides ($^{238}U/^{40}K$; $R^2 < 0.132$) imply slight disequilibrium, a phenomenon commonly observed in disturbed or post-mining environments. Studies by Mkandawire (2019) and Omogunloye *et al*. (2024) corroborate this finding, attributing it to the differential mobility of elements where potassium tends to migrate more freely, while uranium and thorium remain strongly adsorbed onto soil matrices owing to their higher affinity for organic matter and oxides. This disequilibrium, therefore, serves as a tracer of both geochemical remobilisation and anthropogenic disturbance in the mine wasteland.

5.5 Erosion risk (RUSLE) and environmental linkages

Mine wastelands are highly susceptible to erosion; therefore, RUSLE modelling was adopted to estimate and provide a valuable spatial distribution of soil loss risk in Brakpan (Kwa-Thema). The RUSLE modelling estimated soil loss at 75.281 tons/ha/year, which is far above the thresholds for South Africa (<5 tons/ha/year), Australia (<2–5 tons/ha/year) and Canada (<6.7 tons/ha/year) (Table 4.6). This clearly indicates that the Brakpan mine wasteland is experiencing severe soil degradation that exceeds global tolerance limits.

These findings are in close agreement with those of Kumar *et al*. (2022) and van Wyk *et al*. (2022), who also report high erosion rates in post-mining landscapes characterised by low vegetation cover, loose soil aggregates and disturbed geomorphology. Similarly, Van Wyk *et al*. (2019) and Bredenhand *et al*. (2023) documented annual soil losses exceeding 60 tons/ha/year in mine tailing environments across the Witwatersrand Basin, attributing such high values to the absence of erosion control measures and poor land reclamation practices, a concern also emphasised by Cole *et al*. (2024), who linked inadequate post-mining rehabilitation to persistent erosion and stability risks across South Africa's goldfields.

However, the results of this study exceed those observed by Bredenhand *et al*. (2023) in the Mpumalanga coalfields, where RUSLE-estimated erosion ranged between 15 and 30 tons/ha/year. This suggests that the Brakpan (Kwa-Thema) wasteland may be more severely degraded, possibly due to gold and uranium tailings, which alter soil structure and reduce infiltration. The overlap between high erosion areas and heavy metal hotspots further demonstrates that physical degradation and chemical contamination are mutually reinforcing processes, consistent with observations by Laker (2023) and Truong *et al*. (2020) in Australia's Mount McClure, mining district and Smith *et al*. (2023) in Canada's Sudbury mining region.

Overall, the findings of this study support the view that erosion intensity in mine wastelands is driven not only by climatic factors but also by anthropogenic disturbances, especially where reclamation efforts are lacking. The convergence of RUSLE-derived soil loss, vegetation scarcity and contamination patterns underscores the urgent need for integrated mine rehabilitation strategies, including terracing, contour ploughing, re-vegetation, and soil binding interventions, to reduce both radiological and geochemical risks.

5.6 Integrated implications

Overall, the Brakpan (Kwa-Thema) mine wasteland shows a complex interaction of socio-economic exclusion, severe multi-contamination (U, As, Cr and Ni) and a high rate of soil erosion. These interactions highlight Brakpan's unique vulnerability to both social and environmental risks, underscoring the need to evaluate mitigation strategies tailored to the governance and geochemical conditions of the area.

The merging of socio-economic and governance barriers, together with chemical and physical hazards, exhibits the urgent need for integrated rehabilitation strategies, as is also pointed out by DFFE, SA (2022; 2023) and Mpanza (2022). Such strategies should combine local communities' involvement, sustained environmental education and contaminant remediation, forming an integrated approach to addressing environmental and socio-economic risks.

In addition, the findings of this study have direct policy and practical implications for mine wasteland management in South Africa and similar mining-affected regions. From a policy perspective, the findings suggest that the enforcement of existing legislative frameworks such as the MPRDA of 2002 and NEMA of 1998 is often insufficient or inconsistently implemented in mining-affected regions (DFFE, 2022; 2023; South Africa, 2024a), particularly in relation to mine closure, financial provisioning and long-term environmental monitoring. The observed levels of contamination and erosion indicate that current compliance and post-rehabilitation monitoring measures may be insufficient or inconsistently implemented (Chetty *et al*., 2021; Cole *et al*., 2022; Mpanza, 2022). Strengthening regulatory oversight and accountability mechanisms is therefore critical to ensure that mining companies fulfil their rehabilitation obligations.

From a practical and environmental management perspective, the study highlights the need for immediate and targeted rehabilitation interventions. These include the implementation of dust suppression measures to reduce airborne contaminants, the application of phyto-stabilisation and revegetation using indigenous and metal-tolerant plant species to limit contaminant mobility, and the installation of erosion control structures such as terracing, slope reduction and surface stabilisation to minimise soil loss (Truong *et al*., 2020; Omoregie *et al*., 2023; Jansen van Vuuren *et al*., 2024). The integration of RUSLE modelling into municipal and environmental planning frameworks can further support the identification of erosion hotspots and prioritisation of rehabilitation efforts (Getachew *et al*., 2021; Ramirez *et al*., 2023). Continuous long-term monitoring of soil and water quality is also essential to track changes in contamination levels and assess the effectiveness of implemented mitigation strategies (Kragt *et al*., 2021; Baloyi *et al*., 2024).

At the community level, the findings emphasise the importance of inclusive and participatory approaches to mine rehabilitation (Smith *et al*., 2023; Kaonda *et al*., 2024). The limited awareness and involvement of local communities in rehabilitation initiatives suggest a need for improved risk communication, stakeholder engagement and environmental education programmes (Nguyen *et al*., 2023). Empowering communities through participation in decision-making processes and rehabilitation activities can enhance trust, improve the social license to operate, and contribute to more sustainable and context-specific solutions.

A more detailed synthesis combining all observed patterns (community perceptions, heavy metals concentrations and erosion estimates) would be provided in the overall conclusion section.

Chapter 6: Summary, Conclusions and Recommendations

6.1 Summary of the findings

The aim of this study was to assess the environmental impacts, community perceptions, and management strategies associated with historical mine wastelands in Brakpan (Kwa-Thema), South Africa, with the goal of proposing methods to manage mine wastelands. This was achieved using structured questionnaires, erosion estimation modelling and radiometric analytical techniques. The findings showed that the study successfully met its objectives: the structured questionnaires were fully completed, soil loss rates were estimated using RUSLE and rigorous measurements of heavy metals and NORMs activity concentrations were conducted using ICP-MS and gamma spectrometry. The analysis of heavy metals and NORMs and determination of their activity levels obtained from two radiometric techniques were compared, and some were found to be substantially higher, and some were in a comparable range. Moreover, estimation of soil loss using the RUSLE erosion model revealed that soil is being eroded in the area at a significantly higher rate compared to standard thresholds, indicating severe environmental degradation. Local communities who participated in the study highlighted the urgent need for the government to lead rehabilitation and voiced their dissatisfaction with current mitigations and lack of accountability.

The first objective of the research focused on evaluating the environmental impacts and quantifying soil erosion rates and determining heavy metal and NORMs concentrations in mine wasteland. Results highlighted impacts perceived by the community and the elevated radioactivity of heavy metals in the soils and water.

The second objective of the research was to examine the community's perception regarding how these mine wastelands impact their quality of life (health and economics). Questionnaire results showed that 38% of respondents perceived dust as a negative experience of living next to mine wasteland and indicated dust as a potential health risk. The community understands that the government is responsible for rehabilitation. However, according to the NEMA of 1998, mining companies are responsible for rehabilitation post-mining activities, and the government is the enforcer of the legislation. These findings are in line with what was observed in the images taken from the study area and supported by the RUSLE results, which showed that there is a high rate of soil erosion taking place.

The findings related to the third objective, which assessed the challenges and effectiveness of existing measures, showed that no meaningful rehabilitation efforts are currently in place or are being implemented. As a result, soil erosion and pollutant mobility continue in several high-risk areas. These findings, drawn from both field measurements and the community's perceptions, directly inform the development of practical strategies for decommissioning and managing mine wastelands to reduce environmental degradation and safeguard nearby communities, in line with the fourth objective of the study, which aims to evaluate and identify suitable methods for decommissioning, assessment and management of mine wastelands.

The study vigorously addressed the scientific, community involvement and policy gaps regarding the management of mine wastelands in Brakpan (Kwa-Thema), which were highlighted by fulfilling the fourth objective of the study. The environmental and socio-economic impacts posed by mine wastelands in the entire Brakpan region would be a thing of the past.

As stated earlier, the final objective of the study was to evaluate and identify suitable methods of assessing and managing mine wastelands based on the data obtained. This led to the development of the Radioactive Environmental Management System (EMS), a proprietary and intellectual property (IP) protected framework. To support this framework, chapter 3 provides an overview of the methodologies employed to generate the environmental and radiological dataset that informed the development of this frame work.

The EMS combines field analytical data, geospatial modelling, community perceptions and regulatory analysis into a unified decision-support tool. It is designed to assess contamination risks, map and predict erosion and pollutant dispersion, integrate socio-economic and community perspectives, and ensure alignment with environmental and regulatory frameworks. By integrating these components, the EMS provides a comprehensive and practical pathway to mine wasteland rehabilitation. Its implementation is expected to reduce chemical and radiological hazards, restore degraded land, protect community health, and support sustainable land-use planning**,** thereby contributing to long-term socio-economic and environmental resilience in Brakpan and similar mining-impacted regions.

6.2 Conclusions

This study explored the environmental and human health implications of historical mine wastelands from Brakpan (Kwa-Thema), South Africa, using a combination of community perceptions, erosion modelling (RUSLE) and radiometric analytical techniques (ICP-MS and gamma spectrometry). The findings prove pressing environmental concerns where local marginalised communities are disproportionately exposed to pollution risks from heavy metals and NORMs.

Soil and water analyses indicated elevated concentrations of As, Cr, Cu, Co, Ni and U (1.033 to 156.802 mg/kg), surpassing both South African and international acceptable set standards in most samples. These contaminants are known to pose long-term environmental and human health risks, including organ toxicity and carcinogenicity.

The RUSLE model revealed significant spatial variability in erosion across the mine wasteland. Areas with low vegetation cover, steep slopes and less compacted soil, particularly along the top and side edges of the mine wasteland, were identified as the hotspots for potential soil loss and pollutants dispersion, and the necessary interventions required to alleviate further environmental degradation. The findings of these observations were supported by community observations of frequent dust emissions and sediment flow into nearby residential areas and stormwater systems. Local communities also reported symptoms potentially related to environmental exposure, including persistent respiratory conditions and skin irritation resulting from children swimming in contaminated water from mining operations.

Importantly, community participants believe that the government should be the one responsible for mine rehabilitation, reflecting both limited trust in mining companies and concerns over delayed or inadequate rehabilitation efforts. While South African policy frameworks, such as the MPRDA of 2002 and the NEMA of 1998**,** place the legal responsibility on mining companies to undertake and finance rehabilitation, communities perceive the government as the ultimate custodian of environmental and public welfare. This disjuncture highlights a critical policy gap, although legislation mandates industry-led rehabilitation, enforcement, accountability and transparent communication remain weak. Therefore, policy should not only strengthen monitoring and compliance mechanisms for mining companies but also ensure inclusive governance structures that allow community voices to directly inform rehabilitation planning. This intersection of socio-political and environmental disenfranchisement reinforces the urgent need for participatory, transparent and scientifically informed rehabilitation strategies.

By integrating the community's lived experience with scientific evidence, the study offers a community-driven assessment of the post-mining landscape. The results match the key environmental justice guidelines, substantiating that risk burdens should not fall unevenly on vulnerable communities living nearby, and that both accountability and transparency are central parts of remediation efforts.

This study bridges the gap in Brakpan's mine rehabilitation efforts where science, policy and community need to interconnect. While site-specific, the findings from this study provide a replicable framework that helps in addressing risks in the other parts of South Africa and across the Global South facing similar environmental and social challenges. With appropriate policy support, financial models, scientific innovation, and community engagement, the environmental degradation caused by historical mine wastelands can be redirected towards restoration and justice-driven outcomes.

6.3 Recommendations

Based on the results and interpretations of the results of this study, which are based on the survey results, observations and laboratory experimental work, the following recommendations can be made:

6.3.1 Community health, risk communication and education

There is a need to conduct community risk awareness campaigns, particularly for populations residing within a 5 km radius of the Mine wasteland, as they are the most directly exposed to chemical and radiological risks. Additionally, health monitoring programmes should be established to track potential long-term health effects, such as respiratory illnesses or radiation-related conditions, thereby ensuring early detection and intervention. Beyond immediate risk management, educational workshops can build local capacity by raising awareness about environmental stewardship, waste management and safe land-use practices. Such workshops would not only support the sustained management of mine wastelands but also foster socio-economic opportunities through skills training, environmental entrepreneurship and community participation in rehabilitation initiatives.

6.3.2 Policy and governance

Although NEMA of 1998 and municipal by-laws set out clear mine closure and rehabilitation requirements, in practice, historical mine wastelands remain poorly managed. Weak enforcement, unclear responsibilities between authorities and a lack of financial provision for many old sites remain major setbacks. Municipalities also face shortages in technical skills and resources to monitor and rehabilitate these areas, while community involvement is still limited. These challenges underscore the need to amend legislation, integrate mine wasteland risk monitoring into municipal planning, and strictly enforce the "polluter pays" principle against non-compliant parties.

6.3.3 Remediation and environmental management

Given the pressing concerns over inadequate rehabilitation and weak policy enforcement, immediate implementation of soil erosion control measures such as terracing, soil binding agents and contour ploughing are essential to stabilise both soil and water resources within the mine wasteland. Furthermore, fencing and clear signage should be established to restrict access and enhance safety. Building on the EMS framework outlined in chapter 3, developed during this study, targeted phytoremediation trials should be launched within the mine area as a sustainable and community-inclusive approach to rehabilitation.

6.3.4 Research and innovation

Further sampling is needed within the mine wasteland and nearby communities to expand the modelling scope of the area and monitoring. Moreover, there is a need to enhance science innovation by promoting local citizen science platforms and competitions among local communities.

6.3.5 A multi-phased rehabilitation framework

A multi-phased rehabilitation framework for Brakpan (Kwa-Thema) mine wasteland is proposed to serve as a practical translation of earlier recommendations, integrating key environmental, social and governance (ESG) strategies. It is recommended that local government and relevant stakeholders use the study's findings within IP policy boundaries to accelerate Brakpan's rehabilitation process.

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List of Annexures

Annexure A: Heavy metals and their health impacts adopted from Jaikhankar *et al*. (2019) and Tchounwou *et al*. (2019)

Heavy metal	**Common sources**	**Target organs**	**Exposure routes**	**Specific health impacts**
Lead	Mine tailings, piping, batteries and paints	Brain, blood and kidney	Inhalation and ingestion	Neurotoxicity, developmental delays in children, anaemia and kidney damage
Arsenic	Mining runoff, groundwater and pesticides	Skin, lungs, liver and cardiovascular system	Ingestion (food and water)	Skin lesions, cancer (skin, lung and bladder), and heart disease
Cadmium	Lead and zinc mining, batteries and phosphate fertilizers	Bones, lungs and kidneys	Inhalation and ingestion	Lung inflammation, kidney dysfunction, cancer and osteoporosis
Chromium	Tanning, pigments and stainless-steel waste	Kidneys, lungs and liver	Inhalation and ingestion	Respiratory tract irritation, cancer, kidney and liver damage
Mercury	Gold mining, coal combustion and industrial waste	Nervous system, kidneys and brain	Ingestion and inhalation	Neurological damage, cognitive dysfunction, tremors and kidney failure
Uranium	Mine waste, rocks and groundwater	Kidneys and bones	Ingestion and inhalation	Kidney toxicity, carcinogenesis due to radioactivity
Nickel	Mining, stainless steel and welding	Lungs and skin	Inhalation and dermal contact	Allergic dermatitis, asthma, lung fibrosis and possible carcinogen
Zinc	Industrial discharge and galvanized metals	GI tract, pancreas and immune system	Ingestion	Nausea, vomiting and immune suppression (only at high levels)
Copper	Mining, pesticides and plumbing	GI tract and liver	Ingestion	Liver damage and gastrointestinal distress (at high exposures)
Manganese	Mine dust and steel production	Nervous system and brain	Inhalation and ingestion	Neurological disorders, Parkinson-like symptoms (manganism)
Cobalt	Mining, batteries and pigments	Heart, bone marrow and thyroid	Ingestion and inhalation	Cardiomyopathy, goitre, haematological effects
Iron	Mining waste and natural in soil	Heart and liver	Ingestion	Hemochromatosis and oxidative stress (in excess)
Aluminium	Mining and industrial emissions	Brain and bones	Inhalation and ingestion	Possible link to neurodegenerative diseases (Alzheimer's) and bone pain
Vanadium	Steel alloys and fossil fuel combustion	Lungs and kidneys	Inhalation	Respiratory irritation and nephrotoxicity

Annexure B: Activity concentration levels of NORMs and Radiological indices

Sample ID	U-238 (Bq/kg)	Th-232 (Bq/kg)	K-40 (Bq/kg)	AED (external) mSv/y	Excess lifetime cancer risk x10^{-4}
BP1 (Control Sample)	12.79	9.283	13.17	0.074	0.05
BKS3	12.78	19.341	378.5	0.542	0.38
BKS4	131.88	18.221	704.51	0.431	0.30
BKS5	64.78	21.783	814.5	0.541	0.38
BKS6	89.08	21.014	552.78	0.933	0.65
BKS7	251.97	8.243	373.74	0.512	0.36
BKS8	136.07	3.983	465.5	0.193	0.13
BKS9	20.80	74.139	327.1	0.492	0.3446
BKS10	47.30	19.107	288.5	0.964	0.67
BKS11	289.34	5.200	164.5	0.376	0.26
BKS12	111.07	15.710	470.9	0.399	0.28
BKS13	77.63	18.694	345.1	0.906	0.63
BKS14	264.27	20.186	357.8	0.778	0.54
BKS15	216.03	15.625	465.8	0.346	0.24
BKS16	59.60	16.740	517.7	0.761	0.53
BKS17P	200.08	10.244	305.8	0.339	0.24
BKS18	78.69	12.851	475	0.818	0.57
BKS21	229.10	24.855	493.6	0.697	0.49
BKS20	169.13	20.399	696	1.414	0.99
BKS21	409.73	20.951	402	0.669	0.47
BKS28	172.60	16.326	402.9	0.578	0.40
L22	146.30	7.420	20.53	0.130	0.09
L23	34.30	22.070	64.68	0.727	0.51
L24	221.92	17.350	43.24	0.541	0.38
L26	164.38	36.570	144.7	1.030	0.72
L28	302.68	10.230	30.78	0.194	0.14
L29	52.46	11.480	29.39	0.222	0.16
L30	60.63	10.370	29.6	0.192	0.13
L31	51.67	15.293	43.87	0.278	0.19
L32	74.09	10.581	30.74	0.202	0.14
L33	54.75	12.748	33.94	0.232	0.16
L34	62.30	11.708	41.96	0.223	0.16
L35	59.57	11.670	32.91	0.226	0.16

Annexure C: Structured interview questionnaires

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Appendix

Questionnaires

Dear Sir/Madam

Ref: Requesting permission for student to conduct MSc research project

Dear participant

You are invited to participate in a research study

You are invited to participate in a research study of evaluation of mitigation strategies to achieve perpetual reduction targets of mine wastelands (mine dump) in Brakpan. This study is being conducted by Tobius Mawase Mogale who is currently enrolled for MSc in Environmental Management at the University of South Africa (UNISA).

The purpose of this study is to evaluate mine wastelands in Brakpan and develop mitigation strategies to achieve perpetual reduction targets of mine wastelands. Your participation in the survey will help the researcher to understand the impacts of mine wastelands and develop mitigation strategies.

The survey questionnaires will only take you about 10 to 15 minutes of your time and you are not required to put your name or contact details on the survey questioners and all data collected from participants will not be used for any other purposes other than for this research. The data will be kept confidential to the researcher and supervisors. Your help with this research is strictly voluntary and you are free to withdraw your participation from this study at any time.

If you have any questions regarding the survey or this research project in general, please do not hesitate to contact the undersigned

Regards

Researcher: Tobius Mawase Mogale
Tell: 083 348 3896
Email: tobiusmogale@gmail.com
Supervisor: Dr K W Maphangwa
Tell: 011 471 2305
Email: maphakw@unisa.ac.za

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Demographic Questioners

SECTION A

Please complete the following questionnaires by putting an X in the appropriate block.

1. Gender?

Female	Male

2. Age group?

18 – 29 Years	30-39Years	40-49Years	50 - 59 Years	60 Years and above

3. Race/ethnicity?

Black	White	Coloured	Indian	Asian

4. What is your highest level of education you have obtained?

No formal education	Grade 1 to 7	Grade 8 to 12	Graduate	Post- Graduate

5. What is your Occupation

Unemployed	Scholar/student	Employed	Self- Employed	Retired/Pensioner

6. What is your marital status

Single	Married	Separate	Divorce	Widow

7. Citizenship

South African	Non-South African

8. For how long have you been living in Brakpan?

1 – 11 Months	1- 2 Years	3-5 Years	6-8 Years	7 years and above

9. What type is your settlement in Brakpan area

Permanently settlement	Informal settlement	Mobile settlement

SECTION B

Mapping of mine wastelands

10. Do you know what are mine wastelands

Yes	No

11. If yes, how far do you reside from mine wastelands?

0 – 5 km	5 – 10 km	10 – 15 km	More than 15 km

12. Do you think that mine wastelands are dangerous and

Yes	No

Why

……………………………………………………………………………………………………

SECTION C

To examine the socio-economic benefits of mining in Brakpan

1. Do you have access to the mine wastelands?

Yes	No

2. What type of mining operations used to operate or are operating currently in Brakpan

Gold	Uranium	Coal	Other

3. Do mining operations around Brakpan provide employment to local people

Yes	No	Don't know

4. Did/does the community participate in decision making of mining operation in Brakpan?

Yes	No

5. Are you, or a member of your close family, associated with environmental conservation

Yes	No

6. Which organisation?

……………………………………………………………………………………………………..

7. Should local people be allowed to extract resources in mine wastelands?

Yes	No

If yes please give your reasons for your above choice

____

SECTION D

To assess the driving forces of land use and land cover changes in Brakpan in Ekurhuleni region

1. What do you think are the main land uses in Brakpan?

Agricultural practices	Commercial/Businesses	Residential	Mine wastelands

2. What are the causes of environmental degradation in Brakpan?

Mine wastelands	Pollution	Human settlement	Deforestation	Overpopulation	Landfills

SECTION D

To investigate the human activities leading to degradation of environment in Brakpan

1. Which factors do you think are the driving forces of land changes in Brakpan?

Population growth	Construction (mining)	Urbanization	Agricultural practices	Others

2. What are the bad experiences and or problems of living next to the mine wastelands?

Restriction of access to use resources in conservation area	
Loss of land and livelihood	
Hostility and harassment by environmental authority	
Dust	
Any other	

3. How would you describe the benefits of mine wastelands towards the community of Brakpan?

Very good	Good	Neither good nor bad	Bad	Very bad	Good and bad

4. Which of the following pose threats to land conservation in Brakpan

Expansion of agricultural land	Expansion of land development (e.g. construction, mining etc.)	Illegal encroachment by the local community	pollution	Others

5. Did/does the community participate in decision making of mining in Brakpan?

Yes	No

6. If yes, to what extent

Highly involved	Somewhat involved

7. What management practices do you think have to be undertaken to protect the environment around Brakpan

Fencing	Education	None

SECTION E

Mine wastelands reclamation

1. Do you know what mine reclamation is

Yes	No

2. How much would you say you know about mine wastelands reclamation in Brakpan on scale of 1 to 5

1	2	3	4	5

3. Have you observed or heard of any mine reclamation activities taking place around Brakpan or nearby areas?

Yes	No	Not sure

4. Do you approve or disapprove on how the Department of Mineral Resources and other associated government departments handle the mine wastelands

Approve	Disapprove

5. Who should be responsible for rehabilitation cost of mine wastelands in Brakpan?

Government	Mining companies	Local community

6. In your opinion, would the local community willing to contribute towards funding reclamation of mine wastelands

Yes	No	Not sure who

Thank you for taking your time to complete this survey questionnaires that was provided to you and we truly appreciate the information you have provided. Your responses will contribute towards the mapping of conservation areas and analysis of anthropogenic activities impact in Brakpan (Ekurhuleni region).

Research participant's signature: _________________ Researcher's signature: ________

Date: _____________ Date: ________

Annexure D: Radiological hazard indices and their health impacts sourced from IAEA (2019) and UNSCEAR (2020)

Radiological index	**Unit**	**Description**	**Health risk impacts**
Absorbed gamma dose rate	nGy/h	External gamma radiation dose rate in the air at 1 meter above ground	Prolonged exposure leads to increased external radiation dose – cancer risk
Annual Effective Dose Equivalent	mSv/y	Effective dose received annually by an individual from environmental radiation	High doses over time can damage DNA, cause mutations and increase cancer incidence
Radium Equivalent Activity	Bq/kg	Combined radioactivity of Ra-226(U-238), Th-232 and K-40 in a single index	Higher Raeq increases risk of both internal (inhaled radon) and external exposure
External Hazard Index	Unitless	Assesses external exposure hazard from natural radionuclides	If > 1, external gamma radiation may exceed safety standards; continuous exposure raises skin cancer and whole-body radiation dose
Internal Hazard Index	Unitless	Estimates internal exposure risk via radon inhalation	If > 1, risk of lung and respiratory cancers due to radon and its progeny increases; high probability of radionuclide accumulation in soft tissue, lungs, and bones causing chronic illnesses
Gamma index	Unitless	Screening tool for gamma radiation from building materials	If > 1, indicates materials may pose a radiation risk to occupants
Excess Lifetime Cancer Risk	Unitless	Lifetime probability of developing cancer due to radiation exposure	Higher ELCR values increase statistical cancer risk for exposed individuals. Likely organs impacted: lungs (via dust inhalation), gastrointestinal tract (via ingestion), skin and gonads
Activity utilization Index	Unitless	Risk assessment for building materials containing Ra/U, Th and K	Determines if materials are safe for construction use
Representative Level Index	Unitless	Similar to I_γ but used to estimate hazard from soil/rock	Indicates potential risk from natural radionuclides in geological materials
Annual gonadal dose equivalent	µSv/y		Serious threat to reproductive organs Potential for: Infertility (male and female), hereditary mutations passed to offspring and developmental defects in embryos if exposure occurs during pregnancy

Annexure E: Letter of ethical clearance

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UNISA-CAES HEALTH RESEARCH ETHICS COMMITTEE

Date: 23/05/2023

NHREC Registration # : REC-170616-051
REC Reference # : 2023/CAES_HREC/057
Name : Mr TM Mogale
Student #: 42385490

Dear Mr Mogale

Decision: Ethics Approval from 22/05/2023 to 30/04/2026

Researcher(s): Mr TM Mogale
42385490@mylife.unisa.ac.za; 073-414-8156

Supervisor (s): Dr KW Maphangwa
maphakw@unisa.ac.za; 011-471-2305

Prof M Tekere
tekerm@unisa.ac.za; 011-471-2270

Working title of research:

Evaluation of mitigation strategies to achieve perpetual reduction targets of mine wastelands (mine dump) in Brakpan

Qualification: MSc Environmental Management

Thank you for the application for research ethics clearance by the Unisa-CAES Health Research Ethics Committee for the above mentioned research. Ethics approval is granted for three years, **subject to further clarification and submission of yearly progress reports. Failure to submit the progress report will lead to withdrawal of the ethics clearance until the report has been submitted.**

Due date for progress report: 30 April 2024

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

Please note the points below for further action:

1. The researcher proposes two groups to be interviewed - the residential community within 8 km from the mine wasteland, as well as employees of the mine. However, a

sample size of 20 community members (group 1) is provided, but there is no indication of the sample size of the mine employees. The researcher is requested to provide motivation and justification for the sample size in relation to the population size. Will a sample size of 20 in relation to a population size of over 70 000 community members adequately represent the views of the community?

2. The researcher has further indicated that they will also incorporate the use of secondary data, however, the justification provided is for the use of primary data, can the researcher please amend this accordingly.

The ***low risk application*** *was* ***reviewed*** *by the UNISA-CAES Health Research Ethics Committee on 22 May 2023 in compliance with the Unisa Policy on Research Ethics and the Standard Operating Procedure on Research Ethics Risk Assessment.*

The proposed research may now commence with the provisions that:

1. The researcher(s) will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics.
2. Any adverse circumstance arising in the undertaking of the research project that is relevant to the ethicality of the study should be communicated in writing to the Committee.
3. The researcher(s) will conduct the study according to the methods and procedures set out in the approved application.
4. Any changes that can affect the study-related risks for the research participants, particularly in terms of assurances made with regards to the protection of participants' privacy and the confidentiality of the data, should be reported to the Committee in writing, accompanied by a progress report.
5. The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study. Adherence to the following South African legislation is important, if applicable: Protection of Personal Information Act, no 4 of 2013; Children's act no 38 of 2005 and the National Health Act, no 61 of 2003.
6. Only de-identified research data may be used for secondary research purposes in future on condition that the research objectives are similar to those of the original research. Secondary use of identifiable human research data require additional ethics clearance.

University of South Africa
Preller Street, Muckleneuk Ridge, City of Tshwane
PO Box 392 UNISA 0003 South Africa
Telephone: +27 12 429 3111 Facsimile: +27 12 429 4150
www.unisa.ac.za

7. No field work activities may continue after the expiry date. Submission of a completed research ethics progress report will constitute an application for renewal of Ethics Research Committee approval.

Note:

*The reference number **2023/CAES_HREC/057** should be clearly indicated on all forms of communication with the intended research participants, as well as with the Committee.*

Yours sincerely,

Prof MA Antwi
Chair of UNISA-CAES Health REC
E-mail: antwima@unisa.ac.za
Tel: (011) 670-9391

Prof SR Magano
Executive Dean: CAES
E-mail: magansr@unisa.ac.za
Tel: (011) 471-3649

Annexure F: Permission letter to conduct study

DRDGOLD
ERGO

DRDGOLD Mine

Constantia Office Park

CnR 14th Avenue and Hendrik Potgitier Road

Cycad House, Building 17, Ground Floor

Weltevreden Park

1709

Tell: 011 742 1003

Web: www.drdgold.com

25 April 2023

To whom it my concern

Letter of permission

RE: Permission to conduct research study at mine wasteland of DRDGOLD Mine

Dear Sir / Madam

This letter serves as confirmation that Tobius Mawase Mogale (student no 42385490) who is registered at the University of South Africa for a master program under the supervision of Dr KW Maphangwa, has been granted permission to conduct his research study at the DRDGOLD Mine (mine wasteland) in Brakpan for his masters.

Yours sincerely.

Ofentse Phete

Tailings Manager

T: 0117421003
E: ofentse.phete@drdgold.com
C: 0794289965
www.drdgold.com

Annexure G: The permission for sample analysis

NWU®
NORTH-WEST UNIVERSITY
NOORDWES-UNIVERSITEIT
YUNIBESITI YA BOKONE-BOPHIRIMA

Private Bag X2046, Mmabatho
South Africa 2735

Tel: 018 389-2111
Fax: 018 392-5775
Web: http://www.nwu.ac.za

Centre for Applied Radiation Science and Technology
Tel: 018 389 2756
Email: tebogo.kupi@nwu.ac.za

04 November 2022

TO WHOM IT MAY CONCERN:

LETTER OF PERMISSION

RE: PERMISSION TO CONDUCT EXPERIMENTAL WORK AT CARST USING HPGE DETECTOR

Dear Sir/Madam,

The Masters student, Tobius Mawase Mogale (student no. 42385490) registered with the University of South Africa under the supervision of Dr KW Maphangwa have been granted access to conduct his experimental work using Gamma spectrometry for his master's research by the North-West University's Centre for Applied Radiation Science and Technology next year 2023.

Yours sincerely

Tebogo G. Kupi, BSc, PGDM, MSc, PhD, Pr.Sci.Nat.
Nuclear Forensics Laboratory Manager

NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
CARST
04 NOV 2022
Centre for Applied Radiation Science & Technology

Annexure H: Heavy metal analysis

NORTH-WEST UNIVERSITY
ECO ANALYTICA
E-mail : terina.vermeulen@nwu.ac.za
Tel: 018-285 2733

Center for Water Sciences & -Management
11 Hoffman Str
POTCHEFSTROOM
2531

UNISA

Microwave digested (Ethos UP, Magna Analytical) with EPA3051A method and results were obtained by using Agilent ICP-MS - *mg/kg*

24/1/2024

Sample:	**BP1**	**BKS10**	**BKS16**	**BKS21**	**BKS28**				
	mg/kg	***mg/kg***	***mg/kg***	***mg/kg***	***mg/kg***				
Be 9	<0.22500	0,341	0,326	0,3204	0,3372				
B 11	<0.05000	<0.05000	<0.05000	<0.05000	<0.05000				
Na 23	18,373	79,870	192,589	39,5892	1076,6874				
Mg 24	242,610	3845,862	2742,004	6045,0053	2662,1276				
Al 27	7760,371	9507,351	8335,408	13489,5033	8780,6580				
P 31	138,150	123,832	100,077	164,0879	156,6710				
K 39	409,915	1257,215	2942,099	1469,9940	2269,4607				
Ca 43	218,379	652,380	1952,380	1224,2159	15366,8424				
V 51	10,630	18,161	17,270	25,2789	16,1547				
Cr 53	31,654	109,822	122,190	156,8019	99,4464				
Mn 55	33,692	140,552	84,400	237,9763	147,6704				
Fe 57	3177,388	22246,821	22924,875	34812,7560	22635,1620				
Co 59	1,806	8,934	18,493	27,8395	11,9864				
Ni 60	9,799	58,083	78,462	129,0808	78,6180				
Cu 63	5,009	26,737	47,193	33,9660	51,0565				
Zn 66	17,678	34,720	17,658	46,3107	19,0286	CD	CU	NI	CO
As 75	1,005	58,299	71,102	56,1284	52,2226				
Se 78	0,644	1,255	1,404	1,4296	1,8496				
Mo 95	<0.00115	0,337	1,225	<0.00115	11,2414				
Cd 111	<0.00208	0,012	0,005	0,0209	<0.00208				
Sn 118	0,462	1,200	0,357	0,6308	0,4629				
Sb 121	0,107	0,748	0,797	0,5479	0,5300				
Ba 137	31,993	25,307	35,818	32,7192	22,2455				
Hg 201	0,011	0,237	0,109	0,1663	0,0359				
Pb 208	9,125	16,885	7,742	11,3679	7,6351				
U 238	0,367	7,765	10,731	7,6646	9,1599				

ND = NONE DETECTED
<###> = OUT OF CALIBRATION RANGE (CONCENTRATION WAS TOO HIGH)

WATER SAMPLES. Results were obtained by using Agilent ICP-MS - *mg/kg*

2024/03/08					
Sample:	**BPW1**	**BKW2**	**BKW4**	**BKW5**	**BKW6**
	mg/kg	*mg/kg*	*mg/kg*	*mg/kg*	*mg/kg*
Be 9	<0.00900	<0.00900	<0.00900	<0.00900	0,0201
B 11	<0.00200	0,214	<0.00200	<0.00200	<0.00200
Na 23	6,139	57,292	204,281	97,9037	159,1603
Mg 24	1,159	18,261	132,271	97,7930	175,8976
Al 27	0,083	0,021	60,665	62,4824	113,4202
P 31	<0.27149	1,547	<0.27149	<0.27149	<0.27149
K 39	0,106	12,835	22,824	3,1199	2,8052
Ca 43	<4.51990	52,233	267,619	218,3550	230,4258
V 51	<0.00050	<0.00050	<0.00050	<0.00050	<0.00050
Cr 53	<0.00060	<0.00060	<0.00060	<0.00060	<0.00060
Mn 55	<0.00043	<0.00043	25,806	11,9380	22,6854
Fe 57	<0.00292	<0.00292	0,115	<0.00292	<0.00292
Co 59	<0.00002	0,000	3,811	2,8119	5,1419
Ni 60	<0.00012	<0.00012	12,416	9,1270	16,7988
Cu 63	<0.00019	<0.00019	1,033	1,2930	2,2645
Zn 66	<0.00029	<0.00029	3,434	2,4241	4,4234
As 75	<0.00006	0,006	0,008	0,0105	0,0150
Se 78	<0.00114	<0.00114	0,032	0,0369	0,0432
Mo 95	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005
Cd 111	<0.00008	<0.00008	0,004	0,0025	0,0048
Sn 118	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004
Sb 121	<0.00002	<0.00002	<0.00002	<0.00002	<0.00002
Ba 137	<0.00009	<0.00009	<0.00009	<0.00009	<0.00009
Hg 201	<0.00011	<0.00011	<0.00011	<0.00011	<0.00011
Pb 208	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004
U 238	<0.00006	<0.00006	1,163	1,1442	2,6249

ND = NONE DETECTED

<###> = OUT OF CALIBRATION RANGE (CONCENTRATION WAS TOO HIGH)

Annexure I: Isotopic activity ratios

Sample name	Activity Concentration (Bq/kg)						Isotopic activity ratios of radionuclides			
							in U-238 series		in Th-232 series	
	Pb-214	**Bi-214**	**Ac-228**	**PB-212**	**Bi-212**	**Ra-226**	**Ra-226/Pb-214**	**Pb-214/Bi-214**	**Ac-228/Bi-212**	**Pb-212/Bi-212**
BP1 (Control Sample)	12.79	12.75	10.98	9.57	6.65	12.78	0.999	1.004	1.652	1.440
BKS3	135.82	124.14	21.72	22.92	14.10	131.88	0.971	1.094	1.541	1.626
BKS4	66.06	62.40	20.22	20.15	13.79	64.78	0.981	1.059	1.466	1.461
BKS5	93.41	81.30	24.21	24.00	15.05	89.08	0.954	1.149	1.609	1.595
BKS6	261.13	239.00	24.93	26.15	7.57	251.97	0.965	1.093	3.291	3.453
BKS7	144.09	120.61	6.53	21.72	13.27	136.07	0.944	1.195	0.492	1.637
BKS8	30.80	8.61	1.99	19.76	13.79	20.80	0.675	3.579	0.144	1.433
BKS9	0.10	0.07	0.06	0.06	0.06	0.15	1.551	1.361	0.997	0.950
BKS10	294.94	272.13	21.68	25.82	11.07	289.34	0.981	1.084	1.958	2.332
BKS11	124.11	72.70	2.90	31.31	15.49	111.07	0.895	1.707	0.187	2.021
BKS12	104.75	47.71	16.00	25.42	15.38	77.63	0.741	2.196	1.040	1.653
BKS13	425.74	198.91	20.66	33.94	15.87	264.27	0.621	2.140	1.302	2.139
BKS14	316.11	202.12	23.14	32.00	16.12	216.03	0.683	1.564	1.435	1.985
BKS15	92.94	46.53	17.21	23.77	13.25	59.60	0.641	1.997	1.299	1.794
BKS16	278.48	163.20	19.01	28.85	13.64	200.08	0.718	1.706	1.394	2.115
BKS17P	91.18	74.66	12.69	17.77	7.71	78.69	0.863	1.221	1.646	2.305
BKS18	351.34	177.03	14.37	21.61	10.76	229.10	0.652	1.985	1.336	2.008
BKS19	168.24	170.64	170.64	24.87	15.12	169.13	1.005	0.986	11.285	1.645
BKS20	407.63	413.85	25.90	19.36	19.36	409.73	1.005	0.985	1.338	1.000
BKS21	170.04	177.68	24.01	21.61	10.76	172.60	1.015	0.957	2.231	2.008
BKS28	145.49	147.89	17.04	16.41	13.29	146.30	1.006	0.984	1.282	1.235
L22	33.40	33.22	23.90	7.14	5.33	34.30	1.027	1.006	4.485	1.341
L23	216.24	214.22	40.53	20.58	14.57	221.92	1.026	1.009	2.782	1.412
L24	159.82	157.85	44.84	16.25	12.61	164.38	1.029	1.012	3.556	1.289
L26	298.87	293.00	74.41	34.86	24.24	302.68	1.013	1.020	3.070	1.438
L28	51.78	51.45	25.34	9.79	6.62	52.46	1.013	1.006	3.829	1.480
L29	59.39	58.91	29.85	10.80	7.37	60.63	1.021	1.008	4.050	1.465
L30	50.42	50.41	30.04	9.85	8.23	51.67	1.025	1.000	3.652	1.198
L31	71.96	70.98	48.14	14.35	10.24	74.09	1.030	1.014	4.701	1.401
L32	53.49	53.37	23.93	10.14	7.12	54.75	1.024	1.002	3.363	1.425
L33	59.93	60.18	34.63	12.05	9.09	62.30	1.039	0.996	3.808	1.325
L34	58.73	60.06	48.15	10.86	6.05	59.57	1.014	0.978	7.964	1.796
L35	60.11	59.02	65.25	11.23	6.58	61.65	1.026	1.018	9.913	1.706

Annexure J: Language editing certificate

EDITING AND PROOFREADING CERTIFICATE

22 Osche Street

The Reeds

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0157

07 November 2025

TO WHOM IT MAY CONCERN

This certificate confirms that I have edited TM Mogale's dissertation, titled "**Evaluation of environmental impacts, community perceptions and management challenges of historical mine wastelands in Brakpan (Kwa-Thema), South Africa.**"

I found the work easy and intriguing to read. Much of my editing basically dealt with obstructionist technical aspects of language, grammar and syntax, which could have otherwise compromised smooth reading as well as the sense of the information being conveyed. I hope that the work will be found to be of an acceptable standard. I am a member of Professional Editors' Guild.

Hereunder are my contact details:

Jack Chokwe (PhD – University of Leicester (United Kingdom)

Contact numbers: 072 214 5489

jackchokwe@gmail.com

www.academicproeditor.co.za

Professional EDITORS Guild