

Assessment of potential land contamination around abandoned legacy mines in a selected region of South Africa

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ABSTRACT

Land contamination is recognised as an infrastructural challenge with unpredictable intensity and implications caused by historical industrial and waste disposal practices. South Africa accounts for approximately 6 000 legacy mines that generate mineral waste in the form of mine tailings, waste rock dumps and low-grade mineral discards that leach potentially toxic elements (PTEs) into the environment. This leads to unknown contamination of the land around these previous mining sites which strains the availability of land for alternative use. This study assessed potential land contamination around selected abandoned legacy mines located across three different provinces (Limpopo, Gauteng and Mpumalanga) to determine the state of the land.

The study applied the mean hazard index assessment method to calculate land contamination indices using norms and standards contained in the National Framework for the Management of Contaminated Land. Remote sensing was used for land-use land-cover (LULC) classification to detect land-use change and determine factors which pose an environmental risk. The drivers, pressures, state, impacts and responses model was applied to identify sources (drivers), pathways and receptors within the study area by integrating different datasets.

The study discovered that 11.03% of the land had low contamination and 54.60% had moderate contamination, with an index score of less than one which means that the land is suitable for a range of land uses. High contamination accounted for 25.84% and extreme contamination for 8.54% of the land, with an index score greater than one, indicating that the land was contaminated with one or more PTE concentrations above the permissible limit. Remote sensing satellite imagery LULC classification discovered that built-up, forested land, mines and quarries are driving land-use changes which expose risks of land contamination to humans and the environment. Surface water and groundwater were determined to be at risk of potential contamination in contaminated areas. Various receptors (e.g., humans, fauna, flora, wetlands, rivers, lakes, dams and cultivated land) were found to be vulnerable to land contamination.

Keywords

land contamination, toxic elements, legacy mines, mine waste, receptors

ABBREVIATIONS AND ACRONYMS

Ag	silver
AMD	acid mine drainage
As	arsenic
Au	gold
Ba	barium
CBA	critical biodiversity areas
Cd	cadmium
C_{deg}	degree of contamination
Cf	contamination factor
CGS	Council for Geoscience
Co	cobalt
Cr	chromium
CR	critically endangered
Cu	copper
D	driving forces
DMRE	Department of Mineral Resources and Energy
DPSIR	drivers, pressures, state, impacts and responses
DWS	Department of Water and Sanitation
EA	environmental authorisation
ECA	Environment Conservation Act (Act 73 of 1989)
EN	endangered
ERM	ecological risk assessment
ETS	Ecosystem Threat Status
Fe	iron
GN. 331	National Norms and Standards for the Remediation of Contaminated Land and Soil Quality in the Republic of South Africa (GN. 331 of 2014)
Hg	mercury
HI	hazard index
I	impacts
I_{geo}	geoaccumulation index
LC	least concern
LULC	land use land cover
LUS	land-use scheme
m_{hi}	mean hazard index
Mn	manganese

MPDRA	Mineral and Petroleum Resources and Development Act (Act 28 of 2002)
NEMA	National Environmental Management Act (Act 107 of 1998)
NEMBA	National Environmental Management: Biodiversity Act (Act 10 of 2004)
NEMPAA	National Environmental Management: Protected Areas Act (Act 57 of 2003)
NEMWA	National Environmental Management: Waste Act (Act 59 of 2008)
Ni	nickel
NWA	National Water Act (Act 36 of 1998)
<i>P</i>	pressures
Pb	lead
PGMs	platinum group metals
PI	single pollution index
PLI	pollution load index
Pt	platinum
PTEs	potentially toxic elements
RI	risk index
S	state
SA	South Africa
SANBI	South African National Biodiversity Institute
SEMA	specific environmental management acts
SDF	Spatial Development Framework
Sn	tin
SPLUMA	Spatial Planning and Land Use Management Act (Act 16 of 2013)
SSV1	Soil Screening Values 1
SVM	support vector machine
U	uranium
USA	United States of America
V	vanadium
XRF	x-ray fluorescence spectrometer
Zn	zinc

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CHAPTER 1 INTRODUCTION

This chapter conceptualises the study by providing the background, problem statement and rationale. The main aim and specific objectives, scope, assumptions and limitations are outlined. Finally, the potential contributions of the study and the dissertation layout are provided.

1.1 Background

The South African economy has historically thrived through a combination of mining operations and agricultural production (Fourie & Brent, 2006:1085). In 1980, the mining sector contributed 22% of the gross domestic product; however, the figure continued to decrease, with 7.6% reported in 2014 (Macmillan, 2017:273). Past and current mining activities have resulted in environmental challenges throughout South Africa (SA). Wiebelt (2001:170) indicated that solid waste generation in the form of tailings and slags is a major contributor to these environmental challenges. Mine waste stockpiles produce acid mine drainage (AMD) under oxidising conditions, which percolate into the surface and groundwater bodies and poses a risk to humans, domesticated animals, wild animals and ecosystems (Durand, 2012:31). Mine waste has been identified as a major source of potential land contamination, exposing potentially toxic elements (PTEs) to the environment (Khalil *et al.*, 2013:1).

Given the extensive history of mining in SA, mine waste covers a large area of land (Festin *et al.*, 2019:389). Most abandoned legacy mines continue to pose risks to future land use, as many sites have become hotspots for illegal and small-scale mining operations (Mhlongo & Amponsah-Dacosta, 2016:279). For example, Rösner and Van Schalkwyk (2000:138) found that SA accounts for approximately 270 gold mining tailings dams, covering a total area of 182 km². Fairbanks *et al.* (2000:69) projected that 0.14% which covers 175 420.7 ha of soils in SA, is impacted by mining and quarries. Eijsackers *et al.* (2017:129) showed that approximately 12% of the total arable land area is affected by degraded land and mines. However, the exact degree of contamination and its effects remain unclear.

At most sites, mine waste leads to the accumulation of toxic element concentrations on land and soils which present health risks to residents living near mining areas. Accumulating PTEs in the environment pose serious concerns because they are non-biodegradable and persist in the environment for long periods (Mosai, 2017:2). In SA, some mine piles have eroded, and the original disposal site cannot be differentiated but is instead scattered throughout the land. For example, Moreno *et al.* (2010:252) discovered a high percentage of arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), manganese (Mn), mercury (Hg) and nickel (Ni) above reference values within the blood of children living near and exposed to the gold (Au)

and silver (Ag) mining area of Taxco, South Mexico. While Mathee *et al.* (2022), discovered elevated concentrations of lead (Pb) in the blood vessels of residents in proximity to mine tailings facilities in Soweto. In light of this, SA is faced with the challenge of inactive mines and improper disposal of mine waste. This study seeks to assess the potential land contamination around selected abandoned legacy mines in SA. Furthermore, the risks associated with abandoned mines and potential contamination receptors within the selected research area must be determined.

1.2 Problem statement and rationale

Land contamination is recognised as an extensive infrastructural challenge with unpredictable intensity and implications caused by historical industrial and waste disposal practices (Nathanail & Bardos, 2005:1). Land contamination is linked to brownfield development (Cobârzan, 2007:29; Morar *et al.*, 2021:3). There is no common definition for brownfield development but broadly used definition refers to underused, neglected or abandoned and potentially contaminated land or buildings (Venter, 2020:44). Furthermore, this term is associated with the presence of potential or confirmed contamination (Cobârzan, 2007:29; Walker, 2018:2). Previous mining sites were classified as brownfields (Ahmad *et al.*, 2018:14). European countries and the USA recommend assessing contaminated land before redeveloping it for alternative uses (Mahammedi *et al.*, 2022:5).

In 2009, SA accounted for approximately 6 000 abandoned legacy mines which previously exploited different commodities (e.g., Au, diamonds, platinum group metals [PGMs], and asbestos) (Auditor General, 2009:4). Legacy mines generate mineral waste (i.e., mine tailings, waste rock dumps and low-grade mineral discards) that pose risks to natural resources (i.e., soil, water, land and air) as well as human health (Matshusa & Makgae, 2014:160). Potential toxic elements (PTEs) leach from mine waste into the environment (Mkhize, 2020:2). This leads to the unknown quality of land around these previous mining sites which strains the availability of land for alternative use. For example, Mngadi (2020:132) discovered that plant tissues (e.g., roots) and leafy vegetables (e.g., cabbages) bioaccumulate PTEs that might cause adverse human health risks after consumption.

Furthermore, Simpson *et al.* (2019:2) indicated that there is growing tension between mining, energy, water management, arable agricultural land (for food security) and social welfare (for settlement) within the Mpumalanga coalfields. However, there is no indication of how these land use changes affect or contribute to potential land contamination.

These challenges invite research on the extent and level of land contamination in SA, particularly concerning inactive and active mining operations. This study's rationale was to facilitate the allocation of land around areas with abandoned legacy mines for different land uses. To achieve land allocation, potential land contamination must be assessed to comply with Section 24 of the Constitution of the Republic of SA (1996) (hereafter, the Constitution). This guarantees that "everyone has a right to an environment that is not harmful to their health or well-being" (Section 24 [a] of the Constitution of the Republic of SA, 1996). In addition, land-use changes must be detected to assess the vulnerability of the ecological environment and water resources emanating from potential land contamination. Delineating potentially-contaminated areas will serve as a baseline for further in-depth investigations to provide directions for future rehabilitation designs and land-use planning around legacy mines.

1.3 Research aim and objectives

In view of the problem statement, the study assessed potential land contamination around selected abandoned legacy mines located across three different provinces (Limpopo, Gauteng and Mpumalanga). The specific objectives were to:

- Research Objective 1 (RO1): Identify potentially-contaminated areas within the selected region/study area.
- Research Objective 2 (RO2): Investigate the risks associated with abandoned legacy mines and current mining on the land.
- Research Objective 3 (RO3): Determine receptors of potential contamination in the study area.

1.4 Research area and scope

This study interprets regional geochemical data to assess potential land contamination, particularly around abandoned legacy mines. Contamination assessment is expected to provide implications for contamination pathways and receptors before designing rehabilitation guidelines and allocating alternative land-use types. This study covered selected areas within three provinces, (Limpopo, Gauteng and Mpumalanga), which host economic mineral fields (e.g., Au [greenstone belts], coal, asbestos, andalusite, Mn and PGM [Eastern Bushveld Complex]) (Figure 1-1). The goldfield includes the Pietersburg Greenstone Belt. The coalfields cover Springbok Flats and Emalaheni (previously, Witbank). The distribution of asbestos fields includes the chrysotile belt around Groblersdal, and the amosite belt southeast of Polokwane along the Bewaarkloof and Wolkberg Nature Reserves (in the Lebopo and Wolkberg Mountains). The Bushveld Complex includes the eastern and northern limbs which are enriched with PGM. Andalusite and Mn fields are hosted within the Eastern Bushveld Complex.

Remote sensing was applied to detect land-use changes over time to identify competing land-use factors that contribute to potential land contamination apart from legacy mines.

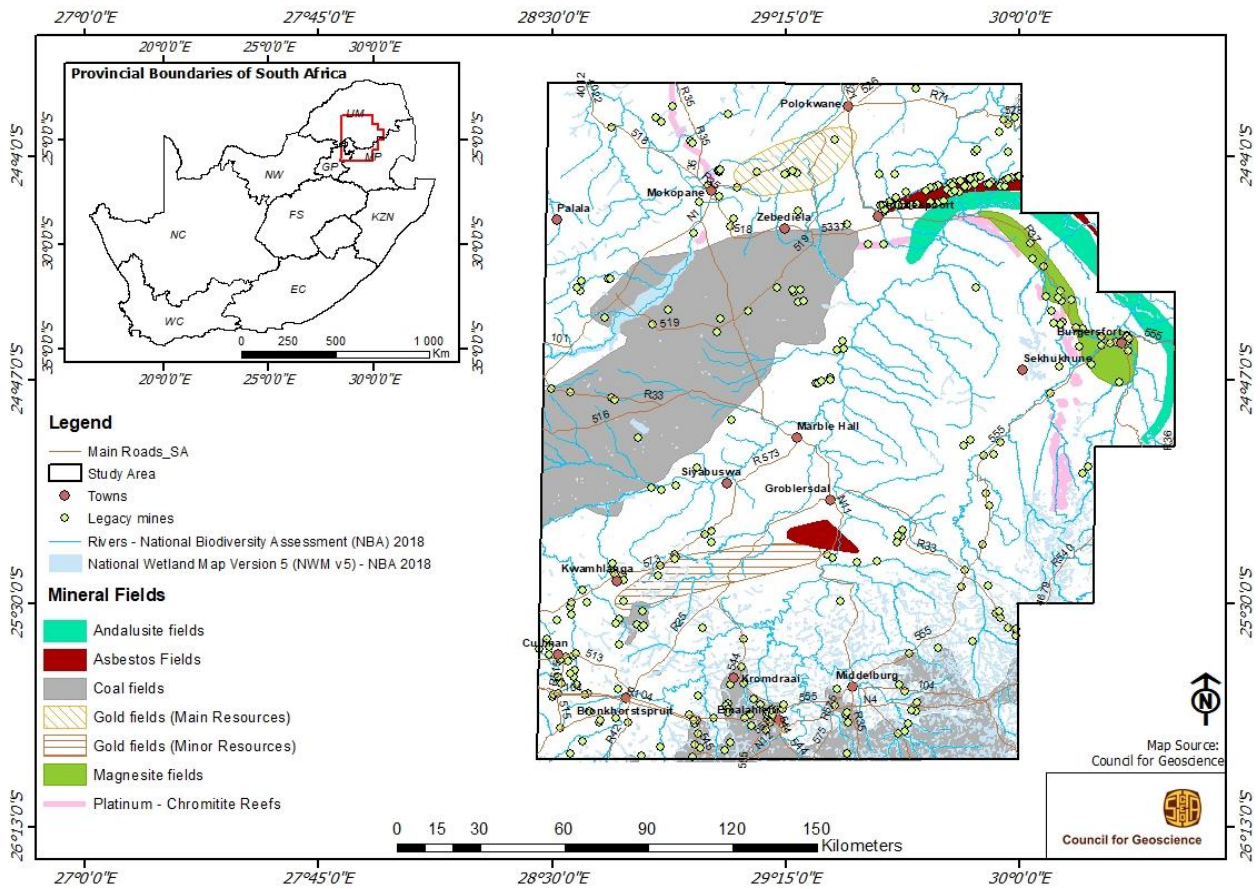


Figure 1-1: Distribution of mineral fields and legacy mines in study area.

1.5 Assumptions and limitations

This study focused on environmentally-sensitive elements (i.e., As, cobalt [Co], Cr, Cu, Ni, Pb, vanadium [V] and zinc [Zn]). These elements were selected based on their high toxicity and common constituents in mine waste that leach into the environment (Mphinyane, 2018:3). Assessing potentially contaminated land was undertaken against regulatory Soil Screening Values 1 (SSV1) for all land uses, as outlined in the National Norms and Standards for the Remediation of Contaminated Land and Soil Quality in the Republic of South Africa (GN. 331 of 2014). The methods applied considered the assessment phases and processes provided within the framework of the contaminated land guidelines. Previous mines were assumed to have been contaminated until the site assessment proved otherwise.

1.6 Potential research contribution

This assessment is expected to produce a map of potential land contamination in areas with past mining operations. Based on the nature of contamination from mining operations, this study is anticipated to determine susceptible ecological and other sensitive environments (e.g., rivers, wetlands, lakes, dams and protected areas). Furthermore, it outlines how land use and competing factors have changed over time, including their contributions to sensitive environments.

1.7 Structure and outline

This dissertation comprises five chapters. Table 1-1 outlines the descriptions of each chapter.

Table 1-1: Dissertation chapter outline.

Chapter	Description
Chapter 1: Introduction	Conceptualises the research by outlining the background, problem statement, rationale, aims and objectives, scope, assumptions and limitations as well as potential contribution.
Chapter 2: Literature review	Provides an overview of the impact of mining on the land and soil quality. This is followed by a brief description of PTEs and historical mining activities within the study. This chapter introduces the economical minerals driving mining in the area and current land uses. Furthermore, it presents previous work undertaken in the area. Finally, policies governing strategic water areas, environmental, biodiversity (protected areas) and ecological attributes adjacent to these key mineral fields are outlined.
Chapter 3: Methodology	The main research methodologies and techniques used to conduct the study. This includes a description of field sampling, laboratory preparations and analysis (XRF–trace elements). Furthermore, it entails the analytical methodology for assessing contamination (i.e., DPSIR framework for analysing environment challenges and remote sensing for land-use change detection).
Chapter 4: Results and discussions	Presents the results of potential land contamination in the form of HI and land-use cover maps produced using remote sensing. This is followed by a discussion and summary of the findings as presented in the form of maps, photos and tables to address the aims and objectives of the study.
Chapter 5: Conclusion and recommendations	All study findings are summarised regarding the manner and extent to which the research objectives have been answered as well as the conclusion reached. Any recommendations arising from the findings are presented.

CHAPTER 2 LITERATURE REVIEW

The literature was used to identify sources, pressures, states and impacts driven by abandoned mines and potential policies as responses to address potential land contamination and associated risks.

2.1 Introduction

A literature review selects relevant sources to extract, analyse, critically evaluate and synthesise existing information, ideas, findings and standpoints relating to the topic, problem statements and research questions (Hart, 2018). The literature review covers the origins and definitions of the topic, key ideas, strategic interactions of the ideas and research methods (Torraco, 2005:361). The drivers, pressures, state, impacts and responses (DPSIR) framework was used as a literature map to express relationships between ideas, arguments and ideas relating to the study as shown in Figure 2-1.

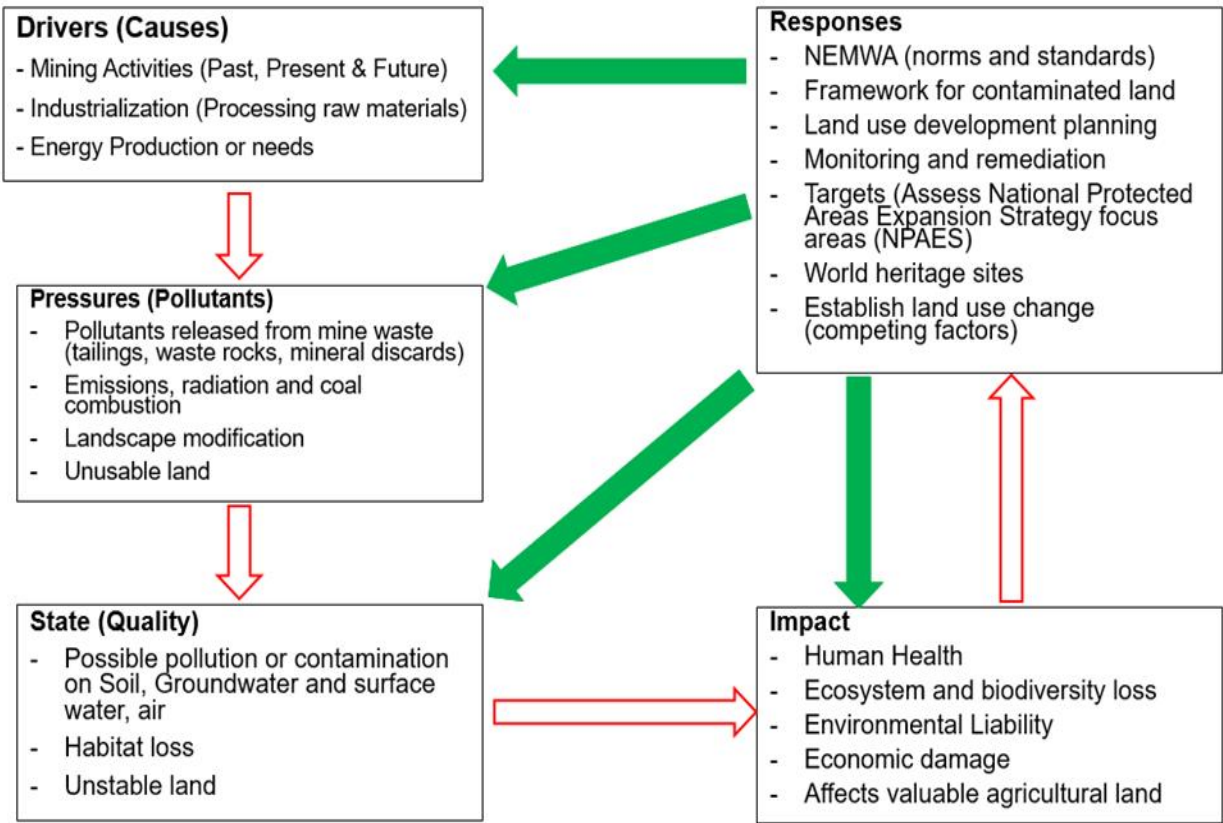


Figure 2-1: Drivers, pressures, state, impact and responses application used to map relationships between ideas in literature.

2.2 DPSIR framework

Friend and Rapport (1991:71) highlighted that the Statistics Canada Office established the stress-response environmental statistical reporting approach in 1979 for the state of environmental reporting. Consequently, the idea evolved and developed into the DPSIR framework by the European Environment Agency in 1995 for the Dobris Assessment of the European environment (i.e., air, water and soil) (Maxim *et al.*, 2009:12; Gari *et al.*, 2015:64). The DPSIR framework is a valuable and adaptive management instrument applied to evaluate environmental problems by understanding the cause-effect relationships between human development activities and their environmental and socioeconomic concerns (Gari *et al.*, 2015:64). Maxim *et al.* (2009:12) elaborated that the causal link in the DPSIR framework starts with social and economic developments as driving forces (*D*) that exert pressures (*P*) on the environment and change the state (*S*) of the environment. This leads to impacts (*I*) on human health, ecosystem and biodiversity loss, environmental liability, affected valuable agricultural land and economic damage, which require mitigation or corrective actions in the form of responses (*R*) by responsible governance to address the *D*, *S* or *I* (Maxim *et al.*, 2009:12; Gari *et al.*, 2015:64).

The literature review focused on the history of abandoned legacy mines as *D* to establish definitions of the idea, previous operations and minerals mined. An overview was found on the characteristics and risks of the selected PTEs (As, Co, Cr, Cu, Ni, Pb, V and Zn) which are leached as *P* from mine waste with the ability to contaminate the environment (Levinson, 1974; Kabata-Pendias, 2000). This study establishes the *S* of land contamination around selected abandoned legacy mines. Therefore, a review of the guidelines for undertaking research and assessment processes on this topic is provided. Documented sources are reviewed to highlight *I* from abandoned legacy mines within the study area to address topics on land use, ecological and biodiversity attributes, arable agricultural land and environmental liability. A description of how GN. 331 from the National Environmental Management: Waste Act (Act 59 of 2008) (NEMWA) deals with norms and standards for contaminated land is provided as part of the *R*.

2.3 Drivers of potential land contamination from abandoned mines

The world is subject to increasing demands of economic development that thrive on the increased consumption of raw materials (Holt, 2000:21). This has led to various anthropogenic activities in major sectors (e.g., agriculture, mining and smelters, industrialisation, transport and textiles) (Holt, 2000:21; Carré *et al.*, 2017:276). These activities are directly or indirectly induced by humans to influence environmental change and are known as anthropogenic processes or activities (Li *et al.*, 2019:382). Waste generated from anthropogenic activities releases

contaminants into the environment that impact natural resources (i.e., land, water, air and ecosystems).

Principal sources or drivers of land contamination are linked to residue waste from mining and abandoned or uncontrolled hazardous waste sites from commercial industries (Nriagu and Pacyna (1988:139). Mining activities and associated mine waste are of particular interest here. Generating mine waste occurs over several centuries without proper disposal approaches and constitutes a driving source of potential environmental contamination (Ledin & Pedersen, 1996:68). Ledin and Pedersen (1996:68) indicated that mine tailings and waste rock drive major contaminants of chemicals used during extraction and processing of the mineral ore. Waste rock is a low-grade overburden material removed to uncover ore deposits that cannot be processed commercially (Blowes, 1997:887). Mine tailings are residue materials generated from mineral processing (e.g., slimes, slurry, tailings, discards and plant waste) (Ledin & Pedersen, 1996:68; Blowes, 1997:888). In the selected study region, mine waste and waste rocks were generated by exploiting:

- Coal from the Emalahleni and Springbok coalfields,
- Au in the Pietersburg Greenstone Belt,
- PGMs in the northern and eastern Bushveld Complex,
- Andalusite and Mn in the eastern Bushveld Complex, and
- Asbestos for economic development that extracted raw materials.

2.4 Potential contaminants exerting environmental pressure

Carré *et al.* (2017:276) indicated that toxic elements contribute 60% of the contaminants discovered on land in Europe, the USA, and Australia. Other contaminants include petroleum hydrocarbons, benzene, toluene, ethylbenzene, xylene, phenols and cyanides (Carré *et al.* (2017:276). Anthropogenic activities through extracting and consuming raw materials disturb the natural geochemical cycle and result in accumulating toxic elements in the environment (Dixit *et al.*, 2015:2192). Mining activities and improper disposal of mine waste influence the dispersion of non-biodegradable toxic elements (Wong *et al.*, 2006:3). Yabe *et al.* (2010:1258) reported that Africa including SA is faced with the challenge of PTEs disposed of in the environment. These PTEs include As, Cr, Cu, Co, Pb, Ni, V and Zn which is why they were selected for this study (Table 3-1). These elements are carried within pathways such as AMD, waste dump erosion, seepages and wind-blown dust that disperse them on the land.

Table 2-1: Potentially toxic elements selected for study.

PTE (Potential Contaminants)	Description
As	A natural element present in all soils and organic matter (Duker <i>et al.</i> , 2005:632). Levinson (1974) indicated that As is used as a pathfinder for Ag, Au, Cu and Pb-Zn deposits with an average crustal abundance of 5 ppm (mg/kg) within the soil. It is found in association with minerals, such as pyrite, galena, sphalerite, other sulphides and apatite. Järup (2003:178) presented that contamination of natural resources (air, water and land) by As relates to two main activities. These involve the smelting of non-ferrous metals as well as mining and producing energy from fossil fuel (mostly coal). Potential land contamination by As is associated with mining and mine tailings (Järup (2003:178).
Co	Co is an uncommon magnetic element with properties comparable to Fe and Ni (Barceloux & Barceloux, 1999:201). Barceloux and Barceloux (1999:203) highlighted that Co is produced as a by-product of Cu and Ni mining as it is often contained within the Ag, Cu, Fe, Pb and Ni ores in concentrations of less than 1%. The mining operations of the mentioned ore deposits expose Co into the environment. The average earth crustal abundance of Co is 25 ppm (mg/kg) (Kabata-Pendias, 2000:306).
Cu	Cu is a chalcophile element and is abundant in mafic and intermediate rocks (Kabata-Pendias & Pendias, 1984:75). Kabata-Pendias (2000:106) noted that Cu is mobile in acidic environments. Cu forms simple and complex sulphides as common primary minerals and has crustal abundance ranges between 25–75 ppm (mg/kg) (Levinson, 1974). In humans, high concentrations of Cu in meat from livestock that graze or drink water contaminated with Cu can cause stomach cancer and asthma.
Cr	Kabata-Pendias (2000) defined Cr as a siderophile and deposits in ultra-basic rocks. Cr is a pathfinder of chromite, Pt and other ultramafic ore deposits (Levinson, 1974). Mining chromite and Pt deposits expose Cr to the environment through waste disposal. Rowbotham <i>et al.</i> (2000:149) indicated that waste disposal activities allow Cr to enter the soil and this potentially leads to the land contamination. Levinson (1974) specified that the average crustal abundance of Cr in soils is 50 ppm(mg/kg).
Ni	Ni is both a siderophile and found in mafic-ultramafic igneous rocks and black shales in sediments (Kabata-Pendias, 2000:314). The element is mobile during weathering and coprecipitates with Fe and Mn (Kabata-Pendias & Pendias, 1984). Ni is a pathfinder

	for massive sulphide, PGMs and certain U deposits with an average crustal abundance of 30 ppm (mg/kg) in the soils (Levinson, 1974). Mining, oil refinery, metal processing and sludge are identified as the sources that expose Ni. Genchi <i>et al.</i> (2020:1) identified cardiovascular, kidney diseases as well as lung and nasal cancers as human health issues associated with high exposure to Ni.
Pb	Pb is a high chalcophile with an average abundance of 15 ppm (mg/kg) in the earth's crust (Kabata-Pendias, 2000:210). It is found in natural parent materials, such as magmatic and ultramafic rocks as well as argillaceous and calcareous sediments. Kabata-Pendias (2000:211) indicated that Pb is hazardous to human health and animals through the food chain and soil dust inhalation. Old mining areas, the metal processing industry, waste sites and sludge have been identified as sources of Pb in the environment (Kabata-Pendias & Pendias, 1984:157; Purves, 2012:9).
V	Levinson (1974) described V as a siderophile and lithophile element. It is used as an indicator when exploring for Ag, Au, Cu and Zn in polymetallic sulphide deposits as well as Sn, Fe and phosphate in vanadiferous magnetite deposits. It has an average crustal abundance of 80 ppm (mg/kg) in soil and is mobile during weathering depending on associated minerals (Kabata-Pendias, 2000:234). Xu <i>et al.</i> (2021:2) indicated that mining smelters, plants and processing waste accounted for concentrations of V released into the environment.
Zn	Based on Kabata-Pendias (2000:136), the metal industry and mining are the main sources of high Zn concentrations in the environment. Zn is soluble and available for plant uptake (Kabata-Pendias (2000:136). The average abundance of Zn in soil is 50 ppm (mg/kg) (Levinson, 1974). The health effects associated with Zn include anorexia and depressed immune response among others taken up through the food chain, such as fish from polluted water (Wuana & Okieimen, 2011:6).

2.5 State of land around abandoned mines

According to Yabe *et al.* (2010:1258), land contamination caused by the leaching of toxic elements from mining activities and related industries has been reported throughout Africa as a hazard. The Department of Environmental Affairs (DEA (2012:3) stated in the 2nd South Africa Environment Outlook report that abandoned legacy mines, urbanisation into areas of previous mining and new mining developments are trends that encroach onto agricultural and water resources as well as conservation areas causing fewer effective ecosystems and loss of productive land. Muller (2020:12) specified that there are no current national and regional data

regarding the extent of contaminated land in SA from mining and related industries. Therefore, this study will delineate and produce a map of potential land contamination around abandoned mines.

Several studies have been conducted, but none have focused on assessing potential land contamination in the selected region. Schoeman (2016) produced a risk map of the impact of coal mining in Emalahleni using remote sensing methods that identified areas of coal combustion, subsidence, potential AMD and air pollution. Sibiya (2019) conducted research that determined the potential acid-base generation and concentration of PTEs affecting the water quality around abandoned mines in the Barberton Greenstone Belt. Sibiya (2019) revealed that abandoned mine dumps leach PTEs into the environment through wind and water seepages, which affected water quality and causes land contamination. Coetzee *et al.* (2006), Oelofse *et al.* (2007) and McCarthy (2011) indicated that abandoned mines in the Witwatersrand were left in a state of generating AMD from previous underground workings that flood to the surface. Furthermore, the characterisation of gold mine dumps revealed the dispersion of PTEs into natural resources (waterbodies and soil)(Coetzee *et al.*, 2006).

2.6 Impact of abandoned mines

Balkau (1999:5) emphasised that countries with a history of mining are susceptible to environmental, social and economic challenges. Countries such as the USA, SA, Brazil, Canada, France, Germany and China are faced with financial and rehabilitation burdens from previous mining activities that commenced without strict environmental legislation and enforcement (Balkau, 1999:4; DEA, 2012:4; Sibiya, 2019:25). This study applied DPSIR to show how potential contamination of land caused by abandoned mines influences and threatens environmental, social and economic aspects.

2.6.1 Environmental impact

The environmental impacts of abandoned mines are manifested in its physical and chemical damage. The physical environmental impacts include (Balkau, 1999:4; Sibiya, 2019:25; Mhlongo, 2022:227):

- Open mine entries (shafts and adits);
- Surface pits or excavations (with high walls and often filled with water);
- Old mine infrastructure;
- Subsidence and sinkholes; as well as
- Unrehabilitated tailings dumps.

All physical environmental impacts are a concern for post-closure land use. For instance, changes in the landscape due to sinkholes within mining properties and neighbouring farms caused by abandoned mines are common in SA (Isiaka *et al.*, 2019:1531). Sinkholes can be natural or induced (Keiller, 2010:4). In SA, natural sinkholes are caused by weathered dolomite and dolomitic limestone which cause instability (Keiller, 2010:4; Isiaka *et al.*, 2019:1531). Induced sinkholes are caused by the dewatering of underground mine workings and extracting groundwater in some areas (Moshodi *et al.*, 2016:2).

Chemical environmental impacts include coal combustion, AMD, water pollution, land pollution, and seepage of toxic elements from mine dumps, slimes and tailings dams (Coetzee *et al.*, 2006; Oelofse *et al.*, 2007). For example, in 2012, the population of Carolina in the Mpumalanga province (17 000 people) were affected by an undrinkable tap water supply contaminated by mine water due to AMD, which became evident from coal mining (Tempelhoff *et al.*, 2014:81). Based on Naidoo (2017:51), the tap water was contaminated with sulphates, As, Co, Cu, Ni, Pb and Zn. Tempelhoff *et al.* (2014) indicated that the Carolina community relied on natural water from catchment (rivers, dams, groundwater) for local water supply after treatment which was affected by mine discards, abandonment mines and coal mining operations.

2.6.2 Economic impact

Some countries have identified the economic impact of contaminated land from abandoned mine sites and have initiated financial approaches to address global challenges. Superfund by the USA is an example of a financial strategy which was introduced to account for contaminated sites of mining (Fogleman, 2014:52). In SA, the national government noticed a weak regulatory system regarding mining responsibility and established the Fanie Botha Accord (1975) between the Chamber of Mines and the Minister of Water Affairs. This meant that the government had to take full accountability for the rehabilitation of closed mines before 1976 (Munnik *et al.*, 2009:8; Cornelissen *et al.*, 2019:1). This led to financial and economic burdens, as environmental impacts (e.g., AMD and asbestos from historical mining) are still evident over long periods after mining ceases. To date, the government is left with the environmental liability and responsibility to rehabilitate approximately 6 000 abandoned mines.

2.6.3 Social impact

Land coverage by waste dumps and tailings from mining activities should be classified as a threat to human health, safety and development as it poses constraints to urban development (Mahao (2017:38). For example, van Breugel *et al.* (2019:2) reported that in 2001, sites where coal discards were disposed resulted in 4 011 ha of unusable land. This indicated the social impact of

abandoned mines across SA. Similar findings were made by Isiaka *et al.* (2019:1531) that sinkholes cost SA more than ZAR 1 billion and led to the deaths of 38 people over a 50-year period. The Merafong City Local Municipality is a good case for the environmental hazard of sinkholes linked with social impacts, especially in the Khutsong township. Moshodi *et al.* (2016:2) noted that the business sector of Khutsong township collapsed into a sinkhole triggering infrastructural damage, financial loss, unstable surface ground for neighbouring farms and damage to residential buildings. This influenced social impacts, such as loss of job creation, income to sustain families, a threat to food security and the right to peaceful homes without fear of another sinkhole.

2.6.4 Health impact

Nkosi *et al.* (2021:1) noted that communities residing near mine dumps were subjected to wind-blown dust that caused air pollution which contained toxic elements that affected residents' health. Furthermore, Nkosi *et al.* (2021) discovered that dispersed toxic elements from wind-blown dust caused high blood pressure in elderly residents near mine dumps. Okerefor *et al.* (2020:13) discovered a high percentage of respiratory and ocular symptoms among residents living near gold mine dumps.

2.7 Responses toward contaminated land

Responses to waste management in SA began with the enactment of an appropriate legislative framework over several years. Godfrey and Oelofse (2017:2) highlighted that major changes came through the Environment Conservation Act (Act 73 of 1989) (ECA) which provided the initial waste definition and requirements for waste management. However, the ECA did not regulate 80% of the volume of mine waste disposed of on land (Alberts *et al.*, 2018:1088), and has since been repealed by the National Heritage Resources Act (Act 25 of 1999). This section describes the National Framework for the Management of Contaminated Land as a response measure.

2.7.1 Constitution of the Republic of SA

The Constitution introduced sustainable development, human health and well-being as principles that govern environmental legislation through environmental rights. The rights in Section 24(a) of the Constitution state that: "Everyone has to an environment that is not harmful to their health or well-being". Section 24(b) of the Constitution promotes the conservation and protection of the environment and undertakes ecologically-sustainable development through all future developments.

2.7.2 MPRDA

The Mineral and Petroleum Resources and Development Act (Act 28 of 2002) (MPRDA) provides provisions for “equitable access to and sustainable development of the nation’s mineral and petroleum resources, and matters connected therewith”. Regulation 56(d) and (e) of the GNR527 (under MPRDA) requires that impact on the land be identified and quantified, and that the land be rehabilitated per the National Environmental Management Act (Act 107 of 1998) (NEMA) and related regulations. Section 43(1A) of NEMWA provides the Minister of Mineral Resources and Energy (under the MPRDA) licensing authority regarding waste management related to residue deposits and stockpiles from mining activities. The MPRDA applies to abandoned mines and related mine waste which makes it relevant and applicable to this study.

2.7.3 NWA

The National Water Act (Act 36 of 1998) (NWA) introduced Sections 21(g) and (h) to manage potential effluent leachate contamination from waste disposal sites. The main focus of these sections was to protect the surface and groundwater from contamination by acid-generating waste. However, NWA does not govern contaminated land. The NWA identifies potential pathways and pressures that are exerted into the environment, such as AMD and seepage from slimes or tailings dams. Surface water bodies as potential receptors for the migration of toxic elements through potentially contaminated land will be identified.

2.7.4 NEMA

NEMA was introduced to affect constitutional environmental rights. Furthermore, this established environmental management principles (Section 2 of NEMA) to guide decision-making and manage human activities in the environment (Oosthuizen *et al.*, 2018:129). Other sections of NEMA focus on corporative governance and procedures but will not be covered by this study. NEMA places requirements on listed activities to apply for environmental authorisation (EA) in Section 24 before commencing with planned development. The EA obliges the applicant to perform an environmental impact assessment. These procedures aim to ensure that the development of listed activities accounts for all actions through an environmental management tool called the Environmental Management Programme described in Section 24N. NEMA made a provision to administer other environmental management laws called specific environmental management acts (SEMAs). This led to the development of SEMAs, such as NEMWA, National Environmental Management: Biodiversity Act (Act 10 of 2004) (NEMBA) and the National Environmental Management: Protected Areas Act (Act 57 of 2003) (NEMPAA) which form an important part of this study. Overall, NEMA oversees all listed activities proposed for the

environment and places responsibility on contaminated land and mitigation measures through Section 28 which deals with the duty of care.

2.7.5 NEMBA

NEMBA was included in the research to identify critical biodiversity areas (CBAs) which host species, ecosystems and indigenous biological resources as potential receptors against the effects of previous or continuous mining activities. NEMBA provides for the protection, conservation and management of SA's biodiversity within the framework of NEMA. Furthermore, this establishes and provides functions of the South African National Biodiversity Institute (SANBI).

2.7.6 NEMPAA

NEMPAA was included here to identify land-use competition among all national, provincial and local protected areas against abandoned mines as potential receptors of possible illegal mining on such sites. NEMPAA's aim is "to provide for the protection and conservation of ecologically viable areas representative of South Africa's biological diversity and its natural landscapes and seascapes" (NEMPAA, Act 57 of 2003). The Act provides a national register for all protected areas.

2.7.7 NEMWA

NEMWA was promulgated in 2009 and governs waste management in SA. Other parts of NEMWA became operational later, such as Part 8 of Chapter 4 which deals with contaminated land. Section 1 of NEMWA concerning Part 8 states that:

contaminated is defined as the presence in or under any land, site, buildings or structures of a substance or micro-organism above the concentration that is normally present in or under that land, which substance or micro-organism directly or indirectly affects or may affect the quality of soil or the environment adversely.

Regulations for Part 8, Section 35, are classified as retrospective for assessing contamination that occurred before NEMWA's commencement, arose or is likely to arise from actual activity, including those that have already been declared as contaminated land in Section 38. This has led to the publication of the Framework for the Management of Contaminated Land which provides norms and standards in Section 7(2)(d) of NEMWA for assessing contaminated land and remediation. This allowed for assessing potential land contamination around the abandoned mines selected for this study.

2.7.8 SPLUMA

Government Notice Regulation 1590 of the MPRDA (i.e., the Housing and Living Conditions Standard for the Minerals Industry, 2019), suggests that previous mining areas can be used for residential development. Spatial planning and land-use management in SA are managed by the Spatial Planning and Land Use Management Act (Act 16 of 2013) (SPLUMA). SPLUMA places the management of local land use matters in the hands of the local government (mostly municipalities). In Section 24, SPLUMA requires that each local municipality prepare, adopt and implement a land-use scheme (LUS) in line with the existing Municipal Spatial Development Framework. Land use is determined based on the jurisdiction of the municipal area in the Local Government: Municipal Demarcation Act (Act No. 27 of 1998). A LUS is a development tool that allows or restricts certain types of land use to certain geographic areas to exercise control over the spatial use of the land (Fourie, 2019). Therefore, to understand what alternative land uses can be applied for areas which have been previously classified for mining use, prospecting rights and mining permits are answered by LUS classes from each municipality under investigation.

2.8 Chapter summary

This chapter provided the driving forces that lead to potential contamination and outlined contaminants from abandoned mines. Previous studies have delineated the impacts and gaps in the literature that led to this study. Finally, responses to land contamination in the form of policies and legislation were provided.

CHAPTER 3 METHODOLOGY

This chapter describes and justifies the research methods used and relates them to different research objectives. Potential land contamination was determined using the concentrations of the selected PTEs. Therefore, a quantitative research method was applied to quantify contamination using selected elements. However, mixed methods were applied, as related to each research objective (Figure 3-1). The research methods included desktop review, fieldwork and sampling, laboratory analysis, hazard index (HI), the DPSIR framework and remote sensing.

3.1 Research design

The research design used a flowchart to outline the processes, methods and procedures used to obtain relevant information.

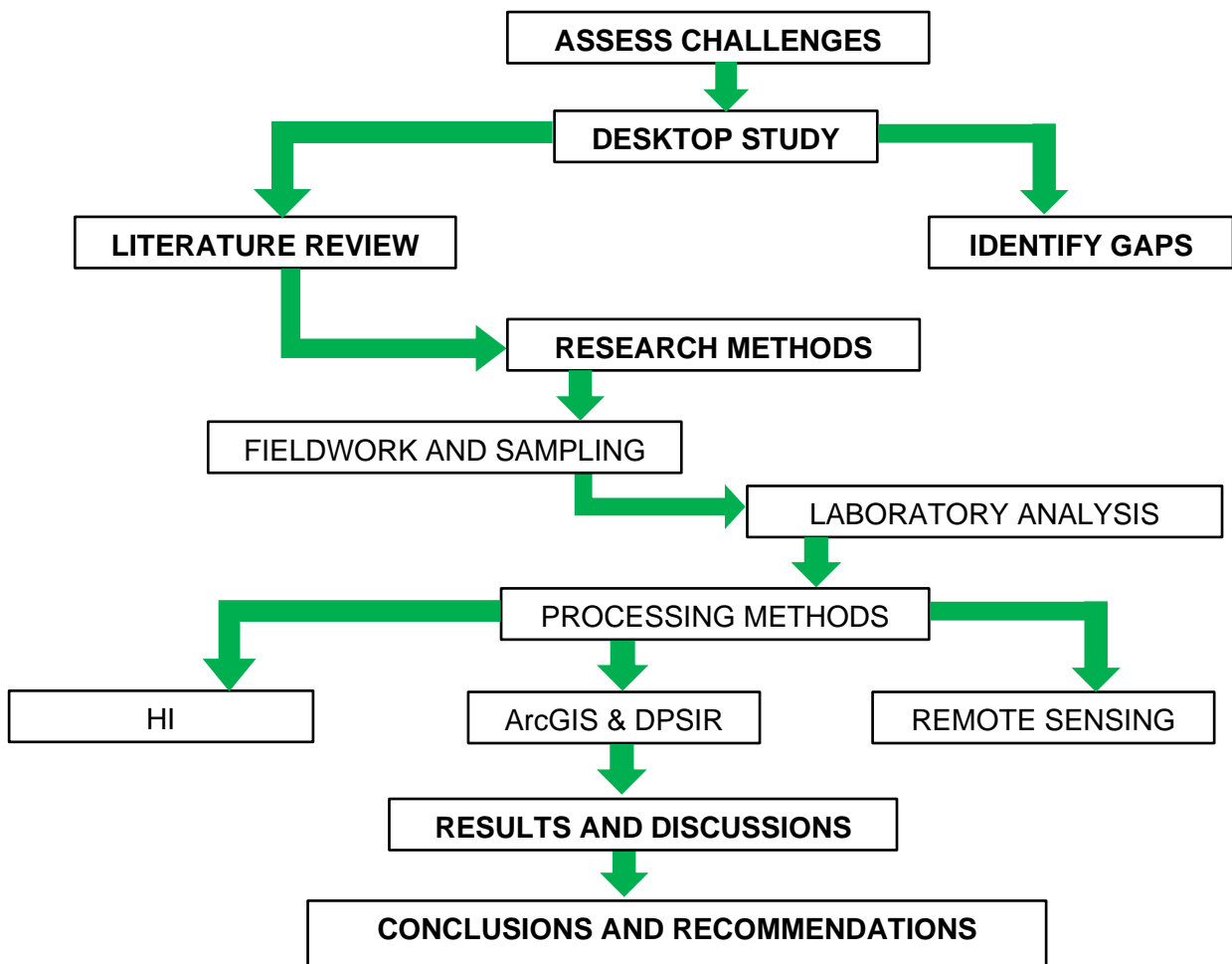


Figure 3-1: Research flowchart and outline.

The research flowchart (Figure 3-1) assisted in outlining how the research developments and methods unfolded until the final chapter. This schematic demonstration summarised standard

operational procedures followed for data collection and processing to obtain the desired products (maps, graphics, statistics, etc.) that are discussed in Chapter 4. It shows the planning, materials, resources, and patterns applied to execute the research which are discussed in detail below.

3.2 Data collection

Two data collection pathways were identified: (1) desktop research and (2) fieldwork and sampling. Desktop research as a method was used to link the literature and identify gaps within research methods to properly design fieldwork and sampling plans, resources and materials (Figure 3-1).

3.2.1 Desktop research

Desktop research was used to assess the location, conditions and trends around abandoned mines within the study area. Furthermore, this assisted with a review of previous studies conducted around these areas regarding land contamination, environmental impact and potential receptors. ArcGIS was used to produce topographic maps that displayed spatial information concerning legacy mines and the design of the sampling points. This instrument aided in the planning of fieldwork for sample collection and identification of existing natural resources in the area.

3.2.2 Fieldwork and sampling

Before geochemical analysis was performed, it was essential to undertake fieldwork and collect representative test soil samples from the area under investigation (Tan, 1995:1). A systematic sampling design was selected and used for soil sample collection because of its effectiveness in gathering information, which is commonly applied in earth science (Carter & Gregorich, 2007:7).

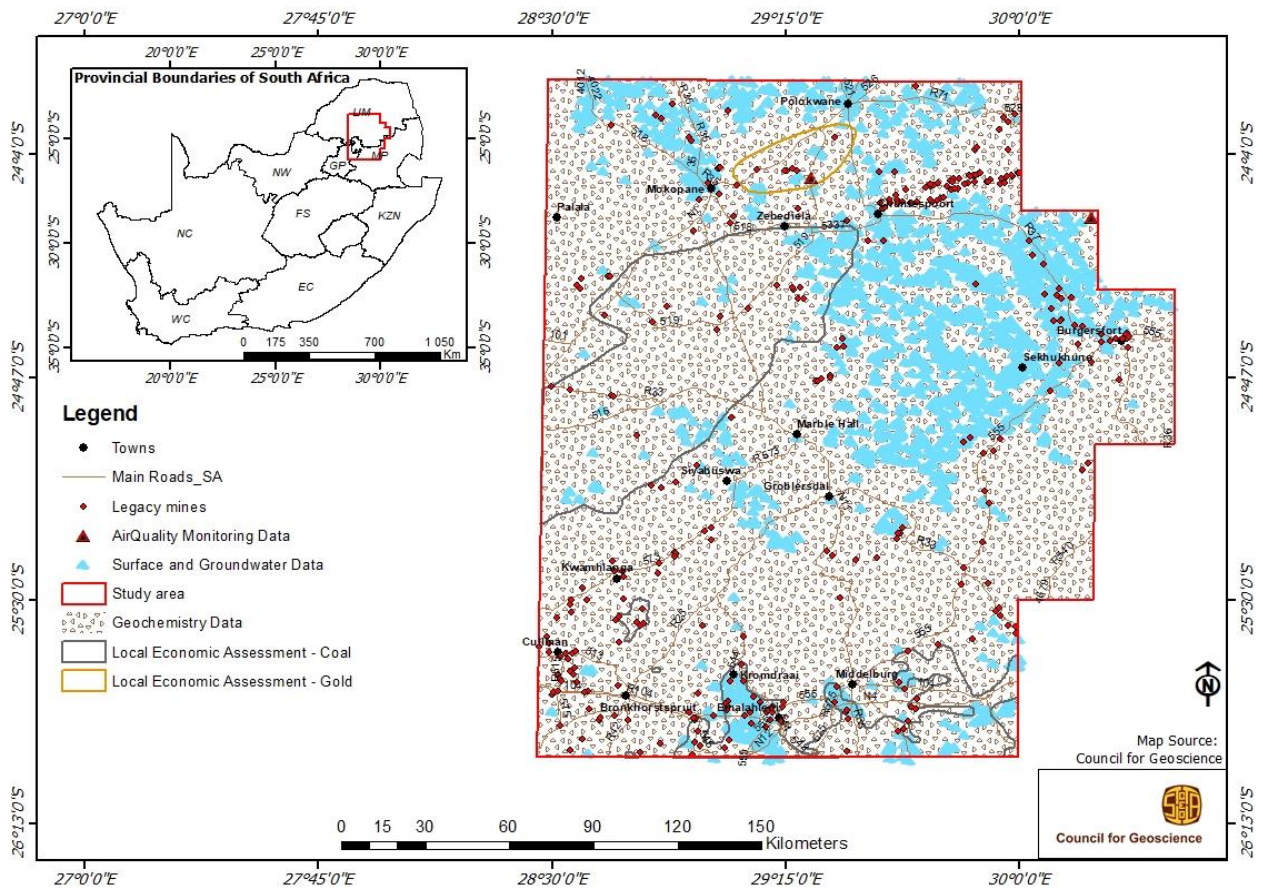


Figure 3-2: Sampled fieldwork points and locations of abandoned mines data (09 January 2023 from Council for Geoscience).

The samples were collected at a spacing of one sample per square kilometre array (Figure 3-2). Composite samples of approximately 5 kg were taken at each point using an auger from the top zero to one metre depth of the soil profile. The samples were passed through a universal sample splitter (Labotec Riffle Splitter) to obtain a homogeneous mixture before being packaged in sample bags. Sampling was performed using the source-pathway-receptor model, as recommended by the Framework for the Management of Contaminated Land provided by NEMWA. Abandoned mines were the main source of contamination and served as reference points for potentially-contaminated areas for sample collection. The other sampling points served as control points for the pathways through which PTEs were likely transported through soil erosion and surface water percolation.

The Framework for the Management of Contaminated Land recommends three phases for contamination assessment:

- Preliminary site assessment (Phase 1)
- Contaminated site assessment (Phase 2)

- Contaminated site remediation plan (Phase 3)

Preliminary site assessment involved desktop research (explained in Section 3.2.1). This was conducted and documented by the Council for Geoscience (CGS) on behalf of the Department of Mineral Resources and Energy (Auditor General, 2009). The current study was for Phase 2 which dealt with contaminated site assessment. This investigation included the sampling and analysis of representative soil and sediment to determine the extent of land contamination.

3.3 Laboratory data analysis

The CGS laboratories were used to perform the analyses. The samples were dried in an oven at approximately 75 °C, and 500 g representative of the whole soil sample material was separated and stored for future use. The sub-75 µm fraction of each of the remaining sample materials was dried and sieved. This process produced a powder pellet that was pressed using a polyvinyl alcohol binder. A grain size of < 75 µm was chosen because most trace elements are concentrated in the clay-silt particle size range (Rosner, 1999:58). The powder pellets were analysed on a Philips PW 1606 Simultaneous X-Ray Fluorescence Spectrometer for the following geochemical elements: As, antimony, Ba, Co, Cr, Cu, Fe, Mn, niobium, Ni, Pb, rubidium, scandium, Sn, strontium, thorium, titanium, U, V, tungsten, yttrium, Zn and zirconium, however, some elements were analysed for research needs that might arise in the future. For quality assurance and precise determination of element concentrations, certain samples taken from abandoned mines were analysed using single and sequential extraction techniques. Single and sequential extractions offer semi-quantitative data on element concentration between operationally defined geochemical fractions (Cappuyns, 2012). The techniques uses Ethylenediaminetetraacetic acid (EDTA) and acetic acid as extraction solutions (Cappuyns, 2012). Based on Filgueiras *et al.* (2002) and (Gleyzes *et al.*, 2002), the availability of trace elements from different media (e.g., soil, sludge and sediments) were examined using single and sequential extraction techniques in the field of analytical chemistry.

3.4 Contamination assessment indices

Assessing the degree of land contamination is an important step in preventing further damage and planning rehabilitation remedies. Based on Kowalska *et al.* (2018:2395), early indices were created by Muller (1969) for sedimentological assessment and improved by Hakanson (1980) for aquatic pollution control using a sedimentological approach. Potential toxic elements pose a threat to land and soil (Mazurek *et al.*, 2019:13). Gąsiorek *et al.* (2017:149) and Ghazaryan *et al.* (2015:444) indicated that natural processes (geogenic) and anthropogenic were main sources of PTE. Naturally-induced PTEs result from parent material sources (mostly lithological units), whereas anthropogenic PTEs are human-induced owing to developments (i.e., mining and

industries). Mazurek *et al.* (2019:14) and Kowalska *et al.* (2018:2396) indicated that many authors highlighted that indices were effective tools for assessing land contamination using PTE. Mazurek *et al.* (2019:16) and Mngadi (2020:63) highlighted pollution indices applicable to different purposes. The determination sought from the indices in this study was land contamination in the selected abandoned legacy mines. Therefore, comparing potential pollution indices that might be relevant were the individual indices (geoaccumulation index [I_{geo}], contamination factor [Cf] and single pollution index [PI]) and group or complex indices (mean hazard index [m_{hi}], pollution load index [PLI] and degree of contamination [C_{deg}]).

3.4.1 Individual indices

Individual indices were used to calculate each PTE separately to identify the contribution of each element to contamination (Kowalska *et al.*, 2018:2402; Mngadi, 2020:41).

3.4.1.1 Geoaccumulation index

Geoaccumulation index (I_{geo}) was applied for assessing contamination using concentrations of PTE derived from laboratory results and geochemical background concentrations of PTE from their natural bedrock or material (Mazurek *et al.*, 2019:16). Kowalska *et al.* (2018:2397) highlighted that I_{geo} strengths included permitting assessment of the current and previous contamination and gave precise scale by using 1.5 multiplication factor to limit potential variation of lithological effects. This method's shortcomings included the use of incorrect geochemical background values which were susceptible to variations depending on location (Kowalska *et al.*, 2018:2397). Mazurek *et al.* (2019) provided the equation as:

$$I_{geo} = \log_2 \left[\frac{C}{1.5 - B} \right]$$

where C was the concentration of PTE in the current collected samples, B the geochemical background concentration of PTE from their natural bedrock or material. The 1.5 was applied as a constant value that allowed the analysis of fluctuations in geochemical background concentrations of PTE due to natural processes. The geoaccumulation index method was not applied here, as it focused on the potential contamination of each PTE at a time, whereas the expected outcome was overall contamination.

3.4.1.2 Contamination factor (Cf)

Contamination factor (Cf) is an index that allows for assessing land contamination using the concentration of PTE from collected soil samples and values of pre-industrial reference level of

PTE as given by Hakanson (1980:982). Contamination factor (Cf) is a simple and straightforward method that can be applied to an individual element. The inadequacies of this method are that it cannot be applied without the use of a pre-industrial reference level and disregard of the required geochemical background values, including variations in natural processes (Kowalska *et al.*, 2018:2398). The equation for Cf is (Kowalska *et al.*, 2018:2405; Mazurek *et al.*, 2019:16):

$$Cf = \frac{Cm}{C_{p-i}}$$

where Cm was the concentration of PTE from collected soil samples, C_{p-i} the values of pre-industrial reference level of PTE given by Hakanson (1980:982). This method was considered for comparison purposes to identify suitable assessment methods for application in the research.

3.4.1.3 Pollution (PI)

The PI is an index applied to determine which PTE represents the maximum risk contamination value for soil or land (Kowalska *et al.*, 2018:2404). The equation that describes PI is:

$$PI = \frac{Cn}{GB}$$

where Cn was measured elemental concentration in soil, GB the geochemical background values.

3.4.2 Group or complex indices

Group or complex pollution indices were applied to assess the overall land or soil contamination based on the concentration of more than one PTE or the sum of individual indices (Kowalska *et al.*, 2018:2402; Mngadi, 2020:41).

3.4.2.1 Degree of contamination

Hakanson (1980) established that the C_{deg} could be used to assess contamination. The advantages of the method included unlimited investigation of the number of PTE and calculating the sum of Cfs on a precise scale (Kowalska *et al.*, 2018:2400). The reliance of the method on Cf which is calculated using pre-industrial values is a disadvantage; hence, it was not selected for this study. Furthermore, pre-industrial values were given to a limited number of PTEs such as As, Cd, Cr, Cu, Hg, Ni, Pb and Zn (Hakanson, 1980:982; Kowalska *et al.*, 2018:2400). Hakanson (1980), Kowalska *et al.* (2018:2407) and Mazurek *et al.* (2019:17) noted that the assessment is calculated as follows:

$$C_{deg} = \sum_{i=1}^n C_f$$

where C_f was the contamination factor, n the number of analysed PTEs.





3.4.2.2 Hazard Index (HI)

Caeiro *et al.* (2005:162) and Mazurek *et al.* (2017:849) indicated that the appropriate assessment for land contamination using soil samples was through applying HI (new pollution index). HI was selected as the best approach among the other indices based on considering legal geochemical threshold limits and the added risk level (e.g., a maximum permissible addition) within the calculation equation (Dung *et al.*, 2013:349). The HI was derived from combining two indices, C_f and C_{deg} . The HI equation was as follows:

$$m_{hi} = \sum_{i=1}^n \frac{X_i}{XL_i}$$

where m_{hi} was the mean hazard index, X_i and XL_i the measured elemental concentrations (from soil samples) and the allowable concentration of X from norms and standards of NEMWA, respectively. n represented the number of elements considered for the research. i was an index indicating the permissible level for element concentrations. Values above one indicated the presence of contamination. HI used legal thresholds from NEMWA as measures instead of the pre-industrial reference level of PTE given by Hakanson (1980:982). HI used classes for contamination assessment (Table 3-1). The classes were divided into low, moderate, high and extreme contamination. The high and extreme contamination indicated the presence of PTE at worrisome concentration levels on the land.

Table 3-1: Classes used to describe contamination based on hazard index method.

Index Model	Class value	Description of quality	Colour on map
HI	$m_{hi} < 0.5$	Low contamination	
	$0.5 > m_{hi} < 1$	Moderate contamination	
	$1 > m_{hi} < 1.5$	High contamination	
	$m_{hi} > 1.5$	Extreme contamination	

3.4.2.3 PLI

PLI was applied for a complete assessment of the degree of contamination within the land and soil quality. Varol (2011) highlighted that indices (such as PLI) provided a direct method to

understand the deterioration of the land as a resource due to accumulating PTEs. PLI was calculated as a geometric average of the PI of the selected PTEs based on this formula:

$$PLI = \sqrt[n]{PI_1 \times PI_2 \times PI_3 \times \dots PI_n}$$

where n referred to the number of analysed PTEs, and PI_1, PI_2 , etc, refers to pollution index (PI) values for each selected element.

3.4.3 Other indices

There are other indices which were not considered for this study but serve different functions. PLI, an average of pollution index (PI_{Avg}) and a modified contamination factor (mC_{deg}) were used to analyse the measure of total pollution (Weissmannová & Pavlovský, 2017:8). The enrichment factor dealt with the source of PTE, while the mean ERM (ecological risk assessment) quotient and RI (risk index) were used for the potential ecological risk of harmful effects (Kowalska *et al.*, 2018:2400).

3.5 Thresholds for soil screening

The assessment of contaminated land was performed using norms and standards called SSV1, as contained in Part 8 of the NEMA (Framework for the Management of Contaminated Land) (Table 3-2). The norms and standards were applied in combination with HI (outlined in Section 3.4.2.2). SSV1 values were selected because their concentration accommodated all land uses, whereas SSV2 and SSV3 only accommodated certain land-use types. The classification in terms of SSV2 is for risk exposure around residential land use whereby the child receptor in informal settlements is applied as the most sensitive receptor. The SSV3 standard is applied for contamination assessment in commercial and industrial land use by determining the exposure of an adult maintenance worker as a receptor on outdoor occupational workings. Herselman *et al.* (2005:509) established baseline concentrations of certain elements with the following maximum natural (geochemical background) baseline total threshold concentrations:

- Cd: 3 ppm (mg/kg)
- Co: 50 ppm (mg/kg)
- Cr: 350 ppm (mg/kg)
- Cu: 120 ppm (mg/kg)
- Ni: 150 ppm (mg/kg)
- Pb: 100 ppm (mg/kg)
- Zn: 200 ppm (mg/kg)

Table 3-2: Norms and standards for Soil Screening Values in all land uses.

Parameter	Units	SSV1	SSV2	SSV3
		All land-uses protective of the water resource	Residential land use	Commercial and industrial land use
<i>Metals and metalloids</i>				
As	ppm or mg/kg	5.8	23	150
Cr (III)	ppm or mg/kg	46 000	46 000	790 000
Co	ppm or mg/kg	300	300	5 000
Cu	ppm or mg/kg	16	1 100	19 000
Ni	ppm or mg/kg	91	620	10 000
Pb	ppm or mg/kg	20	110	1 900
V	ppm or mg/kg	150	150	2 600
Zn	ppm or mg/kg	240	9 200	150 000

3.6 DPSIR

The DPSIR as a study method was not applied as an analytical tool but as a conceptual model for organising causal relations between human activities and the environment. Maxim *et al.* (2009:12) indicated that DPSIR was useful for analysing environmental indicators developed to conserve the environment through policy developments. Here, DPSIR was combined with the ArcGIS tool to produce maps of biomes, heritage sites and protected areas as conservation tools driven by policies to protect sensitive environments (e.g., rivers, lakes and ecological attributes). This study's purpose was to demonstrate the communication value of *R* (DPSI-R) in conserving a sensitive environment by integrating them with the analytical results posed by potential land contamination. The literature presented *D*, *P*, *S* and *I* associated with abandoned mines, including responses in the form of policies. This would indicate how far the responses were implemented and explore economic ecological plans for opportunities for social order in the future. This study aimed to identify a causal link between land-use competition and anthropogenic activities (e.g., mining and environmental receptors).

3.7 Remote sensing

Remote sensing was used to detect land-use changes. Abd El-Kawy *et al.* (2011:483) emphasised that change detection was useful to perform the classification of land use and land cover (LULC) changes between competing factors. The land-use factors chosen were mining and quarries; built-up, cultivated, forested and grasslands; as well as bare soil and water bodies. The

aim was to detect land-use changes around abandoned mines and determine whether land contamination was a contributing factor to land degradation. Landsat 8 satellite images were obtained from the United States Geological Survey¹ and applied using a selected support vector machine (SVM) as a supervised image classifier. Mountrakis *et al.* (2011:256) defined that SVM proved an appropriate and reliable methodology over most alternative algorithms for processing satellite images. The selected images were obtained over a 20-year period between 2000 and 2020.

3.8 Chapter summary

The research methods included desktops, fieldwork and sampling, laboratory analysis, and processing methods. The processing methods for the collected data included comparing indices, remote sensing, and combining ArcGIS and DPSIR. HI was selected as the most appropriate index among other indices. The thresholds for all land-use types were outlined.

¹ <https://earthexplorer.usgs.gov/>

CHAPTER 4 RESULTS AND DISCUSSION

The chapter presents the results for potential land contamination in the form of HI and LULC maps. This is followed by a discussion and summary of findings using maps, graphs and tables to address the aims and objectives of the research.

4.1 Introduction

This section discusses the research aims and objectives. The HI using SSV1 values (discussed in Chapter 3) was applied to address Research Objective 1 (RO1), remote sensing to investigate Research Objective 2 (RO2) and DPSIR to determine Research Objective 3 (RO3). The chapter addresses the proposed research objectives outlined in Chapter 2 which were formulated as follows:

- Research Objective 1 (RO1): Identify potentially-contaminated areas within the selected region/study area.
- Research Objective 2 (RO2): Investigate the risks associated with abandoned legacy mines and current mining on the land.
- Research Objective 3 (RO3): Determine receptors of potential contamination in the study area.

4.2 Results related to RO1

The laboratory results (geochemistry data) for elemental concentrations of As, Co, Cr, Cu, Ni, Pb, V and Zn were used together with the norms and standards threshold of PTE (SSV1 in Table 3-2 as a Framework for the Management of Contaminated Land contained in Part 8 of the NEMA) for calculation of the m_{hi} . Then, the calculated m_{hi} results (Annexure) were plotted using ArcGIS to produce a potential contamination map based on classes (Table 3-1). The potential contamination m_{hi} map indicated the distribution of legacy mines, rivers, wetlands, towns and classes as shown in Figure 4-1.

4.2.1 Potential land contamination m_{hi} map

The calculated m_{hi} based on the available data indicated that an index less than one meant that the land was suitable for all land uses. An index greater than one meant that the land was contaminated with one or more PTEs concentrations above the permissible limit.

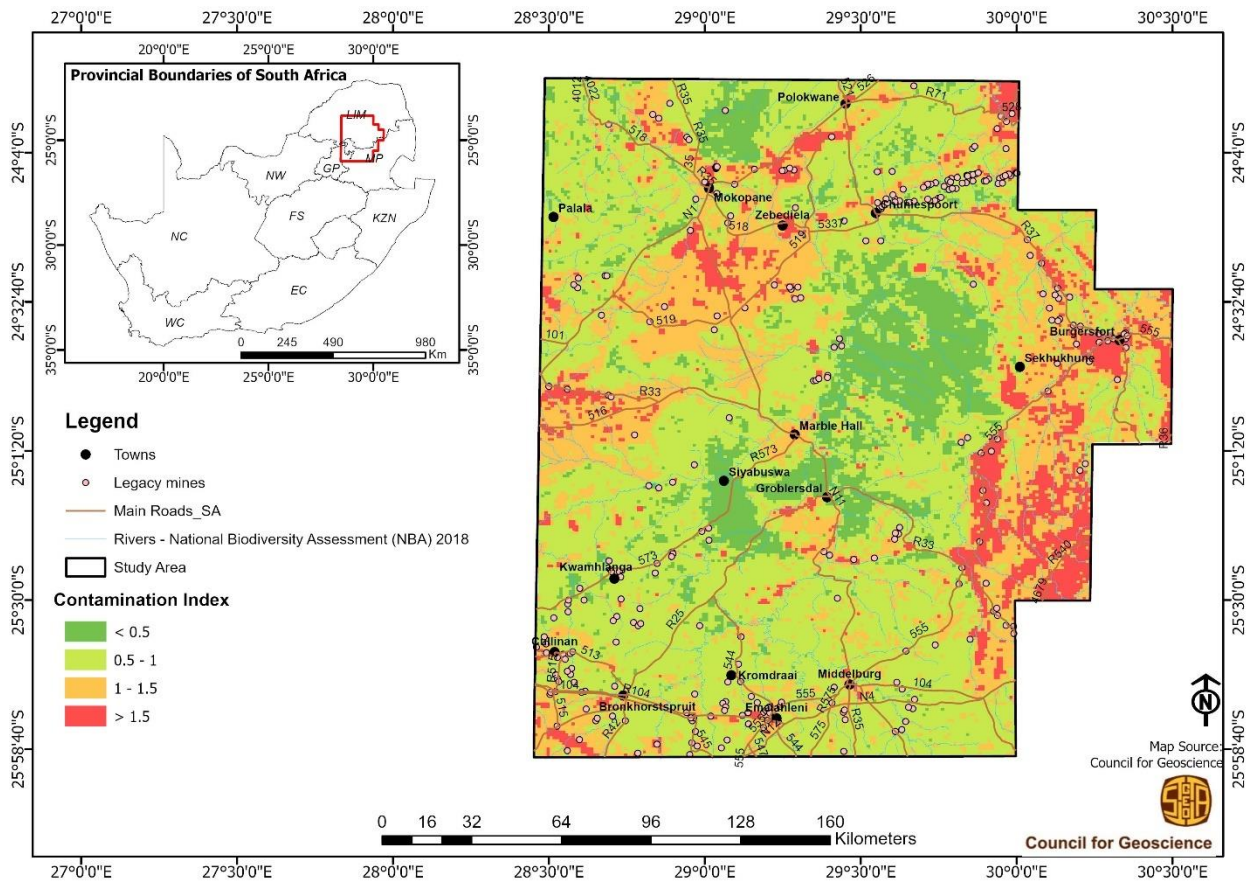


Figure 4-1: Potential land contamination mean hazard index map.

The observable pattern of the results (Figure 4-1) indicated that potential land contamination followed past and present active mineral fields when correlated with Figure 1-1. A potential contamination index greater than one was delineated or existed around towns with historical and/or present mining activities (e.g., Bronkhorstspuit, Emalaheni, Middelburg and Belfast) that exploited or exploit coal commodities within the coalfields (Figure 4-2). A similar pattern was observed in the south and north of Burgersfort and Sekhukhune District Municipality within the eastern limb of the Bushveld Complex known for mining chrome, Co, Cu, Ni and PGMs. East to southeast of Chuniespoort (recently, Chuenespoort), the pattern follows the asbestos field, with historical footprints of asbestos mining as shown in Figure 4-2.

However, in the northern limb of the Bushveld Complex around northwest, northeast and south of Mokopane towards Zebediela, the same pattern of contamination greater than one was detected. Signatures of potential contamination based on more than one index were observed in and around Polokwane in both the south and east. The latter was related to previous gold mining footprints within the Pietersburg Greenstone Belt. In the south of Palala, there were scattered hazard indices greater than one which was the host of coal fields.

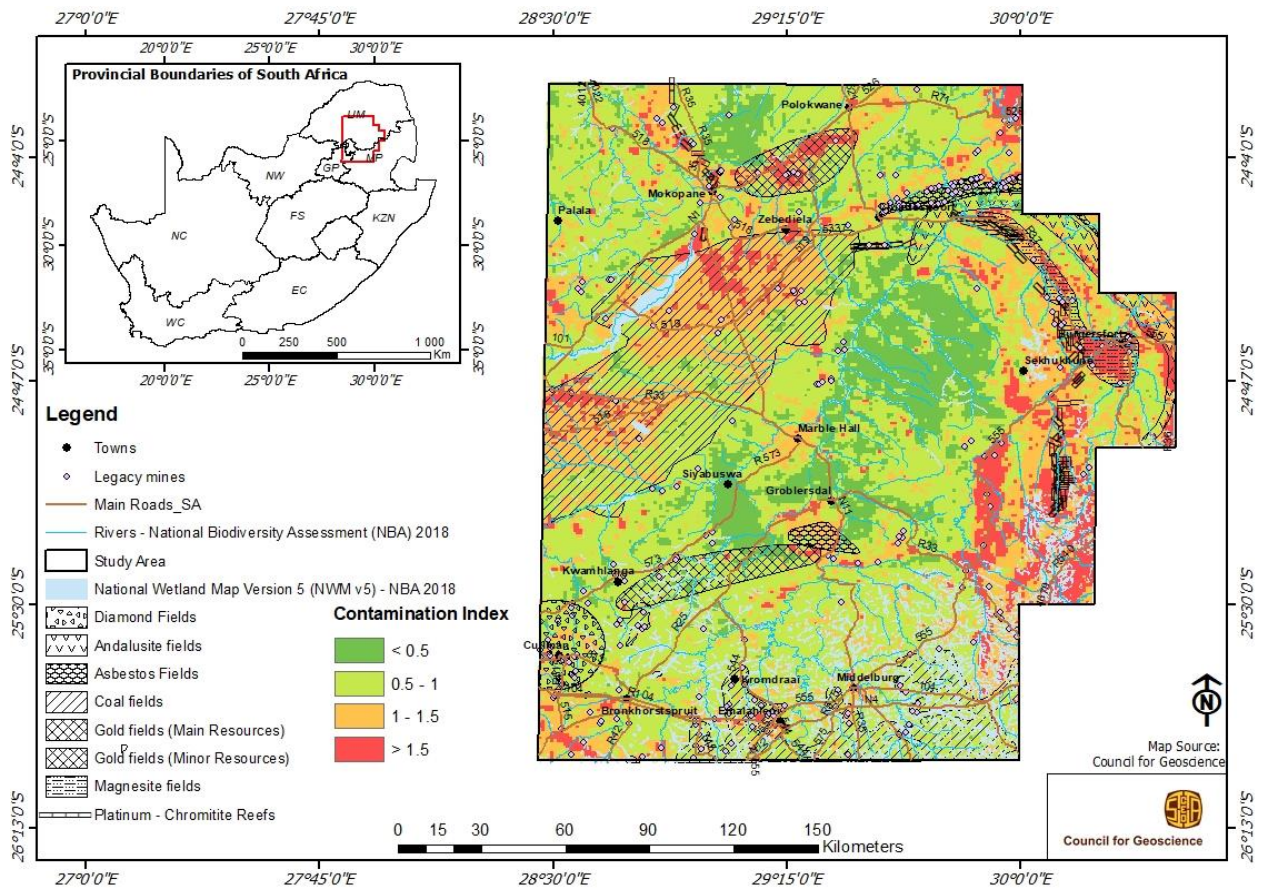


Figure 4-2: Overlay of potential land contamination mean hazard index with mineral fields.

Other areas showed positive signs with contamination less than one for the m_{hi} . The signatures of areas around Groblersdal, Siyabuswa and north to northeast of Marble Hall showed a lack of potential contamination, with an index of less than 0.5. This was because most of the arable agricultural land existed within the area. Furthermore, signatures of contamination between 0.5 and one index indicated extensive land coverage across the research area.

4.2.2 Statistics of potential land contamination

Table 4-1 and the percentage in Figure 4-3 show that the area covered by the research was an average of 43 345 km². The results (Table 4-1) indicated that 11.03% had a low contamination index, which accounted for 4 779 km² of the land. This indicated a lower availability of undisturbed land. The moderate contamination index covered 54.6% which was equal to 23 664 km² of land. The latter findings added concerning challenges since continued anthropogenic activities still disregard environmental compliance and protection. The projection indicates that medium contamination is most likely to turn as high contamination in the future whereby the combination of the two classifications makes up 88% of the study area that is likely to be contaminated.

Table 4-1: Statistics of potentially contaminated land.

Sum of area in square kilometre				
Index	Total area in km ²	Area %	Contamination description	Colour on map
0,0–0,5	4 778.9687 km ²	11.03%	Low contamination	
0,5–1,0	23 664.66719 km ²	54.60%	Moderate contamination	
1,0–1,5	11 200.08585 km ²	25.84%	High contamination	
< 1,5	3 701.335288 km ²	8.54%	Extreme contamination	
Grand Total	43 345.05702 km ²	100.00%		

The high contamination index class accounted for 25.84% covering 11 200 km² of land, and extreme contamination indices accounted for 8.54% covering 3 701 km² of land. Combining high and extreme contamination indices indicated that 34.38% of the land was potentially contaminated or hazardous greater than 1 as an average measure of permissible or none permissible (greater than 1). This high number exposed the environment to PTEs. Common contamination was observed around legacy mines, which was attributed to the fact that there was continuous mining in some of these areas.

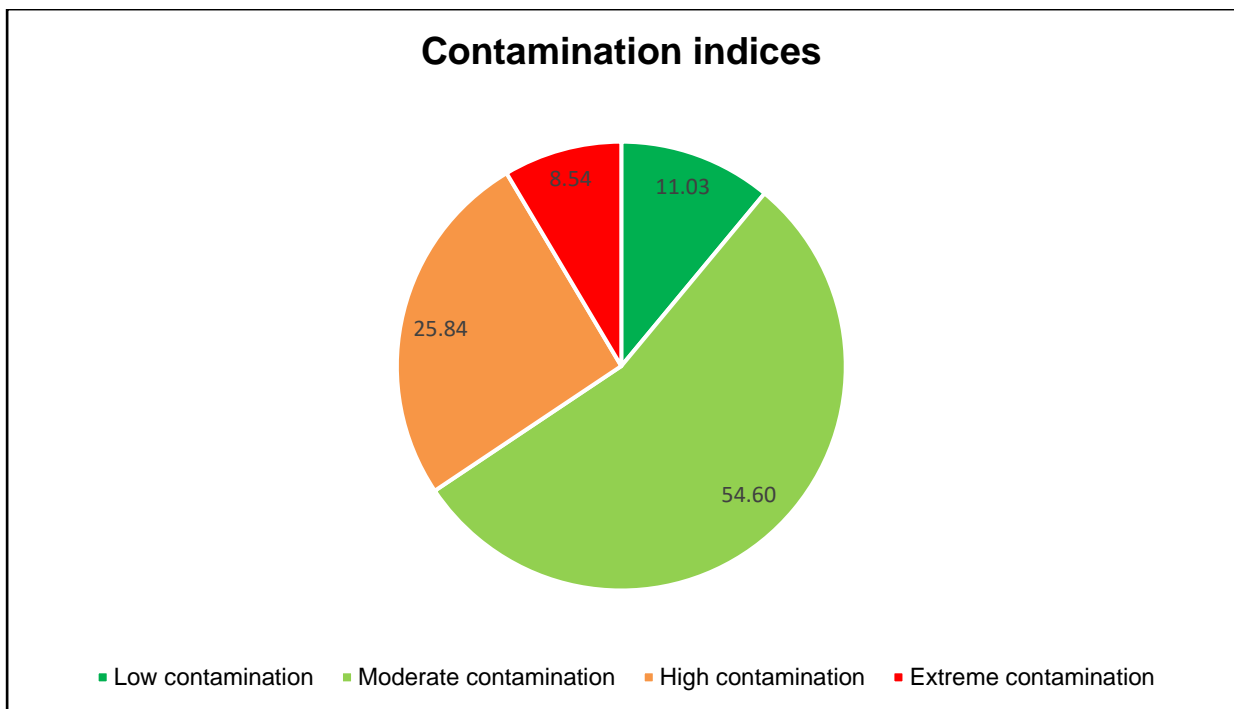


Figure 4-3: Representation of contamination in terms of hazard indices.

4.3 Results related to RO2

Several risks are associated with land contamination. This study assessed land change detection using remote sensing to classify LULC. However, the vulnerability or susceptibility of groundwater resources in the vicinity of potential land contamination was assessed as part of the risk.

4.3.1 LULC-change detection

Classifying LULC competition focused on several classes (i.e., bare soil, built-up areas, cultivated, forested and grasslands, waterbodies, mines and quarries). The study selected two periodical years of assessment based on the change in regulations for mining, water and the environment. The years 2000 and 2020 were used for land-change detection. The accuracy of the results of the two Landsat images was classified using SVM. The overall accuracy for the two classified Landsat images was 89.00% with a kappa coefficient of 0.89 in 2000 and 90.00% with a kappa coefficient of 0.9 in 2020 (Table 4-2).

Table 4-2: Comparison between accuracy of land-cover classification (2000–2020).

Year	Producer accuracy (%)	User accuracy (%)	Kappa coefficient	Overall accuracy (%)
2000	90.24	90.46	0.90	90.00
2020	88.82	89.83	0.89	89.00

Based on Anderson (1976:6), LULC classification must achieve 85% or above for the overall accuracy assessment results as the recommended threshold value. The overall classification accuracy assessment results for both producer and user accuracies in 2000 and 2020 achieved a recommended threshold value of 85% or higher (Table 4-2). This met the requirements for valid LULC classification to present the classes in the form of maps.

The validation results revealed that the findings of the SVM algorithm using different satellite imagery were above 89% overall accuracy for both Landsat 8 OLI/TIRS in 2000 and Landsat 8 OLI/TIRS in 2020.

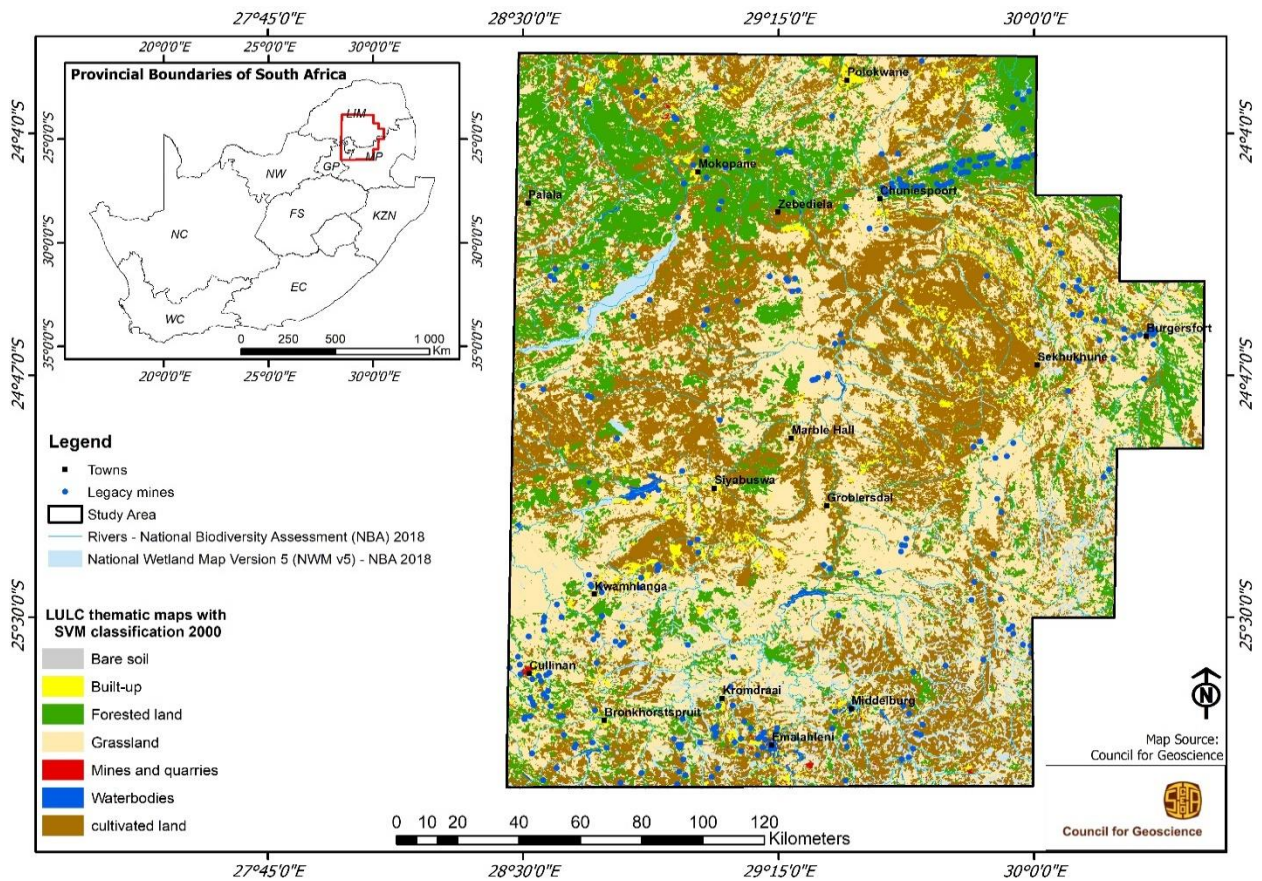


Figure 4-4: Land-use land-cover classification (2000).

In 2000, despite the presence of legacy mines, the visibility of mining operations was limited (Figure 4-4). Limited land use and coverage were observed in the built-up and forestland classes (Figure 4-4). In contrast, there was sufficient land coverage for agricultural purposes, such as cultivated land and grasslands for animal grazing and biodiversity services. In 2020, the classification identified the visibility of growth in mining and quarry operations and built-up and forestland classes. Cultivated land, water bodies and grassland classes decreased (Figure 4-5).

Land-change detection between 2000 and 2020 indicated an increase in bare soil, built-up, forested land, and mine and quarry land-use classes (Table 4-3). However, the increase in both bare soil and mine and quarries was steady or moderate, accounting for 0.50% and 0.72% of growth, respectively. Mines and quarries displayed an increase around Burgersfort and Mokopane, with a similar pattern, whereby there were high potential contamination signatures (Figure 4-1).

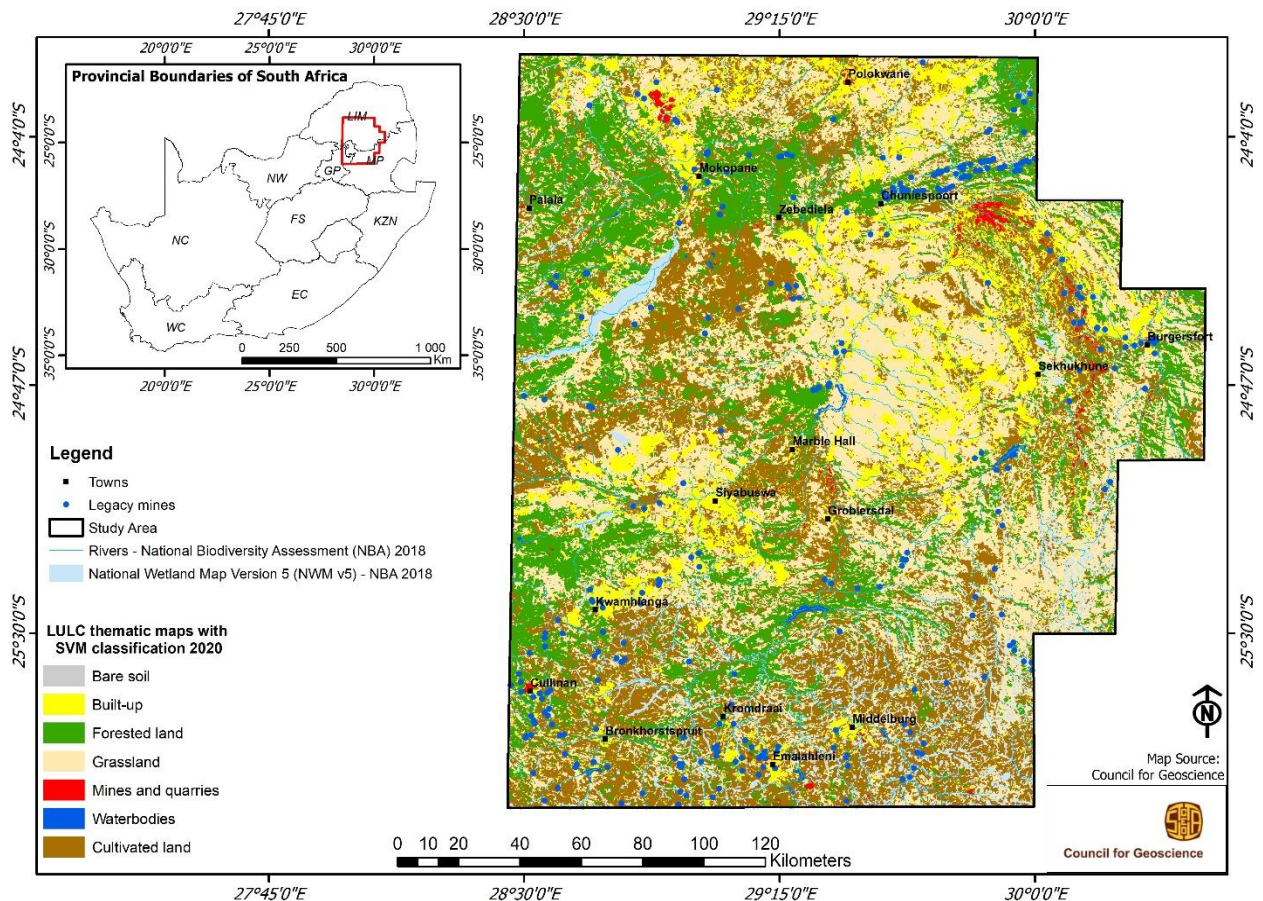


Figure 4-5: Land-use land-cover classification (2020).

Most mines in these areas were underground, and there were mine waste rocks, dumps and spillages on land. Built-up features increased by 7.41%, with most residents moving closer to socially-developed areas, including new mine developments and towns. Therefore, the potential contamination of land around the identified built-up areas indicated an increased human risk of exposure to PTEs, whereby there was an occurrence of potential contamination of greater than one. This could lead to human exposure through dust fall as a pathway or through leafy vegetables based on findings (Mngadi, 2020:132). The latter statement is an indication of how high concentration of PTEs ends up consumed by or exposed to humans in nearby affected areas. Forested land was attributed to a decrease in both cultivated land and grassland. An increase in forested land was classified as a negative risk associated with the conservation of grassland and its expansion within the South African National Protected Areas (Figure 4-11). It limits grazing land for domestic and wild animals.

Other land use factors (specifically, cultivated and grasslands as well as waterbodies) showed a decrease (Figure 4-6). The decrease in water bodies could be attributed to other hydrological factors such as rainfall, drought, temperature and evaporation, however, such factors were not part of the research scope. Both affect diminishing arable and cultivated land increases in mining

development and built-up areas. This posed the risk of encroaching on land designated for food security. This correlated with the findings of Simpson *et al.* (2019:2), which indicated land-use competition between mining, energy, water management, arable agricultural land (for food security) and social welfare (for settlement) in certain areas. The natural grassland factor accounted for a negative reduction of 8.22% from 2000 to 2020, a magnitude that led to biodiversity loss. This led to the alteration of natural forests and grasslands into grazing land to feed livestock and undertake agricultural activities that limit the habitat of certain game-farming animals or wild animals that depend on grass. Potential contamination overstrained the grassland through acidification of the land (soil) which affected vegetation. Furthermore, mining stripped the topsoil from which the grassland developed.

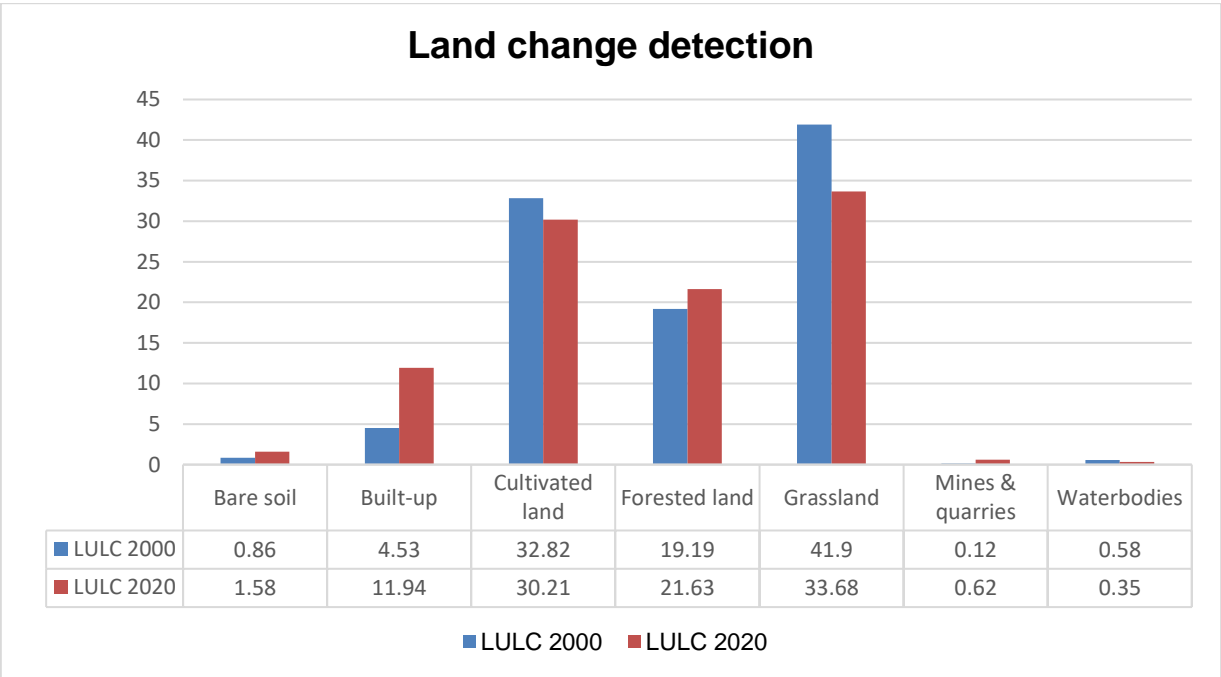


Figure 4-6: Detecting land-change using land-use land-cover classification.

The risk of land contamination in water bodies refers to surface water resources. Surface water resources are prone to contamination emanating from mining areas as sources of high contamination. The HI map suggested that there was a likelihood of surface water contamination in potentially-contaminated areas (Figure 4-1). The reduction in surface water bodies from 0.58 in 2000 to 0.35% in 2020 was likely attributed to drought or man-made channelling or artificial changes in rivers, wetlands, attributes or streams that paved the way for different developments. The risk categories for wetlands identified in the study area were zero, nine, 15 and 16 for the National Biodiversity risk.

Table 4-3: Change in area size of land-use land-cover classification using Landsat data (2000–2020).

Land cover type	LULC (2000)		LULC (2020)		Change in % from 2000–2020
	Area (Ha)	% of area	Area (Ha)	% of area	
Bare soil	37 180.30	0.86	68 420.73	1.58	0.72
Built-up	196 728.16	4.53	518 523.94	11.94	7.41
Cultivated land	1 425 732.81	32.82	1 312 193.37	30.21	-2.61
Forested land	833 743.00	19.19	939 455.62	21.63	2.44
Grassland	1 819 968.42	41.90	1 463 061.95	33.68	-8.22
Mines and Quarries	5 303.39	0.12	26 892.60	0.62	0.50
Waterbodies	25 170.07	0.58	15 261.75	0.35	-0.23
	4 343 826.16	100	4 343 809.96	100	0.00

4.3.2 Vulnerability or susceptibility of groundwater to land contamination

Groundwater is a common natural resource that is at risk in potentially-contaminated areas. The vulnerability map (modified from Musekiwa and Majola (2011)), was used to compare the prospective risks posed by the identified potentially-contaminated areas (Figure 4-7). Groundwater vulnerability referred to the penetrability at which geological ground features allowed contaminants from anthropogenic activities to migrate from the land surface to aquifers that store groundwater (Machiwal *et al.*, 2018). The alphabets from A to F indicate the high to extreme ground vulnerability index.

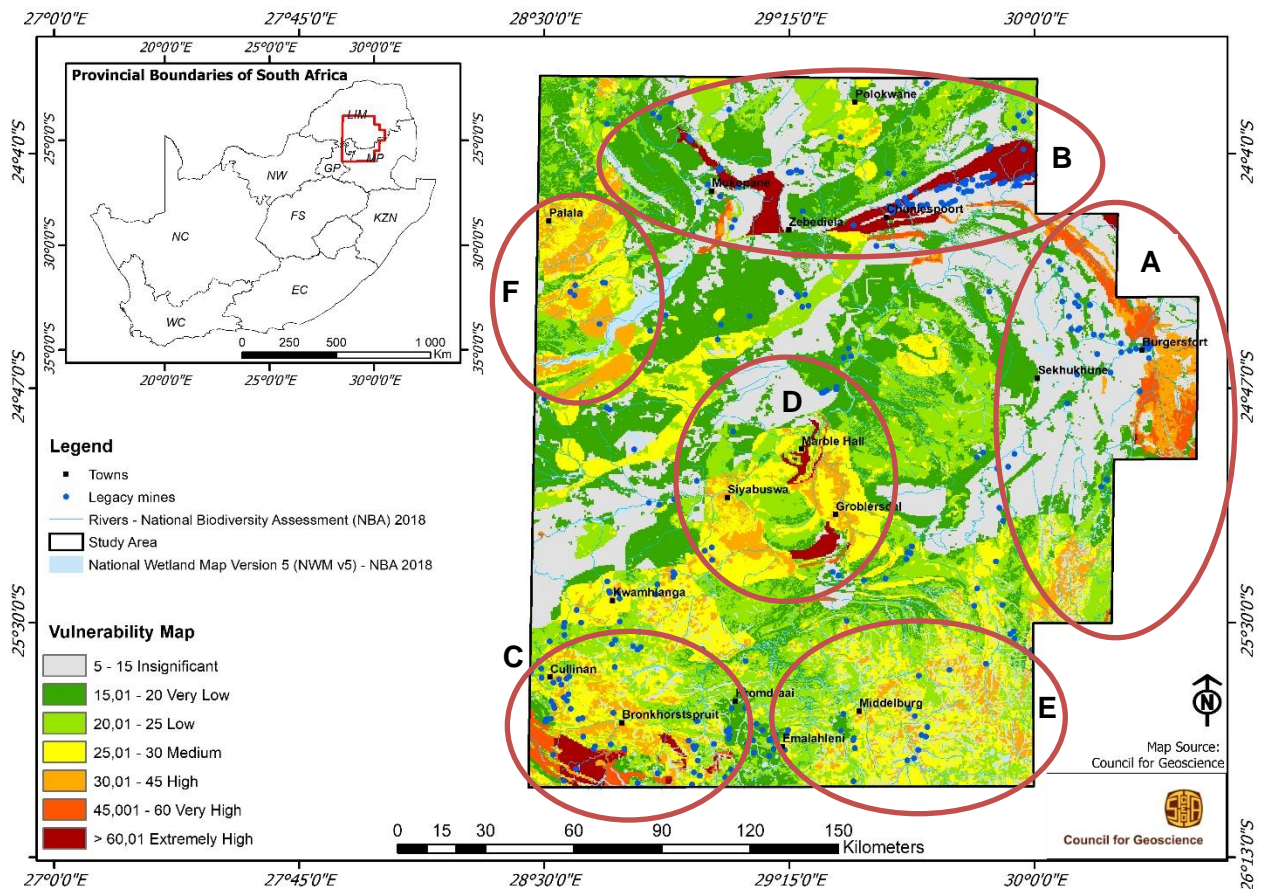


Figure 4-7: Groundwater vulnerability compared to hazard index map (Modified from Musekiwa and Majola (2011)).

The vulnerability index around Burgersfort (where potential land contamination was identified), indicated possible high and very high vulnerability to groundwater contamination, especially in both the north and south (Figure 4-7, Circle A). This was based on the existence of unconfined aquifers which were accessible to contaminants in the area and were exacerbated by previous or current mining that lead to artificial fracturing underground for easy percolation of PTEs. Towards Sekhukhune in the west, the vulnerability to contamination was insignificant or low (Figure 4-7, Circle A), despite the high potential land contamination in the south (Figure 4-1). This was related to the low permeability of the area with a high probability of confined aquifers. The difference between confined and unconfined aquifers was permeability: unconfined aquifers had high permeability (susceptible to contamination), whereas confined aquifers had low permeability (not susceptible to contamination). Other areas where a high to extreme vulnerability index existed and correlated with high potential land contamination included the southwest and southeast of Bronkhorstspuit (Figure 4-7, Circle C). In Figure 4-7, Circle B, the vulnerability index for groundwater contamination linked well with potentially-contaminated areas from northwest to southeast of Mokopane towards Zebediela. Similarly, the latter conditions existed from east of

Zebediela through Chuniespoort along the belt of legacy mines towards the east (Figure 4-7, Circle B).

In Figure 4-7: Circle D, there was a medium to extreme vulnerability to groundwater contamination. However, the correlation with the HI map showed that the land area had a low land contamination of less than one. Suitable land for all land uses was identified in Section 4.2. In Middelburg towards the east, southeast and northeast (Figure 4-7, Circle E), the vulnerability ranged between very low to high with remnants of potentially-contaminated areas and large areas covered by moderate contamination. In the Lephalale surroundings and towards the south (Figure 4-7, Circle F), very low to high vulnerability corresponded to some potentially-contaminated areas.

4.3.3 Biodiversity and ecological risks

The study area was characterised by high-risk categories which were nine, 15 and 16 towards wetlands (Figure 4-8). The threat status of wetlands at Risk Level 9 indicates that wetlands exist around mines. However, there is protection which is poorly managed. Risk Levels 15 and 16 represent ecological threats, indicating that wetlands exist around mining operations without protection. All these risk categories suggest that a buffer zone of 1 km between mining and ecological services, in particular, the wetland within the study area, was not implemented and prioritised. This led to the inland wetland ecological threat status around these mining areas being characterised as critically endangered (CR) and least concern (LC). The CR inland wetlands were more dominant than the LC wetlands around these mining areas (Figure 4-9).

Wetlands are good indicators of the presence of a shallow water table, particularly when the source is groundwater. The existence of legacy and current mines in potentially-contaminated areas was likely to drive the seepage of PTEs into wetlands and groundwater. Seepages from waste dumps, waste rocks and tailings dams were some of the drivers and pathways identified in Sections 2.3 and 2.4.

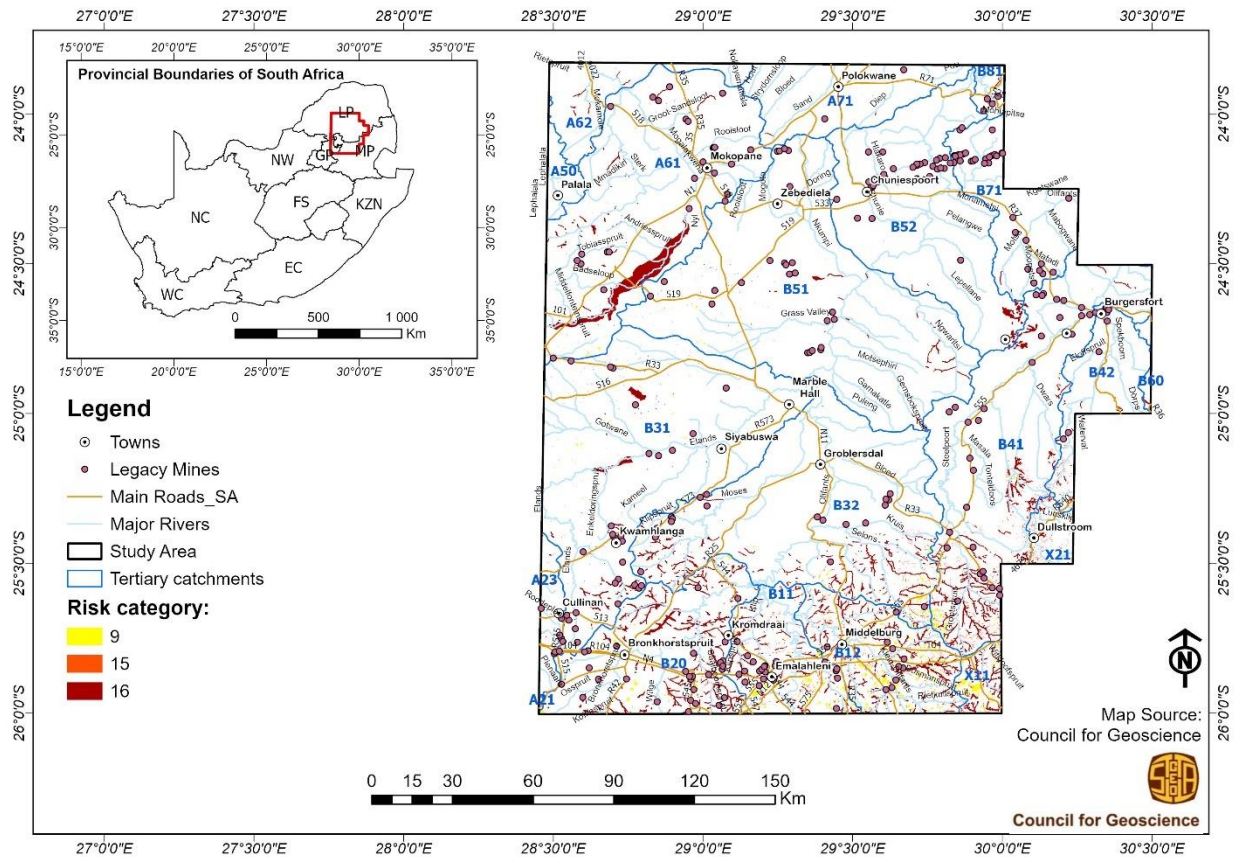


Figure 4-8: Risk categories for ecological threat status of wetlands (SANBI, 2018).

4.3.4 Current and future mining risks

Current mining and prospecting rights which have been issued predict intensified land contamination risks in the future due to current active mining (Figure 4-9) and future places without mining footprints (Figure 4-10). Figure 4-9 shows the correlation link between legacy mines and current active mines, where most legacy mines were within the boundaries of the current active mines. This established a correlation in which the assessed contaminated land areas around legacy mines still followed patterns similar to those around the current active mines. This was based on minerals of interest that were located in the same area and were currently being mined. Current potentially-contaminated areas (Figure 4-1) represented a good baseline study of land contamination around the selected region for current or future mining activities.

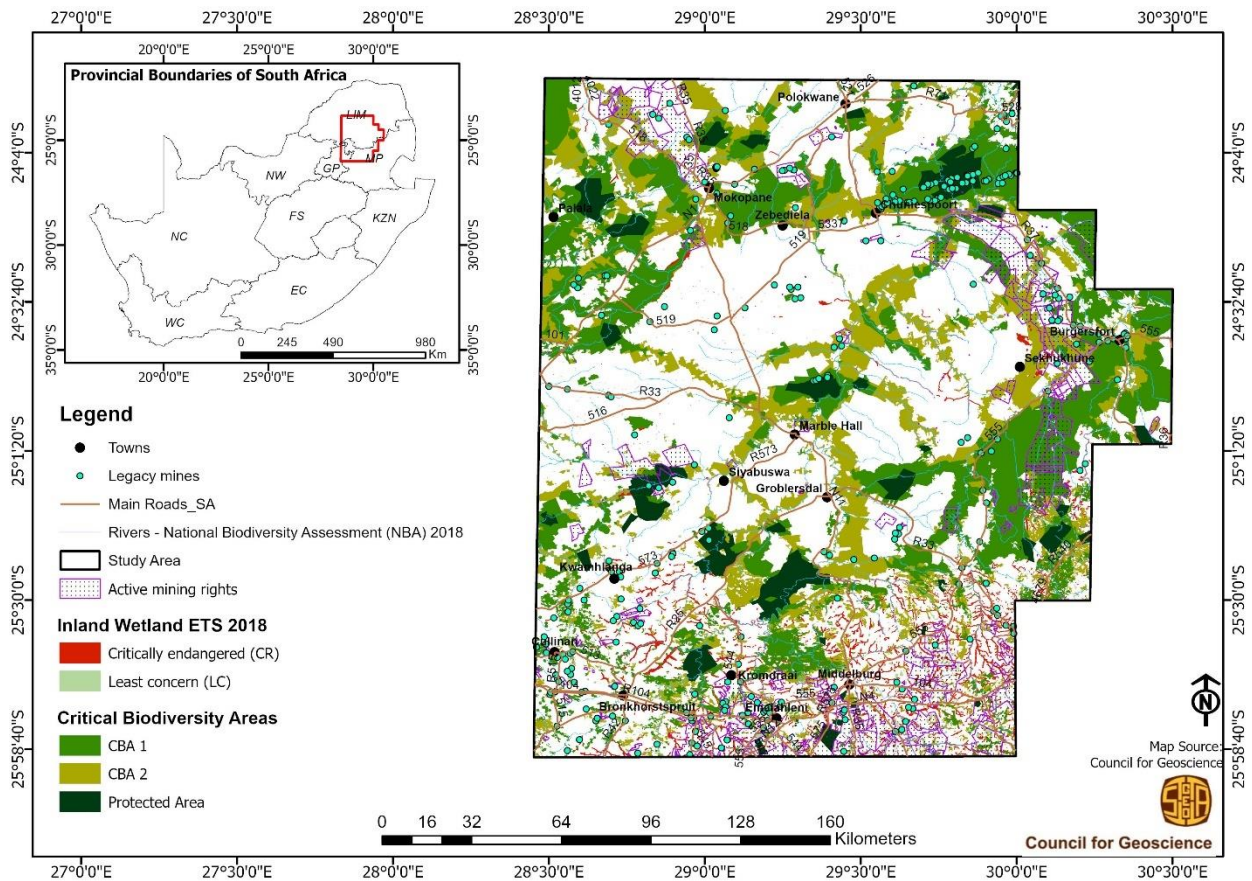


Figure 4-9: Current active mining rights (DMRE, 2023) and ecological threat status

There was a projection of future risks associated with future mining based on issued prospecting rights (Figure 4-10). The latter statement was based on prospecting rights boundaries issued over protected areas, strategic water areas, and arable land, as observed in Marble Hall and Groblersdal (Figure 4-10 and Figure 4-11). Mining drove the exposure of PTEs to the surface environment through waste dumps, tailing dams, waste rock, and spillages of stockpile deposits during haulage. This presented a higher concentration of PTEs which will drive the state of land contamination to an elevated degree in the future since there is much interest in mining even in areas without previous mining footprints. Prospecting rights boundaries encroached on areas covered by sensitive receptors (as discussed in Section 4.4). This raised concerns regarding the future sustainability of mining operations in the environment.

A summary of these prospecting rights suggested that land contamination will increase in the coming years if these rights are upgraded to mining rights. This is based on the fact that there will be more mining operations while such activities have been identified as brownfields and contributors of potentially toxic elements as determined by previous studies and also confirmed by this study. Therefore, such operations will expose PTEs in the environment and change

contamination status to an elevated level if mine wastes, tailings dams and dumps are not managed properly.

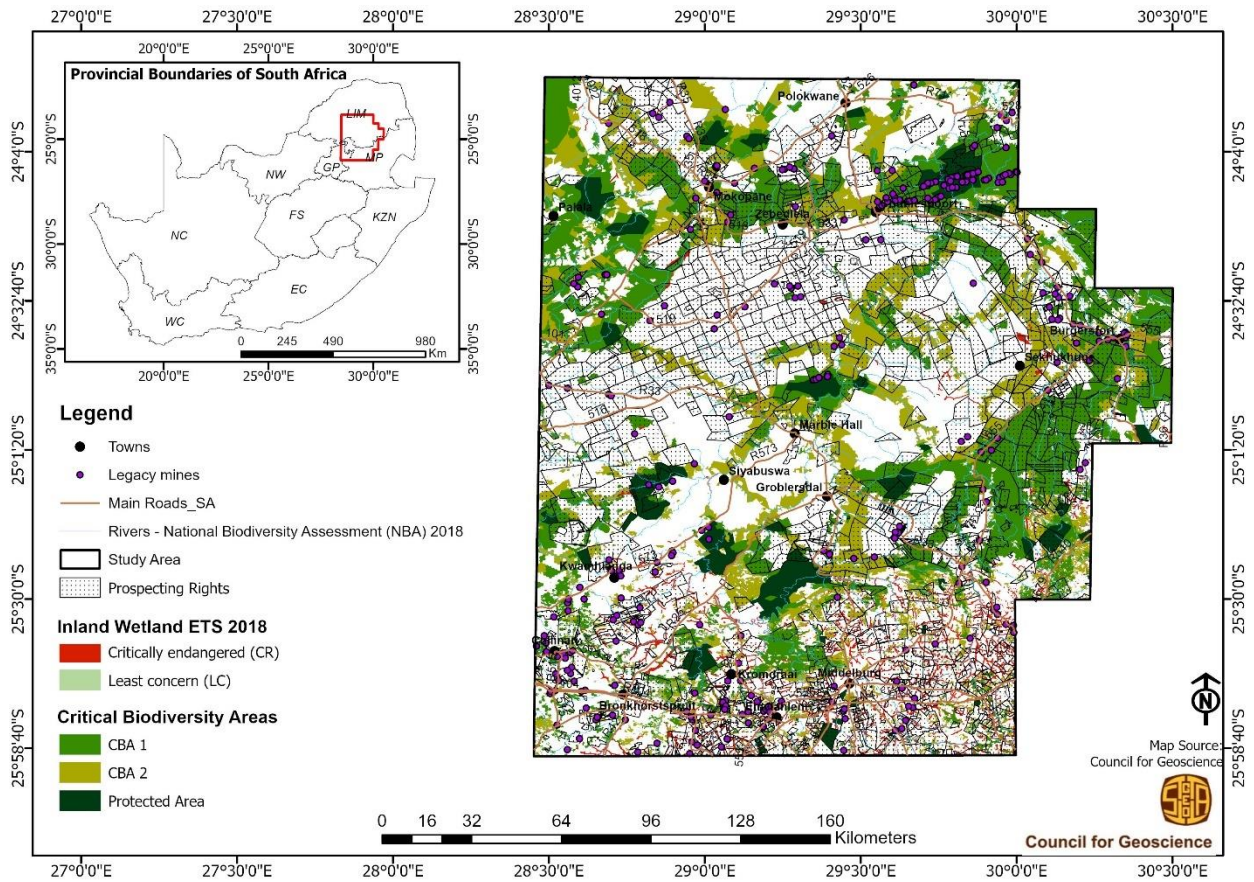


Figure 4-10: Prospecting rights for assessing potential future mining (DMRE, 2023) and ecological threat status.

4.4 Results related to RO3

First, the receptors of potential contamination in the study area were identified using various datasets, including the South African National Biodiversity Institute (SANBI) data (National Biodiversity Assessment 2018 (NBA 2018) and National Wetland Map 5 of 2018). Second, the natural capital of the study area was highlighted as a sensitive receptor. Third, it provided surface water and groundwater as pathways and receptors for PTEs.

4.4.1 Biodiversity receptors of potential contamination

The study area was characterised by three types of biomes (savanna, grassland and forest) as receptors of potentially-contaminated areas (Figure 4-11). The locations and contact boundaries of these biomes were previously documented (Mucina and Rutherford (2006). Biomes are important biodiversity receptors, prospectively endangered of contamination which emanates

from legacy mines and current mining development (established in Section 4.2). The savanna and grassland biomes rely on nutrients from land, as found in the soil, whereas contaminated land has harmful effects. These biomes serve as food sources for commercial and subsistence livestock and wild game animals. There is a likelihood that PTEs from contaminated lands end up within the food chain of animals that graze on the land which could be detrimental to human health through consumption. This was supported by the fact that both biomes were located within areas identified as potentially contaminated (Figure 4-1).

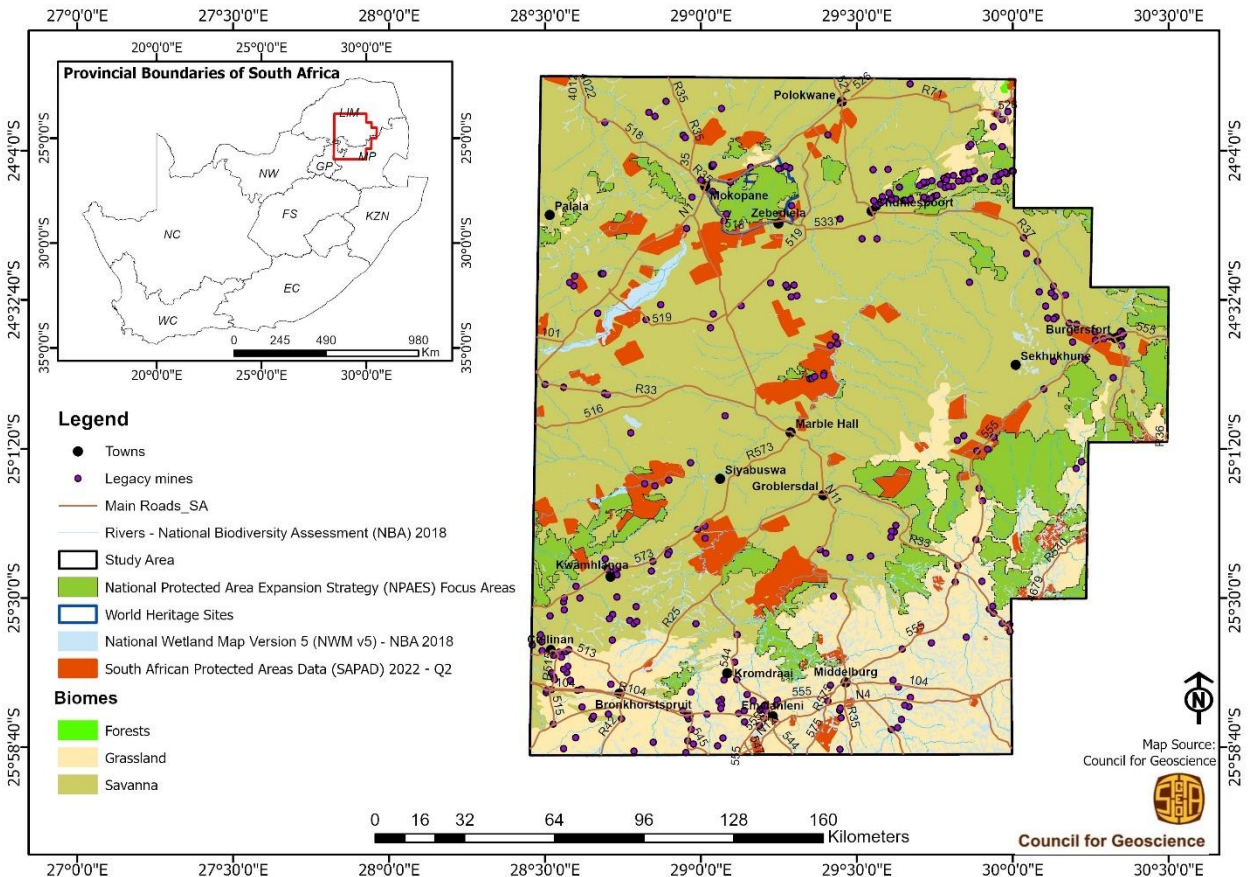


Figure 4-11: Biodiversity receptors and conservation plans within study area (SANBI, 2018) – National Biodiversity Assessment 2018.

Critical Biodiversity Areas 1 (CBA1) and CBA2 have been identified as receptors within the research (Figure 4-12). The protected areas are also included in the map since they are an essential part of the CBA network. CBA1 and CBA2 refer to irreplaceable areas which include threatened species and ecosystems which need to be kept in their natural or near-natural state. While protected areas are recognised in terms of NEMPAA (Act 57 of 2003) and required to meet targets for conservation. CBA1 is a more important priority than CBA2; however, they serve similar ecological importance and services toward preserving biodiversity and protection. The relationship between legacy mines (Figure 4-1), current mining (Figure 4-9) and future mining

(Figure 4-10) with biodiversity regions (CBA1, CBA2 and wetlands: Figure 4-8, Figure 4-11, Figure 4-12) show failure to respect their independent existence.

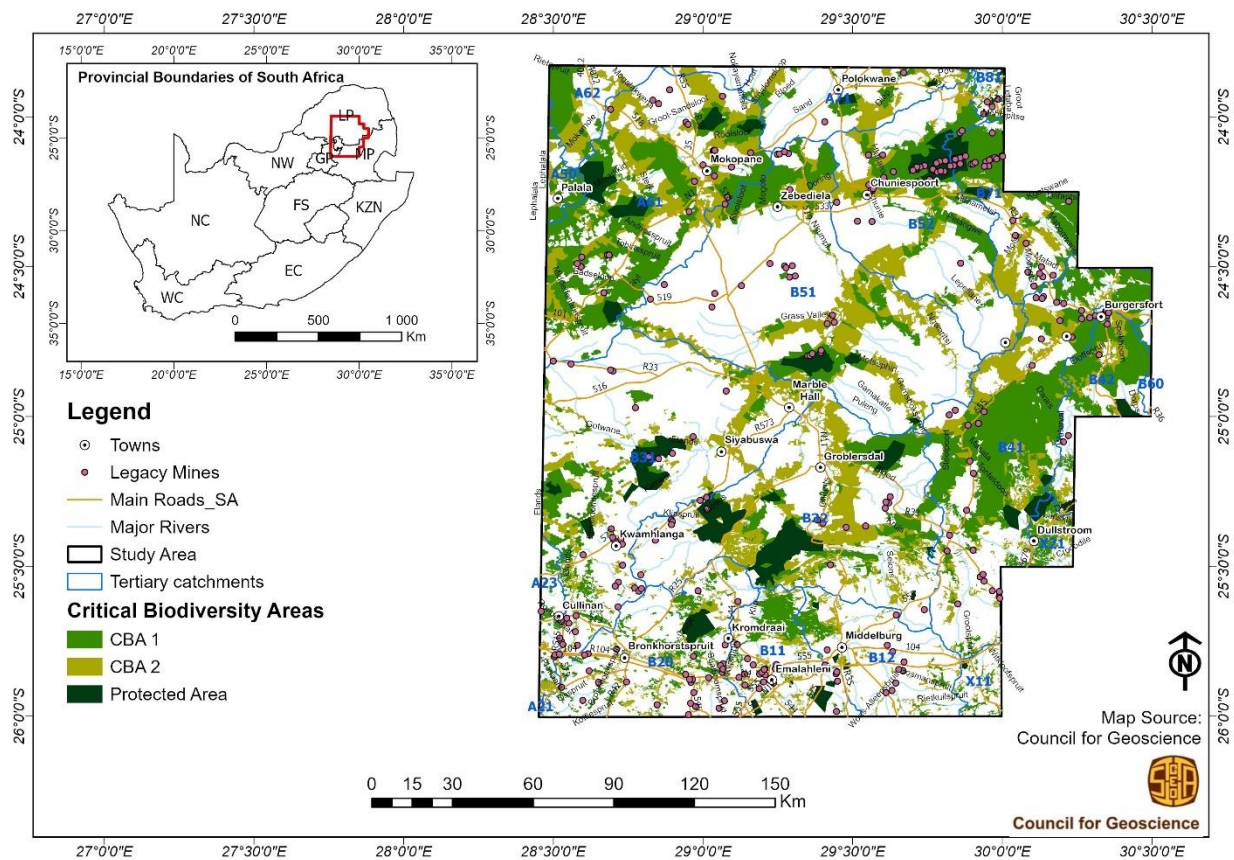


Figure 4-12: Critical biodiversity areas (CBA1 and CBA2) and catchments within the study area (SANBI, 2018).

There is an indication that potential land contamination is likely to affect CBAs and protected areas. An overlay of CBAs and protected areas with the contamination index as shown in Figure 4-13 identified that there are some CBAs and protected areas currently are affected by high to extreme contamination. Examples of such scenarios exist around the north and south of Burgersfort. Similar patterns are visible in minor occurrences around the south and east of Mokopane and Zebediela.

The contamination index assessed appears to counter the objectives of NEMBA which are aimed at the protection, conservation and management of SA's biodiversity against the harmful effects emanating from anthropogenic activities such as mining. Furthermore, the overlap of the contamination index into protected areas identified through NEMPAA might affected ecological biological diversity within such areas.

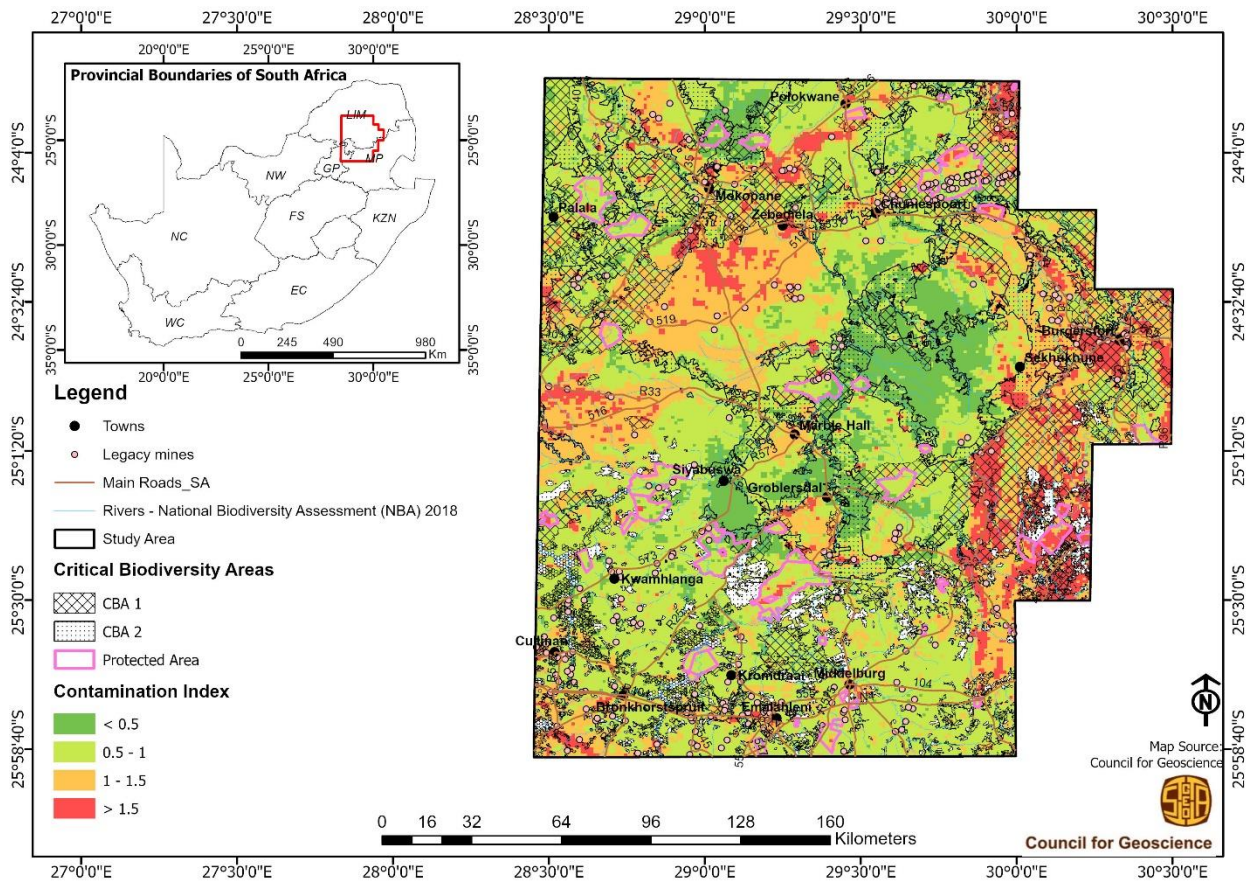


Figure 4-13: Overlay of CBAs and protected areas with the contamination index

4.4.2 Surface water and groundwater bodies as receptors of potential contamination

Surface water and groundwater bodies are essential sources of freshwater for numerous purposes such as drinking water, agriculture, ecosystem support, industrial use, recreation and tourism hence identified as receptors. The tertiary catchment layer was used to outline perennial and non-perennial rivers and wetlands as pathways and receptors of contamination in the study area.

The catchments covered in the study area included northern catchments (A50, A61, A62, A71, B52, B71 & B81), middle catchments (B31, B32, B41, B42, B51, B60 & X21), southern catchments (A21, A23, B11, B12, B20 & X11) as shown in Figure 4-12. Examples of the rivers in the study area included the Mogalakwena and Olifants rivers. These rivers and their associated tributaries serve as receptors of runoff or seepages from land and as pathways for transporting PTEs to different areas.

4.4.2.1 Olifants River

The Olifants River system comprises the upper, middle and lower Olifants River zones. The Upper Olifants flows into the Mpumalanga and Gauteng provinces, Highveld and recharge Loskop Dam. Dams in the middle Olifants include Flag Boshielo and De Hoop. The lower Olifant River is found in the Sekhukhune land closer to previous and current mining operations. The tributaries linked to the Olifants River include the Steenkoolspruit, Klein Olifants and Wilge rivers in the upper zone. The Selons, Moses, Elands and Steelpoort rivers are in the middle zone. While the Great Letaba River is in the lower zone.

4.4.2.2 Mogalakwena River

The Mogalakwena River recharges two major rivers in the area: the Doorndraai and Glen Alpine Dams. The water supply is used for domestic purposes and irrigation in Modimolle, Mookgophong and Mokopane towns. The Mogalakwena River flows into perennial tributaries, such as Mmaditsiri, Rooisloot, Sterk and Tobiasspruit.

4.4.2.3 Wetlands

The area was characterised by terrestrial wetlands as part of the National Wetland Map 5 of 2018 (SANBI, 2018). The wetland localities in the study area were faced with two Ecosystem Threat Status (ETS): CR and LC. CR dominated most parts of the study area, and the presence of contaminated land raised concerns regarding these biodiversity areas. There was an indication that the ecosystem protection level of most wetland areas fell under the unprotected category, whereas a few were classified under the poorly protected category. The latter statement raised the vulnerability of wetland areas to PTEs emanating from mining.

4.5 Chapter summary

This chapter provided findings that addressed the three objectives of the study. The study's main objective was to assess the identified contaminated areas. The findings indicated that continued mining and improper mine waste handling and disposal would lead to increased presence of PTEs on the land which would result in a high contamination index. This chapter emphasised the risk associated with land contamination from exposure to the competing factors of LULC. This has led to damage and loss in the state of waterbodies, cultivated and grasslands. Other factors, such as mining and quarries, forested land and built-up areas were on the rise which increased exposure to PTEs. This study interlinked current mining operation boundaries with legacy mines and identified potentially-contaminated areas. This comparison revealed that current mining operations were likely to elevate the status of contamination within the study areas. Similarly, the

discussions highlighted future risks and found that with an increase in prospecting rights over the study area, there were potential changes in land contamination in the future. Finally, various receptors of land contamination were identified (including biomes, CBAs, wetlands, surface and groundwaters).

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

The preceding chapters provided an introduction which outlined the problem statement and research objectives, as well as a literature review that expanded previous research findings regarding the topic both internationally and in SA. This was followed by data collection and processing using various methods in Chapter 3. This chapter consolidates the conclusions and recommendations of the findings as discovered in Chapter 4 and the overall build-up of research from the introduction, literature review and methods applied. The research presents conclusions in Section 5.2 and recommendations in Section 5.3.

5.1 Conclusions

5.1.1 Potentially-contaminated areas within the selected region/study area

The problem statement highlighted previous and/or current mining areas as brownfield areas that contributed to land contamination. In SA, approximately 6 000 mines located within the study area were identified as contributors to this problem. Furthermore, a literature review highlighted that the state of land contamination in this area is unknown. Therefore, it was important for this study to contribute towards filling this gap. The norms and standards contained in the Framework for the Management of Contaminated Land, Section 7(2)(d) of NEMWA provided an excellent threshold for assessing land contamination.

The study found the state of land contamination in the research area to be 34.38% based on the hazard contamination index (greater than one). The identified contaminated areas were located around legacy mines and within the current mining areas. This supported the literature review that most mining operations and associated smelters or processing plants were drivers of land contamination (Cobârzan, 2007:29; Ahmad *et al.*, 2018:14; Morar *et al.*, 2021:3). The results showed that most of the remaining land was moderately contaminated (54.6%), and 11.03% had low contamination. This study identified that current and future mining based on mineral rights was likely to change the status of land contamination. Therefore, the presented HI map of land contamination could be used as future baseline data for assessing land contamination at a regional scale to monitor and measure deviations.

5.1.2 Risks associated with abandoned legacy mines or current mining on the land

Correlating the hazard contamination index map with the LULC-classification map established factors that contribute to changes in land use which result in the high presence of PTEs on the land. Factors, such as mining and quarries, as well as built-up and forested land, were found to be controlling factors that exert increased pressure for land-use change. The impact included loss

of cultivated and grasslands as well as a decline in water bodies. This study identified the sources or drivers of these environmental changes as primarily anthropogenic, although natural system feedback loops might exist such as floods. Furthermore, the ecosystem risk categories in the study area were found to be CR and LC, with such features attaining risk ratings of nine, 15 and 16. Ground and surface water bodies were vulnerable to potentially-contaminated areas with a high risk of contamination. Current and future mining were identified as drivers that were likely to contribute to an elevated degree of land contamination which overlapped with biodiversity areas and other sensitive receptors.

5.1.3 Receptors of potential contamination in study area

Two types of biomes (savannah and grassland as well as wetlands) were identified as receptors in the study area. Furthermore, ETS in parts of the research area were identified as critical in NEMBA. The NEMPAA and different protected and conservation areas were identified as potential receptors of land contamination. In many cases, such areas were significant tourism destinations that were potentially prone to land contamination. Research on the socio-economic implications of land contamination was potentially wide-ranging, influencing the direct use of land as well as indirect effect through the dispersal of contaminants.

Both surface and groundwater resources were identified as vulnerable to land contamination as essential sources of freshwater for numerous purposes such as drinking water, agriculture, ecosystem support, industrial use, recreation and tourism. Surface water bodies serve as habitats for different species and provide ecosystem services of socio-economic importance. Rivers (Olifants and Mogalakwena), their tributaries (Steenkoolspruit, Klein Olifants, Wilge, Elands, the Selons, Moses, Elands, Steelpoort, Mmaditsiri, Rooisloot, Sterk and Tobiasspruit rivers) and dams (Loskop, Flag Boshielo and De Hoop dams) were identified as major surface water receptors within high to extreme contamination or hazard indexes. The seepage of contaminants into these surface water bodies triggered and compelled management actions in accordance with the requirements of the NWA and related water quality standards (DWS, 2016).

5.2 Recommendations and areas of future research

This study recommended more in-depth research that focused on identifying potentially-contaminated areas.

5.2.1 Physical impact on environment

Future research could map the location of mine waste, waste rock and tailing dams within the research area to geochemically characterise the mine residue and stockpile deposits to determine

their classification category. This would provide a more fine-scaled understanding of the contamination problem and result in more detailed and site-specific management and land-use options.

5.2.2 Perform site-specific contaminated areas

The identified areas should be narrowed for investigation of the paste pH (pH of the land or soil), acid-base accounting and neutralisation potential to design rehabilitation strategies. In addition, the correlation and migration of PTEs from sources to receptors should be investigated by assessing water quality to determine whether there was a causal link between contamination and sensitive receptors (e.g., water resources). Further investigations could include an air quality assessment to determine the concentration and dispersal of PTEs through dust falls in such areas.

5.2.3 Other recommendations

Regulators in national, provincial and local spheres of government should ensure adherence to buffer zones between different land uses, with mining zones maintained to limit exposure of built-up areas and critical water bodies to mining operations. Although buffer zone standards and guidelines already exist, they were neither quantified nor justified based on the potential impact of contamination. The mixing of different land uses and their proximity to different levels of contaminated land was a complex challenge.

The findings of the study such as the Hazard Index classification and subsequent results presented in Chapter 4 should be used to inform the spatial planning instruments (such as municipal spatial development frameworks) of municipalities located within the study area. These aspects normally receive insufficient attention in the preparation of Spatial Development Frameworks (SDFs) and the consideration thereof will contribute towards better informed spatial and land use planning in the study area.

5.2.4 Risks associated with abandoned legacy mines or current mining on the land

The risks associated with LULC changes were discussed on a large scale. The results suggested that the identified classes of LULC should be investigated in greater detail and on a finer scale. For example, changes in or loss of arable cultivated land due to land contamination or mining operations should be assessed. Air quality studies should be conducted around built-up areas to understand human exposure to PTEs in the vicinity of legacy mines or current mining operations. Therefore, a model for the migration of PTEs from sources through pathways to sensitive

receptors (e.g., surface and groundwater), should be developed. This could inform land-use planning as well as future human health and safety standards.

5.2.5 Receptors of potential contamination in study area

Continuously integrating attributes from the biodiversity and ecosystem layers with the land contamination/HI data (map) is recommended to determine the risk of exposure and the magnitude thereof to humans, fauna and flora. This should include support for NEMPAA and NEMBA initiatives that offer strategic plans to protect certain areas from degradation. A more strategic and holistic understanding of land contamination is required for more detailed and site-specific management and land-use decisions.

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ANNEXURE

The geochemical data and index results applied in this study remains the property of the Council for Geoscience but are available through formalised request and memorandum of understanding.