DEVELOPMENT OF AN INTEGRATED APPROACH FOR PRIORITIZATION OF MINE FEATURES OF SELECTED ABANDONED MINES FOR REHABILITATION IN THE GIYANI GREENSTONE BELT

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DECLARATION

I, **Mbebe Noxolo Kindness,** hereby declare that the dissertation for the Master of Earth Sciences in Mining and Environmental Geology at the University of Venda, hereby submitted by me, has not been submitted previously for a degree at this or any other university. This is my own work in design and execution and that all reference material contained therein has been duly acknowledged.

……………Mbebe………………………… ……26 september 2022…..

Student: Mbebe NK **Date**

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DEDICATION

This research work is dedicated to my loving family. A special feeling of gratitude to my mother, I hope the sacrifices you have endured for me to pursue this dream will be rewarded with a great deal of opportunities and joy. To my aunt, grandmother, and uncles, for their undying support and encouragement. To my siblings, my cheerleaders, thank you for believing in me. To my beautiful daughter, Okuhle, you are my inspiration to achieve greatness.

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ABSTRACT

Mining has a potential to provide sustainable economic and social benefits to communities and the regions in which mining companies operate. However, many mines have been abandoned and/or improperly closed which has lasting impacts on public health and safety and the environment. South Africa has more than 5906 abandoned mine sites that were left unrehabilitated. Although the problems of abandoned mine sites are well documented, little has been done to rehabilitate the mine sites. This may be attributed to costs associated with rehabilitation and standard criteria to aid the rehabilitation process. Most of the existing rehabilitation approaches do not adequately address the physical, chemical, and environmental hazards associated with abandoned mines. The purpose of this study was therefore to develop an integrated approach that will not only assess impacts of abandoned mines but also prioritize abandoned mine features for rehabilitation based on their associated physical, chemical, and environmental hazards.

In developing an integrated rehabilitation approach, two abandoned mines were selected, and all the mine features were studied by identifying, locating, mapping, and documenting them. The hazards linked to the mine features were classified as physical, chemical, and environmental hazards. A scoring and ranking approach was developed to quantify physical, chemical and environmental hazards of each abandoned mine feature. Sources of contamination, pathways and impacts of abandoned mine features were scored and ranked for physical and environmental hazards. Abandoned mine features with greater physical, environmental, and chemical scores were then prioritized for rehabilitation.

In quantifying and ranking chemical hazards posed by the abandoned mine features, parameters such as Pollution Load Index, Geo-accumulation index, Contamination Factor and Potential Ecological Risk Index were used. The physical, chemical, and environmental scores were combined to determine the total hazard score for the abandoned mine sites. The hazard scores were then integrated to determine the overall hazard score per mine site.

The results of the study showed that physical, environmental, and chemical hazard scores for Klein Letaba were 2.5, 1.5 and 2.2 times respectively higher than those of Louise Moore. The total hazard score for Louis Moore and Klein Letaba was 47.44 and 89.46 respectively. The

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results also revealed that the overall hazard score at Klein Letaba was higher than that of Louis Moore and this suggests that the associated risks at Klein Letaba are higher. Based on these findings, abandoned mine features at Klein Letaba must be prioritized for rehabilitation over features at Louis Moore.

The new and integrated approach provides a framework to identify, characterize, quantify, and prioritize high risk abandoned mine features for rehabilitation. The drawbacks of the existing rehabilitation prioritization methods have been identified and examined and the new integrated approach of prioritization of mine site rehabilitation addresses these concerns. As such, this new integrated approach provides a holistic, transparent, unique, cost-saving and practicable technique of prioritizing and addressing undesirable impacts of abandoned mine sites. It is recommended that best practicable strategies be developed to mitigate the adverse impacts of the abandoned features and their detailed cost analysis conducted. Additionally, the involvement of local authorities and all other stakeholders will be crucial in increasing awareness of the seriousness of the environmental and safety concerns of the abandoned mine features at the mine sites.

Keywords: *Abandoned mines, Chemical hazards, Environmental hazards, Giyani Greenstone Belt, Physical hazards, Rehabilitation prioritization*

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LIST OF ABBREVIATIONS AND ACRONYMS

AGSA	Auditor- General of South Africa
AIM-SS	Abandoned and Inactive Mines Scoring System
AEACR	Abundance of Elements in Average Crustal Rocks
AMIS	Abandoned Mines Information System
AMD	Acid Mine Drainage
APC	Air Pollution Controls
ASM	Artisanal and Small-scale Mining
CGS	Council for Geosciences
CSIR	Council for Scientific and Industrial Research
DEAT	Department of Environmental Affairs and Tourism
DME	Department of Minerals and Energy
DMR	Department of Mineral Resources
DPMR	Diamond and Precious Metal Regulator
DWAF	Department of Water Affairs and Forestry
EEA	European Environmental Agency
EF	Enrichment Factor
EMP	Environmental Management Plan
EPA	Environmental Protection Agency
GCIS	Government Communication and Information System
GGB	Giyani Greenstone Belt
GPS	Geographical Positioning system
HMS-SS	Historic Mine Site Scoring System
HMS-IRC	Historic Mine Site Inventory and Risk Classification System
IAEA	International Atomic Energy Agency
ICMM	International Council on Mining and Metals
Igeo	Geo-accumulation Index
MGB	Murchison Greenstone Belt
MMSD	Mining Minerals and Sustainable Development
MNDM	Ministry of Northern Development and Mines of Ontario
MPRDA	Mineral and Petroleum Resources and Development Act
NOAMI	National Orphaned or Abandoned Mines

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PERI	Potential Ecological Risk Index
PGB	Pietersburg Greenstone Belt
PLI	Pollution Load Index
SASQS	South African Soil Quality Standards
SAWS	South African Weather Service
SMZ	Southern Marginal Zone
TMF	Tailings Management Facilities
US	United States
USEPA	United States Environmental Protection Agency
WWF-SA	Worldwide Fund South Africa
XRF	X-ray Florescence

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CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

South Africa has left a legacy of abandoned mines which perpetually degrade the environment. In general, there is no universal definition of abandoned mines. The definition of abandoned mines varies from place to place (UNEP and COCHILCO, 2001). According to the Mining, Minerals and Sustainable Development (2002), abandoned mines are sites where advanced exploration, mining or mine production ceased without rehabilitation having been implemented at all or completed. Other terms commonly used to describe abandoned mines include inactive, orphaned, derelict, unattended and ownerless mines. These mines and associated waste dumps pose both physical and chemical hazards which many of them are the result of historic mining practices, ore processing techniques, improper closure procedures, or the surface exposure of ore deposits (Department of Toxic Substances Control, 1994).

Mining provides sustainable economic and social benefits to communities and the regions in which mining companies operate. According to Stamp (2015), gold mining companies are a major source of income and economic growth, with an important role in supporting sustainable socio-economic development. However, the long history of mining that spans for more than a century and inadequate legislative framework and lack of proper financial models in the past has resulted to South Africa having many abandoned mines. According to DMR (2009), South Africa has only recently developed and implemented comprehensive legislation to regulate environmental management and mine closure processes.

The physical concerns linked to abandoned mines include public health and safety, visual impacts, stability issues and dust emission problems. On the other hand, environmental issues include problems associated with spoil dumps and tailing facilities, contaminated aquatic sediments, subsidence, burning coal waste dumps and workings. They also include sites

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characterized by compacted and polluted soils as well as changes in vegetation cover (MMSD, 2002).

Abandoned mines are often characterized by features that are prevalent in the mine site with the potential to pose environmental, health and safety hazards. Abandoned mine features include open shafts, pits and adits, tailings, rock dumps and spoil dumps as well as abandoned mines infrastructure. The risks or impacts associated with these features vary greatly, since they impact the environment differently. In this study, the abandoned mine features at Louis Moore and Klein Letaba abandoned mine sites were identified, assessed, scored, and ranked based on their existing and potential negative impacts on the environment and human health. This was done to ensure that features associated with greater risks receive priority for rehabilitation and features with lesser risks are not prioritized or are prioritized later.

Several prioritization tools and approaches for rehabilitation have been developed throughout the world. However, these tools are similar in the sense that they all consider public health and safety as the priority (MMSD, 2002). The Environmental Protection Agency (EPA) (2004) developed the Historic Mine Site Scoring System (HMS-SS) which uses a scoring system that ranks different abandoned mine sites using existing or easily obtainable information on threats to human health, animal health and the environment in the State of Montana. In 2009, the EPA then introduced the Historic Mine Site Inventory and Risk Classification Scoring System (HMS-IRC) to assess potential risks posed by historic mine sites to human and animal health, safety and to the wider environment. Mitchell and Mackasey (1995) designed a comprehensive four step programme to identify and remediate abandoned mine hazards in Canada.

The existing models are commonly based on scoring systems that represent the most common environmental, human health, and public safety hazards found at abandoned mines (Mavrommatis and Menegaki, 2017). The South African abandoned mine rehabilitation programme has predominantly focused on the hazardous abandoned asbestos mines and abandoned vertical shafts in the Witwatersrand region to mitigate their impacts on human health and safety (MMSD, 2002; Davenport, 2006; and Auditor-General South Africa, 2009). For

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instance, Rembuluwani *et al.* (2014) conducted risk assessment for the abandoned New Union Mine in the Limpopo Province to develop risk management strategies. Although this method assessed some abandoned mine features and their environmental risks, the study mostly focused on environmental degradation issues.

Mhlongo *et al.* (2013) developed a rehabilitation prioritization methodology by compiling physical and environmental hazard maps for the Nyala mine in Limpopo and further suggested that studies like this be conducted to assist in the prioritization of rehabilitation in order to eliminate the hazards presented by these mines. As such, the integrated approach developed in this study will expand on the existing tools and not only focus on environmental, public health and safety issues, but incorporate the assessment of individual abandoned mine features and their associated physical, chemical, and environmental hazards for prioritization. Abandoned mine features with greater risks will take priority in the rehabilitation programme and features with least hazards will not be prioritized for rehabilitation. Direct funding is almost impossible, the restoration of abandoned mines becomes a difficult task and, consequently, prioritization of rehabilitation programmes is necessary.

1.2 Statement of the Problem

There are many unrehabilitated abandoned mines in South Africa, and this has negative effects on the soil, flora, fauna, and the surrounding environment. In 2007, the Council for Geosciences officially listed 5906 abandoned mines (Auditor-General, 2009). Abandoned mine sites are one of the major environmental problems related to mining. The report demonstrated significance and extent of the environmental impacts of unrehabilitated abandoned mine sites, and the lack of effective and timeous rehabilitation approaches. The cost of rehabilitation remains a thorny issue since it is excessively high and there is lack of funds.

The Council for Geosciences estimated the cost of rehabilitating South Africa's abandoned mines at R30 billion; however, the long-term treatment of Acid Mine Drainage and the construction and operating fees of plants were not included in the R30 billion. The Department of Mineral and

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Energy only rehabilitated 5 of 5906 abandoned mines at a cost of approximately R42 billion over the past three years (Auditor-General, 2009). The Auditor-General (2015) indicated that measures were not in place to ensure that abandoned mine sites were rehabilitated effectively and timeously, resulting in environmental and social impacts. Thus, proper guidelines on prioritizing abandoned mine sites in terms of risks associated with each of them are not in place. According to UNEP and COCHILCO (2001), inadequate funds, the absence of criteria and standards of rehabilitation and the high rehabilitation costs make it impossible to address the problems associated with abandoned mine sites.

Abandoned mine features such as underground entries present different types of physical, environmental, and socio-economic concerns at varying degrees (Mhlongo *et al*., 2018). A study undertaken by Matshusa and Makge (2014) revealed that the abandoned Birthday Gold Mine in the Giyani Greenstone Belt (GGB) has 11 unsafe open shafts and unstable grounds which pose safety problems. According to Sieff (2016), at least one illegal or artisanal miner die in abandoned mine shafts weekly in the Witwatersrand Basin alone. The large number of abandoned mine sites, the cost of rehabilitation and the impacts thereof call for an integrated approach that will not only focus on issues of abandoned mines, but also classify low, medium, and high priority features and sites for rehabilitation. The abandoned mine features at Klein Letaba and Louis Moore pose significant physical and environmental hazards and risks. In view of this, this study seeks to come up with a practical and sensible integrated tool that will identify, characterize, and assess all abandoned mine features in these mines and their corresponding impacts, and prioritize high risk features for rehabilitation.

1.3 Research Objectives

The overall objective of this study was to develop an integrated approach of prioritizing abandoned mine features for rehabilitation in the selected abandoned gold mines in the Giyani Greenstone Belt (GGB).

The specific objectives were:

- To critically review the current approaches used for ranking of mine features for rehabilitation,
- To assess the risks associated with abandoned mine features at selected gold mines in the GGB,
- To devise an integrated approach of prioritizing various areas/zones of the mine site for rehabilitation, and
- To ascertain the unique characteristics of the integrated approach for prioritizing different sections and features of the selected abandoned mines for rehabilitation.

1.4 Justification and Significance of the Study

The GGB has a mining history that dates to the 1870s. Unfortunately, all the mines which operated in the area have since been closed because the gold ore in the belt was found to be refractory (Swash, 1988). Consequently, upon closure, mine shafts and mine dumps were left unrehabilitated, and this has created numerous problems to the communities, government, and the mining industry at large. These include several abandoned mines within the belt with severe environmental impacts including mine tailings and the release of Acid Mine Drainage (AMD) to the surrounding communities. Many mine owners fail to put in place measures to ensure that mine sites are rehabilitated effectively after the mining phase is accomplished. Furthermore, the cost of rehabilitation remains a thorny issue on the part of government considering over 5906 officially known abandoned mines in view of limited funds.

Prioritization is an economic process towards cleanup and reuse of abandoned mine sites. Since mine rehabilitation is very costly and there is a considerably high number of abandoned mine sites; it is unlikely that the lowest priority sites will be addressed for many decades. This study is aimed at developing an integrated approach for prioritizing abandoned mine features for rehabilitation. Because rehabilitation is costly and there may not be enough funds to rehabilitate all the abandoned mine sites, mine features should be prioritized for rehabilitation instead. This means that highly hazardous features will receive priority over the less hazardous features to ensure that financial resources and efforts are directed towards features with the highest risks. Current rehabilitation approaches are reviewed to fill in knowledge gaps and expand on the already existing tools to ensure that hazards posed by abandoned mine features are quantified and prioritized.

It is important to note that each mine site has unique features and requires appropriate characterization. In view of this, abandoned mine features at Klein Letaba and Louis Moore were documented, characterized and the risks associated with the features were assessed. Furthermore, hazards posed by abandoned mine features were classified into physical, chemical, and environmental and their scores were computed. These scores were then integrated to compute the total or overall hazard score for the two mine sites, which gave an indication of hazardous mine features to be prioritized for rehabilitation. Site assessment and remediation are predicated on the need to address the most critical areas first which comes to light during the prioritization step. Consequently, prioritization of features at abandoned mine sites in the GGB is essential for proactive planning and response to prevent accidents at these sites. Additionally, increased human populations and encroaching development near these sites necessitate planning through a prioritization system, as well as a means for justifying budget requests for rehabilitation. Therefore, a detailed study on prioritizing abandoned mine features in terms of risks associated with each of them is of uttermost importance.

1.5 Description of the Study Area

This section provides an overview of the study area. It outlines the physical characteristics of the study area, which include geographical location, topography and drainage, climate, pedology and vegetation as well as land-use.

1.5.1 Geographical location of the Study Area

The Giyani Greenstone Belt, previously known as the Sutherland Greenstone Belt, is in the Limpopo Province of South Africa. It is found at the north-easternmost region of the Kaapvaal

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Craton close to the contact with the Limpopo Belt. The belt is a north-eastern trending feature, approximately 70 km long and up to 17 km wide. The geographic coordinates of the area are latitude 30°30'00"E and 31°0'00"E, longitude 23°10'00"S and 23°30'00" (Prinsloo, 1977). The Giyani town which the belt is named after is located South and East of Louis Moore and Klein Letaba gold mines respectectively as shown in Figure 1.1.

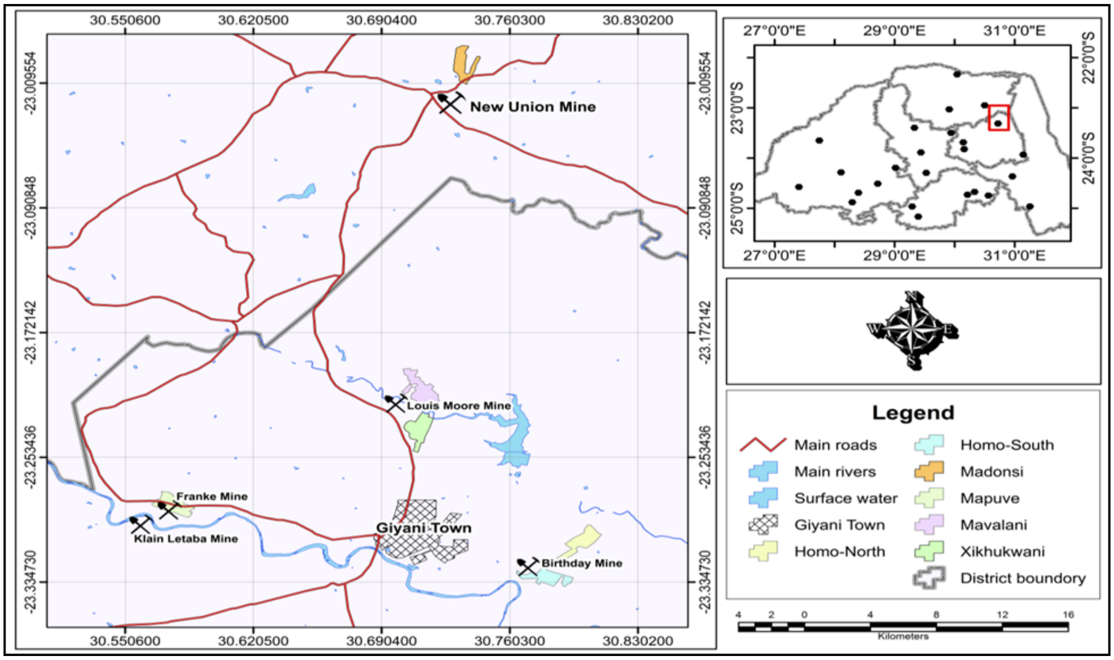

Figure 1. 1: Geographical location of the study area (from Mhlongo *et al*., 2019)

The Giyani Greenstone Belt is home to several abandoned mines that were abandoned without any rehabilitation, namely, Birthday, Franke, Madonsi, New Union (also known as Golden Osprey), Fumani, Klein Letaba and Louis Moore. Although the belt hosts numerous abandoned mines, they are not all accessible. Birthday, Franke, Madonsi, New Union and Fumani mines are fenced and or barricaded, limiting access to these sites. Klein Letaba and Louis Moore are easily accessible, they are not fenced and open to the public. As such, Louis Moore and Klein Letaba were selected for this study based on ease of access

1.5.2 Topography and drainage

The Giyani area is located on the northern bank of the Klein Letaba River. It is comprised of relatively flat to undulating plains of the Lowveld catchment which is drained by the Groot Letaba River. The area is enclosed by four major perennial rivers, namely, the Shingwisi, Nsama, Klein Letaba and Molototsi. These rivers are seasonal and flow during summer months. The Klein Letaba tributaries like the Soeketse and Koedoes rivers are wide and dry with sandy ditches for most of the year. The prominent Khavagari hills are in the south-eastern part of the study area. The study area is, however characterized by a gentle slope (DWAF, 2004).

1.5.3 Climate of the Study Area

The area is part of the Lowveld with a hot climate and rainfall mainly during summer. It is characterized by a warm, dry, and subtropical climate. It can be very hot in summer, reaching a maximum temperature of about 38°C in summer and 22°C maximum in winter. Winters are mild during the day and cold during the night. High rainfall occurs mainly between November and February (SAWS, 2012). Though the region receives high rainfall in summer, it often experiences severe drought conditions.

1.5.4 Pedology and Vegetation of the Study Area

Sandy and loamy soils dominate the study area. In addition, the gravels are dominant at the southern flanks of the study area where these soils may be a product of the weathered tremolite schist rock units which outcrop around the area. Areas surrounding the study area are dominated by agricultural activities. The Klein Letaba region is surrounded by mountains which have dense vegetation at the top and patches of trees at the bottom and there are dense forests next to the Klein Letaba River (DWAF, 2004). The area is dominated by ultramafic lithologies and sheared tremolite/actinolite schist and tourmalite-plagioclase-tremolite schist (Van Reenen & Gan, 1995).

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1.5.5 Land-Use

Giyani is dominated by settlement, which includes both urban and rural settlement. The urban settlement is found within the vicinity of the Giyani town, while rural areas are sparsely distributed in areas away from the town. Rural areas tend to make a linear pattern along the main road. Most of the areas in and around the settlements have been cleared of all vegetation. Very little subsistence farming is practiced in the area (Steenkamp and Clark-Mostert, 2012). There is also land reserved for grazing. The area around Louis Moore Gold Mine and New Union Gold Mine is used for subsistence agriculture. The area is also used for mining activities, more especially small-scale mining.

1.6 Organisation of the Dissertation

This dissertation is comprised of six chapters. Chapter one provides an overview of the geographical and environmental aspects that informed the identification and selection of the problem. It further breaks down the problem setting into objectives, which define the focus and variables to be interrogated in the study. This chapter consists of the background section which covers the research problem, justification, and significance of the study as well as description of the study area.

Chapter two presents a systematic review of literature relevant to the objective of the study. In this systematic review, impacts of abandoned mines, guidelines on mine closure, rehabilitation, and remediation of abandoned mines as well as prioritization tools are explored and discussed. Chapter three presents the research methods, tools and procedures, tools, and approaches employed during data collection and analysis stage of this research. This chapter also integrates the geochemical aspects into the prioritization approach being developed in this research.

Chapter 4 presents and discusses the results obtained in this study. It provides a general description of the abandoned mine sites and the features prominent in these sites, as well as the results of the geochemical analysis conducted in this study. The conceptual model showing the

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sources of hazards, pathways and exposure routes is presented in this chapter. Chapter 5 is earmarked for prioritizing abandoned mine features for rehabilitation through the quantification of the hazards posed by abandoned mine features. The scoring and ranking approach used to prioritize these features is presented in this chapter. Lastly, chapter 6 summarizes the main findings of this study and outlines future perspectives to be considered.

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CHAPTER TWO: LITERATURE REVIEW

This chapter presents the literature relevant to the objectives of this research. It also shows knowledge gaps that this research work aims to fill through the review of impacts of abandoned mines and existing assessment tools towards rehabilitation. It is broadly classified into the geology and mining history of the GGB, overview of closure and rehabilitation of abandoned mines, impacts of abandoned mines, general framework for closure and remediation of closed and abandoned facilities, environmental risks of mining, risk evaluation of abandoned mines, costs of remediation of mine facilities, and review of assessment tools for prioritization of abandoned mine sites.

2.1 Geology and Mining History of the Giyani Greenstone Belt

The GGB is also known as the Sutherland Greenstone Belt and is situated at the north-easternmost region of the Kaapvaal craton close to the contact with the Limpopo Belt. It is dominated by Archean basement rocks such as granite, gneiss, and greenstone. The GGB is well-known for its gold mineralization, and several small-scale mines once operated in the belt. It is known to host gold, tungsten, nickel, magnesite, and other mineral deposits and once sustained numerous gold mines and produced substantial amounts of gold (Bullen *et al*., 1995). Gold was first reported in the GGB by two prospectors, Sutherland, and Bullen in 1870. However, most mines ceased operations in 1928 after it was discovered that the gold ores are refractory at depth (Davis *et al*., 1986).

The GGB bifurcates into two arms towards the southwest. These arms are known as Khavhagari arm (northern part of the belt) and Lwaji arm (at the southern part of the belt). The Khavhagari arm is dominated by ultramafic and mafic sequences while the Lwaji arm is dominated by ultramafic schist, which passes upwards into a thick succession consisting of a variety of meta-sediments in the base succession (Ward, 1998).

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The larger gold mines, which are now the main target for illegal and artisanal mining activities, were abandoned around the early 1990's. During this period the mines were operated under the guise of Gazankulu self-governing territory as GazGold. The mines which operated in the belt during this time were: Giant Reefs (Fumani), Louis Moore, Golden Osprey (Madonsi), Klein Letaba and Franke, Horsehoe I and II and Birthday (Gan andvan Reenen, 1995; Humphreys, 1934; Weilers, 1956; Calder, 1916; Ronaldson, 1952).

Worldwide Archean Greenstone Belts are major gold producers. Up to date, more than 10 gold deposits or prospects have been found in the Southern Marginal Zone (SMZ) of the Limpopo belt and the Sutherland greenstone belt (Gan van Reenen, 1997). The Louis Moore, Osprey and Dornhoek are located within the rehydrated subzone of the SMZ and the Klein Letaba, Franke, Birthday and Fumani in the northern part of the Sutherland belt. McCourt and Van Reenen (1992); Gan and Van Reenen (1995) reported that gold mineralization in the GGB occurs as structurally controlled lode deposits. Thus, gold mineralization at Birthday and Louis Moore are restricted to shear zones and occur as sulphide-quartz veins in mafic, ultramafic and pelitic rocks. The Klein Letaba gold deposit is located within the Hout river shear zone and mineralization occurs as sulphide-quartz veins, altered quartz-biotite-amphibole schist, biotite-garnet-amphibole schist, and amphibolite (Kroner *et al*., 2000).

The Giyani belt, together with the Pietersburg Greenstone Belt (PGB) and Murchison Greenstone Belt (MGB), constitute the Murchison Sequence (SACS, 1980). MGB and PGB are situated in the granite-gneiss terrane of the Kaapvaal craton which is located south of the high-grade Southern Marginal Zone (SMZ). The PGB lies in the northeast of the GGB whilst the MGB is located east of the GGB and is situated in the northeastern part of the Kaapvaal craton (Kroner et al., 2000). While the Pietersburg and Murchison belts are located within the trough of a major isostatic gravity low which surrounds the central Transvaal basin, the Giyani belt is situated on the northern flank of this low southeast of the major gravity high of the SMZ (Coward and Fairhead, 1980).

2.2 Overview of Closure and Rehabilitation of Abandoned Mines

South Africa has a long and somewhat troubled history when it comes to mine closure. Mine closure can be defined as permanent cessation of mining operations and all subsequent activities related to decommissioning and site rehabilitation or monitoring (Heikkinen *et al*., 2009). Formal mining in South Africa is more than 100 years old. Legislation at that time primarily focused on "surface rehabilitation" and the primary emphasis of mining was focused on its economic gains. Regarding environmental management and rehabilitation, mining companies complied with the minimum requirements and followed a re-active approach (Swart, 2003).

Initiatives to close and rehabilitate abandoned mines have been taken worldwide. The most widely known initiatives are the United States Superfund programme and the Canadian National orphaned or abandoned mines initiative (NOAMI) initiative. According to Johnson (1998), rehabilitation programmes need enough funds to ensure adequate and permanent environmental improvements. The economic constraints in relation to the rehabilitation of closed and abandoned mines facilities are well known. However, the necessary prioritization of rehabilitation of closed and abandoned sites should be made primarily on risk-based decisions rather than economic considerations as the environmental and economic consequences of not implementing required rehabilitation measures may become significantly costly than the adequate rehabilitation (Potter, 2011).

The provision for mine rehabilitation and closure regarding Old Mines and Works of 1956 did not address the environmental rehabilitation of mines. It focused on making the mines safe to protect the public against the hazards that may arise from prospecting and mining operations (Davenport, 2006). According to Limpitlaw *et al*. (2005), mine closure was not subjected to any regulative closure requirements before 1956. The acknowledgement of responsibilities and the cost of controlling pollution caused by abandoned collieries was reached in 1976 between the South African mining industry and the then government, and was known as Fanie Botha Accord of 1976 (Dalton *et al*., 1998). This agreement between the government and the mining industry incorporated among other factors, pollution control measures.

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According to a report published in 2012 by the World-Wide Fund for Nature (WWF-SA), some larger companies have, towards the end of life of mine, sold major mining operations to junior miners, thereby divesting rehabilitation obligations to companies that frequently lack the capacity and experience to conduct large-scale rehabilitation. These companies may, in turn, go bankrupt, leading to abandoned or orphaned mines. As these sites will frequently not be fenced-off in any manner, they represent a constant threat to the safety of the community, especially the children who may encounter toxic materials or fall into excavations. These lasting and harmful environmental impacts were recognized and highlighted in the report and imposed a range of obligations pertaining to the management of mine closure and rehabilitation in South Africa.

A performance audit report on rehabilitation of abandoned mines at the Department of Minerals and Energy (DME) conducted by the Auditor-General of South Africa (AGSA) in 2009 demonstrated that the rehabilitation efforts by the DME were ineffective to address the environmental and social impacts associated with unrehabilitated abandoned mines. Furthermore, of the 5906 abandoned mines in SA, the DME only rehabilitated 5 mines at a cost of approximately R42 million over the past three years (that is, 2007-08 and 2008-09 financial years).

The costs for rehabilitating abandoned mines are extremely high and remain a major predicament. The Council for Geosciences estimated the cost of rehabilitating SA's abandoned mines at R30 billion, with the exclusion of the long-term treatment of Acid Mine Drainage (AMD) and the construction and operating fees of plants. Moreover, it is worth noting that of the 5906 abandoned mines, 1730 were classified as high-risk mines and would require approximately R28,5 billion of the R30 billion to rehabilitate (AGSA, 2009).

According to the MPRDA, the right holders should set aside a financial guarantee for rehabilitation. The state requires an application for a closure certificate on the closure of the mining operation. It should be noted that the closure process does not only deal with the cessation of technical operations, but also includes site rehabilitation, which involves both landscape restoration and prevention or mitigation of any potential environmental and safety risks. As a

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result, closure may be viewed as an ongoing process, depending on local circumstances, with monitoring of rehabilitation potentially continuing for many years (Heikkinen *et al*., 2008).

Despite the importance of mining as an economic activity and livelihood strategy in sub-Saharan Africa, illegal mining also known as artisanal and small-scale mining is linked to many negative social, environmental and health impacts and causes sustainable development challenges (Collins and Lawson 2018; Kambani 2003; Lynas *et al*., 2018). The impacts of abandoned mines have been reported in other African countries including Mongolia and Namibia. Liu *et al*. (2021); and Salom and Kivinen (2020) indicated that abandoned mines have resulted in soil pollution, air pollution through wind-blown dust, acid mine drainage that contaminates drinking water for humans, unstable grounds, and death of humans due to falling into mine openings and inhalation of toxic gases, which is dangerous to human health and the environment.

2.3 Recent Guidelines on Mine Closure

In general, mining has significant negative impacts on the environment, and the role of emerging legislation in guiding the performance of mining companies in South Africa is of ultimate importance. Mining companies must comply with the country's constitutional and common laws by conducting their operations including closure activities with due diligence and care for the rights of others. Section 24(a) of the Constitution states that everyone has the right to an environment which is not harmful to his or her health and well-being. This supersedes all other legislation. Any common law claims based on pollution emanating from a closed mine will have to be instituted by the plaintiff within three years of the incident which caused the pollution, unless it is an ongoing source of pollution (Swart, 2003).

Numerous guidelines on mine closure and planning exist at a global scale (World Bank, IAEA, ICMM, and UNDP), national scale (The Finish Mine Closure Handbook, Swedish Guidelines, US, Canadian, Department of Minerals and Energy's Mine Environmental Management guidelines and MPRDA) and industry sector guidelines. In addition, larger mining companies have developed their own company-specific guidelines for mine closure planning, implementation, and follow-up.

Minerals and environmental legislation prior to the constitution failed to prevent significant environmental damage through mining and created legacies for citizens to bear and the state to address. The recent MPRDA (Act 28 of 2002) and its regulations disseminated by the DME focus on sustainable development and end-land use mining, together with internalization of social and environmental costs (Sutton and Weierbye, 2007).

Mine closure is the process of ending operations of a mine. According to Robertson and Shaw (2006), the four key objectives that must be considered when planning for mine closure are: protect public health and safety; alleviate or eliminate environmental damage; achieve a productive use of the land, or a return to its original condition or an acceptable alternative and provide for sustainability of social and economic benefits resulting from mine development and operations to the achievable extent. Orderly mine closure depends on planning for providing the details on design and costs to achieve these key objectives (ICMM, 2008; Australian Government, 2016).

The MPRDA (Act 28 of 2002) is the main regulation governing mine closure in South Africa. The regulations were disseminated by the DME and focusses on sustainable development and end-land use mining, together with internalization of social and environmental costs. The regulations in terms of the MPRDA outline the requirements and processes for mine closure. Although the MPRDA regulations for mine closure contain some core elements of the original DME policy, they also promote a new thinking with the concept of a risk-based approach to mine closure, which is a legal requirement in terms of the Act. The risk-based approach to mine closure is aimed at ensuring a technically sound closure plan and minimal residual technical and environmental risks after closure. Moreover, the MPRDA has expanded to incorporate the social impacts of mine closure.

Guidelines for the rehabilitation of land disturbed by surface coal mining in South Africa were first published by the Chamber of Mines in 1981. The main aim of the guideline was to provide adequate guidance for coal strip mine rehabilitation and closure. However, the legal requirements and rehabilitation objectives and procedures changed over the years, which led to regulation of new guidelines, that is, the Australian mine rehabilitation and mine closure completion guidelines. These new guidelines are meant to update and expand the previous coal-based strip-mining guidelines. Moreover, these new guidelines are a compilation of current best practice, both South African and International, and are aimed at ensuring satisfactory and sustainable rehabilitation (Chamber of Mines of South Africa, 2007).

2.4 Impacts of Abandoned Mines

South Africa has a long history of mining, as a result, there are many abandoned mines in the country that are currently the major source of various environmental and social problems (Mhlongo and Amponsah-Dacosta, 2015). Many mining operations have been abandoned by their operators with little or no regard to the management of the impacts on public health and safety and the environment. According to Chao and Peck (1999), the problems of abandoned mines take two dimensions which are environmental impacts and the cost of environmental protection. A study conducted by Mhlongo and Amponsah-Dacosta (2015) showed that common physical impacts of abandoned surface mine sites include altered landscape, unused pits, altered soil quality or slopes, changes in groundwater regime, contaminated soils and aquatic sediments and changes in vegetation cover. The most common impacts of abandoned mines on the environment include reduction of water (both surface and groundwater), air quality and contamination of the soil even though the impact of these mines vary from one site to the other with respect to the type and degree and the commodity mined (MMSD, 2002).

2.4.1 Surface and Groundwater Pollution by Abandoned Mine Sites

Water is one of the resources most frequently polluted by abandoned mine sites. It is also the main conduit by which impacts from abandoned mines extend beyond the immediate site. Many abandoned mines cause water pollution in the form of acid or saline drainage. In many cases after mining, groundwater levels recover to their pre-mining levels, but the groundwater is polluted due to chemical reactions in the mined-out areas. In the gold and the coal mining areas, this results in the formation of AMD which, as it rises over time to fill the mine voids underground, sometimes

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decant onto the surface, thus polluting surface water bodies and in some cases land suitable for irrigation (Singer *et al*., 1970).

Open water bodies which are close or in direct contact with the mine residue areas, pose high risk to the environment and humans due to the pollution of water resources. If the open water bodies get their water from mine dumps, they contain soluble heavy metals and high acidity and salinity due to chemical reaction in the process. Water flowing from the dumps or decanting from underground also has an impact on natural wetlands which are close to such mine dumps, if this happens, the wetlands get polluted and cease to be functional. In addition to the risk of pollution, some mining activities could also result in the disturbance and diversion of river courses. This can result in silting up of streams or dams, as well as significant soil erosion (Smith *et al*., 1995).

Shafts and adits are visible sources through which water is discharged into the surrounding environment. AMD from abandoned shafts and dumps poses a threat to clean water, as the contaminated water seeps into both surface and underground water reserves. The contaminated water can potentially pollute soil and water supplies through spreading underground and flowing into streams and rivers. The impacts associated with the flow of AMD into surface and ground water systems include degrading the quality of water systems, poisoning food crops, destroying wildlife ecosystems and endangering human health (NPEP, 2016). Waste dumps are also prominent sources of water pollution in abandoned mine sites. Run-off from spoil dams is most likely to be acidic, saline and metal rich (EA, 2008). Tailings dams are eroded during rainfall and wastewater finds its way to the environment and surrounding water bodies causing mine water pollution.

Abandoned mines are associated with the release of AMD into the environment. In the mining industry, AMD is recognized as one of the more serious environmental problems. Though AMD comes mainly from active mining, tailings in abandoned mines are a major source AMD. It is the formation and movement of highly acidic water rich in heavy metals (Roy, 2017). According to DME (2006:4), AMD is the seepage of sulphuric acid solutions from mines and tailings, produced

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by interaction of oxygen in the ground, surface water, and sulphide minerals exposed by mining. A common form of water pollution in areas where mining took place in the past attributed to by AMD is abandoned mine drainage which is water that is polluted from contact with mining activities.

2.4.2 Air Pollution Impacts

The environment around either active or abandoned mine is often characterized by air-borne dust which emerges as a primary air pollutant. In abandoned mines, the disturbed land, spoil dumps and tailings dumps are the major sources of dust. This is due to strong winds blowing finer particles from exposed surface of the land and eventually disposing them at extensive areas. Most old tailings dumps, especially in semi-arid areas of South Africa, are associated with highest levels of dust, resulting in highest wind erosion. Dust dispersion can be a serious nuisance and health hazard to people and animals in nearby settlements. It is also associated with other environmental problems such as degradation of crops, pollution of soil, surface, and groundwater (Blight, 2007).

Air pollution occurs at mining sites during excavation and transportation. Blowing dust from abandoned mine land sites is a common concern, as many are in arid western states. Some sources of dust may be from road traffic in the mine pit and surrounding areas, rock crushers located in pits and in mills, and tailings ponds. The toxicity of the dust depends on the proximity of environmental receptors and the type of ore being mined. High levels of arsenic, lead, and radionuclides tend to pose the greatest risk. Abandoned deep and strips can be sources of gases, especially methane and carbon dioxide. Methane and carbon dioxide are the primary mine gases generated from abandoned underground mines which pose a threat to public safety. Methane primarily from deep mines can be an explosive gas in certain concentrations (EPA, 2009).

2.4.3 Abandoned Tailings Dams

There are many abandoned tailings dams around the world which pose different types of environmental problems as well as health and safety risks. Mine tailings are remnants of materials left behind after the desired mineral is extracted. They are piled on-site while a mine is still active

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and left behind when the mine is abandoned. The tailings are generally toxic, and the exposure of tailings to air, oxidation and climatic conditions favor the release of toxic metals such as lead, mercury, and arsenic. Such metals are carried into nearby areas including wetlands, threatening wildlife, and affecting the quality of water used by human for different purposes. This can have lasting environmental and socio-economic consequences (Bini, 2012). Authors such as Angelovicova and Fazekasova (2014); Zhang (2008); and Reddy *et al*. (2014) indicated that heavy metal contamination from soil and mine tailings is a widespread problem in many countries across the world, where excessive concentration of toxic metals such as Pb, Zn, Cr, Cu, Cd, Hg, and As can be found in soils and sediments.

Although major element compositions of tailings are not always given in literature, silica, and iron together with oxygen, are usually the most abundant elements with Al, Ca, K, Mg, Mn, Na, P, Ti and S also major components (Kossoff *et al*., 2014). One of the major environmental and health concerns of abandoned mine tailings is the production of AMD. Poor management of most of the tailings results in the release of AMD and this can cause soil degradation and water contamination underneath and around the mine sites. Tailings are composed of both an accumulation and a potential subsequent emission source of trace elements (Cu, Fe, Pb, and Zn) with formation of AMD due to the oxidation of sulfides present in the mine tailings.

The physical concerns linked to abandoned mines include public health and safety, visual impacts, stability issues and dust emission problems. On the other hand, environmental issues include problems associated with spoil dumps and tailing facilities, contaminated aquatic sediments, subsidence, burning coal waste dumps and working. They also include sites characterized by compacted and polluted soils as well as changes in vegetation cover (MMSD, 2002).

2.4.4 Socio-economic Impacts

The most important socio-economic concern caused by abandoned mines is the loss of employment and business activities in the community, due to the unscheduled closure. Dust from

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old waste disposal sites is another potential socio-economic impact from abandoned mines. This can be a nuisance and a health hazard if it contains certain minerals and heavy metals. Children playing on and around these sites may ingest dust that may also have health implications.

Abandoned mines may become a target for legal or illegal mining by small-scale miners. In some cases, this involves the expansion of the previous mine workings while in others it is the reworking of the waste materials to extract metal residues. While this might have the advantage of providing jobs and revenue for people who have lost their jobs due to unplanned mine closure, the effects that may be incurred cannot be ignored. Most of these miners lack formal training and, in some instances, could make use of dangerous processing chemicals to extract metals (such as the mercury used in gold amalgamation) and this could have impacts on both their health and the environment. Abandoned mines will continue to have an impact on both the environment and the communities in which they exist unless good mine closure practices are implemented (DHI, 2012).

AMD has become a very visible and highly political issue in South Africa due to the polluted mine water spilling out into the environment (Adler and Rascher, 2007). Mine closure and the associated increase in AMD also have serious consequences for communities previously supported by the mining sector (Adler and Rascher, 2007; Warhurst and Noronha, 2000; Claassen, 2006). Mine closure results in loss of job opportunities and increased unemployment. Most communities often resort to subsistence farming, but AMD may render the available water resources unfit for agricultural use (Warhurst and Noronha, 2000).

2.4.5 Visual and Aesthetic Impacts

Mining operations inevitably cause changes in the surrounding environment, the extent of which depends upon the nature of the ore, mining method and the size, geometry, and location of the deposit (MINEO Consortium, 2000). Surface expression such as caving, troughs, tension cracks, or shearing faults caused by abandoned mine lands results in mine voids that damage property and pose a danger to the public (National Association of Abandoned Mine Land Programmes

(NAAMLP, 2003). Existence of voids and weak supporting pillars in abandoned mines can cause subsidence, regardless how long the mine has been abandoned (Prakash and Singh, 2009).

The aesthetic impact of an iron-rich mine water makes the area less attractive for investment. The water can be unsuitable for other legitimate uses such as fishing, water sports, irrigation, and livestock watering and industrial or potable water supply. A direct consequence of this visual damage is a reduction in the use of a water body for recreational and water sport activities, reducing the economic and social value of the water resource to the local community (EA, 2008).

Landscape alteration is one of the most significant environmental impacts associated with abandoned mine sites. Although this may not directly affect public health, it may produce adverse reaction among potential observers and compromise the use and potential growth of the surrounding territory (Dentoni *et al*., 2013).

2.5 Framework for Closure and Remediation of Abandoned Facilities

The Department of Minerals and Energy (DME), and the Department of Environmental Affairs and Tourism (DEAT), have placed certain requirements on mines before a closure certificate is granted, the main requirement being an environmental management plan (EMP) which is compulsory for any mine and for which DME is the lead agent (Pulles *et al*., 2005). Closure planning as incorporated in EMP reports of gold mines in South Africa is currently inadequate to protect the water resources impacted by mining activities. Banister *et al*. (2005), summarized the EMP report and pertinent misconceptions and shortcomings were described, these included that most mines recognize that tailings dams generate AMD, but it is generally and incorrectly assumed that the impact will decrease to acceptable levels when the mining operations cease. It is also assumed that the larger particle size of waste rock dumps makes them a lesser pollution risk. This view is erroneous, as the waste rock dumps have very large inventories of fine material and are much more permeable to oxygen than tailings dams.

Closed and abandoned facilities should be inventoried only if they contain waste directly resulting from the prospecting, extraction, treatment, and storage at land-based mines (Article 3 of the

MWD). DHI (2012) indicated that the experience from completed and on-going remedial programmes for closed and abandoned mines suggest or call for a need for proper closure and remediation of abandoned mines. Other conclusions drawn include a systematic long-term approach necessary to address abandoned mine issues and performance of remedial programmes on many scales. Rehabilitation works beyond those necessary to ensure safety and eliminate health hazards should not be attempted if funds are not sufficient to ensure lasting environmental improvements.

Reclamation or rehabilitation of the disturbed land is carried out in the final stage in the operation of the mine. Each remediation programme will have to define its objectives and will have its possibilities and constraints. Nevertheless, a proposal for an overall programme strategy for rehabilitating closed and abandoned facilities has been developed and adopted based on the experience from existing programmes (DHI, 2012). The environmental, socio-economic, human health benefits accompanied by remediation and rehabilitation may be significant. The UK environmental authority has carried out several benefits assessments to support remediation of abandoned coal and metal mines with the results showing that the benefits are generally significantly greater than the costs (Potter, 2011).

2.6 Environmental Risks of Mining

Although mining is viewed as one of the important economic activities which have the potential of contributing to the development of economies, the environmental, health and safety impacts of mining on surrounding communities have been a major concern to governments, the public and stakeholder organizations and individuals. The health cost of mining operations sometimes outweighs the benefits gained. From the exploration state through to the post closure or mine decommissioning state, mining of ore bodies has the potential of causing serious environmental impact. As mining is carried out, the land surface is disturbed, affecting to varying degrees the groundwater, surface water, soils, vegetation, wildlife, air quality and cultural resources.

South Africa produces around 450 million tonnes of waste annually, with 70% of this generated by the mining industry alone. Gold mines on the Witwatersrand basin produce 105 million tonnes per annum (23% of the total) with about 200 000 tonnes of waste generated for every tonne of gold produced. As of 1997, South Africa produced an estimated 468 million tons of waste per annum. Gold mining waste was estimated to account for 221 million tons or 47% of all mineral waste produced in SA, making it the largest, single source of waste and pollution (DWAF, 2001).

2.6.1 Water Pollution

Water pollution arises from the large-scale land disturbance associated with mining, whether it is opencast, deep mining, or spoil dumping. A major environmental problem relating to mining in many parts of the world is uncontrolled discharge of contaminated water from abandoned mines (Banks *et al*., 1997; Pulles *et al*., 2005). Mining affects fresh water through heavy use of water in processing ore, and through water pollution from discharged mine effluent and seepage from tailings and waste rock impoundments. Mining below the water table, either in underground workings or open pits can affect groundwater quality. Dissolved pollutants at a mine site are primarily metals but may include sulfates, nitrates, and radionuclides, these contaminants once dissolved, can migrate from mining operations to local ground and surface water (Smith *et al.*, 1995).

Water and soil quality may be adversely affected through stockpiling of waste rock and tailings at the mine, the handling and storage of chemicals and hazardous waste (e.g., used oil or processing chemicals), contamination by routine servicing and maintenance of machinery and equipment at workshops on the mine site, or through accidents and the residue from explosives used at the mine. The risk of groundwater contamination is likely to be greatest in situations where sulphide tailings and waste rock dumps are located over a highly permeable substrate and particularly if topographic relief results in significant hydraulic head. In addition to contamination derived from interaction with ore and rock, waters may contain chemical residues, including nitrogen compounds, from explosives and lubricants or processing and enrichment chemicals. Release of

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such waters into the surrounding watershed may reduce water quality downstream from the mine and have a negative impact on aquatic ecosystem (Heikkinen *et al*., 2008).

Toxic metal contamination and leaching occurs when metals such as Co, As Cu, Cd, Pb and Zn contained in excavated rock or exposed in an underground mine encounter water. Metals are leached out and carried downstream as water washes over the rock surface. Water flowing from mine dumps impact natural wetlands which are close or adjacent to such dumps, wetlands get polluted and in some cases the extent could be transboundary thus affecting water resources of other jurisdictions.

According to DMR (2009), some mining activities could also result in the disturbance and diversion of river courses. This can also result in silting up of streams or dams. Mining activities have the potential to pollute groundwater resources due to chemical reactions in the mined-out areas, this can lead to the localized depression of the water table and a reduction in the availability of groundwater.

2.6.2 Air Pollution

Particulate material (PM) and gaseous emissions are emitted during mining, beneficiation, and mineral processing. Gaseous emissions are generated by process operations, primarily those using heat to treat or convert ores or concentrates (e.g., from sinter, roaster, smelter, or refinery stacks). Fugitive dust is produced from mining operations (e.g., blasting), transportation (e.g., loading equipment, haul vehicles, conveyors), comminution (e.g., crushing and grinding), and waste management operations (i.e., waste rock dumping). Winds also entrain dust from dumps and spoil piles, roads, tailings, and other disturbed areas (EPA, 2006). Fugitive dust may still, however, be emitted from unstabilized waste management units and contaminated sites or from transportation and remediation activities.

According to Warhurst (1994), dust problems from tailings may not appear until after closure/abandonment, when the waste material dries out. Only then may high levels of metals

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(arsenic, for example) trigger concerns. Tailings and waste rock at metal mines usually contain trace concentrations of heavy metals that may be released as fugitive dust to contaminate areas downwind as coarse particles settle out of suspension in the air. Stabilization and reclamation efforts are aimed in part at reducing fugitive dust emissions; remediation often must address the downwind soil contamination.

Blasting during trial mining may produce noise and dust. Quarrying, crushing, and transport are all potential sources of excess noise, vibration, and dust. Tailings and stockpiled concentrate may also cause dust problems. Combustion of mine waste materials resulting in smoke, haze, heat, or venting of hazardous gases and, together with tailings deposition, causes some of the most widespread contamination. Metal smelting, in the absence of adequate air pollution controls, emits particulates high in lead and other metal contaminants from smokestacks that would then settle out of the air stream (Landers and Usher, 2015).

Although deposition at any distance may have been at a relatively low concentration (particularly as stacks became higher), the long period of deposition (i.e., from decades in some cases to over a century in others) and the bio-stability of metals have created soil contamination problems of significant proportions. With the advent of air pollution regulations and subsequent air pollution controls (APC), smelter flue residues were deposited onsite in waste piles or landfills. These wastes often have high metal concentrations, high enough that, when technically feasible, the dusts may be returned to the smelter to recover the metal value.

Once pollutants enter the atmosphere, they undergo physical and chemical changes before reaching a receptor. These pollutants can cause serious effects to people’s health and to the environment. Airborne emissions occur during each stage of the mine cycle, but especially during exploration, development, construction, and operational activities. Mining operations mobilize large amounts of material, and waste piles containing small size particles are easily dispersed by the wind. Large-scale mining has the potential to contribute significantly to air pollution, especially in the operation phase. All activities during ore extraction, processing, handling, and transport depend on equipment, processes, and materials that generate hazardous air pollutants such as particulate matter, heavy metals, carbon monoxide, sulfur dioxide, and nitrogen oxides (IFC, 2007).

2.6.3 Degradation of Land and Vegetation

Mining activities exert a long-lasting impact on landscape, ecosystem, and socio-economic considerations. Land degradation is a major direct environmental impact posed by mining. While land degradation caused by gold mining is pronounced, chemical contamination from gold extraction processes imposes a double burden on the environment, with harmful health implications for mining communities and people residing near such activities (Yelpaala, 2005).

Mining can contaminate soils over a large area. Agricultural activities near a mining project may be particularly affected. According to a study commissioned by the European Union, mining operations routinely modify the surrounding landscape by exposing previously undisturbed earthen materials. Erosion of exposed soils extracted mineral ores, tailings, and fine material in waste rock piles can result in substantial sediment loading to surface waters and drainage ways. In addition, spills and leaks of hazardous materials and the deposition of contaminated windblown dust can lead to soil contamination (IFC, 2007).

Singh *et al*. (2016) indicated that deforestation, siltation, excavations, waste dumps, and soil quality are causes of land degradation associated with surface mining. Changes in topography due to surface mining increases soil erosion, leads to long-term compaction and reduces agricultural capacity. Plants are of particular concern because they extract metals from polluted soils and mine wastes making them available to animals, including livestock, and humans who feed on the plants and animals.

A study undertaken by Sahu and Dash (2011) on land degradation due to mining in India showed that mining activities degrade the land to a significant extent. Removal of overburden results in a loss of large quantities of the rich topsoil and indigenous forests. The impact of mining on land gets reflected when the land gets exposed to erosion, losing its vegetation cover or by getting disturbed due to excavations and overburden dumping, therefore soil contamination occurs, part

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of or total of flora and fauna gets lost, water gets polluted, and this leads to accelerated degradation of land. The study also showed that the estimated land affected due to mining in India is more than 13546 Ha. This decreases the quality and quantity of vegetation, as such, the diversity of vegetation at a site deteriorates.

Mbaya (2013) also conducted a study on land degradation due to mining activities in Nigeria and observed significant changes in vegetation density and composition within the study area or the mined area. Tree/vegetation density measurements were taken, the density of plants for the mined sites were less than that of the unmined sites. Activities such as clearing of land for mining accounted for the decline in tree or vegetation density.

2.7 Risk Evaluation of Abandoned Mines

The old waste storage facilities that have been closed or abandoned without any kind of restoration, or where restoration has been incomplete or negligent, represent a permanent potential risk for the population and the environment, especially when they contain dangerous and contaminating substances. Vertical or steeply inclined shaft or opening that is not sealed or barricaded, or a subsidence-caused opening that has become a hazard and a surface entrance to a drift, tunnel, addict, or entry that is not sealed or barricaded may constitute a significant risk into the environment (Aslibekian and Moles, 2003).

According to article 20 of the MWD, a closed or abandoned facility can cause serious negative environmental impacts or have the potential of becoming in the medium or short-term a serious threat to human health or the environment. Any abandoned mine land-related dilapidated hazardous equipment or facilities (old engines, mine cars, rails, mine entrances, load-out and processing facilities) located near populated areas, along public roads, or other areas of intense visitation are most likely to amount to environmental risks. For this reason, the mining sector has been focusing for several years on the need to implement and develop various risk assessment and management concepts.

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Risk evaluation and assessment for abandoned mines must be carried out systematically, so that the data may be used in future as a baseline for further monitoring. Prioritization based on the individual risks posed by any site is a pre-requisite for decision makers before the commencement of site-specific rehabilitation. Lindahl (2007) indicated that competent authorities should apply methodologies for risk assessment and identification of the closed, abandoned, or orphaned Tailings Management Facilities (TMF) using a step-by-step approach, starting with a basic screening of sites, whereby resources are gradually directed towards sites with the highest risks. Based on the risk identified, competent authorities should make plans for risk reduction measures and/ or monitoring for the closed and abandoned mines.

According to DHI (2012), the abandoned mine risk evaluation criteria incorporate (i) planning of which facilities to inspect and the objectives of the inspections (overall inspection plan), (ii) preparation of the inspection (desk work based on compiling and assessing available information, including but not limited to historical information, older investigations, environmental monitoring information), (iii) site visit, (iv) evaluation and first risk assessment, and (v) reporting.

The manual of the risk evaluation and assessment developed by the Institute for Geosciences and Natural Resources of Germany for Chile (Golder Associates, 2008) prioritizes the hazard potential, and subsequently identifies mitigation requirements of the most severe risks. It includes guidelines for assessing safety and contamination risks, with further details for classifying the risk according to the geological and physical situation on the ground. Risk evaluation of a given abandoned mine involves the identification of hazard scenarios and potential receptors and assessing the likelihood of occurrence and the severity of consequences (Hasheela *et al*., 2014).

2.8 Costs of Remediation of Mine Facilities

Costs related to closure differ considerably between mine sites (World Bank and International Finance Corporation, 2002). The costs of physical mine closure vary greatly, depending on the age, location, and the type of mine and mineral extracted. Closure costs (mainly related to the extractive waste) for environmental issues range from less than US$1 million each for small mines

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to hundreds of millions of dollars for large open pit mines. More typically, closure costs will range in the tens of millions of dollars. Preliminary research indicates that medium-size open pit and underground mines operating in the past 10 to 15 years cost US$ 5-15 million to close, while closure of open pit mines operating for over 35 years, with large waste and tailings facilities, can cost upwards of $50 million. Costs need to be estimated on a case-by-case basis (DHI, 2012).

A policy meant for ensuring planned and financed rehabilitation from the early stages of any operation was developed by the BHP. Provision was made for rehabilitation of mining and processing facilities along with the decommissioning of oil platforms and infrastructure associated with petroleum activities. According to Wikinvest (2006), the estimation of the cost of future rehabilitation is subject to uncertainties. Rehabilitation expenditures are mostly expected to be paid over the next 30 years. The provisions for rehabilitation and decommissioning are derived by discounting the expected expenditures to their net present value. The estimated total site rehabilitation cost to be incurred in the future arising from operations to date, and including amounts already provided for, is US$6,939 million (2005: US$6,284 million).

In evaluating risks associated with environmental impacts, events that might occur after rehabilitation work should be considered. Structural reliability (deficiency risks, risks associated with recurrence periods) and proposed methods, the extent of the potential impacts and control capacity in the event of reduced performance or breakage must also be considered. The evaluation must take potential impacts on the human and natural environment into account (EPA, 2004).

2.9 Commonly used Tools for Prioritization of Abandoned Mines

The assessment tools and methods discussed in this section were developed for prioritization of abandoned mine sites for rehabilitation in several countries. Some of these tools are based on scoring systems and valuable parameters that represent significant environmental, human health and safety hazards at abandoned mine sites. These tools include the Historic Mine Sites Scoring

System, Historic Mine Site Inventory and Risk Classification Scoring System and a four-step approach toward rehabilitation.

2.9.1 Historic Mine Sites Scoring System

The Historic Mine Sites Scoring System (HMS-SS) was developed by the Geological Survey of Ireland and the Environmental Protection Agency to prioritize the historic mine sites from a human and animal health perspective as well as the general environment.

The five steps to scoring a historic mine site include identifying sites to be studied, identifying individual sources on each mine site, conducting field measurements on the individual sources, carrying out scoring for each source separately and amalgamating the individual waste scores to score the site overall. This model identifies the source of any contaminants and the receptor (who or what affected). The collection of field data, observation and estimates confirms whether a linkage exists between the source and receptor. The potential sources can be classified as solid sources, liquid sources, and stream sediment contamination (EPA, 2009).

The scoring is designed to rank differing and disparate sites using existing or easily obtained new information on a common foundation based on the threats to human health, animal health and environment. Potential receptors are humans, groundwater, surface water, freshwater ecosystem, land-based ecosystem, marine and livestock. The overall approach to the scoring system is to take each relevant pathway for each source type and for each pathway three factors, that is likelihood of release, waste hazard characteristics and potential receptors of exposure are evaluated (EPA, 2009).

The HMS-SS is based on the Abandoned and Inactive Mines Scoring System (AIMSS), which is data extensive and requires information from many sources. This can be time consuming and costly since consultants are appointed to carry out some of the work. Individual sources of risks are only assessed for the potential risk to human, animal health and the environment. However, factors such as visual and aesthetic impacts were not considered and scored.

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2.9.2 Historic Mine Site- Inventory and Risk Classification Scoring System

The Historic Mine Site Inventory and Risk Classification Scoring System was developed in Ireland. The objectives of this scoring system were to carry out site investigations at priority historic mine sites in Ireland and to assess the potential risk posed by these sites to the safety and health of human and to the wider environment and to consider issues related to safety at each of the sites. It involves the development of a conceptual model which uses the Source-Pathway-Receptor paradigm. This paradigm requires that each of the parameters within the model is documented, estimated, measured, or recorded. It identifies the source of any contamination, the receptor, and the pathway. The overall approach is to apply scores for the hazard (source), the likelihood of release, and the receptors for each waste type along each pathway at each site (EPA, 2009).

The scoring system also provides an overview of the methodology in practice, it focuses on preliminary screening and site selection for the historic mine sites which involve detailed knowledge on mining history, mining methods, mineral processing, geology, and mineralization, coupled with assessment criteria and environmental setting used to carry out preliminary screening of the sites. Conceptual models are used to inform and drive site investigations to assist with the identification of remedial strategies as well as risk ranking and classification (EPA, 2009).

This scoring system focusses mainly on management of waste in abandoned mines based on their chemical characteristics. Although other features such as shafts and adits are assessed, their impacts are not well pronounced.

2.9.3 A four step approach toward rehabilitation

A study conducted by Mitchell and Mackasey (1995) outlined that there was an occurrence of several incidents involving abandoned mines in the Canadian province of Ontario. This province then embarked on a comprehensive programme to identify and remediate abandoned mine hazards. The Ministry of Northern Development and Mines of Ontario (MNDM) came up with an approach in their abandoned mines programme. The approach was developed after the amendment of a new section of the Mining Act which stipulates that all present and future mines

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are required to have an approved closure plan. A four-step approach was used: (i) conduct a desktop literature review to identify all potential hazards, (ii) conduct field assessments of these sites, (iii) prioritize sites for remediation and (iv) conduct remedial works.

The first step involves a comprehensive desktop study and literature studies of all known and available data compiled in the presence of number and types of mine features; the literature study is undertaken to identify all potential hazardous sites. Field assessment of all potential hazardous sites involved contraction of field inspections out to qualified consulting firms. A final report was then drafted and entailed a listing and description of all mine features and hazards, assessment of the condition and detailed sketch maps showing the location of all mine features of all abandoned mine features with location control points.

In step three, plans were developed to make Abandoned Mines Information System (AMIS) part of the Ministry of Northern Development and Mines of Ontario (MNDM), Earth Resources and Land Information System and this makes abandoned mines information readily available to the public. The last step is based on outlining regulations and a set of standards. Short and long-term remediation options were recommended (Mitchell and Mackasey, 1995).

The scoring system used in this approach favors public health and safety issues, and little consideration is given to environmental issues. Furthermore, this approach prioritizes abandoned mine sites for remediation and not individual mine features. The rehabilitation strategy is aimed at rehabilitating the entire mine site rather than focus on mine features that are more hazardous to reduce the costs associated with the whole mine and some features that are not severely hazardous being rehabilitated.

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CHAPTER THREE: RESEARCH METHODOLOGY

This chapter describes the specific steps, procedures and techniques used to achieve the aim of this research. The research approach involved conducting a reconnaissance survey on the selected abandoned mines to acquire a general overview of the mine sites. A desktop study was undertaken to understand the need for prioritization and rehabilitation. Site characterisation was conducted in the study area with the aim of establishing the nature and severity of impacts associated with the features of abandoned mines. Abandoned mine features which are hazardous to the environment and safety of the populace were assessed through the scoring and ranking of physical hazards and chemical characterization of the sites. The steps followed in conducting this research are shown in Figure 3.1.

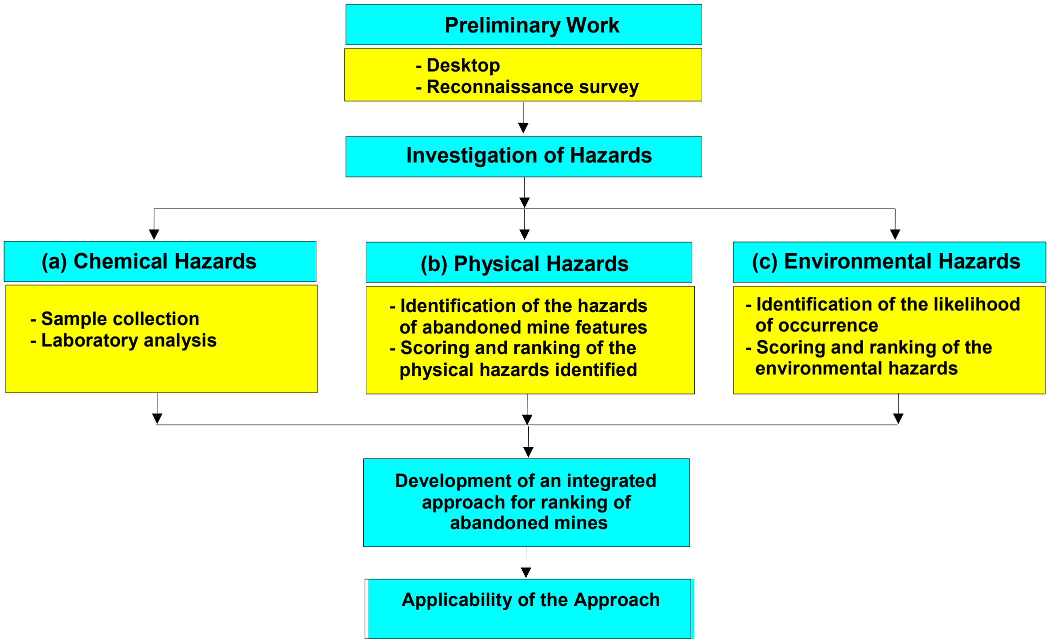

Figure 3. 1: A flowchart of the methodology used in this research

3.1 Preliminary Work

Preliminary work is the initial work or study undertaken to explore and identify key features or areas to be addressed before the actual detailed work or topics are covered in a study. This helps gather information or data available that the researcher may use. In this study, preliminary work was carried out as the first stage of collecting relevant data to meet the objectives of this research. It was conducted in two steps, namely (i) desktop study and (ii) reconnaissance survey.

The desktop study was carried out prior to any field work. The aim of the desktop study was to gather basic information relating to the nature of impacts associated with abandoned mine features and the history of mining and rehabilitation in the study area for enhanced understanding of the sites and their surroundings. This was conducted through collection, compilation and analysis of historical maps and existing information sources. From the desktop study, gaps within existing approaches were highlighted which then informed the key objectives of this work and approach developed for the study. Topographic maps were interpreted to gather information on the geographic location of the abandoned mine sites, elevation, streams, and rivers in the area for better planning of the actual field work.

The reconnaissance survey was undertaken prior to detailed fieldwork. The aim of the survey was to gather valuable information for planning actual data collection methods. It involved identifying the areal extent of the abandoned mine sites and identification of abandoned mine features through traversing around the mine sites. During the reconnaissance survey, the state of the mine features in both mine sites was assessed for documenting the condition of the features and the mine sites. Sites that require collection of samples were identified during reconnaissance survey. Based on the information gathered during preliminary work, the steps, and procedures for carrying out the actual fieldwork were conceptualized.

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3.2 Risk Assessment Procedure

This section provides information on the identification and mapping of various features of the selected abandoned gold mines and their corresponding risks. The mine features were described in terms of number of sources of contamination, pathways of contamination, severity, and seriousness of impacts. The risks associated with the mine features were classified into physical chemical and environmental. In addition, abandoned mine tailings, rock dumps and soils were sampled for the analysis of different metals to determine their toxicity level. Furthermore, hazard parameters such as pollution load index, geo-accumulation index and contamination factor and potential ecological risk index were also determined to assess the risks associated with the selected study areas.

3.2.1 Mapping and Quantifying the Hazards of the Abandoned Mines

The identification and location of the identified mine features involved gathering information about the individual features using tools such as topographic map, Garmin Geographical Positioning System (GPS) 60, orthophotographs, tape measure and high-resolution digital camera. Systematic traversing around the mine was carried out and the identified mine features were located and marked on the topographic map using the coordinates recorded using GPS 60. Through traversing, features such as mine openings, tailings dumps, waste rock dumps, spoil dumps and old infrastructure of the abandoned mine were located and documented.

The individual mine features which are sources of different hazards were described in terms of the potential risks they pose to human health, safety and the environment. The identified risks of the mine features were also quantified to establish their seriousness.

3.2.2 Scoring and Ranking the Mine Features

The mine features prevalent at the mine site were scored and ranked in terms of their associated risks. Factors taken into consideration while assigning scores and ranking hazards were the size of the site and individual mine feature, number of features, current and future land uses, number

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of contaminants present, media contaminated and nature and severity of impacts. Field investigations at the abandoned mine sites were undertaken to gather information necessary to characterize the site, define site interactions, define risks, and develop an integrated approach to mitigate the threats of these mines to the environment, human health, and safety. During field investigations, it was realized that the abandoned mine features vary in size which may translate that the associated hazards or risks vary as well, therefore this was factored in the study.

Hazards were classified into physical, chemical, and environmental hazards thus, the classification was done before the actual hazard scoring and ranking. The scoring system follows the source, pathway, and receptor paradigm. The first step towards scoring was to determine potential sources of hazard/risk, identify pathways and the potential health, safety and environmental impacts associated with the abandoned mine features identified at the mine site. The severity and extent of physical, chemical, and environmental hazards were expressed by assigning numerical scores to the source, pathway, and possible impacts to the receptor. The method employed to establish individual scores is described in the following subsection.

3.2.3 Physical Hazards

Abandoned mine features in each mine site were identified as sources of contamination/ hazard and or risk. The number of each mine feature (source) was documented, and scores were assigned based on the number of each source as per Table 3.1. Pathways or exposure routes associated with each mine feature (source) were also identified and documented. Pathways describe/identify how the source may reach the receptor. Moreover, scores were assigned based on the number of pathways identified (See Table 3.1).

The potential hazards/ risks associated with each mine feature were identified and scored based on their severity. Existing literature was also reviewed to help quantify the impacts. The potential physical hazards/ risks identified were ingestion, dermal/ skin contact, inhalation, physical injury and death, as such, scores were only assigned to these hazards, as shown in Table 3.1. Numerical scores were assigned to the parameters (source, pathway/ exposure routes and possible impacts)

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based on field observations. The identified potential impacts relating to physical hazards were health and safety impacts, i.e., a source may pose health or safety impacts or both. Equation (3.1) was used to compute the physical hazard score for each mine feature.

$$\mathrm{PH} = \frac{\mathrm{S} \times \mathrm{P} \times \mathrm{PR}}{\mathrm{r}} \tag{3.1}$$

Where: *PH* is Physical Hazards, *S* is the number of sources; *P* is the number of pathways; *PR* is the Potential Risk and *r* is the reduction factor.

To quantify the potential physical hazards relating to each mine feature, the scores computed were classified on a scale of 1 to 10, where 1 to 2,99 is low, 3 to 5,99 is moderate, 6 to 9,99 is high and a score of 10 is extremely high. The physical hazard scores computed for the abandoned mine features were then ranked to provide useful information for prioritization of the abandoned mine features (sources of contamination) for rehabilitation.

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Table 3. 1: Scoring and ranking sources, pathways, and risks of contamination

Source of the hazard			The pathway of exposure to hazards			Risk of exposure to the hazard		
Number of sources	**Score**	**Rank**	**Number of pathways**	**Score**	**Rank**	**Type of risk**	**Score**	**Rank**
One source of contamination	2	Low	No traceable pathways	1	Extremely low	No traceable hazards/ risks	1	Extremely low
Two sources of contamination	4	Moderate	One pathway	2	Low	Ingestion	2	Low
Three sources of contamination	6	High	Two pathways	4	Moderate	Dermal/ Skin contact	4	Moderate
Four sources of contamination	8	Very high	Three pathways	6	High	Inhalation	6	High
More than five sources of contamination	10	Extremely high	Four pathways	8	Very high	Physical Injury	8	Very high
			More than five pathways	10	Extremely high	Death	10	Extremely high

3.2.4 Environmental Hazards

The computation of environmental hazards was different from physical hazards since the nature and severity of impacts vary from site to site. The first step towards computation of environmental hazard scores was to determine the probability or likelihood of occurrence of hazards and risks. For each mine site, the environmental hazard score was determined by the proximity or distance of the site from nearby communities/ residences, presence or absence of artisanal mining activities and the number of features per mine site. According to the Agency for Toxic Substances and Disease (2005), prioritizing relative environmental hazards include evaluating accessibility, identifying potential receptors and the proximity to population centers. Concentration of toxic metals are known to decrease with distance from the mine and the effects on biodiversity tend to follow the same pattern.

The proximity (distance to residents) was obtained from field observations during site surveys or by assuming the nearest building to the site is a residence on google maps or aerial photographs. The distance of the mines sites from the neighboring communities, corresponding score and potential impact is shown in Table 3.2.

Table 3. 2: Distance of the mine sites to communities and their level of possible impact.

Distance (m)	Score	Possible Impact
>500	1	Extremely low
400-500	2	Low
300-400	4	Moderate
200-300	6	High
100-200	8	Very high
<100	10	Extremely high

Artisanal mining activities were assessed using visual inspection at the mine sites into the presence or evidence of recent mining activities during field work as shown in Table 3.3., and from interactions or discussions with residents and research work carried out in the study area. Studies conducted by authors such as, Mhlongo *et al*. (2019); Magodi (2017) and Steenkamp and Clark-Mostert (2012) indicated that artisanal mining activities are being carried out in the mine sites.

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Table 3. 3: The impact of the artisanal mining activities

Evidence of ASM	Score	Possible Impact
Absent	1	Extremely low
Present	10	Extremely high

Equation (3.2) was used to compute the likelihood or probability of environmental hazards occurring at Klein Letaba and Louis Moore:

$$\text{Likelihood of occurrence} = \text{Proximity} + \text{ASM} + \text{No. of features} \tag{3.2}$$

The number of abandoned mine features for each mine site was determined to prioritize the mine sites for rehabilitation, in the sense that a mine site with more abandoned mine features is likely to be more hazardous than a mine site with lesser sources of contamination. Furthermore, to prioritize abandoned mine features for rehabilitation with respect to their potential environmental hazards and risks, numerical scores were assigned to the identified potential hazards.

Equation 3.3 was used to compute environmental hazard scores for Klein Letaba and Louis Moore. It is worth mentioning that the formulas for determining physical and environmental hazard scores were similar except that the likelihood of occurrence of potential hazards and risks was first computed for environmental hazard scores.

$$\mathrm{EH} = \frac{\mathrm{S} \times \mathrm{P} \times \mathrm{PR}}{\mathrm{r}} \tag{3.3}$$

where: *EH is* Environmental Hazards, *S* is the number of sources; *P* is the number of pathways; *PR* is the Potential Risk and *r* is the reduction factor.

3.2.5 Determining Total Physical and Environmental Scores

The total physical and environmental hazard scores were obtained by adding all values computed per individual mine feature. This was done to determine whether the abandoned mine features pose more physical or environmental hazards so that prioritization addresses features with more hazards or risks in terms of physical and environmental hazards/risks. Some features may pose only physical or environmental hazards or both, therefore it is important to determine the total physical and environmental hazard scores.

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The overall hazard score or total hazard score was determined by adding or combining the total environmental hazard scores, total physical hazard scores and the pollution load index (see Equation 3.4). The PLI was indicative of the chemical properties of soils around abandoned mine features, thus the PLI is an important tool used to evaluate the degree of soil contamination in the study area.

$$\mathrm{THS} = \mathrm{EH} + \mathrm{PH} + \mathrm{PLI} \tag{3.4}$$

where: *THS is the* Total Hazard Score; *EH is representative of* Environmental Hazards; PH shows Physical Hazards; *PLI* is the Pollution Load Index.

3.2.6 Soil sampling for Chemical Composition Analysis

To determine whether the soil around the abandoned mine features is contaminated or not, soil samples were collected. Surface soil samples were collected from a depth of 10-30 cm around Klein Letaba and Louis Moore. The top layer (0-10cm) was removed, as it was composed of organic materials. The soil samples were then collected from 10-30 cm. This depth was chosen because, generally, the depth of the soil profile around the area ranges from 10-30cm.These samples were collected around abandoned mine features such as shafts, old buildings, mine tailings and old processing plants. Two samples were collected 10 km away from the mine site to calculate background metal concentration. This area was deemed uncontaminated since there was no evidence of mining in the vicinity and it is far from infrastructure such as buildings, processing plants and mine waste.

A spade was used to collect the samples and they were stored in sealed polythene bags and transported to the laboratory for preparation and analysis. According to O'Kelly and Sivakumar (2014), the standard oven drying temperature for inorganic soils is 105-110˚. This is the highest temperature that the samples can stand without changing its physical and chemical characteristics. In the laboratory, the samples were placed in a bench vacate mounted oven (vacutec) drying oven to dry for 12 hours at 110˚C to remove moisture form the samples. They were then removed from the oven and allowed to cool to room temperature. The dried soil samples were then milled for 2-4 minutes at 700 rpm using a Retsch RS 200 milling machine to reduce the soil particles size.

Using X- ray fluorescence spectroscopy, the levels Ni, Cu, Co, Zn, Pb, Hg, Cd, As, Mo and Cr in abandoned mine lands were determined. These metals have been reported to be associated with gold deposits in the Giyani Greenstone Belt and can be toxic to the environment and ecological components.

3.3 Determination of hazardous Parameters

This section describes the methods employed in this study to integrate geochemical data into the approach being developed. Widely used methods include Contamination Factor, Modified degree of contamination, Geo-accumulation Index, Enrichment Factor, Pollution Load Index, Potential Ecological Risk Index and many more. In this study, the following methods were used to evaluate contamination levels of toxic metals in the soil samples at the abandoned mine sites:

Pollution Load Index

The Pollution Load Index is a method used for the total assessment of the degree of contamination in soil. It was proposed by Tomlison *et al.* (1980) for detecting pollution levels and allowing a comparison of pollution levels between sites and at different times. According to Muzerengi (2017), the PLI represents the number of times by which the metal content in the soil exceeds the average natural background concentration and demonstrates the overall metal toxicity in a sample. In this study, the PLI was computed to determine the overall metal contamination in the soil around the mine site. The PLI was calculated using Equation 3.5.

$$\mathrm{PLI} = (\mathrm{CF}_1 \times \mathrm{CF}_2 \times \mathrm{CF}_3 \times \ldots\ldots \times \mathrm{CF}_\mathrm{n})\ {}^{1}\!/_{\mathrm{n}} \qquad (3.5)$$

where: n is the number of metals. PLI<1 implies that the site is free from contamination whilst, PLI=1 implies the base line level of pollution and PLI>1 implies that the site quality is deteriorating. The CF represents the individual impact of each trace metal on the soil obtained using the Equation 3.6.

$$\mathrm{CF} = \frac{\mathrm{C_n}}{\mathrm{C_{ref}}} \qquad (3.6)$$

where: C_n represents metal concentration in the studied environment and C_{ref} being the metal concentration in the background environment.

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Geo-Accumulation Index and the Enrichment Factor

Geo-accumulation index (Igeo) is a common approach used to estimate the enrichment of metal concentrations above background or baseline concentrations as proposed by Müller (1969). It is used to quantify the degree of anthropogenic contamination and compare different metals that appear in different ranges of concentration in the sludge. It is a method/approach used to define metal contamination in sediments and soils and used to assess contamination by comparing the current levels of metal concentration and the original pre-industrial concentrations in the soil. This index (Igeo) of toxic metals was calculated by computing the base 2 logarithm of the measured total concentration of the metal over its background concentration using the following mathematical relation (Ntekim *et al.*, 1993). The Igeo was calculated using equation 3.7.

$$\mathrm{I_{geo}} = \log_2 \frac{\mathrm{C_n}}{1.5 \times \mathrm{Bn}} \tag{3.7}$$

where: C_n is the measured total concentration of element in soil and B_n is the background concentration of the metal. 1.5 is the factor compensating the background data (correcting factor) due to lithologic variations in the soils.

The Enrichment Factor (EF) can be used to differentiate between the metals originating from anthropogenic activities and those from natural sources. Due to its universal formula, it is a relatively simple and easy tool for assessing the enrichment degree and comparing the contamination of different environmental media (Benhaddya and Hadjel, 2013). Moreover, it is a common approach used in environmental contamination studies to estimate how much the soil is impacted (naturally or anthropogenically) with heavy metals above uncontaminated background or reference levels. The EF is expressed as shown in Equation 3.8.

$$\mathrm{EF} = \frac{\mathrm{Metal}}{\mathrm{RE(soil)}} \Big/ \frac{\mathrm{Metal}}{\mathrm{RE(Background)}} \tag{3.8}$$

where: RE is the value of metal, adopted as Reference Element. The numerical results are indicative of different pollution level. Values of 0.5≤EF≤1.5 suggest that the trace metal concentration may completely come from natural weathering processes (Zhang and Liu, 2002).

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Potential Ecological Risk Index (PERI)

The Potential Ecological Risk Index developed by Hakanson (1980) was adopted in this study to evaluate the overall ecological risks of toxic metal pollution in Klein Letaba and Louis Moore soil. The potential ecological risk factor of a given metal (Er) was introduced before calculating the Risk Index (RI) of all the metals in the soil. According to this method, the potential ecological risk index of a single element (Er) and comprehensive potential ecological risk index (RI) can be calculated using equation3.9 and 3.10.

$$\mathrm{Er} = \mathrm{Tr} \times \mathrm{Cf} \qquad (3.9)$$

where:Cf is the toxic response of a specific metal obtained by dividing the metal concentration by its background level.

In equation 3.9, Tr is the toxic response factor; biological toxic factor of a single element, which is determined for Zn=1; Cr=2; Cu=Pb=5; Cd=30; As=5 and Ni=5 (Hakanson, 1980).

$$\mathrm{RI} = \sum_{\mathrm{i-1}}^{\mathrm{m}} \mathrm{Er}^{\mathrm{i}} \qquad (3.10)$$

where: RI is the Ecological Risk Index

The toxic response of a specific metal (Cf) is calculated using equation 3.11.

$$\mathrm{Cf} = \mathrm{Cd}/\mathrm{Cr} \qquad (3.11)$$

where: Cd is the degree of contamination and Cr is the measured concentration of heavy metal in each sampling point.

Table 3. 4: Criteria for quantifying ecological risk of toxic metals in soil.

Er	Ecological risk	Risk Index	Risk Degree	Level
Er< 40	Low	RI < 40	Low	A
40 ≤ Er< 80	Moderate	40 ≤ RI <80	Moderate	B
80 ≤ Er< 160	High	80 ≤ RI < 160	High	C
160 ≤ Er< 320	Very High	160 ≤ RI < 320	Very High	D
Er ≥ 320	Extremely High	RI ≥ 320	Extremely High	E

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3.4 Evaluation of Methods of Prioritizing Mines for Rehabilitation

The challenge of allocating funds for rehabilitation due to poor planning and a lack of a systematic framework to identify and prioritise high risk sites for rehabilitation remains a major concern. Based on this, the Department of Mineral Resources (2009) developed a framework for assessing appropriate and effective methods for the management of abandoned mines. It serves as a basis upon which evaluative judgements around compatibility and applicability of rehabilitation methods/approaches can be made. One of the major challenges of rehabilitation highlighted by UNEP and COCHILCO (2001) is the absence of rehabilitation criteria and standards. The DMR evaluation criteria was used in this study to evaluate and determine whether the commonly used rehabilitation prioritization methods and the integrated approach conform to the requirements in addressing abandoned mine issues.

The evaluation conducted in this study entailed a comprehensive theoretical analysis of the traditional techniques and the integrated approach of mine site prioritization for rehabilitation. The DMR criteria that were used as basis of the evaluation emphasised the importance of classifying, characterizing and quantifying impacts of abandoned mines. Also, the importance of a framework for identification and classification of priority mines is presented. These were used to determine whether the commonly used methods of prioritising mine sites for rehabilitation and the integrated approach satisfy the DMR standards/criteria or not.

Table 3. 5: Description of commonly used methods relative to the new integrated approach

DMR Criteria	**Commonly used methods**	**Source**	**Integrated Approach**
Inventory of abandoned mines - location of the mine, commodities mined and possible impacts	**Historic Mine Site - Inventory and Risk Classification** Abandoned mines in question described and potential impacts presented	Luodes (2013); Geological Survey of Ireland and the Environmental Protection Agency; PGeo *et al*. (2009)	Abandoned gold mines in the GGB located and described and potential impacts presented

Table 3.6: Continue.

Ranking of abandoned mine features based on their potential or already existing negative impacts	**Maturity Chart Tool** Scoring and ranking focused on the entire mine and not individual mine features	Unger *et al*. (2012)	Individual abandoned mine features within each mine site identified, characterized, scored, and ranked to quantify impacts
Classification of impacts	**Abandoned and Inactive Mines Scoring Systems** Focused on addressing either public health and safety or environmental hazards	Pioneer Technical Services (1996)	Hazards classified into physical, chemical and environmental hazards
Provides a framework for identification of priority sites in terms of public health and safety, environmental and social risks	**Historic Mine Site - Inventory and Risk Classification** Risk estimation based on the entire mine and risk scores not computed for mine features	Luodes (2013); Geological Survey of Ireland and the Environmental Protection Agency; PGeo *et al*. (2009)	Risk estimation based on impacts of individual mine features and arranged in their order of priority. Overall risk scores computed to determine priority sites

3.5 Summary of the Chapter

The abandoned mine features in Klein Letaba and Louis Moore were mapped and assessed for their potential risks and hazards. These features were then scored and ranked in terms of their associated physical, chemical, and environmental risks. The scoring system followed the source-pathway-receptor paradigm. Abandoned mine features were classified as sources of contamination or risk, pathways of exposure to hazards and the potential risks of exposure to the hazards were established. Numerical scores were assigned to these parameters to quantify the severity and extent of impacts.

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Mathematical expressions were developed to determine the total physical and environmental hazard scores. Geochemical methods including the geochemical index and contamination factor, potential ecological risk index and the pollution load index were used to determine chemical hazard scores. The integrated approach for prioritization of abandoned mine features for rehabilitation was developed through integrating physical, chemical, and environmental hazard scores of each mine feature and mine site. An evaluation criterion developed by DMR was used to assess the effectiveness of the commonly used rehabilitation methods and the integrated approach.

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CHAPTER FOUR: CHARACTERIZATION OF ABANDONED MINE SITES

This chapter presents the results of abandoned mine site characterization which constitutes the inventory of abandoned mine features in the study area. The results of the quantification of the impacts of the abandoned mine features on the environment as well as health and safety of people and animals are presented in this chapter. The conceptual model which shows the source of the hazards presented by the mine features, pathways and possible exposure routes to the identified hazards as well as receptors or victims is also presented and discussed in this chapter.

4.1. General Description of the Abandoned Sites

Klein Letaba and Louis Moore gold mines are abandoned mines that lie within the Giyani Greenstone Belt. They are both not fenced and or barricaded and easy to access. These mines are characterized by different abandoned mine features that present different forms of physical and environmental hazards. Louis Moore had a total of 14 abandoned mine features and Klein Letaba contained 19 abandoned mine features. These features include several openings (i.e., underground mineshafts), unrehabilitated tailings dumps that are poorly vegetated, waste rock dumps, old mineral processing facilities, as well as old mine buildings. Klein Letaba is also characterized by a massive opening which is a result of ground subsidence. The distribution of some of these mine features on the abandoned mine landscapes of Klein Letaba and Louis Moore Mines can be seen in Figure 4.1 and Figure 4.2 respectively.

The two mine sites are sparsely vegetated, with a few trees and grasses covering the soil although some patches are covered by dense thick vegetation. They are both located not more than 500m from the Nsami and Klein Letaba River. Moreover, they are within the communities and farmlands. The distance from Klein Letaba and Louis Moore to surrounding communities was 450m and 375m respectively. This may potentially result in sediments and mine waste being transported from the mine sites to the farmlands and the water systems, causing water and environmental pollution.

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In addition, the study area is also dominated by artisanal mining activities that have created several dangerous shallow excavations. Studies conducted by authors such as Mhlongo *et al*. (2018) and Magodi (2017) have shown that illegal or artisanal miners randomly dig shallow pits around collars of closed mine shafts to collect soils with the belief that they contain residues of gold particles.

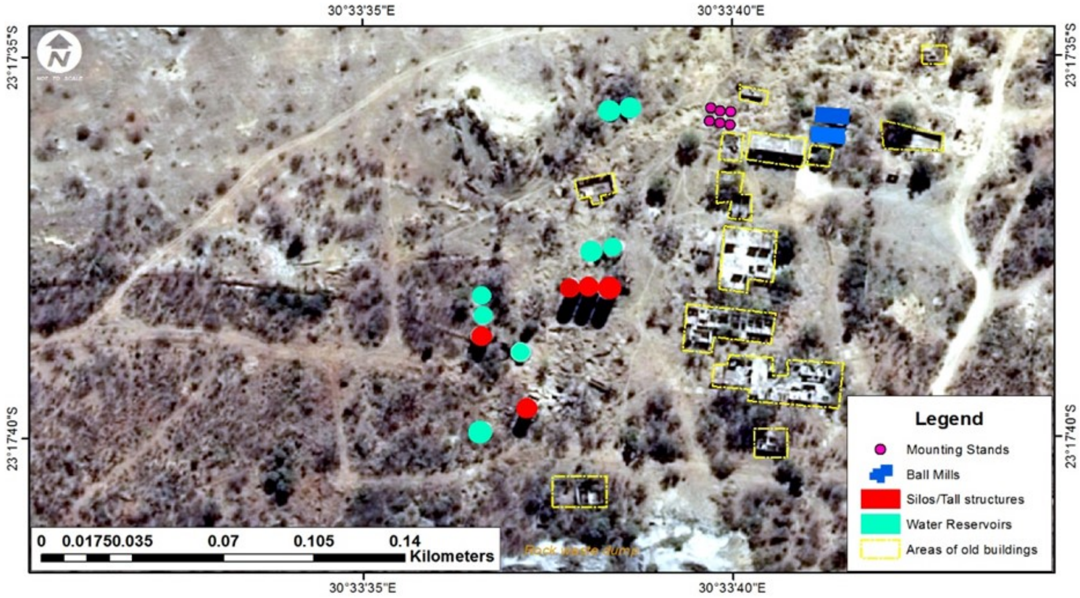

Figure 4. 1: The distribution of abandoned mine features at Klein Letaba site.

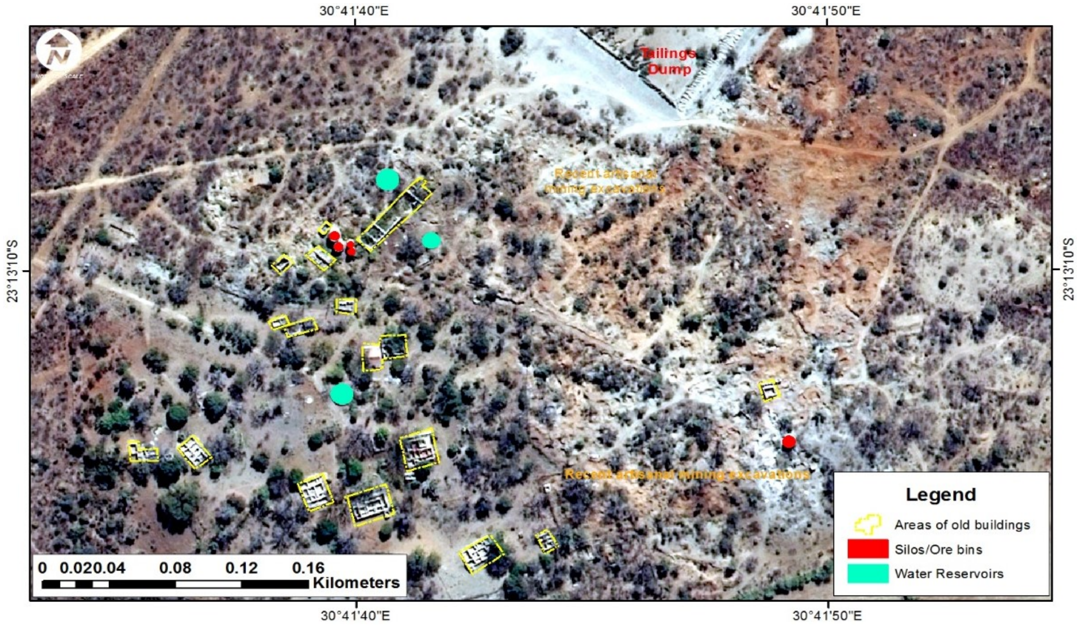

Figure 4. 2: The distribution of abandoned mine features at Louis Moore site.

4.2. Description of Abandoned Mine Features

Klein Letaba and Louis Moore are comprised of several abandoned mine features that are different in nature. The abandoned mine features prominent at the two mine sites are described, characterized, and assessed in this section. This involved location of the mine features, identification, and assessment of the current state of the features and the potential physical, chemical, and environmental hazards they pose. This played an important role in determining the current state of the features, nature of the features and the potential risks and hazards associated with them. This was done through site assessments and sampling of soil, tailings, and rock dumps for toxic metal analysis.

4.1.1 Abandoned Mine Shafts

A total of seven disused underground mine shafts were found in the study area. They are covered by thick dense vegetation and head frame structures, as such they cannot be easily identified. These shafts were found to be rehabilitated using different strategies to address mostly their physical hazards. Three old mine shafts were found at Louis Moore and one of them was lined with bricks and covered or closed with concrete slab. The risks of falling into this shaft were however, presented by the fact that artisanal miners had dug and destroyed the brick lining of the shaft, thus leaving it open once again. This may also suggest that the illegal miners enter the abandoned mines as they are looking for the remnants of the ore and other scrap metals within the old mine workings. This activity is likely to expose the artisanal miners to the risks of rock falls and inhalation of toxic mine gases within the underground mine workings, posing health and safety issues. According to Kissel *et al*. 2009, harmful or potentially explosive gases (monoxide, carbon dioxide and methane) in old mining works are mostly released by the rocks into the cavities generated by mining and they accumulate in such cavities.

The other two shafts were found open, and their lining structure was not identified. According to Unrug (1992), shaft lining provides support for shaft equipment and walls of excavations and enhances the stability of the mine shaft. Therefore, unlined shafts can easily collapse, thus posing safety threats to the people and animals who move around at the site and sometimes come close to these shafts. Moreover, unprotected open shafts allow uncontrolled

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access to the shafts by members of the public and animals. Abandoned mine shafts are mostly associated with ground instability as most of them are unlined. Ground instability leads to shafts having high risks of rock falls, this may threaten the health of people who might want to enter and explore the underground mine workings (Mhlongo *et al*., 2018).

The shafts may also discharge contaminated water into the surrounding environment. This may result in land degradation and water pollution should the contaminants be transported into the nearby rivers and other water systems. The land occupied by the abandoned mine shafts hinders other economic land uses such as agricultural activities, recreational activities to be practiced on the land. Visual and aesthetic impacts were also identified as problems posed by these features as it is aesthetically unpleasant on the landscape/environment.

A study conducted by Mhlongo *et al*. (2018) showed that the ground around some mine shafts is unstable or subsiding and some of them are used as entry points by illegal miners as they scavenge gold residues underground. This exposes them to the risks of drowning in water filling the mine workings, accidental or voluntary ingestion of contaminated mine water underground, and getting exposed to harmful mine gases.

4.1.2 Recent surface excavations

Artisanal gold mining activities in Louis Moore and Klein Letaba have resulted to several shallow excavations and spoil dumps in these areas (see Figure 4.2). Spoil dumps are huge amounts of waste products. This has seriously affected the environment and the general appearance of the abandoned mine landscapes in the study area. The alteration of the landscape has also led to the degradation of the land which occurred due to the removal of vegetation from the site as a way of clearing the site for mining. According to Hilson (2002), in general, artisanal mining involves removal of large quantities of vegetation, thus leaving behind excavations and spoils on the site. A study conducted by Mhlongo *et al.* (2018) confirmed that diggings by artisanal miners in Louis Moore Mine had affected the vegetation growth in the area.

Several pits of varying sizes were found at the abandoned mine sites. They generally ranged from 2-5m in depth. Some of the pits were not visible from a distance as they were

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camouflaged by vegetation growing on and around them. These pits are prone to flooding during rainy days, and this might expose people, especially children and animals, to risks of physical injuries or even death due to drowning if they trip and fall into the flooded pits. On the other hand, impounded water in the pits may be alkaline or acidic due to toxic elements resultant from previous mining activities thus capable of causing skin problems. A huge opening that is approximately 10-15m deep was identified at Klein Letaba. Hazards identified to be associated with the opening include falling into the opening, sharp objects covered by rocks and soil in the opening can cause severe physical body injuries and can be fatal. Furthermore, the major environmental impact identified and linked to this opening was land degradation since a large portion of land was disturbed and degraded.

Figure 4. 3: Land degradation due to artisanal gold mining activities at Louis Moore Mine

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4.1.3 Abandoned Mine Tailings

The tailings dumps found in both abandoned mines are unrehabilitated. According to Yan *et al*. (2013), tailings dams are susceptible to water and wind erosion because they are made up of finely fragmented ore sand with poor structures. The high stockpiles of loose sand are potential sources of pollutants and airborne dusts. Authors such as Blight (1989) and Amponsah-Dacosta (2001) stated that factors influencing slope erosion of tailings dams include slope length and angle, which control the velocity of water running down the slope. Erosion losses are proportional to slope length. Little erosion occurs from slopes flatter than 20^{o} or steeper than 40^{o}. Dust dispersed from tailings dams can be harmful to plants, animals, and human health. Plant cover and rain intensity also play a significant role on the occurrence of erosion on tailings dams.

A clino ruler was used to measure the slope of the tailing dumps. The estimated average slopes of the tailing dumps were found to be 35˚ at Louis Moore and 43˚at Klein Letaba. The tailings on both sites are characterized by lack of vegetation, though some parts of the tailing dumps had little patches of natural vegetation. Moreover, the tailing dumps on both mine sites were eroded. This was evidenced by gullies on the slopes of the tailings. However, the tailing dumps at Louis Moore were characterized by deep erosion gullies that were measured to be up to 1.5m deep in some parts of the dump. These gullies are an indication of the devastating effect of water erosion on the tailings. They also suggest that the tailings materials are highly susceptible to erosion, moreover the erosion is controlled by the slope angle and little vegetation on the slopes of the dumps.

Materials eroded from tailings dams are the main source of contamination of agricultural land. Eroded tailings can also lead to sedimentation in streams, destroying the natural ecology (Rankhododo, 2006). The identified impacts of erosion gullies in the study area were linked to the alteration of the natural landscape by creating artificial hills that are aesthetically unpleasant.

They somehow can compromise the stability of the tailings. Bromhead (1996) stated that aggregated rates of erosion down the slope of waste deposits result in gullies that can damage

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the embankment and lead to instability of part of the slope. This clearly suggests that gully erosion on the slopes of tailings dumps is associated with visual and environmental impacts.

Authors such as Van As *et al*. (1992); Mizelle *et al*. (1995) and Pierzynski *et al*. (1994) confirmed that air pollution is one of the more evident forms of environmental problems emanating from gold mines. They emphasized that fine-grained tailings materials are generally susceptible to wind erosion. Contaminants in tailings can pollute nearby water bodies. In the study area, the rivers that are found near the abandoned mine sites are Klein Letaba River and Nsama River. These rivers are the major source of water used by many communities for different purposes in the Giyani area. The Department of Mineral Resources (2009) reported that water flowing from dumps during rainy seasons can affect the quality of water in nearby streams and rivers since these water bodies can be polluted. This can also have a negative impact on the natural vegetation around the mine site since the presence of high toxic materials such as heavy metals in soil can hinder plant growth.

Figure 4. 4: The evidence of devastating effect of erosion on the slopes of the tailings dumps of Louis Moore

Toxic Metal Concentration in Gold Tailings

The tailings at Louis Moore were analyzed for Cu, Zn, As, Ni, Pb, Co and Cd. These elements were in the decreasing order of Ni >Zn >Pb>Co >Cu >As >Cd (see Table 4.2). The presence of high concentrations of toxic metals in the environment can have serious health issues due

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to their non-degradative nature which makes them persistent and may have long-term effects on the environment (Fashola *et al*., 2016). The availability of toxic metals in sediments affects the activity of soil micro-organisms, thus affecting nutrient cycling and disease risk (Kalshetty et al., 2014). Moreover, elevated concentrations of toxic metals impact the diversity, population size and the whole activity of bacteria. Water contamination resulting from toxic metals is associated with the increasing deaths of farm animals and humans because of diseases linked to the drinking of contaminated water (Okereafor et al., 2020).

The elements Cu, As, Ni and Pb concentrations ranged from 13 to 558 mg/kg and these values exceeded the South African Soil Quality Standards (SASQS), (2012) permissible levels as shown in Table 4.1. On the other hand, maximum concentrations of Zn, Cd and Co were more than 2 folds lower that the permissible standards, indicating low contamination by these metals. These elements also indicated a narrow variation for the 10 samples analyzed.

Table 4. 1: Basic statistical parameters for Louis Moore

	Concentration (mg/kg)						
Variables	**Cu**	**Zn**	**As**	**Ni**	**Pb**	**Co**	**Cd**
Minimum	20	114	5	503	61	30	0.05
Maximum	23	120	13	558	64	32	0.05
Mean	21	117	9	530	63	31	0.05
Median	21	117	9	530	63	31	0.05
Standard deviation	2	4	6	39	3	2	0.00
SASQS	**16**	**240**	**5.80**	**91**	**20**	**300**	**7.50**

The tailings at Klein Letaba were also analyzed for Cu, Zn, As, Ni and Pb. The dominance of these metals in the tailings was in the increasing order of As>Co >Ni >Cu >Zn >Pb>Cd. The maximum concentrations of Cu, Zn, As, Ni and Pb were found to be more than 3 folds above the maximum permissible limits in natural soils as per the SASQS (2012). This indicated that the tailings material was contaminated by these metals. According to the SASQS (2012), maximum allowable levels of Cd and Co are 7.50 and 300 mg/kg respectively. However, Cd and Co content in the tailings were 0.08 and 138 mg/kg respectively, this shows that the elements concentrations fall below the allowable limits, indicating very low contamination levels by these metals. These results showed a wide disparity and may indicate heterogeneous composition of the tailings material. A similar study conducted by Kamunda *et al*. (2016) showed elevated concentrations of As, Zn and Ni in mine tailings and their vicinity.

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Therefore, contaminations from mine tailings not only affect the tailing sites but can also affect the surroundings and may also impact agricultural soils.

Table 4. 2: Basic statistical parameters for Klein Letaba

Variables	**Concentration (mg/kg)**						
	Cu	**Zn**	**As**	**Ni**	**Co**	**Pb**	**Co**
Minimum	26	33	10	69	15	6	0.01
Maximum	81	465	694	1213	138	109	0.08
Mean	50	101	240	535	49	22	0.05
Median	48	52	73	537	47	10	0.06
Standard deviation	19	133	264	317	35	31	0.02
SASQS	**16**	**240**	**5.80**	**91**	**300**	**20**	**7.50**

In both mine sites, fine particles of tailings were found dispersed into the surrounding environment. Results discussed above confirm that the tailings at these sites are contaminated by toxic metals such as Cu, Zn, As, Ni and Pb. The dissemination of these particles was identified as a health hazard especially to communities living nearby the abandoned mine sites. This is because the pollutants carry dust particles that can be inhaled by humans. Therefore, the tailing dumps at the mine sites are a potential source of contamination and public health hazards. Abdelmalek *et al*. (2007) stated that fine textured tailings can seriously pollute the surrounding land with toxic dust due to wind erosion. Vegetation growing on contaminated soils take up nutrients and some toxic elements from the soil, thus leading to redundant growth, death of the plants and destroyed food source of local people and animals.

4.1.4 Waste Rock Dumps

A relatively small, unprotected, and abandoned waste rock dump was found at Klein Letaba. The rock dump was comprised of materials that had particles ranging from sand to boulders in size. Moreover, the dump was covered by a considerable amount of vegetation. This suggests that the dump supports vegetation growth. As a result of this, the effect of erosion on the slopes of the waste rock dumps was minimal. The main environmental hazards associated with the dump were wind-blown dust which may result in contamination of the site, alteration of the natural landscape and original soil properties. Although the erosion rate associated with the rock dump is not significant, environmental impacts such as sedimentation and contamination of water systems are envisaged. Sedimentation reduces the quality of water, posing a threat to aquatic life and the entire aquatic system. According to Eroglu *et al*. (2010), the deposition of sediment lowers the storage capacity and life span of reservoirs as well as river flows. Moreover, leachate from waste rock dumps is the potential source of ground and surface water contamination as well as the pollution of soil.

Maximum concentrations of As, Co and Ni within the rock dump samples in Klein Letaba were more than 12 times higher than the Abundance of Elements in Average Crustal Rocks (AEACR) of 2.30 and 75 mg/kg respectively as recommended by Taylor (1964). Cu, Zn, Cd, Pb and Co concentrations were lower than the AEACR standards. This suggested that the rock dumps are highly enriched in As, Co and Ni indicating high contamination by these metals. A similar study conducted by Gbadebo and Ekwue (2014) in Southwestern Nigeria showed high concentrations of Cd, Pb, Zn and Cu when compared to the AEACR standards. This could be due to the natural/ geogenic occurrence of the major host rocks. Contaminants in mine wastes may affect human health and may lead to the impairment of drinking water and other water resources by natural leaching transport and sediment transport (EPA, 1998). According to DMR (2009), one of the biggest negative impacts of abandoned mines is that a significant portion of South Africa's land is locked up in mine dumps which turn to affect the economic development of where these dumps are found.

Figure 4. 5: A relatively small waste rock dump in Klein Letaba Mine

4.1.5 Abandoned Mine Infrastructure

Abandoned mine infrastructure and old machinery found in the mine sites were identified and documented. This section describes the state and the problems of the abandoned old machinery and dilapidated buildings found in the study area.

Old Buildings

Abandoned mine buildings and infrastructure are usually hotspots for illegal miners. In most cases, abandoned infrastructure is stolen and sold by illegal miners and buildings are vandalized. According to Steenkamp and Mostert (2012), illegal miners remove old and derelict infrastructure. Steel infrastructure is stripped off and sold for cash. The vandalized buildings and infrastructure eventually deteriorate and may collapse at any time. The old buildings at Louis Moore and Klein Letaba were found to be presenting several safety risks. They also affect the aesthetic appearance of the mine landscape as they appear with contracting colors with the surrounding landscape. These buildings have been damaged and vandalized by artisanal miners, this was evidenced by the absence of windows and door frames along with roofing materials (Figure 4.6b), the walls had developed extensive cracks, and, in some areas, the walls had collapsed (Figure 4.6a). The floors are deteriorating with time and the buildings may collapse at any time which may lead to physical injuries or death. Moreover, illegal mining activities are being carried out around these structures, small excavations, and piles of fresh soil next to the buildings were evident. The digging around the foundations of these buildings affects their structural integrity and may destroy even more buildings.

All the buildings found at Louis Moore were approximately 2.8 m high, they had cracks and unstable walls which can fall any time. Dilapidated buildings in Louis Moore and Klein Letaba mine sites occupied an estimated area of 1000m^2 and 1200m^2 respectively. A double storey building around Klein Letaba mine was found with walls that attained an approximate height of 5.5m. This was linked to environmental impacts as the area occupied by these buildings hinder vegetation growth and other economic land uses. It is also important to note that these mines are found near the surrounding communities, as such, children enter these buildings

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without supervision. This also aggravates the safety hazards associated with the mine sites. In addition to this, illegal mining activities are underway. A study by the Canadian Centre for Occupational Health and Safety (2009) showed that unmaintained structures at abandoned mine sites can be dangerous as they may easily collapse. Furthermore, these structures are associated with socio-economic issues as they may be used by criminals as hiding places. Abandoned buildings attract crime and disorder, they provide cover and opportunities for criminals as no one is present to guard and maintain order (Shane, 2012).

Figure 4. 6: The collapsed (a) and (b) standing dilapidated buildings in abandoned mine sites

Silos

Abandoned silos of approximately 12m in height and 4m in diameter were found in the mine sites as shown in Figure 4.7. These silos have cracks and rust on their walls. Several shallow excavations by illegal miners around these structures were evident. This may weaken the foundation of these structures, causing structural failure and bending and may eventually collapse. Moreover, these structures ruin the aesthetics of the area, and the land they occupy hinders vegetation growth which negatively affects biodiversity in the area.

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Figure 4. 7: Abandoned silos and excavations by artisanal miners around these structures

Abandoned Machinery and Processing Facilities

Agitation tanks and ball mills are among the abandoned machinery and processing plant facilities found at Louis Moore and Klein Letaba mines (Figure 4.8). The agitation tanks were mounted on 2m high concrete stands designed to support the tanks. The tanks were estimated to be 4m high and 2m wide. Illegal miners believe there are residues of gold in and around these facilities, as such they dig around old processing facilities to recover the residues. Old processing plants are linked to spillages that can cause health and environmental issues since they are corroded and may have cracks/small openings. Due to the excavations dug by illegal miners, the ground around these structures is unstable, as such, these features are prone to failure or collapse. This poses risks of injury and/or death to the illegal miners, trespassers, and anyone in contact with these structures.

Three water reservoirs were identified at Klein Letaba. These reservoirs provided water used for gravitational floating process during the gold processing stage when the mine was operational. In terms of dimension, they were found to be approximately 1.6m high and 7.5m in diameter but piles of soil were heaped around the reservoirs by illegal miners. The fact that these reservoirs are open to the public make it easy for people and animals to be tempted to drink and/or get in contact with water that accumulates in these structures during rainy days. This can potentially affect the health of people drinking the water as it is contaminated, dermal contact may lead to skin related and other health issues.

(a) **(b)**

Figure 4. 8: Abandoned (a) agitation tanks and (b) ball mills at the mine sites

4.2 Determining Toxicity Levels in Soils

Soil assessment was carried to evaluate environmental and ecological pollution posed by the toxic metals analyzed in this study. Geo-accumulation Index, Contamination Factor, Pollution Load Index and the Potential Ecological Risk Index were employed to evaluate risks inherent at the mine sites associated with distribution of toxic metals in the soil and the surrounding environment. The South African Soil Quality Standards and the United States Environmental Protection Agency are put into comparison.

4.2.1. Metal Distribution

The minimum, maximum, median, standard deviation and mean concentrations of Cu, Zn, As, Ni, Cd, Pb and Co in the soil samples collected from Louis Moore and Klein Letaba abandoned gold mines are summarized in Table 4.1 and Table 4.2 respectively. The elements dominance at Louis Moore was in the order; Ni >Zn >Pb>Cu >Co >As >Cd and the increasing trend of averages of metal levels at Klein Letaba was in the decreasing order of Ni>As >Zn >Co >Pb>Cu >Cd.

The mean concentrations of the toxic metals in the soil at both mine sites showed wide variations between samples, and this was indicative of the heterogeneous distribution of toxic metals around the mine sites. Cd and Ni mean concentrations had a range of 0.08 and 559 mg/kg at Louis Moore. On the other hand, Cd and Ni mean concentration at Klein Letaba ranged from 0.05 to 535 mg/kg. A similar study conducted by Muzerengi (2015) at Louis

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Moore showed a much more similar pattern of concentration levels. It may be concluded that the prevalence of these metals at the study site may have originated from beneficiation of Au during mineral processing.

Table 4. 3: Basic statistical parameters for the distribution of metals in soil at Louis Moore

Variables	Toxic metals (mg/kg)						
	Cu	**Zn**	**As**	**Ni**	**Cd**	**Pb**	**Co**
Minimum	7.0	34.0	0.8	457.0	0.01	33.0	28.0
Maximum	50.0	240.0	28.0	706.0	0.16	111.0	38.0
Mean	30.0	143.0	16.0	559.0	0.08	78.0	31.0
Median	34.0	55.0	20.0	516.0	0.07	91.0	29.0
Standard deviation	22.0	103.0	14.0	130.0	0.07	40.0	6.0

Table 4. 4: Basic statistical parameters for the distribution of metals in soil at Klein Letaba

Variables	Toxic metals						
	Cu	**Zn**	**As**	**Ni**	**Cd**	**Pb**	**Co**
Minimum	26.0	33.0	10.0	69.0	0.01	6.0	15.0
Maximum	81.0	465.0	694.0	1213.0	0.08	109.0	138.0
Mean	50.0	101.0	240.0	535.0	0.05	22.0	49.0
Median	48.0	52.0	73.0	537.0	0.06	10.0	47.0
Standard deviation	19.0	133.0	264.0	317.0	0.02	31.0	35.0

4.2.2 Soil Assessment Using the South African Soil Quality Standards

At Louis Moore, Cu, As, Ni, Pb and Cd concentration exceeded the maximum permissible limit recommended by the South African Soil Quality Standards (SASQS) by more than 3 folds and this being 16, 6, 91, 8 and 20 kg/mg respectively. However, the concentration of Zn was equal to the maximum allowable limit of 240 mg/kg. This indicated that the soil around the mine site was highly contaminated by Cu, As, Ni, Pb and Cd, but contamination by Zn was minimal. The maximum allowable standards for Co were not available at the time when this study was conducted. Figure 4.9 shows the toxic metal concentration levels of Louis Moore soils and the maximum permissible standards recommended by the SASQS.

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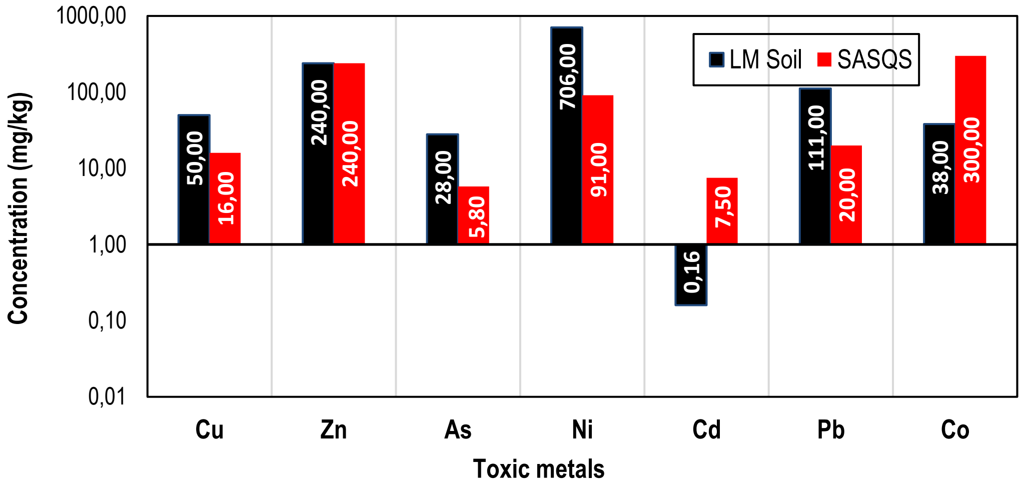

Figure 4. 9: Concentration of toxic metals in the soil and the SASQS

The concentration of Cu, Zn, As, Ni, Cd and Pb at Klein Letaba was more than 2 times higher than the threshold concentration in natural soils, with As concentration of 694 mg/kg and this being 120 times more than the SASQS of 6 mg/kg (see Figure 4.10). This showed that the soil around the mine site is strongly contaminated by these elements.

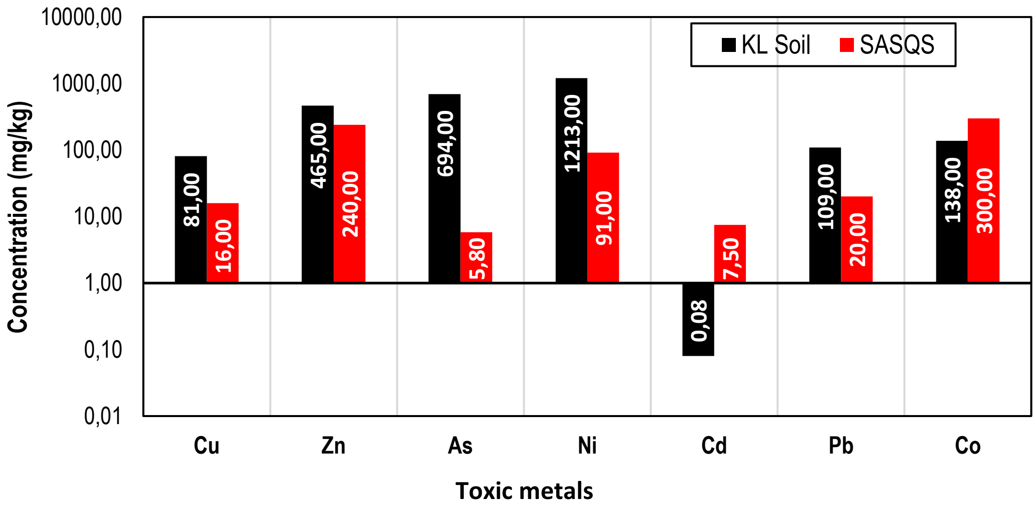

Figure 4. 10: Concentration of toxic metals in the soil and the SASQS

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4.2.3 Soil Contamination Assessment using the South African Soil Quality Standards

At Louis Moore, Cu, As, Ni, Pb and Cd concentration exceeded the maximum permissible limit recommended by the South African Soil Quality Standards (SASQS) by more than 3 folds and this being 16.0, 6.0, 91.0, 8.0 and 20.0 kg/mg, respectively. However, the concentration of Zn was equal to the maximum allowable limit of 240 mg/kg. This indicated that the soil around the mine site was highly contaminated by Cu, As, Ni, Pb and Cd but the contamination by Zn was minimal. The maximum allowable standards for Co were not available at the time when this study was conducted.

The concentration of Cu, Zn, As, Ni, Cd and Pb at Klein Letaba was more than 2 times higher than the threshold concentration in natural soils, with As concentration of 694 mg/kg and this being 120 times more than the SASQS of 6 mg/kg. This showed that the soil around the mine site is strongly contaminated by these elements.

4.2.4 Soil Contamination Assessment using the USEPA

Background values of toxic metals of the soil samples collected at Klein Letaba and Louis Moore mine sites were evaluated by comparison with the soil quality guidelines proposed by USEPA (2002) and Steyn *et al.* (1996) as shown in Table 4.3. Furthermore, concentrations of toxic metals in soils from the study area were compared with the permissible limits in different countries (see Table 4.3).

Table 4. 5: The guidelines in other countries and background values in the Giyani area

Country		Toxic metals (mg/kg)						
		As	**Cd**	**Cu**	**Ni**	**Pb**	**Zn**	**Co**
Australia		20	3	100	60	300	200	-
United States of America		0.11	0,48	270	72	200	1100	-
Germany		-	1,5	60	50	100	100	-
Present Study	Klein Letaba	240	0,08	81	1213	109	465	138
	Louis Moore	28	0,16	50	706	111	240	38

The background values of toxic metals were applied as reference values in this study. These background values were computed from surrounding areas which were deemed uncontaminated. The maximum concentrations of Zn, As, Ni and Pb were 240; 28; 706 and

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111 mg/kg respectively in Louis Moore and these values were found to be more than 2 times higher than the background values. On the contrary, maximum concentrations of Cu and Co were lower than the background values of 79 and 48 mg/kg, respectively. The concentration of As, Cu, Ni, Pb, Zn and Co were extremely higher than the background values of 13.65, 78.48, 302.79, 5.09, 74.57 and 48.05 mg/kg, respectively.

When compared to permissible limits of other countries as reported by Steyn *et al*. (1996), Zn concentration was found to be higher than Germany and Australia and this being 100 and 200 mg/kg respectively. However, this was significantly lower than the maximum allowable levels of 1100 mg/kg in USA. The high Zn content in this study may be a result of sources such as sphalerite (ZnS) and enrichment due to mineral exploitation.

Ni concentration significantly exceeded tolerable levels in Germany, Australia, and USA of 50, 60 and 72 mg/kg. Ni is strongly adsorbed by soil and there are many adsorbing species that affect the extent to which nickel is adsorbed. A similar study conducted by Bowman (1999) showed high concentrations of Ni in soils and the author affirmed that most soils have an extremely high affinity for Ni and once sorbed, it is difficult to desorb.

The permissible limits for As in Germany were not available at the time when this study was conducted, however, the maximum concentration for As recorded at Louis Moore exceeded the threshold values in Australia and USA of 20 and 0,11 mg/kg respectively. This may suggest that the amount of As is bioavailable in significant amounts to the environment around the two mines studied. Amadi *et al*. (2010) confirmed that Arsenic is highly carcinogenic and has no nutritional value for both plants and animals. The elements found in high concentrations in the studied soils can be taken up by the plants and may ultimately enter the food chain causing significant health impacts in the human body. Therefore, remedial strategies must be identified for the soils in the study area. It can be concluded that according to USEPA, Louis Moore soils are not polluted by Cd, Cu, Pb and Zn but highly polluted by As and Ni. The present study shows that As and Ni concentration in Klein Letaba greatly exceed the regulatory standards of toxic metals in natural soils for Australia and USA. The concentration of Ni (706 mg/kg) significantly exceeded the permissible levels in Germany.

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4.2.5 Evaluation of soil status using Geo-Accumulation Index

The geo-accumulation Index (Igeo) was used to compute metal contamination level in soils around Klein Letaba and Louis Moore mines. This index was assessed using the values proposed by Muller (1969). The Igeo values in soil around LM was found to be in the decreasing order of As> Zn > Cd > Ni > Co > Cu >Pb, whilst at Klein Letaba it was in the increasing order of Zn > Cd > As >Pb> Cu > Ni > Co as shown in Figure 4.9.

Based on the Muller scale, Cu, Ni, Cd, Pb and Co in the soil at KL showed extremely low degree of contamination, thus were put in the Igeo Class 0. Arsenic can be considered a strong pollutant in the Klein Letaba soil with an Igeo value of 3.96 which falls in Class 4. The Igeo value of Zn was in Class 1. This suggested that the soil is uncontaminated to moderately contaminated by this metal.

The calculated results of Igeo in the soil around Louis Moore indicated that As, Cd, and Pb fell in Class 1, thus suggesting that the soil is uncontaminated to moderately contaminated by these metals. Zinc was found to be in Class 2 with an Igeo value of 1.05, whilst Cu, Ni and Co Igeo values were found to be in Class 0. In this case, the Igeo values of -0.13 to -2 suggests that the soil at LM is not contaminated by these metals. It can be concluded that KL and LM soil is not contaminated by Cu, Ni and Co. However, KL soil is moderately to strongly contaminated by As and Zn.

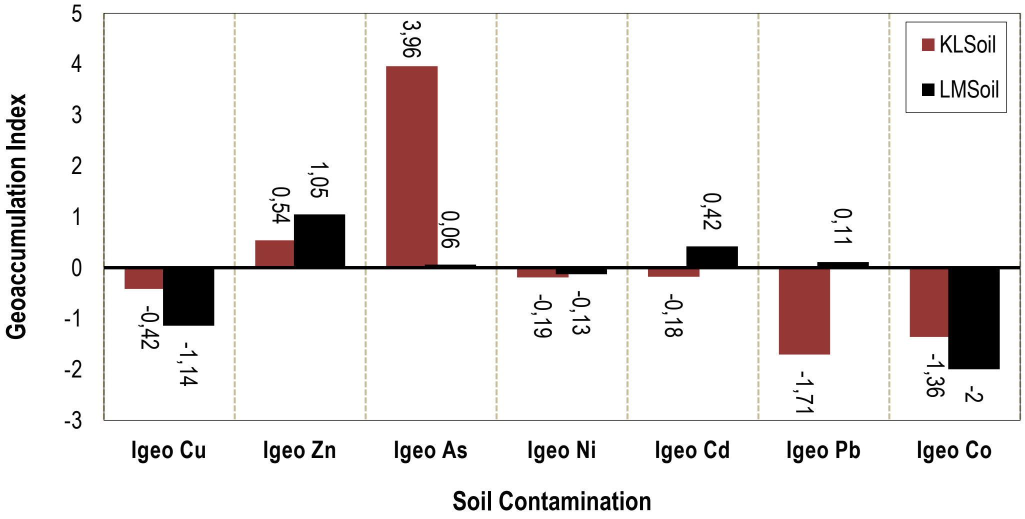

Figure 4. 11: The metal pollution of the soil from the abandoned mine sites

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4.2.6 Contamination Factor and Pollution Load Index of the soil

The Contamination Factor was assessed based on the classification proposed by Bonnail *et al*. (2016) and Hakanson (1980). According to this factor, soil samples in Klein Letaba were in three contamination classes which were low, moderate, and very high. Co and Pb concentration were less than 1(that is, 0.60 and 0.5 respectively) and this indicated low contamination. The determined CF values for Cu, Zn, Ni and Cd showed that the soil in the mine sites was moderately contaminated by these metals. This is because the CF values of these metals ranged between 1.1 and 2.2, that is CF<3. Furthermore, the obtained CF value of 23.3 for Ni indicated very high contamination. Similar results were reported by authors such as Kim *et al*. (2005); Lim *et al*. (2009); McGregor *et al*. (1998) and Johnson *et al*. (2000) in abandoned mine sites of Korea.

However, at Klein Letaba, the obtained CF values indicated that the soil was moderately contaminated with As, Ni, Cd and Pb (As =23.33; Ni =1.37; Cd=2.01 and Pb=1.62), considerably enriched with Zn, the CF value being 3.1 but showed no contamination by Cu and Co, with CF values of 0.7 and 0.4 respectively. Similar contents of Pb and Zn were reported by Tang *et al*, (2017) in China. The PLI calculated from the CF showed that the soils at KL and LM were contaminated by the studied metals, as shown in Figure 4.10. The PLI values for soil at LM and KL were 2.4 and 5.2. This suggested that the soil quality at the two mine sites is deteriorating since PLI values obtained were greater than 1.

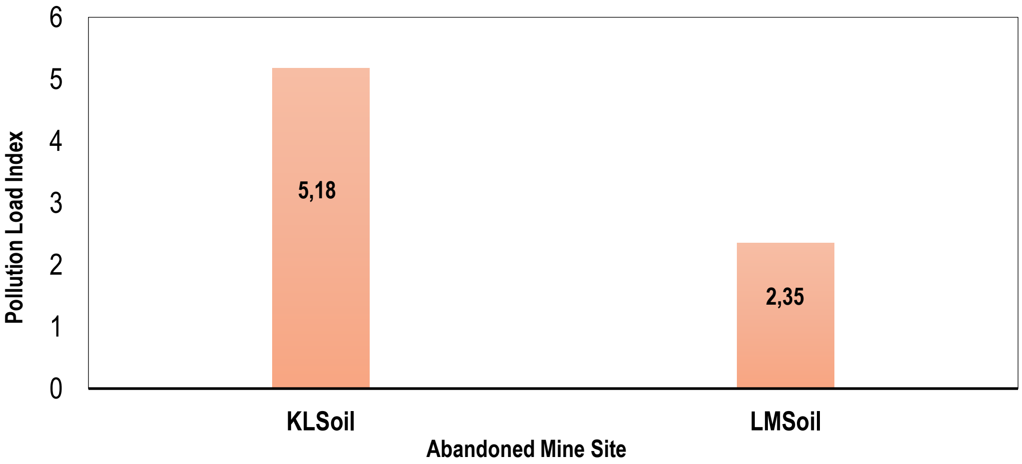

Figure 4. 12: Pollution Load Index for soil at Klein Letaba and Louis Moore gold mines

4.2.7 Potential Ecological Risk Index

The PERI assessment method developed by Hakanson (1980) was employed in this study to evaluate the overall ecological risks of toxic metal pollution in soils from Klein Letaba and Louis Moore mines. The potential ecological risk indices at Klein Letaba were in the decreasing order of As > Cd> Ni> Cu>Pb> Zn. The potential ecological risk factor (Er) values for Zn, Cu, Pb and Ni were found to be lower than 40 which indicated that the sites had low ecological risk of these toxic metals to the surrounding ecological systems. However, Cd has a moderate ecological risk of 40, whilst As indicated a severe Er value of 233.3.

In Louis Moore mine, the potential ecological risk indices were found to be in the decreasing order of Cd> As>Pb> Ni> Cu> Zn. The Er values for Zn, Cu, Pb, As and Ni were below 40, showing a low ecological risk for the surrounding water systems and other ecological components in the area. Cd posed a moderate ecological risk with an Er value of 63. Moreover, the toxic metals under investigation in the soil showed a low ecological risk to the environment with the exception of Cd and As at both mines and consequently posed a moderate to very high ecological risk. It can be concluded that Cd and As are the key influence factors to pose the potential ecological risk in the study area.

The overall risk index (RI) value computed for Klein Letaba abandoned mine site was 289.8. According to the criteria for degrees of ecological risks, the potential ecological risk levels of the soil around the abandoned mine tailings and rock dumps in the mine site fall within Level D and the corresponding ecological damage is very high. Contrarily, the RI value for Louis Moore was 100.15, indicating high potential ecological damage caused by toxic metals in soil. Moreover, the soil potential ecological risk levels around the mine site fall within Level C. Results obtained in this study showed that the soil around the potential contamination sources, which are tailings and rock waste dumps, have been polluted to different levels and appropriate prioritization measures should be taken to control and prevent further ecological deterioration.

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4.3 Discussion of Results

The chemical analysis results obtained for Louis Moore and Klein Letaba showed significant disparities in toxic metal contamination levels around the abandoned mine features. When comparing the concentrations of toxic metals determined for Louis Moore with the SASQS, the soils were contaminated by Cu, Zn, As, Ni, Pb, Cd and Co. However, all the toxic metals analyzed at Klein Letaba exceeded the maximum allowable levels. Therefore, both mine sites are contaminated by the toxic metals analyzed in this study, apart from Zn at Louis Moore. A study conducted by Cheng (2003), showed increased concentrations of Cd, Cu, Pb, and Zn. These contaminants pollute drinking water and food and threated human health.

Toxic metal concentration levels at the two mine sites showed a similar trend when compared against the USEPA threshold values, that is, permissible levels of toxic metals in soils for Australia, USA and Germany. The maximum concentrations of toxic metals at Klein Letaba and Louis Moore were also compared with the average background values for the Giyani area. Maximum concentrations of As, Ni, Pb and Zn at Louis Moore and Klein Letaba were significantly higher than the background values recorded. Concentration levels of Cd and Cu were lower than the background. This showed that the two mine sites are not contaminated by Cd and Cu, but are strongly contaminated by As, Ni, Pb and Zn. A study undertaken by (Fagbenro *et al*., 2021) in Nigeria to determine the concentration of toxic metal contaminants in Igun, Ijana-Gada and Igbadae gold mining sites revealed that the levels of toxic metals in soils exceeded the background concentrations.

Geo-accumulation index and Ecological risk index values determined for Louis Moore were low for As, Cu, Ni and Pb. However, different results were obtained for the two indices for Zn and Cd as Louis Moore is moderately contaminated by Zn in terms of Igeo, but the same toxic metal poses low ecological risk according to PERI. At Klein Letaba, the Igeo and PERI levels for As, Cu, Ni, Cd and Pb were similar, i.e., low for both indices, but contamination by Zn was moderate as per Igeo and the ecological risk was low according to PERI.

The total risk index values computed for Louis Moore and Klein Letaba ranged from high to very high, whilst the PLI values suggested that Louis Moore is moderately polluted, and Klein Letaba is highly polluted. Hence, these two indexes are inter-related and show similar

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contamination levels. Similar studies conducted by Fagbenro (2021) showed PLI values suggesting moderate to high contamination in Igun, Ijana-Gada and Igbadae.

4.4 Development of a Conceptual Site Model

The conceptual site model developed in this study is shown in Figure 4.13. The main aim of such a model is to establish critical parameters and their relationships towards the development of the integrated approach for prioritizing abandoned mine features for rehabilitation in the study area. This model identifies the sources of contamination or hazards, pathways, and potential impacts to receptors, as such, this informed field data collection since all important components of the model were identified beforehand.

Abandoned mine features identified at the two mine sites have the potential to cause harm, potential damage or adverse health effects on people, animals, and the environment. As such, these features were classified as sources of contamination or hazards. Receptors are the people, animals, ecosystems, or protected areas that may be affected by a release of waste from the mine site, and pathways are exposure routes through which the source may reach the receptor.

The hazards identified were classified into physical, chemical, and environmental hazards based on their impacts. Hazards with the potential to cause bodily harm, injuries or death thus resulting into health and safety impacts were classified as physical hazards. On the other hand, hazards linked to environmental and ecological degradation were classified as environmental hazards. Hazards associated with toxic metal contamination in the environment were classified as chemical hazards. Hazard scores were then assigned to the sources, pathways and potential impacts based on the number of mine features, current state of the mine features, likelihood of occurrence of hazards and severity of the impacts. These scores were combined to establish the total or overall hazard score of each mine feature and mine site.

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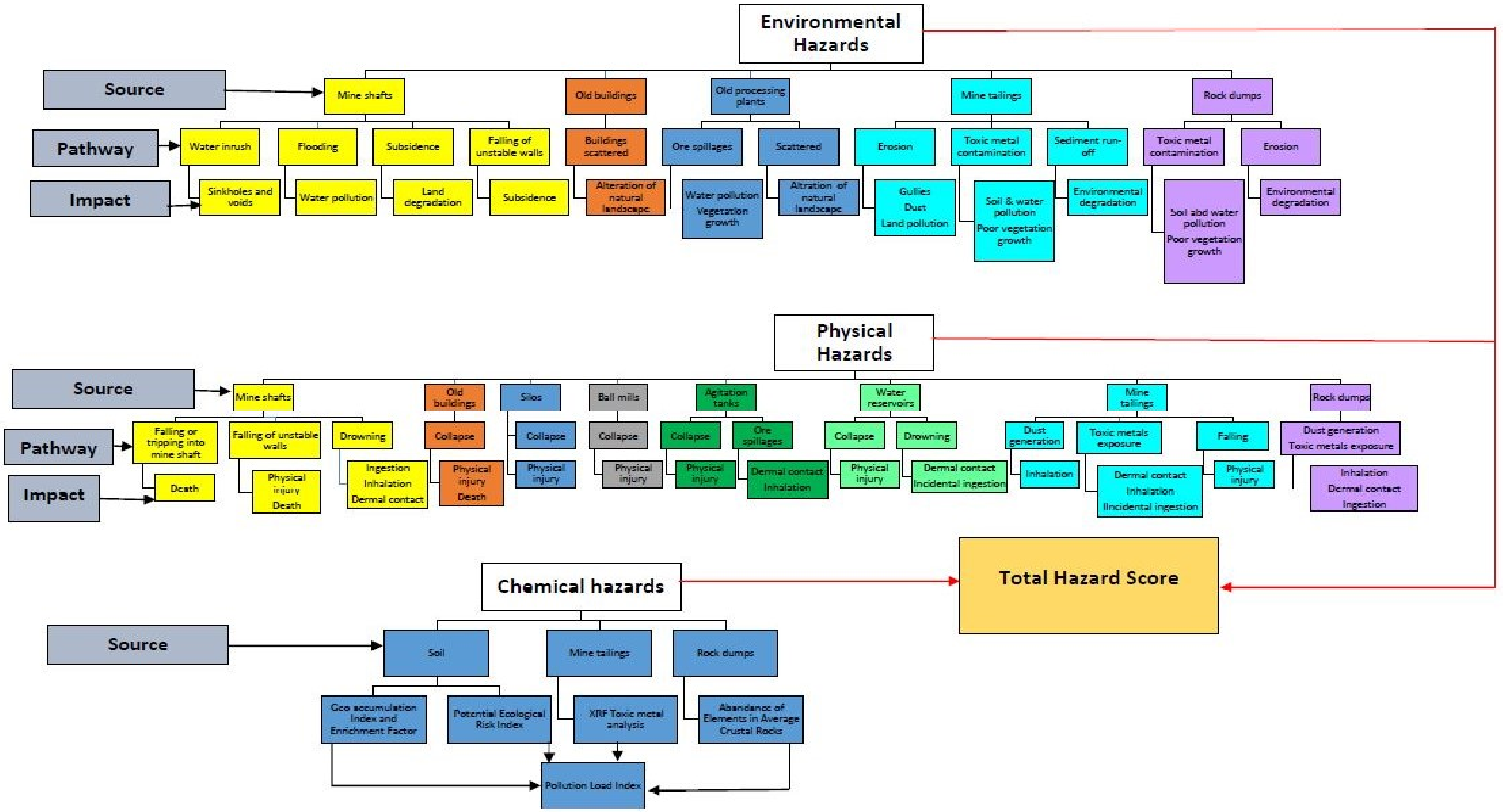

Figure 4. 13: Conceptual site model developed in this study

4.5 Summary of the Chapter

Abandoned mine features identified at Louis Moore and Klein Letaba were described and characterized based on their potential physical, chemical, and environmental hazards and risks. Klein Letaba Mine site was found to have more abandoned mine features when compared to Louis Moore Mine. Moreover, some features at Louis Moore were rehabilitated whilst all features at Klein Letaba were not rehabilitated and continue to deteriorate. Furthermore, the two abandoned mine sites are neither fenced nor barricaded and are located closer to communities, allowing uncontrolled access, thus increasing exposure to hazardous features and elements.

Toxic metal analysis results obtained showed different levels of contamination in the two mine sites. The SASQS and USEPA yielded different results as the maximum permissible levels vary, however, some toxic metal contamination levels were similar or fell within the same class of contamination. Furthermore, toxic metal concentration levels varied with the different indexes applied in this study, but some indexes showed the same trend and contamination levels.

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CHAPTER FIVE: PRIORITIZATION OF ABANDONED MINE FEATURES FOR REHABILITATION

Based on data obtained from field characterization of the abandoned mine features, the physical and environmental hazards of the features were quantified using a scoring and ranking approach. This was done to prioritize the mine features for rehabilitation. The results obtained from the physical and environmental hazards scoring and ranking process are presented in this chapter.

5.1 Ranking of Physical and Environmental Hazards

The abandoned mine features identified at the mine sites are scored based on their associated hazards. This section presents the physical and environmental hazard scores determined for the abandoned mine features, and ranks them in terms of their nature, severity and seriousness. This is essential for establishing mine features that must be prioritized for rehabilitation.

5.1.1 Abandoned Mine Shafts

The physical risks considered in the scoring and ranking of the abandoned mine shafts were physical injury, death resulting from falling into the shaft and drowning in water filling underground workings, falling of unstable walls/ rock falls, ingestion of contaminated water, inhalation of toxic gases and dermal contact. These were identified as the potential physical hazards associated with abandoned mine shafts during field investigations and were further informed by existing literature.

Louis Moore has three mine shafts. One of the shafts was found closed with concrete slabs and timber platform, while the other two shafts were open (not rehabilitated). The closed mine shaft was scored separately from the other two shafts since the physical risks associated with these shafts vary greatly. The only pathway linked to the closed shaft was falling of unstable walls since closed shafts are prone to failure and collapsing if walls are unstable, depending on the treatment or closure technique applied. In this instance, the obtained physical hazard score for this shaft was 0.04 which indicated extremely low hazards.

The other two shafts at Louis Moore were scored and ranked together since they were both open and shared similar risks and hazards. Open shafts present risks of people and animals falling into them and sustaining serious body injuries or possible drowning in the water filling the mine workings. The computed score for these shafts was 9.60 which led to the shafts classified to be having high physical hazards. This suggested that the impact of open shafts on the safety of people accessing or residing closer to the abandoned mine is very high. According to the United States Forest Service (2013), there is a greater potential of falling into open shafts as the entire area is often unstable and may cave into the shaft at any time. This may cause serious injury and death, even if it is for a short distance. Old mine workings are potentially unstable and can cave in at any time. The effects of blasting when the mine was still operational followed by the effects of weathering can weaken what was once strong.

There were four mine shafts at Klein Letaba, and they were all found open. Their computed physical hazard score was 32.00. This score indicated that the shafts had extremely high physical hazards. The risks of these shafts were like those established in Louis Moore mine which include risks of people and animals falling into them and sustaining serious body injuries or possible drowning in the water filling the mine workings. It can be seen in Figure 5.1 that the physical hazard score of the shafts at Klein Letaba Mine exceeded that of the shafts in Louis Moore mine. This was attributed to the higher number of shafts at Klein Letaba as opposed to Louis Moore. Moreover, it is important to note that all the four shafts at Klein Letaba were open and one mine shaft at Louis Moore was closed, suggesting lesser physical hazards and risks.

According to the ranking technique developed in this study, the abandoned mine shafts at Klein Letaba can be classified as having high to extremely high physical hazards. This then translates that the assessment at this mine site yields significant risks, and these risks can cause serious injuries and death. On the other hand, scores computed for abandoned mine shafts at Louis Moore suggest that the physical hazards associated with this feature are low.

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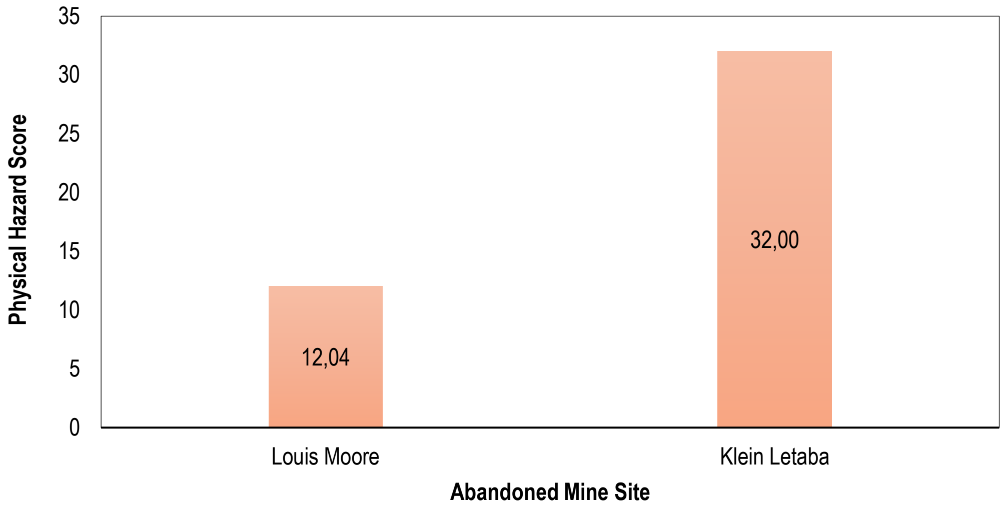

Figure 5. 1: Physical hazard scores of the abandoned mine shafts

Environmental hazards linked to abandoned mine shafts at Klein Letaba and Louis Moore were water inrush into the shafts, flooding, subsidence, and falling of unstable walls/grounds. These may have environmental as well as visual and aesthetic impacts. The environmental hazard score computed for the abandoned mine shafts at Louis Moore was 14.90 and 19.80 at Klein Letaba as shown in Figure 5.2.

According to the scoring criteria employed, the potential environmental impacts associated with the abandoned mine shafts at the two mine sites are extremely high as they exceed a score of 10. However, potential hazards are lower at Louis Moore when compared to Klein Letaba. This may be attributed by the evidence of ground subsidence at Klein Letaba, and subsidence was not evident at Louis Moore. The potential effects of subsidence include contamination of groundwater, and this may lead to alteration of hydrological pathways.

A study conducted by Heath and Engelbrecht (2011), indicated that ponding of water in subsidence basins lead to increased groundwater recharge. Moreover, groundwater circulating through mining cavities becomes polluted and discharges into the natural environment contaminating wetlands and streams. This then confirms that the potential environmental and visual impacts of subsidence in abandoned mine sites may result in highly disturbed landscapes, thus the land affected by subsidence cannot be developed or used for other economic activities.

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The water inrush into the mine shafts may cause flooding and formation of sinkholes and voids. This may in turn result in contamination of nearby water systems, land degradation and subsidence.

Figure 5. 2: Environmental hazard scores for abandoned mine shafts

5.1.2 Old Buildings

The physical hazard identified for old and dilapidated buildings at Klein Letaba and Louis Moore was their unstable or falling walls. The buildings were found damaged and deteriorating, some of the walls had collapsed, filled with extensive cracks and unstable. Some walls were still standing, but they had serious cracks which pose significant hazards to both people and animals. The floors of the fractured buildings in both mine sites had weakened and deteriorated. As such, risks of collapse of the walls of these buildings is anticipated because the walls of the buildings showed deep and extensive cracks that make them extremely unstable and the weakened floors may in turn weaken the entire building and may collapse at any time causing injuries or death.

The buildings are in close proximity to communities (i.e., approximately 500m from residents), people have access to the buildings since they are not fenced, allowing easy access. Studies conducted by authors such as Steenkamp and Mostert (2012) have shown that abandoned mine buildings fall prey to illegal miners who strip and remove window frames, door frames and other equipment they find handy or useful. Once all the valuable material is stolen or removed, illegal or artisanal mining activities may be convened on site. These buildings and structures remain unused for long and are subject to vandalism, this may lead to collapse or damage of the buildings.

The physical hazard score of the old buildings was computed and found to be 0.96 and 0.64 at Louis Moore and Klein Letaba abandoned mine sites respectively. These scores suggested that the risks of physical body injuries due to collapse by such buildings were minimal. Figure 5.3 shows the physical hazard scores for abandoned mine buildings at the two mine sites.

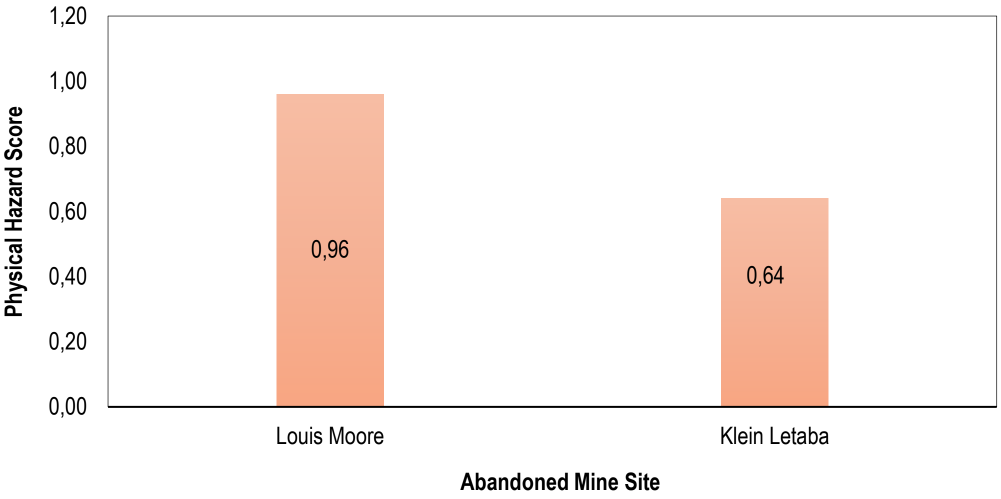

Figure 5. 3: Physical hazard scores for abandoned mine buildings at the mine sites

The environmental hazard scores obtained for old mine buildings was 0.50 at Louis Moore and 0.60 at Klein Letaba (Figure 5.4), indicating low environmental risks that may result from this feature. The buildings in both sites are scattered, dilapidated, filled with cracks and some are collapsing. This may lead to alteration of the natural landscape and has visual and aesthetic impacts. These features may also hinder vegetation growth in these areas, thus presenting environmental impacts and loss of biodiversity.

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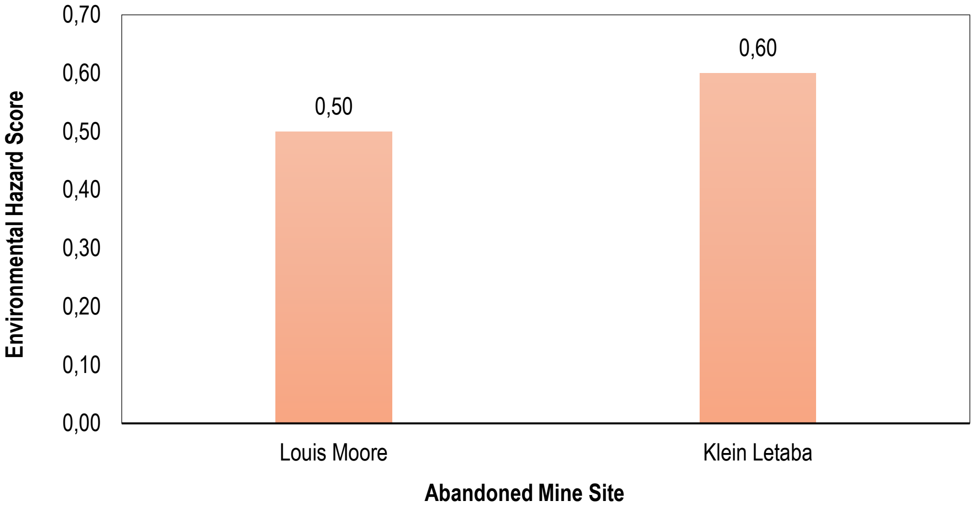

Figure 5. 4: Environmental hazard scores for abandoned mine buildings at the mine sites

5.1.3 Abandoned Mine Infrastructure

The determined physical hazard score for abandoned silos in both mines was 0.96. This score showed that the impacts associated with these features are moderate. Potential collapse of these structures was identified as the major physical risk of these structure. These structures are prone to collapse at any time since they are old and not maintained, and excavations from illegal mining activities around these structures with the aim of recovering remnants of gold that spilled during actual operation of the mine. Moreover, people residing nearby, and artisanal miners have full access to the mine sites, and this suggests that they can be harmed or affected by the hazards posed by these features.

The risk associated with ball mills at Klein Letaba was potential collapse of the structure which may lead to physical injury to people and animals. These structures were found corroded and on concrete stands which the artisanal mines have dug around them, thus making them weaker to effectively support the structure. This may have safety impacts. However, the scoring system employed indicated that the risks of collapse at the mine site are low as the physical hazard score computed was 0.96. There were no ball mills at Louis Moore.

Physical hazard scores of 0.64 were computed for agitation tanks at the two mine sites. The hazards associated with the agitation tanks were physical injury resulting from collapsing of

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the structure. This is because the artisanal miners digging around these structures in search of ore residues weaken the foundation and ground around the agitation tanks which may lead to detachment of the supporting structures. There is a risk of artisanal miners getting injured and encountering toxic metals such as Pb, Cu, Zn, Co, Ni, As and Cd. These toxic metals were found to be contaminating the soil around abandoned mine features at both mine sites during toxic metal analysis. Therefore, the risk of physical injury, inhalation and dermal contact are high.

The physical hazard score computed for water reservoirs at Klein Letaba was 3.36. The main risk linked to water reservoirs was drowning. These water reservoirs are open, artisanal miners and the community have access to these mines including kids who play around such structures without supervision, as such drowning can potentially result. This can cause physical injuries, dermal contact and incidental ingestion of water filling the reservoir during drowning and may cause health impacts. According to the physical hazard score computed for this feature, risks of drowning and other physical hazards are moderate. Figure 5.5 shows the physical hazard scores computed for abandoned mine infrastructure at Klein Letaba and Louis Moore.

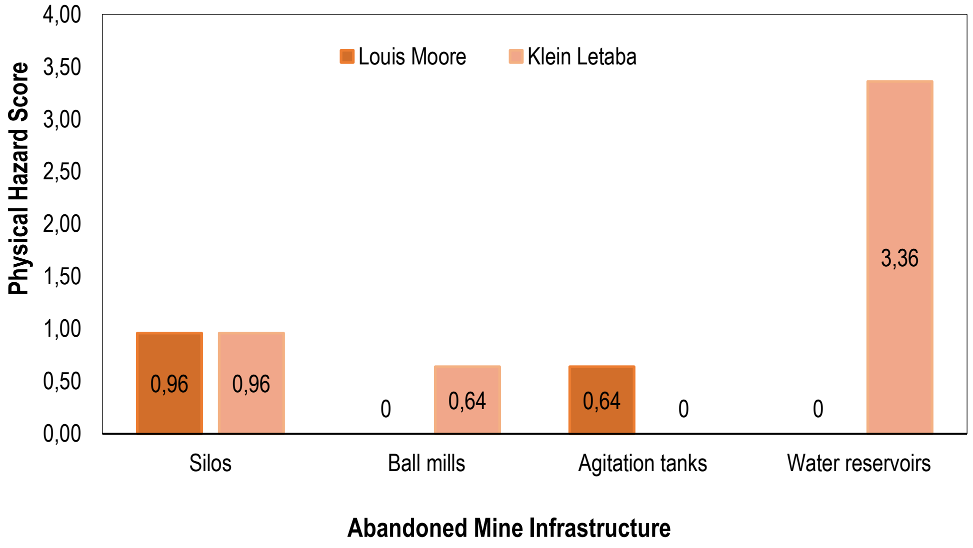

Figure 5. 5: Physical hazard scores for abandoned mine infrastructure

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Environmental hazards associated with old processing plants or abandoned mine infrastructure were computed holistically because the features shared similar potential environmental risks and impacts, as such they were not isolated. Old processing plants have a potential to cause environmental impacts through soil contamination by toxic metals that spilled or leaked when the mine was operational, and these metals were leached into the soil. This may lead to pollution of nearby water systems or sources and may also affect vegetation growth. These features were scattered around both mines and affect the aesthetics of the area. Moreover, these structures hinder vegetation growth and limit biodiversity as nothing grows where these features are mounted. The computed environmental hazard score for old processing plants was 6.80 for both Louis Moore and Klein Letaba as shown in Figure 5.6, suggesting moderate potential environmental risks relating to these mine features.

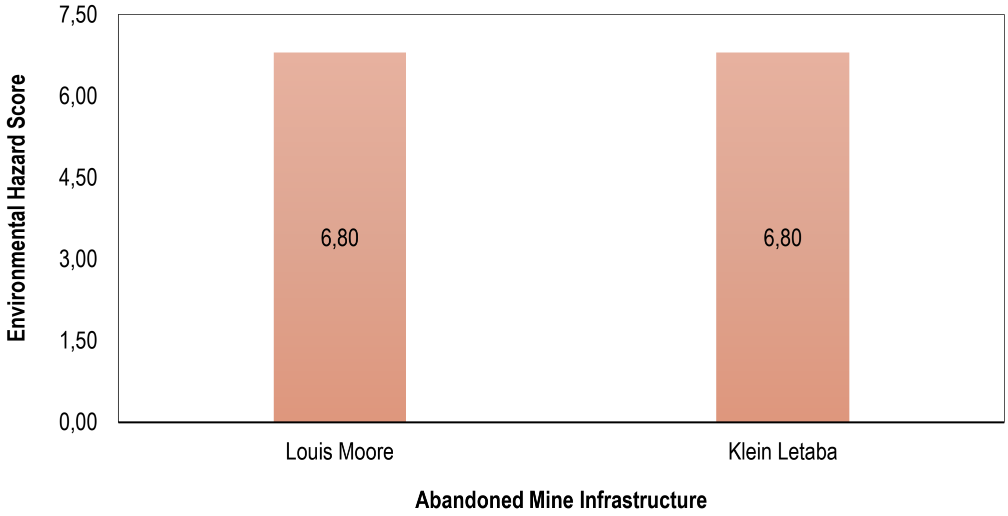

Figure 5. 6: Environmental hazard scores for abandoned infrastructure

5.1.4 Abandoned Mine Tailings

Physical hazards associated with abandoned mine tailings at Klein Letaba and Louis Moore were dust generation, exposure to toxic metals and failure of dumps of the steep slopes. The tailings are neither covered nor protected, as a result artisanal miners and other people have access to the mine sites. Exposure to risks such as toxic dust inhalation, dermal contact and incidental ingestion cannot be ignored. This may have serious health implications as it may

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cause diseases like cancer and lung problems. According to Duque *et al*. (2015), tailings dumps can be massive, and they are one of the most unstable landforms resulting from mining. This can result in failure of the dumps because they are not designed to last, unlike other features or structures such as roads or tunnels that are designed to endure the mine life cycle and little more. Therefore, they are prone to failure. Furthermore, the consequences can be disastrous if there are communities located in close proximity to the tailings dumps and the effects may be greater if the residues reach water bodies.

The risk of physical injury may result from failure of steep slopes of the tailings dumps, thus posing health and safety impacts. The physical hazard score for tailings at Louis Moore was 1.44 and 2.88 for Klein Letaba as shown in Figure 5.7. According to the ranking criteria developed, physical risks or hazards posed by the dumps are low for the two mine sites.

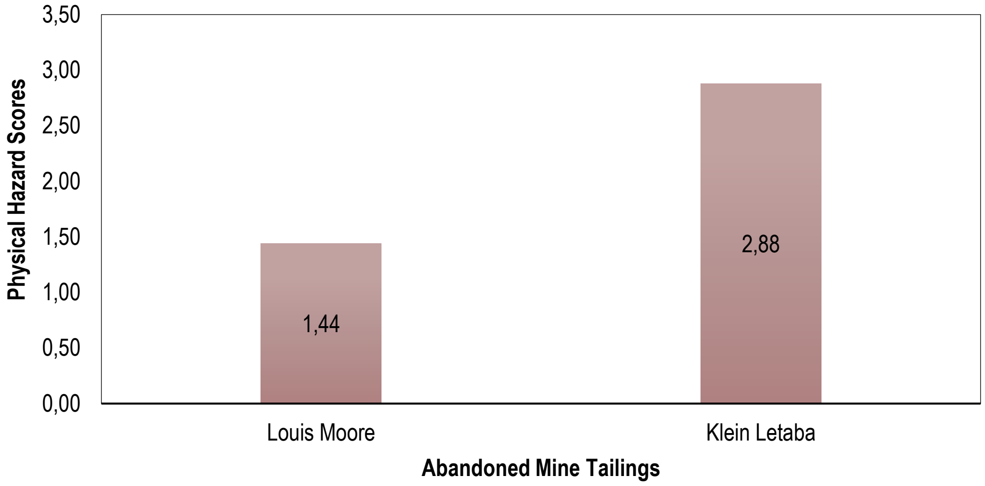

Figure 5. 7: Physical hazard scores computed for Louis Moore and Klein Letaba

The environmental hazard score for abandoned mine tailings was 6.80 at Louis Moore and 13.60 at Klein Letaba, suggesting moderate potential hazards and risks at Louis Moore and extremely high potential risks at Klein Letaba as shown in Figure 5.8. The evaluation of environmental hazards for abandoned mine tailings in the two mines showed high erosion rates evidenced by dense network of gullies on the tailings dumps given that the mine tailings are neither protected nor closed. This may also lead to dispersion of toxic particles from the

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dumps polluting the soil around them and contaminating nearby water systems, noting that the mine sites are located closer to the Nsama and Klein Letaba River.

Sediment run-off may also occur as particles from the tailing dumps are transported to rivers degrading water quality, aquatic life and the environment. According to Duque *et al*. (2015), the greatest concern of having high rates of erosion on tailings deposits is that toxic metals such as Pb and As are dispersed into the environment. This is because gullies transmit ephemeral flows that are very efficient in moving sediments off-site. Poor vegetation growth due to the poor structure of tailing dumps was also recognized as an environmental risk posed by the tailings dumps in the mine sites. Toxic metal analysis results showed that the tailings are contaminated by toxic metals, this may seriously hinder vegetation growth and contaminate surrounding land and water. Moreover, large volumes of tailings dumps create new landforms and transform the natural landscape.

According to the ranking criteria developed in this study, environmental risks resulting from mine tailings at Louis Moore are high and extremely high at Klein Letaba, given that there are two abandoned mine tailings at Klein Letaba and one at Louis Moore.

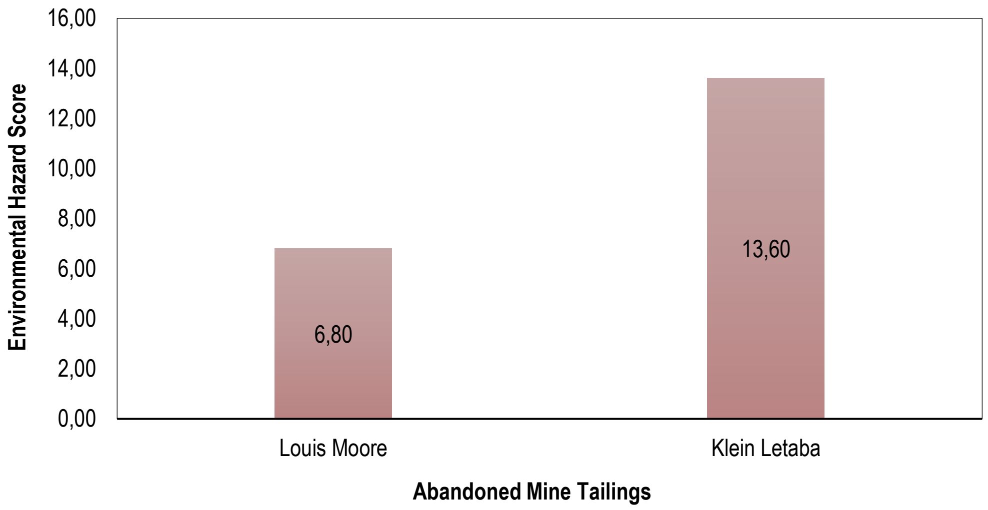

Figure 5. 8: Environmental hazard scores for abandoned mine tailings

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5.1.5 Abandoned Rock Dumps

The major physical risk of abandoned rock dumps at Klein Letaba was dust generation. The rock dumps are open and not protected, people accessing the site including artisanal miners can be exposed to risks of inhalation of contaminated dust from the rock dumps, dermal contact and even incidental ingestion which may threaten their health. The physical hazard score computed for the rock dumps was 0.48 indicating that potential risks linked to the rock dumps are low and the ranking system suggests that these minimal risks require a regular follow-up to monitor possible future degradation at the mine site. There were no rock dumps at Louis Moore.

The environmental hazard score computed for the abandoned rock dumps at Klein Letaba was 2.50, indicating low potential environmental hazards and risks. There were no rock dumps at Louis Moore, therefore a score of zero was assigned. Environmental hazards linked to abandoned rock dumps at Klein Letaba included soil and water pollution caused by dispersion of the contaminated rock dumps particles in the environment due to erosion. This may also have a negative impact on vegetation growth as soil contaminated by toxic metals may not support vegetation growth, affecting the aesthetics of the area.

5.2 Scoring and Ranking Environmental Impacts

Contamination of nearby water systems and soil pollution resulting from flooding of abandoned mine shafts, ore spillages and toxic metal contamination of abandoned mine dumps was scored the highest potential environmental hazard and risk with a score of 9. This was because flooding has a high potential to pollute water systems/ bodies. Water in active mine sites is controlled by pumping, when mine operations seize, the pumps stop working leading to rises in groundwater levels until it reaches the surface or discharges into overlying aquifers. Heavy rainfalls may lead to influx of water into mine shafts and may adversely affect other components of the mine such as mine dumps and spoil heaps.

Flooding of exposed seams stops the oxidation of sulphide minerals but dissolves the metal ions and sulphates to form sulphuric acid. The contaminated water eventually reaches the surface and find its way to nearby rivers and other water sources. Runoff carries contaminated

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sediments; mine dumps and spoil heaps are eroded by rainfall, and this may impair water resources. Moreover, this may lead to deterioration of water quality and may affect aquatic life/ organisms. According to Younger et al. (2005), aquatic ecosystems are polluted by drainage from old mines and erosion of mine waste or tailings still contribute to river sediments. Discharges from shafts, adits, and surface activities such as mineral processing, tailings and waste disposal are a significant source of water pollution. Mine water pollution in rivers and groundwater can also have a significant economic impact. Aesthetic impacts of iron-rich mine water make the area less attractive for investment. Water may be unsuitable for other legitimate uses such as fishing, water sports, irrigation and potable water supply reducing the economic and social value of the water resource to the local community.

On the other hand, one of the environment compartments particularly sensitive to chemical contamination is soil (Bini, 2011). Most plants have low concentration tolerance for metals in the soil, but sensitivity differs among other species. Diversity of some plants eventually die in contaminated habitats though some species are more resistant.

Land degradation, environmental degradation and subsidence resulting from falling of unstable walls or grounds, Sediment run-off and erosion were scored second highest with a score of 8 indicating high potential environmental hazards and risks. According to Bell et al. (2005), the most important and most frequent problems of areas of completed mining operations include mine subsidence and risks to buildings, and damage to infrastructure.

Formation of sinkholes and gullies were scored third highest with a score of 6, indicating moderate potential environmental hazards and risks. Sinkholes may affect surface structures including the abandoned buildings and old processing plants as well as the surrounding infrastructure. Sinkholes may lead to the formation of cavities that have the potential to eventually cave in and form large depressions on the surface. Development of large depressions at the surface without warning can be seriously hazardous to life and property. Gully erosion was evident at both mine sites since slopes of the tailing dumps were characterized by gully erosion. Erosion of mine waste rock deposits may lead to discharge of tailings in rivers and release of metals to the atmosphere (Mihalik *et al.,* 2011); when metals have been released through the atmosphere, they end up as diffuse pollutants in the soil and sediments (Nriagu, 1990; Solomons, 1995). Erosion processes may occur to convey waste in nearby rivers, surface hydrology and the hydrological process may be strongly modified. Sinkholes and erosion are also associated with aesthetic impacts as they alter and modify the natural landscape.

Poor vegetation growth resulting from toxic metal contamination of abandoned mine dumps in both mine sites and alteration of natural landscape obtained a score 4 indicating moderate potential environmental hazards. Mine dumps at Louis Moore and Klein Letaba are exposed and poorly vegetated, these were partly covered by few shrubs and trees including Acacia and Mopani trees. Poor vegetation growth was associated with an increased risk of erosion as plants act as a protective cover on the land and prevent erosion. Old buildings and processing plants in both mine sites seriously impact the aesthetic of the area as they are scattered around the mine sites and affect the appearance of the area, hence altering the natural landscape.

Table 5. 1: The criteria for scoring the environmental impacts

Possible Environmental Impact	Score
1. Generation of dust	2
2. Poor vegetation growth	4
3. Alteration of natural landscape	4
4. Formation of gullies (Gully erosion)	6
5. Formation of sinkholes	6
6. Subsidence	8
7. Land degradation/Environmental degradation	8
8. Soil and water pollution/ Contamination of nearby water systems	9

5.3 Prioritization of Abandoned Mine Features for Rehabilitation

The total physical and environmental hazard scores were determined for Klein Letaba and Louis Moore after each mine feature was scored and ranked for physical and environmental risks. Chemical hazards were also incorporated, in this case, the Pollution Load Index was used as the chemical hazard score since this index gives a summative indication of the overall level of toxic metal concentration in the soil. Once this was done, abandoned mine features were then prioritized for rehabilitation based on the physical, environmental, and chemical

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hazard scores computed. Abandoned mine sites were also prioritized based on the total hazard risk score computed for all the mine features.

5.3.1 Physical Hazards

According to the physical hazard scores computed for each abandoned mine feature at Klein Letaba, abandoned mine shafts must be prioritized for rehabilitation because these features had the highest physical hazard score. Water reservoirs obtained the second highest score, indicating that they must be considered for rehabilitation after the mine shafts have been rehabilitated. This was followed by abandoned mine tailings dumps with a physical hazard score of 2.88, having the third highest score, suggesting that the tailings must be rehabilitated after water reservoirs. Silos had a lower score when compared to mine tailings and were followed by old buildings indicating that they must also be rehabilitated but features with greater scores will be prioritized. Rock dumps had the lowest physical hazard score, as such, they must be rehabilitated once all the other features with higher scores have been rehabilitated.

On the other hand, physical hazard scores computed for abandoned mine shafts were higher than all the other abandoned mine features found at Louis Moore. This suggests that the shafts must be prioritized for rehabilitation, that is., they must be rehabilitated first. This must be followed by abandoned mine tailings dumps, silos, old buildings, and agitation tanks respectively. This order of rehabilitation is in accordance with the physical hazard scores determined for these mine features.

The total physical hazard scores computed for abandoned mine features at Louis Moore and Klein Letaba showed that potential physical hazards/ risks are higher at Klein Letaba with a score of 40.96 and lower at Louis Moore with a score of 16.04, as shown in Figure 5.9. This was due to the number of features present per mine site and the corresponding potential hazards or risks. Moreover, some features or structures were evident at Klein Letaba and not present at Louis Moore. These scores then suggest that abandoned mine features at Klein Letaba must be prioritized for rehabilitation, and those at Louis Moore must be considered for rehabilitation later.

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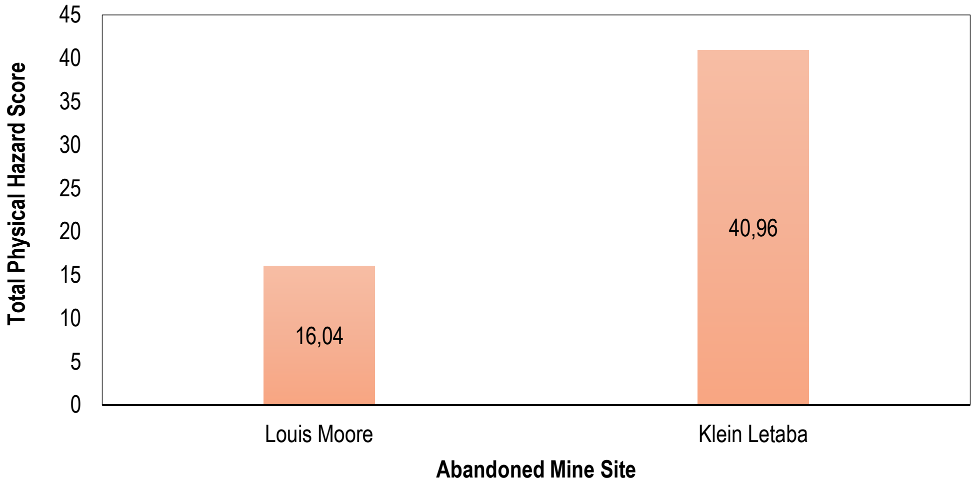

Figure 5. 9: Total Physical Hazard Scores computed for Klein Letaba and Louis Moore

5.3.2 Environmental Hazards

The environmental hazard scores determined for abandoned mine features at Louis Moore showed that the abandoned mine shafts must be rehabilitated first since it had the highest environmental score of 14.90. Old processing plants and mine tailings dumps had the second highest environmental hazard score of 6.80. The lowest environmental hazard score recorded was for old buildings with a score of 0.50 indicating that they may be rehabilitated later. Similarly, environmental hazard scores obtained for Klein Letaba abandoned mine shafts showed that these features must be prioritized for rehabilitation as they had the highest score of 19.80. Mine tailings had the second highest environmental score of 13.60, followed by old processing plants with a score of 6.80 and rock dumps with a score of 2.50. Old buildings had the lowest environmental hazard score suggesting that it may not be prioritized for rehabilitation.

The overall environmental score for abandoned mine features at Klein Letaba was significantly higher than that of Louis Moore as shown in Figure 5.10. This indicated that environmental hazards are severe at Klein Letaba when compared to Louis Moore. Therefore, abandoned mine features at Klein Letaba must be prioritized for rehabilitation over Louis Moore.

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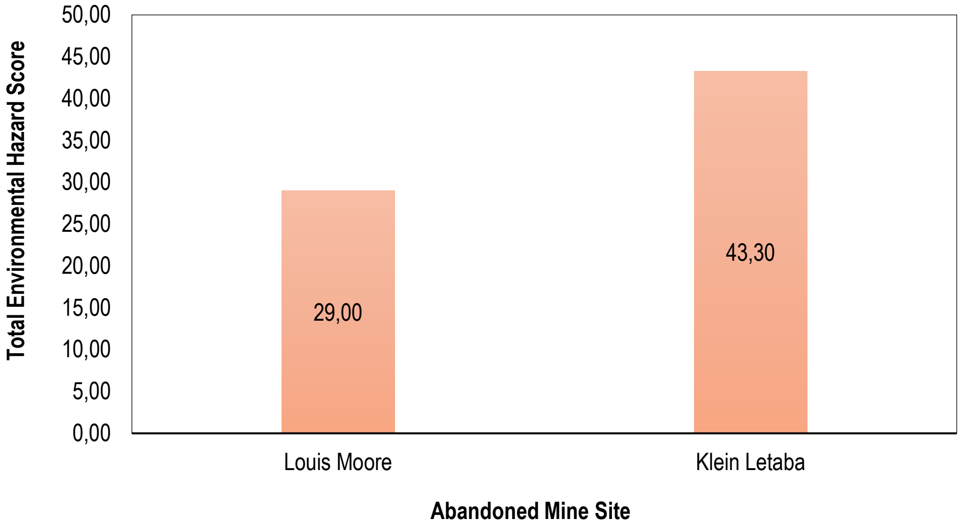

Figure 5. 10: Total Environmental Hazard Scores computed for Klein Letaba and Louis Moore

5.3.3 Total Hazard Scores

The total or overall hazard score was computed for the abandoned mine features and the abandoned mine sites as well. It integrated the physical, environmental, and chemical hazard scores obtained for the mine features and the two mine sites. This was done to prioritize mine features per abandoned mine site for rehabilitation based on the total hazard score of each mine feature. Furthermore, the total hazard scores computed for the mine sites were used to prioritize the abandoned mine sites. It is important to note that it is impractical to rehabilitate all the abandoned mine features simultaneously due to inadequate funds, as such the order of rehabilitation of abandoned mine features at the two mine sites is presented in Table 5.1.

Abandoned mine shafts at Louis Moore had the highest hazard score when compared to the other mine features. As a result, they will receive priority (Priority 1) for rehabilitation. Mine tailings will receive priority 2 as their total hazard was lower than that of mine shafts. This will be followed by silos, agitation tanks and lastly, old buildings.

The total hazard score for abandoned mine features at Klein Letaba suggested that the abandoned mine shafts must be accorded first priority since it was significantly higher than the other mine features. It was followed by mine tailings, rock dumps, water reservoirs, silos, ball mills and old buildings respectively.

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Table 5. 2: Prioritization of mine features for rehabilitation

Mine Site	Mine Features	Total Hazard Score	Priority for Rehabilitation
1. Klein Letaba	Mine shafts	51.80	1
	Mine tailings	21.68	2
	Rock dumps	12.48	3
	Water reservoirs	10.16	4
	Silos	7.76	5
	Ball mills	7.44	6
	Old buildings	1.24	7
2. Louis Moore	Mine shafts	26.94	1
	Mine tailings	10.64	2
	Silos	7.76	3
	Agitation tanks	7.44	4
	Old buildings	1.46	5

The total hazards score for Klein Letaba Mine and Louis Moore Mine was 89.46 and 47.44 respectively. The overall score for Klein Letaba Mine is significantly higher than the score computed at Louis Moore Mine as shown in Figure 5.11. In view of this, Klein Letaba should be prioritized for rehabilitation over Louis Moore.

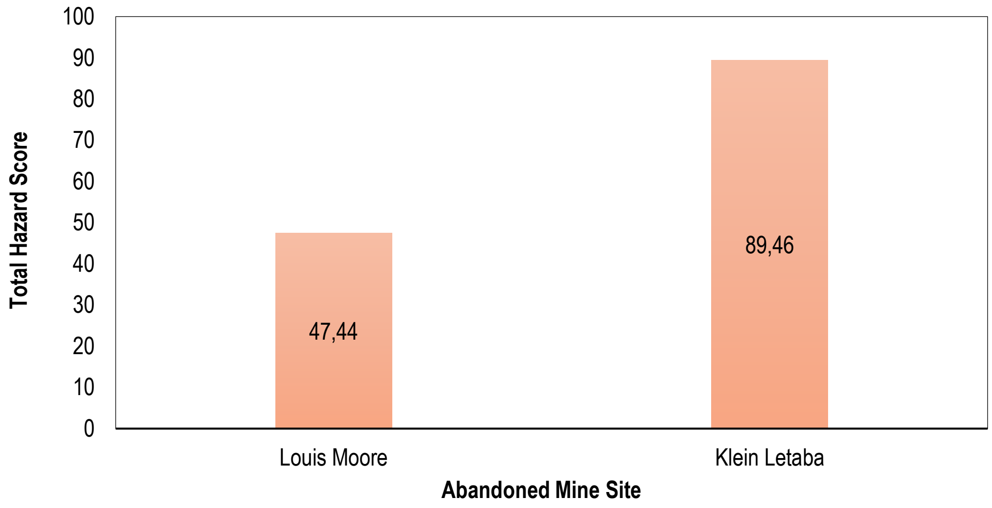

Figure 5. 11: Total Hazard Scores computed for Klein Letaba and Louis Moore

5.4 Comparison of methods of prioritizing mines for rehabilitation

The integrated approach for rehabilitation prioritization and commonly used approaches or methods to prioritize rehabilitation of abandoned mine sites are analyzed and evaluated against the DMR framework or criteria for the management of abandoned mines. This section presents the results of the evaluation of approaches/methods for prioritization of abandoned mines for rehabilitation.

5.4.1 Evaluation of Methods of Prioritizing Mines for Rehabilitation Results

The evaluation process showed that the integrated approach developed in this study meets all the requirements and standards set by DMR as shown in Table 5.2. A comprehensive analysis and characterization of individual abandoned mine features was conducted as part of the integrated approach and an inventory list with all mine features and their properties was compiled. Hazards were scored and ranked based on potential and already existing physical, chemical and environmental impacts. The integrated approach provides a clear framework to identify and determine high priority sites as well as features per mine site.

The commonly used methods of prioritizing abandoned mines for rehabilitation partially satisfy some of the DMR requirements and standards. It is worth mentioning that most of them develop inventories of abandoned mines during their initial assessment stage, however, individual abandoned mine features, and their characteristics are not described in detail. The scoring and ranking approach employed by the traditional methods of prioritizing abandoned mine sites for rehabilitation focuses on the overall mine sites. Hazard scores of the abandoned mine features are not accounted for.

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Table 5. 3: Strengths and weaknesses of the current prioritization approaches

Approach	**Organization**	**Advantages**	**Disadvantages**
Historic Mine Site-Scoring System	The Environmental Protection Agency	• Individual sources of risk are only assessed for the potential risk to human, animal health and the environment.	• Factors such as visual and aesthetic impacts were not considered and scored. • Time consuming • The method is costly/ expensive because it requires the appointment of several specialists and consultants. • It is data extensive since it requires data from many sources.
Historic Mine Site-Inventory and Risk Classification Scoring System	The Environmental Protection Agency	• Conceptual model developed provided a guide for data collection • Identifies features related to mining and classifies mine sites based on potential threats to human and animal health and the environment	• Method was not rigid to prevent the recording of features unique to any site • Data extensive and costly • Method aimed at rehabilitating the entire mine
A four-step approach towards rehabilitation	The Province of Ontario, Canada	• The approach mostly considers public health and safety issue • Abandoned mines in the area are prioritized for rehabilitation	• Little consideration given to environmental issues • Can be expensive because it seeks to remediate the entire mine site

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5.4.2 Unique Characteristics of New and Integrated Approach of Prioritizing Mines for Rehabilitation

Authors such as Mavrommatis and Menegaki (2017); Kubit *et al*. (2015); and Mhlongo *et al.* *(*2019) have revealed that there are other prioritization approaches or methods that are currently being used. However, these approaches have a common drawback in that they are not selective. The commonly used methods of prioritizing abandoned mine sites for rehabilitation focus on the entire mine without the consideration and prioritization of high-risk features, and this results in high cost and ineffective rehabilitation. The integrated approach developed in this study has the advantage of reducing the cost of rehabilitation by prioritizing mine features that are more hazardous and pose greater physical, chemical, and environmental risks. Table 5.3 shows current approaches used for prioritizing abandoned mine features for rehabilitation and the advantages and disadvantages of these approaches.

The integrated approach developed in this study takes into consideration the physical, chemical, and environmental hazards posed by abandoned mine features at Klein Letaba and Louis Moore. This approach was used to study and evaluate all the major abandoned mine features at the two mine sites and the corresponding potential risks. The integrated approach provides an in-depth understanding of problems associated with the abandoned mine features, making it easier to document and quantify the severity and magnitude of the impacts.

The new and integrated approach is unique because it quantifies impacts posed by individual mine features, assesses all abandoned mine features and includes important parameters such as number of sources of contamination, potential impacts of each mine feature and hazard scores, thus enhancing its transparency. This approach provides a quantitative and transparent process that overcomes the deficiencies found in many existing prioritization approaches. The integrated approach of prioritization of mine features for rehabilitation is robust, practicable and provides long-term solutions of addressing physical, chemical and environmental hazards and can be applied in the prioritization of features at other abandoned mine sites. Moreover, the approach is cost-effective in that rehabilitation effort is directed to more hazardous features and less hazardous features receive little attention

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CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

The aim of this study was to develop an integrated approach for prioritizing abandoned mine features for rehabilitation. The study has provided insights on the physical, chemical, and environmental hazards of abandoned mine features at Klein Letaba and Louis Moore, and features that must take priority in the rehabilitation programme are presented. This chapter provides concluding remarks on how the objectives of the study were achieved, a summary derived from the findings of this study and highlights recommendations for future research.

6.1 Conclusion

The following conclusions were made:

- This study was aimed at developing an integrated approach of prioritizing abandoned mine features for rehabilitation at Louis Moore and Klein Letaba. To develop an integrated approach of prioritizing various areas/zones of the mine site for mine rehabilitation, the principal mine features were studied and subsequently scored and ranked based on the risks associated with each of them.: The study integrated physical, chemical and environmental hazards of the abandoned mine features identified in the two mine sites. Physical, chemical and environmental scores were computed to determine the severity of impacts posed by the abandoned mine features and the results and order of prioritization was presented in this study. Consequently, the specific objectives of the study were achieved as outlined below:
- The current approaches that are used for the scoring and ranking of abandoned mine features for rehabilitation were reviewed and analyzed. The review showed that the current scoring and ranking approaches are similar in one respect, they all consider public health and safety as a priority and do not necessarily focus on the individual mine features that are the main sources of contamination at abandoned mine sites. As a result, these approaches are not adequate in addressing the high costs of rehabilitation, which is a major constraining factor in rehabilitating all abandoned mines.

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- The potential risks, hazards, and impacts linked to the individual abandoned mine features in Klein Letaba and Louis Moore were assessed and presented in this study. The hazards were classified into physical, chemical, and environmental. Hazard scores were computed, and the total hazard index was determined to quantify the potential risks of the mine features.
- Scoring and ranking of the identified risks for each mine feature was dependent on the number of sources, pathways, and the severity of hazard weight. In this case, the abandoned mine features were regarded as sources of contamination. The risks associated with contamination were more prominent at Klein Letaba than at Louis Moore. Consequently, physical, environmental, and chemical hazard scores for Klein Letaba were higher than scores computed for Louis Moore. This means that Klein Letaba has greater risk than Louis Moore and therefore, should be given priority when decision is being made regarding rehabilitation of the abandoned mines in the area.
- The integrated approach developed in this study is cost-effective in that it is aimed at prioritizing abandoned mine features that pose greater physical, chemical, and environmental hazards over mine features with lesser risks within each mine site, preventing spending money on features whose impacts are not significant.

6.3 Recommendations

This section presents the recommendations made in this study after the in-depth analysis and discussion of the main objective, which is to develop an integrated approach for the prioritization of abandoned mine features for rehabilitation. Based on the outcomes or results of the study and conclusions drawn, the following recommendations were made:

- Several mine features were identified that pose significant health and safety hazards to the surrounding communities. However, geochemical modelling of the hazards at both mine sites needs to be undertaken to fully understand the migration patterns of toxic contaminants into nearby environs to enhance hazard ranking.
- A study should be conducted to determine suitable rehabilitation strategies for the abandoned mine features. Given the high costs of rehabilitation, it is important to examine rehabilitation strategies that will not only focus on the abandoned mines but

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also focus on addressing both physical and environmental impacts of individual mine features. This will mitigate the detrimental effects of abandoned mines and sustainability of the surrounding areas.

- A detailed cost analysis study on the rehabilitation of the abandoned mine features at the two mines needs to be undertaken. This will be crucial in projecting the fiscal budget that will be required for the rehabilitation programme.
- It is important that the critical parameters of the integrated approach developed in this study are continuously evaluated and updated for a more improved and effective prioritization process. The mining environment is dynamic in nature, as such, characteristics of abandoned mine features are prone to change over time. This will ensure that the characteristics of abandoned mine features, and the priority list are frequently updated. Parameters of the integrated approach should remain compatible with DMR standards to effectively alleviate impacts of abandoned mine features.
- Stakeholder engagement is an important process to increase relevance of the research and increase stakeholders’ awareness. Therefore, local authorities and all other relevant stakeholders need to be involved and be alerted for the urgent need to monitor physical hazards such as dangerous shafts which are rarely visible at the two mines sites. This is likely to save both human and livestock life by preventing risk of falling into these hazardous features and will in turn, raise awareness on the presence of these features at the mine sites.

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APPENDICES

Appendix A: Sample collection points in the two mine sites

Louis Moore

Sample number	Sample ID	Location	Description
1	LMS1	23˚13'07.4"S; 30˚41'41.2"E	Sample collected next to the reservoirs.
2	LMS2	23˚13'09.8"S; 30˚41'38.1"E	Sample collected next to the old processing plants
3	LMS3	23˚13'09.3"S; 30˚41'39.5"E	Sample collected between the two silos.

Klein Letaba

Sample number	Sample ID	Location	Description
1	KLS1	23˚17'38.8"S; 30˚33'40.7"E	Sample collected next to old buildings.
2	KLS2	23˚17'36.3"S; 30˚33'42.1"E	Sample collected next to the processing plant.
3	KLS3	23˚17'35.7"S; 30˚33'41.2"E	Sample collected 1.5m away from the ball mill.
4	KLS4	23˚17'35.4"S; 30˚33'45.2"E	Sample collected next to the grizzle.
5	KLS5	23˚17'40.8"S; 30˚33'39"E	Sample collected next to the rock dump.
6	KLS6	23˚17'39"S; 30˚33'37.7"E	Sample collected next a silo.
7	KLS7	23˚17'38.2"S; 30˚33'37.7"E	Sample collected next to the three silos.
8	KLS8	23˚17'38.9"S ;30˚33'36.3"E	Samples collected next to the clarifier.
9	KLS9	23˚17'41.3"S; 30˚33'33.7"E	Sample collected next to shaft number 1.

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Appendix B: Toxic Metal Analysis Results for Louis Moore and Klein Letaba

Element	**Cu (mg/kg)**	**Zn (mg/kg)**	**As (mg/kg)**	**Ni (mg/kg)**	**Cd (mg/kg)**	**Pb (mg/kg)**	**Co (mg/kg)**
LMS1	34,2	155.0	28.2	456.6	0.1	111.0	28.2
LMS2	7.1	34.0	0.8	705.6	0.0	33.3	38.2
LMS3	49.8	239.6	19.4	515.6	0.2	90.5	28.5
KLS1	31.7	155.8	50.5	473.3	0.1	109.1	28.3
KLS2	25.7	35.1	33.7	1213.0	0.0	6.1	138.8
KLS3	47.9	52.5	48.8	631.9	0.1	9.3	52.8
KLS4	56.1	61.1	95.2	600.1	0.1	9.9	53.3
KLS5	48.6	32.7	693.9	704.9	0.0	10.0	55.8
KLS6	38.2	49.3	447.9	696.8	0.1	5.8	50.8
KLS7	72.8	43.1	48.8	372.8	0.0	7.0	40.0
KLS8	34.1	50.8	613.6	68.7	0.1	25.6	15.2
KLS9	64.4	464.8	9.8	215.8	0.0	17.0	17.3
KLS10	81.4	63.3	358.9	369.9	0.1	22.1	42.4
KLT-1	48.5	21.0	702.4	58.3	0.0	12.8	6.0
LMT-1	22.6	114.4	13.5	557.8	0.1	64.4	29.6
LMT-2	20.4	119.8	5.1	502.8	0.0	60.9	32.1
KLRD-1	26.5	32.0	4099.2	858.9	0.0	4.4	63.3

***NB:** LMS stands for Louis Moore Soil Samples; KLS= Klein Letaba Soil Samples; LMT= Louis Moore Tailings; KLT= Klein Letaba Tailings and KLRD= Klein Letaba Rock Dumps*

Appendix C: Total Risk Index recorded for Klein Letaba Soils

Klein Letaba	**Zn**	**Cu**	**Pb**	**Cd**	**As**	**Ni**
Toxic response factor (Tr)	1	5	5	30	10	5
Toxic response (Cf)	2.2	1.1	0.5	1.3	23.3	1.3
Ecological Risk (Er)	2.2	5.6	2.3	39.9	233	6.6
Risk Index (RI)	**289.8**					

Appendix D: Total Risk Index recorded for Louis Moore Soils

Louis Moore	**Zn**	**Cu**	**Pb**	**Cd**	**As**	**Ni**
Toxic response factor (Tr)	1	5	5	30	10	5
Toxic response (Cf)	3.1	0.7	1.6	2.1	1.6	1.7
Ecological Risk (Er)	3.1	3.4	8.1	63	15.7	6.9
Risk Index (RI)	**100.2**					

Appendix E: Geo-accumulation Index Values for Louis Moore Soils

Element	**Contamination Factor**	**Geo-accumulation Index**
Cu	0,7	-1.14
Zn	3,1	1.05
As	1,6	0.06
Ni	1,4	-0.13
Cd	2	0.42
Pb	1,6	0.11
Co	0,4	-2

Appendix F: Geo-accumulation Index Values for Klein Letaba Soils

Element	**Contamination Factor**	**Geo-accumulation Index**
Cu	1.1	-0.42
Zn	2.2	0.54
As	23.3	3.96
Ni	1.3	-0.19
Cd	1.3	-0.18
Pb	0.5	-1.71
Co	0.6	-1.36

Appendix G: Average background values in Giyani

Element	**Background Value (BV)**
As	13.65
Co	48.05
Cu	78.48
Ni	302.79
Pb	5.09
Zn	74.57

Appendix H: Physical hazard scores for abandoned mine features at Louis Moore and Klein Letaba

Abandoned Mine Site	Shafts	Old buildings	Old Processing Plants	Mine Tailings	Rock dumps
Louis Moore	12.04	0.96	1.60	1.44	0.00
Klein Letaba	32.00	0.64	4.96	2.88	0.48

Appendix I: Environmental hazard scores for abandoned mine features at Louis Moore and Klein Letaba

Abandoned Mine Site	Shafts	Old buildings	Old Processing Plants	Mine Tailings	Rock dumps
Louis Moore	14.90	0.50	6.80	6.80	0.00
Klein Letaba	19.80	0.60	6.80	13.60	2.50

Appendix J: Total physical, environmental, and chemical hazard scores

Abandoned Mine Site	Physical Hazard Score	Environmental Hazard Score	Pollution Load Index
Louis Moore	16.04	29.00	2.40
Klein Letaba	40.96	43.30	5.20

Appendix K: Total Hazard Score for Louis Moore and Klein Letaba

Abandoned Mine Site	Total Hazard Score
Louis Moore	47.44
Klein Letaba	89.46

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