University of Venda

EVALUATION OF STRATEGIES FOR REHABILITATION OF SELECTED ABANDONED/HISTORIC MINE SITES IN THE GIYANI GREENSTONE BELT, LIMPOPO PROVINCE OF SOUTH AFRICA

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DECLARATION

I, **Sigxashe Sibulele,** do hereby declare that this dissertation for Master of Ecology and Resource Management at the University of Venda, hereby submitted by me, is my own original work; has not been previously submitted for masters' work at this or any other university; and, that all reference material contained therein has been duly acknowledged.

Undersigned

……………………………………………… 04 September 2020
Student's signature Date

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Supervisor's signature Date

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Co-Supervisor's signature Date

DEDICATION

I dedicate this work to my family for their support.
My Late Sister Luleka Zana Sigxashe
and
Makazi, Nomaza Mxinzeleli

ACKNOWLEDGEMENT

My first acknowledgment is to my Lord and saviour Jesus Christ, who when moments of being weary and worn out, gave me the strength to start and finish this dissertation. It is true indeed, that without Him I could have not finished and none of this would have been attainable.

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ABSTRACT

Mining has historically been the mainstay of the South African economy and has both shaped its social and environmental fabric. However, it has left the country with a negative legacy of abandoned mines that present environmental problems, and public health and safety concerns. The common physical and environmental problems of most of these abandoned mines are associated with open shafts, unstable slopes of waste dumps and pits, and dilapidated mine infrastructure. Even though the problems of these abandoned mines are known, little has been done to rehabilitate these mines. Some attempts have been made to rehabilitate mine openings but efforts to rehabilitate features such as mine waste dumps and dilapidated infrastructure has been woefully inadequate. The reasons for ineffective rehabilitation measures may include inappropriate measures that are used in rehabilitation of the abandoned mines, lack of financial resources to carry out the rehabilitation and the need to prioritize abandoned mine features and mine sites for rehabilitation in view of the fact that there are many of these abandoned mines that require urgent attention and resources to rehabilitate them are limited. It is therefore important that practicable rehabilitation strategies are developed and used to rehabilitate mine features and sites to provide long-lasting solutions to the physical, environmental, and social problems. This study focused on the evaluation of strategies for rehabilitation of selected abandoned mine sites in the Giyani Greenstone Belt.

The approach used in this study involved conducting a detailed field inventory and characterization to establish the nature and seriousness of the physical and environmental conditions of the selected abandoned/historic mining sites in Giyani Greenstone Belt. Field inventory and characterization involved traversing around the mine-site to locate and describe abandoned mine features. The Global Positioning System (GPS) was used in capturing the absolute location of the identified major abandoned mine features such as open mine shafts, tailings dump, and dilapidated infrastructure.

Each of the identified mine features was critically analyzed by scoring and ranking the associated hazards. The scoring focused on the source of the hazard, exposure pathways, and possible damage that might be caused by the hazard. Analytical Hierarchy

Process (AHP) and Pugh Matrix were used to devise a multi-criteria framework for evaluating mine site rehabilitation strategies. AHP method was utilized to evaluate the significance of the deciding factors and the Pugh Matrix to relatively compare the strategies for the selection of the appropriate rehabilitation options.

The results of the study showed that the best approach to effectively address the physical and environmental hazards at Louis Moore and Klein Letaba abandoned mines of the Giyani Greenstone Belt was to give priority to extremely hazardous open mine shafts and tailings dumps. Mine shafts present a high risk of falling and drowning in water in the mine workings. Such risks are likely to lead to death with no hope of recovery of the body. The next mine features to be rehabilitated are the tailings dumps since they have relatively less physical hazards but extremely high environmental hazards. Abandoned mine infrastructure was found to be less hazardous and should, therefore, receive the least attention.

The preferred rehabilitation strategies for abandoned mines features were evaluated after a comprehensive characterization of the site, this was done to ensure that the selected strategy addresses both physical and environmental problems identified on the site. Based on the results of evaluation, backfilling was selected to be the most suitable rehabilitation strategy for mine shafts as it has a very high potential to eliminate the risks of people falling into the mine shaft and the chances of water contamination by abandoned mine shafts. The most ideal rehabilitation option for tailings dumps was revegetation, since it ensures the safety of the site after implementation and minimizes the future environmental impacts such as the discharge of contaminants to the nearby environment. The most preferred rehabilitation strategy for dilapidated abandoned infrastructure in the study area was the demolition of the infrastructure, this strategy will improve the safety status of the mine sites and make the land they occupy available for other traditional post-mining land uses.

It was concluded that the approach of prioritizing the extremely and moderately hazardous abandoned mine features is appropriate for use in developing countries where there are numerous abandoned mines and limited resources to rehabilitate them. This will go a long way in ensuring that characterization and rehabilitation of the abandoned mine features are effectively carried out within the constraints of resources.

Keywords: *Abandoned mines, rehabilitation strategies, multi-criteria framework, negative legacy, Giyani Greenstone Belt*

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CHAPTER ONE

INTRODUCTION

1.1. Background of the Research Problem

In general, there is no single definition of abandoned mine. According to UNEP and COCHILCO (2001), the definition of abandoned mines varies from one region to the other. The Mineral and Petroleum Resources Development Act (MPRDA) (Act No. 28 of 2002) of South Africa classifies those mines for which a closure certificate has not been issued and no party can be traced to assume responsibility for their liabilities as abandoned mines and the government may have to provide funds for their rehabilitation. It should also be noted that a mine can be considered abandoned if there are no identifiable owners and/or operators for the facilities, or if the facilities have reverted to the government ownership (MMSD, 2002). According to UNEP and COCHILCO (2001), reasons for inaction and lack of real progress in addressing the issue of abandoned mines relate to the lack of appropriate definition of what is an abandoned mine site. Mhlongo and Dacosta (2016) have emphasized that the definition of abandoned mine needs to be addressed to ensure that the seriousness of the hazards at the mine sites as well as the nature and conditions of the features and structures at the sites are taken into consideration.

In many countries including South Africa, historic mining has left a legacy of ownerless and abandoned mines which are continuously damaging the environment (Swart, 2003). Environmental degradation has been found to be one of the most terrible legacies of historic mining since these operations were not subjected to the current environmental regulations. Abandoned mines constitute environmental pollution sources that pose significant public health and safety risks (Nikolaidis *et al.,* 2013). These are particularly high when the public has a direct access to the sites, which is the case in most abandoned/historic mine sites in South Africa (DMR, 2009). Public concerns at abandoned mine sites can include altered landscape, accessible openings (i.e. unblocked pits, tunnels and shafts), hazardous mine waste, abandoned infrastructure, and ground surface instability (Tripathy and Sisodia, 2014; NOAMI, 2009). The common environmental problems associated with abandoned mine sites include decrease in land use due to loss of soil or soil contamination, changes in groundwater flow/quality, contaminated soils and aquatic sediments, spoil heaps covering the land and abandoned tailings dumps (Kubit *et al.,* 2015; Maramba *et al.,* 2006; MMSD, 2002). These mines are also considered to be a source of environmental contamination, including heavy metal and acid discharges that degrade surface and ground waters, or potential release of toxic and explosive gases (MSSD, 2002).

Even though, the problems of abandoned mine sites are well known in almost all countries, little has been done to rehabilitate these abandoned mines (Mhlongo and Dacosta, 2016). According to UNEP and COCHILCO cited by Mhlongo and Dacosta (*op cit*.), the reasons for the delay in the rehabilitation of abandoned mines are lack of clearly assigned responsibilities, the absence of criteria and standards of rehabilitation for these mines, and the high cost of rehabilitation. Some of the current rehabilitation challenges are technical skills (know-how), leadership focus, poor planning, cost saving initiatives, and the government's lack of capacity to enforcement rehabilitation requirements (Nzimande *et al.,* 2012). The legal situation of the abandoned mines is not always clear, with uncertainty about the ownership of the surface and/or mineral rights (Limpitlaw *et al.,* 2005).

Any decision related to abandoned mine must contribute to the safe and secure living of current and future generation. The best solution is to rehabilitate the site by removing all signs of the abandoned mine which might be hazardous to people and the environment. The main objective of rehabilitation is to return the land to the state where it can support viable post-mining use. For purposes of having an effective management and rehabilitation programme, it is crucial that the mines in question are ranked based on their potential or already existing negative impacts on the environment and human beings (DMR, 2009). Ranking and prioritization of the site's public health and safety concerns and/or environmental impacts are particularly relevant as they can contribute to the accomplishment of rehabilitation efforts. According to Mhlongo *et al.* (2013), different regions have different ranking and prioritization criteria for rehabilitation of abandoned mines. Typically, the criteria used in the prioritization focus on public safety and then the environment. In South Africa, the role of the government with respect to rehabilitation of abandoned mines is to address first the safety and health of its citizens, as well as the environment (MMSD, 2002), as guaranteed in Section 24 of the constitution of the country. During the past decade, the Department of Mineral and Energy (DME) has focused its rehabilitation efforts on abandoned asbestos mines and safety threatening abandoned vertical shafts found in and around the Witwatersrand region (Auditor-General South Africa, 2009; DMR, 2009; Mhlongo *et al.,* 2013).

Based on the of studies conducted by DMR (2009), Auditor-General South Africa (2009) and MMSD (2002), it is evident that the industry lacks practical solutions to address the problems of abandoned mines. Numerous studies have been conducted on assessment of negative legacy of abandoned mines, but very little has been done to evaluate and identify appropriate strategies for addressing the problems of abandoned mines in South Africa and elsewhere in the world (MMSD, 2002; DRM, 2009). Hence, this study comprises an appraisal of abandoned mine sites problems, which focuses more on the development of sustainable, cost-effective and integrated rehabilitation strategies for abandoned mine sites in South Africa.

The case study used for this research is the Giyani Greenstone Belt (GGB) which is a host to numerous abandoned mines. Many of the abandoned mines in this region were closed without any form of rehabilitation. They have been reported by Steenkamp and Clark-Mostert (2012), to be a hot spot for small-scale and illegal mining activities. Abandoned gold mines in this region present a range of environmental and public health and safety risks, which are exacerbated by the socio-economic issues that exist in the nearby communities.

1.2. Statement of the Problem

The current challenges of rehabilitation are poor planning, the absence of criteria and standards of rehabilitation for these mines, and the potential high cost of rehabilitation (Nzimande *et al.,* 2012). Most of the existing rehabilitation methods are inadequate for eradicating of both physical and environmental hazards of the abandoned mines. Therefore, there is a need for evaluation of strategies in order to establish a rehabilitation strategy that can address both physical and environmental hazards.

Rehabilitation of abandoned mines is largely dependent upon the prevailing physical hazards, environmental conditions, and the characteristics of the site (Beukes, 2008). For purposes of selecting appropriate rehabilitation options, it is crucial to rank the abandoned mine features based on their potential or already existing negative impacts on the environment and human beings (DMR, 2009). Ranking and prioritization of the site's public health and safety concerns and/or environmental impacts are particularly relevant as they can contribute to the accomplishment of rehabilitation efforts. Adoption of most suitable rehabilitation strategy is a problem with multi-dimensional nature and there are so many factors in this problem which have serious influence on the decision-making process.

1.3. Objectives of the Research

1.3.1. Main objective

The main objective of this research was to carry out an evaluation of strategies for rehabilitation of selected abandoned mine sites in the Giyani Greenstone Belt.

1.3.2. Specific objectives

The specific objectives of this research were:

- To carry out characterization of the abandoned mine features in the study area.
- To score and prioritize the physical and environmental hazards of the mine features at the selected historic mine sites.
- To determine the most suitable rehabilitation strategies for mitigating the problems associated with the main mine features of the selected mine sites.

1.4. Research Questions

This research was conducted to answer the following questions:

- What are the characteristics of the abandoned mine features in the study area?
- What are the most practicable means of ranking the physical and environmental hazards of the mine features at the selected historic mine sites?
- What are the most appropriate rehabilitation strategies for addressing the problems of the identified abandoned mine features at the study sites?

1.5. Research Hypotheses

A well-designed hypothesis displays the characteristic features of the research and analysis conducted. In this regard, the following hypotheses were developed to shed light on assumptions made in accordance with the research conducted

- Some components/features of the abandoned mine sites have greater impact on the environment than others
- Abandoned mines vary in size and danger and each site requires its own degree and site-specific rehabilitation strategy

1.6. Significance of the Research

This study was conducted to provide information on the state and nature of the seriousness of the physical and environmental hazards at the abandoned mine sites and the establishment of the appropriate rehabilitation options. The selection of Klein Letaba and Louis Moore was based on the fact that little has been done to rehabilitate the land. The government had used temporal rehabilitation strategies which requires frequent monitoring and maintenance. Besides, the strategies used did not consider the possibility of post-mining land use. The study aimed at determining the best rehabilitation options that will address the problems associated with the selected abandoned mine sites and the issues of cost, the durability of rehabilitation options and the self-sustainability of the land after rehabilitation.

The outcomes of this study will benefit the government by providing legitimate information that will assist in tackling the issues of abandoned mines before they get out of hand. It will also assist in ensuring that the need for post-mining land use is considered when selecting rehabilitation options. This will ensure that communities in the vicinity of the abandoned mines are safe in case of physical and environmental hazards. Rehabilitation, if done successfully will restore the pre-mining environment and respective conditions; returning the original ecosystem as close as possible, in terms of structure, function and dynamics and creating a land-use to benefit the local community. Reshaping of mined land blends mined areas into the surrounding landscape, reduces the likelihood of erosion, by reducing slope angles and lengths, and allows natural drainage patterns to be re-established.

1.7. Description of the Study Area

This section presents an overview of the study area. It focuses on physical characteristics of the study area which includes geographical location, climate, vegetation and pedology, land use, drainage pattern and topography, geological setting of the study area.

1.7.1. Geographical location of the study area

The Giyani Greenstone Belt, formerly known as the Sutherland Greenstone Belt, is part of the Greater Giyana Local Municipality under the jurisdiction of Mopani District Municipality of the Limpopo province of South Africa (Munyangane, 2012). The Limpopo Province is in the north-eastern corner of South Africa, bordering on Zimbabwe in the north and Mozambique in the east. Giyani lies 470 km north east of Johannesburg by road, 104 km from Tzaneen and 105 km from Pharaborwa Gate of the Kruger National Park at 23° 19´ 0" South, 30° 40´ 0" East (Makhado *et al.,* 2009).

The two mines that will be used for the purpose of this research are Louis Moore Gold Mine and Klein Letaba Gold Mine. The Louis Moore Gold Mine is situated in an isolated body of mafic rock lying in an extensive terrain of granite gneiss, 10 kilometers of Giyani and the Klein Letaba Gold Mine is located 13 km west of Giyani as shown in Figure 1.1.

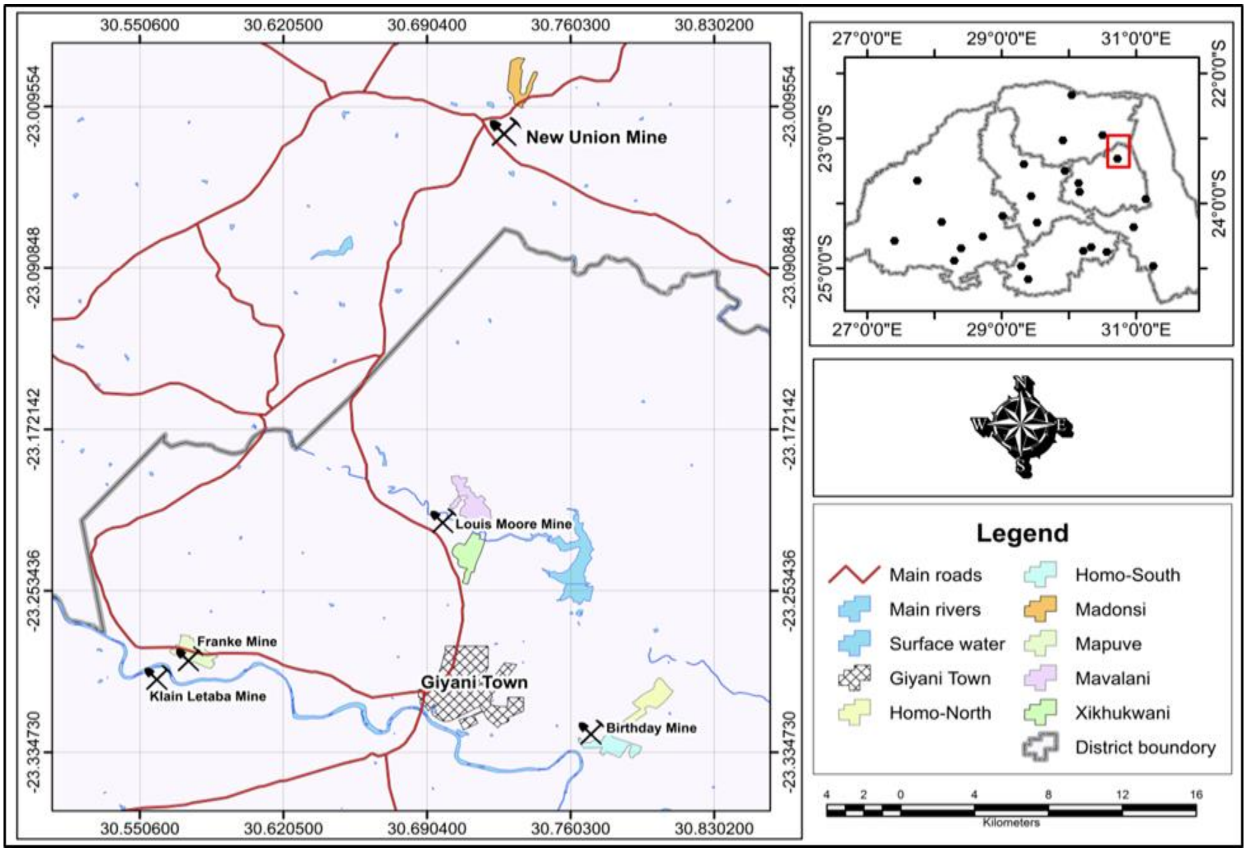

Figure 1.1: A map showing the location of Louis Moore and Klein Letaba abandoned gold mines (Mhlongo *et al.,* 2019).

1.7.2. Climate

Giyani is situated within the sub-tropical zone. It can be very hot in summer with the temperatures reaching 38°C in summer. Winters are mild during the day and cold during the nights with temperatures reaching 22°C maximum during winter (Makhado *et al.,* 2009). The area is characterized by a warm, dry and subtropical climate with summer rainfall. High rainfall occurs mainly between November and February of each year (South African Weather Service, 2012). Though the region receives high rainfall in summer, it often experiences severe droughts conditions that result in serious water shortage (DWAF, 2006).

1.7.3. Vegetation and pedology

The vegetation in the Greater Giyani Municipality is classified under the Lowveld Mopaneveld savannas (Rutherford *et al.,* 2006), characterised by a mixture of trees, shrubs and grasses. In this area, *Colophospermum mopane* occurs in abundance together with many other tree species such as *Combretum api culatum, Sclerocarya bi rea, Dichrostachys cinerea, Terminalia sericea, Diopsyros mespiliformis, Cassine aethiopica, Dalbergia melanoxylon, Acacia species* and *Commiphora species*. The soil is loamy sands and clayey soil and is characterised by gentle undulating valleys of the Soutpansberg mountain range (Acocks, 1988).

1.7.4. 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).

1.7.5. Drainage pattern and topography

The hydrology of the greater Giyani is generally characterized by feature-bound aquifers formed mainly within the rocks of the Goudplaats Gneiss, the Giyani Greenstone Belt and to the smaller extent the shimariri Granite and schiel Alkaline complex. The major rivers that transect the area are the Nsami, Klein Letaba, Shingwedzi, Middle Letaba and Groot Letaba River, which flow in the easterly direction towards the Indian Ocean. These rivers form part of the secondary drainage region B8 and B9, which falls within the Letaba/Luvuvhu Water Management Area (WMA) (Munyangane, 2012). The topography of the study area is relatively flat to undulating plains of the Lowveld catchment.

1.7.6. Geological setting of the study area

The Giyani Greenstone Belt (GGB) is located in the Limpopo province of South Africa. The surrounding host rock is the Swazian age Goudplaats Gneiss. The GGB is also of Swazian age and forms part of the Murchison Sequence as the Giyani Group (Steenkamp and Clark-Mostert, 2012). The GGB is located 40km northeast of the Pietersburg belt and has about a length of 70km (Kroner *et al.*, 2000). The north-east trending Greenstone Belt is a roughly sinusoidal-shaped supracrustal complex with a widened central area and a 30km extension towards the west, which bifurcates into two arms, a Lwaji and north-west Khavangari Arm (Brandl, 1987). In the southern Lwaji Arm, the base succession consists of the ultramafic schists, which passes upward into a thick sequence of metasedimentary rocks including phyllite, quartz-sericite-chloritr schists and quartzite (Munyangane, 2012) (see Figure 1. 2). In the Khavangari Arm, a large intrusive body of altered dunite probably representing part of a layered ultramafic complex is developed at the structural base of succession. The dunite body is followed by a thick unit of ultramafic schist which, in turn, is overlain by metapelites. The latter, in places, carry abundant staurolite and kyanite. An ultramafic-mafic unit containing several thin horizons of spinifextextured komatiite is developed at the structurally determined top of the succession (Kroner *et al.*, 2000).

The regional geology can broadly be divided into mafic and ultramafic sequences in the north, and mafic and subordinate felsic units in the south of the GGB. The Giyani Group consists of a lower ultramafic unit, consists mainly of tremolite-actinolite schist and amphibolites. This unit also contains a banded iron formation (BIF), which is in places auriferous. The ultramafic unit is overlain by sedimentary and mafic to ultramafic units (Steenkamp and Clark-Mostert, 2012).

The supra-crustal rocks in the GGB (SACS, 1980) are flanked to the north by migmatised tonalitic gneiss (Klein Letaba Gneiss) and to the south by younger granite. Within the GGB, geophysical modelling by Kleywegt *et al.* (1987) indicate the thickness of the Giyani Group to be between 1.5 and 3 km, increasing towards the SE margin of the belt. They also concluded that the GGB is not situated along a major crustal boundary.

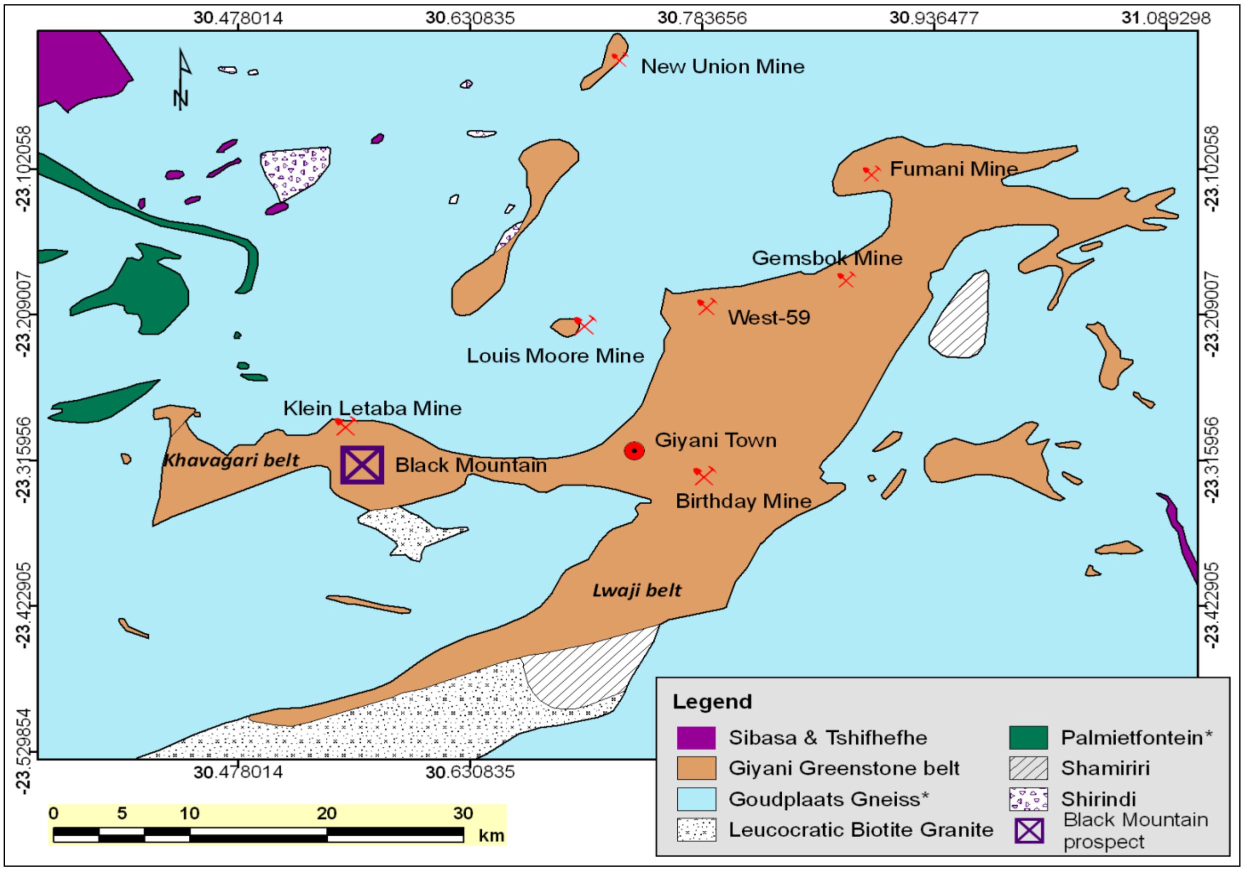

Figure 1. 2: A map showing Geological setting of Giyani Greenstone belt (Adapted from Muzerengi, 2012).

CHAPTER TWO

LITERATURE REVIEW

This chapter presents an overview of abandoned mine issues in South Africa, together with different rehabilitation strategies to treat these sites with the purpose of eliminating their physical and environmental hazards. Literature was reviewed to acquire a basic understanding of the issues of abandoned mines in order to avoid using inappropriate rehabilitation strategies which may easily collapse or get removed after installation thus failing to fulfil the purpose of the treatment. Given this, literature review focused on the history of gold mining in the Giyani Greenstone Belt and problems of abandoned mines in South Africa with emphasis on environmental and physical impacts. This was followed by a discussion on the rehabilitation of abandoned mines, an overview of risk ranking systems and different rehabilitation strategies for abandoned mine features.

2.1. History of Gold Mining in the Giyani Greenstone Belt

Gold in GGB was discovered in the 1870s (Steenkamp and Mostert, 2012). Several mines were opened which include historic, small gold mines like Klein Letaba, Frankie, Birthday, Horseshoe and Louis Moore (Wilson and Anhaeusser, 1998). Klein Letaba gold proclaimed in 1984, but erratic yields, heat and malaria drove most prospectors away. In 1934, gold mineralization was discovered at the new union deposit. A comprehensive re-appraisal of many of the prospects was undertaken by the Klein Letaba Mining company during the 1940s and 1950s. By 1968, after Klein Letaba closed down, the Louis Moore was discovered. The mine was worked intermittently from 1905 to 1978, while the dumps were reworked from 1981 to 1985. Increases in the gold price stimulated renewed interest and Giant Reef Mine was reopened in 1976 and renamed Fumani Mine (Wilson and Anhaeusser, 1998).

Klein Letaba was discovered in 1887 (Wilson and Anhaeusser, 1998). The mine is located 13 kilometres west of Giyani and is one of the oldest in the Klein Letaba goldfields

(Anonymous, 1977). During the 1960s, Klein Letaba was the largest gold producer in the Giyani, but was closed in 1968 following a rock burst. In 1986, the Klein Lethaba Mine recommenced operations as Gazankulu Gold Mining Company Ltd (GazGold) (Wilson and Anhaeusser, 1998; Anonymous, 1977). In mid-1995, it went into provisional liquidation and the mine was abandoned after major rock slides (Anonymous, 1977).

Louis Moore was the second largest producer of gold in Giyani. It is situated on a Greenstone remnant 8km north of the main belt (Anonymous, 1977). The mine operated intermittently from 1905 to 1978. In 1980, Louis Moore Mine was reassessed by Mining Corporation and the dumps were reprocessed between 1981 and 1985 (Wilson and Anhaeusser, 1998; Anonymous, 1977).

2.2. Problems of Abandoned Mines

The issue of abandoned mines with its associated physical health and safety and environmental concerns constantly emerges around the world as a reminder of the legacy of the past mining operations (MMSD, 2002). Some of these historic mine sites are in a deplorable state and continue to cause damage to the environment and potential risks to human and animal health in the surrounding areas (Mhlongo *et al.,* 2013). Environmental degradation due to mine waste, acid mine drainage and soil erosion outlasts the lifespan of a mine, resulting in a legacy that poses a daily threat to the health, safety and well-being of communities around the mine (Krause and Snyman, 20014).

2.2.1. Environmental impacts of abandoned mines

Environmental consequences of abandoned mines include altered landscape, unused pits, shafts and adits, land no longer useable due to loss of soil or soil contamination, spoil heaps covering the land, abandoned tailings disposal facilities, contaminated aquatic sediments, derelict work sites with compacted and polluted soil, and changes in vegetation (MMSD, 2002). These environmental concerns are localized and only affect the mine lease area, but pollution as a result of the waste rock, tailings and spoil dumps that are generated can have severe impact that extends to nearby properties (Allen *et al.,* 2001).

Mine waste, including tailings, are generally considered as one of the largest environmental concerns of defunct mines in South Africa (Nelushi *et al.,* 2013). According to Matshusa *et al.* (2013), tailings are rich in heavy metals such as Mn, Zn, Cu, Cd, Co, Ni. Heavy metals are non-degradable and readily accumulate to the toxicity levels. During intensive rainfall, these metals can be transported to the nearby environment and contributed to surface water and groundwater pollution. A study by Mundalamo *et al.* (2015), demonstrated that tailings dams at New Union Gold Mine are thinly covered by vegetation on slope and on the surface such that water and wind erosion are likely to occur. Louis Moore tailings dam is not rehabilitated and has no vegetation, consequently it is highly eroded and susceptible to wind erosion and water (Muzerengi, 2015).

Acid mine drainage (AMD) is the most significant problem affecting water resources (Mhlongo and Dacosta, 2016). Acid mine drainage occurs when surface or groundwater flows from or over abandoned mine features containing sulphide mineralization. Discharge from adits or open pits, as well as surface flow over and seepage through sulphide rich waste rock and tailings can produce acid drainage (MMSD, 2002). AMD generated from abandoned mines may be dispersed into the areas downstream of the mine, result in release of metals in the surrounding environment posing potential risk for water and soil system (Comero *et al.,* 2012). Water is one of the resources most frequently polluted by abandoned mines. It is also the main conduit which impacts from abandoned mines extend beyond the immediate site (MMSD, 2002). AMD is recognized as a multi-factor pollutant and the main factors are acidity, salinisation, metal toxicity and sedimentation processes in natural water systems (Akcil and Koldas, 2005).

In South Africa, AMD problems worsen daily (Mhlongo and Dacosta, 2016). AMD from coal mining has been reported to be problematic in the Highveld Coalfield in Mpumalanga. This problem has attracted significant media attention on the consequences of severe pollution seen in the Loskop Dam and the Olifants River Catchment (DWAF, 2001). The Olifants River in Mpumalanga is reported to be one of the most threatened river systems in South Africa (Ballance *et al.*, 2001). This is due to the reports of unexplained fish and crocodile deaths within the catchment (De Villiers and Mkwelo, 2009).

Another example is that of Witwatersrand basin which is characterized by vast number of abandoned mine sites that contribute significantly in the discharge of acidic water into the major rivers of South Africa (Mhlongo and Dacosta, 2016). The contamination of the streams adjacent to Witwatersrand Goldfields mine tailings pose a health risk for the people in the nearby informal settlements who drink the river water without appropriate treatment (Wide *et al.,* 2004).

Another consequence of abandoned mine is loss of productive land. Due to a long history of mining, a significant portion of South Africa's land is locked up in mine dumps. It is estimated that 45 million cubic meters of underground mine excavations exists between Crown and Carletonville on the West Rand and that there are three billion cubic meters of gold tailings in South Africa (MMSD, 2002). These mining activities and tailings occupy a large area without any proper development or land use.

2.2.2. Physical hazards of abandoned mines

Abandoned mines constitute environmental pollution sources that pose significant public health and safety risks. These are particularly high when the public has a direct access to the sites, as is the case in the most areas of abandoned/historic mine-sites in South Africa (DMR, 2009).

Public concerns at abandoned mine sites can include accessible openings (i.e. unblocked pits, tunnels and shafts), hazardous mine waste, abandoned infrastructure, and ground surface instability (NOAMI, 2009). A study by Matshusa and Makgae (2014), found that Birthday Gold Mine in Giyani area is characterized by unsafe open shafts and unstable grounds which pose safety problems and limits future land use. In this region, processing was done elsewhere, as such there are only shafts in the village. A study by Rembuluwani *et al.* (2014), demonstrated that open shaft at New Union Gold Mine is not covered or protected to prevent access by community members. The minimum health hazard associated with these shallow openings at this mine is pollution as a result of the community throwing domestic wastes in the open voids such as diapers. According to Rembuluwani *et al.* (2014), the open voids can also cause a problem during rainfall season due to flooding. The flooding may pose health hazard and also infiltrate and contaminate ground water with heavy metals.

A study by Mhlongo *et al.* (2013) revealed that Nyala Mine is characterized by four shallow and less extensive pits. The mine has one extensive pit which contains water throughout the year, and it is rated the most hazardous mine feature to both the environment and the members of the public and animals. Mhlongo *et al.* (2013), further explain that the pit contains large volume of water, thick sticky mud at the pit floor, and has unstable pit walls which presents a serious physical hazard.

Another physical impact from abandoned mines is the dust from old waste disposal sites. This can be nuisance and a health hazard if it contains certain minerals and heavy metals (MMSD, 2002). Dust and soils from abandoned mines might contain contaminants such as silica, asbestos fibres, chromium and heavy metals which are hazardous to human health (Mhlongo and Dacosta, 2016). Children playing on and around these sites may ingest dust that may have health implications (UNEP, 2001).

Heavy metal contamination is one of serious problems in the vicinity of abandoned mine sites. The study of Muzerengi (2015), showed that the level of Ni, Co, Zn, As and Cr in soil within the vicinity of Louis Moore Gold Mine were significantly higher than the tolerable levels. The study of Mundalamo *et al.* (2015), showed that the soil and *C. dactylon* at New Union Gold Mine contain high level of As and Hg. Pollution of soil from contaminated mine waste is a source of danger to communities in the vicinity of the abandoned mine (Muzerengi, 2015).

Heavy metals are potentially hazardous to the soil and may poison people and animal through the food chain (Nikolaidis *et al.*, 2013). The presence of these heavy metals in soil and vegetation is worrisome because communities cultivate and grasses are frequently grazed upon by livestock and wild animals, which may lead to bio-magnification in the food chain (Mundalamo *et al.,* 2015). Humans can also accumulate these potential toxic elements through ingesting mine tailings and drinking contaminated waters as well as feeding on fish from contaminated streams (Adamu *et al.,* 2014). This may therefore have some health implications on the humans and animals through bioaccumulation and bio-magnifications (Siegel, 2002). Serious systemic health problems can develop as a result of excessive dietary accumulation of heavy metals such as Cd, and Pb in the human body (Oliver, 1997).

The Silvermines area in County Tipperary, Ireland, had been associated with a legacy of health and safety issues of abandoned mines (Connelly, 2009). These include the mine tailings, the rock waste, and other process waste from mining, containing heavy metals, which are mobilized after heavy rain, entering the streams. These tailings impoundments have also produced severe dust blows, with the wind-blown particles containing heavy metals (Connelly *et al.*, 2005; Connely, 2009). In 1999, the deaths of cattle on a farm adjacent to this tailings pond were said to be attributed to Pb poisoning (Connelly *et al.,* 2005).

2.3. Rehabilitation of Abandoned Mines in South Africa

Mining in South Africa is significant for local and global economy. According to Glazewski (2005), mining has historically been the mainstay of the South African economy and has both shaped its social and environmental fabric. The mineral wealth has formed the backbone of the country’s economy for over 100 years (Swart, 2003). However, the toll on the environment has been enormous, leaving the current government with legacy of ownerless and abandoned mines which are continuously damaging the environment (Swart, 2003). The need to rehabilitate abandoned mines is increasing, owing to public health and safety issues and more recently to increased awareness of sustainable development and the importance of environmental preservation (UNEP, 2001). According to Du Plessis and Brent (2006), the primary concerns for rehabilitation are to ensure public safety and health, and environmentally stable conditions compatible with the surrounding environment, and consequently minimize the environmental impacts caused by mining.

The South Africa’s liability of ownerless and abandoned mines stems from a historic lack of environmental regulation (Swart, 2003). Under traditional weak regulation system, many mines became defunct and ownerless (Munnik *et al.,* 2010). Many companies have exploited minerals without properly rehabilitating the land, thus leaving behind the excavations and improperly closed mines (Nzimande and Chauke, 2012). There were 5906 officially listed abandoned mines in South Africa that were closed down prior to the promulgation of the Mineral and Petroleum Resource Development Act (28 of 2002) (Auditor-General South Africa, 2009).

The Apartheid government attempted to deal with this situation through Fanie Botha Accord, which was the agreement between the Minister of Water Affairs and Chamber of Mines. It was agreed that the state was to take 100% of the responsibility for all mines closed before 1976 while 50% of the mines closed between 1976 and 1986 were to be state responsibility and 50% the owner’s responsibility. After 1986 all mines and their closure were to be the responsibility of the owner (Munnik *et al.*, 2010; Auditor-General South Africa, 2009).

2.4. The Common Risk Ranking Systems for Abandoned Mines

Given the vast number of abandoned mine-sites in South Africa, it is not possible to immediately rehabilitate all derelict and ownerless mines because of the limited availability of capital and manpower (DMR, 2009; Kim *et al.,* 2015). Therefore, it is necessary to score and rank the abandoned mine-sites in terms of risks associated with each one of them (Kim *et al.,* 2015; Day and Harpley, 1992; DMR, 2009). The ranking of the mines in terms of their potential impact on public health and safety and the environment (DMR, 2009), assist in identification of the mine features with greatest hazards and that should be given a high priority for rehabilitation. The purpose of the priority setting process is to identify abandoned mine-sites that require attention and support mine reclamation planning by comprehensively quantifying the nature and extent of hazards associated with abandoned mines (Haness and Warwick, 1991).

There has been a number of priority setting mechanisms established to address large number of abandoned mine sites. Variety of priority setting approaches have been developed for specific use to assist in setting priorities for site-remediation efforts or for general use in ranking alternative remedies (Caldwell and Ortiz, 1989; Haness and Warwick, 1991). These approaches differ considerably according to the single or multiple objectives of priority ranking types of data measures used and their degree of uncertainty and methods for treating intangible but nevertheless instrumental factors.

Several abandoned mine hazard rating systems have since been developed in various parts of the world with the purpose of prioritizing the locally existing abandoned mine-sites for remedial action. Some of the existing models focus on pollution, suited for geographic area are intended for, and developed based on the legislation of their respective states. The Risk Screening System (RSS), a site hazard evaluation system based on the source–pathway–receptor equation was originally developed in 2001 by the Pattle Delamore Partners Ltd. (2001) and then modified in 2004. The presence of all three components means there is some level of risk, while the absence or near absence of any of the components means there is no or minimal risk. The hazard and pathway components of the risk equation are, in turn, defined by a variety of parameters that are considered to be the most important in determining the degree to which the hazard exists, or in defining whether a pathway to a receptor is complete. The RSS has been designed for ease of use, based on readily obtainable information. The information required to assign parameter values in the RSS is easily available through maps, regional council databases, phone calls, site visits, and the like. However, the ranking is too coarse to greatly benefit from such detail, although it may boost the confidence placed on the final ranking. The RSS is intended to be sufficient to prioritize sites for further investigation. If a more detailed assessment is required, consider using the RHAS (Pattle Delamore Partners Ltd., 2001).

The CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act) Hazard Ranking System (HRS) was developed based on Section 105(8)(A) of CERCLA for determining priorities among releases or threatened releases of hazardous substances, pollutants, and contaminants, throughout the United States to take remedial action (Wu and Hilger, 1984; USEPA, 1990). The HRS combines various characteristics of the sites, waste and surrounding environment to compute an overall score. As part of the calculation, separate scores are calculated for each exposure pathway which includes groundwater, surface water, soil and air (USEPA, 1990). The procedures for determining and combining HRS scores provide a relative ranking of sites. According to EPA (1992), the scorer must realize that the HRS is a screening tool, not a detailed risk assessment. Given the considerable uncertainties regarding specific characteristics of a site and its surrounding environment at the time of scoring, the HRS score should not be viewed as a measure of absolute risk that must be determined to the last decimal point.

Montana’s AIMSS is a fully developed and implemented prioritization methodology which is based on the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Hazard Ranking System (HRS) with significant modifications employed to fit mining scenarios (Pioneer Technical Services,1994; Jordan and Abdaal, 2013). AIMSS was developed to consider multiple constituents of concern at the concentrations observed in site samples, in contrast to HRS, which is based on the contaminant of concern observed to be present in the highest concentration (USEPA, 2008). The data used for AIMISS is physically collected at each site to assign the rank scores and also allows for evaluation of potential safety hazards of the abandoned mine sites (Pioneer Technical Services,1994; Jordan and Abdaal, 2013).

A few states have their ranking systems. For example, the Washington Ranking Method (WARM) which was developed by Science Application International Corporation (1990), for use by the US State of Washington for assessment of the relative potential risks from waste sites (Pioneer Technical Services,1994). When ranking a site, the WARM considers the primary routes through which humans or the environment could be exposed to hazardous substances found on that site. These routes include air, surface water, and groundwater. (Arranz-Gonza´lez *et al.,* 2015). According to the Pioneer Technical Services (994), this ranking method provides several types of information about the relative risks posed by a site. It provides individual exposure pathway scores and a more general overall relative risk ranking. The information acquired for the WARM can be used by Ecologists, along with other established factors, in setting its priorities for cleanup actions. The Washington Ranking Method employs a "general" look at potential exposure from a site with a limited set of data. Cleanup standards are established as specific concentrations of a chemical in a particular medium which will be protective of human health and the environment. The WARM provides a framework in which to organize and compare sites (Arranz-Gonza´lez *et al.,* 2015). However, it is not the only factor used to determine which sites receive priority for Ecology’s resources. Other considerations include the availability of funds, the potential cost of cleanup, the level of cooperation shown by a responsible party, and public concern about a site (Arranz-Gonza´lez *et al.,* 2015).

RRM was developed by the Crown Contaminated Sites Branch (CCSB) in British Columbia, to provide a scientifically based, defensible and systematic methodology for the evaluation and ranking of priority Crown contaminated sites based on potential risk to human health and the environment (Power *et al., 2010;*). RRM separates risk criteria into ecological and human health risks, as well as aquatic and terrestrial risks which is done in a formal risk assessment. This is done to avoid the problem of “diluting” issues during ranking, as well as allowing independent evaluation of these risks, which may have different management actions (Power *et al.,* 2010). According to Stewart (2015), the process uses two components to prioritize sites: A risk ranking support tool (RRM Tool), which is a data entry and calculation spreadsheet that compares contaminants in soil, water, and sediment to regulatory standards, and, a risk ranking workshop (RRM Workshop) brings together internal and external experts on contaminated sites, including geologists, engineers, biologists, and toxicologists, to review and assess the information available on Candidate Sites.

All the hazard rating systems mentioned above, evaluate relative site hazard based on a set of major parameters characterizing sites. The selected parameters are assigned numerical scores based on field data and qualitative judgment and then combined into a final score, known as the site hazard score. These systems adopt a qualitative or semi-quantitative approach to assess site risks and describing risks in terms of scores. Risk scores assigned to hazardous sites or potentially hazardous sites allow for ranking in order to decide about resource allocation and priorities for action in terms of the detailed investigation.

2.5. Mine Rehabilitation Strategies

Activities intended to alter and improve biological and physical conditions at a degraded site are referred to as rehabilitation, restoration, and reclamation (Beukes, 2008). These terms are closely linked but refer to distinct phases in the process of ecological recovery (Nazan, 2013). Restoration is the process of repairing the damaged to diversity and dynamics of ecosystems (National Research Council, 1992). Reclamation is the process of reconverting disturbed land to the previous state or another productive land (Beukes, 2008). According to Nazan (2013), rehabilitation is required when an ecosystem is changed so dramatically that returning to the original landscape is no longer possible.

According to the Chamber of Mines guidelines for mine rehabilitation, rehabilitation means putting the land impacted by the mining activity back to a sustainable usable condition (Tanner, 2007). Mine rehabilitation is carried out to improve the disturbed part of the environment to a degree that integrates well with the surrounding environs thus effectively supporting other land uses (Mhlongo *et al.*, 2012). The ultimate aim of reclamation activities is to create a landscape, which correspond to the interests of society (Zasterova *et al.*, 2015).

The general rehabilitation goals for areas disturbed by mining are to create sites that are safe to human and wildlife, nonpolluting, stable and able to sustain post-mining land use (Nzimande and Chauke, 2011). According to Mhlongo *et al.* (2013), rehabilitation activities should focus more on all facilities that pose safety and health hazards to the citizens. Many rehabilitation designs exist and one could make use of many methods to achieve the goal and objectives of rehabilitation. However, it is necessary to always consider the end use of the land (DMR, 2009). When selecting rehabilitation strategy, it is necessary to take into account not only the ecological condition of the site, but also socioeconomic conditions (Zasterova *et al.,* 2015).

2.5.1. Strategies for Rehabilitation of Mine Shafts

There are various methods by which an open shaft can be made safe. The best options on this always depend on the nature of the site that requires rehabilitation and its openness to the public (Entec, 2007). These strategies range from erecting masonry walls or wire fences, placing concrete or steel slabs or grates across the tops of the openings to inserting concrete plugs (DRM, 2009).

The erection of fencing with appropriate warning signs around the shaft may be used to prevent public access (BML, 2010). According to Entec (2007), protection provided by these measures may be limited. Fences have a limited lifespan and need regular inspection and maintenance to be kept in good condition or order. Another method that can be employed is capping. This involves the installation or placing of a cover over the entrance to a shaft (Entec, 2007). According to the Division of Minerals and Geology (2002), shafts may be capped with reinforced concrete. The concrete cap must be anchored to a competent rock, so the area around the perimeter of the opening generally requires some excavation and stripping of overburden to expose the rock conditions. In the same view, Tanner (2007), states that shaft capping requires excavation, clearing, chipping or trimming to remove loose, weathered or otherwise deteriorated rock to establish a stable collar for the cap. Cap dimensions are based on the size of the opening and surrounding unstable areas, as caps will not prevent the collapse of shaft sidewalls.

In other cases, the procedure involves the filling of the shaft, with inert rubble from demolition, or other waste materials (Tanner, 2007). According to Entec (2007), Shaft filling is a drastic measure which should only be considered in extreme cases where there is no other way to make them safe. Shaft fillings are permanent, completely eliminate the hazard, and are maintenance free (Division of Minerals and Geology, 2002). Shaft filling includes backfilling, Polyurethane Foam (PUF) Plug and Blasting (BML, 2010). According to Robertson (1996), shafts must be backfilled or sealed off and leveled to blend in with the surrounding topography. Another alternative is structural sealing, which includes precast concrete panels and poured in place concrete slabs installed over vertical or near-vertical mine openings (Division of Minerals and Geology, 2002).

2.5.2. Strategies for rehabilitation of areas occupied by mine infrastructure

Once mining has ceased, all buildings/infrastructure are to be dismantled, unless they are in satisfactory condition to support the socioeconomic development of the area (Robertson, 1996). In some circumstances, certain portions of the existing infrastructure can be gainfully used after closure such as offices and workshops. According to Tanner (2007), these structures need to be identified and protected. This could be adapted for sustainable use including small business enterprise, light industry and/or warehouse use (Wood, 2014). Another consideration is that some of the infrastructure could be of significant historic value (Steenkamp and Mostert, 2012). There are also examples where mine buildings and infrastructure are of cultural and historical significance and are maintained as mining museums (MRM, 2011). Transportable infrastructure/buildings are usually sold as scrap or disposed of at waste dumps (MRM, 2011).

Infrastructure/buildings can also be inhabited by local people. According to Matsabatsa (2009), following the mine closure at Penge, approximately 250 houses and other buildings previously belonging to the miners were used by local people and former employees for residential purposes. After identifying the structures that can be gainfully and sustainably used after closure, the remainder of the structures are dismantled and buried so that the land can be converted to its final use (Tanner, 2007). Administrative buildings and accommodation walls are razed to the ground. Foundation remains only if it is covered with mineral substances that permit the growth of self-sufficient vegetation (Robertson, 1996). Once all infrastructures are removed the ground should be ripped and allowed to rehabilitate naturally once a suitable seed mix has been applied (MRM, 2011).

2.5.3. Strategies for rehabilitation of mine waste dumps

A sustainable rehabilitation of mine waste includes the effective reuse and recycling of waste streams (Lottermoser, 2011). It also includes the shaping to acceptable configuration, applying topsoil or appropriable soil conditions, planting and ensuring successful growth for the required post mining period (Zasterova, 2015).

Provided that it is chemically non-reactive, mine waste can be used in various ways outside the mine environment. Solid mine waste (overburden, waste rock, solidified tailings, slag, dust) can be used as backfill in underground or open pit workings (Lottermoser, 2011). According to Mhlongo *et al.,* (2013), backfilling of shallow excavations with tailings and spoils materials has potential of eliminating both physical and environmental hazards associated with surface open excavations. Back-filling is also a useful way to return piles of overburden and spoil materials removed during mining back to the landscape thus avoiding the need for disposal (Sloss, 2013).

Waste rock and tailings can be selectively used in earthworks and road construction. They may also be sold for use as aggregate in a variety of applications (Lottermoser, 2011). Tailings can be used as a fertilizer or supplement to enhance soil quality. Manganese tailings have been used in agro-forestry. Clay-rich tailings can be used for making bricks, floor tiles, and cement (Menezes *et al.,* 2012). Waste dump piles can be further stabilized with the aid of re-vegetation programs, which simultaneously reduces dust hazards (Australian Government, 2006).

Other alternative approaches of rehabilitation include covering mine dumps with appropriate material to prevent their escape surrounding into the environment. They are covered to prevent ARD and AMD from occurring (Zasterova, 2015). There are essentially two options for isolating tailings and waste rock; these include burial beneath a layer of overburden, or covering with water (INAC, 2007). Prior to covering, it is customary to dewater the tailings, and to allow consolidation of the material (European Commission, 2009). Compacted clay or equivalent material at the site of discharge can be used to provide an impermeable seal (INAC, 2007). Covering waste dumps may be required if establishment of desired vegetation demands landscaping and improvement of soil quality (Robertson, 1996). To prevent dust at Silvermines Ireland, tailings were capped and vegetated (Conelly, 2005).

2.5.4. Strategies for rehabilitation of contaminated soil and water

Treatment methods for contaminated water can be categorized into hydrologic controls, passive and active treatment. Most hydrologic controls are preventive measures (Division of Minerals and Geology, 2002). Remediation methods for contaminated soil include excavation, stabilization of the metals in the soil on site, and the use of growing plants to stop the spread of contamination or to extract the metals from the soil (phytoremediation) (Lambert *et al.,* 2000).

Hydrologic controls involve minimizing water ingress to workings or coming into contact with waste rocks or tailings (Younger, 2000). This technique can control water volume, direction and minimize the effects of acid mine drainage (AMD) on receiving streams (DMR, 2009). Surface diversion of runoff involves construction of drainage ditches to move surface water quickly off the site before infiltration or to limit its movement into the backfill (Johnson and Hallberg, 2005). This is the most cost-effective reclamation approach because it eliminates the cause of the problem rather than treating symptoms (Division of Minerals and Geology, 2002). Another alternative is to exclude either water or oxygen (or both), to prevent the formation of Acid Mine Drainage. According to Johnson and Hallberg (2005), this is possible by flooding and sealing abandoned deep mines.

Biological rehabilitation methods involve the use micro bacterial activity and wetlands to enable the degradation of some contaminants to harmless intermediate phases and end products (Hattingh, 2003). Biological controls are also known as passive treatment systems to rely on the natural behavior of soils, rocks and ecosystems (Division of Minerals and Geology, 2002). Biological processes have considerable scope for integration with other rehabilitation processes and are applicable to both contaminated soil and groundwater (Hattingh, 2003). They involve passing mine water through an environment where geochemical and biological processes purify water to the extent that it can be ultimately released into the surrounding environment (Johnson and Hallberg, 2005). Sometimes a contaminated site is simply revegetated in a process called phytostabilization (Lambert *et al.* 2000). This technique does not eliminate the cause of the problem, but it can be a feasible and cost-effective alternative to address the problem. Passive treatments are more appropriate for abandoned mines (Sloss, 2013).

Active treatment systems are intensive treatment systems involving chemicals and require regular operation and maintenance (Johnson and Hallberg, 2005). Active treatment involves oxidation, dossing with alkali and accelerated sedimentation (Younger, 2000). Alkaline dosing can be accomplished by diverting surface water into beds of alkaline material to pick up alkalinity and allowing the alkaline water to flow into spoils or underground mine pools. Alkaline water flowing into old shaft can be useful attempt to neutralize the acidic drainage (DMR, 2009). Active treatment systems are used for both operational mine sites and occasionally post closure scenarios (Taylor, 2005). According to Connelly (2005), aerobic wetlands were used to aid in the removal of remaining metals which have been seen to precipitate in the existing lagoon at the Silvermines, Ireland.

Excavation and physical removal of the soil is perhaps the oldest remediation method for contaminated soil (Lambert *et al.,* 2000). It includes excavating and removing contaminated soil and place into a designated and properly managed containment area on-site (Hattingh, 2003). The other option is excavation and relocation of contaminated soil to approved facilities off-site.

CHAPTER THREE

RESEARCH METHODOLOGY

This chapter provides a detailed account of the methods and procedures that were used in the collection and processing of data required to meet the objectives of this research. Therefore, the research approach that was adopted for this study comprised preliminary work which is divided into desktop study and reconnaissance survey, fieldwork which involves the compilation of the field inventory of the abandoned mine features, scoring and ranking of the hazards of the mine features and development of the multi-criteria framework for selection of the rehabilitation strategies for abandoned mines (see Figure 3.1).

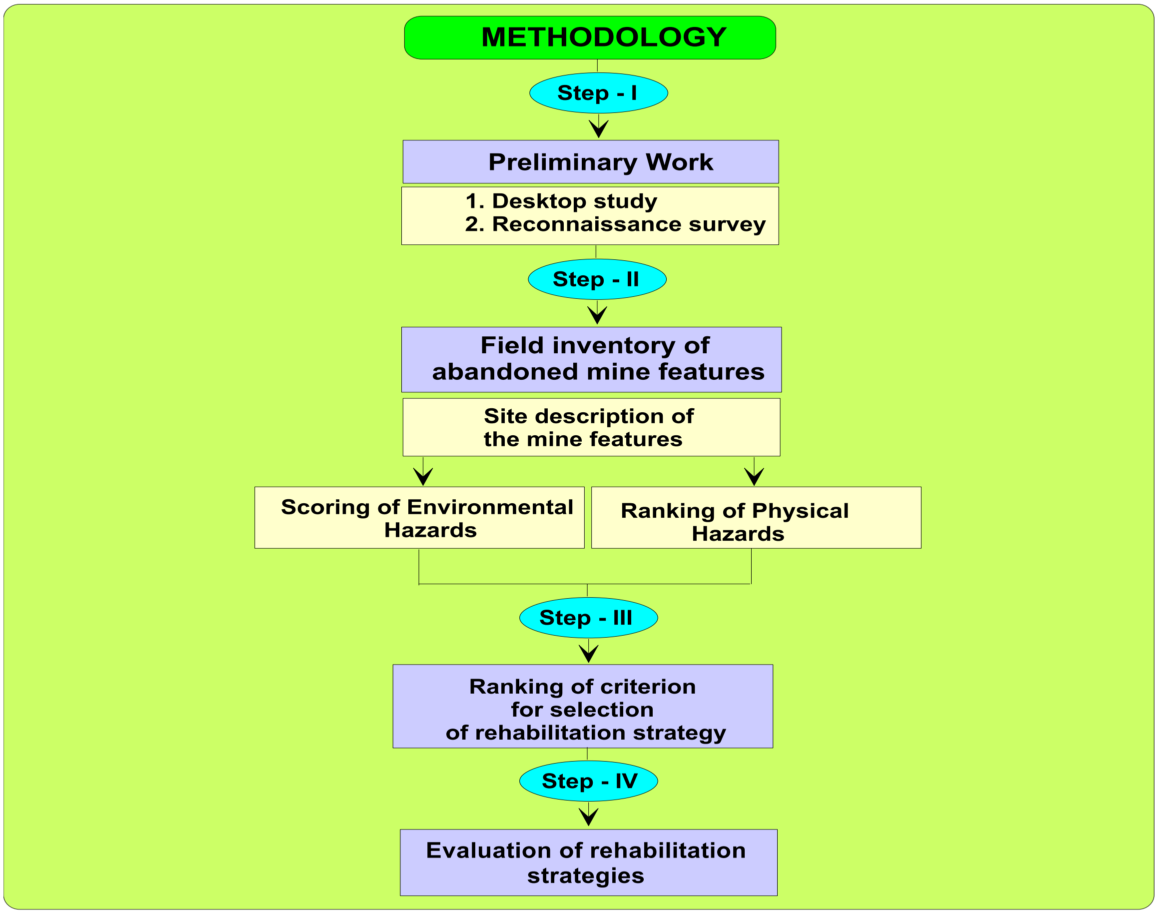

Figure 3.1: Flow chart of methods and procedures for collection of data

3.1. Preliminary work

The preliminary study was conducted to evaluate existing information on abandoned mine sites in the Giyani Greenstone Belt. This was carried out to establish the background and/or history of mining in the study area. Preliminary work was divided into desktop study and reconnaissance survey.

3.1.1. Desktop study

The desk study was undertaken prior to the commencement of the actual field work. It comprised a review of historical maps of the study area and interpretation of aerial photographs. It was undertaken for the purpose of understanding the wider environmental setting of the site and its surroundings. This study will allow for a better planning of the actual field work.

3.1.2. Reconnaissance survey

Reconnaissance survey is a brief survey of the study area that provides valuable information for planning the actual data collection procedures. It was carried out to examine the current conditions of the site to establish the most feasible methods and procedures to be used in carrying out the detailed investigation. It provided first-hand information about the site and its surroundings. In this research, the survey involved traversing around the mine site while making observations of the critical mine features. The reconnaissance survey assisted in documenting the current state or conditions of the abandoned mine sites.

3.2. Compilation of the field Inventory of Abandoned Mine Features

This research began with the compilation of the field inventory of the abandoned mine features. This was carried out in the form of site characterization. Such characterization involved identification, locating and mapping of the abandoned mine features. It also involved the collection of samples of mine tailings to determine their chemical characteristics to establish their potential environmental and health hazards.

The mapping of the abandoned mine features involved traversing around the mine-site to locate and describe the abandoned mine features, such as mine shafts, tailings dumps and dilapidated infrastructure. The description of the mine features placed special emphasis on the current state of the features and the associated environmental and physical hazards. It also involved the identification of potential receptors of each hazard scenario. This included mapping of abandoned mine features such as mine shafts, open pits, tailings dumps, and abandoned infrastructure. The receptors that were considered included people and animals (health and safety risk types), and the environment (aquatic life, fauna, and flora, environmentally sensitive areas).

The abandoned mine features were located and marked on the topographic map using the handheld Garmin Global Position System (GPS) 60. The sketch map produced in the field was georeferenced and superimposed on the orthophotographs of the scale of 1:10 000 and spatial resolution of 5m covering the study area. The Global Positioning System was used in capturing the absolute location of the important features that may not be visible on the topographic map and orthophotographs due to the limitation of the resolution of the orthophotos used. The abandoned mine features were digitized from the orthophotographs and sketch maps to produce a decoded feature map of the abandoned mine-sites. This was carried out using ArcGIS 10.4 software package.

3.3. Scoring of Physical and Environmental Hazards

Once the mine features were identified and associated hazards were established, the ranking of the features in terms of their associated hazards was then conducted. The extent and seriousness of hazards to the victim were expressed by assigning scores to the source, exposure routes and possible damage to the victim of the hazard. The source of the hazard was scored based on the nature of the mine feature established through abandoned mine site characterization. Exposure routes were evaluated based on the ease to access the site or feature and the land use around the site. Possible damage was scored based on the magnitude of the identified potential risk. Such ranking assisted in identifying features that need to be given serious attention in the rehabilitation work.

For each identified abandoned mine feature, a score for the source of the hazard, exposure routes and possible damages to the victim was assigned. Scores were assigned on a scale of one to five. Where there is no hazard detected a value of 0 was recorded. The criteria that were used in assigning scores are shown in Table 3.1.

Table 3.1: The criteria for assigning hazard scores to each mine feature

Scores	**Description**		
	Source	**Exposure Route**	**Possible damage**
1	No. of sources	None	Negligible
2	No. of sources	Low	Low
3	No. of sources	Moderate	Moderate
4	No. of sources	High	High
5	No. of sources	Extremely high	Extremely high

The selected parameters were assigned numerical scores based on the field data and then combined into a final score, known as the hazard score. Risk scores assigned to mine features allowed for site ranking in order to decide about resource allocation and priority for action in terms of detailed site investigation. Equation 3.1 was used to generate hazard scores for each mine feature.

$$\mathbf{H_{PorE}} = {\sum \frac{\mathbf{S} \times \mathbf{E} \times \mathbf{P}}{\mathbf{Q}}} \Big/ \mathbf{H_{Total}} \qquad (3.1)$$

Where: ***H*** represents hazard score for each mine feature, ***S*** is the number of risks presented by the mine feature, ***E*** is the exposure routes to the hazard, **P** represents the possible damage of the hazard and ***Q*** is the factor used for the reduction of the scores. Each criterion was assigned a maximum point score (ranging from 1 point to 5 points) based on the perceived importance of the criterion. Based on this point scale, the maximum total score possible for each abandoned mine feature is 25 points. The most dangerous sites had the highest hazard scores.

This scoring method was reformed from the Historic Mine Site Scoring System (HMS-SS) whose primary objectives are to rank abandoned mine sites based on their impact on human health, animal health and the environment. The conceptual model used the Source–Pathway–Receptor paradigm. This paradigm required that each of the parameters within the model is documented, estimated, measured or recorded (Mhlongo and Dacosta, 2013).

3.4. Ranking of the Hazards

The total risk hazard was determined by integrating physical and environmental hazard scores using the risk matrix technique. Once all the hazard risks were scored and ranked, the total hazard score for each mine feature was calculated by multiplying the physical hazard score by the corresponding environmental hazard score. This was then presented in the risk matrix. Ranking of hazards was conducted in order to categorize hazards in terms of seriousness.

Table 3.2: The physical hazard and environmental hazard ranking and classification guidelines

Score	Rank	Colour Code	Description
>4	Extremely high	**Red**	Both environmental and physical hazard risks are most critical
>3<4	Very high/high	**Orange**	Environmental hazards are very high than physical hazards
>2<3	High	**Yellow**	Both physical and environmental hazard risk are high.
>1<2	Moderate	**Green**	Physical hazards are moderate; they need less attention than environmental hazard risks.
<1	Low	**White**	Both Physical and Environmental hazard risk can be ignored as they usually do not pose any significant

3.5. Evaluation of Rehabilitation Strategies

Mine rehabilitation is a significant and essential element of mining that is carried out to improve the disturbed part of the environment to a degree that integrates well with the surrounding environs thus effectively supporting other land uses (Mhlongo and Dacosta, 2016). Adoption of the most suitable rehabilitation strategy is a problem with multi-dimensional nature and there are so many factors in this problem that have a serious influence on the decision-making process (Wood, 2014). An appropriate rehabilitation strategy normally mitigates the adverse effects of abandoned mines and improves the sustainability of the surrounding areas. Mine site should be rehabilitated so that the ultimate land-use and morphology of the site are compatible with either the current land-use in the surrounding area or with the pre-mining environment.

Though there are several factors that need to be considered for determining the optimum post-mining land use, the Analytical Hierarchy Process (AHP) and Pugh Matrix were efficient for selecting the most appropriate rehabilitation strategies. AHP method was utilized in this research for weighting/evaluating the factors that were considered in the selection of appropriate rehabilitation strategies. Pugh matrix was utilized to classify more appropriate alternatives of rehabilitation strategy. Reconciling these two methods resulted in an improved decision process. This is based on the concept that in order to develop a reliable framework, it is necessary to consider all possible types of alternatives.

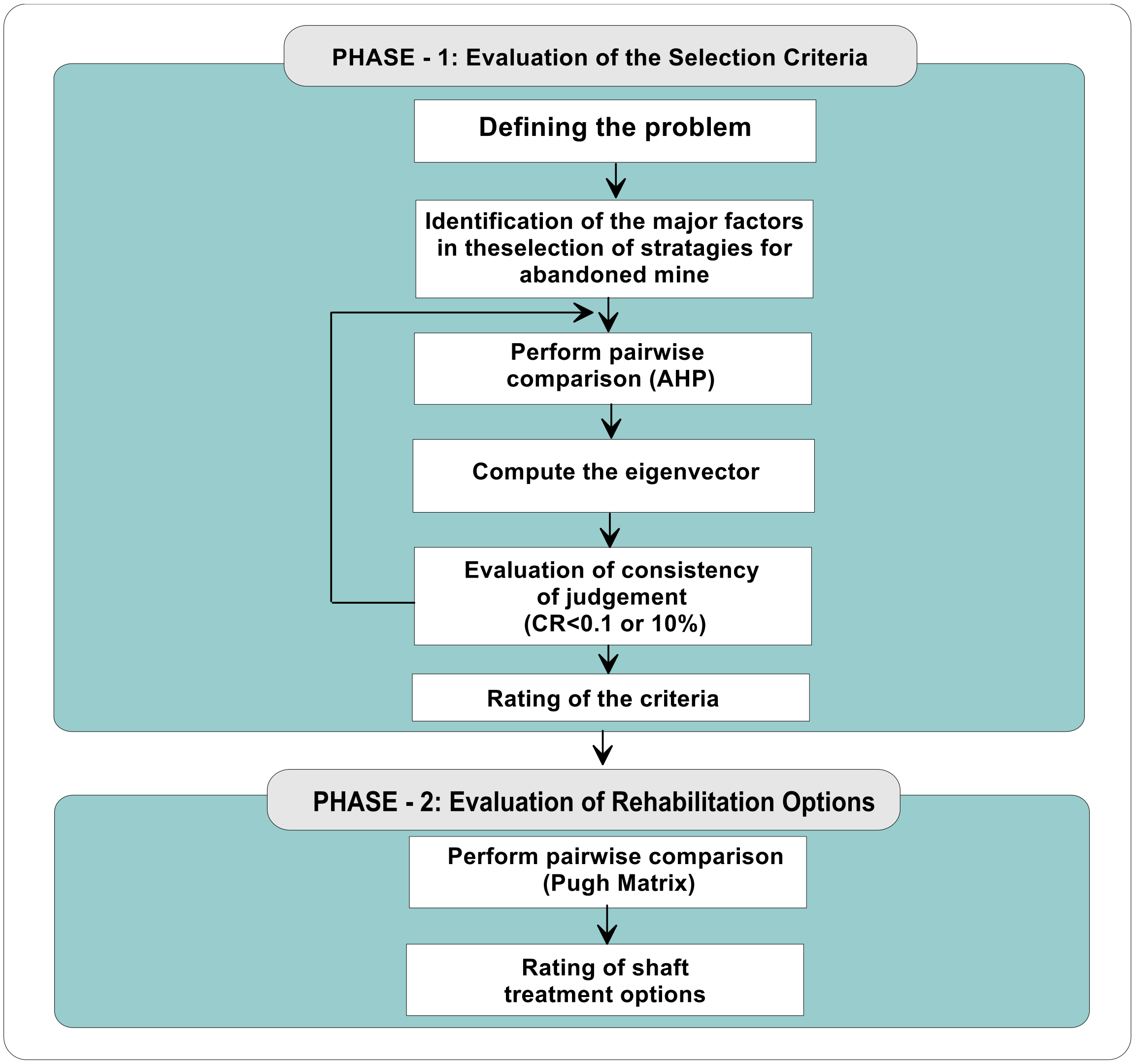

Figure 3.2: Flow chart of methods and procedures for the development of multi-criteria framework.

3.5.1. Evaluation of factors for selection of rehabilitation options

AHP method was used for weighting the criteria considered significant in the selection of appropriate rehabilitation strategies. According to Ataei *et al.* (2008), AHP is defined as a quantitative technique that facilitates the structuring of a complex multi-attribute problem and provides an objective methodology that is applied to a wide variety of decisions in the human judgment process. According to Ataei *et al.* (2008), AHP provides a flexible and ease to understand the way of analyzing complicated problems. The main advantage of

AHP is its ability to handle complex and ill-structured problems, which cannot be handled by rigorous mathematical problems (Ataei *et al.,* 2008).

The factors that were taken into consideration in the evaluation and selection of rehabilitation options include cost-effectiveness, duration of the treatment, application of the treatment, maintenance requirements, risks of physical injury, risks of ground movement and risk of water contamination. The weighting for each criterion was determined using a pairwise comparison matrix. This included the completion of the pairwise comparison matrix, calculation of the criteria weights and assessment of the consistency matrix.

To complete the considered selection, factors were evaluated against each other in terms of their relative importance. Index values 1 to 9 (or their reciprocals), from the Fundamental Scale represented in Table 3.3 of the AHP was used to weight the factors. The judgments were entered in the upper triangular half of the matrix. The number of comparisons was determined by using the formula n(n−1)/2 judgments, where n is the number of criterion being compared, in the case of this research n is equal to 7. So for this evaluation, 21 judgments were required.

Table 3.3: Fundamental scale for pairwise comparisons (from Kluge and Malan 2011)

Preference weights	Definition	Explanation
1	Equally preferred	Two activities contribute equally to the objective
3	Moderately preferred	Experience and judgment strongly or essentially favor one activity over another
5	Strongly preferred	Experience and judgment strongly or essentially favor one activity over another
7	Very strongly preferred	An activity is strongly favored over another and its dominance demonstrated in practice
9	Extremely preferred	The evidence favoring one activity over another is of the highest degree possible of affirmation
2,4,6,8	Intermediate values	Used to represent compromise between the preferences listed above
Reciprocals	Reciprocals for inverse comparison	

The reciprocals of the upper diagonal were used to fill the lower triangular matrix. If a_{ij} is the element of row *i* column *j* of the matrix, then the lower diagonal is filled using Equation 3.3.

$$a_{ji} = \frac{1}{a_{ij}} \tag{3.3}$$

Following the development of the comparison matrix, the weights of the individual factors were calculated. First, a normalized comparison matrix was created by dividing each value in the matrix by the sum of its column. To get the weights of the individual criteria, the mean of each row in the matrix was determined. Since the weights are already normalized; their sum is expected to be 1.

Furthermore, the AHP approach allowed for the consistency test to be performed. The pairwise comparisons are considered to be adequately consistent if the corresponding consistency ratio (CR) is less than 10% (Ataei *et al.,* 2008). The CR will be calculated using the consistency index (CI), determined by adding the columns in the pairwise comparison matrix and multiplied by the resulting vector by the vector of priorities (i.e., the approximated eigenvector). This yields an approximation of the maximum eigenvalue (denoted as λ_{max}). Then, the CI value was calculated using equation 3.4.

$$\mathrm{CI} = \frac{(\lambda_{max} - \mathrm{n})}{(\mathrm{n} - 1)} \tag{3.4}$$

The Comparison between CI and random index (RI) for a matrix is defined as the Consistency Ratio (CR) expressed in Equation 3.5. Where RI is the average index value generated randomly obtained through experiments using samples with large quantities. Random value index (RI) for the matrix of the order of 1 to 15 as shown in Table 3.4. If the value of Consistency Ratio is smaller or equal to 10%, the inconsistency is generally considered, however if CR is greater than 10%, the subjective judgment is revised (Ataei *et al.,* 2008).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{3.5}$$

Table 3.4: Random Index (from Kluge and Malan 2011)

N	1, 2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

3.5.2. Identification of suitable rehabilitation strategy

Identification of the most appropriate rehabilitation strategy out of the many alternatives is a key success to the rehabilitation of abandoned mine-sites. To assist with this process, the Pugh Matrix technique was used as the tool for selecting the most suitable rehabilitation strategies for different features of the mine. The Pugh Matrix is one of the most widely used methods of finding out the best solution once several alternatives have been generated (Lonmo and Muller, 2014). It facilitates the evaluation of alternative solutions against significant criteria (Madke and Jaybhaye, 2016). According to Raudberget (2010), the purpose is to identify the rehabilitation strategies that are most suitable or best satisfy the criteria. The Pugh Matrix is not intended to be a mathematical matrix; it is simply a format for expressing ideas and the criteria for the evaluation of these ideas in a visible, user-friendly fashion (Lonmo and Muller, 2014). The Pugh Matrix is easy to use and relies upon a series of pairwise comparisons between design candidates against several criteria or requirements. One of its key advantages over other decision-making tools is its ability to handle a large number of decision criteria (Madke and Jaybhaye, 2016). The key outputs of using the Pugh matrix are that it gives a greater understanding of the potential solutions and an understanding of the interaction between the proposed solutions, which can give rise to the additional solution (Lonmo and Muller, 2014).

The matrix was constructed using Microsoft excel. The factors and relative weight obtained in AHP were used to generate the weights of the factors required in the use of the Pugh matrix. The factors were listed down vertically in the matrix, and rehabilitation strategies will be listed horizontally after the relative weights obtained from the AHP (see Table 3.1). After a matrix with the factors on the vertical axis and the rehabilitation strategies on the horizontal axis were created, the performance of each rehabilitation strategy was evaluated against each of the criteria by assigning a + (where rehabilitation strategy was more favorable or better), – (where rehabilitation strategy was less favorable or worse) and S (where there was no clear difference or same). The scores were then aggregated by counting the number of + and – that a solution has. The product of all positives and negatives identified the most suitable rehabilitation strategies.

Table 3.4: The use of Pugh Matrix in the Identification of the suitable rehabilitation strategy

Matrix	**Rating (AHP)**	**Rating (1-10): Pugh Matrix**	**Alt-1**	**Alt-2**	**…**	**Alt$_i$**
F_1	1	6				
F_2	2	5				
F_3	3	4				
…	4	3				
F_j	6	1				
Sum of Positive (+)						
Sum of Negative (–)						
Sum of Same (S)						
Weighted Sum Positive (+)						
Weighted Sum Negative (–)						
Totals						

CHAPTER FOUR

EVALUATION AND ANALYSIS OF HAZARDS OF ABANDONED MINE FEATURES

The evaluation of strategies for rehabilitation of abandoned mine features required that a comprehensive inventory be conducted and an in-depth understanding of the hazards of the abandoned mine sites or features gained. In general, these aspects of the research were conducted to quantify the degree of hazards posed by the abandoned mine sites or features. This chapter presents the results of assessment of nature and seriousness of the hazards associated with the mine features in the study area. It provides a description of the current state of the mine features and the associated environmental and physical hazards.

4.1. General Description of the Abandoned Mine Sites

Figure 4.1a and b shows the distribution of abandoned mine features around the Klein Letaba and Louis Moore abandoned mine sites. These mine sites were both found covered by sparse trees (mainly Acacia and Mopani trees) and few shrubs. They were found extremely degraded and characterized by recent surface excavation created by artisanal miners and resulting to the alterations of the natural abandoned mine landscape. Table 4.1 depicts the areal coverage of different features found in Klein Letaba and Louis Moore abandoned gold mine sites. These features include large tailings dumps, rock dumps, mine shafts and dilapidated surface infrastructure and mine houses (see Figure 4.1 and 4.2).

The two study sites are characterized by two huge tailings dumps which were left unrehabilitated. The top parts of the tailings dumps were covered by patches of natural grass. However, the slopes of the dumps were found without any cover and there was an evidence of serious erosion on these slopes. The effect of water erosion can be seen by deep and wide erosion gullies development on the slopes of Louis Moore tailing dumps. This erosion is being influenced mainly by the slope angles and lack of vegetation cover on slopes. Such was not observed in the case of the Klein Letaba tailing dumps, as the slope was less steep than that of Louis Moore tailings dumps. However, a small unprotected heap of waste rock dump was identified in Klein Letaba Abandoned Mine Site.

The infrastructure left by mining in the area was found to have become a target to illegal mining activities and most of the structures have been vandalized and are in a deplorable state. This includes the old buildings, the mineral processing plant and storage facilities such as silos and ore bins. These abandoned mine sites are also characterized by a total of five abandoned mine shafts. The two mine shafts found at Louis Moore Mine seem to have been previously closed with timber platform and concrete slabs but they have been demolished by illegal miners who are operating at the site. The other three openings were found in Klein Letaba Mine. One of them was closed with a concrete slab, while the other was found closed with galvanized steel gate. The structure in the latter opening was no longer attached to the ground to which it was mounted. The third opening was identified as ground subsidence.

The two mines used as case studies in this research were found not more than 500maway from the two major rivers in the area of Giyani. These rivers are Nsami and Klein Letaba River and they are also found in close proximity to agricultural lands in the area. There is a potential for sediments washed out from these mine sites to accumulate in the adjacent agricultural land and rivers, thus resulting to environmental contamination in the area.

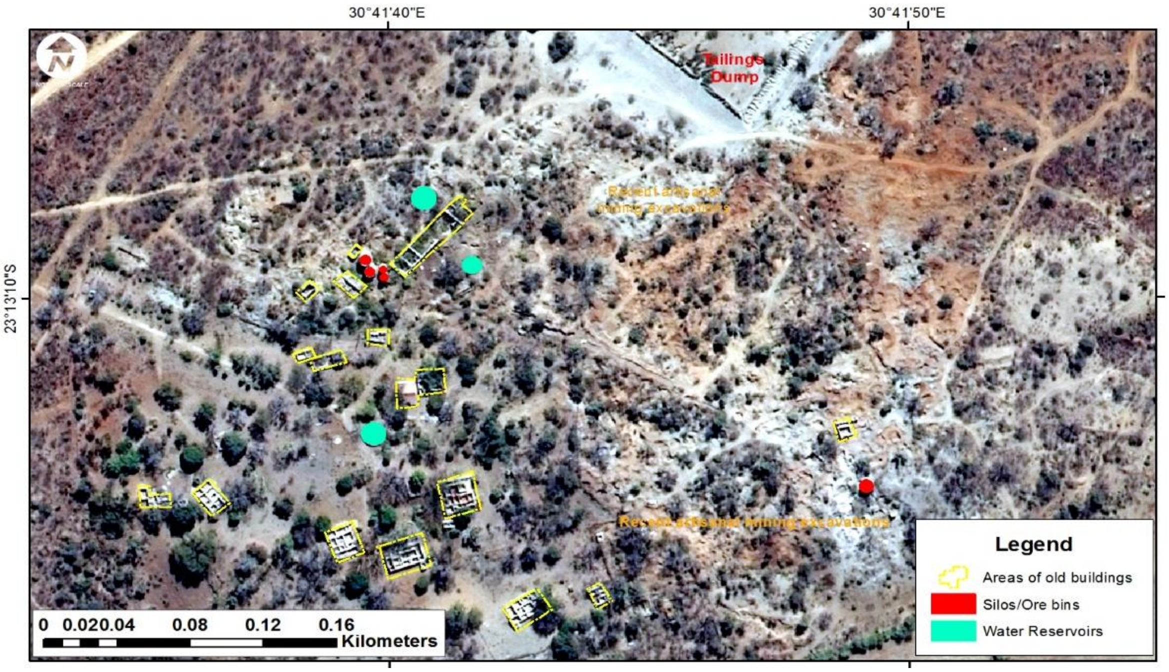

Figure 4.1: Distribution of abandoned mine features at Louis Moore abandoned Gold Mine.

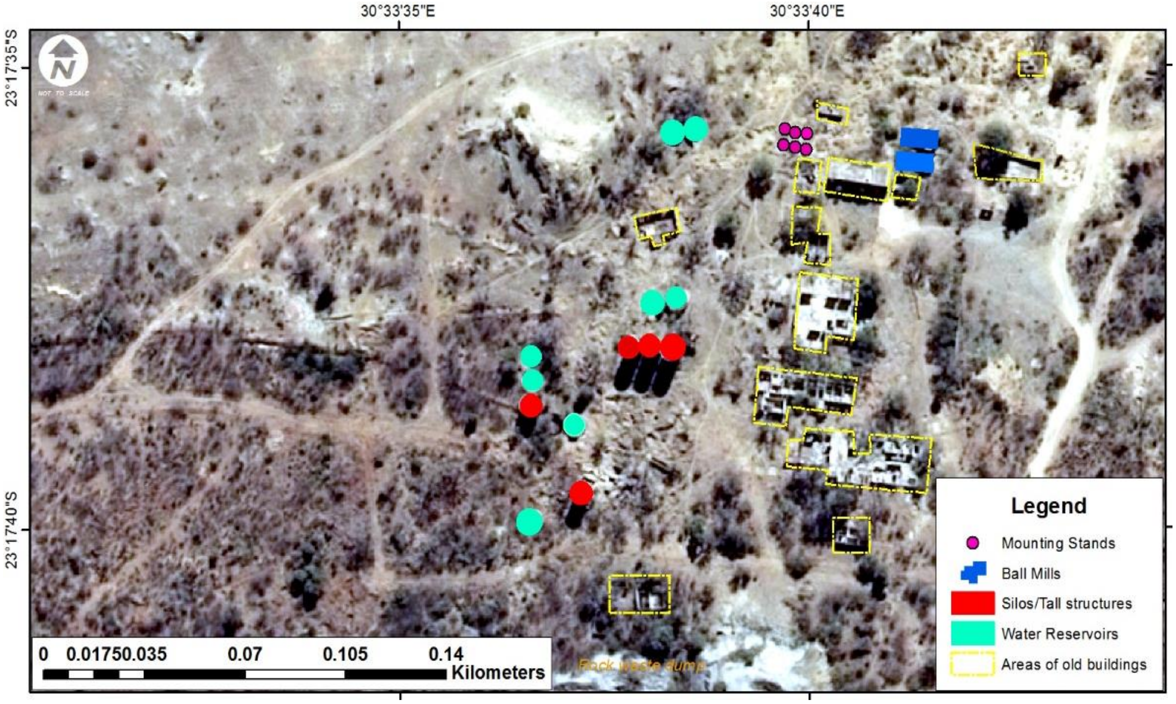

Figure 4.2: Distribution of different abandoned mine features at Klein Letaba abandoned Mine.

4.2. Description of the Abandoned Mine Features

The description of abandoned mine features placed emphasis on the current state of the mine feature and the nature of environmental and physical risks they present. This involved identification, locating and carrying out field assessment of the abandoned mine features. This process also involved–sampling of tailings material to determine their chemical composition to determine their potential of polluting the environment. In addition, it also involved identification of potential receptors of the hazard identified. These features include mine shafts, tailing dumps, waste rock dumps, dilapidated mine buildings and old abandoned mine processing plants.

4.2.1. Open mine shafts

Open mine entries are common features of abandoned mine sites where mining was conducted using underground mining techniques (Mhlongo *et al.,* 2017). They are mostly associated with risks of accidentally falling into the mine workings. These features are commonly found to be at deplorable state, untreated or treated with old techniques which have no guarantee of sustainability (Mhlongo *et al.*, 2018).

There were five mine entries that were found at Klein Letaba and Louis Moore Mines. Two of these mine entries were found at Louis Moore and they were closed with concrete slabs and timber platform. The other three mine entries were found at Klein Letaba Mine and they were closed with galvanized steel and concrete plug while one of them was ground subsidence. These mine entries can present a significant environmental hazard and may pose danger of collapse as well as potential leak of noxious gases and acid mine water (Gunn *et al.,* 2008). Mine openings can fail for various reasons if not remediated properly for closure and such failure may be attributable to the fact that; (i) timber, steel platform closure material can over time deteriorate and weaken, (ii) support and roof spans weaken, deteriorate and can fall without warning, and (iii) underground mine working which is close to the surface can cave and collapse and this may subsequently lead to ground subsidence. Issues such as the use of timber platforms and concrete slabs in the treatment of mine shafts as observed in the study area are discussed in the following sections.

Timber Platform

According to Lecomte e*t al.* (2014), some old mineshafts were closed by old closure system techniques which presented no guarantee of sustainability. More commonly, old mine shafts were closed using a single on-surface or near-surface wooden platform, eventually completed by filling material on the shaft head whilst leaving the whole column empty (Lecomte *et al.,* 2014*;* Gallagher *et al.,* 1978). In the same breath, Littlejohn (1979), discovered that timber platform was erected at the surface of the bedrock and heterogeneous infill between the platform and surface. According to Gallagher *et al.* (1978), over time timber platform deteriorates and weakens.

The case in Louis Moore Mine illustrates this kind of a situation. The risks observed at Shaft-A in Louis Moore are linked to the deterioration of the sealing structure at the shaft head (which is the timber platform). There were three situations that were observed about the shafts that were closed with timber platform. Firstly, the wooden platform was found deteriorated, thus leading to a possibility of failure of the timber platform. Failure of the decayed wooden platform can be attributed to the subjection of the platform to excessive loads or when surface material ground on which they rest fail (Lecomte *et al.,* 2014).

In the second case, the timber was concealed by years of vegetation growth (see Figure 4.3) such that the shaft was extremely difficult to identify. This may pose serious threats to people and animals that frequently visit or move around the site. These people and animals may fall into the mine shaft. Consequently, this may lead to death due to physical body injuries and drowning in water that is contained in the mine workings (Wrona *et al.,* 2016). According to Rembuluwani *et al.* (2014), the occurrence of water in a shaft can induce the creation of voids which may destabilize the lining of the shaft, resulting in its collapse.

Figure 4.3: An illustration of the shaft covered with a deteriorated concrete slab and timber platform at Louis Moore Mine.

Concrete slab

At Louis Moore Mine, Shaft-B was found sealed with concrete slab, whilst the shaft lining of burnt clay bricks was exposed. According to Yang *et al.* (2017), many shaft collapses are related to failure of the shaft lining. Lecomte *et al.* (2014), further explains that, the most frequent failures of the shaft lining result from a decrease of resistance or from increased pressure of the grounds. The lining of the shaft could break due to deformation caused by the pressure excreted on the ground that exceeds the strength of the shaft lining (bricks, stone blocks, concrete). Yang *et al.* (2017), further stated that the behaviour of concrete and brick shaft lining can be considerably affected by long-term exposure to harsh mine water, as well as harsh weather conditions.

There were three scenarios observed from Shaft-B. The first one is the fact that, the artisanal miners managed to break the shaft lining which was constructed using bricks (see Figure 4.4). According to Steenkamp and Mostert (2012), the breaking of the mine shaft lining was done in order to gain access to the underground mine workings where they mined the remnants of the ore. This unscrupulous act by artisanal miners created a big hole on the shaft lining. Secondly, the shaft was closed using a single on-surface or near-surface concrete leaving the whole column empty, hence susceptible to cave in. Thirdly, the ground around the collar/entrance of the shaft was unstable; as the artisanal miners have dug all the supporting material around the collar of the shaft. This was evidenced by the diggings that were observed around the shaft.

Figure 4.4: An illustration of the shaft lining destroyed by illegal miners.

Galvanized Steel

One shaft at Klein Letaba Mine was found closed with galvanized steel gate as shown in Figure 4.5. Two scenarios were observed from this shaft. The first is that the structure used to close the shaft was no longer in contact with the ground to which it was mounted. The structure has potential to fall or shift and this may lead to the shaft not being properly closed. This may result to physical injury to anyone climbing on or walking around the structure. Secondly, the shaft was used to pump underground water for different purposes such as irrigation and domestic use. According to Mhlongo *et al.* (2018), the pumping of water from the underground mine workings can cause an upward migration of contaminated groundwater. Thus, this shaft has a relatively high potential of discharging contaminated and acidic water to the environment.

Figure 4.5: An illustration of mine shaft closed with steel structure at Klein Letaba.

Ground subsidence

Surface subsidence is particularly common in areas of shallow mine workings. According to Bell et al. (2000), subsidence of the ground surface can be regarded as the ground movement that takes place because of extraction of mineral resources or abstraction of fluids. In Klein Letaba, the effect of ground subsidence was clearly visible on the mine landscape. This might have been caused by the collapse of the underground mine tunnels due to failure of the structures that were used to support them (Xie and Liang 2010; Strozik, 2016). According to Bell et al. (2000), subsidence can be responsible for flooding and can lead to sterilization of land or call for extensive remedial measures or specific construction design in site development.

Surface subsidence can contribute to increase infiltration to underground mine workings, potentially resulting in increased acid mine drainage generation and a need for greater water treatment capacity (Bell et al., 2000). The groundwater flow may be interrupted as impermeable strata break down and could result in flooding of the mine voids. This feature has a relatively high potential of contaminating groundwater and surface water recharge. As a consequence, decimating plant life and vegetation lands over an area of 3 ha, where the seepage may occur.

4.2.2. Mine waste dumps

The selected abandoned mine sites were characterized with two relatively large volumes of tailings dumps and waste rock dump. These dumps occupy a large area without proper development or land used. Both dumps were left without any form of rehabilitation hence they are susceptible to erosion and they are threat to the environment and health and safety of people and animals. This section describes the state of the waste dumps in the study area as well as their environmental, health and safety concerns.

Description of the physical characteristics of tailings dumps

Mine waste dumps and dams are dangerous structures in terms of associated accidental deaths and continuing environmental hazards. These facilities sometimes contain toxic substances. Therefore, mine waste storages need to be constructed and protected in such a way that their adverse effects on human health and the natural environment are minimized on a long-term, continuing basis.

The two study sites namely Louis Moore and Klein Letaba Gold Mines have two large tailings dumps which are unrehabilitated. Mine tailings are potentially subject to wind and water erosion, acid generation and the release of heavy metals (Amponsah-Dacosta, 2015). There were three scenarios that were observed in the abandoned tailings dumps. Firstly, the tailing dumps in the study area were not rehabilitated and with the surface partially covered with native grass and few shrubs and trees; mainly, Acacia Karoo and Mopane trees as shown in Figure 4.6. This provides evidence that the tailings at the two mines can support the establishment of native vegetation on the top parts and slopes of the tailings dumps.

The other issue was the nature and seriousness of erosion of the tailings dumps observed at the mine sites. According to Amponsah-Dacosta (2015), erosion is a very serious problem at mine disposal sites, particularly if the surface is left unprotected as it was observed in the study area. Dust from the tailings can be harmful to human, animal and plant life. Both wind and water were identified to be the major agents in eroding the slopes of the tailings dumps in the study area. A clino ruler was used for measuring the slope of the tailings dumps. The estimated average slope angle of the tailings dumps at both abandoned mine sites was 40^{o}. This erosion in both sites is being influenced mainly by the slope angles and the absence of vegetation cover on the slopes of the dumps (Rembuluwani *et al.,* 2014). The type of erosion observed at both sites was piping erosion, which is the subsurface erosion along a seepage pathway within or beneath an embankment which results in the formation of low-pressure conduit allowing concentrated flow (Wilson *et al.,* 2007). Another form of erosion that was observed at Louis Moore Mine was gully erosion, which according to Wilson *et al.* (2007), was evidence of piping erosion, which continued resulting in gully erosion.

At Klein Letaba Mine the impact of erosion on the tailings dump was minimal as the erosion trenches were shallow. Yet the tailings dump of Louis Moore Mine was found to be highly eroded as the erosion gullies were very conspicuous and devastating on the slope of tailings, as shown in Figure 4.6. This may cause physical body injuries to people and animals that frequently walk around the dump. The severity of the erosion is high and a probability of erosion occurring again is also high due to the rainwater and wind action. There is evidence that crest walls were used to virtually eliminate erosion on both tailing dumps. Crest walls also prevent precipitation on top of the dumps from cascading down the outer slopes, thus the increased erosion on slopes (Blight, 1989). The horizontal top surface of these tailing dumps was found to be relatively little-affected by erosion. The tailing dumps at Louis Moore Mine are designed in two benches, with lower bench and upper bench height ranging from 5-10m and 10-15m respectively.

The tailing dumps in the study area were both found to be located at less than 500m distance from Nsama River and Klein Letaba River. The tailing dumps found in these mine sites are made up of fine particles, hence the potential to be carried to the rivers through surface runoff (sedimentation) are high (Rembuluwani *et al.,* 2014; Blight and Stephan, 1979). Sedimentation can result in the destruction of habitat for aquatic species and thus disrupting the natural ecosystem. It can also reduce the level of water in the stream and result in deterioration of water quality thereby posing a health risk for the people and animal drinking such water (Bell *et al*., 2000).

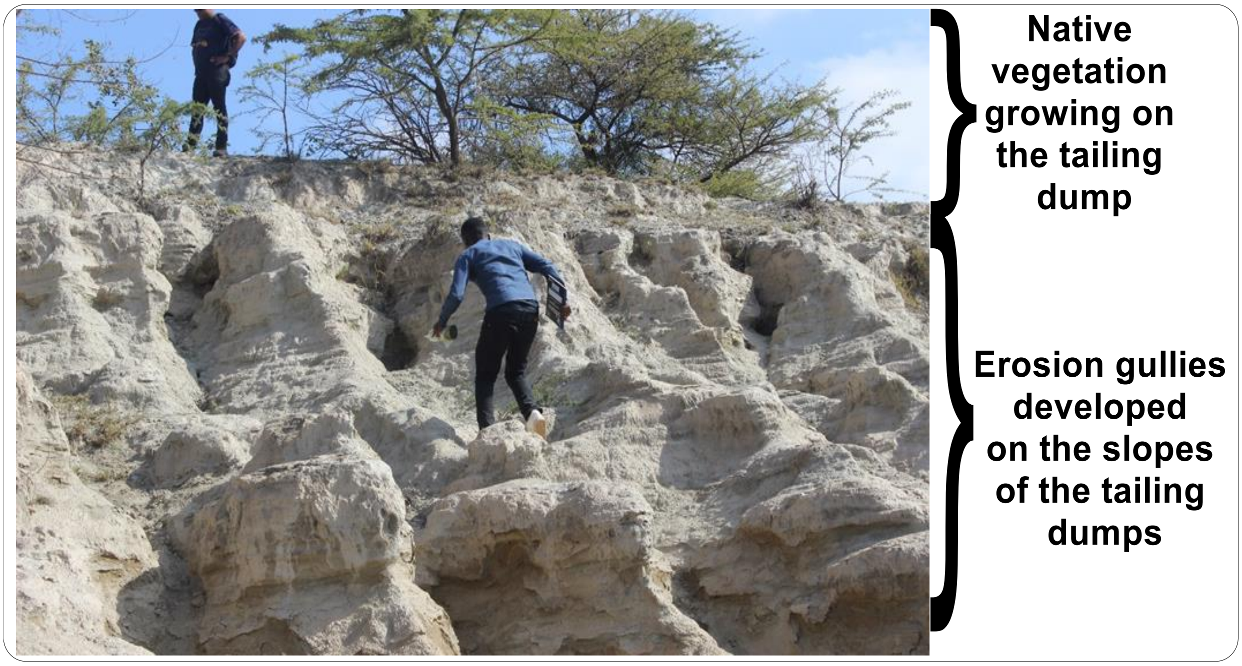

Figure 4.6: Evidence of growth of vegetation on the top surface and devastating effects of gully erosion on the slope of tailings.

Toxic metal concentration in mine tailings materials

Mine wastes are generally considered as one of the most serious environmental and human health concerns and this is particularly the case with defunct mines in South Africa (Nelushi *et al.,* 2013) and the selected sites are no exception. Mine waste dumps at abandoned mine sites release harmful elements and these are likely to affect the affect the health of the communities living near the mine sites. Nelushi *et al.* (2013), assert that toxic metals originating from abandoned gold mine tailings may have a huge impact on the environment and human health.

Tailings dumps at Louis Moore and Klein Letaba are currently exposed, not rehabilitated and have patches of vegetation, highly eroded and hence susceptible to wind erosion. Animals grazing around uncovered tailings dumps being uncovered allow for animals to forage around them, may be exposed to heavy metals through dermal contact, and ingestion of contaminated forage (Ngole-Jeme and Frantke, 2017). This may, therefore, have some health implications on the humans and animals through bioaccumulation and bio-magnifications (Siegel, 2002). The unprotected or uncovered nature of the tailings also facilitates erosion which contributes to extensive spatial dispersion of the tailings particles and consequently heavy metals (Mangonono *et al.,* 2011; Ngole-Jeme and Frantke, 2017). Heavy metals contained in mine tailings dumps are spread to various ecological receptors (fauna and flora), water resources, and the atmosphere when particles of the tailings are dispersed to surrounding environments through various environmental fate pathways. Tailings dumps, therefore, do not just affect the scenic view of the landscape but may also present significant risks to biotic and abiotic environments. The extent of contamination is not strictly limited to the vicinity of mines; contaminated material (i.e. tailings, contaminated river bed and floodplain sediments) may be physically remobilized in high flow conditions (Hudson-Edwards, 2003), thus dispersing pollutants over hundreds of kilometers away from historical mining sites (Resongles *et al.* 2014).

Heavy metals that were considered for this study were arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), manganese (Mn), nickel (Ni), and zinc (Zn). Their concentration in both the tailings dumps was examined considering their contents and impact on the environment and health risks caused by heavy metals. However, the concentration of these heavy metals varies from one site to the other. For instance, the concentration of Ni and Pb metals in Klein tailings was found to be below the permissible limits in soil and while in Louis Moore tailings they were above limits. As and Cu were also found to be above the permissible levels, while the concentration of Zn and Cd were below the permissible limits in S.A soils.

Arsenic and Nickel were found to be the highest accumulated heavy metals in the study area (see Figure 4.7). According to Matshusa and Makgae (2014), an abundance of As and Ni in tailings materials at both abandoned mine sites could be attributed to the presence of pentlandite and arsenopyrite minerals in the ore mined in the area. According to Eisler (2004), these metals are toxic even at low levels of exposure. Once absorbed by the body, they continue to accumulate in vital organs like the brain, liver, bones, and kidneys, for years or decades causing serious health consequences. Consequently, long term exposure to Ni dust is known to cause carcinogenic pneumonia disease (Panoviz *et al.,* 2006). Dermatitis, lung inflammation, eczema and cancer are health conditions associated with excessive Ni intake. Arsenic is regarded as a human carcinogenic from extremely low level of exposure (Panoviz *et al.,* 2006). Arsenic toxicity may cause lung cancer in human and animals, reduce milk yield in cattle, type 2 diabetes, damage to the nervous system, deafness, paraesthesia, organic psychoses with drowsiness, agitation, stupor, delirium, schizophrenia (Matshusa and Makgae, 2014). According Eisler (2004), to arsenic is also associated with excess mortality from cancer of the lungs, stomach, and respiratory tract.

Some elements found in these sites at low concentration have essential nutrients to plants, animals and human health, but at elevated quantities, they become toxic and can cause harm to life (Gashi *et al.,* 2016). Copper (Cu) and zinc (Zn) provide clear examples, both being essential for normal metabolism and both can be toxic in high concentrations as it is the case in both sites. According to Gashi *et al.* (2016), When the quantities of Cu and Zn in the body increase (above Zn-150 mg and Cu-1500), they become toxic which can result in damaged and malfunctioning human organs. For instance, Zn and Cu are considered to be pollutants in water because of their high toxicity to aquatic life, despite their relative toxicity to humans. However, Cu is ubiquitously distributed and toxic only in high concentration (Gzik *et al*., 2003). Consequently, the most commonly reported adverse health effects of Cu and Zn are gastrointestinal distress including nausea, vomiting, and/or abdominal pain but irritation of the respiratory system is also common (Gashi *et al.,* 2016). High concentration of Zn can also affect seed germination. According to Ngole-Jeme and Frantke (2017), high concentration of Zn has the potential of preventing organic matter accumulations in the soil, which would otherwise serve as a source for nutrients for soil biota.

Louis Moore and Klein Letaba tailings were also dominated by Pb, Mn, and Cd. Cd and Pb that are generally carcinogenic and prolonged exposure to low concentrations could lead to kidney disease, lung damage, and fragile bones for Cd, and nervous disorder in the case of Pb (Gashi *et al.,* 2016)**.**

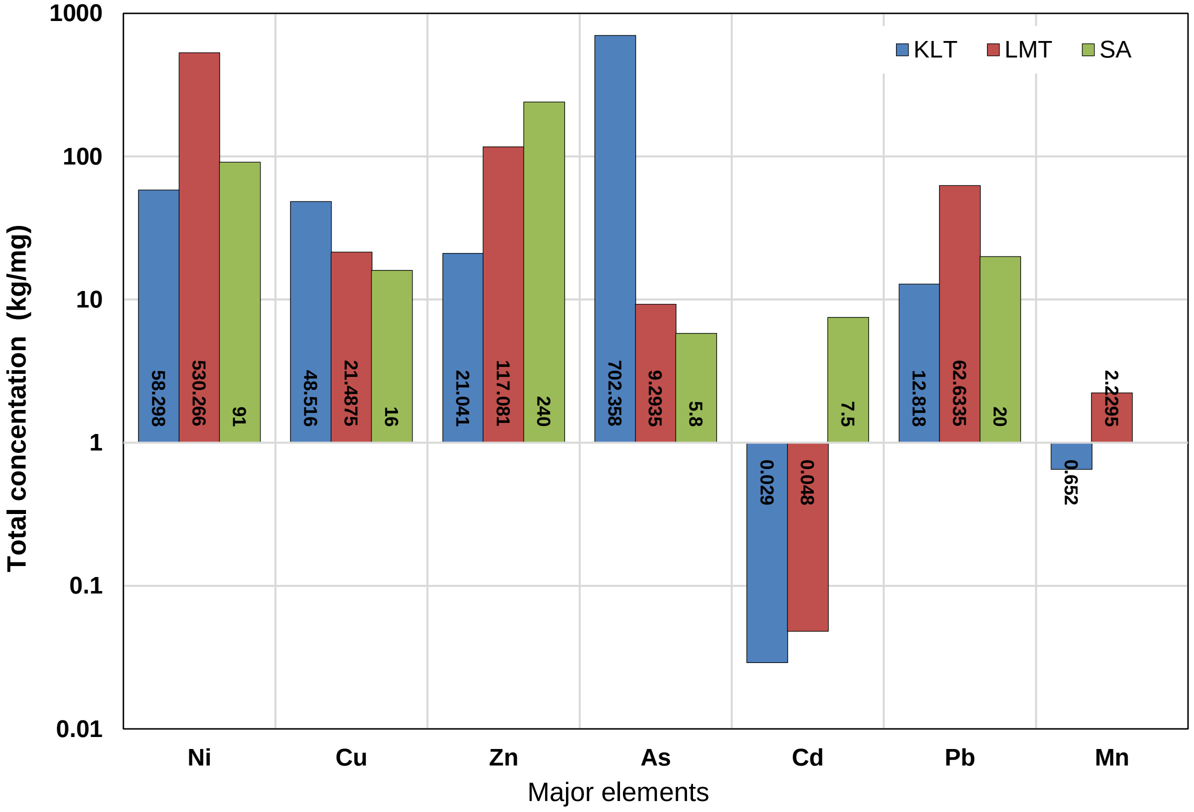

Figure 4.7: Metal concentration in tailings materials at Louis Moore and Klein Letaba mines.

Waste rock dumps

The waste rock dumps are heterogeneous deposits piled up in abandoned mines which are often sites of environmental concern as they commonly contain high concentrations of metals and metalloids, which may be released to the circulating waters during weathering (Marescotti *et al.,* 2015). Apart from altering the natural environment, waste-rock dumps pose serious pollution hazards to the environment and human health. According to Marescoti *et al.* (2015) and Goumih *et al.* (2017), just like tailings dumps, waste rock dumps are also the most prone to erosion. The erosion processes continuously transform the deposit redistributing sediments downslope. This erosion and sedimentation can have serious environmental impacts on watercourses such as clogging up and siltation of river beds, including the destruction of aquatic life. In addition, the major hazards associated with this feature is the in situ soil pH alteration and change in the topography (Marescoti *et al.*, 2015).

In the case of Klein Letaba Mine, as shown in figure 4.8, a relatively small volume of rock dump was abandoned without any security and environmental protection with increased potential to cause hazards. The hazards associated with this rock dump included their potential to alter the soil quality of their surrounding environs. The rock dumps at the study area present artificial hills and these alter the mined terrain. In addition, they contribute to the ruggedness of the terrain as they present major depression on the landscape. These dumps are composed of sand size to boulder particles. The sand-sized particles are found on the top of the rock dump, this has allowed the growth of vegetation on these dumps. Due to their stability and presence of vegetation, there was no evidence of erosion taking place on the waste rock dumps.

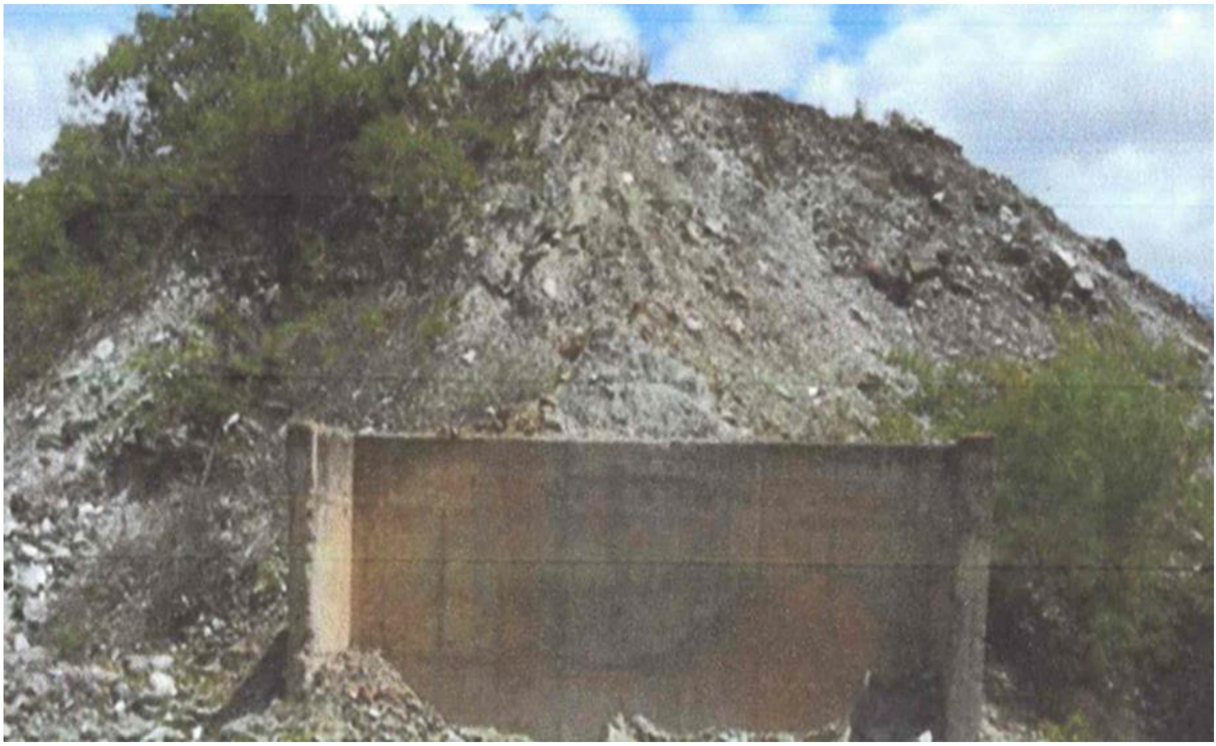

Figure 4.8: Waste rock dump with patches of vegetation at Klein Letaba.

4.2.3. Dilapidated mine buildings

After a mine has been abandoned the buildings and infrastructure are likely to be hijacked by illegal miners. The initial target of opportunistic scavengers after a mine has been abandoned is the steel infrastructure that is stripped and sold as scrap metal. Any remaining infrastructure is then usually randomly vandalized. After all the high-value material is stolen, illegal mining activities may commence on site (Steenkamp and Mostert, 2012). Through weathering and lack of use and vandalism, these structures might deteriorate and collapse.

In the of case Louis Moore and Klein Letaba mines, both sites were found with dilapidated old buildings that have deteriorated with time (see Figure 4.9). It became apparent that the structures have to been taken over by illegal miners, this was evident by the extent of vandalism that was observed at both abandoned mine sites. Buildings at both mine sites were damaged to the state where some of the walls have collapsed or are extensively unstable. The walls that were still standing had developed serious cracks which posed serious hazards to both people and animals. Other features such as cemented/paved floor or foundation of the completely demolished buildings were observed at both sites. Deteriorated foundation of the building may suddenly weaken and the entire building may collapse anytime without warning and cause injuries or fatalities.

The conditions of the structures coupled with illegal mining activities present serious physical hazards which may include fatal injuries to people and animals. In addition, these buildings pose socio-economic concern to community members because they have become a hiding place for thieves and from the surrounding communities. Furthermore, Impacts associated with vandalizing these structures includes the destruction of buildings that may have had some historical significance.

Figure 4.9: An illustration of vandalized abandoned building at Klein Letaba Mine.

4.2.4. Old Mineral Processing Plants

Field survey conducted during the study revealed that there are dilapidated processing plants and ore storage facilities such as silos at Klein Letaba and Louis Moore abandoned mine sites. Figure 4.10 is an illustration of one of the silos and wrecked processing plant at Klein Letaba Mine. The silos at both sites were found to be in a cylindrical shape and are about 6m to 20m high above ground level. Also found at the two mine sites were concrete stands to support agitation tanks. The agitation tanks which were supported by a 3m concrete stands were estimated to be 6m in diameter and 12m high.

These structures are believed to have attracted artisanal mines. This is because the illegal miners dug around them with the aim of recovering the remnants of the gold ore. The spillage from the abandoned structures has a potential of causing public health and environmental hazards since it can result in soil contamination around the processing plant. The area around the mineral processing plants was found to be unstable due to excavations made by the artisanal miners. Over time, these structures can be detached from foundations, thus the potential to fall or shift causing injury to anyone climbing.

Mineral processing plant at Louis Moore Mine

Mineral processing plant at Klein Letaba Mine

Figure 4.10: Dilapidated mineral processing plant at the study area.

4.3. Conceptual model of impacts of abandoned mines

A conceptual site model (CSM) synthesizes and crystallizes what is already known about a site that is pertinent to decision-making requirements. It describes sources and receptors, and interactions that link these. The CSM serves as a planning instrument, a modelling and interpretation aid, and a communication device. The CSM was developed to illustrate the relationship between abandoned mine features and associated physical and environmental hazards.

The conceptual model presented in Figure 4.11 demonstrates the comprehensive review of the identified abandoned mine features with associated hazards and exposure routes in the study area. Based on the study conducted, the abandoned mine shafts were found in a deplorable state and presents the risk of people accidentally falling into old mine workings. This can lead to physical body injury, suffocating, and drowning in water inside the shaft. These features also present a significant environmental hazard, in the worse cases, of surface water contamination. The other environmental hazards associated with shafts included land degradation that limits the substitute use of land, the potential contribution of the shafts to pollution on the environment, and the impact of shafts on the aesthetic beauty of the landscape. The social concern of the abandoned shafts is that these shafts are used for criminal purposes i.e. storage sites for illegal or stolen goods/items.

The abandoned mine tailings were associated with the risks of falling off the dumps due to the steep slope of dumps. Dry tailing deposits contain small particles that are picked up by the wind, transported, and deposited on communities nearby which can cause serious health problems. When rain falls on tailings, it leaches away materials that can cause water pollution (sulfuric acid is often produced when water interacts with tailings). Aquatic life downstream can be disrupted by highly acidic water that leaks from tailings. The heavy metals contained in the tailing dumps can be spread through various ecological receptors, water resources, and atmosphere when particles are dispersed to the surrounding environment through various environmental pathways. These also have a capacity to bio-accumulate, presenting a health risk to humans, animals, and the environment.

The dilapidated buildings and processing plants presented the physical hazards which included the risk of physical body injury with potential accident points where suspending debris or the whole building can fall on passersby/trespassers, junks and thrashes can contain sharp objects that can injure residents in the neighborhood. Other environmental hazards related to neglected buildings and processing plants included the risk of soil contamination and soil texture modification leading to plant community changes in the area and land sterilization since the land cannot be used for development.

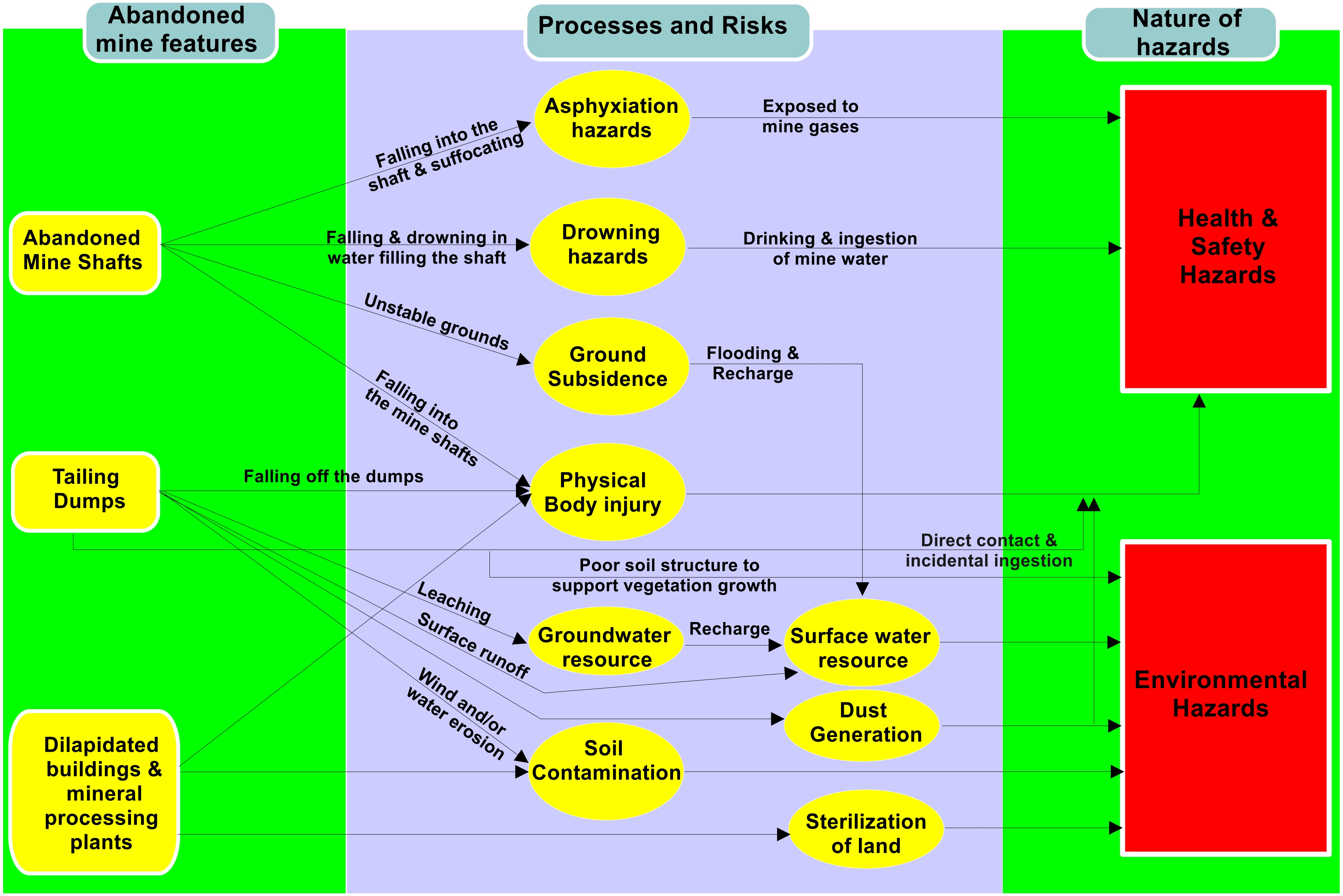

Figure 4.11: Conceptual model representing abandoned mines**.**

4.4. Seriousness of the Hazards of the Abandoned Mine Features

The information on abandoned mine sites collected through literature review and field investigations allowed that the identified abandoned mine features be quantified in terms of their current state and associated hazards. The extent and seriousness of physical and environmental hazards were scored based on the field description of the problems of mine attributes. This is essential for prioritizing and identification of site-specific rehabilitation strategies for the abandoned mines. The following sections present the results of the scoring and ranking of hazards of the identified abandoned mine features.

4.4.1. Problems of abandoned mine shafts

The risk of physical body injury obtained the highest physical risk score of 8 as shown in Figure 4.12. The physical body injuries can result from people and animals accidentally falling into the shaft. Since they were found open, untreated or treated with old techniques that are susceptible to cave-in. Moreover, the shaft in Louis Moore was found concealed with vegetation such that it was extremely difficult to identify. These shafts were also found in a deplorable state and is highly unstable or subsiding grounds as there was evidence of ground subsidence in Klein Letaba, thus increasing the risk of people and animals accidentally falling into the shaft. The risk of people and animals drowning in water in the underground mine workings was scored as the second highest physical hazard of 6 (see Figure 4.12).

The risk of drowning can result from the fact that one of the shafts identified in Louis Moore was without lining, and as such illegal miners managed to create an excavation in order to gain access to the underground mine. Once they get there they can mine remnants of the ore. The destruction the illegal miners cause to the shafts also create avenue for adventurous people to enter the underground mine. Consequently, this caused an increase in the risk of drowning in water in the underground mine workings. The lowest scored physical risks were accidentally or voluntary ingestion of the contaminated water or having dermal contact with contaminated water and the exposure to toxic gases inside the shafts. These risks can be a consequence of people accidentally falling or voluntarily entering the shaft.

The results of scoring for environmental hazards portrayed contamination of water resources at Klein Letaba River as the highest hazard due to ground subsidence. Contamination of water resources emerged as the most serious concern with the highest environmental hazard score of 10 as shown in Figure 4.13. This is because ground subsidence has a relatively high potential of contaminating groundwater and surface water recharge, which can be caused by flooding. Consequently, this poses a serious threat of decimation of aquatic life and vegetation lands in the proximity of 3 ha in the area. The second highest environmental hazard was the cave-ins which was scored 6.4 as shown in Figure 4.13. The risk of cave-in can be caused by the unstable grounds around the shafts since there were diggings that were observed around the shafts, mostly at Louise Moore. This was followed by the risk of the development of sinkholes and major cracks due to water entry. Sterilization of land due to subsidence was scored as the lowest environmental hazard but this prevents land use for development.

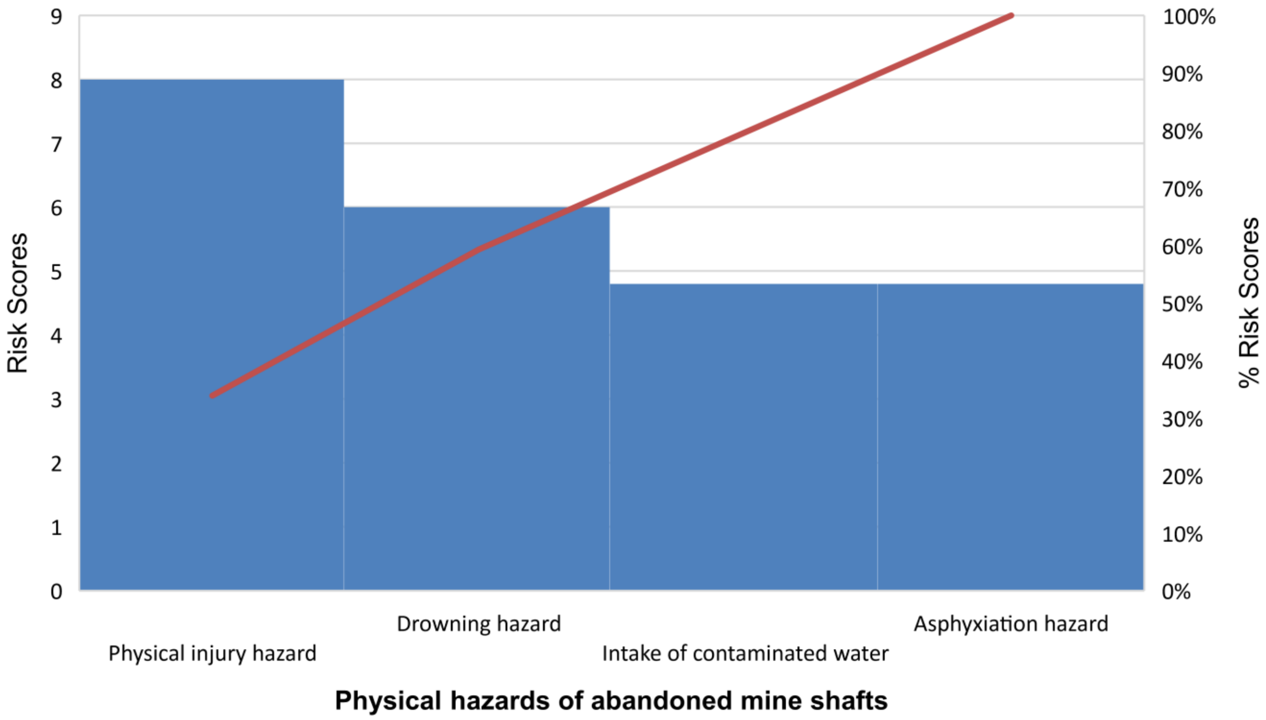

Figure 4.12: The physical hazards scores for abandoned mine shafts.

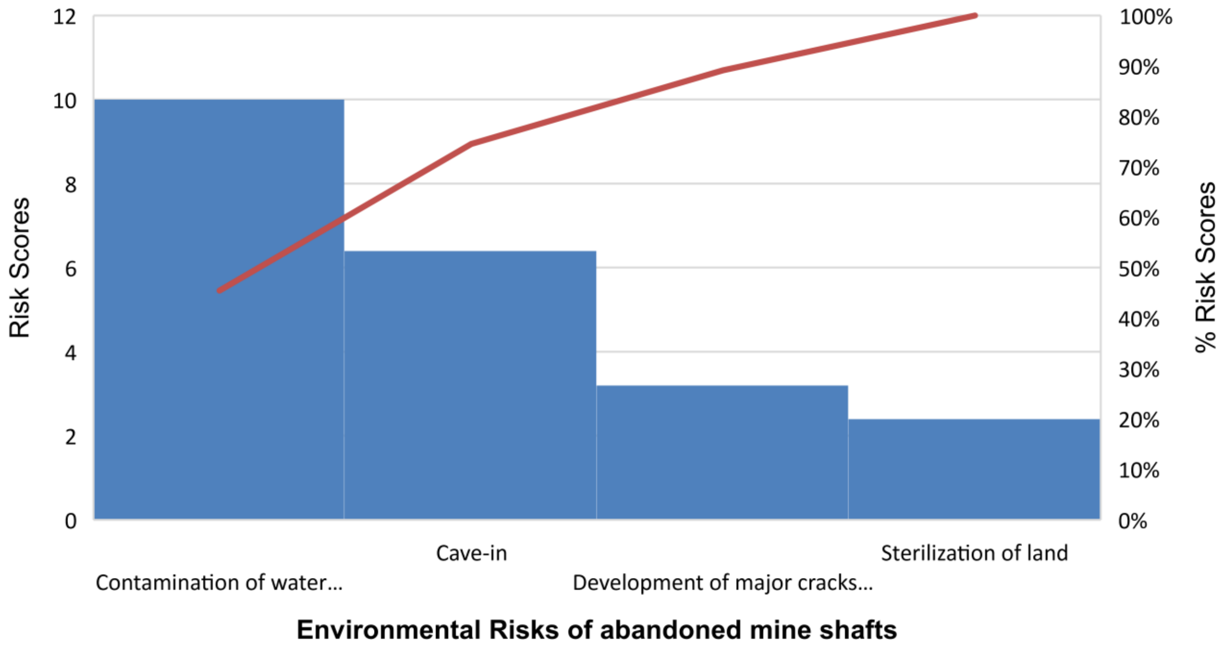

Figure 4.13: The environmental hazards scores for abandoned mine shafts.

4.4.2. Physical and environmental hazards of tailings dumps

The evaluation of the physical hazards of mine tailings dumps in the study area revealed that the major physical hazard of tailings dumps in the study is physical body injuries. The hazard of physical body injury was scored the highest physical risk score of 6.4 as shown in Figure 4.14. The physical body injuries can result from people/animals falling from the steep slope of the dumps and falling into the gullies. The exposure of tailings dumps allowed animals and people gain access to the tailing dumps, thus exposing them to heavy metals found in tailings dumps, which can result in a serious health hazard. Therefore, the people who frequently move around the study area are at risk of developing cancer and non-cancer health complications associated with the exposure to heavy metals. The risks that can result in serious health hazards were scored and are presented in Figure 4.14. These included dermal contact with tailings dumps, inhalation of tailings particles, accidentally or voluntary ingestion of contaminated water and consumption of contaminated food. The risk of dermal contact with tailings dumps was scored the second highest physical hazard score, followed by the risk of inhalation of tailing dumps particles, and the lowest score hazards were the risk of ingestion of contaminated water and the risk of consumption of contaminated food.

The scoring of environmental hazards of tailings dumps showed that the dumps have high risks of pollution which was scored 10 as shown in Figure 4.15. The exposure of tailings dumps can facilitate the erosion which contributes to extensive spatial dispersion of tailings particles. This can also result to surface runoff to nearby water bodies, bearing in mind that the tailings dumps are very close to the major rivers in the Giyani area. In view of this, the tailings dumps had the highest environmental hazard score since they have great potential of polluting water resources in the study area. The second highest environmental hazard was the loss of structural integrity of the tailings dumps as a result of water erosion. This was then followed by sedimentation and dust generation due to wind erosion. Sedimentation can be a result of tailings damps particles carried to low lying areas and/or rivers through surface runoff, later resulting in the destruction of habitat for aquatic species and thus disrupting the natural ecosystem. The lack of vegetation growth due to the poor structure of tailing dumps was also identified as one of the environmental concerns of the tailings dumps in the study area.

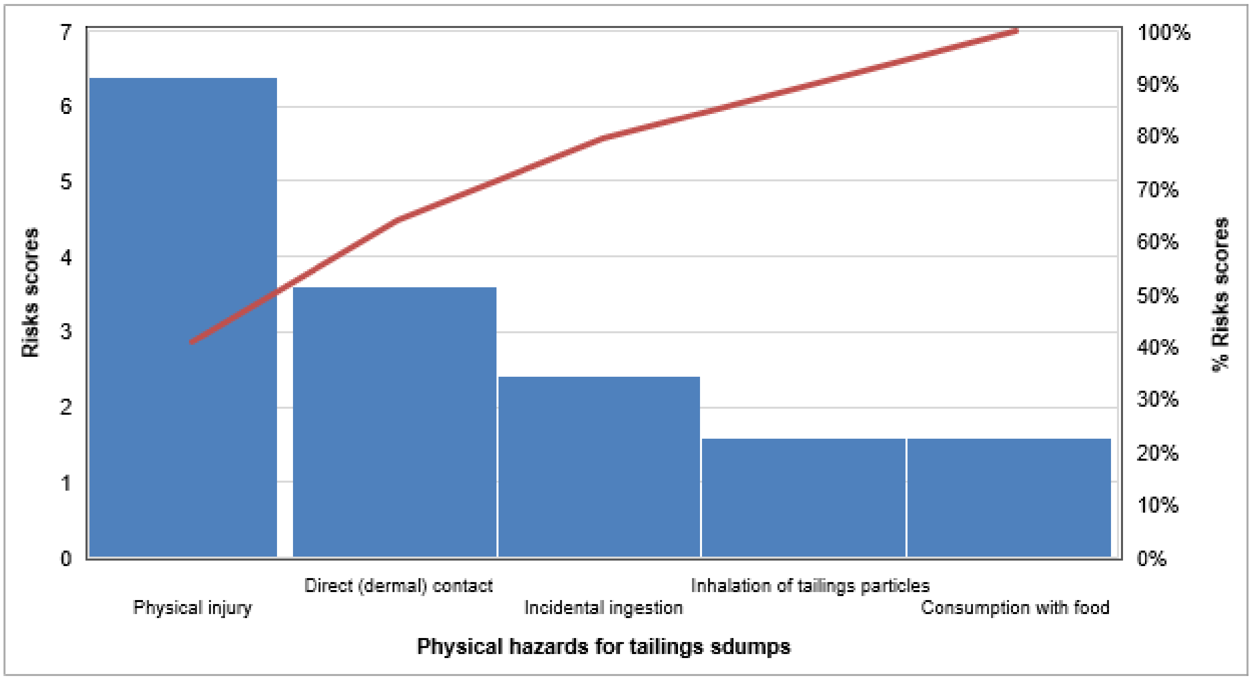

Figure 4.14: The physical hazards scores for tailings dumps.

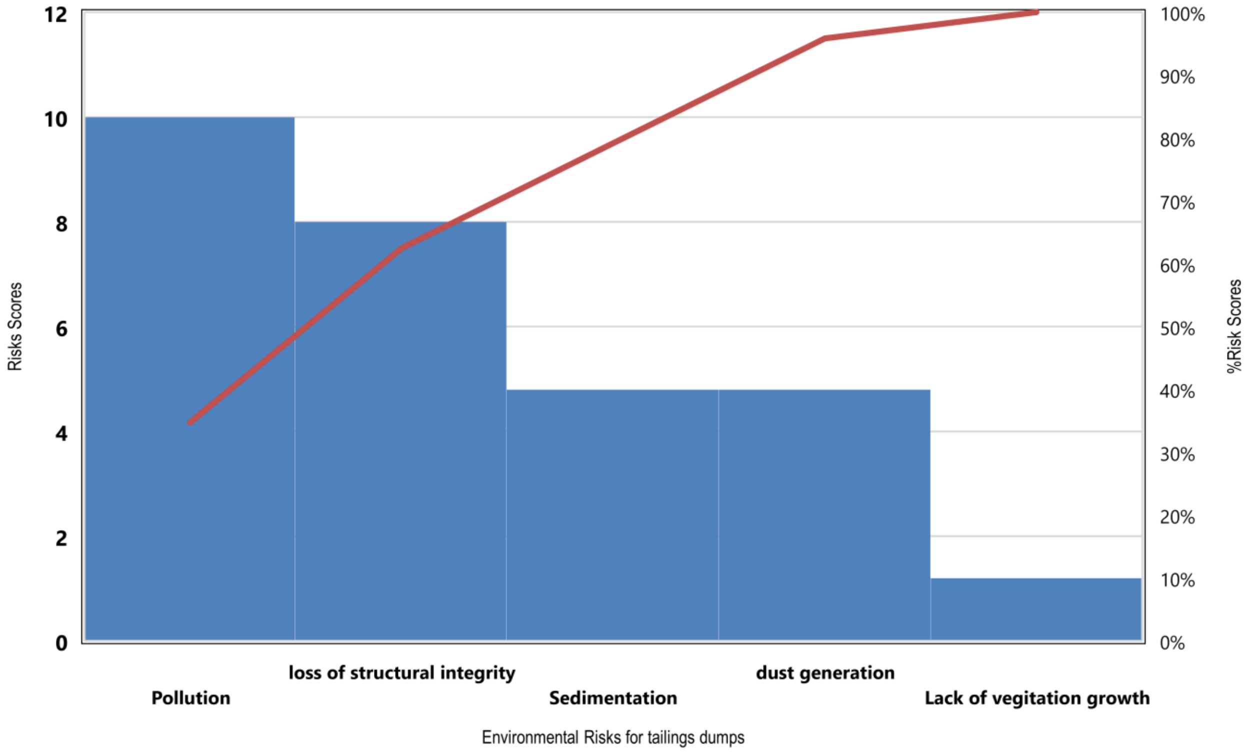

Figure 4.15: The environmental hazards scores for tailings damps

4.4.3. Results of hazard scoring of abandoned mine buildings

The risk of physical body injury associated with abandoned mine buildings can be caused by collapsing of the buildings without warning. This is because these buildings were found in a deplorable state. This coupled with the fact that these buildings were characterized by cracked and unstable walls which pose a safety threat to people and animals moving around the study area.

The aesthetic value of the study site was scored as the highest environmental hazard. This is due to the fact that there were many dilapidated buildings that were found in the study area and these seriously impact the beauty of the area. In addition, it was found that the dilapidated buildings obstruct other forms of land use, as they occupy a large space of the site.

Table 4.1: The physical and environmental hazard score for dilapidated buildings

Classification of hazard	Description of the hazard	Risk score	Risk score %
Physical	Physical body injury	2.4	26.7
Environmental	Aesthetic impact	0.4	8.0
Environmental	Hindering of vegetation growth	0.8	13.3

4.4.4. Results of scoring of old processing plants

The old processing plants were also scored based on their possible impacts observed at the selected abandoned mine sites. The physical body injury was scored the highest physical hazard risk score. The physical injuries can be caused by collapsing of the processing plant without warning. This is because the land around these rending processing plants structure was found to be unstable, due to diggings around them. The health risks as a result of exposure to the spillage of heavy metals from the gold mine ore were also scored. This included the scoring of dermal contact and inhalation of tailings particles which were scored 1.8 and 1.2, respectively (see Figure 4.16). The artisanal miners are in serious risk of being exposed to heavy metals as they frequently visit these processing plants in an attempt to recover the ore from the site.

Contamination of soil around the processing plant emerged with the highest environmental hazard score of 0.4 as shown in Table 4.3. The risk of contamination of soil by heavy metals could result from the spillage of gold mine ore from the processing plants, thus affecting the agricultural land. This was followed by the risk of the aesthetic value of the site. This is because these structures affected the appearance of the landscape as they were scattered around the study area.

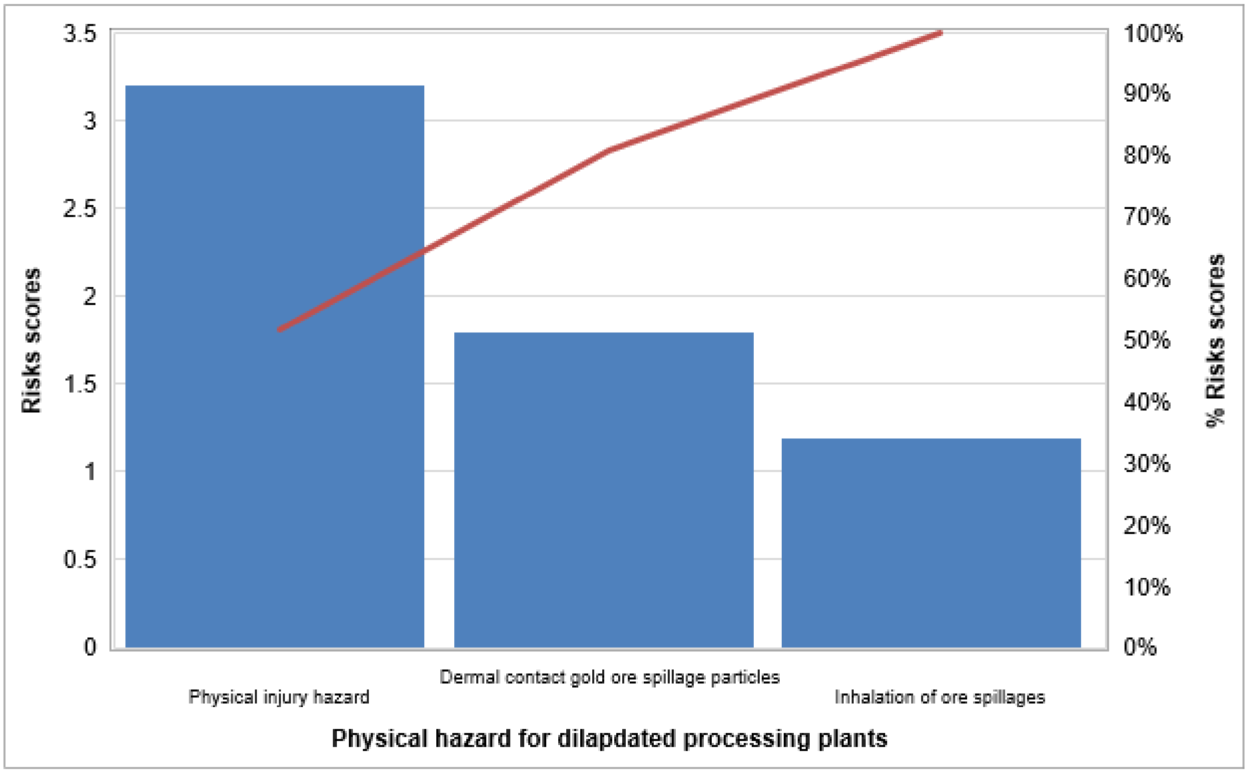

Figure 4.16: The physical hazards scores for abandoned dilapidated processing plants

Table 4.2: The environmental hazards scores for abandoned dilapidated processing plants.

Environmental hazards	Risk Score	Risk score (%)
1. Aesthetic impact	0.4	8%
2. Hinder vegetation growth	1.6	20%

4.5. Physical and Environmental Hazards

The scoring and ranking of abandoned mine features in the study area revealed that physical hazards are slightly higher than environmental hazards. The major physical hazards were found to be mine shafts with score of 5.9 as shown in Figure 4.17. The mine shafts present high risk of people and animals falling into the shaft and this may lead to physical body injuries. The risk of drowning in the water in the abandoned mine workings is also of serious concern, such risks are likely to lead to death with no hope successful recovery of the body. Comparatively, the environmental hazard of the mine shafts was scored 4.2 (see Figure 4.17). The environmental hazards associated with these mine shafts included increased risk of contaminating water resources and groundwater due to flooding. Compounding the problem is the fact that the ground where these shafts were found is unstable and cannot even support the basic post-mining land uses such as farming and grazing sites.

The environmental hazards associated with mine tailings dumps were scored the second-highest. The risks of tailings dumps in the study area was aggravated by erosion from the mine tailings dumps since they were left exposed without any form of vegetation cover. Thus, erosive forces increase risks of contaminating water resources and contribute to loss of structural integrity and sedimentation. The physical hazard score of tailings dumps was influenced by the increased risk of falling into erosion gullies and this can lead to physical body injuries. This coupled with the physical and health hazards associated with the exposure to heavy metals, which might result in serious health hazards.

The physical hazards associated with abandoned processing plants such as physical body injuries can be caused by collapsing of the processing plant without warning. The area of the processing plants was found to be unstable, due to diggings that occurred in their surroundings. However, the environmental hazards score for the processing plant was associated with risks of soil contamination by heavy metals resulting from the spillage of gold mine ore. The dilapidated mine buildings were found to have the lowest physical hazards score of 2.4 and the environmental hazard score of the buildings was 0.6. these results have been shown in Figure 4.17. The dilapidated buildings in the study area had cracked and unstable walls and these pose safety threat to people and animals who move around the study area. The buildings also present serious aesthetic impacts to the site due to the way and manner these buildings are dotted in the study area.

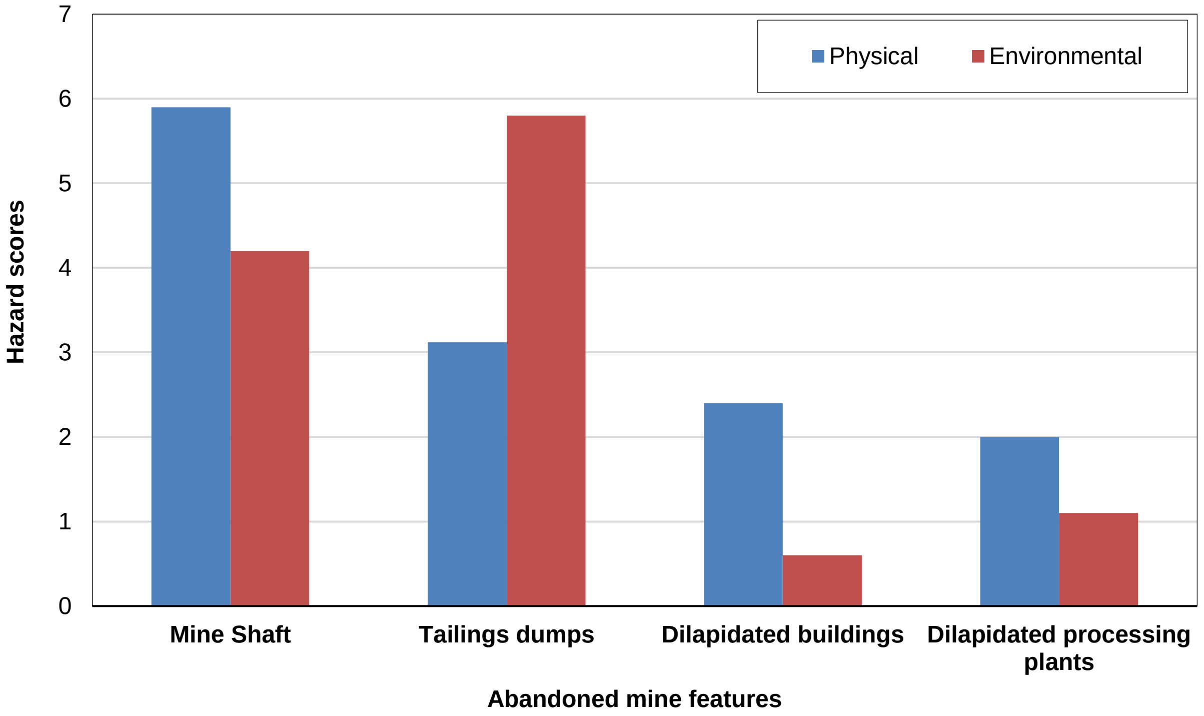

Figure 4.17: Physical and environmental hazards of abandoned mine features

CHAPTER FIVE

SELECTION OF REHABILITATION STRATEGIES FOR ABANDONED MINE

Many mine rehabilitation options exist, and there are many methods to select a suitable rehabilitation strategy for each feature at a mine site. It is necessary to select an appropriate rehabilitation strategy for dealing with the problem of abandoned mines. The use of appropriate rehabilitation strategy mitigates the adverse effects of abandoned mines and improves the sustainability of the surrounding areas. This chapter presents the results of the ranking of different strategies for rehabilitation of abandoned mine sites or features.

5.1. Rating of Factors for Selection of Rehabilitation Strategies

The ranking of the important factors in the selection of rehabilitation or treatment strategies for abandoned mines in the study area was carried out using the AHP. The analysis achieved a comparison consistency ratio (CR) of 0.07 as shown in Table 5.1. According to Ataei *et al.* (2008), a CR less than 0.1 suggests that the judgements in comparison are considered to be adequately consistent. Therefore, the derived weights can be used. The results showed that addressing the physical risks was the significant factor in the priority list with the weight of 0.32 (see Table 5.1 and Figure 5.1). This is due to the fact that these sites are dominated by unsafe mine shafts that are associated with high risk of people/animals falling into the shaft and drowning in water in the mine workings. Such risks are likely to lead to death and the body may be difficult to recover or irretrievable.

The risk of water contamination was ranked the second criterion for selection of the treatment strategies for mine features with the weight of 0.29. This might be influenced by the fact that these sites and their tailings dumps are located at a short distance of about 500m from the two major rivers in the area, hence there are high risk of water contamination resulting from erosion and deposition of contaminated tailings into the rivers. In addition, water is the main conduit by which contaminants from abandoned mines are spread/ distributed beyond the immediate site (MMSD, 2002). Following water contamination was ranking of the risk of ground movement, since the sites have the potential of repurpose for other uses such as grazing, agricultural purposes or any form of development by the surrounding communities.

The durability of the strategy was ranked as the fourth factor. The main reason for prioritizing the durability of the strategy for rehabilitation of abandoned mine features is that the selected action may require less maintenance, thus saving cost of maintenance of rehabilitation strategy. This was then followed by the issues of addressing the cost-effectiveness of the strategy with the score of 0.04. The least important factors to consider were the implementation and maintenance requirements. Each of these factors has a of score of 0.02. The very low score for implementation and maintenance requirements may be due to the fact that these factors normally do not have a direct impact on physical (health and safety) and environmental hazards identified in the study area

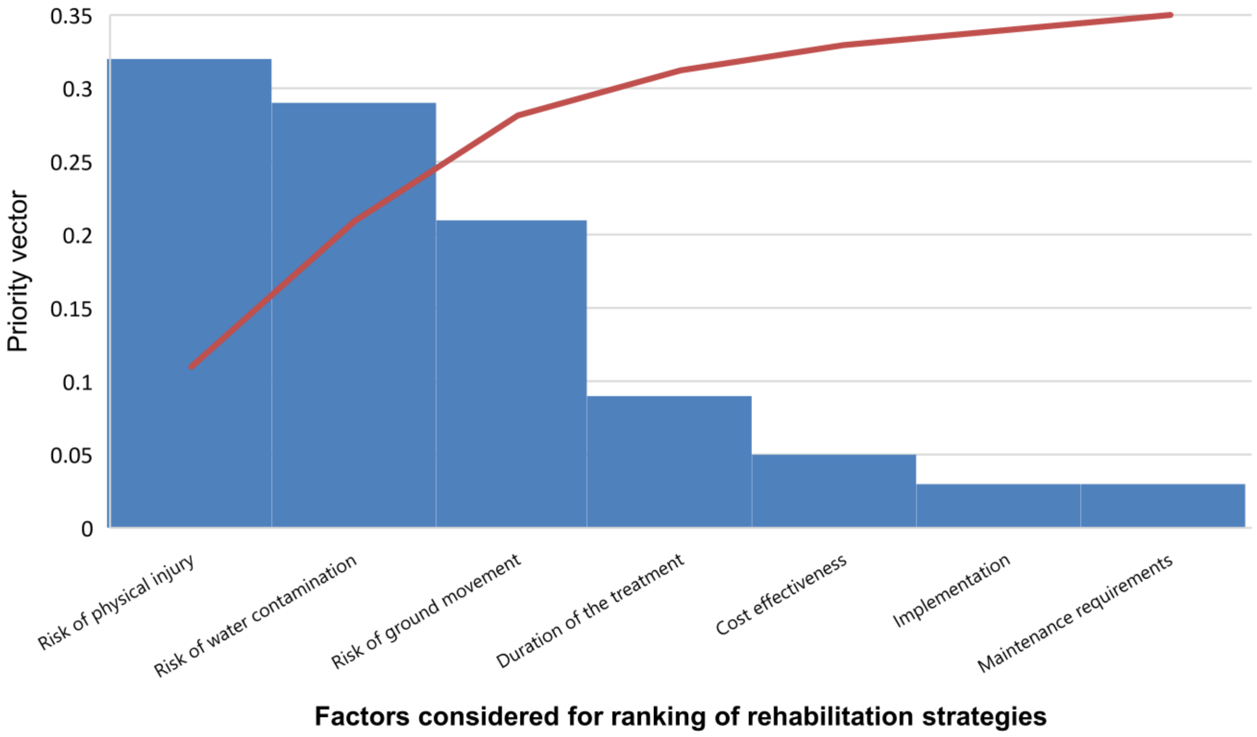

Figure 5.1: The rank of the factors for selection of rehabilitation strategies for abandoned mines

Table 5.1: Pairwise comparison criteria for selection of rehabilitation strategies for abandoned mine features.

Matrix	**Cost Effectiveness**	**Durability of the Treatment**	**Implementation**	**Maintenance Requirements**	**Risk of Physical Injury**	**Risk of Ground Movement**	**Risk of water contamination**	**Normalized Weight**
Cost effectiveness	1	0.25	3.00	3.00	0.14	0.14	0.14	0.05
Durability of the treatment	4.00	1	3.00	3.00	0.25	0.25	0.25	0.09
Implementation	0.33	0.33	1	1.00	0.14	0.14	0.14	0.03
Maintenance requirements	0.33	0.33	1.00	1	0.14	0.14	0.14	0.03
Risk of physical injury	7.00	400	7.00	7.00	1	2	2	0.32
Risk of ground movement	7.00	4.00	7.00	7.00	0.50	1	0.33	0.21
Risk of water contamination	7.00	4.00	7.00	7.00	0.50	3	1	0.29
$\lambda_{max} = 7.53$		CI=0.24		CR=6.5% (0.07)				

5.2. Ranking of Strategies for Rehabilitation Abandoned Mine Shafts

Based on the results obtained from the rating of important factors for selection of rehabilitation strategies for abandoned mine features using AHP, the datum scores were used for comparison of the strategies with the developed criteria using Pugh Matrix techniques. The datum was generated through comparison of factors against each other by assigning numerical values, in order to measure/obtain the significance of each factor over the other. The Pugh matrix was adopted in this work in order to facilitate the evaluation of alternative solutions against significant criteria (Madke and Jaybhaye, 2016). Therefore, this section serves to select the suitable rehabilitation strategies for the identified abandoned mine features. In addition, rehabilitation strategies that are commonly used to rehabilitate abandoned mine features were compiled through literature review and evaluated for their suitability for addressing the problems of abandoned mine features in the study area.

5.2.1. Evaluation of rehabilitation strategies for abandoned mine shafts

Figure 5.2 illustrates the results of the evaluation of rehabilitation strategies for abandoned mine shafts using the datum scores generated through the use of the AHP. The Pugh matrix results indicate that backfilling of the abandoned mine entries is the most suitable option for the rehabilitation of abandoned mine shafts. This option had the highest weight of 26 (see Figure 5.2). Backfilling has a very high potential to effectively address both physical and environmental hazards of the mine entries while allowing the alternative use of land around the mine shafts (Aboriginal Affairs and Northern Development Canada, 2011). It is also preferred in terms of duration, as it is a permanent closure method that completely closes off an abandoned mine opening thus eliminating access. This option also has an advantage of reducing or eliminating problems of downward flow and discharge of water, thus eliminating the chances of water contamination by abandoned mine shafts. In addition, backfilling strategy requires very little maintenance, which is likely to reduce the maintenance cost.

The second suitable rehabilitation strategy was blast closure with weight of 20. Blast closure method offers permanent remedial measure as it completely closes off an abandoned mine opening and eliminates public access and requires minimum maintenance. However, according to Ceto and Mohmud (2000), the costs associated with the implementation of blast closure may be significant. In addition, blasting may expose fresh rock faces to air, which could lead to increased risks of generating acid mine drainage (Ceto and Mohmud, 2000).

Both Polyurethane foam (PUF) plugs and concrete caps (seal) rehabilitation strategies had weight of 18 (see Figure 5.2). These shaft closing strategies completely seal and secure against unauthorised access (Aboriginal Affairs and Northern Development Canada, 2011), thus addressing the risk of people falling into the mine shafts. They both offer long-term duration of approximately 50-100 years. These two strategies require minimal maintenance, however, periodic inspections are recommended to check for subsidence on the plugs and for deterioration of the concrete. The costs of implementation of these options are generally higher than many other strategies (Aboriginal Affairs and Northern Development Canada, 2011).

The least preferred options for dealing with the issues of abandoned mine entries included barriers and signage. Barriers and signage rehabilitation strategies are temporary measures that can be implemented to reduce the hazards of abandoned mine openings prior to the implementation of a long-term strategy. Both options restrict access to the study area but do not completely eliminate the possibility of entry into the mine openings. However, both options were preferred since they are the least expensive and easy to implement.

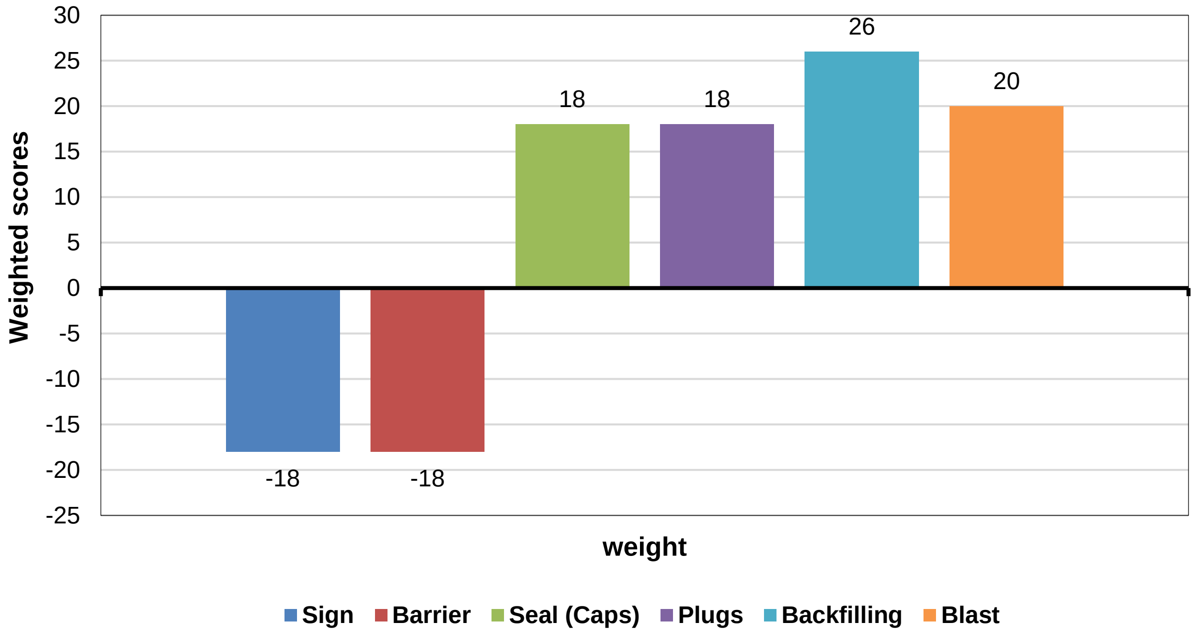

Figure 5.2: The ranking of rehabilitation strategies for abandoned mine shafts.

5.2.2. Rehabilitation of mine tailings dumps

The most preferred rehabilitation option for tailings dumps was revegetation with the weight of 28 (see Figure 5.3). Revegetation has the potential of returning the original ecosystem to as close as possible after and minimizes the future environmental impacts such as the discharge of contaminants to the nearby environment. Therefore, it offers the potential of addressing the risk of water contamination and falling off the slopes. When successfully implemented, revegetation can sustain itself thus significantly reducing the cost of maintenance. In addition, revegetation allows for the development of plant communities and provide habitat for wildlife, as well as supporting other post-mining land uses such as agriculture, forestry, lake or pool, intensive recreational land-use, non-intensive recreational land-use and conservation. However, according to Mendez and Maier (2008), revegetating mine tailings in arid or semi-arid environment, as is the case in the study area, involves the use of drought-, salt-, and metal-tolerant plants for immobilization of heavy metals in the tailings substrate.

In the decreasing order of preference, the second rehabilitation strategies were biological treatment and slope grading with each of them having weight of 18 (see Figure 5.3). These two options have advantage of minimizing the rate of erosion of the tailings, thus reducing the chances of tailings contaminating other parts of the environment. They offer potential of eliminating the risk of ground movement and people falling off the slopes after implementation. However, they require periodic maintenance. Biological treatment may require significant costs for implementation and maintenance (Ceto and Mahmud, 2000). Slope grading may also require significant cost, as it uses heavy earthworks machinery such as bulldozers, scrapers, loaders and backhoes and excavators to fill the holes and grade the slope.

The least preferred rehabilitation strategy included re-use and recycling, chemical and physical treatments. The re-use or recycling of materials is an effective means of eliminating contaminants and have the potential of reducing environmental and physical impacts after implementation. According to Lottermoser (2011), provided that it is chemically non-reactive, mine waste can be used in various ways outside the mine environment. Solid mine waste (overburden, waste rock, solidified tailings, slag, dust) can be used as backfill in underground or open pit workings. The cost of re-use or recycling may range from profitable to high depending on the cost of the re-use or recycling minus the value paid for the metals or other materials. Chemical treatment may require significant costs for the operating and maintenance over the life of the remediation. Physical treatment can be used as a short-term interim measure since it does not completely address the physical and environmental impacts of abandoned mines (Ceto and Mahmud, 2000). Installation of a cap or cover on solid mining waste can reduce or eliminate erosion, dust emissions, and infiltration of water to prevent the migration of contaminants. The Maintenance costs of physical treatment such as the cap could be significant, particularly if the cap or cover can be easily damaged.

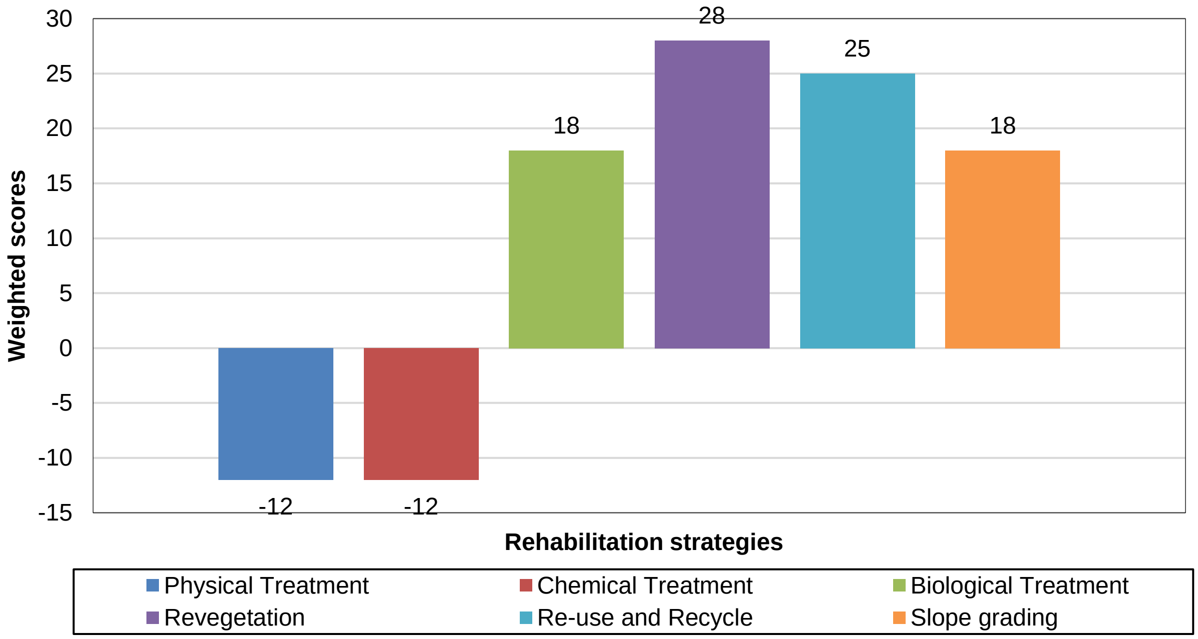

Figure 5.3: The ranking of rehabilitation strategies for abandoned tailings dumps.

5.2.3. Rehabilitation of dilapidated buildings and processing plants

The most preferred rehabilitation strategy for dilapidated buildings in the study area was the demolition of the buildings. Demolishing of abandoned dilapidated buildings involves destroying the infrastructure to the ground and the materials removed and disposed to an established dumping site (Zahir, 2015). In this case, the material can be used for backfilling underground mine workings. This option was preferred with respect to the duration of the method and level of maintenance. Demolition also offers the potential to address the risk of the building collapsing on people or people falling from the buildings, thus reducing the risk of physical body injuries. In addition, this option ensures the safety of the site and supports other post-mining land uses such as agriculture, forestry, lake or pool, intensive recreational land-use, non-intensive recreational land-use and conservation.

The second preferred rehabilitation strategy was declaring the site a heritage site. The potential threats to the surrounding communities will be eliminated as the site will be made safe. However, significant cost will be required for transforming the abandoned mine site into a tourist attraction site. Regular inspection and maintenance will be required. This option takes advantage of existing infrastructure and contributes to the local economy after the mine has been closed. The least preferred option for the rehabilitation of abandoned mine buildings was barrier construction. It was preferred in terms of duration and cost-effectiveness. However, regular maintenance would be required. Barriers construction option can be adopted as a temporary measure prior to the implementation of a long-term strategy. Since this option only restricts access to the site but do not completely eliminate the possibility of people moving around the dilapidated buildings and does not completely address the physical and environmental impacts of the abandoned mine site. However, both options were preferred since they are the least expensive and easy to implement.

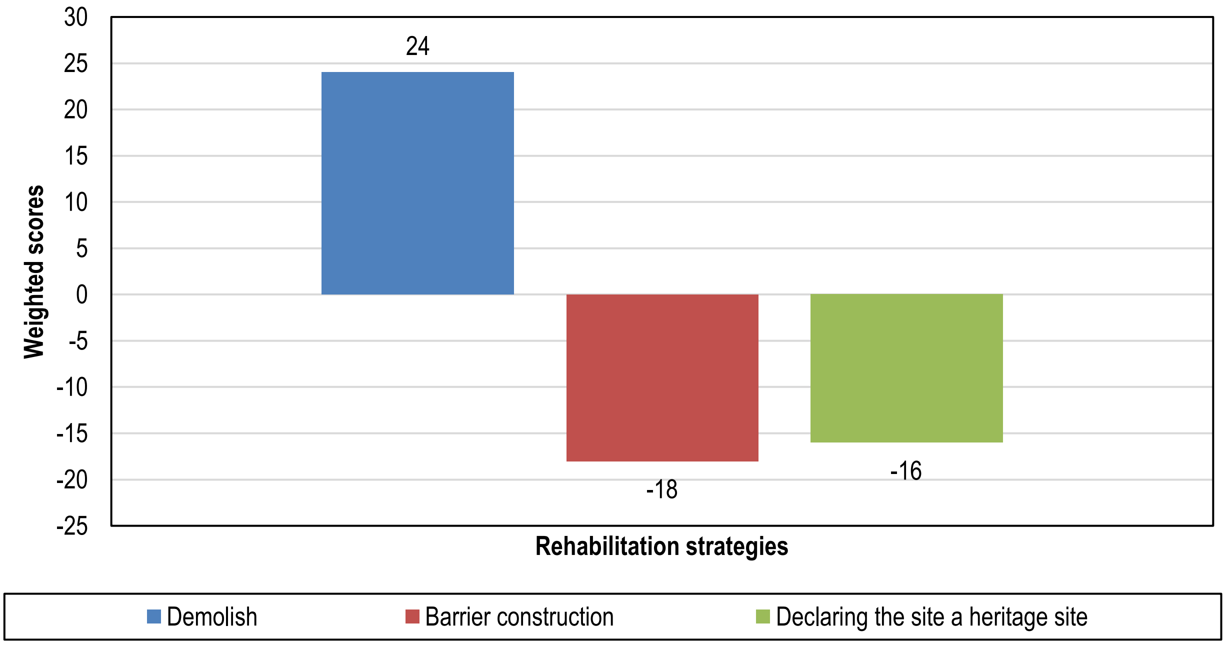

Figure 5.4: The Selection of rehabilitation strategies for dilapidated buildings and processing plants.

5.3. Discussion of the Findings

The preferred rehabilitation strategies for abandoned mine features were evaluated after a comprehensive characterization of the site, this was done to ensure that the selected strategy addresses both physical and environmental problems identified at the site. Therefore, based on the characterization of the abandoned mine features in the study area, the AHP was used to compare the significance of the deciding factors. The factors depicted in Table 5.1 are based on the comprehensive review of the overall situation of the abandoned mine features in the study area. Then the Pugh Matrix technique was used to evaluate the suitability of rehabilitation strategies for dealing with the physical and environmental problems of abandoned mine features in the study area.

The AHP results of significant factors revealed that the suitable rehabilitation strategies should be capable of addressing the risks of physical body injuries, risks of water contamination, risk of ground movement, duration of the strategy, cost-effectiveness, application of the treatment and maintenance requirements. As a result, the selection of the preferred strategies favoured strategies with long-term closure systems. For instance, the preferred rehabilitation strategies were backfilling and blast system since they are appropriate methods to permanently seal a mine opening. Mhlongo (2018), suggested that the decision on which of these long-term or permanent strategies to use will need to take into consideration the evaluation of future land use. On the other hand, according to Aboriginal Affairs and Northern Development Canada (2011), PUF plugs and slabs have the potential to address the hazards and allow for removal of the strategy of entry into the mine is required. However, these strategies have the potential for physical deterioration and would require periodic inspection and maintenance.

The most preferred option for abandoned mine tailings was revegetation due to its potential to reduce the likelihood of erosion and retain the natural vegetation after implementation and minimizes the future environmental impacts such as the discharge of contaminants to the nearby environment. However, Mendez and Maier (2008) suggested that plants that are suitable for revegetation, especially in a semi-arid environment, must be native, drought, salt, and metal tolerant. Furthermore, the ultimate objective for successful revegetation is the long-term succession of the plant community in mine tailings dumps to promote and restore soil ecosystem functions to a state of self-sustainability (Adams and Lamoureux, 2005). The least preferred strategies included physical and chemical treatments. According to Ceto and Mahmud (2000), physical treatments are not appropriate for the semi-arid environment. For instance, clay caps in the semi-arid environment may crack from wetting and drying cycles. Thus requiring periodic inspection and maintenance.

The most preferred rehabilitation strategies for abandoned mine buildings and processing plants were demolition of dilapidated abandoned mine structures since the strategy ensures the safety of the site and supports other post-mining land uses. However, Aboriginal Affairs and Northern Development Canada (2011), suggested that during the demolition process the hazardous materials found in the abandoned mine structures often require special handling.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

This chapter presents summary, conclusion and recommendation of the study. The summary of the study entails the overview of the problem statement, objectives, methodology and findings of the study.

6.1 Summary of the Study

South Africa, like any other country with historical mining, is facing enormous physical and environmental problems posed by abandoned mines. The issue of abandoned mines is important because it represents many thousands of former mining sites that continue to cause threat to human safety and health and/or environmental damage. The need to address abandoned mine issues is increasing owing to public health and safety issues, as well as the importance of environmental conservation. The current challenges of addressing abandoned mines are poor planning and absence of criteria and standards for rehabilitation for these mines. Rehabilitation of abandoned mines is largely dependent upon prevailing physical and environmental hazards and characterization of the site in question. The main purpose of this study was to carry out an evaluation of strategies for rehabilitation of abandoned mine sites in the Giyani Greenstone Belt. This study was conducted in order to establish appropriate rehabilitation strategies for addressing problems associated with abandoned mine sites, by providing guidelines for dealing with the problems of the abandoned mine sites.

The research approach used to accomplish the purpose of this study involved conducting a comprehensive field inventory of abandoned mine features. This was carried out in the form of site characterization, which entailed identification, locating and mapping of the abandoned mine features. The characterization involved scoring and ranking the abandoned mine features on the basis of their potential or already existing physical and environmental problems. The identified abandoned mine features included abandoned mine shafts, mine tailings dumps, dilapidated buildings and processing plants. The physical and environmental hazards were then scored in order to identify the nature and seriousness of the hazards for each abandoned mine feature. The scoring and ranking of abandoned mine features in the study area revealed that physical hazards are slightly higher than environmental hazards. The major physical hazards were found to potential people and animals falling into the shaft and then drowning in the water in the abandoned mine workings. The major environmental hazard in the study area was found to be erosion from the tailings dumps. The dumps were left exposed without any form of vegetation cover and therefore have the propensity of contaminating water resources in the study area.

Beside the site characterization, Analytical Hierarchy Process (AHP) and Pugh Matrix were used for evaluation and selection of preferred rehabilitation strategies for the identified features. The AHP method was utilized for weighting the factors considered significant for the selection of appropriate rehabilitation strategy. The factors that were taken into consideration for evaluation and section of rehabilitation options included the; risk of physical bodily injury, the risk of water contamination, the risk of ground movement, duration of the strategy, cost-effectiveness, Application of the treatment and maintenance requirements. The Pugh Matrix applied the datum obtained from AHP to select the appropriate rehabilitation strategies for identified abandoned mine features. The results of the Pugh matrix revealed that the ideal strategy for abandoned mine shaft is the backfilling option. For tailings dumps, the desired option was revegetation. For dilapidated abandoned buildings and processing plants, the preferred option was the demolition of the structure, since it ensures the safety of the site and supports other post-mining uses.

6.2. Conclusion

The main objective of this research was to evaluate strategies for rehabilitation of selected abandoned mine sites in the Giyani Greenstone Belt. This section provides the accomplishment of the research objectives and answers to research questions.

Based on the site characterization and description of the study area, both study sites had dilapidated old infrastructure that had deteriorated with time. The infrastructure left by mining in the area was found to have become prey to illegal mining activities and most of the structures were vandalized and in a deplorable state. This included the old buildings, the mineral processing plant and storage facilities such as silos and ore bins. In addition, the site description showed that five mine entries were found in both study sites, thus making them the second dominant abandoned mine features in the study area.

The scoring of the seriousness of the hazards of abandoned mine features revealed that the abandoned open mine entries were the major physical hazards. This was due to the increased risk of people or animals falling into the shafts, thus leading to physical body injuries or death. The second-highest risk score was environmental hazards associated with abandoned mine tailings dumps. These tailings dumps were found to be highly susceptible to erosion since they were left exposed without any form of vegetation cover, thus increasing the risk of contamination of water resources and sedimentation. The least scored hazards were dilapidated buildings as they obtained the least environmental hazard score. The dilapidated buildings present serious impact on the aesthetic of the site.

Generally, in South Africa and other countries, the first priority in rehabilitation of abandoned mines is given to those mines that present severe public safety hazards and then to those with adverse impact on the environment. Since it is not possible to rehabilitate all mine sites at the same time due to limited financial resources. It was therefore concluded from the physical and environmental hazards established in this research that the best approach of effectively reducing these hazards was to give priority to features with extremely high physical and environmental hazard scores.

Based on the results AHP, special attention is to be given to the open mine entries having high risk of falling and drowning in water in the mine workings. Such risks are likely to lead to death with no hope for the successful recovery of the body. This was followed by tailings dumps with less severe physical hazards but extremely high environmental hazards. The abandoned infrastructure was found to be less hazardous and therefore require least attention on priority of rehabilitation.

The rehabilitation strategies for abandoned mine features were evaluated after a comprehensive characterization of the site, this was done to ensure that the selected strategy addresses both physical and environmental problems identified at the site. Based on the results of the evaluation, backfilling was selected to be the most suitable rehabilitation strategy for addressing the identified hazards of the abandoned mine shafts found in the study area. Backfilling has a very high potential to effectively address both physical and environmental hazards of the mine entries and it allows the alternative use of land. In addition, backfilling has an advantage of reducing or eliminating problems of downward flow and discharge of water, thus eliminating the chances of water contamination by abandoned mine shafts.

The desired rehabilitation option for tailings dumps was revegetation, since it has potential of returning the original ecosystem to as close as possible and minimizes the future environmental impacts such as the discharge of contaminants to the nearby environment. It emerged that the most practicable rehabilitation strategy for dilapidated abandoned infrastructure in the study area was the demolition of the infrastructure. This strategy will improve the safety status of the mine sites and make the land available for other traditional post-mining land uses.

The approach established to address the problems of abandoned mines involved compilation of inventory and characterization of abandoned mine features, scoring of the hazards based on information collected by conducting preliminary field assessment of the abandoned mine sites. This also included the utilization of the MCDM methods, which resulted in an improved decision making process in prioritization of rehabilitation efforts and then the selection of appropriate rehabilitation options for abandoned mine features. This approach will be useful for use in developing countries where there are numerous abandoned mines and limited resources to rehabilitate them. This will go a long way in ensuring that characterization and rehabilitation of the abandoned mine features are effectively carried out with limited resources

6.3 Recommendation

Based on the findings of the study, the following recommendations were made:

- Rehabilitation of abandoned mines must not only focus on eliminating physical and environmental hazards but also take cognizance of the future land use that will benefit the community and nature conservation.
- Before the government rehabilitation these sites, comprehensive research should be conducted on each abandoned mine site to create a basic understanding of the problems of abandoned mines in order to use appropriate strategies that address site-specific physical and environmental conditions.
- The rehabilitation strategies selected for abandoned mine features should address issues of cost, the durability of rehabilitation options, and the self-sustainability of the land after rehabilitation.

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Appendix A: Physical hazard scores

Mine feature	Potential Source	Potential Hazard	Source	Exposure pathway	Potential Damage	Risk Score	Total hazard risk	Physical Hazard Score
Abandoned mine shafts	Accidentally falling into the mine shaft	Physical body injury hazard	4	4	5	8	23.6	5.9
	Drowning in water filling the underground workings	Drowning hazard	4	3	5	6		
	Ingestion of the contaminated mine water	Intake of contaminated water	4	3	4	4.8		
	Exposure to toxic gases inside the shaft	Asphyxiation hazard	4	4	3	4.8		
Abandoned tailings dumps	Falling down steep slope, erosion trenches, unstable walls	Physical injury	4	4	4	6.4	15.6	3.12
	Exposure to heavy metals	Direct (dermal) contact	3	3	4	3.6		
	Exposure to heavy metals	Inhalation of tailings particles	2	2	4	1.6		
	Exposure to heavy metals	Incidental ingestion	3	2	4	2.4		
	Exposure to heavy metals	Consumption with food	2	2	4	1.6		
Dilapidated buildings	Collapsing of the building without warning	Physical body injury hazard	2	3	4	2.4	2.4	2.4
Abandoned old processing plants	Exposure to gold ore spillages	Dermal contact gold ore spillage particles	2	3	3	1.8	6.2	2.1
	Exposure to gold ore spillages	Inhalation of ore spillages	2	2	3	1.2		
	Collapsing of the processing plants	Physical injury hazard	2	4	4	3.2		

Appendix B: Environmental hazards scoring

Mine features	Potential Source	Potential Hazard	Source	Exposure pathway	Potential Damage	Risk Score	Total hazard risk	Environmental Hazards Score
Mine shaft	Flooding due to subsidence	Contamination of water resources	4	4	4	6.4	16.8	4.2
	Water entry	Development of major cracks or sink holes	4	2	4	3.2		
	Unstable grounds	Cave-in	4	3	4	4.8		
	Subsidence	Sterilization of land	3	4	2	2.4		
Tailings dumps	Run-off from the tailings	Pollution	4	5	5	10	28.8	5.76
	Sedimentation	Sedimentation	4	3	4	4.8		
	Poor structure to support vegetation	Lack of vegetation growth	2	3	2	1.2		
	Water erosion	Loss of structural integrity	4	4	5	8		
	wind erosion	Dust generation	4	4	3	4.8		
Dilapidated buildings	Dilapidated buildings scattered all around the study site	Aesthetic	2	2	1	0.4	1.2	0.6
	Dilapidated buildings	Hinder vegetation growth	2	2	2	0.8		
Processing plants	spillages of the gold ore	Soil contamination	2	2	4	1.6	3.2	1.1
	Dilapidated processing plants scattered around the study site	Aesthetic	2	2	1	0.4		

Appendix C: Rating factors for selection of rehabilitation options

The factors taken into consideration for selection of treatment strategies using AHP.

Factor	**Description**
Cost effectiveness	Is the performance of the strategy cost saving implementation and maintenance
Duration of the treatment	Duration of the strategy to ensure sustainability or long-tem of the treatment
Application	Is the treatment easy to implement and maintenance
Maintenance requirements	Rehabilitation of the treatment strategy
Risk of physical injury	The ability of the strategy to address the risks of physical injury
Risk of ground movement	The ability of the strategy to address the risks of ground movement
Risk of water contamination	The ability of the strategy to address the risks of water contamination

Appendix D: Rehabilitation strategies

A list of rehabilitation options for abandoned mine entries

Method	Types	Description
Warning	Signage	Signage is used as a temporary measure to warn or alert trespassers about the presence of mine openings. Signs are considered temporary fixtures prior to the implementation of a longer term remediation measure. As they neither secure the opening nor deter wildlife, their use is limited to warning humans to exercise caution, and suitable only for low risk hazards. To ensure their continued functionality, frequent inspection and maintenance is required.
Barriers	Fences	Fencing is used as a temporary measure to limit access to the shaft. It can be installed around the perimeter of a mine shaft and subsidence to discourage access to the underground workings. Since no seal is placed over the opening, the possibility of entry is not eliminated. Fences, like signs, are a temporary measure and require regular inspection and maintenance to sustain effectiveness for as long as possible.
	wire screens	Steel wire screen can be used as a temporary measure to restrict unauthorized access to the underground workings. The screens can deter entry more effectively than fencing; however, the screen does not provide a permanent seal. If future entry into the mine is required for mineral exploration or historical purposes, the barrier can easily be removed.
	steel grates	steel gate closure can be used as a temporary measure to restrict entry into the abandoned mine opening of various shape while permitting airflow, drainage and access for bats. Access to the hazard is restricted; however, removal is possible if entry into the mine is required at a later date. Grate materials include angle iron, rebar or floor grating, attached to a rigid steel frame.
Seals (Caps)	Concrete cap	Concrete cap can completely seal the shaft and has a life expectancy of 50-100 years. It requires minimal maintenance with recommended periodic inspection to check for deterioration of the concrete. If future re-entry to the site is anticipated, locking hatches can be built into a concrete panel design.
	Concrete bulkhead	These consist of a barricade or wall constructed across horizontal to sub-horizontal mine openings. Bulkheads provide a secure seal that completely restrict access. Future entry can still be gained into the mine opening for mineral exploration or historical purposes by demolition of the bulkhead or incorporating a locking hatch into the bulkhead design.
Plugs	Tire plug	Tire plugs consist of a stack of tires connected with galvanized steel cables is compressed by an excavator and forced into the vertical or sub-vertical mine opening. Once in place, the tires expand to fill the void, forming the plug.
	PUF plug	PUF is a foam produced by mixing two liquid reagents, resin and catalyst. This mixture is then poured on top of a lightweight form constructed out of lumber, plastic sheeting, cardboard, plywood, etc. near the mine entrance. A rapid exothermic reaction occurs generating foam that expands to fill all voids and cracks in the mine opening. Within 15-30 minutes, the foam hardens to create a rigid plug firmly bound to the rock.
Backfilling		Backfill closures completely seal horizontal or shallow vertical mine openings with on-site or imported fill. Future access via the opening is not possible and entry for wildlife, fluid and natural airflow is impeded.
Blast closure		Blast closures permanently seal the shaft. Access into the abandoned mine opening is fully restricted and generally resistant to damage from vandalism and natural deterioration.

A list of rehabilitation strategies for abandoned mine waste

Method	Types	Description
Physical treatment	Dumping (Relocation of mine waste)	This involves relocating mine waste dump to a new site and establishing new waste storage.
	Covering (capping)	Capping or covering of solid mining waste can be used as a short-term interim measure or as a long-term or final action. Installation of a cap or cover on solid mining waste can reduce or eliminate erosion, fugitive dust emissions, and infiltration of water to prevent the migration of contaminants.
	Solidifying	This technique consists of encapsulating waste into a solid monotholic structure with high structural integrity.
Chemical treatment	Soil leaching/acid extraction	Leaching of metals in tailings involves numerous geochemical and transfer processes that control the concentration of extracted elements.
Biological treatment	Phytoremediation	Phytoremediation is a technique that utilizes plants to remove, eliminate, or decrease environmental contaminants (heavy metals, organics, radionuclides), attenuating the environmental risk derived from mine works.
Rock cladding		This involves applying a layer of waste rock to cover the entire surface of mine waste dump.
Revegetation		Generally, revegetation refers specifically to the process of establishing vegetation. It consists of introducing plant species that can stabilize the dumps and minimize the rate of erosion. Vegetation has an important role in protecting the soil surface from erosion and allowing accumulation of fine particles.
Re-use and Recycle	Aggregate	Waste rock and tailings can be selectively used in earthworks and road construction. They may also be sold for use as aggregate in a variety of applications (Lottermoser, 2011).
	Backfill open pits and underground mines	Solid mine waste (waste rock, solidified tailings) can be used as backfill in underground or open pit workings (Lottermoser, 2011). Back-filling is a useful way to return piles of overburden and spoil materials removed during mining back to the landscape thus avoiding the need for disposal (Sloss, 2013).
	Reprocessing of mine waste	This involves recovering of valuable materials in mine waste dumps. As noted by Blight (2010), mine waste dumps can yield significant amount of rare earth elements.
Slope grading		This involves stabilizing the slope of mine waste as a way to prevent water erosion.

A list of rehabilitation strategies for abandoned mine buildings

Method	Description
Demolish	This involves destroying the infrastructure to the ground and the materials are being removed and disposed to an established dumping site.
Barrier construction	This involves using fencing as a measure limit access to the buildings to present unforeseen accidents.
Clean the buildings	This involves cleaning buildings using water, especially walls and the floor.
Declaring the site for heritage	This involves a process of transforming the site that was formally known for economic development into tourism attraction. The process takes advantage of the existing infrastructure and contribute to local economy after the mine has been closed.

A list of rehabilitation strategies for abandoned mine processing plants

Method	Description
Demolish	This involves destroying the infrastructure to the ground and the materials are being removed and disposed to an established dumping site.
Barrier construction	This involves using fencing as a measure limit access to the buildings to present unforeseen accidents.
Declaring the site for heritage	This involves a process of transforming the site that was formally known for economic development into tourism attraction. The process takes advantage of the existing infrastructure and contribute to local economy after the mine has been closed.