DEVELOPMENT OF A COMPUTER-BASED ADVISORY SYSTEM FOR SELECTION OF APPROPRIATE REHABILITATION STRATEGIES FOR DESIGNATED ABANDONED MINE SITES IN LIMPOPO PROVINCE OF SOUTH AFRICA

Name: Mhlongo Sphiwe Emmanuel
Student Number: 11542669

Promoter: Dr. F. Amponsah-Dacosta
Co-Promoter: Prof. A. Kadyamatimba

A Thesis Submitted to the Department of Mining and Environmental Geology, School of Environmental Science, University of Venda, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Environmental Sciences (Geology)

September 2020

DEDICATION

In Living Memory
of
Vinna Shongwe
(Grandmother)

Doctor "Mlungudodi" Mhlongo
(Grandfather)

Ezekiel "Magunundu" Mhlongo
(Father)

To my wife Phophi Lucy Mhlongo, my son
Siyabonga Jaden Mhlongo and daughter
Sinegugu Yoanda Mhlongo

DECLARATION

I declare that this thesis is my own work in design and execution. Where the work of others is used, it has been duly acknowledged. It is being submitted for the Doctor of Philosophy in the Department of Mining and Environmental Geology, University of Venda. The work presented in the thesis has not been submitted before in any form for any degree or examination in this or any other University.

Signed:

____

Student: Sphiwe Emmanuel Mhlongo

This 09th day of September 2020

____

Promoter: Dr. F Amponsah-Dacosta

This 09th day of September 2020

____

Co-Promoter: Prof. A. Kadyamatimba

This 09th day of September 2020

ACKNOWLEDGEMENT

This thesis could not have been completed without the help and support of several people.

- First and foremost, I would like to humbly thank the ALMIGHTY GOD for giving me the strength and wisdom to carry out this work from the beginning to completion.

- My greatest gratitude goes to my promoters, Dr, Francis Amponsh-Dacosta and Professor Armstrong Kadyamatimba for their encouragement, pieces of advice and motivation that enabled me to achieve this task.

- I would also like to acknowledge the financial assistance I received from the Office of the Deputy Vice Chancellor Academic (University of Venda) as support for the field work part of the research presented in this thesis. Moreover, I am grateful to the University of Venda for the assistance in paying the tuition fees for my PhD studies.

- Many colleagues and friends in the School of Environmental Sciences (University of Venda) motivated me in diverse ways during the research work and the write-up of the thesis. Among them are Confidence Muzerengi, Glyn Pindihama, Avhasei Mudau, and Ndivhuwo Nemapate.

- Lastly, I would like to thank my wife (Phophi), son (Siyabonga), and daughter (Sinegugu) for the sacrifices they differently had to make to support me during the research and writing up of this thesis.

ABSTRACT

South Africa has many abandoned mines which seriously affect the environment and the livelihood of the host communities. The lack of in-depth knowledge of the problems of these mines, limited resources for their rehabilitation, lack of clearly assigned responsibilities for rehabilitation, and the absence of criteria and standards of rehabilitation have led to the use of inappropriate strategies to rehabilitate abandoned mines. The main objective of this research was to develop a computer-based advisory system for selecting suitable rehabilitation strategies for designated abandoned mines. The research methodology involved characterization of the selected abandoned mine sites, devising methods for prioritization of mine features for rehabilitation, development of three expert systems that provide guidance on different aspects of rehabilitation of abandoned mines, and development of a framework for estimation of costs of rehabilitation of abandoned mines.

The first part of this research involved development of methods for characterization and prioritization of abandoned mine entries and tailings dumps as well as selection of strategies for rehabilitation. These methods were written in an expert system shell to create expert systems (ESs) for ranking of abandoned mine entries and tailings dumps for rehabilitation. The study also used semi-quantitative methods such as SWOT (Strength, Weaknesses, Opportunities, and Threats) analysis as well as the Quantitative Strategic Planning Matrix (QSPM) technique and Multi-Criteria Decision-Making (MCDM) methods such as Analytic Hierarchy Process (AHP) and Pugh Matrix to evaluate different strategies for their suitability to deal with the issues of abandoned mines. Based on the current situation of abandoned mines in the study area, a framework for estimation of costs of rehabilitation of abandoned mines was developed by taking into consideration direct cost and other key cost estimates which were previously disregarded.

The method for ranking the problems of abandoned mine entries was developed based on information collected during preliminary assessment of the mine entries while that of ranking the abandoned mine tailings was based on the potential of the dumps to pollute the surrounding environment and the landscape and the visual impact they present. These approaches are relatively less data demanding than the current tools used for rehabilitation of abandoned mines. Thus, these methods have the advantage of being suitable for use in developing countries where there are many abandoned mines but limited resources for their rehabilitation. The application of these methods at selected abandoned mines in Giyani and Musina areas showed that mine shafts had moderate physical and environmental hazards. The risks of people and animals falling into the shafts and the problems of ground movement around the shafts were identified as the major concerns. Strategies that provide long-term or permanent closure of the abandoned mine shafts were identified as the most suitable options. These include backfilling of the shafts, use of concrete plugs to seal the shafts, use of blast closure and injection/inclusion strategies.

The results of the study showed that tailings dumps in the study area have the potential to pollute the environment with toxic materials such as Cd, As, Ni, Pb, Zn and Cu. Based on the determined mean pollution index, dispersion index and the index of landscape and visual impact of the tailing dumps in the study area it was found that rehabilitation of these mines is likely to require moderate efforts. The priority of rehabilitation of these mines should be in the following decreasing order: Fumani Gold Mine Tailings, Klein Letaba Gold Mine Tailings, Nyala Magnesite Mine Tailings (A), Nyala Magnesite Mine Tailings (B), Louis Moore Gold Mine Tailings, and Mesina Copper Mine Tailings.

The description of the hazards and evaluation of the strategies for dealing with the problems of abandoned surface mine excavations and other structures demonstrated that repurposing of these features should be considered before application of traditional rehabilitation methods. The rule-based expert systems that provide guidance on the rehabilitation of abandoned mines were developed. The fact that these expert systems are web-based make them easily accessible for use in different parts of the world. Based on this, the characterization, prioritization and selection of strategies for rehabilitation of abandoned mines can be conducted in different regions following the same procedures and methods as described in this thesis. The framework which was developed for estimation of the costs of abandoned mines rehabilitation emphasized the need for inclusion of critical indirect costs in the estimation process to reduce elements in the risks of under estimation.

Keywords: abandoned mines, rehabilitation prioritization, expert systems, cost estimation, rehabilitation strategies.

TABLE OF CONTENT

Contents **Page**

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

As	Arsenic
AIDS	Acquired Immunodeficiency Syndrome
AMHAZ	Abandoned Mines Hazard Ranking System
AIMSS	Abandoned and Inactive Mines Scoring System
AHP	Analytic Hierarchy Process
ANP	Analytical Network Process
AMD	Acid Mine Drainage
ARD	Acid Rock Drainage
BC	British Columbia
CAD	Computer Aided Drafting
COG	Centre of Gravity
Cu	Copper
COCHILCO	National Copper Corporation of Chile
DEA	Department of Environmental Affairs
DMR	Department of Mineral Resources
ES	Expect system
ES-RAME	Expert system for ranking the problems of abandoned mine entries
ES-RWDR	Expert System for ranking of abandoned mine waste dumps for rehabilitation
GGB	Giyani Greenstone Belt
HM	Height Method
HIV	Human Immunodeficiency Virus
HMS-SS	Historic Mine Site Scoring System

MMSD	Mining, Minerals and Sustainable Development
UNEP	United Nations Environment Programme
RRM	Risk Ranking Methodology
RAIMSS	Reclaimed Abandoned and Inactive Mines Scoring system
Pb	Lead
PRA	Preliminary Appraisal and Ranking Model
PSI	Preliminary Site Investigation
Op cit.	in the work already cited
SWOT	Strength, Weakness, Opportunities, and Threats
QSPM	Quantitative Strategic Planning Matrix
ICP-MS	Inductivity Coupled Plasma Mass Spectroscopy
MCDM	Multi Criteria Decision-Making
MPRD	Mineral and Petroleum Resource Development
MCM	Mine Closure Model
MOM	Mean of Maximum
Mn	Manganese
Ni	Nickel
Zn	Zinc

LIST OF UNITS OF MEASUREMENT

Ha	Hectare
%	Percent
m	Metre
°	Degree
′	Minutes
"	Seconds
km^2	Kilometer square
ppm	Parts per million
mg/kg	Milligram per kilogram

PUBLICATIONS FROM THE THESIS

Journal Publications

1. **Sphiwe Emmanuel Mhlongo**, Francis Amponsah-Dacosta and Armstrong Kadyamatimba (2020). Appraisal of Strategies for Dealing with the Physical Hazards of Abandoned Surface Mine Excavations: A Case Study of Frankie and Nyala Mines in South Africa. *Minerals,* 10(2), 145. https://doi.org/10.3390/min10020145.

2. **Sphiwe Emmanuel Mhlongo**, Francis Amponsah-Dacosta, Armstrong Kadyamatimba (2019). Incorporation of the Method of Ranking the Hazards of Abandoned Mine Entries into a Rule-Based Expert System. *Minerals*, 9(10); https://doi.org/10.3390/min9100600

3. **Sphiwe Emmanuel Mhlongo**, Francis Amponsah-Dacosta and Armstrong Kadyamatimba (2019). Development and application of a methodological tool for prioritization of rehabilitation of abandoned tailings dumps in the Giyani and Musina Areas of South Africa. *Cogent Engineering,* 6: 16198946 (1), 6 (1). pp. 1-24 https://doi.org/10.1080/23311916.2019.1619894

4. **Sphiwe Emmanuel Mhlongo**, Francis Amponsah-Dacosta and Armstrong Kadyamatimba (2018). Development and use of hazard ranking system for abandoned mine entries: a case study of the mine shafts in Giyani and Musina Areas of South Africa. *Cogent Engineering*, 00: 1491776, 5 (1), pp. 1-19. https://doi.org/10.1080/23311916.2018.1491776

5. **Mhlongo S.E** and Amponsah-Dacosta F (2016). A Review of Problems and Solutions of Abandoned Mines in South Africa, *International Journal of Mining, Reclamation and Environment*, *Taylor and Francis*. 30 (4), pp. 279–294. http://dx.doi.org/10.1080/17480930.2015.1044046

Conference Publications

1. **S.E Mhlongo**, F. Amponsah-Dacosta and A. Kadyamatimba (2018). Appraisal of Strategies for Treatment of Abandoned Mine Shafts in the Giyani and Musina Areas of Limpopo Province of South Africa. In: Drebenstedt, C., von Bismarck, F., Fourie, A. and Tibbett, M (editors). Mine closure 2018: Proceedings of the 12th International Conference on Mine Closure. Mine Closure. *Technical University Bergakademie Freiberg*, pp 414-424. ISBN 978-3-86012-590-8.

2. **S.E Mhlongo**, F. Amponsah-Dacosta and A. Kadyamatimba (2018). A procedural approach for prioritization of rehabilitation of gold tailings dumps of abandoned mine sites in the Giyani Greenstone Belt, South Africa. In: JN Edokpayi, WM Gitari, EM Stam, S.E Mhlongo, Proceedings of the First International Conference in Sustainable Management of Natural Resources (ICSMNR2018). 15th -17th October 2018, Polokwane, South Africa. ISBN: 978-0-620-82267-1

3. **Emmanuel Mhlongo**, Francis Amponsah-Dacosta, Armstrong Kadyamatimba, Sibulele Sigxashi and Noxolo Kindness Mbebe (2017). Development and Application of Abandoned Mine Entries' Hazard Ranking System (AME-HRS). In: Doina Priscu (editor). Proceedings of the Enviromine.Srmining2017 (5th International Seminar on Environmental Issues in Mining, 4th International Conference on Social Responsibility in Mining. *Gecamin*, Santiago, Chile. ISBN 978-956-9393-90-7.

CHAPTER ONE

INTRODUCTION

1.1. Background of the Research

The mining industry remains the backbone of the economy of many developing countries (Yirenkyi, 2008) and South Africa is not an exception. The South African economic and infrastructure development, employment and foreign exchange earnings has for many years (more than 130 years); relied heavily on the mining industry (Segal and Malherbe, 2000; Swart, 2003; Chamber of Mines of South Africa, 2012). Currently, South Africa is the world's largest producer of gold, platinum, manganese, chromium and vanadium. It is also among the biggest producer and exporter of coal (Segal and Malherbe, 2000). Because of the long history of mining, South Africa has many abandoned mine sites which contribute significantly to environmental contamination and pose serious physical hazards to both nearby human populations and animals (Swart, 2003; Makgae, 2012). According to Munnik *et al.* (2010), there are approximately 6000 official listed abandoned mines in South Africa which their rehabilitation rest with the state. The estimated rehabilitation cost for these mines is R30 Billion and at the current pace, it is expected that their rehabilitation will last for 3000 years (Auditor General-South Africa, 2009; Saving Water SA and Water Rhapsody, 2010).

Over the years there has been a noticeable shift in the strategies used to rehabilitate mined land. In South Africa over the past 40 years; mine rehabilitation has moved through three phases which are land stabilization to monotonous grasslands and to a multiplicity of different landscapes/habitats or ecotopes (Rethman, 2000). The traditional approaches to mine rehabilitation include the development of rehabilitation strategies to address the goals of the mine, regulatory bodies and the expectations of the communities with regards to the use of the land after mining operations have ceased (Eckels and Bugash, 2010). For example, the popular guiding principles in rehabilitation efforts of mine waste has been on minimizing footprints, optimization of earth work to reduce cost, and meeting environmental regulations (Eckels and Bugash, *op cit*.). In general, the past trends in mine rehabilitation focused more on environmental protection by stabilizing the mined-out areas as well as the mine waste dumps. Very little attention has been given to cleaning up the mine site for alternative use of the disturbed land. According to Rethman (2000), the emphasis in mine rehabilitation in South Africa has for a long time focused on erosion control through revegetation while very little attention has been paid to land capacity development.

In mine rehabilitation projects, biophysical environment receives more attention while aspects such as aesthetic and cultural considerations as well as the socio-economic issues are generally given less attention (Riley and East, 1990). The approach commonly used in the stabilization of the mine biophysical environment includes the development of predictable landform design for the site and this is followed by the work of establishing sustainable ecosystem (Spitz and Trudinger, 2009). In designing the best landforms, geomorphic principles must be considered before the engineering approaches (Riley and East, 1990). In view of this, computer aided drafting (CAD) packages such as GeoFluv have been developed to assist in the development of appropriate rehabilitation options for lands disturbed by mining operations based on fluvial geomorphic principles (Eckels and Bugash, 2010).

Expert systems are basically all computer-based techniques (especially those used in the field of artificial intelligence) that are used in modeling the expertise of humans in specific or specialized field (Kappes *et al.,* 1990; Reffat and Hardness, 2001; Chu *et al.,* 2009; and Ianca and Buta, 2011). According to Anjaneyulu (1998), expert systems can be developed for almost any domain for which experts exist. Although expert system technology has been in operation for approximately 71 years, its application to mining; especially mine rehabilitation projects is still at limited level. The only application of computer-based decision support system (AMHAZ) for mine site rehabilitation was reported by Mitchell and Mackasey (1995) to have been used in the prioritization of abandoned mines rehabilitation in the Province of Ontario (Canada). This technique was to be further developed to be an expert system with a capacity to provide advice to the user based on the data stored within the knowledge base component of the system (Mitchell and Wackasey, *op cit.*).

1.2. Statement of the Problem

Abandoned mines are found in all parts of South Africa, mostly within densely populated communities. However, the nature of the environmental problems, public health and safety hazards as well as the socio-economic issues of these mines are not well-known. In general, the insufficient understanding of the problems of abandoned mines in the country has in many occasions led to the implementation of inappropriate rehabilitation strategies. For example, there has been no/less effort made to address the socio-economic impact of abandoned mines in South Africa. In view of these, this research was conducted to build in-depth knowledge of the problems of abandoned mines through detailed characterization of selected abandoned mine sites. Such knowledge will be used to develop abandoned mine ranking system that will take into account the site-specific nature of environmental problems, public health and safety hazards as well as the socio-economic impacts of the abandoned mines. It will also form a basis for identification of strategies suitable for rehabilitation of abandoned/historic mines in the country. All this information will assist in creating a most needed priority list of rehabilitation strategies of abandoned mines in South Africa.

Adding to the problem of implementation of unsuitable rehabilitation options is the fact that the budget allocated for rehabilitation of abandoned/historic is often limited. This promotes the use of low-cost rehabilitation options which are not always effective. In view of the aforementioned issues and the fact that there are currently very few abandoned/historic mines rehabilitation experts throughout the world, there is a need for the development of a simple, easy to understand, accurate, interactive and versatile computer-based advisory system for selection of appropriate strategies for rehabilitation of abandoned mines. This system will be the first abandoned and/or historic mines rehabilitation system with a capacity to rank the hazards of the abandoned mine sites or features and assist in the selection of rehabilitation strategies suitable for dealing with site-specific problems of the abandoned mines. An important element of this research was the development of a framework for estimating the cost of implementation of different rehabilitation strategies or approaches. The use of this formwork for estimation of cost of rehabilitation of existing, inactive and abandoned mines will be invaluable.

1.3. Research Objectives

1.3.1. Main objectives

The main objective of this research was to develop a computer-based advisory system to assist in the selection of appropriate strategies for rehabilitation of abandoned/historic mine sites.

1.3.2. Specific objectives

The specific objectives of this research were:

- To carry out a detailed characterization of the selected abandoned/historic mine sites in the study area,
- To devise methods for prioritization of mine features for rehabilitation,
- To create expert systems for selection of suitable strategies for rehabilitation of abandoned mines, and
- To develop a framework for estimation of cost of rehabilitation of abandoned mines.

2.4. Research Questions

In order to meet the objectives of this research, the following research questions were to be answered:

- What is the nature and relationship of the environmental, public health and safety and socio-economic concerns of the abandoned/historic mine sites?
- What are the practical strategies for addressing the problems of abandoned mines?
- What are the factors that need to be taken into consideration in selecting suitable abandoned mine rehabilitation strategies?
- How can computer-based decision-making model for selection of appropriate rehabilitation strategies be developed from factual knowledge?
- What is best way of estimating the costs of rehabilitation of abandoned mine sites?

1.5. Research Hypothesis

This research was carried out with the purpose of testing the following hypothetical statements:

- South Africa has many abandoned mines due to its long history. The nature of environmental problems, public safety and health hazards as well as the socio-economic issues of these mines are not well-known. Therefore, such knowledge can be established through detailed and systematic characterization of the selected abandoned/historic mines.
- There are several rehabilitation strategies that are currently being used in addressing the environmental problems of operational and abandoned/historic mines. However, not all these rehabilitation options are appropriate for the purpose. This is because some of these strategies are not durable enough to provide long-term protection of the site while others require prolonged post-rehabilitation monitoring which is mostly not provided for in the programme of rehabilitation of these mines. Therefore, an appraisal and ranking of different mine rehabilitation strategies will enable appropriate strategies to be identified for rehabilitation of abandoned/historic mines.
- An understanding of the problems posed by mining operations to the environment and the host communities is an important factor in the selection of rehabilitation strategies for both operational and abandoned/historic mines. In view of this, development of a computer-based advisory system that takes into consideration site characterization and in-depth understanding of site-specific problems of the selected abandoned/historic mine sites will greatly assist in selecting suitable rehabilitation strategies for abandoned mines.

1.6. Significance of the Study

Abandoned and historic mines are well known for their environmental problems, public safety and health concerns as well as socio-economic issues. However, the nature and the seriousness of these problems are not well-understood. The main cause of these problems is the fact that mining operations were ceased without any form of rehabilitation of the disturbed site or that in some cases inadequate rehabilitation strategies were implemented. Generally, the hazardous nature of abandoned mines is complicated by the fact that their associated problems are not known with certainty. This research is aimed at identifying and assessing site-specific problems of the abandoned mines in the selected study areas. This will create a better understanding of the problems of abandoned mines in the region and the country at large.

There are several abandoned mines for which inappropriate attempts of addressing their environmental and/or physical hazards were made. The most possible reason for these could be insufficient understanding of the nature of the problems associated with these mines and that the rehabilitation strategies were selected randomly on ad hoc basis. This research will appraise and rank various rehabilitation strategies applicable to derelict mines. This will assist in ensuring that all rehabilitation alternatives considered are evaluated according to their potential of effectively addressing the problems of the mine sites or features. The outcome of such an undertaking will serve as valuable information and input for the development of a computer-based advisory system for making decisions in different aspects of rehabilitation of abandoned mines.

The advisory system will use the knowledge of the status of the abandoned mine sites or features to identify the best ways of dealing with their environmental problems, public safety and health hazards as well as the socio-economic impacts of abandoned mines. To assist in making sound decisions on the selection of the most appropriate rehabilitation strategies, important factors for the selection of rehabilitation options will be identified and used to formulate rules for the computer based advisory system for rehabilitation of abandoned mines. This will have benefits of making sure that only appropriate rehabilitation strategies are considered for addressing the negative legacy of abandoned and historic mines in the country and in other parts of the world where similar problems exist.

Although mine rehabilitation is now a legal requirement for the mining industry, the advocacy is currently on progressive rehabilitation of active mines while the abandoned mines are still confronted with the problems of lack of clearly assigned responsibilities to assume rehabilitation. This coupled with the fact that the rehabilitation of abandoned mines is carried out with limited resources, it is necessary that sound, and/or critical decisions are made in the process of rehabilitation of these mines. These decisions involve identifying areas or mine features to be rehabilitated and selecting the most appropriate strategies for addressing the problems of these mines. The development of a computer-based advisory system will assist in ensuring that appropriate rehabilitation strategies for abandoned mines are selected based on situation analysis and even in the absence of experts. The system will be an important contribution to the national abandoned mines rehabilitation programme. This is because the developed computer system can be written on disks to create many copies of it or it can be published on the internet and used in different parts of the country to provide important advice on rehabilitation of abandoned mines. This will significantly reduce the time and cost of training many people and increase throughput while reducing personal cost.

1.7. Geographical Location of the Study Area

This research was conducted at selected abandoned mines within the two district municipalities of the Limpopo province of South Africa, namely; Vhembe district and Mopani district. These municipalities are Vhembe district; comprise of four local municipalities with an estimated total population of approximately 1294722 people and Mopani district municipalities with five local municipalities. The Mopani district municipality comprise of the population of about 1261463 people (Lehohla, 2014). 2014). The study area covers approximately 36.3% of the total land mass of the Limpopo Province (Lehohla, 2014). It is located between 29° 00′E and 31° 00′ E (Longitudes) and 24° 30′S and 22° 00′ S (Latitudes) as shown in *Figure 1.1.*

The Limpopo Province is basically characterized by approximately 729 abandoned mines that are found across all its districts and local municipalities (Development Through Mining, 2007). The study area, which forms part of the Limpopo Province, hosts several gold, ferrous-and-base metals and industrial minerals mines that have been abandoned and un-rehabilitated or poorly rehabilitated. These abandoned mines include medium-to large-scale gold mines within the Giyani area (those are mines found in the Giyani Greenstone Belt), large-scale copper mines and few magnesite mines along the northern boundary of the province (*i.e.* along the Limpopo Belt in the areas of Musina and Tshipise respectively).

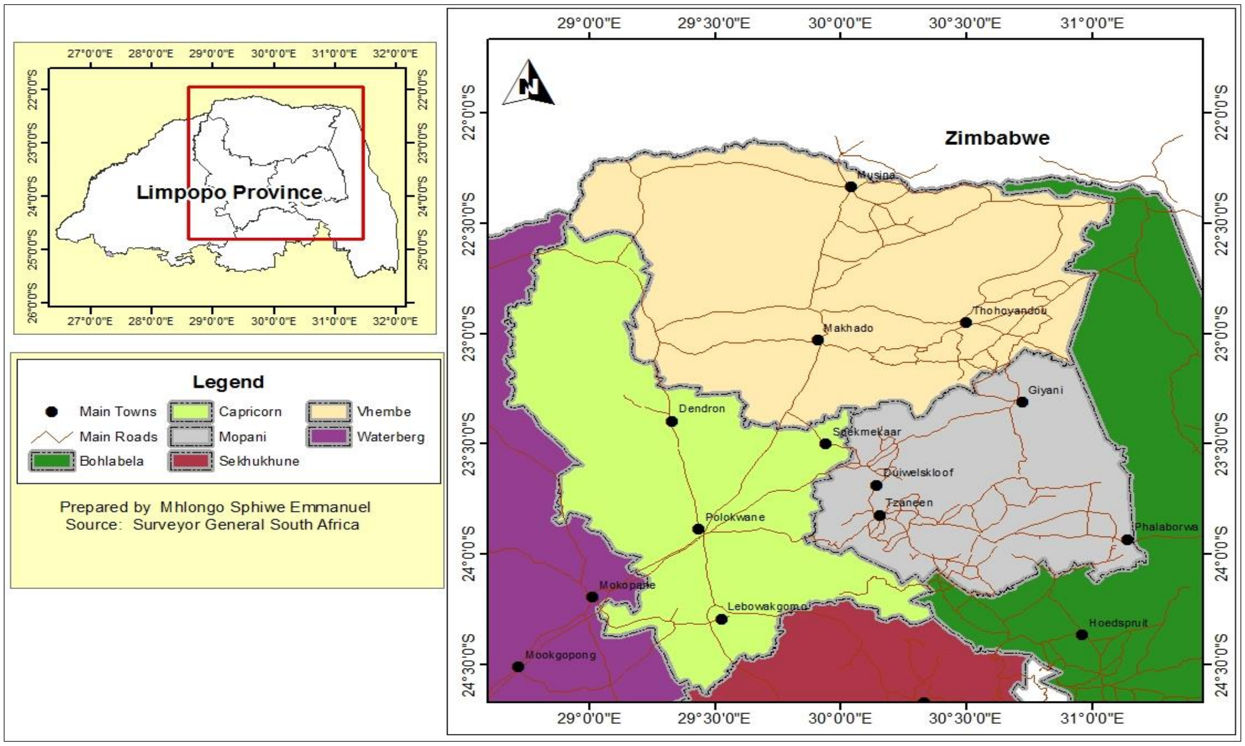


Figure 1. 1: Geographical location of the study area.

1.8. Operational Definitions and Terminologies

For better understanding of the work presented in this proposal, certain terminologies and expressions are to be clearly defined. This section provides definition and explanation of key concepts, terminologies and expressions as used in the proposal.

- *Computer-based advisory system:* this is a system that include both computer and humans as essential players in making-sound decisions. It is developed to either replace or support human decision-makers.
- *Environmental hazards:* can be defined as a state of events or practice that has the potential to threaten the environment and adversely affect people's health. These hazards can be classified as physical, chemical, mechanical, biological and psychosocial.
- *Expert systems*: these are computer-based programs that attempts to act like a human expert on a particular field or subject. These systems are often used to provide advice to non-expert's individuals in situations where human experts are not available.

- *Expert-system shell:* this is a computer program which when supplied with a particular knowledge base will yield an expert system. The minimum capability of an expert-system shell is reasoning or inference with the knowledge within the knowledge base, producing conclusions based on entered findings or facts.
- *Mine rehabilitation:* this is defined as a process of returning the land disturbed by mining to a condition that is chemical and physical stable, productive and self-sustaining while taking into consideration the future uses of the land.
- *Physical hazards:* are factors within the environment that has a potential to harm the body.
- *Treatment:* is used in this research to refer to the work conducted to render abandoned mine entries safe. The objectives of such work include prevention of falling into the shafts and human and animal intrusion into the mine entries, prevention of the risks of ground movement in the form of ground subsidence or collapse of surface land, control/monitoring of discharge of atmospheric gases and protection of species inhabiting the abandoned mine entries and/or workings.

1.9. The Structure of the Thesis

This thesis is organized into eight important chapters.

Chapter One provides a background of the research, overview of the statement of the research problem and presents the objectives of the research. The research questions, hypothesis as well as the significance of the research are also presented in the chapter. The last part of the chapter describes the location of the study area and lists the operational definition and terms used in this research.

Chapter Two provides a comprehensive review of literature related to the topic of this research. In this case, the important issues of abandoned mines and their rehabilitation were reviewed. These issues include the environmental problems, physical hazards and the socio-economic concerns of these mines. The literature review also looked at the legislative framework and prioritization of rehabilitation of abandoned mines in South Africa. The approach to mine rehabilitation and the popular tools for prioritization of rehabilitation of abandoned mines were also reviewed. The last section of this chapter deliberates on the issues of decision making and use of expert system as decision making tool. This is then followed by the discussion of the mine closure and rehabilitation cost estimation.

Chapter Three focuses on the presentation and discussion of the method developed for prioritization of rehabilitation of abandoned mine entries. The situation of abandoned underground mine shafts in Giyani and Musina areas is used to developed and test the functionality of the method for prioritization of abandoned mine entries. Moreover, the evaluation of strategies for treatment or rehabilitation of abandoned mine entries was also carried out in this chapter.

Chapter Four reports on the method developed for prioritization and selection of strategies for rehabilitation of abandoned mine tailings dumps. The situation of abandoned gold, coper and magnesite tailings dumps in the areas of Musina and Giyani was used in developing and validating the functionality of such method. The discussion of the findings of the use of this method in the chosen case study and the summary of the chapter are presented at the end of chapter four.

Chapter Five reports on the nature of hazards presented by surface mine excavations and different infrastructure of abandoned mines. The structures found on landscapes of abandoned mine sites in Giyani and Musina areas which are discussed in this chapter includes dilapidated buildings and areas of mineral processing, different concrete structures such as water reservoirs, mounting strands, and concrete floors. The evaluation of strategies for dealing with the problems of abandoned surface mine excavations and surface structures conducted using different semi- quantitative methods is also presented in this chapter.

Chapter Six is focused on presenting the computer-based advisory system for rehabilitation of abandoned mines developed in this research in the form of three expert systems. Those systems are the expert system for ranking of the problems of abandoned mine entries, expert system for ranking of abandoned mine tailings dumps for rehabilitation, and the expert system for selection of strategies for rehabilitation of abandoned mines. This chapter discuss these expert systems in terms of their attributes, production rules, and the structure of their decision trees. The last part of this chapter discusses the findings and presents the summary of the work conducted.

Chapter Seven presents the framework for estimating the cost of rehabilitation of abandoned mines. The first part of this chapter reports on the approaches for estimation of the costs of rehabilitation while the last part discusses a generic framework developed in this research for estimation of rehabilitation costs for abandoned mine sites.

Chapter Eight summarizes the major observations made when conducting this research and state the concluding remarks drawn from the discussion of the results and findings presented in the previous chapters of the thesis. It also gives recommendations for further research to improve on the findings of this research.

CHAPTER TWO

LITERATURE REVIEW

The review examined the nature of physical and environmental hazards as well as socio-economic issues of abandoned mine sites, covered issues of abandoned mines in different pieces of legislations in South Africa, and efforts made towards rehabilitation of abandoned mines in the country. In addition, review of the well-known abandoned mine sites ranking systems was carried out and this was followed by an overview of the use of expert systems (*i.e.* knowledge-based and fuzzy logic system) as decision making tools.

2.1. Abandoned Mine Issues

There is no clear and widely accepted definition for abandoned mines. The mine is generally considered abandoned if there are no identified owners or operators for the facilities. The term can also be used to describe sites where the proponent has ceased or suspended activities such as advanced exploration, mining, or mine production until further notice without rehabilitating the site (Mhlongo, 2012). Other terms referring to these mines include: derelict mines, orphan mines, unattended mines, and inactive mines. The consideration of the public and environmental hazards rather than the ownership aspects of these mines is of great significance in the selection of an appropriate definition of abandoned mines (Mackasey, 2000).

According to Newton *et al.* (2000), abandoned mines refer to areas of any mineral extraction, exploration or borrow operation where mining operations have ceased for a period of one year or more, where there is no interim management plan in effect, and there are no approved financial assurances that are adequate to perform reclamation. These sites include but not limited to shafts and adits, buildings and workings, open pits, stockpiles, roads, processing areas, and waste disposal areas such as tailings dumps and ponds. Thus, abandoned mine sites can be precisely defined as mine sites and mineral operations that are no longer operational, not actively managed, not rehabilitated, are causing significant environmental and/or social problems, and for which no one is currently accountable for the site's remediation or rehabilitation (UNEP and COCHILCO, 2001).

The most important abandoned mine issues that confronts all countries with long history of mining like South Africa are environmental problems, physical hazards (public health and safety), and socio-economic problems. These mines are considered by many as negative legacy of post mining operations. Although the problems of derelict mining operations are well known in almost all countries, the industry, governments and community efforts towards cleaning-up of these mines have delayed. The reasons for the delay were outlined by the UNEP and COCHILCO (2001) to be (among others); the lack of clearly assigned responsibilities, the absence of criteria and standards of rehabilitation, and the potential cost of rehabilitation. According to Haskin (2012), abandoned mines rehabilitation projects are invariably expensive and often with no clear view of where the necessary funds will come from as the economic phase of the mine will have ceased.

Moreover, abandoned mines (especially abandoned gold mines) have become hot-spots for small-scale and illegal mining operations. This practice turns to promote the environmental problems and physical hazards of the abandoned mines. For an example, the impact on water courses can be seen along the rivers near the abandoned gold mines in Giyani area where artisanal illegal miners dig out washing sites and/or dam water and build sluice tables. Increasing the exposure to physical and/or health hazards of abandoned mines, the illegal miners would in most instances dig their own access ways into the old underground workings and manually remove ore from underground (Steenkamp and Clark-Mostert, 2012). This action can be considered threats to the viability of mine closure efforts (Reichardt, 2012). The year 2007 and 2006 incidents where 5 and 61 illegal miners died because of rockfall and mine fire in inactive shafts of Fairview Mine in Barberton and Harmony Gold Mining in the Witwatersrand are indications of human tragedy that can result from illegal mining operations at abandoned or inactive mine sites (Reichardt, 2012; Macharia, 2009).

2.1.1. Environmental problems

The most influential factor on the environmental impact of mining is the type of mining method employed in the extraction of mineral resources and the geographical location of the mine (Smith, 2009). This is because of the disturbances associated with surface mines are generally different from those of underground mining operations. According to Allen *et al.* (2001), the type of mining method has significance influence on the visual appearance of the area. In most cases; the mining methods affect a relatively small area which is mostly the mining lease area. However, relatively large areas outside the mining lease are affected by pollution and accumulation of waste material (Sahu and Dash, 2011; Allen *et al.,* 2001). The environmental problems associated with mining operations are currently minimized by using well-designed, well-operated, and well-regulated mining operations. However, in all mining countries there are many abandoned mines that constantly stand as major environmental challenges facing the governments.

Common physical environmental problems found at most abandoned mine sites include: altered landscape; unused pits and shafts; land no longer usable due to loss of soil, pH, or slope of land; abandoned mine waste disposal facilities (namely; tailings, spoils and rock dumps); changes in ground and surface water regimes; contaminated soils and aquatic sediments; subsidence; changes in vegetations; derelict works sites with compacted and polluted soil; and burning coal waste dumps and workings (UNEP and COCHILCO, 2001; MMSD, 2002).

Water resources which are also conduits through which contaminants can escape to the environs away from the immediate mine sites are most frequently polluted by abandoned mines. The chemistry of the discharge by mines varies greatly and their effect differs, thus the drainage from the mines may be alkaline, moderately or high saline, alkaline and ferruginous, or acidic and ferruginous (Johnston *et al.,* 2008). The way by which both surface and groundwater turn to be contaminated by pollutants from the mining sites is shown in *Figure 2.1*.

The major problem affecting water resources throughout the world is acid mine drainage (AMD) and in South Africa it is a serious concern. The AMD issue has for the recent past received considerable attention and has turned to be a costly environmental challenge facing the South African government (Makgae, 2012). Generally, AMD is the process that occur as the result of the interaction of oxygenated water with sulphides; especial pyrite (FeS_2)

minerals (McCarthy, 2011; Bowell *et al.,* 2000). According to Nordstrom and Alpers (1999), because of the concentration of pyrite in rocks, its grain sizes and distribution; from an acid-generation perspective it is the most relevant sulphide. Although it is not all mineral deposits of South Africa that are afflicted by production of AMD, the country's extensive coal and gold field (Witwatersrand basin) are characterized by high number of abandoned mine sites and these contribute significantly to discharge of AMD to major rivers and surface water bodies of South Africa (McCarthy, 2011). The distribution of gold and coal fields of South Africa is shown in *Figure 2.2*.

The AMD problem in the country is likely to persist for centuries to come (Oelofse, 2008). This is because within the Witwatersrand area alone there are huge pyrite-bearing tailings (6 billion tonnes over 400 km^2) that are expected to continue to release acidic water; reach in iron and sulphides to the environment (Chapman, 2011; Winde, 2010 and Pratt, 2011). In addition, even though AMD from abandoned coal mines is already affecting water quality in the Olifants River Catchment, prospecting rights across 45% of Mpumalanga land mass are still being granted; thus, giving clear indications of the future potentials of AMD generation in the country (Salgado, 2011).

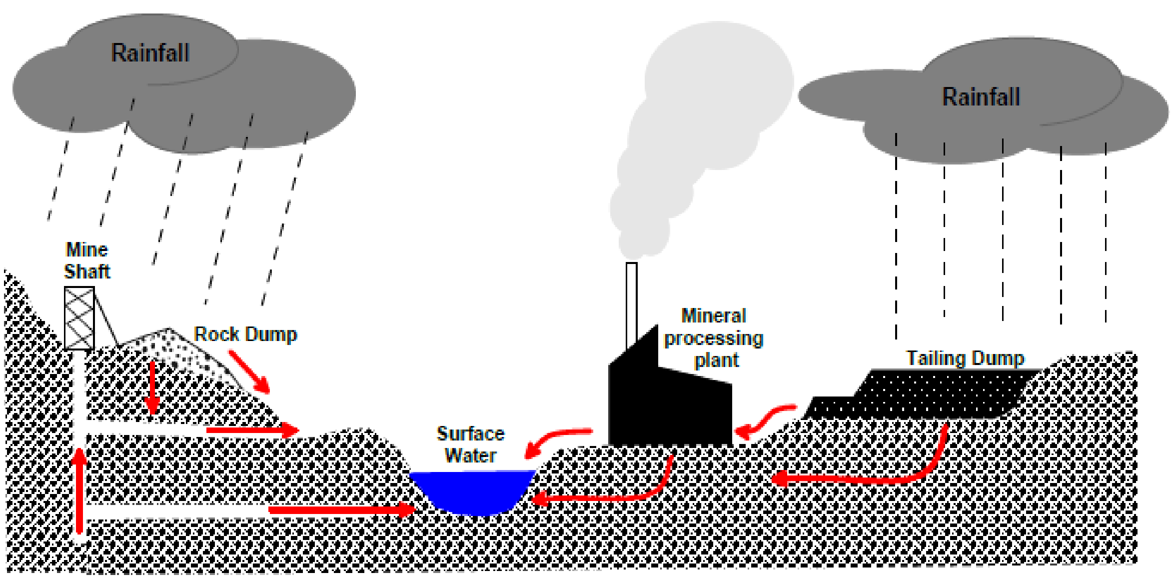


Figure 2.1: An illustration of surface and ground water contamination by mining operations (MINEO, 2003).

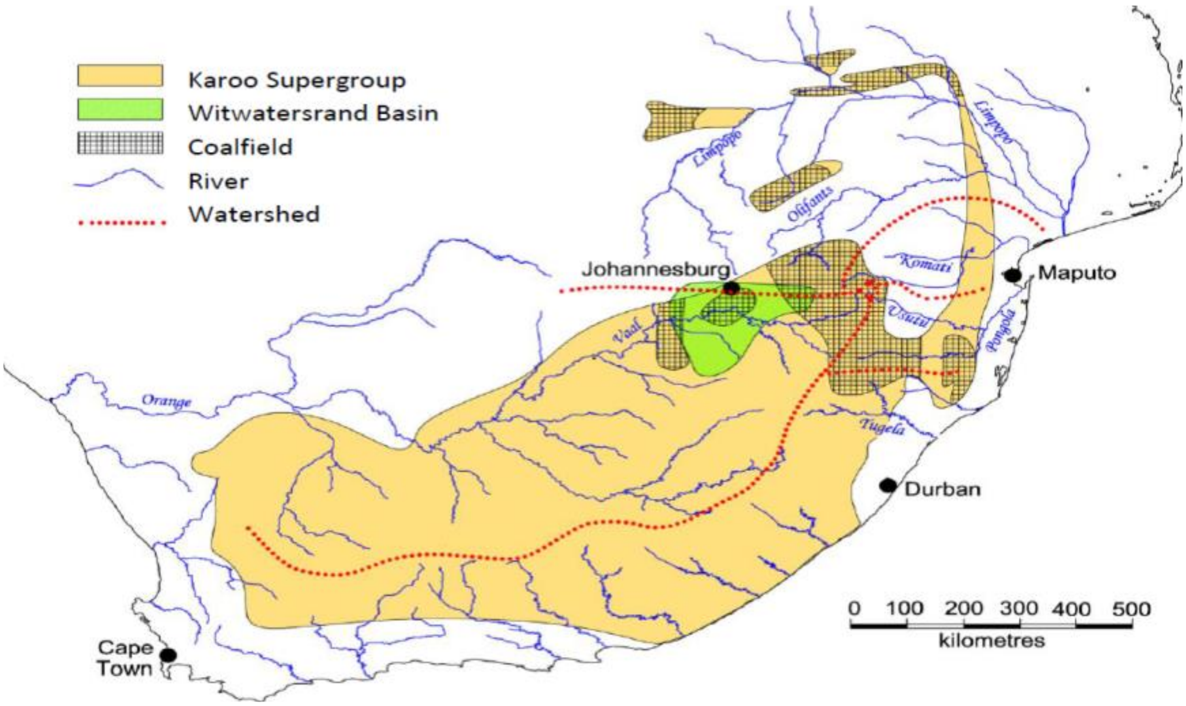


Figure 2.2: The distribution of gold and coal deposits within the watershed areas of South Africa (McCarthy, 2011).

2.1.2. Socio-economic impacts of abandoned mines

Mining by its very nature brings to the communities' huge investment and this contributes to the socio-economic development of such communities in diverse ways. These include the creation of new jobs opportunities, infrastructural development and attraction of basic needs such as running water, electricity, building of schools and health care centers in the area. With the socio-economic opportunities being presented by the establishment of new mines in poor and remote communities, mushrooming of new communities around the mine sites are also identified and remain an issue of concern. This is because these communities become dependent on the economic opportunities generated by the mine. As a result, abandoned mines are commonly not found in isolation but are found within communities. According to Goldammer and Nusser (1999), abandoned uranium mines with large volumes of mine waste and extensive excavations are found within densely populated areas of Soxony and Thuringia in Germany. It was established that about 300 and 200 million m^3 heaps of waste rocks and tailings dumps respectively cover a large area of Soxony and Thuringia. In South Africa, the location of abandoned mines in relation to population density is as shown in *Figure 2.3.* It can be seen from *Figure 2.3* that there is dense cluster of abandoned mines in areas of high population around Gauteng, North-west and Limpopo provinces.

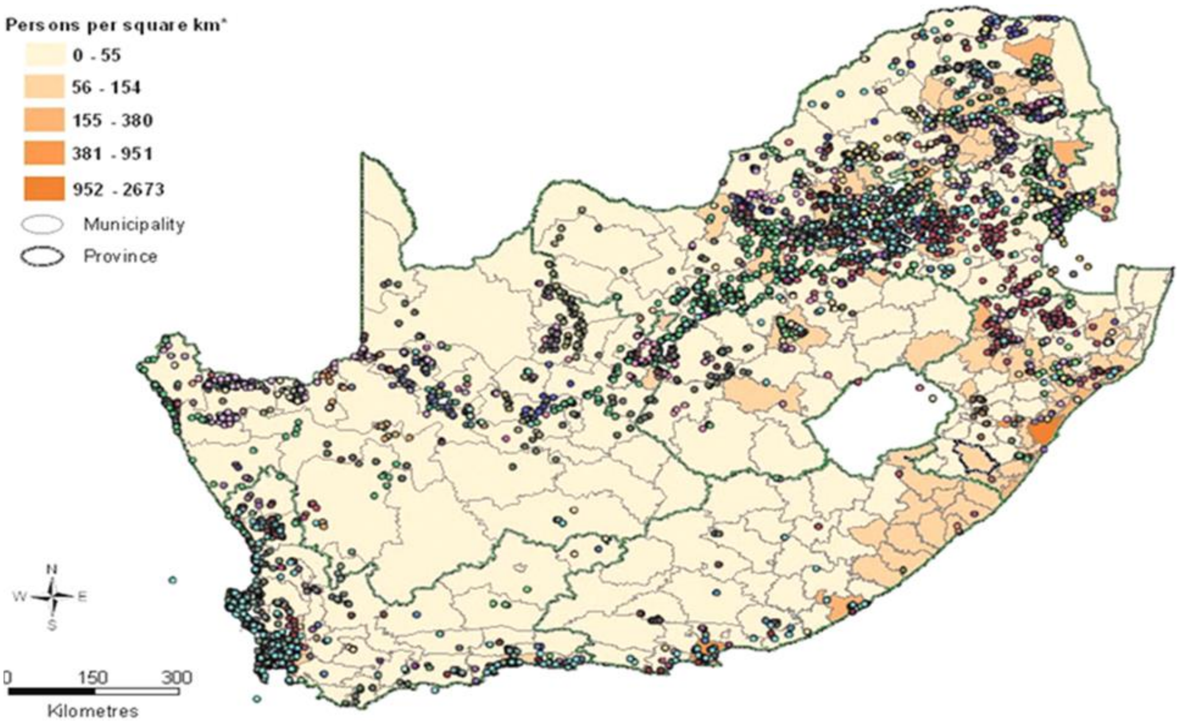


Figure 2.3: The abandoned mines localities and their corresponding population density (from Auditor General South Africa, 2009).

Commonly, environmental problems of abandoned mines can as well have serious impact to the quality of life and livelihood of people around abandoned and/or historic mine sites. According to Johnston *et al.* (2008), iron rich water from the mines may have aesthetic impact on the receiving water bodies and this makes the place less attractive for investment. This can make the water unsuitable for other uses. It reduces its economic and social value to the communities that use the water.

It has been reported by (Winde, 2010) that water from abandoned gold tailings at Wonderfonteinspruit Catchment around West and far West Rand have uranium concentration ranging from 900 to1000 mg/kg and elevated heavy metal content and these pose serious health threats to the communities using the water for different purposes. Most of the inhabitants of this area live in informal settlements with high HIV/AIDS infections, chronic and acute malnutrition thus the detected uranium poses additional stress to their immune system (Liefferink, 2010). The survey of abandoned mines in Australia identified several major socio-economic problems of these mines. These challenges include decrease in the number of residents and visitors to previous mining areas, financial impact on communities and creation of "ghost towns", increased social and community resistance to mining, loss of jobs and livelihoods, loss of sense of community, loss of services, loss of opportunities for local people, and impact on local council and their ability to sustain infrastructure (van de Graaff *et al.,* 2012).

Other socio-economic problems that can arise from the environmental problems of abandoned or poorly rehabilitated mines include: loss of productive land, degradation of water resources (both surface and ground water) that can have detrimental effect on aquatic life, change in river regimes, air pollution from dust and toxic gases, risk of injury or death as a result of falling into open shafts and pits, and landslides (UNEP and COCHILCO, 2001). The dust and soils from abandoned mines might be containing contaminants that are health hazardous (silica, asbestos fibers and chromium) and heavy metals. The death of fish because of the dispersion of pollutants to surface water bodies has potential of affecting the livelihood of communities that depend on fishing (MMSD, 2002).

2.2. Legislative Framework and the Priority of Rehabilitation of Abandoned Mines

The economy of South Africa has for over a century relied on mining activities. Unfortunately, mining has left the country with enormous economic, social and environmental legacy (Swart, 2003). Mining in South Africa operated for a long time under traditionally weak regulation systems that placed the responsibilities for mining impacts to the mine owners and in the process many mines (approximately 6000 mines) were abandoned (Munnik *et al.,* 2010). According to Swart (2003), prior to the passing into law of the Minerals Act (Act 50 of 1991) many mining companies used irresponsible mining methods with no regard towards protecting the environment and left these mines unrehabilitated prior to them being liquidated or leaving the country. The previous (apartheid) government tried to address the situation through 1975 Fanie Botha Accord agreement between the Minister of Water Affairs and the Chamber of Mines of South Africa (Munnik *et al.,* 2010). It was agreed that the government was to take 100% responsibility for all mines closed before 1976, and 50% responsibility for those closed between 1976 and 1986 while the other 50% is taken by the mine owner. After 1986 all mines including their closure were to be the responsibility of the owner (Munnik *et al.,* 2010 and MMSD, 2002).

In general, the first piece of legislation that comprehensively covered the issues of environmental management, rehabilitation and financial provision for the rehabilitation work was the Minerals Act 50 of 1991. It is important to note that prior to the promulgation of the Minerals Act of 1991, there was no regulation that controlled the abandonment of mines without the rehabilitation of the affected land in South Africa (DMR, 2009). According to van der Schyff (2012), the objectives of the Minerals Act 50 of 1991 was to ensure that the responsibilities of the state towards the community in respect of the minerals industry are fulfilled. Such responsibilities included the regulation of prospecting for minerals and optical exploitation; processing and utilization of minerals; and the orderly utilization and rehabilitation of the land where prospecting and mining operation have or are taking place.
Currently, the issues of rehabilitation of abandoned mines are controlled by the Minerals and Petroleum Resources Development (MPRD) Act 28 of 2002. This is possible because the MPRD Act 28 of 2002 incorporates within it the aspects of social and labour plan, and sustainable development principles of the National Environmental Management Act (NEMA) as well as the National Water Act (NWA) (Adams, 2010).

Although the most important issues of abandoned mines are physical hazards, environmental problems and socio-economic issues, the primary focus of abandoned mine rehabilitation programme in South Africa has been on those mines that present significant health and safety hazards. According to the official statement from DMR, rehabilitation of abandoned mines in South Africa has since 1986 focused on rehabilitation of health hazardous asbestos mines and public safety threatening mine shafts (Davenport, 2006; Auditor-General South Africa, 2009). This rehabilitation approach put those mines that present public safety and health threats at the top of the list and those characterized by significant environmental stresses are placed at the bottom. Basically, it does not recognize the extent of socio-economic issues of abandoned mine lands. In the year 2010, the then Department of Mineral Resources prioritized the rehabilitation of abandoned mines in South Africa as shown in *Table 2.1*. Such prioritization criteria placed the mines with high environmental problems at the highest. In response to the 2006 Auditor-General South Africa report and the outbreak of AMD-related problems in the Witwatersrand, the DMR (the former Department of Minerals and Energy) grouped those mines that pose high environmental risks at high priority following the heath hazardous abandoned mines as shown in *Table 2.1*.

Table 2.1: High priority hazardous historical mines in South Africa (from DMR, 2010).

Region	Commodities	Comments
*Asbestos mines	Asbestos	High risks due to adverse health impacts
Wits gold basin (from the Free State to Evander)	Gold, uranium	High environmental risks due to uranium content and Acid Mine Drainage (AMD).
Gold mines occurring in the greenstone belt of Mpumalanga	Gold, silver, arsenic	High risks due to arsenic, AMD and uranium content.
Gold occurring in the greenstone belt in Limpopo	Gold, antimony	High risks due to AMD and the presence of antimony and, in some cases, mercury
Coal mines in Mpumalanga	Coal	High risk due to land subsidence, AMD and spontaneous combustion
*Copper mines	Copper, tungsten, molybdenum, bismuth	Water related risks due to the presence of bismuth – Medium Risk
Pegmatites in Northern Namaqualand	Many commodities	Risks are primarily due to radioactive components or bismuth – Medium Risk

Note: *site not specified

2.3. Approach to Mine Rehabilitation

Over the years (>130 years) there has been a noticeable shift in the strategies used to rehabilitate mined land (Yirenkyi, 2008). In South Africa within the past 40 years; mine rehabilitation has moved through three phases, that is from land stabilization to monotonous grasslands and to a multiplicity of different landscapes/habitats or ecotopes (Rethman, 2000). The traditional approaches of mine rehabilitation include the development of rehabilitation strategies to address the goals of the mine, regulatory bodies and the expectations of the communities with regards to the use of the land after mining operations have ceased (Eckels and Bugash, 2010). The popular guiding principles in traditional mine rehabilitation efforts are minimizing of footprints through piling mine waste in a form that resembles a flat-topped pyramid in a small area, optimization of earth work by moving overburden for a short distance as possible to reduce cost, and meeting environmental regulations by keeping mine waste dumps stable and good water quality as per the regulatory requirement (Eckels and Bugash, 2010). In general, the past trends in mine rehabilitation focused more on environmental protection by stabilizing the mined-out areas and the created mine waste dumps. Very minimal attention has been given to cleaning up the mine site for alternative use of the disturbed land. According to Rethman (2000), the emphasis in mine rehabilitation in South Africa has for the past years placed more emphasis on erosion control through revegetation while very little attention was paid to land capacity development. Some of the recommended post-mining land uses in the increasing order of their value include unused land, range land (natural pasture), range land (improved posture), crop land, land use for intensive agriculture, residential and/or commercial land (Spitz and Trudinger, 2009).

Although mine rehabilitation has several aspects, biophysical environment deserves more attention. Other important mine rehabilitation aspects that are generally receiving less attention in rehabilitation projects include aesthetic and cultural considerations as well as the socio-economic issues (Riley and East, 1990). The approach commonly used in the stabilization of the mine biophysical environment includes the development of predictable landform design for the site and this is followed by the work of establishing sustainable ecosystem (Spitz and Trudinger, 2009). According to Riley and East (1990), in designing the best landforms, geomorphic principles must be considered before the engineering principles. In view of this, computer aided drafting (CAD) packages such as GeoFluv were developed to assist in the development of appropriate rehabilitation options for lands disturbed by mining operations. The GeoFluv approach is based on fluvial geomorphic principles that describe how landscapes functions and operate (Eckels and Bugash, 2010).

There are numerous factors that need to be taken into consideration when assessing the abandoned or inactive mine site for rehabilitation purposes. Among others, these issues include the age of the mine site, the level of environmental impact presented by the site, public safety and health issues, social issues, availability of government support, and the commitment of the community to rehabilitation effort. According to Goldammer and Nusser (1999), the clean-up of contaminated mines requires appropriate and efficient decision-making methodologies thus the goals of rehabilitation are to protect the people and the environment while saving money and other resources. In this regard the rehabilitation of abandoned mine lands is not an exception. In South Africa and other countries; priority in the rehabilitation of abandoned mines is given to those mines that present severe public safety concerns and then to those that have serious/significant adverse impact on the environment (MMSD, 2002; Davenport, 2006; and Auditor-General South Africa, 2009).

2.4. Methods for Prioritization of Rehabilitation of Abandoned Mines

Abandoned mines present a legacy of environmental problems and physical hazards which their complexity varies from one site to the other since these mines are mostly abandoned without any rehabilitation of the land (Power *et al.,* 2009; Kubit *et al.,* 2015). As a result, the identification, characterization and ranking of the hazards of abandoned mines is an important part of the program of their rehabilitation (Greeley, 1999). Such ranking exercise is mostly conducted at the beginning of the abandoned mine rehabilitation program, following or during the site characterization stage. The processes involved in characterization and ranking of abandoned mine sites and the nature and seriousness of the hazards has at times led to rehabilitation of abandoned mines without completing the site characterization and hazards ranking exercise. This makes the identification of appropriate hazards ranking system for abandoned/historic mines a challenging task to tackle.

Despite the challenging nature of the exercise of ranking the abandoned mine sites, different counties and organizations have/are making great efforts in developing site-specific schemes to guide the rehabilitation of this mines in different parts of the world. Some of the most known and celebrated systems for ranking abandoned mine sites are: (i) Abandoned and Inactive Mines Scoring Systems (AIMSS), (ii) Reclaimed abandoned and Inactive Mines Scoring System (RAIMSS), (iii) Historic Mine Site Scoring System (HMS-SS), (iv) Abandoned Mines Hazard Rating System (AMHAZ), (v) Preliminary Appraisal and Ranking Model (PAR), (vi) ARD Potential Based Ranking of Abandoned Mines, and (vii) Risk Ranking Methodology (RRM) (Day and Harpley, 1999; Herma, 2010; Mitchell and Mackasey, 2005; Power *et al.,* 2009). According to Kubit *et al.* (2015), the challenge in the adoption and use of most of the existing ranking systems is mainly the fact that they lack transparency, leave out some of the important parameters and reclamation methods, and they also lack model calibration. A brief description of the common abandoned/historic mine sites ranking methods is given in *Table 2.2.*

Table 2.2: Description of some of the common abandoned mine sites ranking systems.

System	Description	Source
Abandoned and Inactive Mines Scoring Systems	▪ It was used to ranked abandoned and inactive mine sites in Montana ▪ Developed based on the CERCLA-HRS*. ▪ The data physically collected in each site to assign the rank scores ▪ It is capable of evaluating potential safety hazards of the abandoned mine sites.	Pioneer Technical Services (1994) Jordan and Abdelaal (2013)
Reclaimed abandoned and Inactive Mines Scoring System	▪ Used to estimate the risks of reclaimed abandoned mine sites in Montana ▪ It was developed based on the principles of the AIMSS	Pioneer Technical Services (1994)
ARD Potential Based Ranking of Abandoned Mines	▪ It was used in ranking abandoned mine sites based on ARD potential in Britain Columbia (BC). ▪ It used information about mineral occurrences and that provided by government officials to rank the sites. ▪ The ranking is manly based on environmental problems of the sites	Day and Harpley (1992)
Risk Ranking Methodology	▪ It was used in ranking abandoned mines in Britain Columbia ▪ It ranked based on the results of risk-based Preliminary Site Investigation (PSI) ▪ Considered both human health and environmental impacts in the ranking	Power (2009) Tremblay and Hogan (2009)
Historic Mine Sites Inventory and Risk Classification Scoring System	▪ Employed in the ranking of abandoned mines in Ireland ▪ Developed with significant modification of the AIMSS ▪ Ranked abandoned mine sites based on their impact on human health, animal health and the environment	Luodes, 2013; Herma, 2010 PGeo *et al.*, 2009
Abandoned Mines Hazard Rating System	▪ Employed in ranking abandoned mines in Ontario (Canada) ▪ First computer-based expert system for ranking abandoned mines ▪ It considered factors such as public safety, public heath, environmental problems, social concerns and economic issues	Bolger *et al.* (1995), Mackasey (2000)
Preliminary Appraisal and Ranking Model	▪ It's a system comprising of two components for ranking the physical and chemical hazards ▪ It was used extensively in the ranking of abandoned mine sites in California	Kubit *et al.* (2015)

***Note:** CERCLA-HRS, Comprehensive Environmental Response, Compensation and Liability Act-Hazard Ranking System.

2.5. Decision Making Problem

Decision making is a process of resolving a specific choice or course of actions (Seram, 2013). It was previously defined by Efstathiou and Rajkovic (1979) as a process of selecting an option from a set of possible; to best satisfy the aims or goals of the decision maker. Making decisions about the most appropriate mine rehabilitation strategies can be a complex task. This is because human and financial resources for abandoned mine rehabilitation are limited thus bringing about a dilemma in making decision on which sites are to be rehabilitated first (Mitchell and Mackasey, 1995). Generally, decision making is a daily problem in almost all fields of human activity. The complexity of decision-making problem depends mainly on the number of parameters influencing the decision, how clear are the goals and/or knowledge, the number of defined alternatives, the presence of different decision-making groups within different objectives, and the time constraints in making decision (Bohanec and Rajkovic, 1990). According to Bohanec and Rajkovic (1990), decisions can be broadly classified as programmed decisions and non-programmed decisions. Programmed decisions are concerned with routine problems and they are generally simple while non-programmed decisions deal with unique; unstructured problems; and are consequential (Christensen, 1968; Bohanec and Rajkovic, 1990; Woehrle, 2011).

2.6. Expert System (ES) as Decision-Making Tools

Expert systems refer to all computer-based techniques that are used in modeling the expertise of humans in specific or specialized field (Kappes *et al*., 1990; Reffat and Hardness, 2001; and Chu *et al*., 2009). These include all computer programs used mainly in the field of artificial intelligence (Ianca and Buta, 2011). According to Reffat and Hardness (2001), ES provide problem solving knowledge and advice that are comparable with those from experts in a given field. If they are well maintained, these systems can become a repository for corporate knowledge that keep experiences alive even when engineers have retired or resigned (Barai and Pandey, 2004). According to Ianca and Buta (2011), expert systems are commonly designed to fulfill the requirements of risks reduction in decision making, ensuring successive leaning, and simulation of creatively.

These systems have an advantage of being able to reduce the time spent learning certain tasks and increases the amount of time spent at a level of competence performance (Kappes *et al.,* 1990). Unlike human experts, expert systems do not forget, many copies of the system can be made thus reducing time and cost of training many people, they can increase throughput while reducing personal cost, and they provide consistent answers or recommendations in situations that are similar (Churilov, 2009). Their obvious shortcomings are that they lack common sense; they cannot give creative response like human (especial to unusual situations), if errors occur in the knowledge base then wrong decisions can be made, they are dependent on symbolic inputs thus they lack sensory experience. In addition, expert systems need explicit update for them to adapt to changing environment and they are unable to recognize when the problem is outside their area of expertise. According to Anjaneyulu (1998), these systems can be developed for almost any domain for which experts exist. The development and use of expert systems date back to the 1940's. The chronological presentation of some expert systems is presented in *Table 2.3*. This is expected to provide indications of the long history and evolution of ES over the years.

Although ES technology has been in operation for more than 71 years, its application to mining; especial mine rehabilitation projects has not been given attention. The expert systems recently developed to assist in making decisions in mining include the ES for hydraulic excavator and truck selection in surface mining and the ES-VENT which is the ES for on-line ventilation network analysis and graphic representation of mine ventilation parameters (Kirmanli and Ercelebi, 2009; Bandyopadhyay and Sinha, 2002). The only known use of computer-based decision support system in the rehabilitation of abandoned mines was reported by Mitchell and Mackasey (1995) to have been used in the prioritization of the rehabilitation of abandoned mines in the Province of Ontario. According to Mackasey (2000), this system was used in ranking the abandoned mines based on factors such as public safety, public heath, environmental problems, social concerns and economic issues. This method was based on multi-criteria and pairwise comparison in providing advice on which areas or parts of the abandoned mines are to be rehabilitated first. This system was to be further developed to be an expert system with a capacity to provide advices to the user based on the data stored within it (Mitchell and Mackasey, 1995).

Table 2.3: A chronology of expert systems development (From Norou, 2003).

Year	The system name and developer(s)
2009	A Bayesian Expert System for Clinical Detecting Coronary Artery Disease (Chi-Ming Chu1),
2000	Intelligent - Web, E- commerce, Search engines
1998	More than 12500 Expert Systems were developed (only at United of America)
1996	GUESS - Generically Used Expert Scheduling System
1994	Commercial Artificial Neural System
1993	Lumiere Project (Microsoft)
1990	Artificial Neural Systems
1985	CLIPS Expert System Tool (NASA)
1983	KEE Expert System Tool (IntelliCorp)
	Japan - Fifth Generation Project (Intelligent computer)
	Hopfield Neural Net
1982	SMP Math Expert System
1980	LMI and symbolics founded for manufacturing LISP machines
	Inference Corp formed
	Artificial Intelligence goes commercial
1979	RETE Algorithm for fast pattern matching developed by Forgy
	Meta-DENDRAL- metarules and rule indication (Buchanan)
1978	XCON/R1 (DEC computer system configuration) Stated (McDermott, DEC)
1977	OSP Expert system shell for XCON/R1 (Forgy)
	Theory of Reasoning under Uncertainty (Dempster-Shafer)
	PROSPECTOR Expert System started by Duda, Hart, …
1976	Artificial Mathematician (AM) descovery of math concepts (Lenat)
1975	Frames and knowledge representation (Minsky)
	HEARSAT II - cooperating experts blacboard model
	EMYCIN - Expert System Shell (Shortliffe, Buchanan, van Melle)
	TEIRESIAS - explanation facility concept (Davis)
	GUIDON (intelligent tutoring) (Clancey)
1973	MYCIN Expert System for medical diagnosis (Shortliffe)
	Human problem solving (Newell, Simon)
1971	HEARSAY I (Speech recognition)
1970	PROLOG work started by Colmerauer, Rousell, …
	Perceptrons (Minsky and Papert)
1969	MACSYMA Math Expert System (Martin, Moses)
1968	Semantic nets, associative memory model (Quillian)
	Dendral started by Feigenbaum, Buchanan, …
	Fuzzy Logic (Zadeh)
1965	Automatic Theorem Proving via Resolution Method (Robinson)
1962	Principles of Neurodynamics on perseptions (Resenblatt)
1958	LISP Artificial Intelligent language invented by McCarthy
1957	Perceptron invented. General Problem Solver started by Newell, Shaw, Simon, …
1956	Artificial intelligent term used. Logistic Theorist. Heuristic Search
1954	Markov Algorithm (control rule execution)
1943	Post production rules. The neuron model (McCulloch, Pitts)

2.6.1. Expert systems architecture

Expert systems consist of arranged rules that are extracted from evidenced data (Chu *et al.*, 2001). According to Reffat and Hardness (2001), they are comprised of two major parts which are the development environment and the consultation environment. The development environment of the system is basically used to build the components and to introduce knowledge to the system. This part of the system contains components such as knowledge acquisition facility, inference engine, and the knowledge base used to facilitate the creation of expert systems as well as the advice (Reffat and Hardness, 2001 and Chu *et al.*, 2001).

According to Ogbeide *et al.* (2010), the knowledge base component of the system contains specialized knowledge on a given subject. On the other hand, the consultation environment used to obtain expert knowledge and pieces of advices contains components that facilitate the use of the model and provides the users with expert advice and answers to their queries.

The inference engine is the most important component of the expert system. Its role is to drive new information through using of the information available in the working memory and that contained in the knowledge based (Ogbeide *et al.,* 2010; Anjaneyulu, 1998). Miyabe *et al.* (1993) mentioned that the inference engine is developed as a prototype. It is designed to produce reasoning on rules (Sharma *et al.,* 2013). It is based on the description of knowledge using the basic IF/THEN rules. The simplified expert system architecture is shown in *Figure 2.4*.

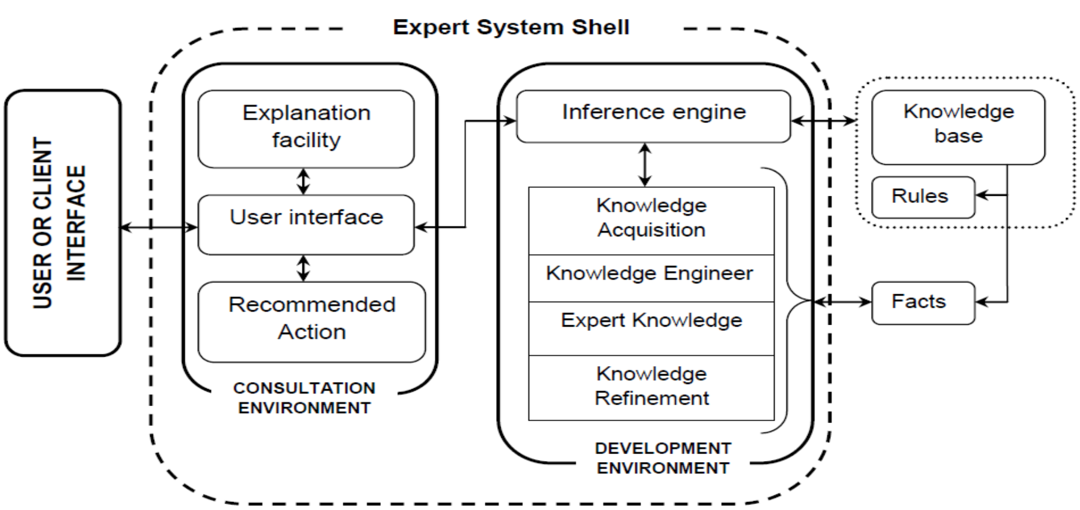


Figure 2.4: Typical expert system components (modified from Reffat and Hardness, 2001).

2.6.2. Expert system development

Expert system shells are used to develop expert systems and they can be developed to provide solutions in any specialized field. Although expert systems can be constructed by starting from the beginning, the use of the shell significantly reduce the amount of time and labor required in creating artificial intelligence programs by eliminating the need to carry out the general-purpose programming using programming language such as C/C++ and Cobol (Salim *et al.*, 2003). The shells provide interactive interfaces for basic operation, tracing inference and displaying working memory during the development stage (Miyabe *et al.,* 1993).

In terms of cost and performance as well as friendliness to the user, expert systems vary greatly (Salin *et al.*, 2003). According to Stylianoun *et al.* (1992), the selection of expert system shells is often the difference between a successful and an unsuccessful industrial application. As a result, for an expert system shell package to be pedagogically useful; it must be both powerful and friendly. The evaluation of the most common expert system shells products revealed that Art* enterprise and EXSYS CORVID shells are simple packages which yield satisfactory results lower than those of MP2. On the other hand, the MP2 shall was found to be complex with relatively high satisfactory results as shown in *Figure 2.5* (Salim *et al.*, 2003). Beside the expert systems shells discussed in this session, CLIPS is one of the shells that have gained much popularity in government sectors, industry and academia.

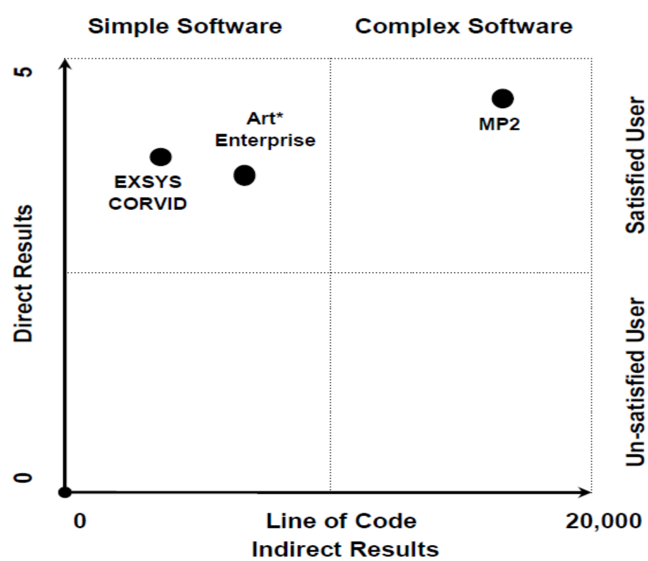


Figure 2.5: Comparison of the most common ES Shells (from Salim *et al.*, 2003).

Several steps are followed in the development of expert systems. According to Waterman and Lenat (1996), the universally accepted approach in the development of expert system is: identification, conceptualization, formalization, implementation, and finally testing of the system (Ogbeide *et al.,* 2010). The initial step is generally about identifying the applicability of expert system in a given situation. It is where human expert in a given discipline and the expert in expert system design and development meet (Iancu and Buta, 2011). The conceptualization stage is the initial stage of knowledge acquisition that involves ensuring that the relationships in problem domain are understood. However, the problems logic is designed during formalization stage. The stage is also used to group the collected knowledge. The stage that follows is the implementation of the developed prototype which includes the implementation of the inference rules while controlling and enhancing strategies established in the previous step (Ogbeide *et al.,* 2010). The final stage is model testing and validation. This is generally the step that is aimed at carrying out the validation of the program performance, verification of individual relationships as well as identification and fixing of syntax errors (Ogbeide *et al.*, 2010; Iance and Buta, 2011).

2.6.3. Chaining of rules in the expert system

The searching of production rules in an ES is carried out in the inference engine. The main purpose of the engine is to seek information and relationships from the system's knowledge base and to provide answers, predictions, suggestions, and advice to the user of the system. It generally finds facts by using three rule inference methods, *viz.*, forward chaining, backward chaining and mixed chaining (Abraham, 2005).

Forward chaining is a data driven inference method that involve running the rules in order. It is when the system works forward from the information it carries in the working memory (Anjaneyule, 1998). This is by matching data in the working memory against the conditions of the rules in the rule-base. Forward chaining approach provides advice by searching the inference rule until the solution is identified (Sharma *et al.,* 2012). Two types of fact searching approaches are used in forward chaining method and those are depth-first and breadth-first. Although both searches deal with how the outcome is obtained, depth-first approach evaluates the rules that form the knowledge database on a priority base; while the breadth-first approach evaluates each rule in the same level of the tree before proceeding to the next level down (Magary, 1997). Both depth-first and breadth-first searching methods of forward chaining method are illustrated in *Figure 2.6*.

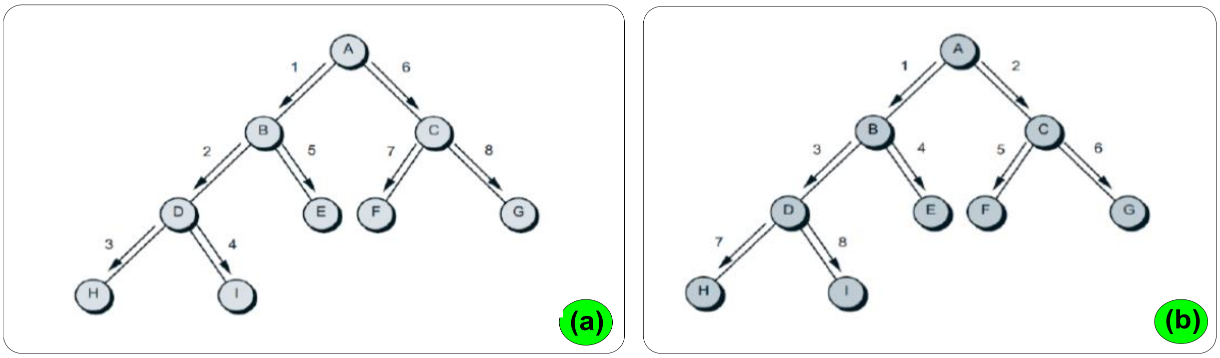


Figure 2.6: Typical forward chaining inference method; (*a*) depth-first search and (*b*) breadth-first search (modified from Magary. 1997).

Backward chaining is an inference method where the path to the solution start with conclusions; working backward to the supporting facts (Abraham, 2005; Siler and Buckley, 2005). In backward chaining, the inference engine attempts to find the evidence to prove the hypothetical solution or goal which is a conclusion part of the rule (Crowley, 2012). According to Luger and Chakrabarti (2009), in the expert system that uses the backward chaining approach; the goal expression is placed in working memory and the system matches the conclusions of the rules with it; thus, selecting and moving one rule into the working memory to setting a new sub-goal. The system then matches the new goal against the new set of rules and this process is repeated till there are no alternatives, meaning that the goal of problem-solving will have to be derived (Anjaneyulu, 1998). It is used to test and use rules in an expert system (Maher, 1986). According to Paruma (2004), backward chaining is mostly used in solving goal-oriented tasks such as classification, diagnosis and assessment. Like forward chaining, backward chaining also uses both depth-first and breadth-first search methods in a backward manner. In this; the depth-first search will first check one condition rule and then check each possible cause of the given condition. In contrast, a breadth-first search will first examine both condition rules and then obtain the cause for each of the conditions (Magary, 1997).

However, there is also a third inference method called mixed chaining. This method uses forward chaining to infer new facts and backward chaining to confirm facts by questioning the user. Systems that uses mixed chaining perform more precisely like human because the diagnosis is found with maximum efficiency. The main advantage of expert systems that use mixed chaining is that the user is only expected to supply the data relevant to the problem at hand; not all possible data value (Maher, 1986).

2.7. Fuzzy logic Expert System

Fuzzy logic system is a division of artificial intelligent that attempts to capture valid reasoning patterns about uncertainty (Elkan, 1993). According to Abraham (2005), it is an expert system that provides a framework to model uncertainty in engineering, the human way of thinking, reasoning, and the perception process. The fuzzy logic together with inferencing system forms a tool for approximate reasoning (Rudas *et al.,* 2013). There are four main components of the fuzzy logic system, namely; fuzzification inference, a fuzzy rule base, fuzzy inference engine, and defuzzification (Mendel, 1995). The basic architecture of a fuzzy expert system is illustrated in *Figure 2.7.*

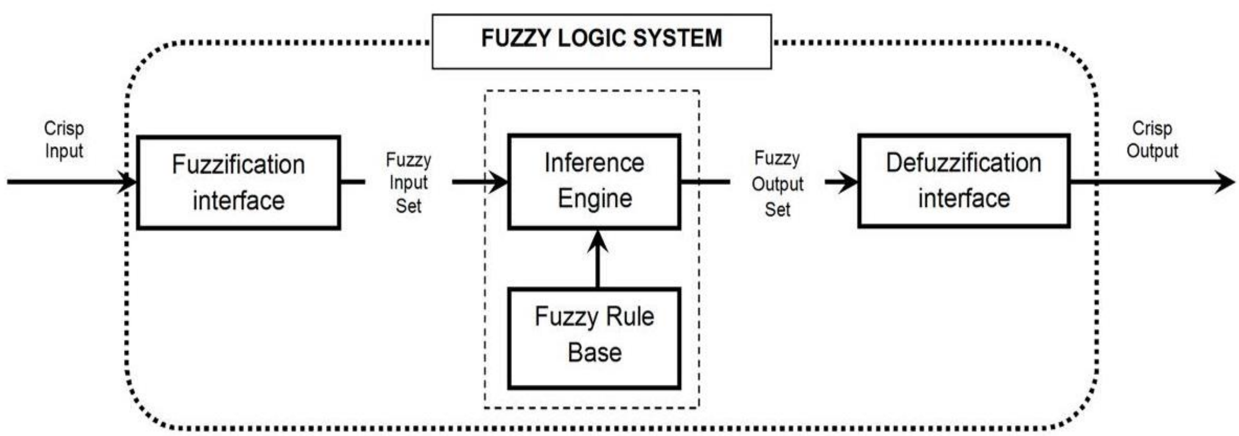


Figure 2.7: The elements of fuzzy expert system (Abraham, 2005).

2.7.1. Fuzzification interface

Fuzzification is basically a process of making a crisp quantity fuzzy (Bai and Wang, 2006). It is a first step in the fuzzy inferencing process that involves a domain transformation where crisp inputs are transformed into fuzzy inputs (Ross, 2004). According to Abdollahi (2010), it can be simply defined as a mapping from a real-value point ($x^* \in U \subset R^n$) to a fuzzy set ($A' \in U$). The two processes involved in fuzzification are driving the membership functions for input and output; and representing the membership functions with linguistic variables (Bai and Wang, 2006). Fuzzification is carried out by recognizing that many of the quantities that are considered crisp and deterministic are actually not; and this is due to the fact that they carry considerable uncertainties (Ross, 2004). If a certain form of uncertainty happens to arise due to imprecision, ambiguity, or vagueness then the variable is probably fuzzy and can be represented by a membership function (Ross, 2004, Abdollahi, 2010). Generally, there are three fuzzifiers which are used in the fuzzification process and those are singleton fuzzifier, Gaussian fuzzifier and triangular or trapezoidal fuzzifier (Abdollahi, 2010). The Singleton fuzzifier is the most commonly used and it is defined by *Equation 2.1*. It simplifies the computations involved in the fuzzy inference engine for any type of membership functions (Bai and Wang, 2006; Abdollahi, 2010).

$$\mu_A(x) = \begin{cases} 1 & \text{if } = x^* \\ 0 & \text{otherwise} \end{cases} \tag{2.1}$$

where: $x = (x_1, x_2, \ldots\ldots\ldots, x_n)$

On the other hand, the Gaussian and triangular fuzzifiers defined by *Equation 2.2.* and *2.3* respectively differs from singleton by the fact that they can suppress noise in the input, while the singleton fuzzifier cannot (Abdollahi, 2010). Similar to singleton fuzzier, both Gaussian and triangular fuzzifiers can also simplify the calculations in the fuzzy inference engine of the membership into IF-THEN rules or Gaussian and triangular (Abdollahi 2010).

$$\mu_{A'}(x) = e^{-\left(\frac{x_1 - x^*_1}{a_1}\right)^2} \star \ldots \star e^{-\left(\frac{x_n - x^*_n}{a_n}\right)^2} \tag{2.2}$$

where: $x = (x_1, x_2 \ldots, x_n)$ and $\star$ is any t-norn usually algebraic product or min.

$$\mu_{A'}(x) = \begin{cases} \left(1 - \frac{|x_1 - x_1{}^*|}{b_1}\right) \star \ldots \star \left(1 - \frac{|x_n - x_n{}^*|}{b_n}\right) \\ 0 \qquad\qquad\qquad\qquad\qquad\quad otherwise \\ b_1 > 0 \end{cases} \tag{2.3}$$

A graphical representation of Singleton, Gaussian, triangular and trapezoidal fuzzifiers is shown in *Figure 2.8*. It is worth mentioning that common fuzzifies usually have a triangular or trapezoidal shape and to guarantee general applications, it needs to have programmable parameters such as horizontal, position, height, width and edge shape (Ghanavati, 2012).

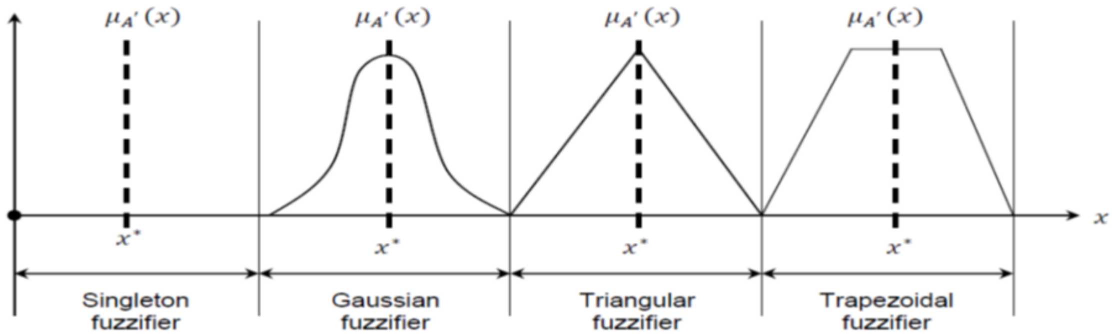


Figure 2.8: Graphical representation of membership function shapes in different fuzzification methods.

2.7.2. Interface engine and fuzzy rule base

The inference engine is the central component of the fuzzy expert system. Its basic function is to compute the overall value of the control output variable based on individual contribution of each rule in the rule base (Patel, 2005). Generally, the fuzzy rule consists of two parts, namely; antecedent and consequent (Kadhim *et al.*, 2011; Silar and Buckley, 2005). The antecedent is a logical proposition whose truth can be determined, while the consequent is the proposition that provide instructions based on the considered antecedent rule. Once the antecedent rule is evaluated to be sufficiently true, the consequent instruction is executed (Shi and Sen, 2000).

As a result, the fuzzy rule is represented by a sequence of the form IF-THEN, leading to algorithms describing what action or output should be taken (Bai and Wang, 2006). According to Silar and Buckley (2005), there are three types of rule-based fuzzy inference methods and those are monotonic, non-monotonic and downward monotonic. In the monotonic method; the consequent truth values may increase but not decrease. These values may increase or decrease in the case of non-monotonic while in the downward monotonic they only decrease without any increase (Silar and Buckley, 2005).

2.7.2. Defuzzification interface

The purpose of the defuzzification process is to make fuzzy output available to real application by converting a fuzzy output (linguistic variable) back to the crisp output or variable (Bai and Wong, 2006). There are basically seven defuzzification methods and these are Max Membership Principle, Centroid Method, Weighted Average Method, Mean Max Membership Method, Center of Sums, Center of Largest Area Method, and the First or Last of Maxima (Ross, 2004). The algebraic expressions of these defuzzification methods are shown in *Table 2.4*.

According to Keshwani *et al.* (2008); Van Leekwijck and Kerre (2007), defuzzification methods can be broadly classified into three categories, namely; Maximum Methods, Distribution Methods and Area-based methods. The common property of all maxima methods is that they select an element from the core as defuzzification value. Distribution methods are characterized by the property of continuity and it includes both general and specific methods. On the other hand, the third group of defuzzification methods (area methods) uses the area under the membership function to determine the defuzzification value (Van Leekwijck and Kerre, 1999). The mostly used defuzzification methods are Mean of Maximum (MOM), Centre of Gravity and the Height method (Nurcahyo and Shamsuddin, 2003; Bai and Wong, 2006).

Mean of Maximum Method calculates the average of the fuzzy output that has the highest degrees (Bai and Wong, 2006; Saade and Diab, 2004). According to Shi and Sen (2000), the MOM strategy generates a control action which represents the mean value of all local actions whose membership function reaches the maximum. An illustration of the Mean of Maximum method is shown in *Figure 2.9*.

Centre of Gravity (COG) Method is the mathematical expression that is used in the computation of mass of the triggered output membership function (Mazzini, 1997). In this method; the weighted average of the centre of the gravity of area bounded by the membership function curve (as shown in *Figure 2.9*) is calculated to be the crispest value of the fuzzy quantity (Bai and Wang, 2006). The method is accurate, consequently; it is the most common defuzzification method (Mazzini, 1997). According to Uitenbroek (2003), this method has a disadvantage of not allowing control action towards the extremes of the output range. However, the COG method of defuzzification is the most prevalent and physically appealing (Lee, 1990).

The Height Method is the defuzzification approach where the centroid of each output membership function for each rule is first evaluated (Shi and Sen, 2000). It is the simplest method of defuzzification (Bai and Wang, 2006; Detynieck and Yager, 2001). The final output computed using this method is basically the average of individual centroids, weighted by their heights. According to Bai and Wang (2006), the Height Method can be divided into two steps. In the first step; the consequent membership function (h_i) is converted into a crisp consequent ($x = h_i$) on which (h_i) is the centre of gravity of (h_i). In the second step; the centre of gravity method is applied to the rules with crisp consequents.

Table 2.4: Mathematical expression of traditional defuzzification methods.

Defuzzification Methods	The method's mathematical expression	Description of the symbols
1. Max-membership Principle	$\mu_{\underline{c}}(x^*) \geq \mu_{\underline{c}}(x) \ \forall \ x \in X$	
2. Mean of Maximum Method	$\text{MOM}\ (x^*) = \frac{a+b}{2}$	
3. Centre of Gravity (COG)	$\text{COG}\ (x^*) = \frac{\sum_{i=1}^{n} x_i \mu(x_i)}{\sum_{i=1}^{n} \mu(x_i)}$	x is the output which is the number of counts to be used for the output and μ is the fuzzy grade level
4. The Height Method (HM)	$\text{HM}\ (x^*) = \frac{\sum_{k=1}^{n} x_k . h_i}{\sum_{k=1}^{n} h_i}$	x_i = is the degree to which the i-th rule marches the input data
5. Center of Sums Method	$\text{COS}\ (x^*) = \frac{\int_x \bar{x} \sum_{k=1}^{n} \mu \underline{c}_k\ (x) dx}{\int_x \sum_{k=1}^{n} \mu\ \underline{c}_k (x) dx}$	$\bar{x}$ is the distance to the centroid of each of the respective membership functions
6. Center of Largest Area Method	$\text{COA}\ (x^*) = \frac{\int \mu \underline{c}_m\ (x) x dx}{\int \mu\ \underline{c}_m\ (x) dx}$	$\underline{c}_m$ is the convex sub-region that has the largest area making $\underline{c}_k$.
7a. First of Maxima **7b.** Last of Maxima	$x^* = \underset{x \in X}{\inf} \{x \in X \vert \mu_{\underline{c}_k}(x) = \text{hgt}(\underline{c}_k)\}$ $x^* = \underset{x \in X}{\sup} \{x \in X \vert \mu_{\underline{c}_k}(x) = \text{hgt}(\underline{c}_k)\}$	hgt($\underline{c}_k$) is the largest height in the union, $\underline{c}_k$ is the union of all individual output fuzzy set.

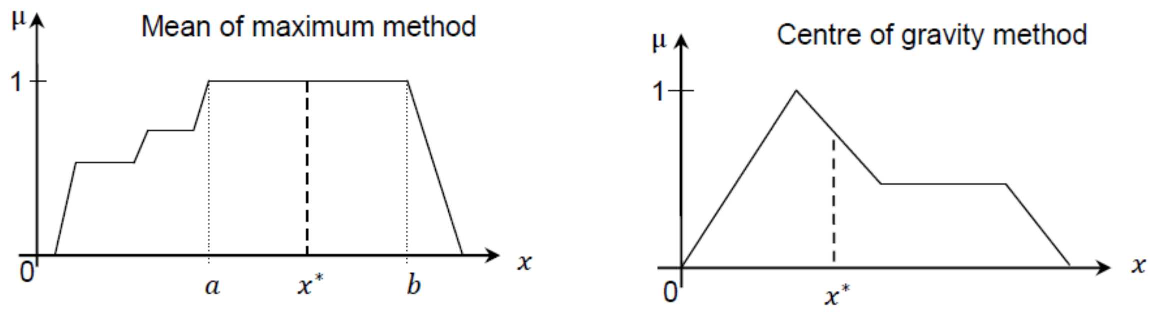


Figure 2.9: An illustration of MOM and COG methods of defuzzification.

2.8. Cost Modeling Techniques

A cost model is a framework developed for estimating the cost of providing services and/or cost of product or project. According to Brinke (2002), common steps in the construction of cost models are determination of the scope which include subdividing the different types of costs which must be modeled, determination of the overhead costs, and determination of cost functions which include the relation between the product parameters and the costs. Compare to other models such as models of weight; performance; and reliability, cost models are inadequate and that is due to several factors such as complexity of cost, cost model validation, cost drivers outside design and non-objectivity of cost estimators (Collopy and Curran, 2005). Although the most accurate cost estimators are achieved using the generative cost estimating models, the cost estimating approaches can be broadly classified as generative methods, variant-based models, intuitive methods, and parametric techniques (Shehab and Abdalla, 2001).

Generative cost modeling project costs based on details of production requirements and operational conditions. According to Scanlan *et al.* (2002), the generative approach can be further subdivided into feature-based and feature precognitive. In contrast, variant-based model uses similarities between current and past products and/or processes to project costs. Because variant-based costing model relies on previous products or activities and this makes it less useful for new operational conditions (Brinke, 2002). The third type of cost estimation model (intuitive cost estimation technique) is based on using the experience. In this a domain expert's knowledge (stored in the form of rules, decision tree and judgments) is systematically used to generate cost estimates for the operation or products (Miazi *et al.*, 2006). Lastly, the parametric approach seeks to identify high-level relationship between cost and the design parameters; also known as cost drivers (Brinke, 2002). Parameters such as volume and mass have been used in the past as high-level costing parameters (Scanlan *et al.,* 2002).

2.8.1. Mine Closure and Rehabilitation Cost Estimation

There are basically two popular models used to estimate mine closure and rehabilitation cost and these are mine closure model (MCM) and rule-based model. According to du Plessis and Brent (2006), the mine closure model describes the way the mine closure or rehabilitation can be carried out in a more systematic manner based on project management principles while the rule-based model is the closure costing approach that describes the methodology for determination of the quantum for financial provision. This is the model currently used by DMR. In addition to these methods, mine closure costs can also be estimated using decision tree developed from the closure elements, and Monte Carlo simulation (also known as probability simulation) (Hutchison and Dettore, 2011). The minimum requirements for acceptable cost estimation methods include a quantified details of rehabilitation work and that should include costs against each line item, subtotals and total costs as well as the schedule of unit costs. On this, the basic costs for mine rehabilitation are mobilization costs; project management cost (which is 10% of the total), monitoring costs (made-up of 5% of the total), contingency costs (made-up of 10% of the total) and the indexation for inflation (Environmental Sustainability Unit, 2010). In addition, it is generally easier to estimate the minimum and maximum costs for a mine closure project than to determine a specific cost (Hutchison and Dettore, 2011). According to van Zyl *et al.* (2002), the mine closure cost should be estimated based on the selection of appropriate closure technology and according to the cost of implementation of the selected strategy as well as the socio-economic closure measures.

Rehabilitation of abandoned mines is generally a costly venture because it is normally not clear of who should provide funds for this undertaking (van Zyl, 2002). In many countries including South Africa; the costs of addressing the problems associated with abandoned mines are borne by the government. In addition to the stated challenges regarding funding of abandoned mines rehabilitation projects is the fact that the costs of carrying out this work are mostly uncertain. The reason being that costs for rehabilitation of abandoned mines depend exceptionally on the rehabilitation strategies adopted and the standards to be achieved. According to van Zyl (2002), abandoned mines rehabilitation costs are generally affected by the lack of agreed criteria as to what conditions need to be remediated and what should be the goals for rehabilitation. Moreover, the uncertainty regarding the number and state of abandoned mines also make it impossible to estimate their rehabilitation costs with precision (van Zyl, 2002). The dynamic nature of rehabilitation work was mentioned by van Zyl *et al.* (2012) as one of the factors that makes the determination of abandoned mine rehabilitation costs complex. The estimated cost for remediation of current officially listed abandoned mines in South Africa is R30 billion (van Zyl *et al.,* 2012).

2.9. Summary of the Chapter

In order to gain the necessary understanding of the general problems of abandoned mines and the key issues of their rehabilitation, a comprehensive review of literature pertinent to the topic was undertaken. The review investigated the nature of physical and environmental hazards and socio-economic issues of abandoned mine sites in South Africa and elsewhere in the world. It also covered issues of abandoned mines in different pieces of legislations in South Africa and the efforts made towards abandoned mines rehabilitation in the country. Moreover, the review of the well-known abandoned mine sites ranking systems was carried out and this was followed by the review of the use of expert systems (*i.e.* knowledge based and fuzzy logic system) as decision making tools.

Based on the review conducted it emerged that there is interdependency between the environmental and physical hazards of abandoned mine sites with the social-economic issues prevailing in the communities where these mines are found. It showed that most efforts of abandoned mines rehabilitation in and outside South Africa had very little consideration for socio-economic issues. In addition, it was established that although attempts to develop an expert system for ranking abandoned mines were made by the Ontario Ministry of Northern Development and Mines and Laurentian University (Bolger *et al.,* 1995), no attempts for the development of a comprehensive computer based advisory system for rehabilitation of abandoned mines have been made.

Consequently, there is a need for carrying out more research aiming at development of computer-based tools for rehabilitation of abandoned mines. The following chapters of this thesis will present the work conducted to contribute to the development of computer-based advisory systems (*i.e.* expert system) discussed for selection of suitable rehabilitation strategies for abandoned mine sites.

CHAPTER THREE

SELECTION OF OPTIONS FOR TREATMENT OF ABANDONED MINE SHAFTS

The process of treatment of abandoned mine shafts is generally costly and tedious. The selection of appropriate strategies is the foundation step towards cost effective treatment of abandoned mine shafts. This chapter presents the work conducted with the aim of identifying the best treatment options for abandoned mine shafts in the study area. These involved carrying out a field inventory of abandoned mine shafts and developing an easy to use but effective shaft treatment prioritization system. This was then followed by the identification and evaluation of different mine shaft treatment options using Analytic Hierarchy Process (AHP) and Pugh Matrix techniques.

3.1. Background of the Study

The term "mine shafts" refers to the mine openings that that are developed to provide entry into an underground mine or to provide access to deposits that are too deep to be mined by surface mining methods. According to Holl and Fairon (1973) and Rupprecht (2012), mine shafts are designed with different sizes and configuration depending on the envisaged work during the life of the mine and they can be vertical or included. In this research, the terms "mine shafts" and "mine entries" are interchangeably used to mean the same thing.

According to Holmes (2008), the underground mine entries present serious risks of people accidentally entering or falling into them. Falling into abandoned shafts may lead to death due to physical body injuries, drowning in flooded old mine workings, suffocation, and exposure to explosive methane gas (Salmon and Degas, 2003; Wrona *et al.,* 2016). In general, the number and nature of accidents and fatalities associated with abandoned mine shafts are under-reported. This is mainly because there are generally no formal ways of reporting accidents of abandoned mine shafts throughout the world (Skinner and Beckett, 1994). The safety risks of abandoned mine shafts are escalated by the fact that they are mostly at deplorable state and were left open or closed with temporary structures which easily collapse when there are minor ground movements (Chambers *et al.,* 2007). The collapse or failure of some of the structures used to close abandoned mine shafts can occur after a long time after the closure of the shaft (Culshaw *et al.,* 2000; Wrona *et al.,* 2016). In view of this, it is therefore important that the strategies for treatment of abandoned/historic mineshafts are carefully selected.

The socio-economic issues that prevails in communities were abandoned gold mines are found have somehow resulted to some of the community members practicing illegal mining activities in and around the disused underground mine shafts. According to Boning (2015), there are about 14000 people who illegally mine gold by going underground through old shafts in South Africa. These activities expose many people to safety and health hazards of the abandoned mine shafts. For example, gas poisoning, suffocation and rock falls were collectively reported to have killed a total of 68 illegal gold miners in South Africa between the year 2013 and 2015 (Johnson, 2016). It should be noted that this number of fatalities can actually be higher than reported.

Depending on the age of the abandoned mining site and the availability of historic data about mining in the area, the detection or location of the abandoned mine shafts can be a challenging task. There are several techniques that are used to detect these shafts, however their reliability is still uncertain (Gunn *et al.,* 2008). These techniques include the use of geophysical methods, ground survey, drilling and trenching, and the use of remote sensing techniques (Gunn *et al.,* 2008; Chambers *et al.,* 2007). According to Gunn *et al.* (2008), the use of geophysics to detect abandoned mine shafts has not always yielded positive results thus some professionals lack confidence in these methods. Moreover, it is still not clear of which geophysical method is the most effective in locating abandoned mine shafts (Gallagher *et al.,* 1978). On the other hand, ground survey, drilling and trenching are known to be time consuming, expensive and not safe; while the use of remote sensing has numerous restrictions (Gallagher *et al.,* 1978, Gunn *et al.,* 2008). For example, the location of underground mine shafts using remote sensing techniques requires that the characteristics of these shafts that can be observed or recorded from the aircraft or satellite are clearly visible on the surface of the earth. Consequently, the abandoned mine shafts that have surface expression can be easily recognized on aerial photographs while those that are without the surface expression may not be easily identified (Gunn *et al.,* 2008).

There are several techniques that are used to treat the abandoned mine shafts with the purpose of addressing their public safety and environmental hazards. Such strategies include erecting and/or installing a fence and signage, capping, and filling techniques. According to Davies (1988), the selection of the best shaft treatment strategies depends on factors such as the conditions of the shaft, state of the fill, the surface terrain, and the objectives of the treatment. Some of the objectives of treatment of abandoned mineshafts includes the removal and/or elimination of public health and safety hazards, rehabilitation of the shaft to blend-well with the surrounding landscape and replacing the removed/failed capping structure.

The main aim of this part of the research was to conduct a detailed field description of the status of the hazards of the abandoned underground mine shafts found in the study area and evaluate the strategies for the treatment of these shafts to address their physical hazards, environmental problems and socio-economic concerns. In this regard, field inventory of the mine shafts was conducted to gain in-depth knowledge of the conditions of the shafts and the nature of the associated environmental and physical hazards and socio-economic concerns. This was followed by evaluation of different mine shaft treatment strategies to ascertain the most suitable strategies for dealing with the identified problems of abandoned mine shafts.

3.1.1. Objectives of the study

The main objective of the work presented in this chapter was to evaluate the issues of abandoned mine entries and develop a method for selection of appropriate strategies for treatment of the abandoned mine entries.

The specific objectives of this part of the research was:

- To conduct a field inventory of abandoned mine entries in the study area with the purpose of establishing in-depth knowledge of environmental, physical and socio-economic concerns of the abandoned shafts, and

- To evaluate strategies for treatment of old mine shafts to identify the most suitable strategies for dealing with the major issues of abandoned mine entries.

3.1.2. Underground mining in the study area

The study area (*i.e.* Giyani and Musina areas) has several gold and copper mining sites which were abandoned without any rehabilitation of the land. The well-known historic underground copper mines in the study area are found in the Musina area. These mines include the Mesina, Campbell, Harper, Artonvilla and Spence Mines as shown in *Figure 3.1a*. According to Wilson (1998) and Bahnemann (1986), large scale underground copper mining in the area began in 1906 and ceased in 1991. On the other hand, historic underground gold mining sites in the study area are found in the Giyani Greenstone Belt (GGB). The historic gold mining sites in the area include Klein Letaba, Louis Moore, Golden Osprey (also known as New Union), Fumani, Franke, and Birthday Mines and these are shown in *Figure 3.1b* (Ward and Wilson, 1998). Although there is no clear knowledge of the depth of copper mining in the Mesina area, in 1972 mining had reached the depth of 1310m (Hammerbeck, 1976; Visser, 1989). Comparatively, underground gold mining took place at relatively shallow depth (*i.e.*, <300m depth) in the GGB. Large scale gold mining in this area is known to have begun in 1930 and ceased in the early 1990's (Steenkamp and Clark-Mostert, 2012).

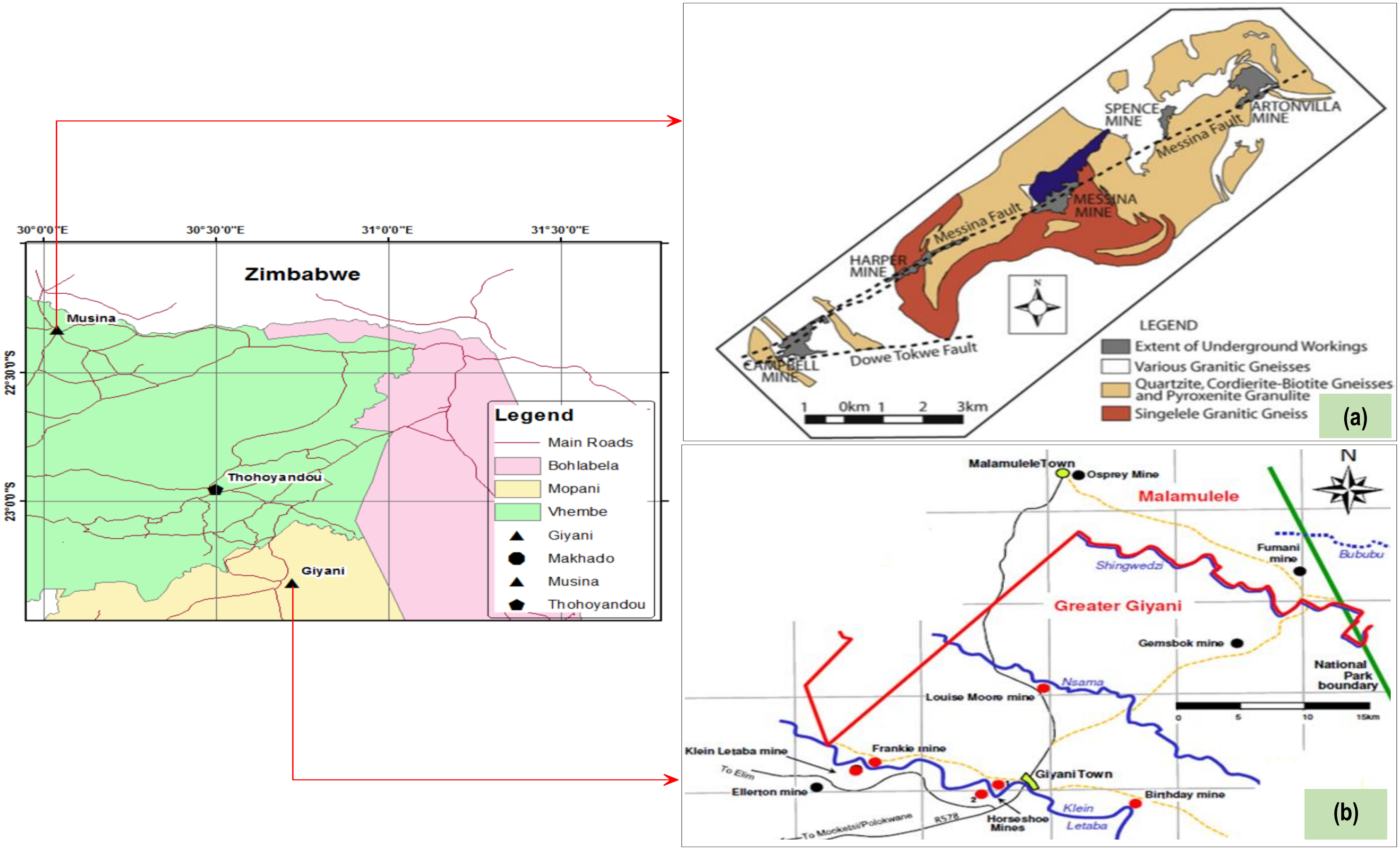


Figure 3.1: Distribution of abandoned mine sites in the Musina and Giyani areas (From Chaumba *et al.,* 2016; Parnham, *n.d*).

3.2. Research Method Design

The procedure followed in the characterization of the abandoned/historic mine shafts began with conducting a field inventory of the mine openings. The method used in locating the mine shafts was ground survey which involved traversing around the abandoned mine sites with an aim of locating these features of abandoned underground mine. This method was chosen mainly because most abandoned mines in the study area are in densely vegetated sites thus making their identification using alternative methods difficult. The guidance by the local people, some of them were employees of these mines or are illegally mining around the abandoned mines, was instrumental in locating the most hidden shafts. Such guidance was quite important as the historic maps of the abandoned mines could not be obtained.

The current state of the identified mine shafts was described in order to establish their environmental and public health and safety risks. Critical analysis of the current use of the mine shafts was carried out to determine their socio-economic concerns. The site characterization of the abandoned mine shafts allowed that the key factors responsible for the hazards of the shafts are identified and scored to establish the seriousness of their associated problems. In this regard, the socio-economic impact of the shafts was quantified based on the established scores of the environmental and physical hazards of the mines.

The identified and documented problems of the abandoned mine shafts allowed that the evaluation of their treatment strategies is conducted. This was done with the purpose of finding the most suitable strategy for dealing with specific problems of abandoned mine shafts. An overview of the sequence of methods followed in the characterization of the abandoned mine shafts hazards and evaluation of their treatment strategies is shown in *Figure 3.2*. In general, the method used in carrying out the work presented in this chapter was divided into three important phases (see *Figure 3.2*).

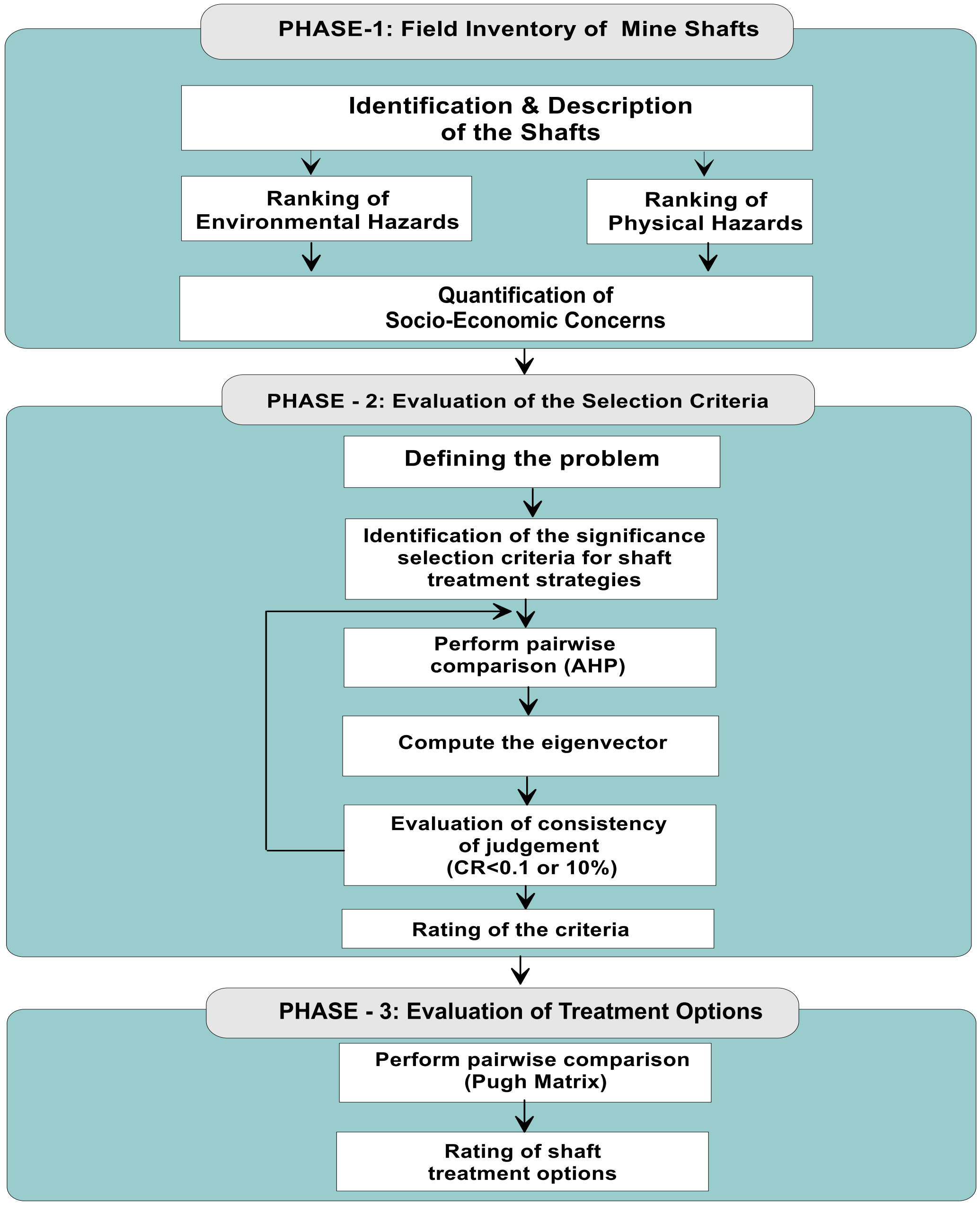


Figure 3.2: An illustration of the flow of methods followed in the characterization and evaluation of abandoned mine shafts treatment strategies.

3.2.1. Scoring and ranking of physical and environmental hazards

Based on the results of preliminary field characterization of the shafts, their environmental and physical hazards were quantified using a scoring and ranking technique. This involved assigning numerical scores categorized as Low (1.5 – 3.0), Moderate (3.5 – 5.0) and High (5.5 – 7.0) to (i) the source of the identified risk of the shafts, (ii) the ways of exposure to the risk or pathways which the identified risk may affect the environment, and (iii) the potential impact of the risk to people, animals and other parts of the environment. The average score of the environmental as well as the safety and health risks of the shafts were used to compute their total hazard scores. The individual environmental risk (Ev_r) scores of the shafts were calculated using *Equation 3.1* which was developed for this research. In this equation Q_i was the source of the risk presented by the shaft, P_j was the pathway (in the case of the problems of land degradation and impact on the aesthetic appearance of the environment; P_j was assigned the value of 1), and R_x was the magnitude of the consequences of the identified risk.

$$Ev_r = Q_i \times P_j \times R_x \qquad (3.1)$$

In order to calculate individual physical risk scores (P_r) of the shafts, *Equation 3.2* was used. In this case, the value Q_s, E_a and $(N_i + M_i)/2$ represent the source of the health and safety risks of the shafts, the way of exposure to the risks, and the average of the magnitude of the shaft's safety risks (N_i) and associated health risks (M_i). In cases where the shaft presented only safety or health risk, the absent factor was scored zero.

$$P_r = Q_s \times E_a \times \left(\frac{N_i + M_i}{2}\right) \qquad (3.2)$$

In order to determine the total hazard scores (*i.e.,* environmental and physical hazard score), the averages of the scores of the respective individual risks were obtained and reduced to an easy to work with figures (*i.e.* reducing large scores to smaller numbers). This is achieved through applying an appropriate NF value to reduce the large number scores to the desired range. In this research, the factor of 8 (NF which is a score reduction factor) was employed to reduce the magnitude of the scores to fit the ranking criteria described in the section below. This process can be mathematically expressed as shown in *Equation 3.3*.

$$HZ_{total} = \frac{\sum R_i \div NF}{n} \qquad (3.3)$$

Where: HZ_{total} is the total physical or environmental hazard, $\sum R_i$ is the sum of the scores of physical/environmental risks, and n is the number of either physical or environmental risks identified.

Ranking of hazards

The hazard ranking criteria presented in *Table 3.1* was developed based on the expected minimum and maximum total hazard scores of the scoring process. This hazard ranking criteria allowed that both physical and environmental hazards of abandoned shafts are classified into four categories (denoted as A, B, C and D). As depicted in *Table 3.1*, the system categorizes the degree of the hazards into High (22-45), Moderate (5-21), Low (0-4) and Negligible (<0). This classification of the hazards of the shafts enabled socio-economic concerns to be classified in similar categories using the method and procedure described in the section below.

Table 3.1: The guideline for classification and ranking of the hazards of the mine shafts.

Ranking of the hazards	Hazard category	Description of the categories
22-45	A	High
5-21	B	Moderate
0-4	C	Low
<0	D	Negligible

3.2.2. Evaluation of socio-economic impact

The socio-economic issues associated with the mine shafts were quantified using the chart shown in *Figure 3.3*. The example of the socio-economic issues of abandoned mines shafts may include but not limited to loss of productive land and deteriorating quality of water resources, problems of personal safety, and increasing criminal activities around the abandoned mine sites. The position of the mine shaft when its environmental problem score is plotted in the chart against the shaft's physical hazards score allowed that the socio-economic concerns of the shafts are classified as Low, Moderate, and High. The shafts with low socio-economic concerns fall between the zone of 0 to 4 on the chart while those with moderate and high fall between the zones of >4 to 21 and >21 to 45 respectively (see *Figure 3.3*). This chart was developed based on the assumption that physical hazards of the abandoned mine shafts/entries affect greatly the social well-being of the host and surrounding communities while their environmental problems turn to affect mainly the economic status of these communities. For example, open shafts near the communities are likely to present psychological and social challenges to the community while problems of ground instability and discharge of contaminated/acidic water turn to affect a larger part of the environment thus negatively affecting the economic value of the land. Base on the chart (*i.e. Figure 3.3*), shafts with less than zero physical and environmental hazard score were considered having socio-economic impacts that are negligible.

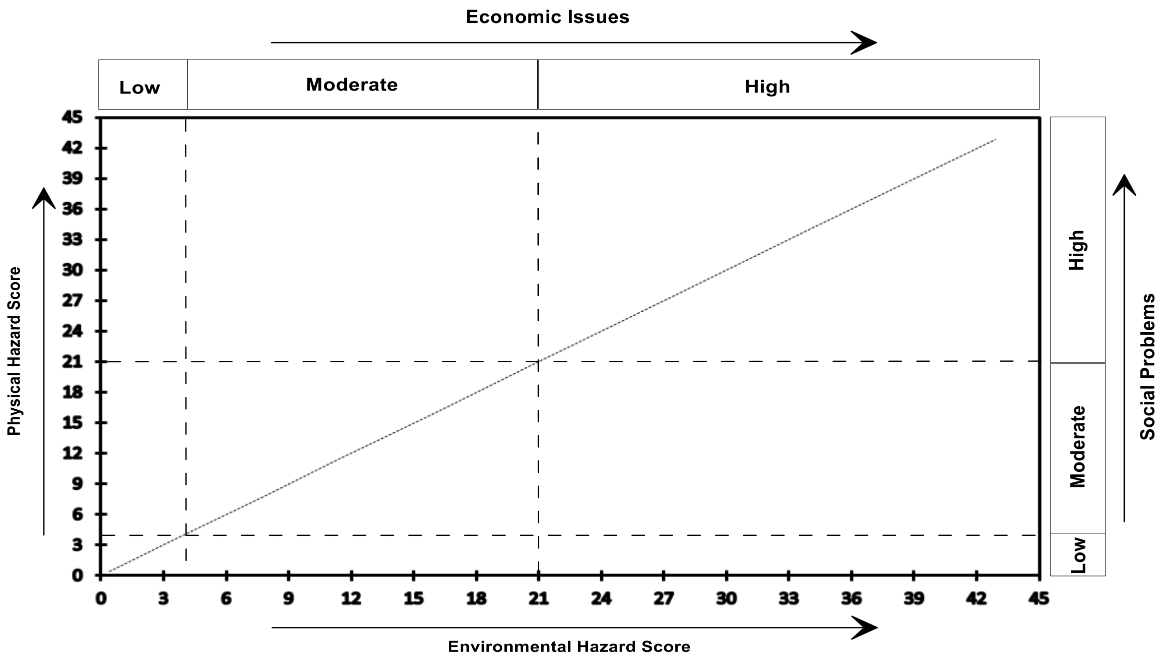


Figure 3.3: Model used in ranking the social-economic problems of abandoned mine shafts.

3.2.3. The sensitivity of the scores process

The general structure of the expected outcome of the scoring process in the developed method was visually analyzed using the cobweb plots shown in *Figure 3.4*. These plots allowed that the local sensitivity of the scoring process is examined. *Figure 3.4a* depicts the situation where the potential impact (PI) of the identified hazards of the mine shafts are generally high, hence scored between 5.5 and 7.0. In this case, it is expected that the source of the risk (S) and the exposure routes/pathways (E/P) are given the scores ranging between 1.7 to 6.9 and 2.1 to 7.0 respectively. Comparatively, where the impact of the mine shaft is moderate thus scored between 3.5 and 5.0, the source of the hazard is expected to be assigned the scores of 2.0 to 6.7 with the corresponding exposure route/pathways having the scores ranging from 1.6 to

5.7 (see *Figure 3.4b*). Lastly, in the case where the mine shafts presented low risks, the source of the identified risk is expected to have the scores of 1.5 to 6.2 while the exposure route/pathway is to be scored between 1.8 and 5.4 as shown in *Figure 3.4c*.

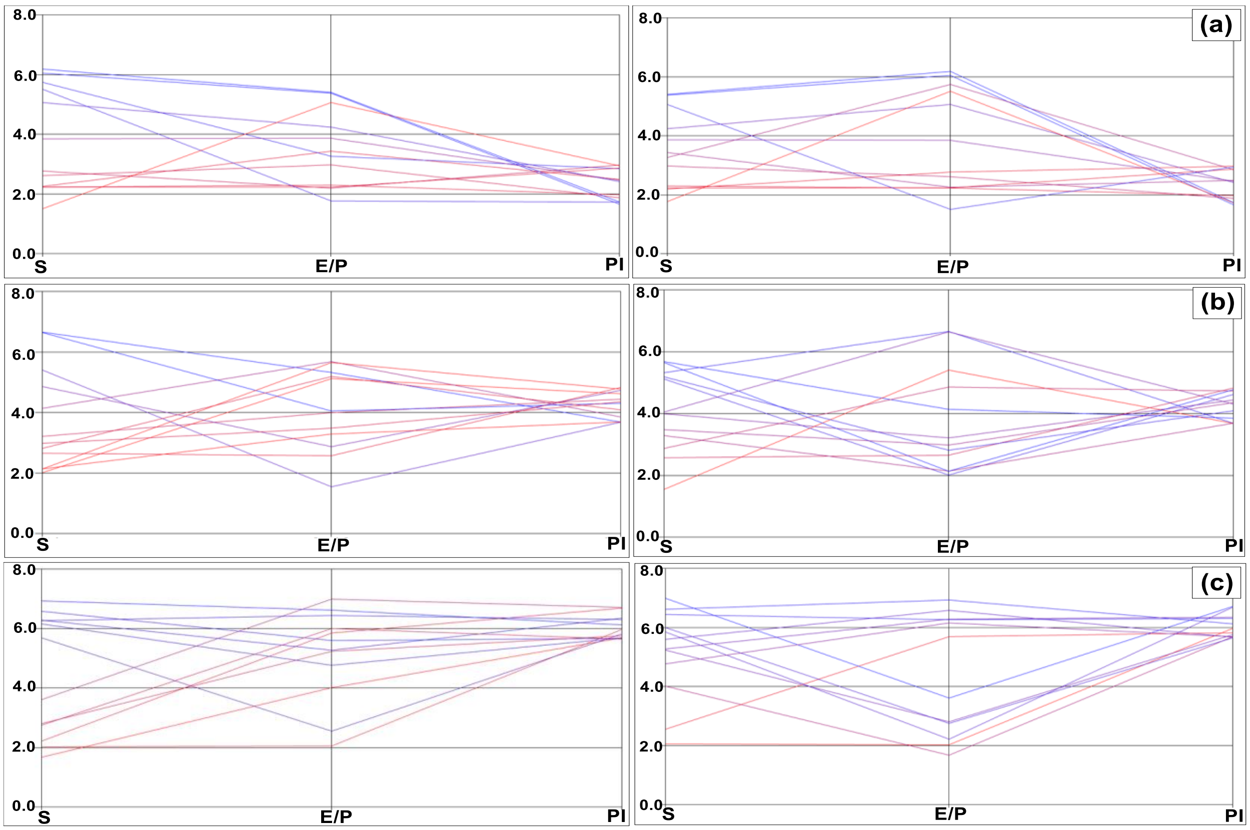


Figure 3.4: Conditioned and un-normalized cobweb plots of the hazard scoring process. (a) is when the scores assigned to the impact of the mine feature are in the high category, (b) is when the scores are in the moderate category and (c) are in low category.

3.2.4. Selection of treatment strategies

The evaluation of the strategies for treatment of abandoned mine shafts was carried out using a combination of two Multi-Criteria Decision Making (MCDM) techniques, namely; Analytic Hierarchy Process (AHP) and Pugh Matrix methods. The AHP was used in ranking the criterion presented in *Table 3.2* considered important in the selection of appropriate strategies for treatment of abandoned mine shafts. The selection of the criterion and their scoring was based on detailed review of different shaft treatment options and their application in different parts of the world in addressing the problems of the abandoned mine shafts. On the other hand, Pugh Matrix method was used in the evaluation of the options for abandoned mine shaft treatment strategies against the developed criteria. The main emphasis of the evaluation was not on pin-pointing the most appropriate options, but on showing the strength and weaknesses of different options in addressing the major issues of abandoned mine shaft.

Table 3.2: Factors rated for their influence in making decisions regarding the treatment of old shafts.

Symbol	Description of the factors
PS	Ability of the strategy to protect the species that inhabits in old mine shafts (e.g. bat species)
DR	The durability of the strategy to ensure long-term treatment of the shafts
MR	Is the frequency of maintenance requirements of the implemented strategy
SI	Is the simplicity of implication or installation of the treatment strategy
CS	The performance of the strategy in saving cost during installation and maintenance periods
GE	The ability of the strategy to address the risk of gas emission
GM	The ability of the strategy to address the problems of ground movement
PI	The ability to the strategy to address risks of physical injury

Rating of criterion for selection of abandoned mine shafts treatment options

The Analytic Hierarchy Process (AHP) was employed in the ranking of the criterion for selection of strategies for treatment of abandoned mine shafts. The comparison matrix of the AHP was developed by comparing the criterion over one another (C_i over C_j). The relative importance of each criterion over the other was measured by assigning numerical values as defined in *Table 3.3*. The matrix was developed to be reciprocal and transitive. Reciprocal matrix represents consistent judgments while transitivity matrix suggest that the matrix is developed in a way that if the judgment detects that ***A*** is important than ***B***, and ***B*** is important that ***C***, then ***A*** is more important than ***C*** Masingwini and Minnitt, 2008 and Ataei *et al.,* 2008). Based on the developed matrix, the eigenvector was computed to satisfy the *Equation 3.4*.

$$AE_{ij} = \lambda_{max} E_{ij} \text{ and } \lambda_{max} \geq n \tag{3.4}$$

Where: $\mathbf{E_{ij}}$ is the eigenvector of comparison matrix corresponding to the maximum eigenvalue λ.

Based on the developed matrix, the relative eigenvector (E_{ij}) and λ_{max} (largest eigenvector) were computed. The eigenvector was used as the measure of the significance of the criterion and it was computed by applying the product of the entries of every row in the matrix to the

n^{th} root (1/n) which was the number of the considered criterion. The calculated value of the eigenvector was normalized (EN_{ij}) by dividing each entry of the matrix by the sum of the eigenvector value in a column of the matrix (see *Equation 3.5*) and this brought the sum of the element of each column vector to 1. In addition, the principal eigenvector (W_{ij}) was normalized by dividing the number of the criterion considered for the evaluation by the sum of the normalized column as it is mathematically expressed in *Equation 3.6*.

Table 3.3: The scale of the relative importance of the factors (from Saaty and Vargas, 1991).

Scale	Degree of Preference
1	Value equal important to the other criterion
3	Moderate important than the other criterion
5	Strong or essential importance value
7	Very strong
9	Extremely important
2, 4, 6, 8	Intermediate values between the two-adjacent judgment

$$EN_{ij} = \frac{E_{ij}}{\sum_{i=1}^{n} E_{ij}} \tag{3.5}$$

$$W_{ij} = \frac{\sum_{j=1}^{n} EN_{ij}}{n} \tag{3.6}$$

Because the decision matrix was developed based on human judgments, inconsistencies in judgment were expected to occur. Thus, the degree of such inconsistency was measured by calculating the Consistency Index (CI) and Ratio (CR) using Equations *3.6* and *3.7* respectively. The CI value is basically a measure of the degree of departure from consistency while the RI is an average index of the randomly generated weights. The RI is an index value that is dependent on the number of criterion that are being compared. The random consistency index values shown in *Table 3.4* were used in the calculation of the CR values of the comparison on the criterion for selection of the abandoned mine shafts treatment strategies.

$$CI(n) = \frac{\lambda_{max} - 1}{n - 1} \tag{3.6}$$

$$CR(n) = \frac{CI(n)}{RI(n)} \tag{3.7}$$

Table 3.4: Random consistency values (from Saaty and Vargas, 1991).

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.49

3.2.5. Evaluation of the abandoned mine shafts treatment options

The evaluation of mine shaft treatment options was carried out using the Pugh Matrix technique. It was conducted with the aim of establishing a priority list of the strategies suitable for treatment of abandoned/historic mine shafts. In general, Pugh Matrix is known as one of the best methods for evaluation of alternative solutions against the important criteria (Lonmo and Muller, 2014). According to Cervone (2009), the method is an excellent decision-making method to use where there are several factors that might influence the outcome of the decision-making process. Based on the results of the rating of the criteria for selection of abandoned underground mine shaft treatment options using the AHP, the datum scores (which are basically starting values used to compere the strategies for treatment of the abandoned mine shafts with the developed criteria in the Pugh Matrix method) were established.

The most important criterion according to the AHP ranking was given the highest datum value of 8 while the least important was assigned the score of 1. The use of Pugh Matrix method in this research involved entering a **+** (where the strategy was judged to perform better than the datum) and a **–** (where the strategy was judged to perform worse than the datum). In the case were the worse or better performance of the strategy could not be clearly justified, the **S** (same as the datum) was entered in the comparison matrix. Based on the traditional Pugh Matrix model, each matrix cell (A_{ij}) corresponded to mineshaft treatment alternative ***i*** and the criterion ***j*** (see *Table 3.5*).

Table 3.5: The use of Pugh Matrix in the evaluation of mineshaft treatment strategies

Matrix	Rating (AHP)	Rating (1-10): Pugh Matrix	Alt-1	Alt-2	…	…	Alt_i
C_1	1	6					
C_2	2	5					
C_3	3	4					
…	4	3					
C_j	6	1					
Sum of Positive (+)							
Sum of Negative (–)							
Sum of Same (S)							
Weighted Sum Positive (+)							
Weighted Sum Negative (–)							
Totals							

3.3. The State of Abandoned Mine Shafts

In order to come up with appropriate strategies of addressing the problems of abandoned mines entries, it was necessary that a detailed site characterization of the abandoned mine shafts is conducted. This section describes the state of the abandoned mine shafts in the study area. The characterization paid a special emphasis on the state of the shaft and the treatment strategies adopted in reducing and/or eliminating the physical hazards of the abandoned shafts.

A total of 38 abandoned/historic mine shafts and 1 sinkhole of about 60m diameter were identified in the study area. The majority (15, ± 39% of the studied shafts) of these shafts were found open. Although this was the case, attempts of closing some of the shafts with the aim of addressing the risks of accidentally falling into the mine shafts or deliberately entering the shafts were made by the government. A variety of mine shaft's treatment options were considered and used at different parts of the study area. These options include the use of a heavy steel grate, concrete slab with steel wire screen, and the steel wire screens as shown in *Figure. 3.5a*, *b* and *c*. As illegal miners (locally known as Zama-Zamas) tried to gain access to the remnants of the deposit (especially gold deposits in the GGB) underground, they destroyed and removed the materials/structures used to close the mine shafts. Some of these materials such as steel and structures such as heavy steel grate used as reinforcement of concrete slabs were removed and subsequently sold.

As a result, many of the shafts treated using steel grates and/or concrete slabs were found completely or partially opened. The strategy adopted to limit the vandalism of the shaft sealing structures while providing permanent or long-term prevention of physical hazards of abandoned mine shafts was the use of concrete plugs. According to DMR (2010), the plugs are installed at about 3 to 10m below the surface of the earth and are completely buried into the ground with only 2.5 tonnes concrete landmark exposed to the surface as shown in Figure. *3.4e*. In general, the concrete plugs can be self-supporting or anchored and they are used to address the risks of ground movement and falling into the mine shafts (Lecomte and Niharra, 2013).

The extent of the use of different abandoned mine shafts treatment strategies in the study area is depicted is in *Table 3.6.* Such results show that there were about 7 (18% of the studied shafts) mine shafts that were never closed and/or treated in the study area. Some of these shafts were identified within highly vegetated areas with highly unstable walls due to the absence or collapsed shaft lining structures (see Figure. *3.5f*). The location of shafts and their deplorable state have potential of leading to high safety hazards. According to Chambers *et al.* (2007), mine shafts without or with failed lining turn to form a cone or creator with loose and unstable steeply dipping slopes which present high risks to people and animals sliding into the shaft as they enter the cone shaped upper part of the shaft.

Table 3 6: Efforts of treatment of abandoned mine shafts in the study area.

State of the closing structure	Concrete Slab	Concrete Plug	Concrete Slab and Steel Wire Screen	Heavy Steel Grate	Never Closed	Steel Wire Screen	Total
Never sealed	—	—	—	—	7	—	7
Removed	1	—	—	2	—	—	3
Destroyed	3	—	2	—	—	—	5
Failed or failing	3	2	—	—	—	—	5
Undamaged	7	11	—	—	—	1	19
Total	**14**	**13**	**2**	**2**	**7**	**1**	**39**
Total %	**36**	**33**	**5**	**5**	**18**	**3**	**100**

Note: *— the issue not applicable*

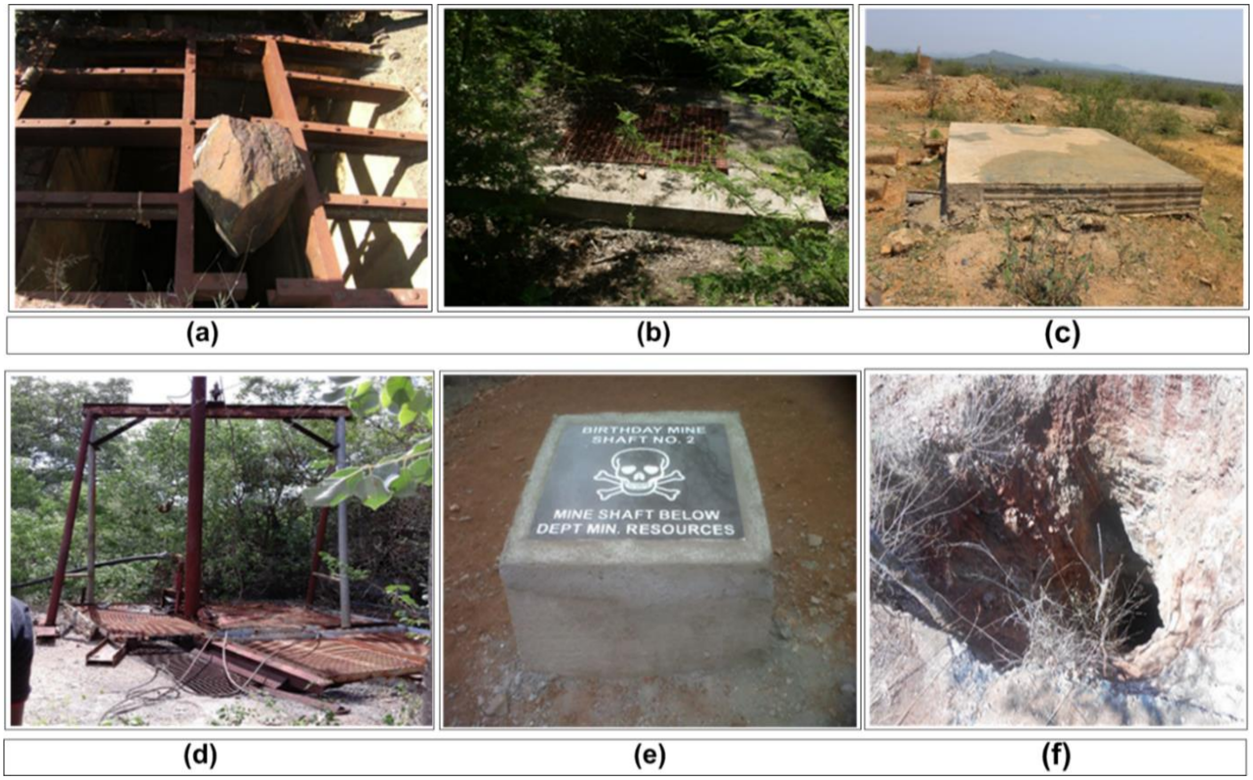


Figure 3.5: Types of mineshafts treatment options used in the study area. (a) heavy steel grate, (b) concrete slab with steel wire screen, (c) concrete slab, (d) steel wire screen, (e) concrete plug and (f) is the shaft that was never closed.

3.4. Issues of the Underground Mine Shafts

Based on literature review and preliminary field assessment, an inventory of abandoned mine shafts in the study area was compiled. The inventory assisted in identification and quantification of environmental and physical hazards of these mine shafts. The fact that the conditions and problems that prevail at abandoned mine sites vary from one site to the other make the work of characterizing and prioritizing the rehabilitation of abandoned mines a real challenging undertaking (Fortier and Moore, *n.d.*). In view of this, the most common physical and environmental risks of abandoned mine shafts were used as the criteria for prioritization of their treatment. The physical risks considered in ranking the physical hazards were (i) physical injury due to falling into the mine shafts, (ii) drowning in the water filling the underground mine workings, (iii) exposure to dangers of rock/ground falls, (iv) exposure to dangerous mine gases, and (v) ingestion or getting to contact with contaminated mine water within the shafts. On the other hand, the environmental risks of the shafts that were considered were (i) the problems of land degradation that limits the alternative use of the land, (ii) impacts of the abandoned mine shafts on the aesthetic beauty of the landscape, and (iii) the potential contribution of the shafts to pollution of the environment.

Based on the site investigation of the hazards of the mine shafts, numerical values were assigned to the source of the risk, way of exposure and potential impact to the victim. The values were assigned following the criteria presented in the methodology. Such numerical values were used to compute the scores that serve as measure of individual environmental or physical risk identified. The calculated scores for individual risks and the total environmental and physical hazards of the mine shafts are shown in *Table 3.7*. This approach of measuring the seriousness of the hazards of abandoned mines is comparable to that developed by Mhlongo *et al.* (2013) by modifying the Historic Mine Site Scoring System used to rank historic mine sites in Ireland. The final scores of both health and safety risks as well as the environmental problems of the studied mine shafts in the Giyani and Musina areas is shown in *Appendix-A*.

Table 3.7: The scores of the major risks of individual abandoned shaft.

No	Shaft-ID	Coordinates		Physical Risks					Total Physical Hazard Score	Environmental Risks			Total Environmental Hazard Score
		Latitude	Longitude	Physical Body Injury	Drowning Hazards	Intake of Contaminated Water	Mine Gases	Rock Falls		Land Degradation	Pollution Potential	Aesthetic Appearance	
1	MCM-1	22° 20′ 15"	30° 02′ 38"	1.69	1.1	0.5	1.0	1.7	0.15	12.0	3.4	2.3	0.73
2	ATV-1	22° 18′ 14"	30° 05′ 45"	15.5	3.8	2.5	5.0	3.8	0.76	16.0	3.4	2.3	0.76
3	ATV-2	22° 18′ 33"	30° 05′ 44"	159.3	1.7	0.5	11.3	1.1	4.35	20.0	3.4	9.0	1.35
4	CCM-1	22° 22′ 28"	30° 59′ 2"	171.5	6.0	0.8	13.5	171.5	9.08	49.0	3.4	42.0	3.93
5	CCM-2	22° 22′ 25"	30° 59′ 1"	171.5	6.0	0.5	6.0	171.5	8.89	35.0	2.3	20.0	2.39
6	CCM-3	22° 22′ 31"	30° 59′ 5"	171.5	6.0	1.7	7.5	171.5	8.95	49.0	4.5	49.0	4.49
7	CCM-4	22° 22′ 16"	30° 60′ 8"	90.8	6.0	0.5	6.0	32.0	3.38	16.0	3.4	3.0	0.93
8	KLM-1	23° 17′ 41"	30° 33′ 34"	68.3	205.6	52.5	105.0	171.5	15.07	36.0	75.0	30.0	5.88
9	KLM-2	23° 17′ 41"	30° 33′ 39"	147.9	192.5	159.3	0.8	2.8	12.58	36.0	180.0	16.0	9.67
10	KLM-3	23° 17′ 42"	30° 33′ 36"	171.5	123.8	2.8	43.3	79.6	10.53	25.0	3.4	25.0	2.22
11	HSM-1	23° 11' 11"	30° 50' 39"	-	-	-	1.7	-	0.04	4.0	3.4	4.0	0.47
12	HSM-2	23° 11' 10"	30° 50' 41"	-	-	-	1.7	-	0.04	4.0	3.4	4.0	0.47
13	HSM-3	23° 11' 12"	30° 50' 38"	10.5	-	-	1.7	-	0.30	10.5	2.3	18.0	1.28
14	HSM-4	23° 11' 12"	30° 50' 36"	7.3	-	-	1.7	-	0.23	9.0	3.4	10.5	0.95
15	FGM-1	23° 17' 21"	30° 24' 17"	21.0	4.5	1.7	1.7	1.7	0.76	6.0	3.4	6.0	0.64
16	FGM-2	23° 17' 20"	30° 34' 16"	14.0	3.4	1.7	1.7	1.7	0.56	12.0	2.3	9.0	0.97
17	FGM-3	23° 17' 19"	30° 34' 17"	4.5	—	0.0	3.4	-	0.20	12.0	3.4	12.0	1.14
18	FGM-4	23° 17' 22"	30° 34' 5"	9.0	3.4	0.0	1.7	-	0.35	9.0	3.4	9.0	0.89
19	FGM-5	23° 17' 35"	30° 34' 38"	15.8	9.0	0.0	6.8	-	0.79	16.0	3.4	20.0	1.64
20	BDM-1	23° 19' 23"	30° 46' 19"	-	-	-	1.7	-	0.04	5.0	3.4	4.0	0.52
21	BDM-2	23° 19' 22"	30° 46' 19"	-	-	-	1.7	-	0.04	5.0	3.4	4.0	0.52
22	BDM-3	23° 19' 22"	30° 46' 20"	-	-	-	1.7	-	0.04	5.0	3.4	4.0	0.52
23	BDM-4	23° 19' 24"	30° 46' 17"	-	-	-	1.7	-	0.04	4.0	4.5	4.0	0.52
24	BDM-5	23° 19' 29"	30° 46' 14"	-	-	-	1.7	-	0.04	4.0	4.5	4.0	0.52
25	BDM-6	23° 19' 28"	30° 46' 14"	-	-	-	1.7	-	0.04	4.0	4.5	4.0	0.52
26	BDM-7	23° 19' 38"	23° 19' 38"	-	-	-	1.7	-	0.04	4.0	4.5	4.0	0.52
27	BDM-8	23° 19' 39"	30° 46' 16"	-	-	-	1.7	-	0.04	4.0	4.5	4.0	0.52
28	BDM-9	23° 19' 38"	30° 46' 18"	-	-	-	1.7	-	0.04	4.0	4.5	4.0	0.52
29	BDM-10	23° 19' 35"	30° 46' 15	-	-	-	1.7	-	0.04	4.0	4.5	4.0	0.52
30	NUM-1	23°01'2.3"	30°43'37"	105.6	8.3	-	4.0	50.0	4.20	36.0	18.0	36.0	3.75
31	NUM-2	23°01'28"	30°43'31"	105.0	22.0	-	13.5	37.5	4.45	25.0	3.4	25.0	2.22
32	NUM-3	23°01'11"	30°44'6"	171.5	7.0	1.7	7.8	4.0	4.80	36.0	3.4	36.0	3.14
33	NUM-4	23°01'08"	30°44'08"	171.5	20.3	-	4.0	60.0	6.39	36.0	3.4	49.0	3.68
34	NUM-5	23°01'28"	30°43'31"	147.0	9.0	-	4.0	72.0	5.80	36.0	3.4	33.0	3.02
35	NUM-6	23°01'21"	30°44'2"	171.5	7.0	-	4.0	24.0	5.16	42.0	3.4	49.0	3.93
36	NUM-7	23° 01' 21"	30°44'3"	171.5	7.0	-	1.7	24.0	5.10	33.0	3.4	33.0	2.89
37	LMM-1	23° 13' 13"	30°41'48"	171.5	78.0	-	4.0	108.0	9.04	30.0	48.0	32.5	4.60
38	LMM-2	23° 13' 13"	30°41'45"	171.5	153.0	-	4.0	75.0	10.09	30.0	48.0	36.0	4.75
39	LMM-3	23° 13' 13"	30°41'46"	56.0	3.4	-	4.0	1.7	1.63	25.0	48.0	25.0	4.08

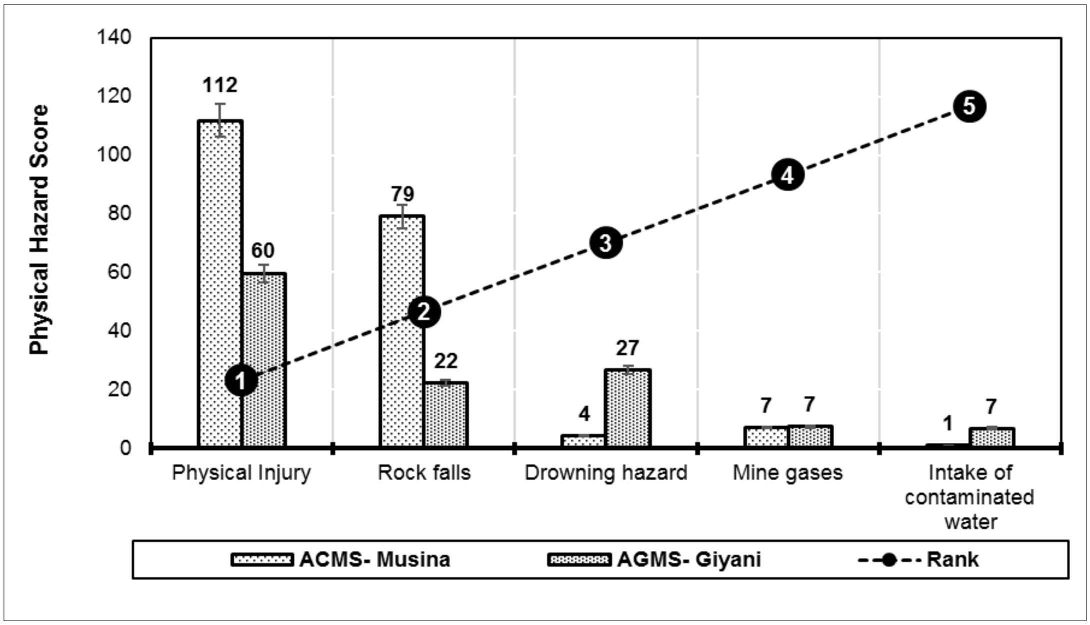
Note: - the issue does is not applicable

3.4.1. The risks of abandoned mine shafts

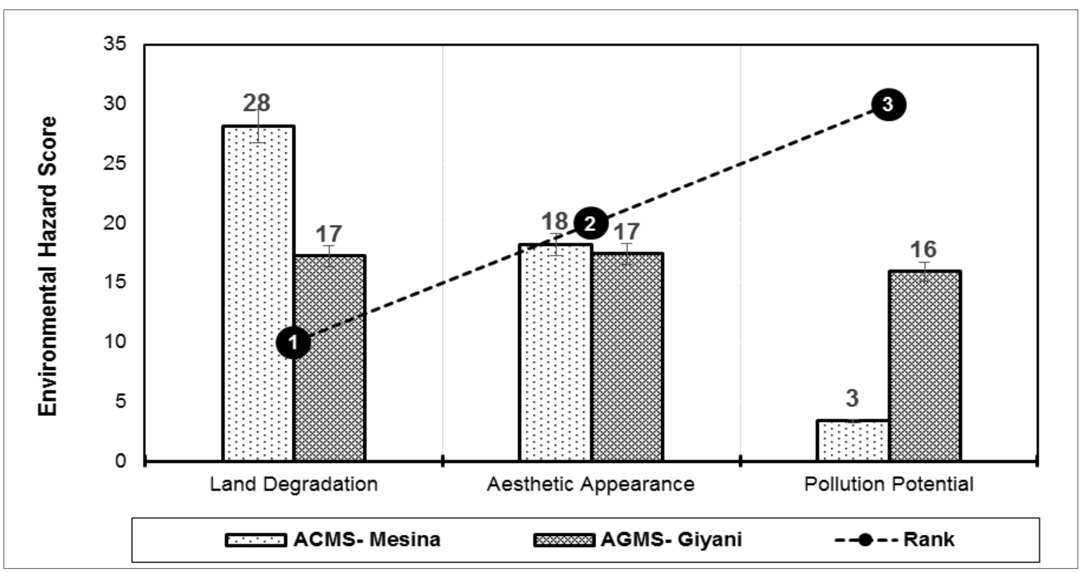
The scoring of hazards of the shafts showed that mine shafts in the Giyani and Musina areas had physical hazards that are slightly higher than environmental concerns. A large group of shafts that had relatively high physical hazard scores were in the Musina area. These shafts present increased risks of falling into them since they were found open or inadequately closed and in highly unstable/subsiding grounds. Such ground instability also resulted to these shafts having higher risks of rock falls which present safety threats to adventurous people who might want to enter the underground mine workings. Moreover, the greater depth of mining (>1300m) in the Musina area contributed to the risk of falling into the shafts being rated high. This is because this risk of old shafts is likely to result to death with no hope for successful recovery of the body.

Comparatively, the shafts that were never treated or those which the structure used to treat the shafts was vandalized by illegal miners in the Giyani area were found with relatively low risks of falling into the shafts and rock falls (see *Figure 3.6a*). The fact that these shafts were without lining structures and/or shaft collars increased the risks of falling into them. Moreover, the fact that illegal miners at the GGB (especial at Klein Letaba Mine) go underground through the old inclined shafts in their endeavors of exploiting the remnants of the deposit underground made the exposure to the risks of drowning in water filling the mine workings, accidental or voluntary ingestion of contaminated mine water in the underground environment, and getting exposed to harmful mine gases slightly higher than in the case of the copper mine shafts (see *Figure 3.6a*).

In general, the major environmental problems of abandoned mine shafts or entries is that they are at times found discharging contaminated and acidic water. The shaft that is used to pump water for irrigation and other domestic purposes at Klein Letaba Mine was the only shaft that had relatively higher pollution potential risk score in the whole of the study area. However, the major environmental issues of most of the shafts in the Giyani and Musina areas was physical degradation of the land which also affects the aesthetic appearance of the landscape. The shafts found in physically unstable grounds in Musina had the highest score for land degradation issues (see *Figure 3.6b*). The reason for this was that the land occupied by these shafts is at the state where it cannot support even the basic post-mining land uses such as crop farming and development of animal grazing site. The comparison of the seriousness of the risks of abandoned shafts which gives an indication of what should be the focus of the efforts of treatment of the shafts in the areas of Giyani and Musina is shown in *Figure 3.6a* and *3.6b*.



(a)



(b)

Figure 3.6: Comparison of physical and environmental hazards of the mine shafts.

Physical and environmental hazards of the shafts

Although the government tried addressing some of the safety risks of the mine shafts in the Giyani and Musina area, these shafts were found still presenting varying degrees of physical and environmental hazards. The total physical hazard scores of the shafts ranged between 1.2 and 26.8 while the environmental hazards ranged between 7.2 and 21.6. The main reason behind this distribution of the total hazard scores may be due to the fact that the underground mine shafts or entries were treated with temporary structures to reduce or eliminate safety risks, but these had a comparatively higher environmental hazard (mostly relating to subsiding grounds around the shafts). For example, a total of 21 shafts (*i.e.,* 54% of the total) which were well treated with concrete plugs and slabs had low physical hazard score of 3.4 while the four shafts (10% of all studied shafts) which had collapsed treatment structures in highly physically unstable ground had the highest physical hazards score of 26.8.

Based on the hazard classification scheme developed and used in this work, about 10% of the shafts had physical and environmental hazard scores of 26.8 and 21.6 scores respectively. These shafts were therefore found to be in Category-A (high hazard class) in the hazard ranking. Many shafts (60% of the shafts) had moderate physical hazards while 16% of the shafts were placed in Category-C with low physical hazards. However, most of the shafts which were never closed or those for which treatment structures were vandalized had a physical hazard score at the breaking point value between moderate and high physical hazards as shown in *Figure 3.7*. It was also found that a very high percentage (90%) of all studied mine shafts had moderate environmental hazard scores and were thus classified under Category-B.

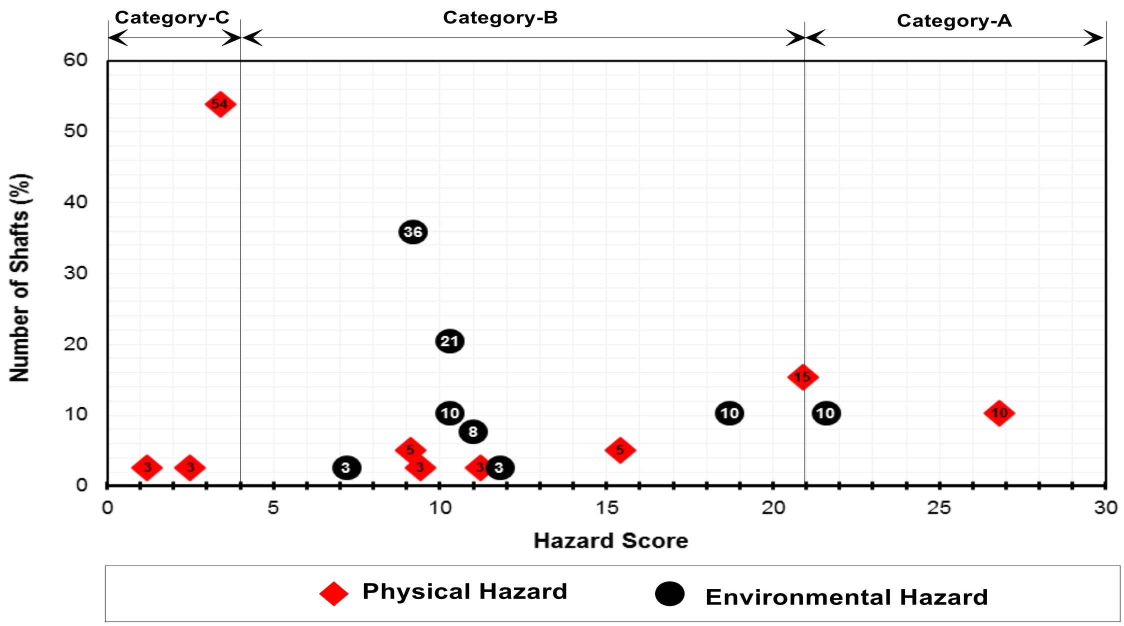


Figure 3.7: Classification of hazards of abandoned mine hazards.

3.4.2. Socio-economic issues of the mine shafts

Plotting the environmental and physical hazard scores on the socio-economic impact evaluation chart showed that the abandoned mine shafts in the Giyani and Musina areas are generally characterized by low to moderate socio-economic concerns. Based on *Figure 3.8*, the shafts found with intact treatment structures (*i.e.* concrete plugs and slabs) had negligible (<0 score) level of social concerns and very low economic issues. The untreated shafts, those for which the treatment structures were vandalized or removed, and the only shaft used to pump ground water for irrigation and domestic uses were also identified with more social problems than economic concerns. The use of the abandoned gold mine shafts for illegal/artisanal gold mining activities were identified as the major social concerns of these shafts. This is because these activities expose many people to different health and safety risks of the mine shafts. These activities are also associated with several environmental problems such as cutting and/or uprooting of trees and deposition of contaminated soils from the abandoned mine sites into the nearby surface water bodies (mainly rivers) during the process of sluicing to concentrate gold (Magodi, 2017). On the other hand, the major social concern of the abandoned copper mining shafts is that these shafts are used as storage sites for illegal or stolen items.

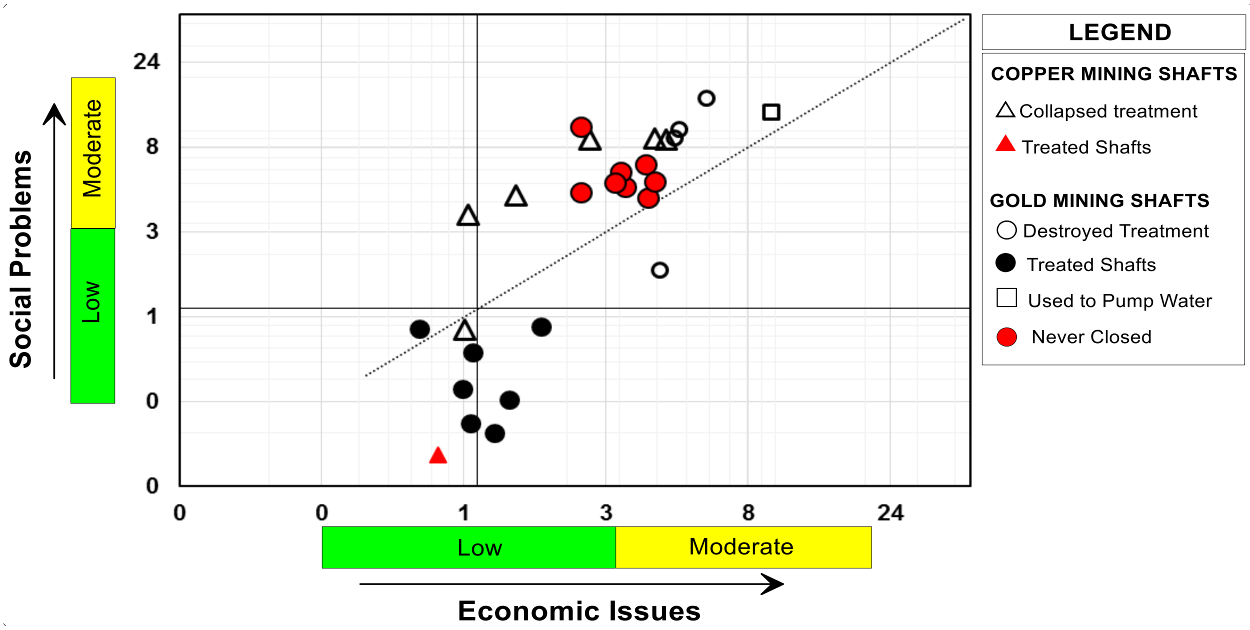


Figure 3.8: The seriousness of the socio-economic issues of the abandoned mineshafts.

3.5. Rating of Criteria for Selection of Abandoned Shafts Treatment Options

The AHP was used to rank the significance of different criterion in the selection of strategies for treatment of abandoned mine shafts. The results of the AHP shown in *Table 3.8* and *Figure 3.9* were obtained within the acceptable level consistency in judgment (consistency index value of 0.083). According to different authors including Coyle (2004); Musingwini and Minnitt (2008), the consistency index values that are less than 0.1 suggest that the judgments made in the process of comparison of criteria were at a tolerable level of inconsistency. This together with the fact that the criteria that were compared were less than nine made the results of the AHP method as used in this work acceptable and reliable. According to Musingwini and Minnitt (2008), results of AHP derived from eight criteria; as it is the case in this work; can be considered reliable. The results depicted in *Table 3.8* showed that the important criterion in the selection of treatment strategies for abandoned shafts was their ability to address the physical impacts or injuries that might be caused by these shafts. This is due to the fact that most of these shafts are found in areas that are easily accessible to people and animals.

The durability of the shaft treatment strategies was ranked second in the selection criteria. The main advantage of durable treatment strategies is that they require very little maintenance thus reducing the cost of maintenance. This criterion was about 10% less important than the ability of the strategies to address the physical hazards of the shafts and 7% more important than the ability of the strategies to address the risks of ground movement around the shafts. The significance of the prevention of ground movements is that a considerable number of abandoned mine shafts are found within the communities with limited land for development. Therefore, expansion of any form of development towards the areas of abandoned mine shafts can have devastating effects on the land-used around the shafts if ground movement problems are not contained during the treatment of the shafts.

The issues of the cost of the treatment strategy and its ability to address mine gas emission problems obtained equal scores of 0.05 (5.2%) which is 13.6% less important than their suitability for addressing the problems of ground movement. The main reason for this, was that these criteria have less or no direct effect to the health and safety of the general members of the public or communities. The least important criteria had 0.03 scores. These criteria are the strategy's simplicity of implication, their requirements for maintenance, and their contribution to protection of species that hibernate in old mine shafts such as different species of bats which according to Barclay (2014) use old mine shafts seasonally for hibernation purposes.

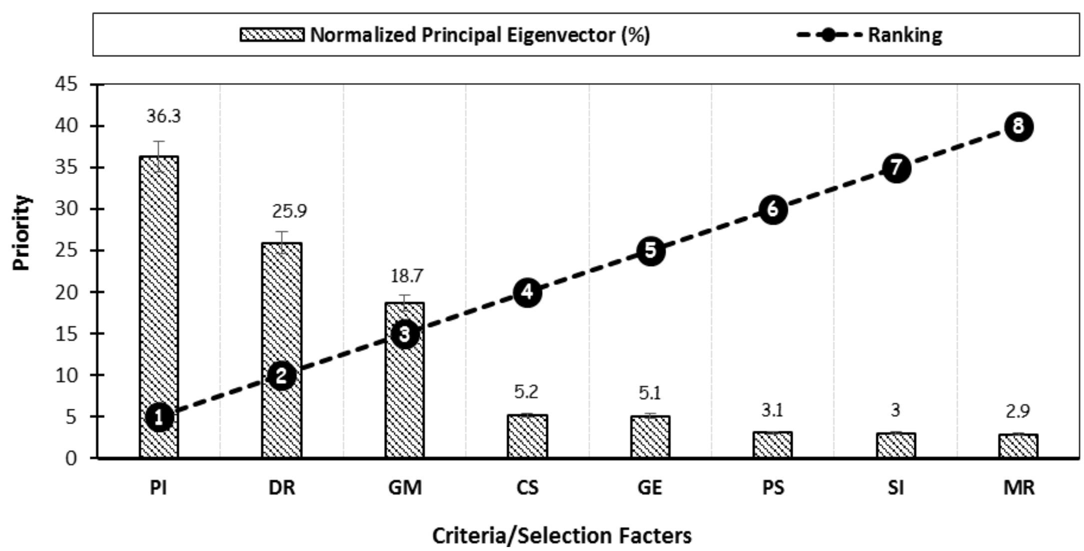


Figure 3.9: Ranking of key criteria for selection of abandoned mineshafts treatment options.

Table 3.8: Pairwise comparison matrix of important criteria for the selection of abandoned shafts treatment options.

*Factors	PI	GM	CS	SI	MR	DR	PS	GE	Normalized weight
PI	1.00	3.00	8.00	8.00	7.00	3.00	8.00	8.00	0.36
GM	0.33	1.00	6.00	7.00	7.00	0.33	6.00	7.00	0.19
CS	0.13	0.17	1.00	2.00	5.00	0.14	2.00	0.50	0.05
SI	0.13	0.14	0.50	1.00	2.00	0.14	0.50	0.50	0.03
MR	0.14	0.14	0.50	0.50	1.00	0.14	2.00	0.50	0.03
DR	0.33	3.00	7.00	7.00	7.00	1.00	7.00	7.00	0.26
PS	0.13	0.17	0.50	2.00	0.50	0.14	1.00	0.50	0.03
GE	0.13	0.14	2.00	2.00	2.00	0.14	2.00	1.00	0.05
λ_{max} = 8.82; CI = 0.30; and CR = 0.083 (8.3%)									

*__Note:__ **PI** is the ability to address physical injury, **GM** is the ability to address risk of ground movement, **GE** is the ability to address the risk of gas emission, **CS** is the cost saving ability, **SI** simplicity of implementation, **MR** is maintenance requirements, **DR** is the duration of the strategy, **PS** protection of the species that are inhabitants of the mine shafts

3.7. Suitability of Strategies for Treatment of Abandoned Mine Shafts

The evaluation of different treatment strategies for old mine shafts using the Pugh Matrix method allowed that strategies that can effectively address both environmental and physical hazards of abandoned mine shafts while addressing their socio-economic concerns are identified. A total of 19 strategies that are commonly used in treating old mine shafts were evaluated for their suitability for dealing with the problems of abandoned shafts in Giyani and Musina areas. As suggested by Madke and Jaybhaye (2016), the use of Pugh matrix in this work was to show the most un-preferred shaft treatment options instead of the most suitable strategy. This allowed that a cluster of strategies that are suitable for treatment of abandoned shafts for a given treatment objective be identified. This approach of selection of strategies for treatment of abandoned shafts is expected to have an advantage of providing guidance on the preferred strategy; which their implementation is to take into consideration some of the site-specific issues of abandoned shafts.

The results of the evaluation showed that the most preferred options for treatment of abandoned mine shafts were those with high potential to address both risks of ground movement and falling into the shafts. These included options such as backfilling with or without warning signs. This option also has an advantage of reducing or eliminating problems of emission of mine gas and restriction of downward flow and discharge of water. However, it is to be noted that these benefits of backfilling depend largely on the nature and design of the backfilling material and process of implementing the strategy. According to Davies (1988), the preferred backfill materials are the ones that are incombustible, chemically inert and with low compatibility to minimum settlement of the backfill.

The second most attractive old shafts treatment option was injection/inclusion options followed by concrete plugs (both self-supported and anchored plugs). The blast-closure was the fourth most preferred treatment option. However, it should be noted that blast-closure option is best suited where the mine entry is an adit or a decline. This is because this strategy involves closing the mine entry with large boulders generated by blasting of the walls of the mine entry. Such treatment makes human and animal intrusion into abandoned mine workings very difficult. However; it can only effectively provide a deterrent to casual intruders of old mine workings, not those who are technological capable (Dixon and Keto 2009).

In their decreasing order of lack of preference, the least preferred options for dealing with the problems of abandoned mine shafts were dams sealing, steel capping, use of warning signs, steel grate, and concrete slabs. The lack of preference of these strategies is mainly because they do not address many of the major risks of abandoned mine shafts and they can be easily removed and/or destroyed by illegal miners thus making them to be also characterized by relatively high maintenance cost.

During the field characterization of abandoned shafts, it was found that where these strategies were used in the Giyani and Musina areas they were somehow vandalized, completely removed or collapsed due to minor ground movements. In view of this, these old shaft treatment options can be used as temporary treatment strategies in these areas. In the case where the protection of species that hibernate in old mine workings is deemed necessary, the use of steel grate, barrier sealing, and fencing options can be adopted. Although, treating abandoned mine shafts to reduce their physical hazards by fencing and use of warning signs is common due to easy implementation (Holmes 2008), the socio-economic issues prevailing in most communities around abandoned mines in South Africa make these options less attractive. Thus, they were ranked slightly equal to closing of the old mine entries (*i.e.* adits) using the barrier seals. *Figure 3.10* shows the priority of strategies for treatment of abandoned mine shafts in the Giyani and Musina areas. The raw Pugh Matrix results of the ranking of strategies for treatment of abandoned mine shafts are shown in *Appendix-B.*

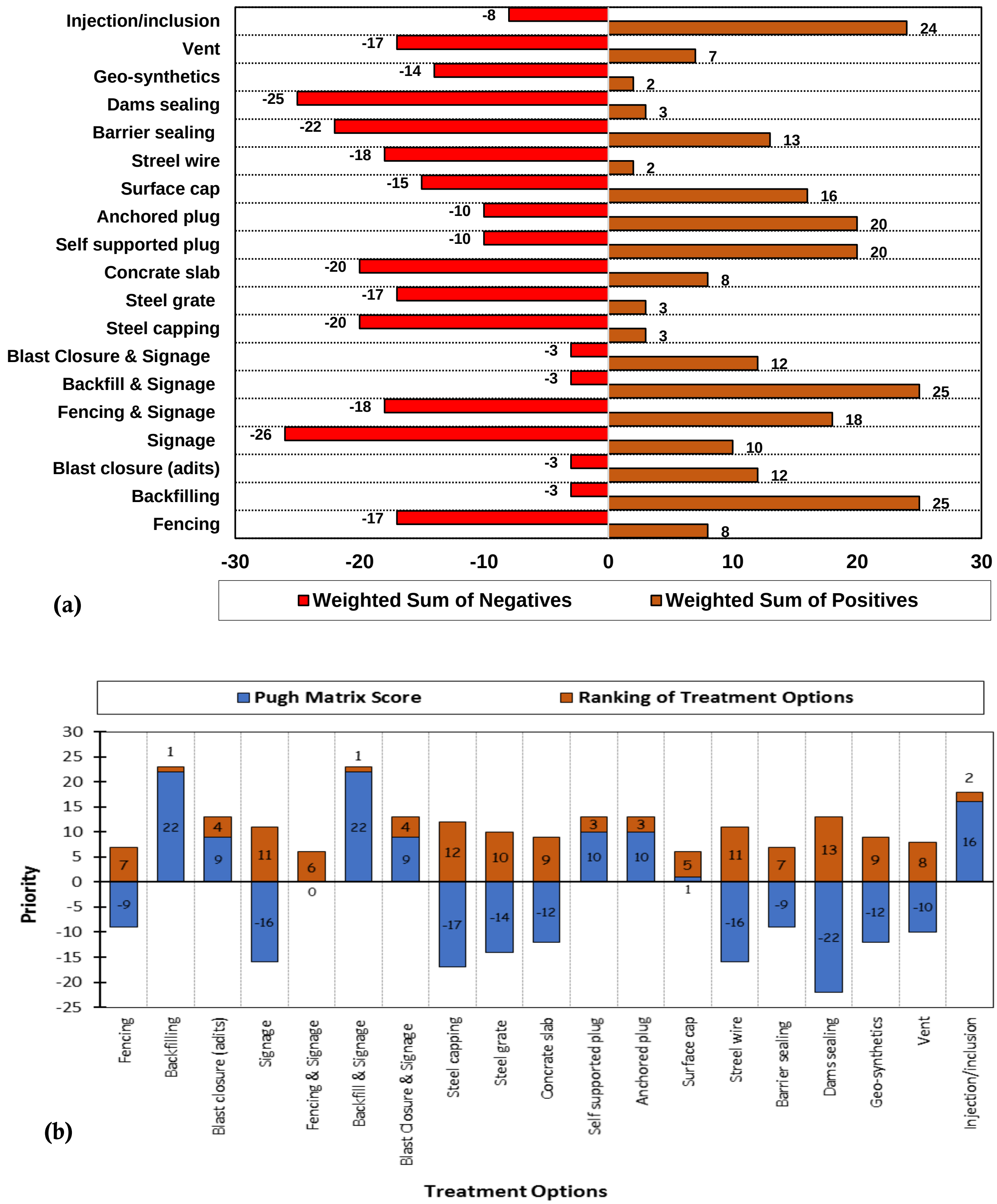


Figure 3.10: Weighted sum of positives and negatives (a), and the ranking of the mine shafts treatment strategies (b).

3.8. Discussion of Findings of the Study

The study conducted to identify the best treatment options for abandoned mine shafts in the study area showed that although the existence of abandoned mines in the Giyani and Musina areas are known, there is still a need for systematic mapping and characterisation of individual features of these mines. The importance of such an initiative is that hidden features such as mine shafts can be located, their hazards identified and evaluated, and the objectives of their treatments defined. This will enable identification of all the features so that they may be considered during rehabilitation or/and prevent use of inappropriate rehabilitation strategies (as it happened with the treatment of abandoned mine shafts in the Giyani and Musina areas). According to Matshusa and Makgae (2014) and DMR (2010), the presence of open shafts on the abandoned mine lands of Giyani and Musina areas was the reason these mines were classified as high priority mines in the national abandoned mines rehabilitation programme. In view of this, the work of treating abandoned shafts or mine entries in these areas has been ongoing for many years. Even though this is the case, a total of seven shafts at New Union Mine (GGB) appeared to have been omitted during treatment of the shafts while some were treated with strategies that barely addressed the major problems of these shafts.

The ranking of the hazards of abandoned mine shafts showed that falling into the shafts and the problems of ground movements around the shafts were the major physical and environmental risks. The seriousness of these risks may be attributed to the fact that these shafts were found adjacent to densely populated communities. Moreover, some of them were in unstable or subsiding grounds while others were used by illegal miners to go underground in their mining endeavour. This suggests that treatment strategies with a potential of providing long-term sealing of abandoned shafts while preventing the problems associated with the movement of the ground around the shaft should be considered first in the treatment of abandoned mine shafts to address their physical and environmental hazards.

It is important to note that the success of most abandoned mine rehabilitation efforts also depend largely on prevailing socio-economic issues in the communities around the mines. For example, mine shafts treated with credible sealing structures such as concrete slabs and steel grate were in few months completely vandalised by illegal miners in the Giyani and

Musina areas. Contrary, in Oklahoma (USA); the mine shafts closed using old car bodies and railroad ties lasted for 60 years without a need for replacement or maintenance (Graves *et al.,* 2000). Based on the socio-economic evaluation of abandoned mine shafts conducted in this study, it was only the shafts closed with concrete plugs that were found with negligible level of socio-economic concerns. One of the reasons for these is the fact that this shaft treatment strategy can provide long-term treatment of the shaft. According to Graves *et al.* (2000), concrete plugs can effectively close old mine shafts for a period of not less than 100 years.

The method developed for ranking of hazards of abandoned mine shafts in this study is generally consistent with the generic rational decision-making processes as explained by Turpin and Marais (2004). Such an approach involves finding occasions of deciding through conducting a preliminary field assessment of the mine shafts, investigating and/or analyzing the possible sources of action through identification of the sources of physical and environmental risks of the shafts, and selecting a source of action by ranking the risks presented by the shafts. This method has the advantages of being methodological which make it easy to understand and apply in different situations of abandoned mine shafts. It is also less data demanding when compared with other popular strategies used to prioritize rehabilitation options of abandoned mines. However, the hazards scoring process is criteria guided and therefore assigning of actual scores to represent the seriousness of the component of the risk identified is based on the judgement of the experts assigning the scores. In view of this, the method is best suited for preliminary assessment and prioritization of hazards of abandoned mine shafts.

The ranking of abandoned mine shafts based on information gathered during preliminary field assessment of the shafts is comparable with that used by the Risk Ranking Methodology employed in ranking abandoned mines in the British Columbia in 2007/8 (Power *et al.*, 2009). The development and use of abandoned mines ranking systems that uses basic information gathered from preliminary field assessment of the mine features is the sound bases for effective mine site rehabilitation for developing countries with large number of abandoned mine sites like South Africa and with limited resources to rehabilitate the numerous sites. This approach requires that detailed characterisation of these sites be done after conducting preliminary site characterisation.

The evaluation of different treatment strategies showed that backfilling, injection/inclusion, use of plugs, and blast closure were the most preferred treatment options for the abandoned mine shafts in the Giyani and Musina areas. The decision on which of these long-term or permanent strategies to use will need to take into consideration evaluation of future use of the land as well as the future mining activities to be conducted. The reason for this is the fact that plugs can be designed in a way that they can be removed if the shaft is to be once again used for mining activities. However, if the surface use of the land requires that the void below the treatment structure is completely closed-up, permanent treatment of the shaft with appropriate backfilling material and use of blast closure can be considered.

3.9. Summary of the Chapter

The process of treatment of abandoned mine shafts is generally costly and tedious. The selection of appropriate strategies for treatment of abandoned mine shafts is the foundation step towards cost effective treatment of abandoned mine shafts. This chapter detailed the work conducted with the aim of developing method for prioritization of rehabilitation of abandoned mine shafts and finding the best strategies for dealing with the physical and environmental hazards of these shafts. The approach used involved compiling an inventory of abandoned mine shafts in the Giyani and Musina areas of the Limpopo Province of South Africa and based on such inventory developing an easy to use but effective shaft treatment prioritization system. This was then followed by the identification and evaluation of different underground mine shafts treatment strategies using two Multi-Criteria Decision-Making (MCDM) methods, *viz*; the Analytic Hierarchy Process (AHP) and Pugh Matrix. The purpose of such evaluation was to establish the suitability of the treatment strategies for abandoned mine shafts.

Application of the mine shaft hazards ranking system revealed that the risk of falling into the mine shafts and the discharge of contaminated water by the shafts were the major physical and environmental risks of the abandoned mine shafts. As a result, open shafts presented the highest physical hazards while the water in the mine workings presented the highest environmental hazards. In general, the level of both physical and environmental hazards of the abandoned mine shafts were found to be associated with low to moderate socio-economic concerns. The use of permanent mine shaft treatment strategies such as backfilling of the shafts, blast-closure and use of concrete plugs with warning signs were rated the high in addressing the major risks of the abandoned mine shafts.

The method for ranking the risks of the abandoned mine shafts for rehabilitation as discussed in this chapter will be incorporated into the expert system for ranking of the hazards of abandoned mine entries presented in Chapter Six of this thesis. The next chapter (*i.e*. Chapter Four) presents the method that was developed in this research for ranking the abandoned mine tailings dumps for rehabilitation.

CHAPTER FOUR

CHARACTERIZATION AND REHABILITATION OF ABANDONED MINE TAILINGS DUMPS

Mining generates large volumes of waste mainly in the form of tailings, spoils and waste rock. These waste materials are usually dumped at most convenient sites. The focus of this chapter is on tailings which are generated during mineral processing to extract the valuable minerals and the problems associated with their disposal and containment. Tailings disposal facilities, and in particular tailings dumps, have different types and degree of environmental problems, health and safety risks as well as socio-economic concerns. The problems of abandoned tailings disposal facilities are greatly influenced by their chemical characteristics, textual properties and the proximity to sensitive areas. This chapter presents an overview of a systematic method that was developed and used for evaluation of problems associated with tailings dumps in order to prioritize them for rehabilitation. This method prioritizes the rehabilitation of the dumps based on factors such as the pollution potential of the tailings, the possibility of the material to be dispersed to the surroundings, and the landscape and visual impact of the dumps. The applicability of this method was tested using waste dumps found in different geographical settings in the Giyani Greenstone Belt, Tshipise Magnesite Field and Musina copper mining areas.

4.1. Background of the Study

Mining and processing of solid minerals produce different types of waste material such as tailings and waste rock (Kim and Jung, 2004). In general, abandoned tailings dumps are of major concern throughout the world. This is because they are known for having physical and chemical properties that have serious impact on the environment as well as the health of people and animals (Rodrıguez *et al.,* 2011). For example, toxic metals found in tailings are mostly in higher concentrations than they are in the ore mined and most tailings dumps are potential candidates for discharge of Acid Mine Drainage (Choi *et al.,* 2005). According to Olobatoke and Mathuthu (2016), the composition of mine tailings depends largely on the type of ore mined, the gangue associated with the ore, and the extraction method used. Some of the common toxic metals in tailings are Lead (Pb), zinc (Zn), Copper (Cu), Nickel (Ni), Manganese (Mn), and Asenic (As) (Li and Huang, 2015). The impacts that these metals have on people and animals are generally aggravated by their long-term persistence on the environment (Mani and Kumar, 2014). Their accumulation in soils, water and air are direct ways the metals enter the human food chain (Kamunda *et al.,* 2016). The transportation of tailings material through different forms of erosion can result to pollution of other parts of the environment away from the mining site and the impacts on the environment are mostly reflected by the changes in land use patterns of the region (Moosavirada and Behnia, 2016).

In many countries or regions, the rehabilitation of abandoned mine sites have taken different forms. In South Africa, the focus of rehabilitation of abandoned mines has for many years been on addressing safety and health risks and then the environmental hazards at these mines (DMR, 2010). However, the method used to set such rehabilitation priority of abandoned mines in the country has not been broadly communicated or published. For this study, abandoned gold, copper and magnesite tailings dumps in the Giyani Greenstone Belt (GGB), Musina and Tshipise Magnesite Field were respectively used to develop a tool for prioritization of rehabilitation of abandoned tailings dumps. The tool was developed to be methodological, less data demanding and appropriate for use in developing counties with many abandoned mine waste dumps and limited resources to carry out their rehabilitation.

4.1.1. Objectives of the study

The main aim of the work presented in this chapter was to develop a tool for selection of appropriate strategies for rehabilitation of abandoned mine tailings dumps. The specific objectives were:

- To quantify the pollution potential of the abandoned gold, copper and magnesite tailings materials in the Giyani and Musina areas.
- To come up with a set of criteria and use them for quantifying landscape and visual impacts of tailings dumps in the study area.
- To develop and apply techniques for identifying the best combination of methods for addressing the problems of abandoned tailings dumps.

4.1.2. Description of tailings dumps in the study area

Gold mining in the Giyani greenstone belt left behind four large tailings dumps at four abandoned mine sites, namely; Klein Letaba, Louis Moore, Fumani and New Union (also known as Osprey). On the other hand, magnesite mining at Nyala Mine resulted to two large tailings dumps while copper mining in the whole of Musina area created one huge tailings dump. Attempts of planting trees on copper tailings were made but did not yield any positive result while others were abandoned without any attempts of protecting the environment from potential contamination of toxic metals from the abandoned tailings dumps. Currently, all these tailings are barren with extensively eroded slopes and located in areas that are close to surface water bodies. This is a general issue of concern as the current state of the tailing dumps can lead to pollution of the major rivers and soils in agricultural fields. The location and general morphology of the studied dumps in this research are shown in *Figure 4.1*. It is worth mentioning that due to the problems of accessibility of the New Union Mine, the tailing dump of this mine was not considered in this research.

Table 4.1: The general characteristics of the studied tailings disposal facilities

Mine	Coordinates		Area of the Dump (ha)	Ave. distance from the surface water bodies (m)
	S	E		
KLMT	23°17′40"	30°33′20"	6.0	55
LMMT	23°13' 03"	30°41'46"	5.5	260
FGMT	23°06'36"	30°53'40"	6.8	>1000
NMMT-(a)	22°31'54	30°37'24"	2.9	>1000
NMMT-(b)	22°32'03"	30°36'36"	2.6	>1000
MCMT	22°19′40"	30°3′00"	74.2	454

Note: KLMT is Klein Letaba Mine Tailings, LMMT is Louis Moore Mine Tailings, FGMT is Fumani Gold Mine Tailings, NMMT is Nyala Mine Magnesite Tailings and MCMT is Musina Copper Mine Tailing

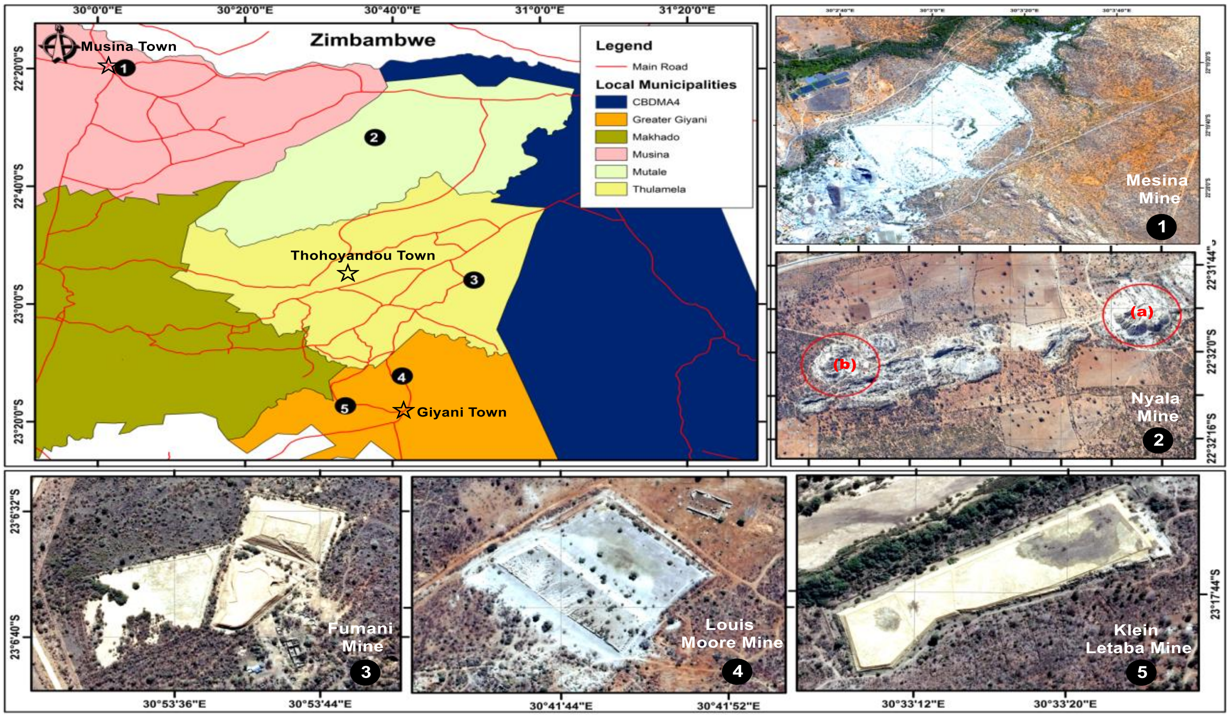


Figure 4.1: Location and morphology of the tailing dumps.

4.2. Research Method Design

The method used for characterization and identification of preferred combination of rehabilitation methods for abandoned tailings dumps was developed. The development of this method was based on the fact that tailings dumps contain high levels of toxic metals that result to wide ranging and serious environmental problems when the tailings materials are eroded to areas away from the mine. It considered the fact that the requirements for rehabilitation of abandoned tailings dumps can be influenced by this and the effect that the dumps have on the visual appearance of the landscape. Based on this, the method developed for this research used the scoring approach to determine the index values for environmental pollution by multiple toxic metals, potential of dispersion of contaminated tailings material to the surrounding areas, and the landscape and visual impact of the dumps. These index values were used to set the priority of rehabilitation of the dumps. In situations where several tailings dumps need to be rehabilitated, these scores assist in identification of the dumps that require urgent attention. This is generally important in developing countries with limited resources to rehabilitate the numerous abandoned mine tailings dumps. Based on the calculated index values, a triangle for identification of preferred combination of rehabilitation methods for the abandoned mine dumps was developed. The flow of the three-step procedure followed in setting rehabilitation priority of abandoned tailings dumps in shown in *Figure 4.2*.

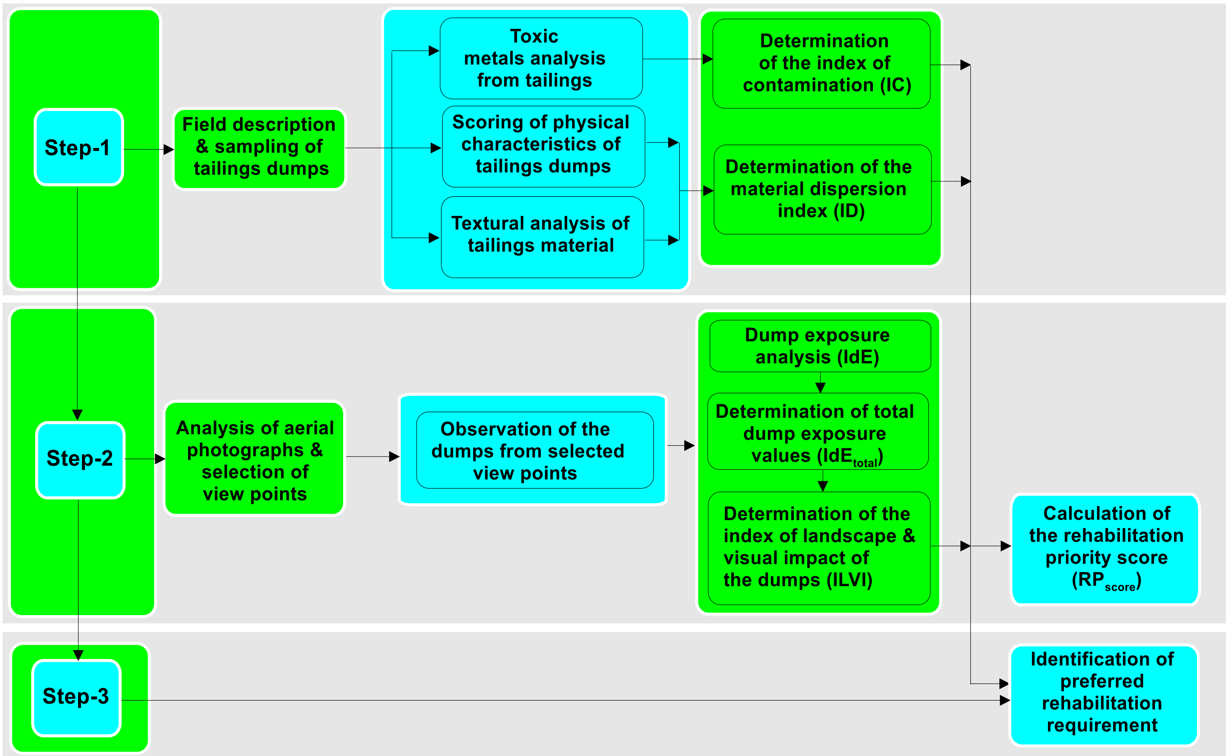


Figure 4.2: Stepwise procedure of the method developed for this research.

4.2.1. Determination of index of contamination

The determination of the rehabilitation prioritization score (RP_{score}) began with the determination of contamination potential of the tailing dumps. This was determined by calculating the combined toxic metal contamination of the dumps using the method described by Reis *et al.* (2012) as mean hazard index. The method involved dividing the concentration (mg/kg) of toxic metals in tailings by their respective maximum allowable limits in soils. The sum of the quotient values obtained was then divided by the number of toxic metals considered in the study. This can be mathematically explained by *Equation 4.1* where C_i is the concentration of the *i*th metal in tailings material, PL_C is the maximum permissible limit of a toxic metal C in soil as reported by DEA (2010) and Kamunda *et al.* (2016). $\mathcal{N}$ is the number of toxic metals ratios considered in the study and IC is the value of the index of contamination. The metals considered in this study and their maximum permissible limits in soils are shown in *Table 4.2*. The Inductively Coupled Plasma Mass Spectroscopy (Agitent 7900 model ICP-MS) instrument was used determine the concentration of these metals in tailings.

$$\mathrm{IC} = \frac{1}{\mathcal{N}} \times \sum_{i=1}^{n} \frac{\mathrm{C_i}}{\mathrm{PL_C}} \tag{4.1}$$

Table 4.2: Permissible level of toxic element concentration in agricultural fields of South Africa (DEA, 2010; Kamunda *et al.,* 2016).

Metals	Cd	As	Cr	Ni	Pb	Zn	Hg	Cu	Co
Max. Permissible Limit in Soil (SA) (mg/kg)	7.5	5.8	6.5	91	20	240	0.93	16	300

4.2.2. Material dispersion to surrounding environment

The second step in the determination of rehabilitation prioritization score for the tailings dumps was to determine value (ID) which describes the probability of dispersion of tailings material to the surroundings areas thus affecting the quality of nearby surface water bodies. This value was determined from the scoring of five factors relating to the resistance of tailings material to erosion. *Equation 4.2* where the sum of factor i_e (relating to the textural properties of the material), i_{f} (relating to the types of dump surface cover), i_d (efficiency of the erosion control measures of the dumps to prevent scattering of the material to the surroundings) and i_a (which is the average of the dump from the nearest surface water body) was multiplied by the planner area ($\mathcal{A}$) of the tailing dump. The criteria used to assign weights to these factors is shown in *Table 4.3*.

$$\mathrm{ID} = \mathcal{A} \times (\mathrm{i}_e + \mathrm{i}_{f} + \mathrm{i}_d + \mathrm{i}_a) \tag{4.2}$$

4.2.3. The exposure of the dumps and their landscape and visual impact analysis

The determination of the index for landscape and visual impact (ILVI) was determined by first calculating the factor relating to the exposure of the dump (IdE). This was accomplished by selecting viewpoint (VP) which the waste dumps can be observed from the critical areas in nearby communities, access and main roads situated at 0.5-1.5km and 1.5-2.5km distance zones from the dumps. Care was taken to ensure that the VP at each site are not at less than 500m distance from each other. At each point, an area of the dump visible ($\mathcal{A}_{\mathrm{vis}}$) was captured in images and estimated from 5m resolution aerial photographs in ArcGIS 10.1 Software™. The areas of the dump visible from a VP and the total area of the dump ($\mathcal{AV}_{\text{Total}}$) were used to calculate the IdE value for individual viewpoints using *Equation 4.3*. The viewpoints of the dumps in the study area are shown in *Figure 4.3*.

$$\text{IdE} = \frac{\mathcal{A}_{\text{vis}}}{\mathcal{AV}_{\text{Total}}} \tag{4.3}$$

Table 4.3: Criteria for scoring of the factors for determination of the index of dispersion of tailings material to the surroundings areas.

Description	Weight
The factor relating to the general morphology of the dumps	i_d
The classification of mine waste dumps	
▪ Heaped fill	1.00
▪ Side hill fill	0.80
▪ Ridge crest fill	0.60
▪ Valley fill	0.40
▪ Cross valley fill	0.20
The textural properties of the waste material	i_e
▪ Gravel soil (>0.25mm): 50% or more of coarse fraction is retained in No.4 sieve	0.10
▪ Sandy soil: 50% or more of coarse fraction passes the No.4 sieve	0.50
▪ Clayey soil: 50% of fine fraction passes 2.0**µ**m	0.80
▪ Silt soil: 50% of fine fraction is retained between 0.6mm and 0.002mm sieves	1.00
Factor relating to the cover property of the waste dump	i_f
▪ Both slopes and top surface of the dumps are without any cover	1.00
▪ The top surface is covered by indigenize plant/grass species	0.75
▪ Slopes are covered by indigenize plant/grass species	0.50
▪ The dump is completely covered by indigenize plant/grass species	1.25
Factor relating to the distance of the dumps from surface water bodies	i_a
▪ < 100m	1.00
▪ 100-300m	0.75
▪ 300-600m	0.50
▪ 600-1000m	0.25
Factor relating to the dump's area coverage (ha)	$\mathcal{A}$
▪ Dumps occupying a planner greater than 625ha	1.00
▪ Dumps occupying about 25-625ha planner area	0.80
▪ Dumps occupying about 5-25ha planner area	0.60
▪ Dumps occupying 1-5ha planner area	0.40
▪ Dumps occupying less than 1ha planner area	0.20

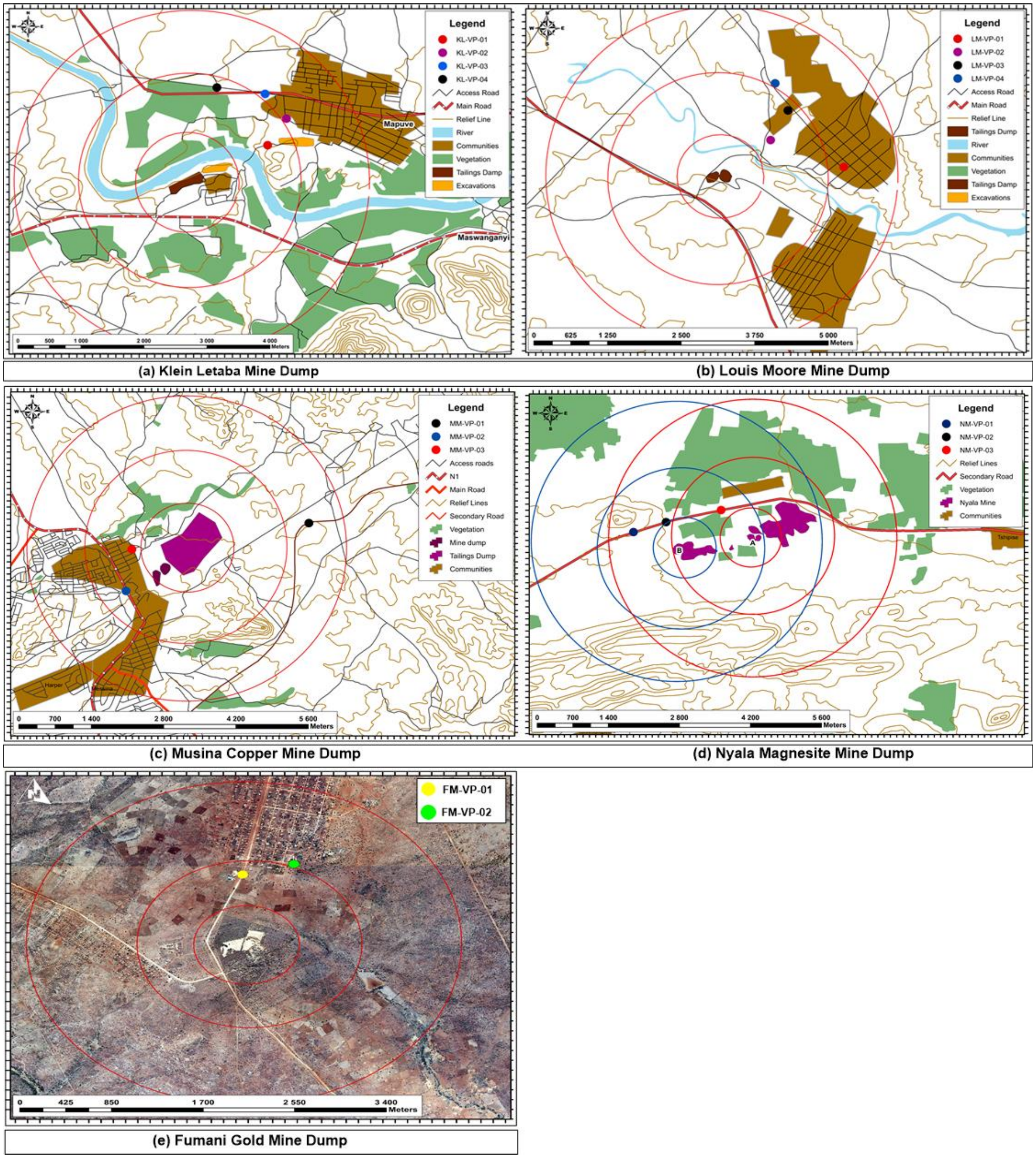


Figure 4.3: Maps of the viewpoints of the abandoned tailings dumps in the study area.

Based on the determent index of exposure of the dump, the value the represent the total exposure of the dump (IdE_{Total}) was computed using *Equation 4.4.* This involved dividing the average index of exposure of the dumps (IdE_{av}) in each viewing distance area by the corresponding number of viewpoints (n_i) and the sum of these values was taken as the total exposure of the dump. The IdE_{Total} was used to multiply the sum of the weight of factors relating to (i) chromatic contrast (i_c), (ii) morphology and shape of the dump (i_r), and (iii) the relationship of the nature of the dump with the surroundings (i_n) to determine the index of landscape and visual impact values (ILVI) as shown in *Equation 4.5.* The criteria used to assign weights to the factors i_n, i_r and i_c is depicted in *Table 4.4.*

$$IdE_{Total} = \sum_{i=1}^{n} \frac{IdE_{av}}{n_i} \quad (4.4)$$

$$ILVI = IdE_{Total} \times (i_c + i_r + i_n) \quad (4.5)$$

Table 4.4: Criteria for scoring of the factors for landscape and visual impact analysis (Rodrıguez *et al.,* 2011).

Description	Weight
Impact factor by chromatic contrast	
Appearance	i_c
▪ Visual similarity (no significant difference from over 1km)	0-1
▪ Significant chromatic contrast (yellow-brown, gray-black)	3-6
▪ Clear differences of colour: natural colours	6-8
▪ Clear differences of colour: artificial colours	8-10
Impact factor on the morphology or shape of the physical environment	
Deposit shape	i_r
▪ Shape of the deposit filling into the natural morphology	0-1
▪ Divergence only in shape, but not in volume	2-4
▪ Divergence in volume and shape	4-10
Impact factor related to the nature of the deposit and its relationship to the surroundings	
Nature of the deposit	i_n
▪ Mining waste like the natural surface materials	0-1
▪ Mining waste different from the natural surface materials	1-4
Waste dumps located in arid zones	
▪ With natural colours	1-2
▪ With unnatural (anomalous) colours	3-5
Waste dumps located in humid zones	
▪ With natural colours	0-1
▪ With artificial colours	2-3

4.3. Determination of Rehabilitation Priority of Tailings Dumps

The rehabilitation priority score (RP_{score}) of abandoned tailings dumps was determined by adding the index of landscape and visual impact to the product of the index of contamination and the index of dispersion of tailings. The mathematical representation of this is shown in Equation 4. 6. The sensitivity of the scores of rehabilitation priority to the changing ILVI and IC values was tested by varying these index values. In each case the ILVI or the IC values were varied, the changes to the RP_{score} was critically observed. Figure 4.4*a* shows that when the ILVI was increased by a difference of 4 units, at high material dispersion and contamination potential values, the maximum rehabilitation priority score obtained was ≥211. The maximum rehabilitation priority scores reduced drastically to ≥ 57 when the IC values were varied by the same 4 units.

On the other hand, when the material dispersion and contamination potential values were kept at lowest possible scores, the variation of ILVI or IC values by 4 units gave rehabilitation priority score that start from the minimum of 1 (*i.e.,* ≥ 1). When the ILVI values were increased up to 49, the RP_{score} reached the maximum value of 49. However, when the IC values were increased to 49 (maximum), the RP_{score} increased to just up to 11 (see *Figure 4.4b*). The sensitivity analysis demonstrated that high rehabilitation priority scores are mostly influenced by increasing impact of tailings dumps on the appearance of the landscape while low rehabilitation priority scores are influenced by increase in pollution potential scores of tailings dumps. The sensitivity analysis presented an opportunity to understand the range of RP_{score} attainable in different situations of abandoned tailings and/or tailings dumps.

$$RP_{score} = (IC \times ID) + ILVI \qquad (4.6)$$

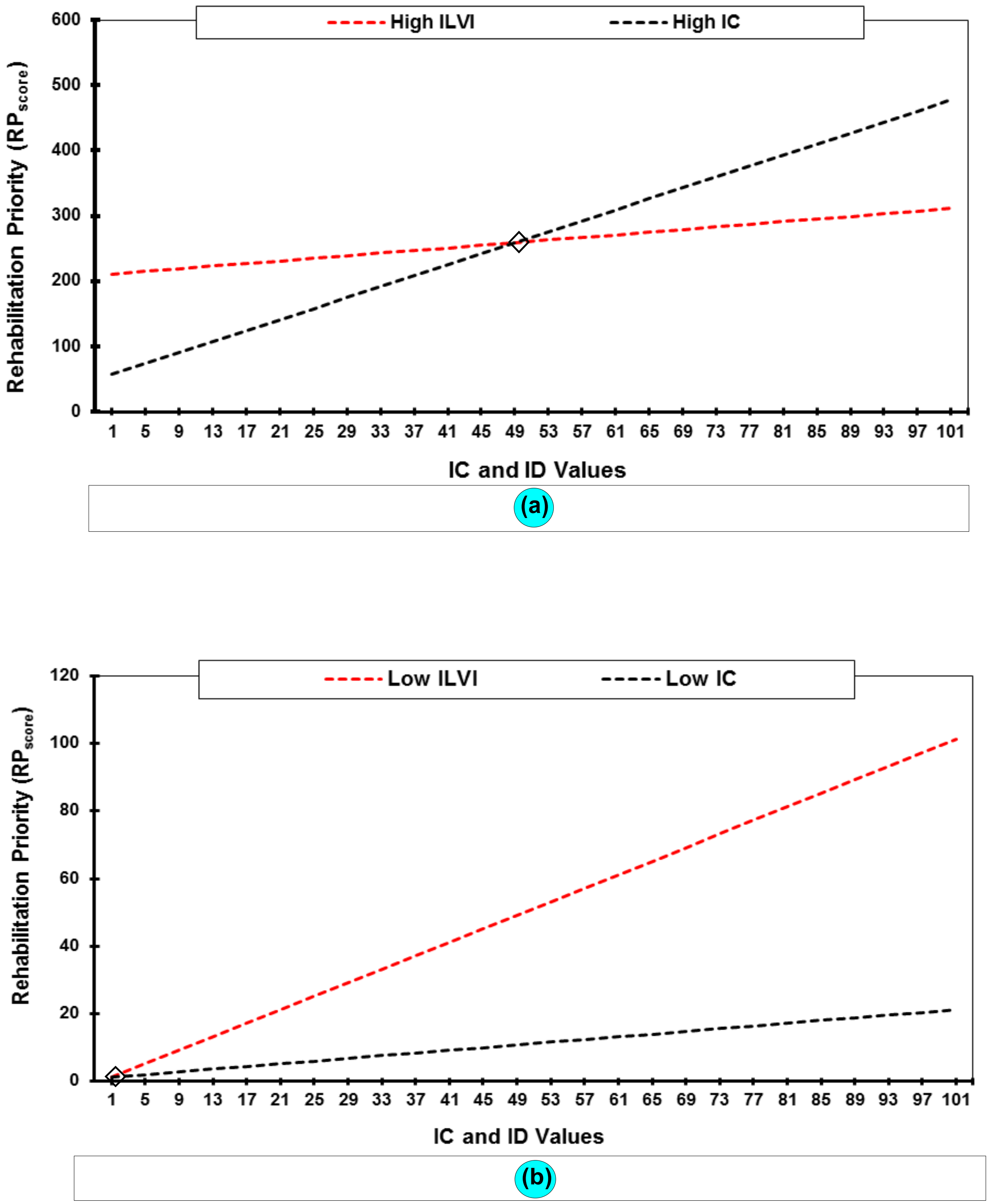


Figure 4.4: An illustration of the sensitivity of the index values to the output of the system (a and b).

Plotting the rehabilitation prioritization score of the tailings dumps on the rehabilitation prioritization curve shown in *Figure 4.5* allowed that a clear sequential view of the priority of rehabilitation of tailings dumps be observed. As a way of quantifying the urgency of rehabilitation of the tailing dumps, the model in *Figure 4.5* allowed the tailings dumps to be classified as requiring (i) low (>10), (ii) moderate (10-100) and (iii) high (>100) rehabilitation attention. This classification of the urgency of rehabilitation requirement was based on the rehabilitation concerns of the dumps as indicated by their respective rehabilitation priority scores. According to this classification, the tailings dumps that do not present any landscape and visual impact or have no potential to pollute the environment are considered to require low rehabilitation attention. The dumps that have high values for all the three indices are considered to require high rehabilitation attention.

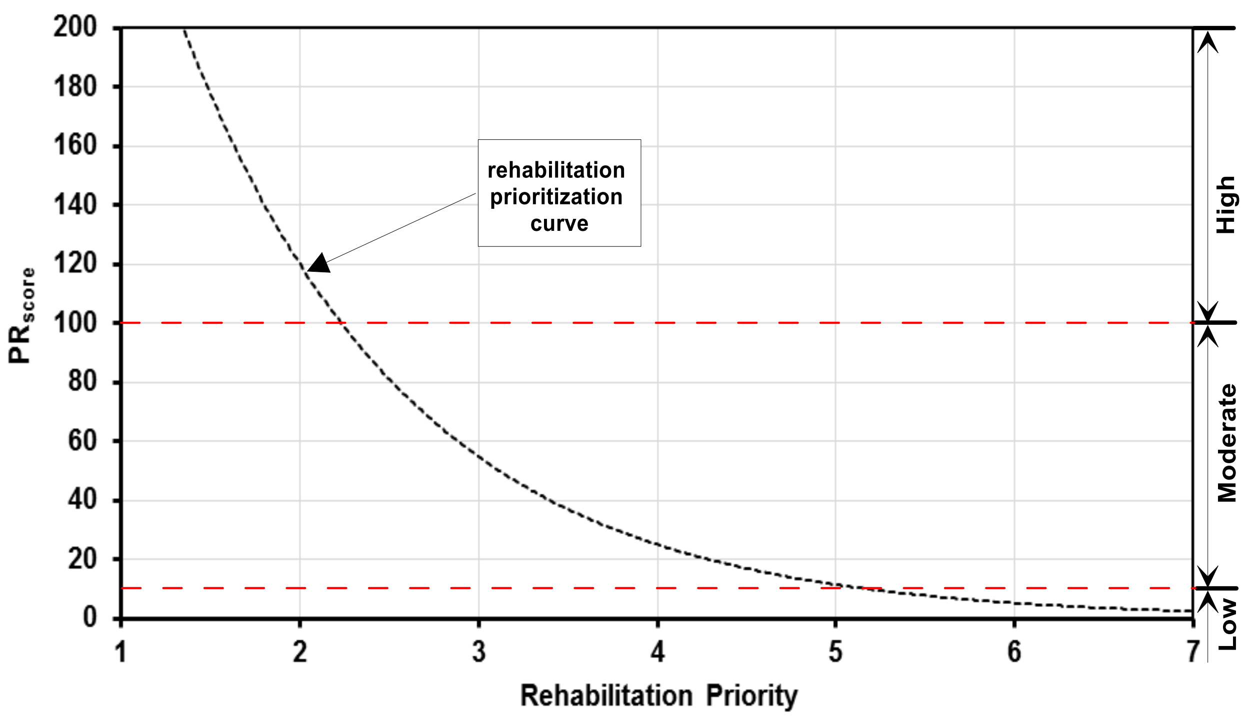


Figure 4.5: Rehabilitation prioritization curve of rehabilitation of abandoned tailings dumps.

4.4. Identification of Rehabilitation Requirements of the Tailing Dumps

The technique developed for identification of the most suitable methods for rehabilitation of tailings dumps is based on potential of the dumps to pollute the environment, their impact on the aesthetic appearance of the landscape, and the potential of tailings material to be dispersed to the surrounding environment. Based on the numerical values determined for quantifying the significance of these factors, a triangle for identifying a suitable combination of strategies for rehabilitation of tailings dumps was developed and this is shown in *Figure 4.6*. The main objective of the rehabilitation of abandoned tailings dumps using the approaches indicated in the triangle is to create a safe, stable and pollution-free landform that blends very well with the surrounding natural landscape. An important consideration for ensuring that rehabilitation of the abandoned tailings dumps meets these requirements/criteria was to make use of a combination of physical, biological and/or chemical rehabilitation techniques.

Figure 4.6 illustrates the triangle for determining the most appropriate rehabilitation options for tailings dumps. This triangle has been divided into zones that represent different rehabilitation strategies. In order to determine the most suitable rehabilitation strategy or a combination of strategies for a particular tailing dump IC and ILVI values are used. A line is drawn joining the IC and the ILVI values of the dump. The ID value of the dump is determined on the ID axis and a vertical line is drawn from this point to intersect the line joining IC and ILVI. The point of intersection of these two lines determines the zone of rehabilitation strategies for the tailings dump. This allows that tailings dumps with IC and ILVI values that are greater than 100 are plotted in Zone-I of the triangle while those with IC and ILVI values that are between 10 and 100 are plotted in Zone-II. The dumps with IC and ILVI values that are less than 10 and the ID values that are greater than 2.2 and less than 2.2 are respectively plotted in Zone-III and IV (see *Figure 4.6*). The description of the abandoned tailings dumps rehabilitation approaches in the different Zones of the triangle is provided in *Table 4.5*.

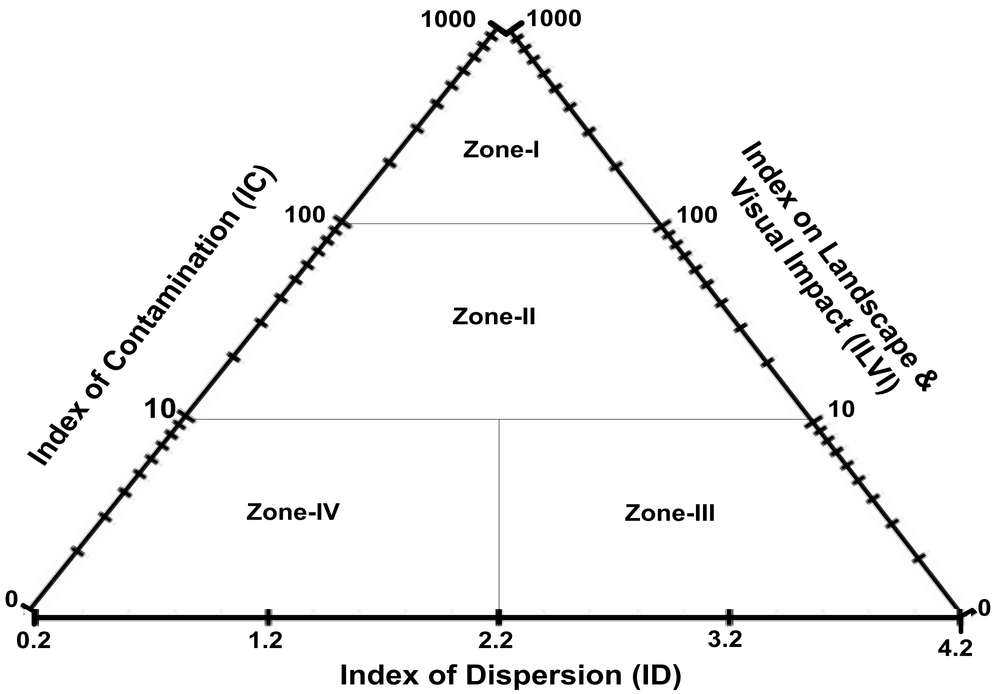


Figure 4.6: Triangle diagram for identification of tailings dump rehabilitation strategies.

Table 4.5: Description of the zones of rehabilitation efforts of the tailing dumps.

Zone	Preference of rehabilitation methods	Description
I	P + B + C	▪ Require creation of stable landscape with reduced erosion and improved soil physico-chemical quality for easy revegetation. There is a need for removal and mobilization of toxic metals using biological and chemical methods.
II	P + B	▪ Require physical stabilization and removal of toxic metals using biological methods such as the use of Microbes, Phytoextraction and Phytostabilization. Little chemical methods are used.
III	P + C	▪ Require physical stabilization and enhancement of nutrient availability in tailings material to promote easy growth vegetation. Little biological methods are used.
IV	C + P	▪ The dump requires chemical improvement of the soil quality to promote vegetation growth and followed my manner physical stability of the slopes of the dumps.

Note: *P*, *B* and *C* represent the physical, biological and chemical methods of rehabilitation of the waste dumps respectively.

4.5. Pollution Potential of the Dumps

The results of toxic metals analysis showed that the concentration (mg/kg) ranges of Cu (22.6-1548.2), Cr (159.5-1088.6) and Cr (22.6-1548.2) were all above the maximum permissible limits values while the Co (6.0-87.0) and Hg (0.0-0.4) concentration were below the limit in all tailings dumps. The concentration of arsenic (As) was high in gold tailings dumps and were in the order of FGMT>KLMT>LMMT. However, it was below the limit in copper and magnesite tailings material. The concentration of Ni and Pb was above the permissible limit in tailings material from Fumani and Louis Moore mines while Ni was also noticeable high in magnesite tailings (see *Figure 4.2a*). It is important to state that metals such as Pb, As and Ni are generally high in soils around gold mining areas. According to Muzerengi (2015) and Fashola *et al.* (2016), this is due to the fact that these metals are found associated with minerals such as sphalerite (ZnS), arsenopyrite (FeAsS), and galena (PbS) which are found in most gold orebodies associated with mineralization.

According to the calculated index of contamination (IC), the tailings dumps in the study area are contaminated by combined toxic metals. The lowest IC value of 1.2 was obtained in magnesite tailings while the highest (19.2) was found in gold tailings of Fumani Mine. The tailings material from Mesina, Louis Moore and Klein Letaba mines had IC values of 4.1, 2.3 and 2.0 respectively (see *Figure 4.7b*). According to Chon *et al.* (1996), the IC value >1 indicate that the material is contaminated by multiple toxic metals. Thus, the high IC values for copper and gold tailings indicated that these dumps are highly contaminated by metals from anthropogenic or geologic activities (Nimick and Moore, 1991; Reis *et al.,* 2012). The greater IC value indicate that the tailings material has higher potential to pollute the surrounding environment and this can form the initial bases for ranking (Arranz-Gonzalez *et al.*, 2016). Based on IC Value alone, the work of removing pollutants from the tailings material in the study areas should begin with gold tailings from Fumani Mine followed by the copper tailings from Musina Mine. The magnesite tailings in Nyala Mine should be considered last in the rehabilitation progamme (See *Figure 4.7b*).

The reduced IC value for magnesite tailings can be deduced to be the result of that magnesite tailings are produced from sorting and sieving of broken ore. Thus, the tailings produced does not contain any chemicals from mineral processing and/or extraction (Sibanda *et al.,* 2013). In view of this, magnesite tailings are generally inert mine waste with chemical composition that is like that of the ore mined.

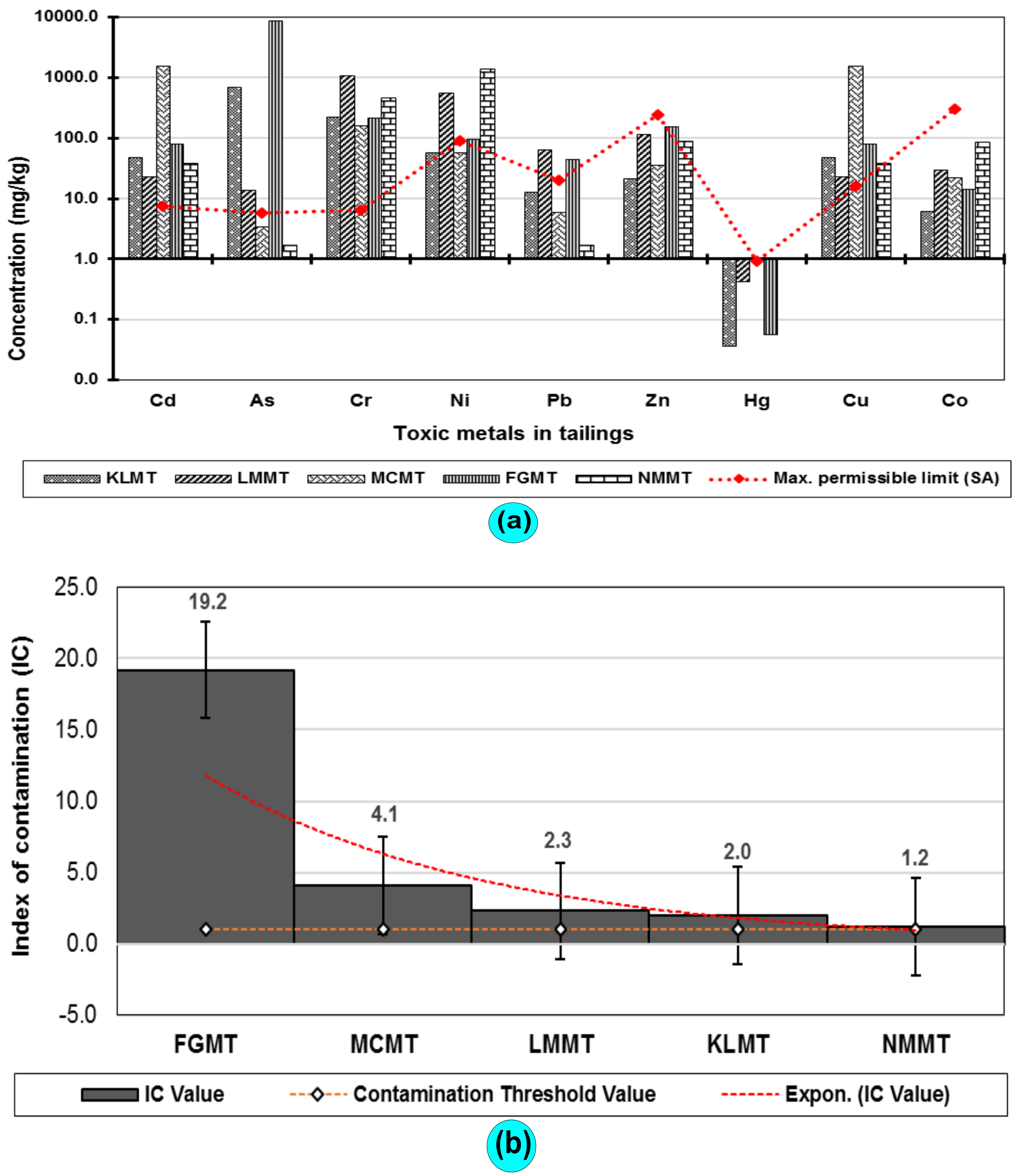


Figure 4.7: Comparison of the average concentration of toxic metals in tailings with the maximum permissible limit in soils (a) and (b) is the index of contamination values of abandoned mine tailings dumps.

4.6. Potential of Tailings Materials to be Dispersed to the Surrounding Areas

The impacts of tailing dumps on the surrounding environment as well as the health of people and animals depends on tailings material being carried to the surrounding environs which include surface water bodies. In view of this, a numerical value stated as index of dispersion was calculated and used to rank the significance of this factor in all tailings dumps in the study area. The results showed that the copper tailings from Mesina Mine had the highest potential (with the ID value of 3.00) of being dispersed to the surrounding areas. During the field assessment of the dumps, magnesite tailings dumps of Nyala Mine were found with extremely eroded slopes when compared with gold tailings from different parts of the Giyani Greenstone Belt. The effect of erosion on copper and magnesite tailings slopes is shown in *Figure 4.8.* Although these dumps showed to have been seriously affected by water erosion evidenced by V-shape erosion gullies developed on their slopes, magnesite tailings had the lowest ID values of 1.2 (see *Table 4.5*). The reason for this is the fact that magnesite tailings occupied relatively smaller areas and were at a distance greater than 1km from the nearby surface water bodies. Comparatively, the gold tailings dumps appeared to be relatively stable and they covered almost equal areas in locations that are less than 300m away from surface water bodies. This resulted to gold tailings dumps having almost equal ID values (see *Table 4.5* and *Figure 4.9*).

Although the slopes gold tailings dumps were also barren, they were less affected by erosion accept a portion of Klein Letaba and Louis Moore tailings which were observed with evidence piping erosion. The variation in the type of erosion affecting the different mine tailings dumps in the study area indicated that the material in the dumps had varying textural or physical properties. For example, piping erosion is known to develop in soils of uniform fine sands that are cohesionless; while gullies are developed in soils with easily detached sands particles. According to the established textural properties of the tailings, the dumps in the study area are comprising dominantly of sand particles with a very small portion of fines. The slight variations in textural properties of the tailing material is confirmed by small variations in the alignment of gradational carves of the tailings shown in *Figure 4.10*.

According to the Unified Solid Classification System (USCS), the gold tailings from Klein Letaba and Louis Moore mines and copper tailings from Mesina Mine can be classified as poorly-graded sands (PW); while the magnesite and gold tailings from Fumani and Nyala mines qualified to be classified as well-graded sands (SW) (see *Table 4.6*). This classification supports the development of gully and piping types of erosion on the tailings dumps from the study area. According to Masannat (1980), piping erosion is common in poorly-graded (well-sorted) silty sands with very low percentage of clay and this was found to match the characteristics of the copper tailings and gold tailings from Louis Moore and Klein Letaba mines.

Table 4.6: The calculated index of dispersion of the tailings dumps to the surrounding environment.

Dump	Area of the dump (ha)	Scoring of the waste material dispersion factors					Index of Dispersion (ID)
		$\mathcal{A}$	i_d	i_f	i_e	i_a	
KLMT	6.2	0.60	1.00	1.00	0.50	0.75	1.95
LMMT	5.5	0.60	1.00	0.75	0.50	0.75	1.80
FGMT	6.8	0.60	1.00	1.00	0.50	0.75	1.95
MCMT	87.8	1.00	1.00	1.00	0.50	0.50	3.00
NMMT(a)	2.9	0.40	1.00	1.00	0.50	0.25	1.10
NMMT(b)	2.6	0.40	1.00	1.00	0.50	0.25	1.10

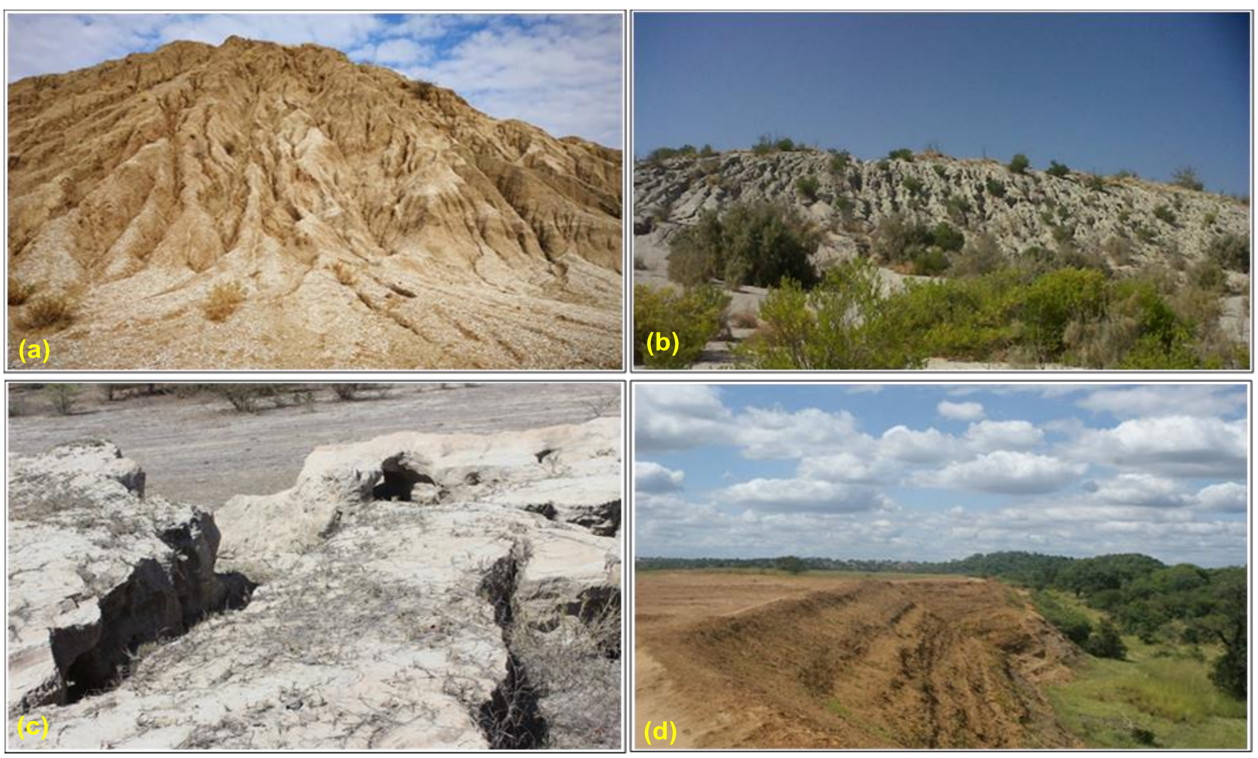


Figure 4.8: Illustration of the devastating effect of erosion on the slopes of tailings dumps. (a) is magnesite tailing, (b) is copper tailings dumps, (c) is the nature of piping erosion on Louis Moore mine tailings and (d) show the stable slopes of Klein Letaba gold mine tailings.

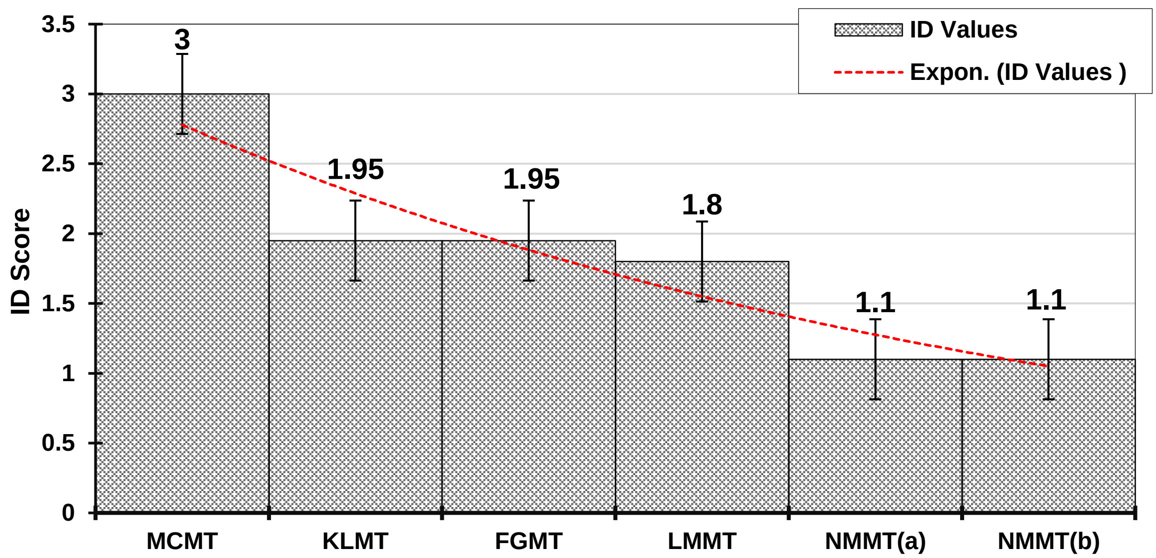


Figure 4.9: Comparison of the potential impact of mine tailings on surrounding areas.

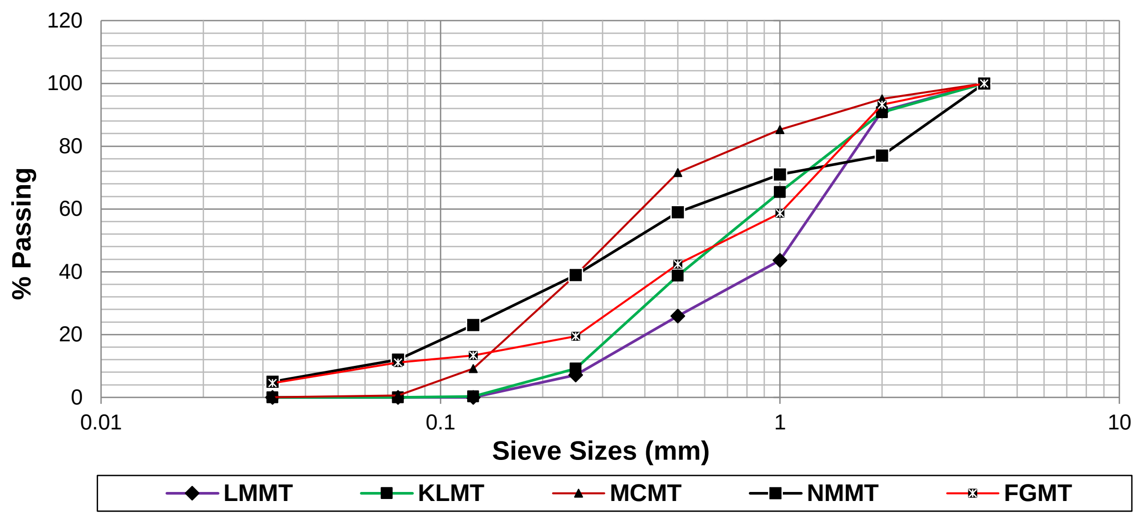


Figure 4.10: Gradational carvers of the copper, gold and magnesite tailings.

Table 4.7: Textural characteristics of gold, copper and magnesite tailings material.

Dump	%Clay (<0.002mm)	%Silt (0.075-0.002mm)	% Sand		% Fine gravel (>2mm)	C_u	C_z	Classification (USCS)
			Fine Sand (0.425-0.078mm)	Coarse Sand (0.425-02mm)				
MCMT	–	–	51.0	43.0	06.0	2.7	0.7	PW
FGMT	–	10.1	18.9	64.0	07.0	14.3	1.8	SW
LMMT	–	–	13.0	78.0	09.0	4.3	1.0	PW
KLMT	–	–	20.0	71.0	09.0	3.6	0.7	PW
NMMT	–	03.0	16.0	51.0	40.0	11.0	1.1	SW
Note: *PW* is the poorly graded soil, *SW* is well-graded soils								

4.7. Landscape and Visual Impact of Tailings Dumps

In general, the presence of tailings dumps alters the natural landscape by creating artificial hills of contrasting colours with the surroundings. The chromatic contrast of the colour of the dumps and the surrounding landscape is often negatively perceived very by people who live outside the host town of abandoned mines. Based on such unpleasant appearance of the landscape, rehabilitation of the dumps to match the surrounding landscape may be necessary. The assessment of the landscape and visual impact of tailings dumps in this study considered the exposure of the dumps to viewers on critical areas within the nearby communities.

Based on this method, Klein Letaba and Louis Moore mine tailings were well exposed or visible in four viewpoints while magnesite tailings were visible in three viewpoints within the Zwigodini Village. Gold tailings of Fumani Mine was visible in two points located within the Mutititi Village and the copper tailings in one point. The tailings dump of Klein Letaba, Louis Moore and Fumani mines were all clearly visible in viewpoints KL-VP-02, LM-VP-02 and FM-VP-02 respectively. The Mesina Mine copper tailings dump could be clearly viewed in viewpoint MT-VP-01. On the other hand, magnesite tailings dump (a) at Nyala Mine was well visible in point NM-VP-03 while dump (b) was equally visible in all the three points. The results of the visibility of the dumps in different viewpoints are shown in *Figure 4.11* and the appearance of the dumps in viewpoints with the highest exposure scores (IdE) are shown in *Figure 4.12a-f*.

The tailing dumps that appeared highly elevated in the surrounding natural topography and those that appeared with brighter colours compared to the surroundings that had higher had higher contrast with the surrounding areas (see *Figure 4.12b, c, d* and *e*). In view of this, the chromatic contrast of these dumps was assigned relatively high scores that ranged from 7 to 9 as depicted in *Table 4.8.* However, the grayish colour of the copper tailings dump in Mesina Mine and the fact that the dump has the height that well fits the surrounding topography and that it has few trees growing on its slopes made this dump to contrast relatively less with the surrounding landscape as shown in *Figure 4.12f.* The details of the results of the determination of the landscape and visual impact of the tailings dumps in the study area are shown in *Appendix-C.*

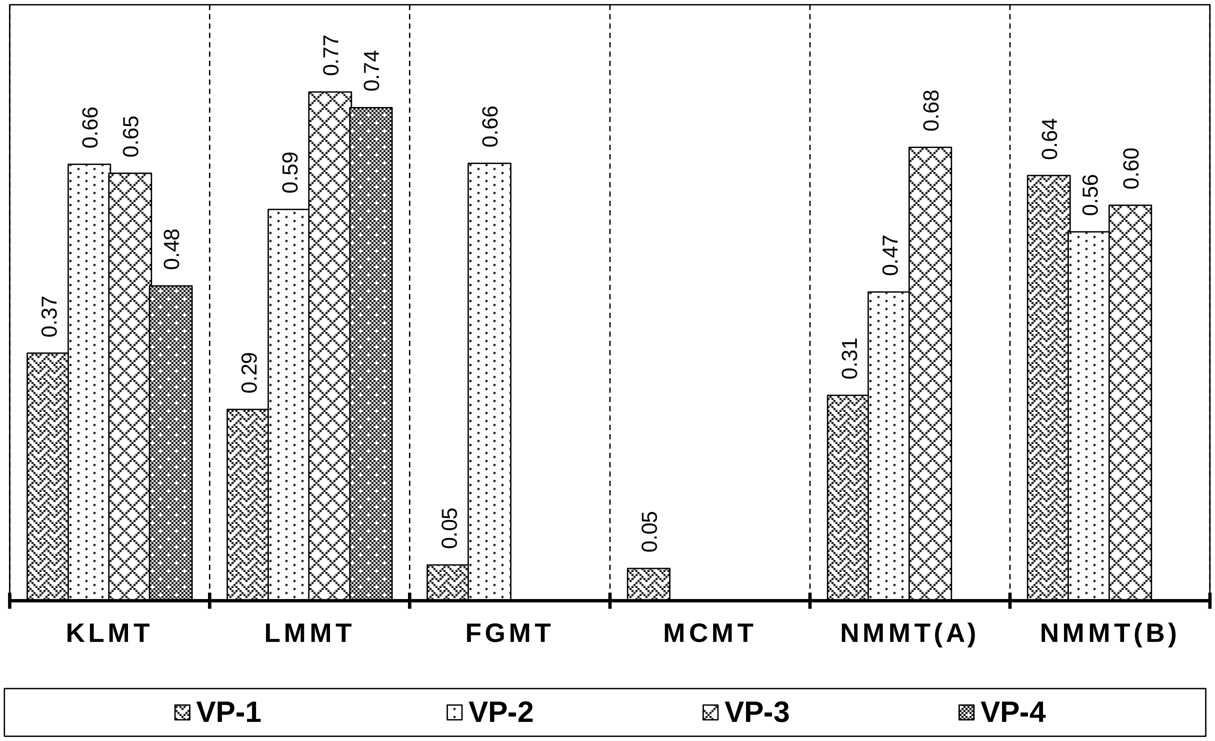


Figure 4.10: Comparison of the tailings dumps exposure in different established viewpoints.

The determined index of total exposure (IdE_{Total}) of the dumps showed that the tailings dump of Louis Moore Mine was highly exposed to the public followed by the tailings dump of Klein Letaba and Nyala mines (see *Table 4.7*). The fact that the copper tailings dump was found to be largely not visible in most busy sections of Musina Town and its surroundings resulted to it having the least IdE_{Total} score. The visibility of Klein Letaba, Louis Moore and Funani tailings dumps was encourage by location of the dumps in low laying areas than the viewpoints which the dumps can be viewed. However, the larger of the slopes these dumps were obscured by woody trees of the surrounding landscape. As a result, these dumps were mostly visible from the top.

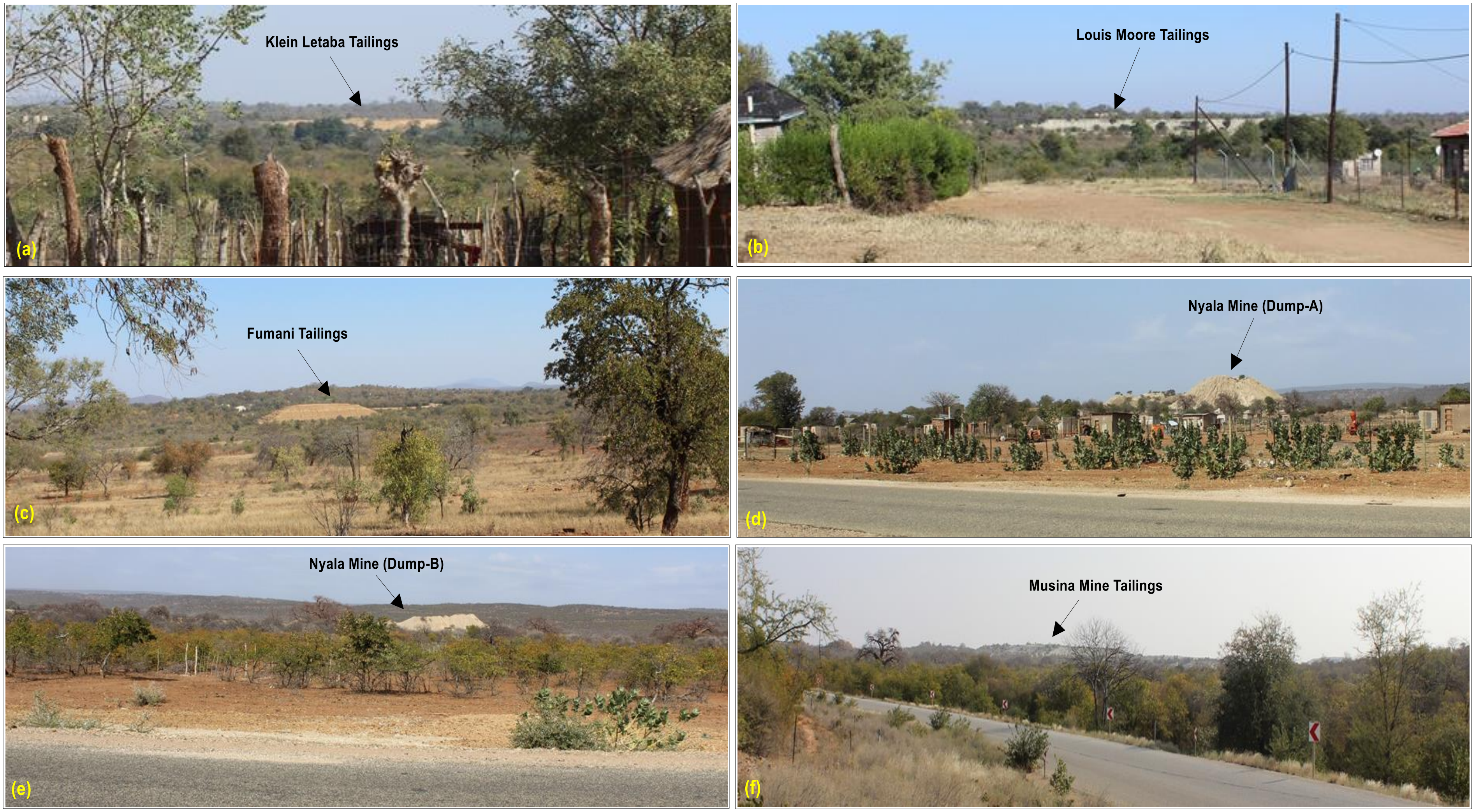


Figure 4.11: Scenery of tailings dumps from selected viewpoints.

Table 4.8: Total index of exposure of the abandoned tailings dumps in the study area.

Dump	i_c	i_r	i_n	$(i_c + i_r + i_n)$	View Distance Zone		IdE_{Total}
					A (0.5-1.5km)	B (1.5-2.5km)	
KLMT	8	10	5	23	0.4	0.7	1.1
LMMT	7	3	3	13	0.7	0.5	1.2
FGMT	8	10	5	23	0.1	0.7	0.7
MCMT	8	7	5	20	0.0	0.0	0.0
NMMT(a)	9	10	5	24	0.7	0.4	1.1
NMMT(b)	9	10	5	24	0.0	0.9	0.9

On the other hand, the fact that the terrain around Nyala Mine is characterized flat topography covered by shrubs and few trees resulted to the slopes of magnesite tailings dumps being so well exposed. However, magnesite tailings dump (a) had the highest landscape and visual impact index (ILVI). Consequently, the work of rehabilitation of the tailings dumps in the study area should aim to improve the aesthetic appearance of the landscape and should be done in the order of NMMT(a) >KLMT >NMMT(b) >FGMT>LMMT>MCMT as shown in *Figure 4.13*.

The location of magnesite tailings dumps close to the road to Sagole Baobob Big Tree (≈3000 old tree) which is an important tourist destination in the region make the presence of unrehabilitated magnesite tailings dumps in the area an unpleasant distraction to people viewing the landscape around the Nyala Mine topography. This can indirectly affect the growth of tourism in the area this can indirectly limit the socio-economic growth of the region. This is because features of historic mining such as old tailings dumps can present a very negative view of the landscape to tourist or people who occasionally visit the area (Dentoni *et al.,* 2006).

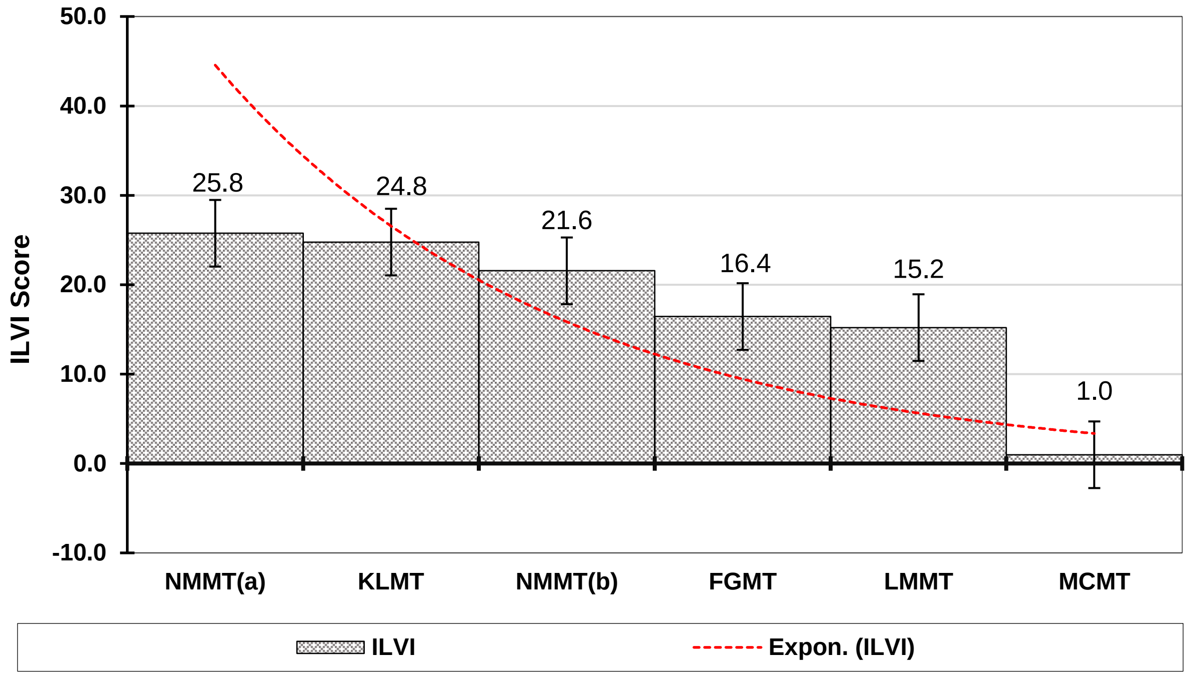


Figure 4.12: Landscape and visual impact of abandoned tailings dumps in the study area.

4.8. Prioritization of the Rehabilitation of the Dumps

Based on the index values describing the pollution potential of tailings dumps, their potential of getting dispersed to the environment and the impact of the dumps on the appearance of the landscape, the scores that define the priority of rehabilitation of tailings dumps were determined. In general, the results demonstrated that the tailings dumps selected as case studies were classified to be requiring moderate rehabilitation efforts or attention (see *Figure 4.14*). However, they also showed that the rehabilitation of tailings dumps should begin with gold tailings of Fumani Mine. This dump had the highest rehabilitation priority score of 53.9 in the study area (see *Figure 4.14*). This dump was found with relatively high IC value (19.2) that makes it to have a relatively high potential to pollute the environment in the study area.

Although the tailings dump of Klein Letaba Mine was ranked second for rehabilitation, its potential to be dispersed to the surrounding areas was found to be almost equal to that of Fumani mine tailings but it had a relatively low IC value. This reduced its rehabilitation priority score (RP_{score}) by almost half from that of Fumani Mine tailings. Magnesite tailings dumps had slightly low rehabilitation priority scores and that placed them at the third and fourth place in the priority list. The slight differences in rehabilitation priority scores of magnesite tailings dump A and B was observed to be mainly influenced by their differences in ILVI values which were 25.8 and 2.6 respectively. The copper tailings covered the largest area (≈87.8ha) of all the studied dumps, however, its visibility to the public and the alteration to the landscape it causes led to it having the lowest ILVI score of 1.1. This contributed to this tailings dump having lowest rehabilitation priority score that put it at the bottom of the rehabilitation prioritization list (see *Figure 4.14*).

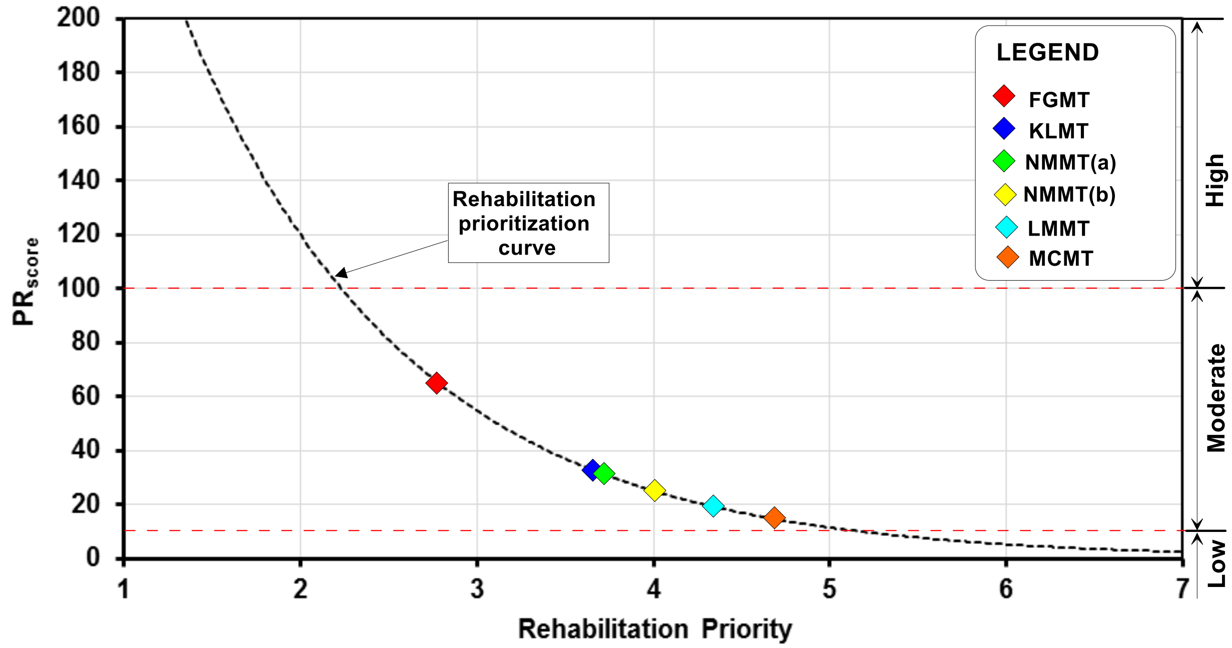


Figure 4.13: Rehabilitation priority scores of the studied tailings dumps.

4.9. Rehabilitation Requirements of the Dumps

Plotting the IC, ID and ILVI values on the triangle developed for identifying preferred rehabilitation options for abandoned tailings dumps placed the tailings dumps in the study area in three zones, *viz*.; Zone-II, III, and IV (see *Figure 4.15*). The less polluting gold tailings dumps (*i.e.*, KLMT and LMMT) and magnesite tailings dumps (NMMT) were located in Zone-IV. This implies that the rehabilitation of these dumps should be accorded relatively less priority and that slightly less effort should be expended in rehabilitating them. Based on the results of this study, it is recommended that rehabilitation of these dumps should be carried out using chemical methods that promote vegetation growth in combination with minimum application of physical stabilization of the dumps.

The copper tailings dump had relatively less potential to pollute the environment and was less visible from the busy areas of Musina Town and its surroundings. These factors contributed to the dump having low rehabilitation priority score. These factors coupled with their low erodibility potential to the surrounding areas resulted to this dump being in Zone-III of the triangle for identification of rehabilitation options. A dump that falls within this zone means that more effort is required in controlling erosion using physical and chemical methods. At minimum application, biological techniques can be used to remove excess metals from the tailings to allow ease growth of vegetation.

The gold tailings of Fumani Mine had the highest pollution potential and impact on the appearance of the landscape. In view of this, it was found to be in Zone-II of the triangle (see *Figure 4.15*). The rehabilitation of this dump will require use of combination of physical and biological methods. In this case, physical methods are to be employed in stabilizing the dump to prevent them from contaminating the surrounding areas while biological methods are to be used to reduce the level of toxic or heavy metals in the tailings.

It is important to state that the method used in this work assist in identifying rehabilitation options that reduce and/or eliminate the risks of tailings dumps polluting the environment while addressing the impact of the dumps on aesthetic beauty of the landscape. However, efforts of finding alternative uses of tailings material should be explored. Such approach of dealing with the problems of tailings dumps was stated by Lottermoser (2011) to be the second preference followed by recycling, energy recovery, and treatment of tailings before disposal. This has an advantage of converting waste to resources which will contribute to reducing the amount of waste stored at the dump. For example, previous studies in the study area showed that magnesite tailings of Nyala Mine are suitable for use as replacement for sand and borrowed soil material in the construction industry (Mhlongo, 2012; Sibanda *et al.,* 2013). It has also been found that copper tailings from Mesina Mine possess properties that support utilization of the material for development of geopolymers (Gitari *et al.,* 2018). In addition, the volume of abandoned tailings material in the Giyani and Musina areas can be reduced by using them to backfill unstable underground mine workings in the study area. According to Lottermoser (2011), tailings can be mixed with cement and used in underground mine workings as backfill to support the roof and walls of the openings. This assists in creating stable grounds in the areas of abandoned underground mining operations.

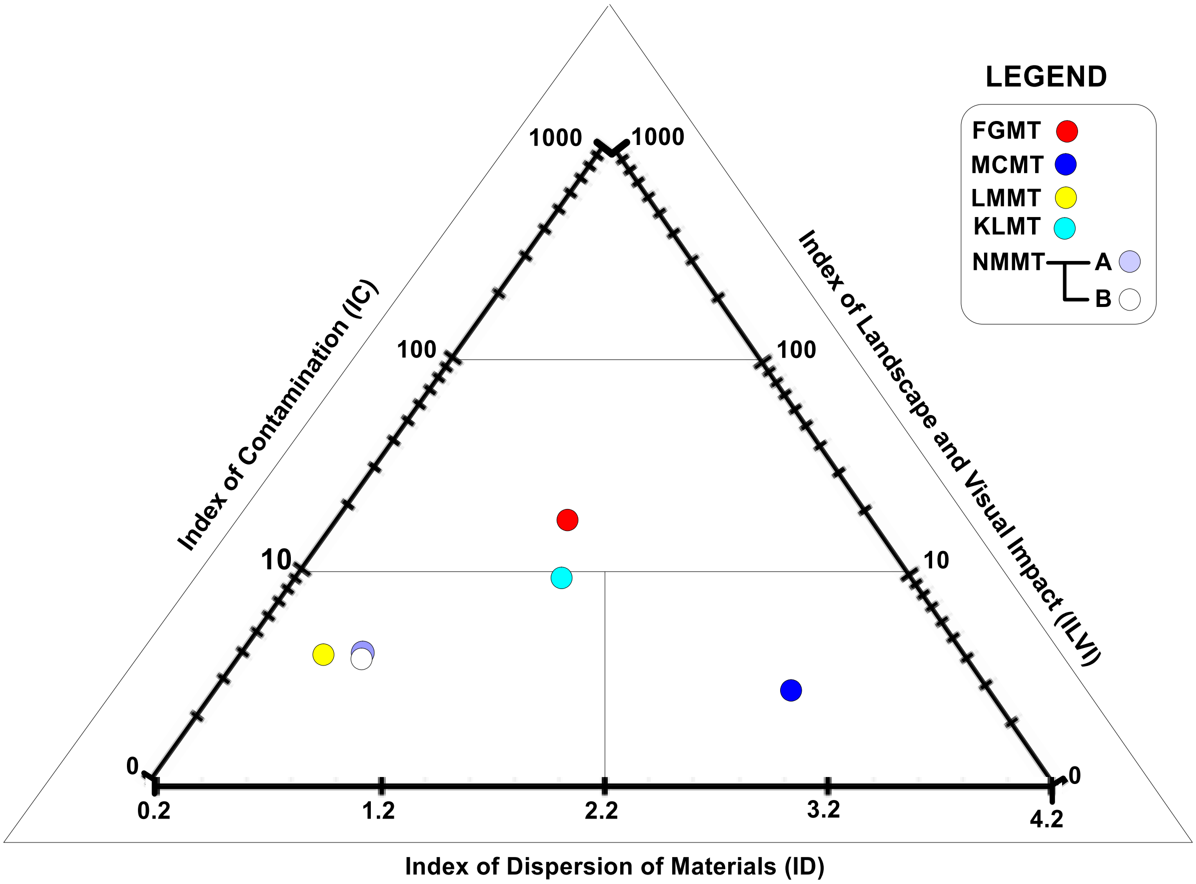


Figure 4.14: Preferred rehabilitation requirement for the tailings dumps in the study area.

4.10. Discussion of Findings of the Study

Rehabilitation of abandoned tailings dumps is generally costly and requires to be done with utmost precision to ensure that the problems presented by dumps are fully addressed. In view of this, characterization of tailings dumps to determine the nature and severity of their problems and concerns is very important for their effective rehabilitation. In the light of this, most countries with many abandoned mines have developed and applied different tools in compiling inventories of abandoned mines and coming up with suitable means of rehabilitating them. Most of these tools or systems are developed based on existing information about the general characteristics of abandoned mines in those countries or regions. Some of these tools were developed to make them easy to use, inclusive, and updatable. The method developed for prioritization of rehabilitation of abandoned mines in Manitoba Province of Canada is a perfect example of these efforts (Priscu *et al.,* 2018). However, the fact that these tools are developed based on site specific understanding of abandoned mines makes their application outside the context they were developed limited. The key factors contributing to the limited application of these tools or methods were identified and discussed by Kubit *et al.* (2015). Such factors include the fact that these tools lack model calibration and transparency, some important parameters and reclamation methods are not considered, and that they are mostly data demanding and time consuming.

The method developed and used in this study, is so far the first to combine the potential of tailings dumps to pollute the environment with their impacts on the aesthetic appearance of the landscape in prioritizing the dumps for rehabilitation. It is important to indicate here that the method that prioritizes the rehabilitation of abandoned tailings dumps based on their potential to pollute the environment was first developed and applied by Arranz-Gonzalez *et al.* (2016) in sulfide tailings dumps of Mazarron in Spain. Like the tool developed by Arranz-Gonzalez *et al.* (2016), the tool reported in this work used the total metal contents of tailings dumps to establish their potential to pollute the environment. It is worth noting that in this study the index of contamination determined for all the tailings dumps in the Giyani and Musina areas was greater than 1. This gave an indication that the dumps were all contaminated by toxic metals. It is important to indicate that the index of contamination determined in this study was not only used to establish if the tailings contained pollutants or not; but it also established which tailings dump is more contaminated than the other. The reason being that mine tailings are generally characterized by high concentration of toxic metals than most natural soils and therefore, are expected to be somehow contaminated (Bhattacharya *et al.,* 2006). In addition to this, it is important to note that the actual availability of the metals in tailings to the environment largely depends on the chemical conditions of the environment where the tailings material get to be finally deposited by erosion processes (Arranz-Gonzalez *et al.,* 2016).

The use of the impact of abandoned mine sites on the appearance of the landscape to set priority of their rehabilitation was attempted by authors such as Mavrommmats and Menegake (2017) while authors like Rodrignez *et al.* (2011); Dentoni *et al.* (2006); Dentoni and Massacci (2013) used landscape and visual impact techniques to qualify the problems of abandoned/historic mining sites. Incorporation of landscape and visual impact into the method used in this work allowed that important site-specific issues that have direct impact on socio-economic development of abandoned mines on host-communities to be considered in the process of setting priority for their rehabilitation. For example, Dentoni and Massacci (2013) mentioned that alteration of natural landscape by mining can produce adverse negative reaction to potential observes and can significantly compromise potential development of abandoned mine host communities. Moreover, this factor was found to be a dominant influence in the determination of the rehabilitation priority scores in varying conditions of abandoned tailings dumps (*i.e.* including sites where tailings dumps of similar chemical and physical properties are to be rehabilitated).

One of the essential and unique features of the rehabilitation prioritization tool developed in this study is the aspect of the technique for identifying the most preferred rehabilitation strategy or a combination of rehabilitation options. This was identified by Kubit *et al.* (2015) as one of the most important elements of a sound mine site rehabilitation plan but a deficiency in most of the existing ranking systems. The guidance provided by the tool on rehabilitation strategies take into consideration the fact that there is no single panacea for addressing the problems of abandoned mine tailings dumps. In this regard, this important element of the rehabilitation prioritization tool provides guidance that the rehabilitation of tailings dumps combine physical or engineering methods with some element or aspect of chemical and/or biological methods. These methods include but not limited to those presented in Table 4.9. The combination of rehabilitation methods recommended by the developed system is in line with the current trends in remediation of soils contaminated by mining. For example, depending on the level of contamination of soils, the chemical methods have been mostly applied in conjunction with biological methods (Ozkan and Ipekoglu, 2002; Festin *et al.,* 2018, Hamner *et al.,* 1999).

Table 4.9: Description of some of the methods and practices that can be adopted in the rehabilitation of tailings dumps (Festin *et al.,* 2018; Vieire and Stefenon, 2017).

Methods	Practices	Description of the purpose and application
Chemical	▪ Use of nanoparticles ▪ Adding of synthetic chelates ▪ Adding of fertilizer ▪ Application of lime	▪ Improve soil physical and chemical properties, enhance soil fertility, stabilize soil contaminates or reduce soil erosion. ▪ Increasing substrate pH. ▪ Enhancing nutrition and plant growth. ▪ Improving heavy metal solubility and bioavailability. ▪ They are temporal stabilization techniques that are often used before revegetation ▪ They need constant monitoring
Biological	▪ Phytostabilization ▪ Biomineralization ▪ Hyperaccumulation ▪ Dendroremediation ▪ Cyanoremediation ▪ Biomineralization ▪ Genoremediation ▪ Rhizoremediation ▪ Biostimulation ▪ Mycoremediation ▪ Biosorption	▪ Modifying heavy metals bioavailability in soil thus increasing plant growth. ▪ Uptake and translocation of heavy metals ▪ Immobilization of heavy metals through soil amendment and planting of fast-growing species. ▪ Choosing an appropriate technique might require detailed characterization of the problem.
Physical	▪ Retaining wall ▪ Loose rock or stone check dam ▪ Pole or log check dam ▪ Gabions or wire-bound loose stone or rock check dam ▪ Rock gabions ▪ Riprap or stone terrace ▪ Bench terraces ▪ Mulch spreading ▪ Topsoil cover ▪ Contouring	▪ Recreating the desired landform, ▪ Reducing erosion and surface runoff ▪ Improving the physico-chemical quality of substrate for revegetation ▪ They mostly do not fully address the problem of pollution of water bodies because of the continuous leaching of toxic/heavy metals ▪ Their application is mostly limited by availability of appropriate material to be used and the cost of transporting such material from borrowed sites.

4.11. Summary of the Chapter

One of the important features of abandoned mine sites are large volumes of mine waste such as tailings dumps, spoil and waste rock dumps. These dumps (especial tailings) pose different types of physical and environmental hazards as well as socio-economic concerns to the communities around the abandoned mines. In view of this, the rehabilitation of abandoned mine tailings dumps is one of the most important aspect of rehabilitation of abandoned mines. The aim of the work presented in this chapter was to develop a method for ranking the abandoned mine tailings dumps for rehabilitation and selection of strategies for their rehabilitation. The development of such method took into consideration issues such as the potential of the dumps to contaminate the surrounding environment, their susceptibility of erosion which determines their dispersion to the surrounding areas, and their landscape and visual impact. The functionality of the developed method was applied to the situation of abandoned mine tailings dumps in the areas of Giyani and Musina, Limpopo Province of South Africa.

The results of using the developed method in the selection of abandoned mine tailings dumps in the study area showed that all the tailings dumps require moderate rehabilitation attention and efforts. It also emerged that rehabilitation should be conducted in the decreasing order of Fumani Gold Mine Tailings > Klein Letaba Gold Mine Tailings > Nyala Magnesite Mine Tailings (A) > Nyala Magnesite Mine Tailings (B) > Louis Moore Gold Mine Tailings > Mesina Copper Mine Tailings. The study also showed that the efforts of rehabilitation of the abandoned tailings dumps in the study area mostly involve moderate use of physical and biological methods with relative less use of chemical techniques. The method of ranking the abandoned mine tailings for rehabilitation developed and discussed in this chapter (Chapter Five) was incorporated into the expert system for ranking of tailings dumps for rehabilitation presented in the next chapter (Chapter Six).

CHAPTER FIVE

REHABILITATION OF SURFACE EXCAVATIONS AND MINE INFRASTRUCTURE

Regardless of the mining method used, abandoned mine sites have different derelict infrastructure which present different forms of hazards to people, animals and environment. In the same way, abandoned surface excavations found at some of these mines' present serious public safety threats and environmental problems. This chapter discusses problems of different surface mine infrastructure and excavations. It also describes the technique used to find appropriate strategies for dealing with the problems of these abandoned mine features. The technique used in conducting this study involved SWOT (Strength, Weaknesses, Opportunities, and Threats) analysis to evaluate the appropriateness of different strategies of addressing the problems of these mine features. The most suitable strategies for addressing the problems of the abandoned mine surface infrastructure and excavations were identified by applying the results of Quantitative Strategic Planning Matrix (QSPM). The rehabilitation options of the features were ranked according to their identified internal (strength and weakness) and external (opportunities and threats) factors. The abandoned mine infrastructure and open excavations in Giyani and Musina areas were used as a case study for this part of the research. The following sections provide background to the study, objectives of the research, the methodological approach employed to meet the specific objectives, results and discussion, and concluding remarks of the work presented in this chapter.

5.1. Background of the Study

Abandoned mine features such as dilapidated mineral processing infrastructure, mine houses (including hostels and offices) are expected to be demolished or removed to make the land they occupy available for other post mining uses. The aim of the mine rehabilitation programme in this case is to make the land occupied by abandoned mine infrastructure safe and usable and to control access to the abandoned mine features (MMSD, 2002). However, according to Limpitlaw and Briel (2014), abandoned mine infrastructures can be maintained or repurposed to maximize their value, so that they contribute to the post-mining economy of the region of abandoned mines.

In the same way, in different countries surface excavations have been repurposed for different uses which include development of pit-lake which turn to be the major driver of the local economy after the closure of the mine. According to McCullough *et al.* (2020), pit lakes have been used for a range of uses which includes fishery, recreation, wildlife conservation, water source or storage area, and treatment of different waste. Maintenance and reuse of abandoned mine infrastructure and excavations can also assist in preserving the important elements of the culture of mining in the regions of historic mining (Wirth *et al.,* 2012). The aim of this chapter is to find the best and easy way of making-decision on actions to be taken in dealing with the problems of abandoned surface mine infrastructure and excavations. The methodology applied in this research took into consideration the fact that addressing the problems of these abandoned mine features at times require that innovative approaches are considered rather than just removal or demolishing of the structures and backfilling of the excavations. Based on this, it is important that alternative uses of the mine features are found and used as a way of addressing their concerns in a way that enhance the socio-economic status of the abandoned mines host-communities. The approach used in identifying appropriate strategies for dealing with the problems of abandoned mine infrastructure and surface excavations encourages that at least three alternative uses of the features are identified and evaluated or ranked with the possible traditional rehabilitation strategies for the features.

5.1.1. Objectives of the study

The main aim of this part of the research was to find the most appropriate ways of dealing with the problems of defunct surface infrastructure and excavations at selected derelict mine sites.

The specific objectives were:

- To conduct field characterization of surface infrastructure and excavations at the selected abandoned mine sites to establish the nature of the problems they present

- To come up with the most suitable strategies for addressing the problems of these abandoned surface infrastructure and excavations.

5.2. Methodology of the Study

The method used to find appropriate strategies or options for dealing with the issues of abandoned mine infrastructure and surface excavations combined the use of conventional SWOT analysis with Quantitative Strategic Planning Matrix (QSPM). SWOT analysis is generally based on qualitative analysis without any means of analytically quantitating the intensity of the SWOT factors (Shinno *et al.,* 2006). As a result, in cases where the determination of the importance of the SWOT factors is necessary, this technique has been used with relevant Multi Criteria Decision-Making methods (MCDM) such as the Analytical Network Process (ANP), Analytic Hierarchy Process (AHP) and the TOPSIS (Azimi *et al.,* 2011; Shinno *et al.,* 2006; Yogi *et al.,* 2017; Tahernejad *et al.,* 2012).

5.2.1. The use of SWOT analysis and QSPM

The work of trying to find the most appropriate strategies or approaches for dealing with the problems of abandoned mine infrastructure and surface excavations started with field characterization of the abandoned mine features. Such characterization was accomplished by conducting a detailed field description of the abandoned mine features. The purpose of this description was to find the basis for identification of possible rehabilitation strategies or alternative uses of abandoned mine infrastructure and surface excavations. It involved the documentation of the current state and uses of the abandoned mine features coupled with the nature of hazards presented by the features. For each identified option for dealing with the problems of the abandoned mine features, the SWOT analysis was performed by following the steps as shown in *Figure 5.1a*. The SWOT analysis takes into consideration important issues regarding the use of the best practicable strategies to address the identified problems of the abandoned mine features. In general, this process is the most important and first step of the strategic planning process in any business or project (Tahernejad *et al.,* 2012; Houben *et al.,* 2009).

The identified SWOT factors of the rehabilitation strategies or alternative uses options of the abandoned mine features were quantitatively assessed by applying the Quantitative Strategic Planning Matrix technique. This process involved assigning weight (ranging from 0.00 to 1.00) to individual SWOT factors in the manner that demonstrate the significance of each factor over the other. On this, the weight of 0 meant the factor was not relevant while 1 indicated that it was very important. The next step on this was rating the SWOT factors by assigning attractiveness scores to the factors. The descriptions of these scores are depicted in *Table 5.1*. The weight and attractiveness score of individual factors were multiplied to get the value known as the total attractiveness score of given factors. The total attractiveness scores were summed up to determine the total sum attractiveness scores which is the value representing the relative attractiveness of the option for addressing the problems of a particular abandoned mine feature. The flowchart of this procedure in shown in *Figure 5.1b*.

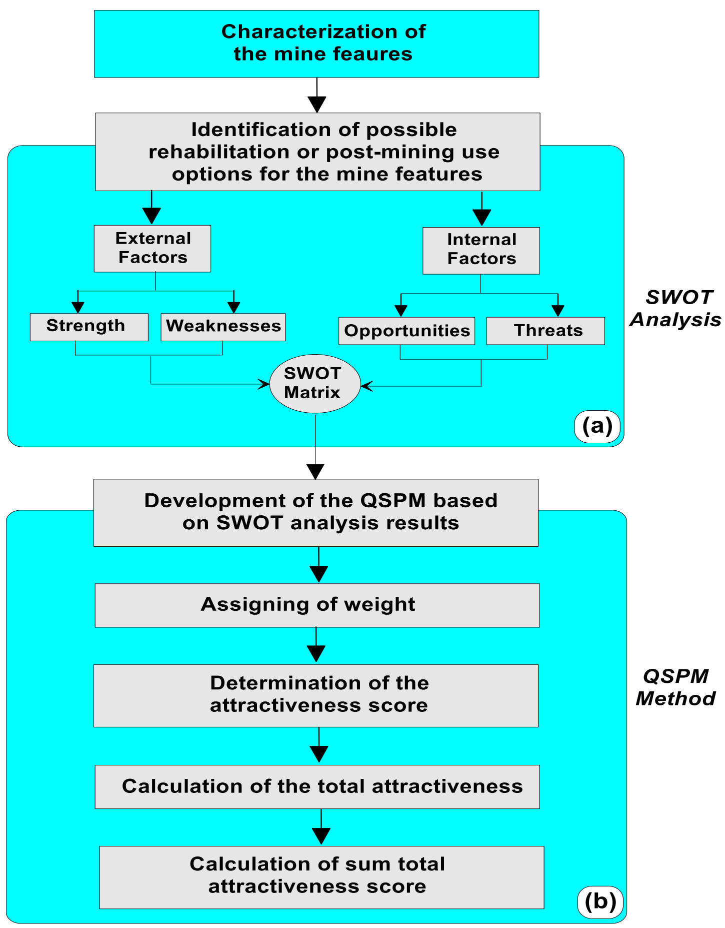


Figure 5.1: Flow of the methodology used to find suitable strategies for dealing with the problems of abandoned surface mine excavations.

Table 5.1: Criteria for scoring the attractiveness of the SWOT factors (David *et al.,* 2009).

Attractiveness score	Description of the score
1	Not attractive or with major weaknesses
2	Somewhat attractive or with minor weaknesses
3	Reasonably attractive or with minor strength
4	Highly attractive or with major strength

5.3. Surface Infrastructure and Excavations at Abandoned Mine Sites

The abandoned mine sites usually have various structures which among others may include a wide range of old and dilapidated buildings, mineral processing structures or areas, water and diesel tanks, paved grounds and foundations of collapsed buildings. The section below is earmarked for description of the state, hazards and the current uses of the surface mine infrastructure at selected abandoned mines in the Giyani and Musina areas of Limpopo Province of South Africa. These mines are: Mesina, Altonvilla, Campbell, Louis Moore, Klein Letaba, Frankie, New Union (also known as Golden Osprey), and Nyala. These mines have different types of tall structures (*i.e.,* silos and ore-bins), dilapidated buildings, cement floors, water reservoirs, mounting stands, ore bankers, old ball mills, and other debris of steel materials. The distribution of these mine features around the studied abandoned mines landscapes is shown in the Figures presented as *Appendix-D*.

The surface excavations were observed only in two abandoned mines landscapes (*viz*, Nyala and Frankie Mines) but their surface area is far greater than most of the mine features in the study area. The mining of magnesite at Nyala Mine left an extensive landscape (≈19.51ha) altered by unrehabilitated surface excavations. The other mine features which occupy a relatively large area were old and dilapidated buildings (≈1.56ha) followed by silos and water reservoirs (See *Table 5.2*).

The old mine machinery and concrete mounting stands occupied the least area of abandoned mines in the study area. Regardless of the size of these features, they turn to present a considerable amount of health and safety hazards and they also affect the visual appearance of the landscape in the manner that decreases the quality of the landscape (Favas *et al.,* 2018). However, according to Bini *et al.* (2017), abandoned mine infrastructure such as dilapidated buildings and areas of mineral processing plants can be developed as mine-archeological parks, recreational tours and museums. Although this is the case, it is important to note that the reuse of any abandoned mine feature for whatever purpose depends largely on their safety status.

Table 5.2: The distribution and sizes of land occupied by abandoned surface infrastructure and excavations

Mine Site	**Areas occupied by the mine features (ha)**				
	Surface Excavation	**Silos or Ore Bins**	**Dilapidated Buildings**	**Old Machinery and stands**	**Water Reservoirs**
Louis Moore	-	0.02	0.39	-	0.04
Klein Letaba	-	0.04	0.34	0.04	0.07
Frankie	1.84	-	0.03	-	-
Nyala	19.51	0.00	-	-	-
*New Union	-	-	-	-	-
Campbell	-	0.004	-	-	0.03
Artonvilla	-	0.003	0.80	-	0.05
*Mesina	-	-	-	-	-
Total area (ha)	**21.35**	**0.067**	**1.56**	**0.04**	**0.19**

Note: * the mapping of the mine features was not conducted.

5.4. Problems and Concerns of Abandoned Mine Features

Beside the different types of excavations and large volumes of mine waste, abandoned mines are also found with different types of disused surface infrastructure. These structures present various forms and extents of public health and safety hazards as well as environmental issues. The section below presents a comprehensive description of abandoned mine features and their associated hazards as identified in the study area. These features include tall cylindrical structures (*i.e.*, silos, agitation tanks, and ore-bins), old equipment or machinery, dilapidated buildings and other concrete structures such as paved floors, water reservoirs, and mounting stands. The sites are also characterized by different types of litter.

5.4.1. Abandoned tall cylindrical structures

The physical stability of tall structures such as silos at abandoned mine sites is one of the key concerns as their collapse can result to injuries or death of people and animals that might be in the vicinity. The stability of these structures to some extent depends on the durability of the material used to construct them. For example, steel and/or reinforced concrete are often used to build silos and ore-bins and these are normally constructed on met foundation (Dogangun *et al.*, 2009). In the study area, these structures have been built using reinforced concrete, steel, and cement blocks (*i.e.* plastered and protected with zinc or un-plastered) as shown in *Figure 5.2a-d*.

Figure 5.2: An illustration of the abandoned tall cylindrical structures in the study area. (a) reinforced concrete silo, (b) steel made agitation tanks, (c) cement bricks made ore-bin, and (d) zinc protected plastered cement bricks silos.

The abandoned mine structures normally become unstable and susceptible to collapse due to structural weakening caused by weathering due to long period of lack of use. Their height and cylindrical shape design are mostly responsible for their catastrophic failure or collapse that can result to death of people and animals (Dogangun *et al.,* 2009).

During the field description of the abandoned mine features, the silos built from reinforced concrete around Altonvilla and Mesina mines appeared to be competent and stable than those built of cement blocks which are plastered and protected with zinc. The zinc protection used in the plastered cement blocks silos was found to be extremely corroded thus exposing the plaster and cement bricks to weathering forces. This has a potential of weakening the structural integrity of these silos. On the other hand, the ore-bins constructed from cement blocks (mostly un-plastered) were found to be having serious structural weakening. These ore-bins were found at Louis Moore Mine with well-developed fissures that serve as zones of weaknesses during the collapse of the structures (see *Figure 5.3a*).

The other factor identified to be compromising the structural integrity of the ore-bins in the study area was the fact that artisanal gold miners (locally referred to as Zama-Zamas) have extensively dug shallow excavations below the foundations of the structures thus leaving them not well supported and subjecting them to potential failure. The same practice was observed at Campbell Mine where aggregate production from crashing of the waste rocks left by copper mining in the area have led to excessive digging around the foundation of the ore-bin (see *Figure 5.3b* and *c*). Because the production of aggregate around the abandoned Campbell Mine is continuing, the collapse of this ore-bin might even lead to damage of equipment and loss of life of the miners that work around this bin. In one occasion, it was observed that the Zama-Zamas at Louis Moore Mine have made excavations at the bottom of the ore-bins (see *Figure 5.3d*) as they were looking for the remnants of unprocessed ore left in the bin during the abandonment of the mine.

Figure 5.3: An illustration of the state of the unstable abandoned cylindrical structures in the study area.

The steel made agitation tanks found at Louis Moore Mine were observed to be comparatively structurally stable than silos made of reinforced concrete. This was the case although the foundations of tanks were also found altered by artisanal mining excavations. According to Maynard (2013), the structural integrity of the silos made of steel are normally affected by the processes of corrosion of steel. However, in the study area these structures were found less affected by corrosion. Consequently, they appeared relatively more stable than the ore-bins and silos made of cement blocks (*i.e.*, plastered and zinc protected or plastered and without zinc protection). It is important to indicate that the continuing artisanal gold mining activities around the agitation tanks and other mineral processing structures may increase the risks of the miners getting exposed to undefined health hazardous chemicals used in gold processing. This is because no efforts were made to free such areas from the hazardous chemicals during the abandonment of the mines in the study area.

In addition, these structures are mostly not less than 10m high and because of this they are normally one of the features of abandoned mines that can be visible to people from a very long distance. In the study area, the silos, old ore-bins, and agitation tanks appeared with different shades of gray colours above the green vegetation growing around abandoned mine terrain. The appearance of these features or structures on the landscape have varying effect to the aesthetic beauty of the landscape. The level of visual receptor sensitivity to the structures on the landscape can create varying degree of negative perception of the areas of abandoned mines. This worsens when the site is viewed by people who are from outside the mine host-community. Based on such perception the development and economic potential of the tourism industry in the area or region can be extremely affected. In view of this, analysis was conducted using the standard GLVIA3 (Guidelines for Landscape and Visual Impact Assessment) to ascertain the visual receptor sensitivity of the tall cylindrical structures in the study area.

The results of this analysis showed that about 44.4% of tall cylindrical structures in the area had visual receptor sensitivity ranging from Low, Medium and High (L-M-H). The structures that had Medium to High (M-H) and those that had Low to Medium visual receptor sensitivity results were respectively 3 (≈16.7%) (see *Table 5.3* and *Figure 5.4*). Comparatively, it was only 2 (≈11.1%) of the structures that were found with "No" visual receptor sensitivity. This is because these structures were generally not visible in any part of the nearby communities. The structures that had only High (H) and only Medium (M) visual receptor sensitivity were respectively 1 (≈5.6%) as depicted in *Table 5.3* and shown *Figure 5.4.*

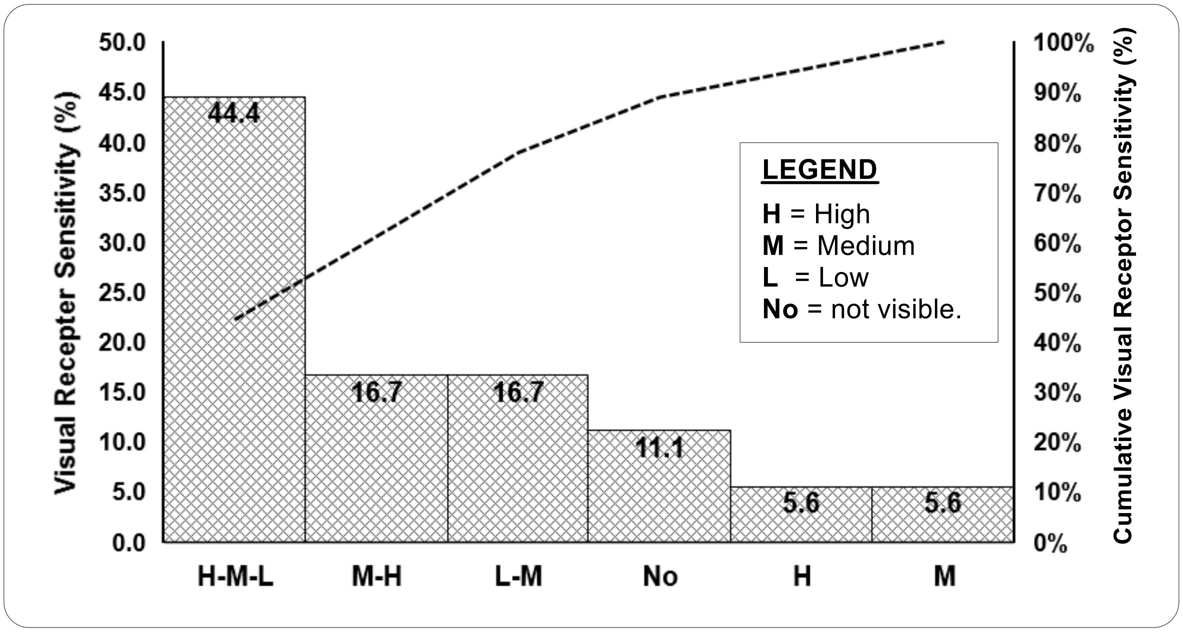


Figure 5.4: Variation of visual receptor sensitivity of high cylindrical structures.

Table 5.3: Visual receptor sensitivity to the tall abandoned mine structures.

Mine Site	Structure ID	High	Moderate	Low	Sensitivity	Comment
Klein Letaba	KL-1	▲	□	-	M-H	The abandoned mine features can be seen from different parts of Ka-Mupuva Village and other major and minor access roads
	KL-2	▲	□	-	M-H	
	KL-3	▲	□	-	M-H	
	KL-4	-	-	-	O	
	KL-5	▲	-	-	H	
Louis Moore	LM-1	▲	□	◙	H-M-L	The different structures of can be seen from Mavalani Village and other major and minor access roads
	LM-2	▲	□	◙	H-M-L	
	LM-3	▲	□	◙	H-M-L	
	LM-4	▲	□	◙	H-M-L	
	LM-5	-	□	-	M	
New Union	NU-1	-	-	-	O	The feature is not visible
Altonvilla	AM-1	-	□	◙	L-M	The features can be seen from the road to Musina Town
	AM-2	-	□	◙	L-M	
Mesina	MM-1	▲	□	◙	H-M-L	The mine features are visible from almost all parts of Musina Town and surrounding settlements.
	MM-2	▲	□	◙	H-M-L	
	MM-3	▲	□	◙	H-M-L	
	MM-4	▲	□	◙	H-M-L	
Campbell	CM-1	-	□	◙	L-M	The mine was visible from the aggregate quarry operating in the area and from the nearby access road.

Note: ▲ High visual receptor sensitivity, □ Moderate visual receptor sensitivity, and ◙ Low visual receptor sensitivity

The visual receptor's sensitivity of abandoned mine features in the study area and elsewhere in South Africa is linked to the fact that these mines are mostly found near settlement areas. Thus, tall structures like silos and others can be generally viewed from different parts of the abandoned mines host-communities. The visual receptor sensitivity to the abandoned mine features can serve as initial bases or justification for the need for their removal, maintenance, and/or reconditioning to ensure that the mine features blend well with the developments of the host-communities. This is important because the landscape and visual impact of mining are now becoming an important part of mine closure and can the considered at any stage of mine closure planning (Higson *et al.*, 2018).

5.4.2. Abandoned mine machinery

Abandoned mine landscapes are sometimes found with different types of old and unwanted equipment or machinery. These features turn to present different forms of physical hazards on abandoned mines landscape. They also have effects on the natural appearance of the landscape. In the study area, about four different types of abandoned mine machinery were identified, namely; (*i*) two ball mill found at Klein Letaba Mine, (*ii*) ventilation shaft structure (i.e. the ventilation ducting) identified at Frankie Mine, (*iii*) two hoist winch drums with cables found at New Union Mine, and (*iv*) an ore banker found at Nyala Mine.

The ball mills were found mounted on concrete stands and the average height of these mills was approximately 3m above the surface (see *Figure 5.5a*). Because the structural integrity of the mounting stands and the ball mill structures weaken overtime, they present safety hazard to people and animals. Because the site is not fenced, there were many access routes to the ball mills at Klein Letaba Mine. Thus, people and animals from the nearby communities easily gain access to these ball mills. In addition, adventurous people (especially children from the community) may be tempted to climb on these structures. Domestic animals like goats are also likely to use these ball mills to hide from bad weather conditions (*e.g.* during extremely hot or rainy days). The ball mills can fall on such animals or people climbing on them can fall and get injured or be cut by sharp ages of the structure.

The problems highlighted above were also encountered with abandoned mine machinery like the ventilation shaft structure, hoist winch drums with cables and ore-bunker shown in *Figure 5.5b-d*. The ore-bunker found at Nyala Mine was about 7.5m high and it was a steel constructed frame and was lined with treated timber (see Figure 5.5*b*). Its feeder box was observed to be gradually moving downwards which present a safety threat to the children from Zwigodini Village who play under this structure (Mhlongo *et al.,* 2013). Falling of people from the top part of this structure as well as loose rocks falling from the sides of this structure were identified as some of the safety threats of this feature.

The ventilation structure at Frankie Mine appeared to be firm on the ground and it is about 7m high. It presents safety risks to people because they may be tempted to climb on the structure this may result to them falling. The rusty wire-mesh used to reduce the sizes of the opening of the ventilation can lead to body cuts and injuries to people climbing the structure. In the case of the hoist winch drums, the broken rusty small wires that make-up the cables rapped around the drums present risks of body piercing to any person who carelessly touch these wires. Although the drums appeared stable, their stand-up position make them to suffer potential failure (especially when people continually play around or climb on these structures) (see *Figure 5.5d*).

Figure 5.5: An illustration of abandoned mine machinery found in different parts of the study area. (a) is an old ball mill at Klein Letaba Mine, (b) is ventilation structure at Frankie Mine, (c) is are hoist winch drums, and (d) is the ore-bunker at Nyala Mine.

5.4.3. Dilapidated buildings and other concrete structures

Old dilapidated buildings and other concrete structures such as water reservoirs and mounting stands are among the features that are normally found scattered on abandoned mine landscapes. In the study area, many dilapidated mine buildings (*i.e.* 29 or ≈34% of the total) were recorded at New Union Mine while abandoned water reservoirs (*i.e.* 8 or ≈36%) and concrete mounting stands (*i.e.* 9≈60%) were found at abandoned Mesina Mine. It can be seen in *Figure 5.7a* that the landscapes of Klein Letaba and Mesina mines had almost equal proportion of old buildings, water reservoirs and mounting stands. The reason for this can be the fact these two mines had lager abandoned areas of mineral processing which are mostly dominated by mounting stands of varying height and water storage areas or reservoirs that are generally about 2m high and 8m diameter. The percent composition of old mine buildings, water reservoirs and stands in the abandoned mine sites studied in this research can be seen in *Figure 5.6b*, *c* and *d*. None of these features was found at the abandoned Nyala Magnesite Mine.

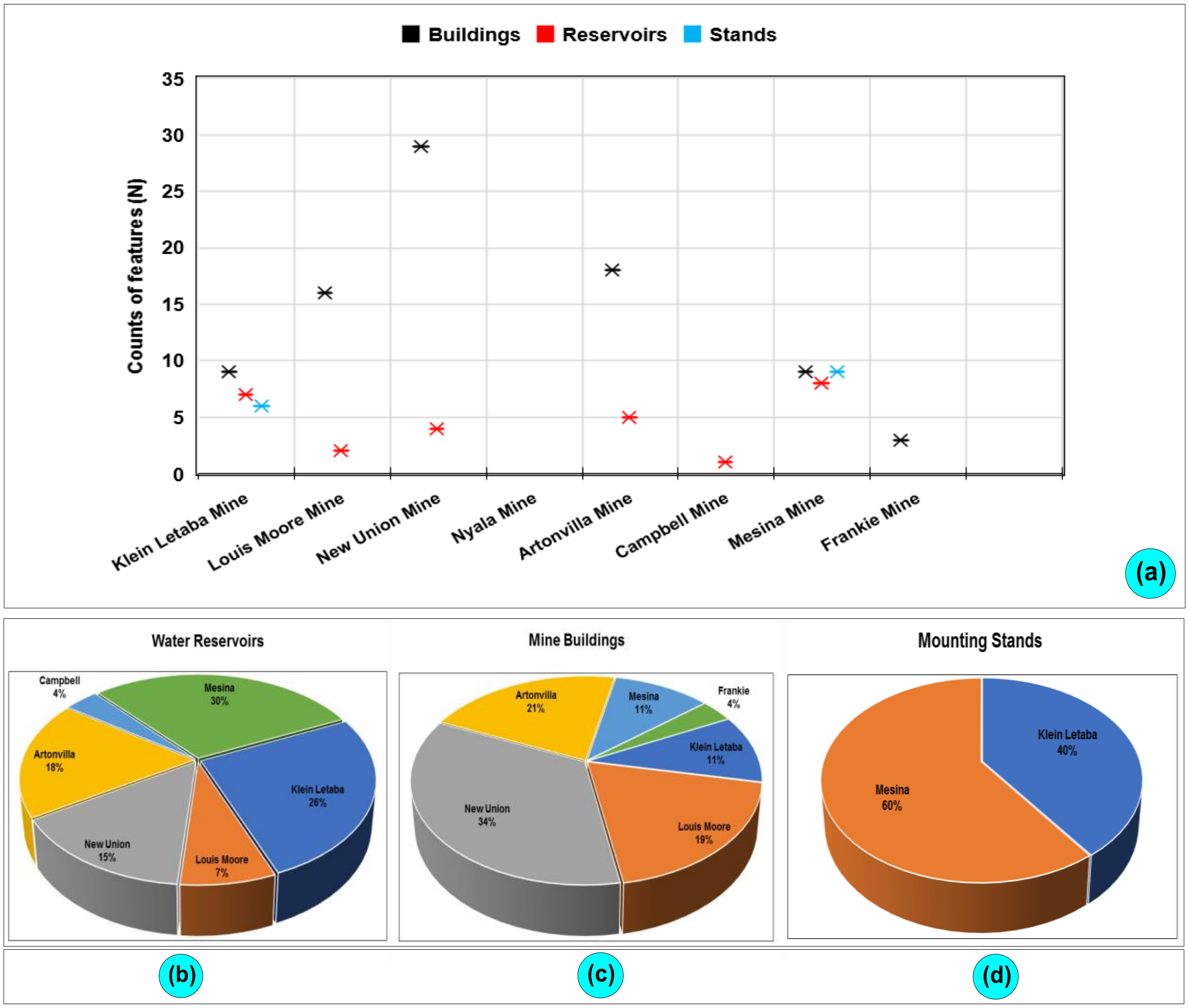


Figure 5.6: Comparison of abandoned buildings, water reservoirs and mounting stands found at abandoned mine sites in the study area.

Most abandoned mine buildings in the study area were found to be at a deplorable state with no windows, doors and roof cover. Some of these buildings were found with some of their walls fallen while others had massive cracks. In some cases, cracks on the buildings were observed to have propagated through the concrete floors and foundations. These issues extensively compromised the usability of such buildings for other purposes and rendered them serious safety threats around the abandoned mine sites in the study area. The instability of abandoned mine buildings of the abandoned gold mines in the Giyani area was observed to have been to some extent triggered by artisanal gold mining activities that are ongoing around these sites. This is because artisanal mining in the Giyani Greenstone Belt has always focused on digging gravel material around and underneath the foundations and floors of old buildings and plants previously used for mineral processing. This practice therefore disturbs the foundations of the buildings and affects the structures of the disused mineral processing plant. An example of excavations in an abandoned mine building floors at Louis Moore Mine is shown in *Figure 5.7a*.

Some of the collapsed buildings pose serious safety and environmental problems. This is because some of the walls of abandoned buildings had collapsed in a way that make the area unsafe to people who walk around the site. The concrete rubbles of the collapsed walls were found to be constraint to vegetation growth and other land uses. The presence of excavations of the conventional septic tanks around the areas of abandoned mines landscape that are occupied by dilapidated buildings were found to be presenting safety hazards to people and animals who walk around the abandoned mine sites. This is because accidentally walking into these excavations can result to serious physical body injuries that may include leg fractures. An example of collapsed abandoned mine buildings and pits excavated around septic tanks are shown in *Figure 5.7b* and *c* respectively.

In the situation of abandoned gold mine sites in the Giyani area, the old buildings showed evidence that they were roofed with asbestos roof sheets which when the buildings collapsed were broken into small pieces that are now scattered all around the abandoned mine sites. Based on this, the small pieces of broken asbestos roof sheets can be expected to be releasing some amount of asbestos fiber to the environment. An illustration of the broken asbestos tiles in the study area can be seen in *Figure 5.7d*. This is likely to expose the members of the community to medium risks which are mostly associated with unsafe removal of asbestos during the house renovations (Environmental Health Standing Committee, 2013). Due to the seriousness of problems associated with exposure to asbestos, careful cleaning of asbestos fiber at these sites should be given utmost consideration.

Although many old buildings at the abandoned mine sites are at deplorable state and appear unusable, a large part of the old mineworker's hostel in Artonvilla copper mine was found to be at a relatively stable state and with roof and window frames (see *Figure 5.7e*). The grounds around the hostels are occasionally used by the members of the South African Defense Force (SADAF) as a camping site. This activity around these buildings have protected the hostels from vandalism by the nearby communities. However, it is important to note that the fact that these buildings have been not actively used for many years, their immediate occupation can present a safety hazard.

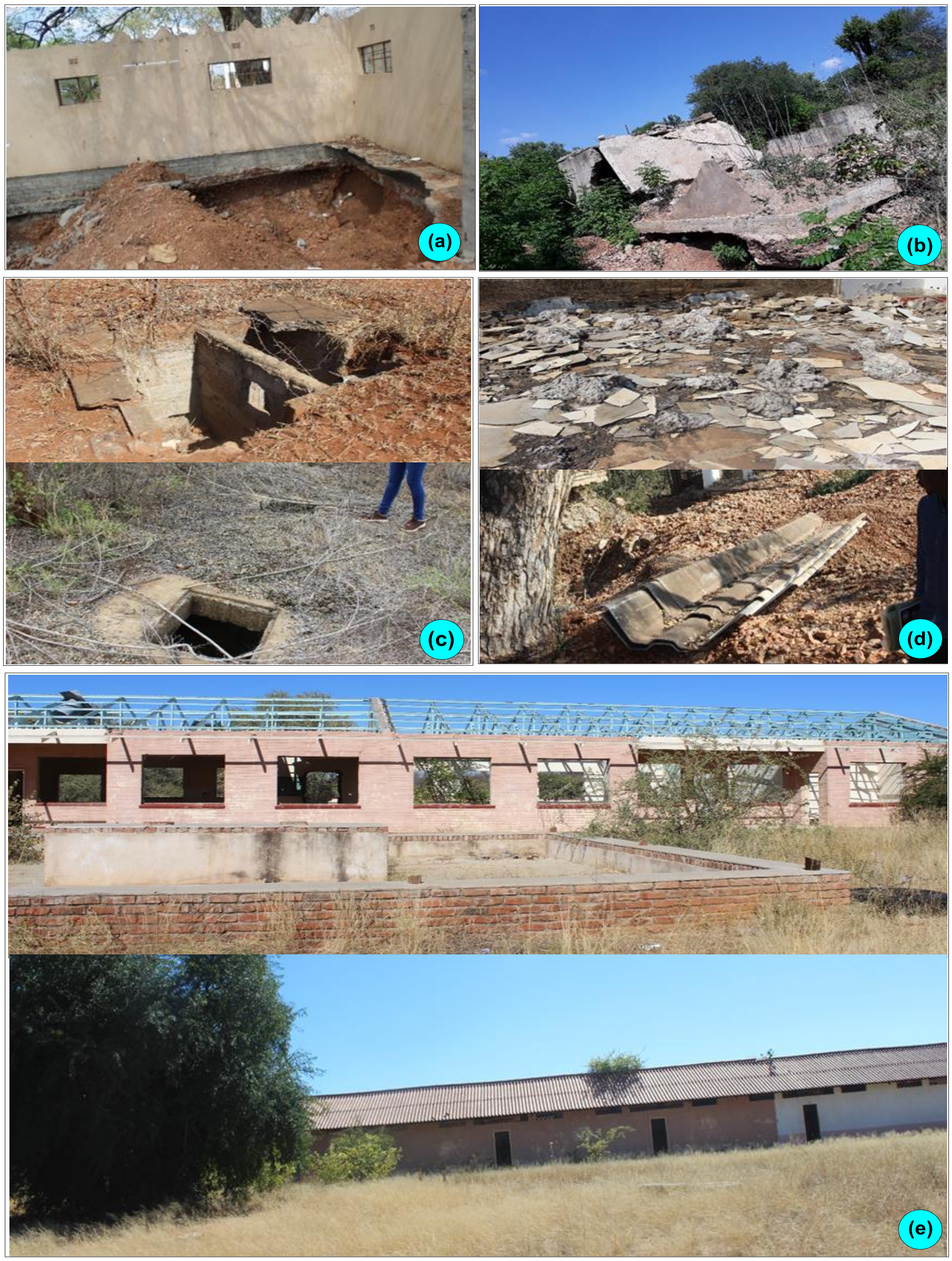


Figure 5.7: An illustration of the state of the abandoned mine buildings.

5.4.4. Abandoned surface excavations

Surface excavations or pits are common features at abandoned surface mines. These excavations turn to occupy a large portion of land that can be used by the host communities for other purposes. They present safety risks due to their high slope angles, instability of the walls, and the visibility of the highwalls. In the study area, surface excavations characterized the landscapes of two mine sites which are Nyala Mine and Frankie Gold Mine. The number of surface excavations found/identified at abandoned Nyala Magnesite Mine and Frankie Mine were five and two respectively. The general properties of these excavations are described in *Table 5.4*. Some of these excavations usually get filled with water during rainy days or seasons while others turn to contain water throughout all seasons.

The deepest excavation at Nyala Mine was Pit-I (≈44m maximum depth) and at Frankie Mine it was Pit-A which was approximately 30m deep. The fact that these pits also contain water throughout the year present secondary public health and safety risks which include drowning, consumption and having dermal contact with the contaminated mine water in the pits. For example, the water in Pit-I of the Nyala Mine is mostly used by domestic animals as drinking water and the public as water for washing clothes, swimming and domestic fishing activities (Mhlongo and Dacosta, 2015). On the other hand, the water in Pit-A of Frankie Mine is currently not used by the community. The reason behands this, is the fact that the mine and the nearby community are both found close to the Klein Letaba River which is the main source of water used by the community for different purposes. Therefore, this make it easier for the community to avoid using the water in the unsafe abandoned surface mine excavations. However, it is important to indicate that domestic animals that graze around the abandoned mine site may be tempted to drink the water in the pit. In addition to the risk of drinking the water in the abandoned pits, the animals who go to abandoned pits at Nyala Mine to drink water in the pits gets trapped in the mud at the pit floor and subsequently die (see *Figure 5.8a*). Although no death of animals has been reported due to animals becoming stacked in the mud at the pit floor at Frankie Mine, animals falling into the water in this pit can result to death with no possibilities of recovery of the body. This is because the bottom part of this pit is connected to the underground open stope which is filled with groundwater (see *Figure 5.8b*).

Table 5.4: General characteristics of the abandoned surface excavations.

Mine site	Pit ID	Ava. Highwall Height (m)	Ava. Highwall angle (°)	Total Highwall length (m)	Area of the pit (m²)	Frequency of flooding
Nyala	Pit-I	13-44	20-87	440.1	90,476.5	●
	Pit-II	15-20	83- >90	200.4	16,933.8	◐
	Pit-III	04-23	74- >90	314.6	30,010.1	◐
	Pit-IV	16-18	65-86	126.8	51,818.5	◐
	Pit-V	08-13	78-86	116.8	5,824.4	◐
Frankie	Pit-A	20-30	70-90	487.8	14,199.6	●
	Pit-B	05-15	60-90	172.4	4,191.0	◐

***Note:** ◐ indicate that the pit gets flooded only during rainy days or seasons while ● indicate that the pits is flooded throughout the year.

Figure 5.8: An illustration of skeletons of animals killed by being trapped in mud (a) and the connection of the surface excavation with the underground open stope filled with water.

The other obvious risk of abandoned surface excavations is falling from deep highwalls which might result to serious body injury or death. The injuries can also be caused by the walls collapsing on the victim who might be within the pit during the incident. Some sections of the highwalls of Pit-A of Frankie Mine are in locations on the landscape that are not easily visible to people who drive through the nearby access roads and others are camouflaged by vegetation which make them not easily recognizable. These were identified to be some of the major factors that can lead to people and animal falling from the highwalls of the abandoned surface mine excavations in the study area and elsewhere were similar situation exists. The approximate location and view of the highwalls section of the excavation from the access road at Frankie Mine is shown in *Figure 5.9a*. These issues were also the concerns with most of the pits at Nyala Mine. These pits were all found open to the public and domestic animals from the nearby communities are mostly found grazing at these abandoned mining sites.

In addition, the risks of falling from the highwalls or being injured by the rock falls from highwalls was identified as a common problem associated with all abandoned surface excavations in the study area. All excavations were found to be having highwalls which are noticeably high (mostly more than 5m high). This alone contributes to these walls being unstable. The other factor contributing to these walls being prone to collapse is the fact that the rock mass deteriorates with time and this generally makes it easy for rock falls to occur (van Rensburg and Melis, 2012). Some of these walls have slopes greater than 90° (see *Figure 5.9b*) while others had fissures because of the movement of the ground towards the excavation (Mhlongo *et al.,* 2015). The major concerns of this situation are the fact that both people and animals are likely to unknowingly be tempted to work above these highwalls or take refuge on their shadows thus being exposed to risks of being injured or killed by collapse of the highwalls. Generally, in operational mines no person is allowed to be at a distance less than 25% of the highwall height (Rupprecht, 2015). However, with unrestricted public access to abandoned surface excavation, its entirely impossible to control public exposure to dangerous highwalls of abandoned mine sites. This safety hazard of was identified as being common at all the abandoned surface mine excavations in the study area.

Figure 5.9: An illustration of unstable highwalls of the abandoned surface excavations.

5.4.5. Issues associated with mine debris and other unwanted materials

Mine debris and other unwanted materials are common features found on landscapes of abandoned mines and these present different environmental and physical hazards. For example, things like steel packs, cables, empty chemical containers and other loose steel objects were identified at different parts of the abandoned mine sites in the study area. An illustration of these materials found at the abandoned mine sites are shown in *Figure 5.10a-c.* The major concern of these undesirable objects was that they can result to cutting or piercing of the body of people who make physical contact with them. Consequently, their removal from the abandoned mine landscapes is always necessary and important. In addition, the empty containers of chemicals used in the processing of minerals at New Union Mine were identified as threat to the environment as well as the health of people and animals. This is because the remnants of the chemicals (sodium cyanide) can be released to the environment thus resulting to pollution of the environment. Chemicals such as cyanide can be poisonous to the wildlife and people (Donate *et al.,* 2007). The containers can be used by the members of the public for different purposes and this may expose them to health risks of cyanide poisoning.

Figure 5.10: Examples of some of the discarded items found at the abandoned mines sites.

5.4.6. Mounting stands and water reservoirs

The other features that are common at abandoned mine sites are stands which were mostly used to mount different structures and machineries. In the study area, these features were mostly identified around the areas of old mineral processing plant and are made of concrete. Such stands were designed to carry the weight of tanks with mineral processing chemical solutions. These features were found in two designs which can be seen in *Figure 5.11a* and *b*. The mounting stands found at Klein Letaba Mine were about 25cm thick, made of 5m diameter concrete slab, and supported by four small concrete pillars (see *Figure 5.11a*). They were of different heights; ranging from 1 to 3m above the surface. The presence of these structures on the landscape turns to affect the aesthetic appearance of the landscape and it also hampers vegetation growth in the area. Moreover, the fact that overtime the competency of these structures weakens, they are likely to collapse and result to injury of people and animals who might be in the vicinity. The extent of physical body damage due to these structures is likely to depend on the weight and the falling height of the platform of the stands. This is because people and animals can be tempted to find refuge under these structures which may expose them to the risks of the structures falling on them.

The mounting stands at Mesina Mine were designed with solid support structures, subsequently they are expected to be more physically stable than the stands found at Klein Letaba Mine (see *Figure 5.11b*). The fact that they are supported by fully closed-up or solid structure eliminate possibilities of people and/or animals finding taking refuge under the stands and consequently being exposed to the risks of the structures falling on them. Although this is the case, most of the stands in Mesina Mine were found to be at deplorable state because the concrete used to construct these stands has been seriously affected by corrosion. This clearly is enough justification for the need for removal of these structures from the abandoned mine landscape.

The other structures which were found affecting the physical appearance of the abandoned mines landscapes were the old water reservoirs. These structures were commonly found around the defunct mineral processing plant as well as in the areas of old mine houses. These old water storage features are mostly without water or with very little water after rainy days.

This has directly eliminated the risk of people being tempted to swim in these reservoirs. In view of this, the old water reservoirs were in their current state identified to be without any obvious physical hazards. However, their presence at the mine site turn to affect the appearance of the natural landscape of the mine. Adding to this, is the fact that some of the water reservoirs had collapsed or deteriorated walls which make them to be not reusable without major makeovers. An example of the abandoned water reservoirs found in the study area can be seen in *Figure 5.11c*.

Figure 5.11: An illustration of the mounting stands and water reservoirs found at different parts of abandoned mine sites in the study area.

5.5. General problems of Surface Infrastructure and Excavations

The field description of the state as well as the hazards of surface infrastructure and excavations of abandoned mine sites in the study area allowed that the general issues of these mine structures are identified. Based on the state of the abandoned features, the features were found to be presenting different forms of physical and environmental concerns as depicted in *Table 5.5*. The environmental issues of these features include commonly the effect they have on the appearance of the abandoned mines landscape and the alteration of the landscape by extensive and dangerous surface excavations. The chemical containers found scattered on the landscape of the abandoned New Union Mine posed risks of contamination of the environment by cyanide. These containers are also a threat to the health of people in the area.

The other common concern of the abandoned surface infrastructure and excavations was public safety hazards. These include risks of body injuries or death due to falling from or off the dilapidated buildings, mounting stands, tall structures (silos and ore-bins), and highwalls of the surface mine excavations. These problems are worsened by the fact that the abandoned mines sites in the study area are generally open to the public which increases the possibilities of people and animals getting tempted to get close to the abandoned mine features. The major risks of the abandoned mine infrastructure and excavations in the study area are depicted and their environmental concerns and physical hazards are concisely described in *Table 5.5.*

Table 5.5: Problems of abandoned surface mine infrastructure and excavations documented in the study area.

Mine feature	Environmental concerns	Physical hazards
1. Mine excavations or pits	▪ Land degradation. ▪ Effects on aesthetic beauty of the landscape. ▪ Occupying land for development.	▪ Falling from highwall. ▪ Falling of highwalls on people and animals. ▪ Health issues due to consumption or getting into contact with the water in the pits/excavations. ▪ Drowning in water in the pits ▪ Risks of animals getting killed by being stack in mud at the pit floor.
2. Mounting stands	▪ Effect on aesthetic beauty of the landscape. ▪ Occupying land for development.	▪ Falling of stands on animals/people.
3. Buildings	▪ Land degradation. ▪ Effect on aesthetic beauty of the landscape. ▪ Occupying land for development. ▪ Release of asbestos fiber to the environment thus resulting to pollution of the environment	▪ Present walking hazards (septic tanks pits). ▪ Falling off the walls of old building on people and/or animals ▪ Health risks of getting exposed to asbestos containing building materials
4. Cylindrical tall structures (silos and ore bins).	▪ Effect on aesthetic beauty of the landscape. ▪ Pollution of the environment by undefined chemicals left in some of these structures (e.g. steel agitation tanks).	▪ Falling of the structures on people and animals. ▪ Health risks of being exposed to the ruminates of chemicals found around the old mineral processing structures
5. Mine litter	▪ Pollution of the environment	▪ Present walking hazards. ▪ Poisoning of people and animals by chemicals in old containers ▪ Getting cut or pierced by sharp objects or packs on the ground
6. Surface machinery	▪ Effect on aesthetic beauty of the landscape. ▪ Limits and affects the alternative use of the abandoned mine land	▪ Falling of the feature on people and animals. ▪ Risks of being cut by the sharp edges of the structures.

5.6. Approaches for Rehabilitation of Abandoned Surface Excavations

The evaluation of possible approaches for dealing with the issues of abandoned surface excavations was carried out using the QSPM method. In this case a total of five possible ways of dealing with the concerns of surface mine excavations were evaluated. These approaches ranged from no action option, backfilling of the pits, fencing of the excavations, reshaping of the highwalls and stabilization of the slopes of the pits to promote their alternative uses, and combining the reshaping of highwalls with fencing of the excavation to enhance their safety status for any post-mining uses. The evaluation of these abandoned surface excavation rehabilitation approaches was conducted based on their identified SWOT elements presented in *Appendix-E.*

The results of the analysis demonstrated that both excavations with water and without water indicates that the use a combination of rehabilitation strategy is the most attractive approach. This is because the implementation of this approach has a potential of dealing with the problems of abandoned excavations in the manner that promote reuse of the pits while improving the aesthetic appearance of the landscape. However, the second most attractive strategy for water containing excavations was found to be the reshaping of the highwalls and stabilization of the slopes of the pits to allow for practicable uses. In the case of dry excavations, prevention of easy accessibility of abandoned surface excavations through fencing of the excavations was identified as the second most attractive rehabilitation approach (see *Table 5.6*).

The differences in the position of these rehabilitation approaches in the priority list of rehabilitation options for pits containing water and dry excavations may be due to the fact that the identification of appropriate post-mining uses of dry excavations generally take longer to conceptualize compared to the case of water containing excavations. Therefore, fencing of dry excavations can provide a temporary protection of people and animals from the risks of exposure to the different hazards of the excavations. As a result, the fence around the excavations can be maintained until the long term uses of the excavations are identified and the pit walls reshaped according to its post-mining uses requirements.

In both situations, the least attractive approach of dealing with abandoned surface mine excavations was the no action option. This is mainly because this approach tends to maintain the current unsafe use and unsafe conditions of the excavations. The second least attractive rehabilitation approach for abandoned surface mine excavations was backfilling of the pits with different materials depending on its availability. Some of the materials that are mostly used for backfilling of open pit mines and/or quarries with the aim of realizing morphological recovery are mine tailings, waste rock, soil, and overburden material (Favas *et al.,* 2018). Although this approach appears ideally for abandoned mines situation, it was identified to be having several shortcomings than the other options. The major disadvantages of backfilling of abandoned surface mine excavations includes the unavailability of adequate backfill material at or/and near the site and high requirement of earthwork which is mostly costly. In addition, backfilling turn to eliminate the possibilities of future beneficial uses of the surface mine excavations. The comparison of the attractiveness of approaches for dealing with the problems of abandoned mines excavations research can be seen in *Figure 5.12*. The detailed results of the attractiveness of the approaches for dealing with the problems of abandoned surface mine excavations and other structures of abandoned mines as generated in this study using the QSPM technique are shown in *Appendix-F.*

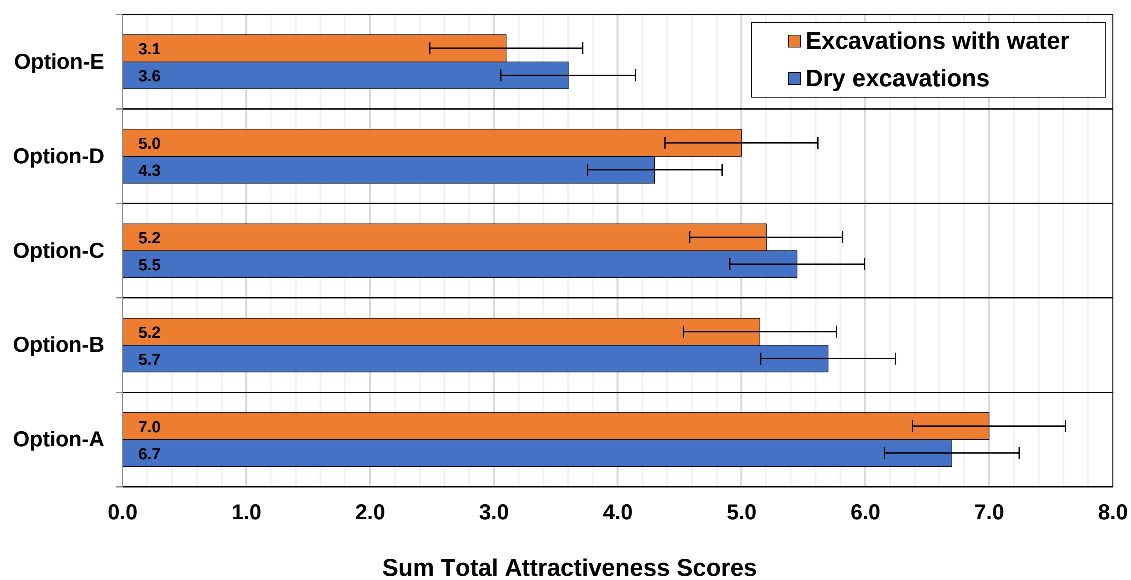


Figure 5.12: Comparison of the attractiveness of the rehabilitation options in addressing the issues of abandoned surface excavations. **A** is the combination of strategies, **B** is reduction of highwalls and reuse of the excavations, **C** is fencing of the excavations, **D** is backfilling of the excavations, and **E** is a no action option.

Table 5.6: Attractiveness of rehabilitation options for abandoned surface excavations.

Excavations with water throughout all reasons			
Rank	***Rehabilitation Strategies***	***Attractiveness Score***	***Option Code***
1	Combined strategies (*i.e.,* reduction of highwall, fencing and reuse of the excavations)	6.70	A
2	Reduction of highwalls and reuse of the excavations	5.70	B
3	Fencing of the excavations	5.45	C
4	Backfilling of the excavations	4.30	D
5	No action option	3.60	E
Seasonally flooded excavations			
Rank	***Rehabilitation Strategies***	***Attractiveness Score***	***Option Code***
1	Combined strategies (*i.e.,* reduction of highwall, fencing and reuse of the excavations)	7.00	A
2	Fencing of the excavations	5.20	C
3	Reduction of highwalls and reuse of the excavations	5.15	B
4	Backfilling of the excavations	5.00	D
5	No action option	3.10	E

5.7. Dealing with debris and forsaken structures at abandoned mine sites

The approaches of dealing with the problems of abandoned concrete mounting stands, water reservoirs and tall structures such as silos and ore-bins were to find alternative uses of the structures or demolishing and removing them from the mine sites. The renovation and use of silos or ore bins as platforms for commercial advertisement was found to be the most competitive strategy to use to deal with the problems of these structures and ensuring that they blend well with the developments in the surrounding areas or communities. As a result, this strategy was evaluated against the removal of the tall concrete structures from the abandoned mines landscapes. The suitability of these structures for commercial advertisement was motivated by the fact that these structures are generally tall and clearly visible in many parts of the landscape around the abandoned mine sites and other urban developments. Many of these structures were found to be structurally sound to support this alternative use and this is because silos are mostly built to be highly durable. Therefore, handing advertisement billboards on them can guarantee that the advertisement will surely be seen by potential clients or customers.

The analyses of the attractiveness of this approach of addressing the problems of dealing with the tall structures showed that the approach was slightly attractive compared to the removal of the structures (*see Figure 5.13*). This reuse option was found attractive since its implementation has potential for creating opportunities of the abandoned mine site attracting different recreational activities that are likely to boost the tourism status of the host communities.

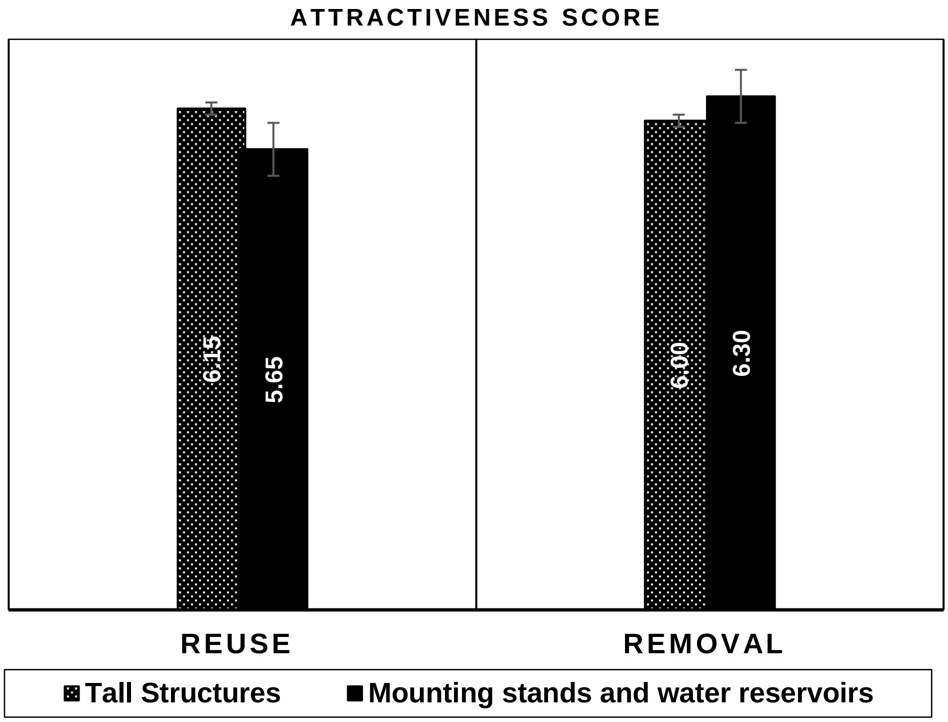


Figure 5.13: Attractiveness scores of the tall structures, cement mounting stands and water reservoirs**.**

5.7. Assessment of Potential uses of Abandoned Mine Buildings

Some of the abandoned mine sites are characterized by old and/or derelict buildings. These buildings include mine worker's hostels, offices and other buildings around the old mineral processing plants, and mine houses (residential complex or mine village). Most of these buildings and the other infrastructure in the mine are mostly destroyed and removed from the site during the closure and rehabilitation stage of the mine. However, when the mine is abandoned, the buildings are normally left on site without caring for their subsequent health and safety hazards which arise as the buildings get dilapidated. According to Tanner (2007), the reusable mine infrastructure should be identified and handed over for reuse during the closure and rehabilitation stage of the mine.

In view of this, the process used in this research to identify the best ways of dealing with the issues of abandoned mine buildings involved evaluating the possibilities of reusing the buildings or destroying and removing them from the site. The possible reuse options that were considered were (i) adoptive-reuse of the mine buildings for residential and commercial and/or community development purposes, and (ii) the demolishing and removal rubbles of the buildings coupled with some aspects of reuse potential. According to Iacovidau and Purnell (2016), the term "reuse potential" refer to the measure of the ability of a building component (*e.g.* bricks) to retain its functionality after the end of its primary life. On the other hand, the "adoptive reuse" is the method where part or the whole building need to be upgraded to ensure that it best support the requirements of the new uses (Iacovidau and Purnell, *op cit*.).

In this study the old buildings at the abandoned mine sites were evaluated for their potential to support commercial and community development projects, and the requirement for their removal with the purpose of making the land available for other uses. The SWOT and QSPM analysis results showed that the use of the abandoned mine buildings for commercial and/or community development purposes was the most attractive option for dealing with the problems of abandoned mine buildings in the study area (*Figure 5.14*). The structure that was identified to be having a potential of being easy repurposed for commercial or community development projects in the study area was the old miner worker's hostel found in Artonvilla Mine in Musina. This is because the mine workers' hostels were found to be structurally sound and less vandalized compared to other structures in the study area. This suggested that the process of repurposing of these buildings to be used for commercial and/or community development projects will require little or less renovations. On the other hand, the old mine worker's houses were found suitable for development of residential houses and this was the second most attractive option. All buildings found in old mineral processing areas were identified to be extremely dilapidated and affected by artisanal mining activities. In view of this, most of these buildings need to be demolished. Depending on the reusability potential of the materials of the buildings, some of these materials can be used by local people or municipality in their planned or ongoing construction projects.

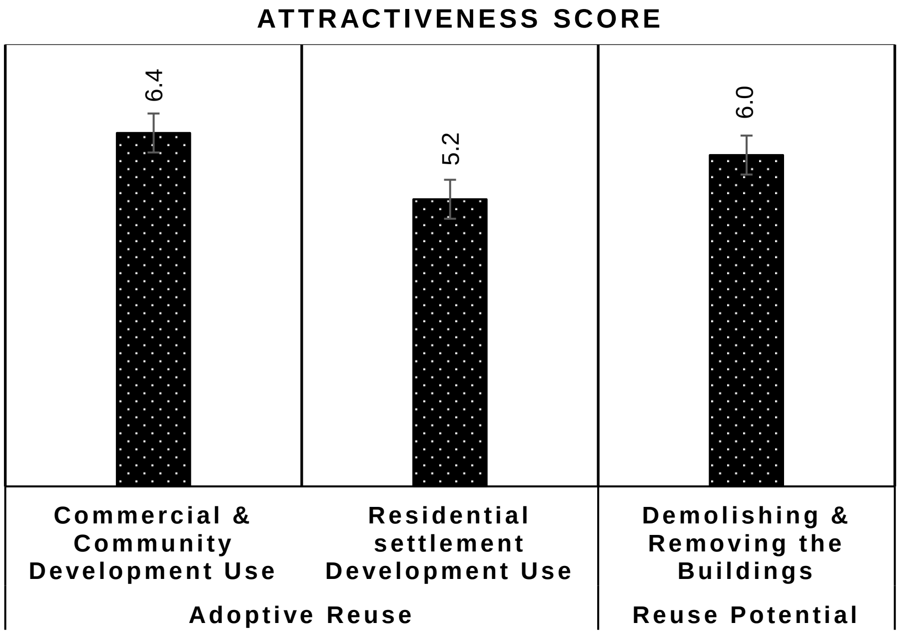


Figure 5.14: Attractiveness score of dealing with the issues of abandoned mines buildings.

5.8. Discussion of the Findings of the Study

Based on the field description of the current state of the abandoned mine sites in the study area, the major issues of surface excavations and other infrastructure were established. This allowed that strategies for addressing the problems of these abandoned mine features are identified and evaluated using both SWOT and QSPM techniques. The major concerns of these mine features were that they are generally associated with various forms of safety and health hazards. The presence surface mine structures and excavations on the landscapes of abandoned mines also turn to affect the natural beauty or appearance of the landscape (Dentoni *et al.,* 2006; Dentoni and Massacci, 2013; Kivinen, 2017). According to Tsolaki-Fiak *et al*. (2018) and Misthos *et al.* (2019), the appearance of surface excavation or quarries with contrasting colours on the landscape turn to reduce the aesthetic appeal of the landscape and this result to deterioration of the scenic quality of the area.

In this research it was established that the abandoned surface mine excavations mostly occupy a large part of the mine landscape. Depending on the location of the excavations, they can be a serious hindrance to urban development (Wirth *et al.,* 2012). They also have safety and health risks due to the nature of the highwalls and the fact that some of the excavations are filled with water. In order to carry out morphological restoration of the mine landscapes, it is suggested that the excavations be backfilled with materials such as waste rock, mine tailings, soil and spoils material. Backfilling can be implemented as complete or partial backfilling and can be followed by establishment of vegetation on the backfilled areas (Favas *et al.,* 2018; Johnson and Carroll, 2007).

Although the backfilling of excavations for morphological restoration have several advantages, the attractiveness of this method for abandoned mine situation is constrained by the potential high cost of backfilling and the lack of local availability of material required to backfill the excavations. As a result, less costly strategies that have great potential to protect the public from the physical hazards of the excavations and promote their use for other purposes were found to be better attractive than backfilling option. For example, in different countries (e.g. Germany, Poland, Czech Republic *etc.*) old surface mine excavations have been developed to pit-lakes (or lake districts) that support a variety of activities which includes but not limited to aquaculture, aquatic sports, shipping and recreational activities (Wirth *et al.,* 2012; Kivinen, 2017). The old mine excavation can also be developed for use as waste disposal facility or landfill sites (Mhlongo, 2012; Venter and Senne, 2014). All these reuses of abandoned surface mine excavations require that the slopes of the excavations are graded to maintain a safer and more stable angle. The prevention of easy accessibility of the excavations may be accomplished by erecting fence around the excavation.

The adoptive reuse of abandoned surface mine infrastructure in the study area favored features such as the silos and ore bins as well as some of the abandoned mine buildings (mostly mine worker's hostels and mine houses). The fact that some of the buildings that were meant for other purposes rather than to provide accommodation for mine workings are mostly found in areas that are contaminated by heavy metals and/or radiation (Kivinen, 2017), the adoptive reuses of such buildings was found to be less attractive. In view of this, the buildings in potentially contaminated areas like sites of mineral processing or old metallurgical plants might need to be demolished and removed from the site. However, different materials (*e.g.* bricks, roofing materials and doors as well as window frames) can be reused in other construction projects (Iacovidau and Purnell, 2016).

Tall mine structures like ore bins and silos can be utilized for commercial advertisement as well for recreational activities in the almost the same way as it done with the old coal fired power station in Orlando (Orlando Towers shown in *Figure 5.15*) was repurposed for outdoor recreational activities. Such reuse of silos has a potential of stimulating the use of other abandoned mine infrastructure and old machinery for different purposes. For example, old or abandoned metallurgical areas have been used to explain historical, archeological, socio-economic and industrial aspects of former mining activities in many mining towns. This has resulted to development of mine archeological-parks, recreational areas and museums in abandoned mine sites in areas such as Sordinia, Tuscany and Veneto (Bini *et al.,* 2017). The best local (South African) examples of this type of use of abandoned or historic mining sites are the mine museum of the town of Pilgrims Rest (Mpumalanga Province) and the tourist attraction site of Gold Reef City (Gauteng Province) shown in *Figure 5.15b* and *Figure 5.15c* respectively. The summaries of the practical approaches for dealing with the problems of abandoned surface mine excavations and infrastructure are shown in *Figure 5.16* and *Figure 5.17* respectively.

Figure 5.15: Practical examples of reuse of old industrial sites. (a) the outdoors recreational area constructed from old coal power station in Orlando (b) the old mining sites converted int to the museum of the preservation of gold mining history in Pilgrim's rest, and (c) the outdoor recreational and tourist attraction areas build from the old mine infrastructure at Gold Reef City.

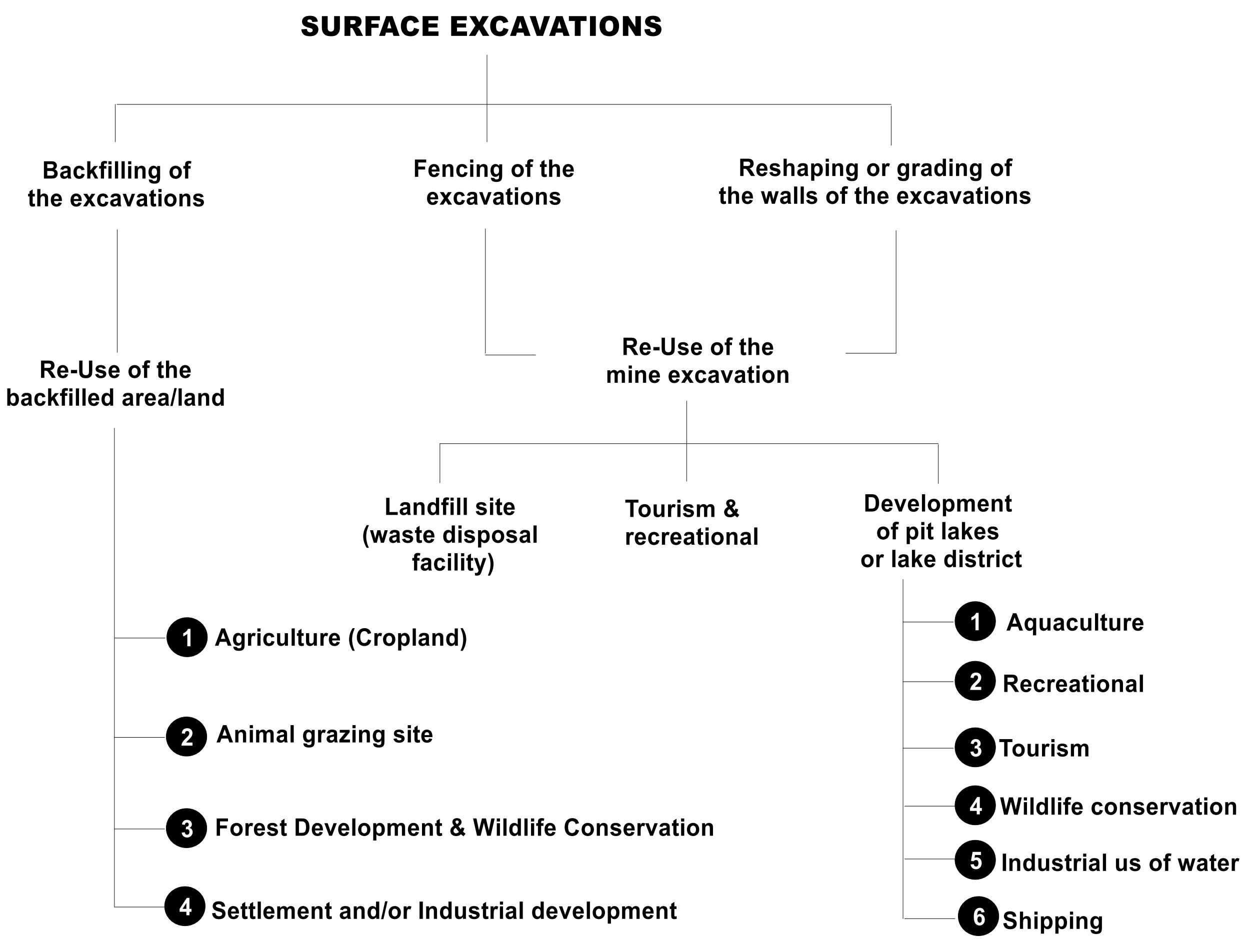


Figure 5.16: A summary of the practical approaches for dealing with the abandoned surface mine excavations.

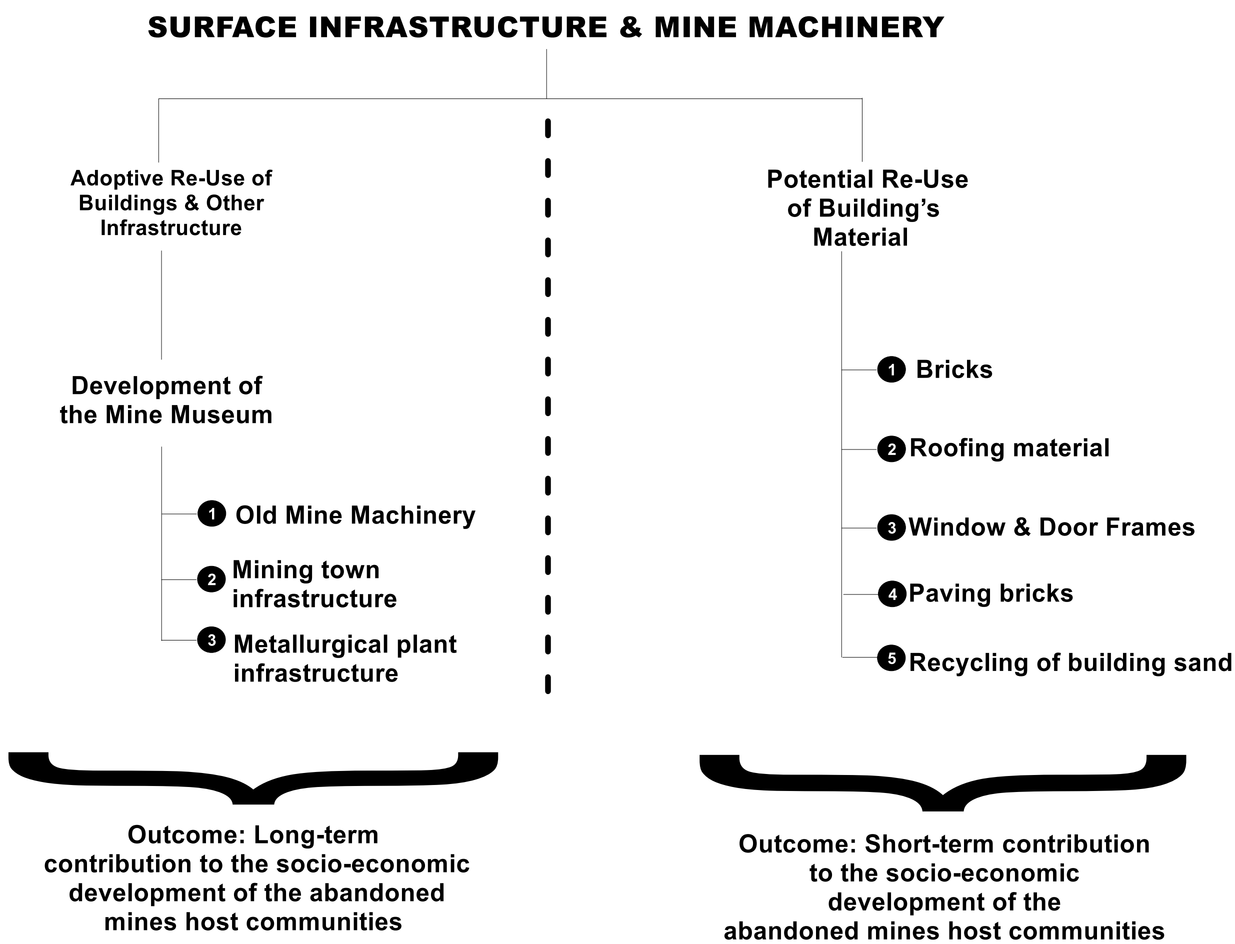


Figure 5.17: A summary of the practical approaches for dealing with surface mine infrastructure and machinery.

5.9. Summary of the Chapter

At many abandoned mine sites, derelict infrastructure and open excavations are found. These mine features present different forms of hazards to people, animals and environment. This chapter discussed the problems of different surface mine infrastructure and excavations in selected abandoned mines found in Giyani and Musina areas which were chosen as study areas for this research.

The study involved semi-quantitative method, *viz*; SWOT analysis and Quantitative Strategic Planning Matrix (QSPM) to find practical strategies for dealing with the problems of abandoned surface mine excavations and infrastructure found in the study area. In this case, SWOT analysis was used to identify the internal (strength and weakness) and external (opportunities and threats) factors of the identified possible strategies for dealing with the problems of the selected abandoned mines. Based on the established SWOT factors, the QSPM technique was then used to determine the level of attractiveness of the selected strategies for the site. This made it possible for the most suitable strategy for dealing with the problems of surface mine excavations and infrastructure in the study area to be identified.

The field characterization of the abandoned surface mine excavations identified the physical hazards of these excavations to be associated with their highwalls, highwall's stability and the sticky mud that trap and cause death to animals that drink the water in the abandoned excavations at Nyala Mine. The abandoned surface mine infrastructures (*i.e.* silos and ore-bins, dilapidated buildings, cement floors, concrete water reservoirs and mounting stands, ore bankers, old ball mills, and other remains of steel materials) were also found to be presenting different types of physical and environmental hazards. Moreover, these infrastructure and excavations affect the aesthetic beauty of the landscape of abandoned mine sites. Based on these problems it became apparent that strategies need to be found to deal with the problems of the abandoned surface mine excavations and infrastructure in the study area. The SWOT and QSPM analysis of the possible and practical approaches for dealing with the problems of abandoned surface mine excavations and infrastructures showed that repurposing of these features for other uses should be considered first before the use of traditional strategies like backfilling of the excavations and demolition of the disused buildings.

The knowledge of the problems of abandoned surface mine excavations and infrastructure generated in the work presented in this chapter assisted in developing the production rule of the expert system for selection of rehabilitation strategies for abandoned mines. This system together with the other two expert systems (*i.e.* expert system for ranking the abandoned mine entries and the expert system for ranking the mine tailings for rehabilitation) are discussed in the next Chapter (Chapter Six) of this thesis.

CHAPTER SIX

A COMPUTER-BASED ADVISORY SYSTEM FOR REHABILITATION OF ABANDONED MINE

One of the objectives of the research presented in this thesis was to develop a computer-based advisory system for rehabilitation of abandoned mine sites. This chapter is earmarked for presentation of the work conducted to accomplish this objective. The development of such a computer-based system involved creation of three standalone expert systems using web based expert system shell. Based on the knowledge of the problems of abandoned mines and the strategies for dealing with these problems, the decision trees and knowledge base of the computer systems were created in the ES-Builder Shell©2013 McGoo Software. These computer systems were developed to provide guidance on which problems of the abandoned mine features need to be given utmost attention in the rehabilitation of these mines and their features. They were also designed to assist in identifying rehabilitation strategy or strategies for abandoned mines. The applicability and/or usefulness of the developed expert system was tested using site-specific information from selected abandoned mines in the Giyani and Musina areas of South Africa. Each of the components of the developed expert systems in this research can be used by both experts and non-experts in the field of rehabilitation of abandoned mine sites to identify actions to take in the different stages of the rehabilitation work. They possess interactive characteristics that enables them make use of site-specific information or issues of abandoned mines in ranking of rehabilitation efforts and selection of appropriate strategies for rehabilitation of the mine sites.

6.1. Background of the Study

The work of rehabilitation of abandoned mines is concerned with making critical decisions on what strategies to use in order to address the specific problems presented by abandoned mine sites. In general, it is important that rehabilitation of these mines be conducted in a manner that eliminate their hazards while promoting the alternative uses of the site or the mine features. The need for making sound decisions in the process of rehabilitation of abandoned mines is increasingly becoming necessary manly because the rehabilitation of these mines is mostly conducted with limited resources. In view of this and the fact that the demand for rehabilitation of abandoned mines to meet the requirements of the regulations and the expectations of the communities is increasing, it becomes important that expert systems that provides pieces of advice on different aspects of the rehabilitation of these mines are developed. This chapter presents a computer-based advisory system (*i.e.* expert system) that was developed for rehabilitation of abandoned mines. This system was developed in three separate expert systems using a web based expert system shell called an ES-Builder©2013 McGoo Software. According to Matthew *et al.* (2016), this software package is commonly used to design expert systems that are accessible as web page. The development of expert systems using internet technology make their design and accessibility easy and this has resulted to so many expert systems being available on the internet (Hogo *et al.,* 2009).

In general, expert systems deal with decision making in different knowledge field (Burhan, 2016). According to Kirmanli and Ercelebi (2009), these systems are generally intended to act as human experts who can be consulted on the range of problems regarding their area of expertise. They can be designed or created from information obtained from human experts or model-based information. The first case involves coding of knowledge of human expert to build an expert system capable of providing pieces of advice in a specific knowledge domain. However, in the second case, a stand-alone model or a model that is part of the decision support system (DSS) can be used by the expert system to provide pieces of advice that assist decision-makers (Turban and Watkins, 1986). In whatever way, the knowledge used by an expert system to make decisions should be organized into formats that distinguishes between data, knowledge, and rules (Jadhav *et al.,* 2016).

6.1.1. Objectives of the study

The main objective of this part of the research was to develop a computer-based advisory system for rehabilitation of abandoned mines.

The specific objectives were:

- To create decision trees used by the system as logic structure to provide pieces of advice on different aspects of rehabilitation of abandoned mines,
- To use factual and model-based information of abandoned mines to create knowledge-based rules of the expert system, and
- To test the applicability of the developed expert systems by making use of site-specific information of selected abandoned mines at Giyani and Musina towns of Limpopo province of South Africa.

6.2. Approach for Development of Computer Based Advisory System

The development of expert systems that provides advice/guidance on different aspects of rehabilitation of abandoned mines began with knowledge acquisition by conducting a detained characterization of abandoned mine site or features in the Giyani and Musina areas, Limpopo Province of South Africa. The aim of the characterization was to gather in-depth knowledge on problems associated with different features of abandoned mines and to identify practical ways or strategies for dealing with these problems. The results of the characterization of abandoned mine features in the study area are presented and discussed in the different chapters (*i.e.,* Chapter Three, Four and Five) of this thesis. The information and knowledge generated from this process was used in creating the decision tree and the decision rules of the expert systems. Three expert systems were developed to provide advice on different issues of rehabilitation of abandoned mines and these were: (*i*) expert system for ranking environmental and physical hazards and socio-economic impacts of the abandoned mine entries, (*ii*) expert system for ranking abandoned mine tailings for rehabilitation, and (*iii*) expert system for selection of rehabilitation strategies for addressing the problems associated with abandoned mine features. These systems were collectively created to provide answers to two key questions of rehabilitation of abandoned mine sites and/or features. These were:

- Which part(s) or element(s) of abandoned mine sites require immediate rehabilitation?
- Which rehabilitation option(s) is or are appropriate for dealing with the specific issues or problems of abandoned mines or features?

The actual development of the computer-based advisory system which is basically expert systems that provide pieces of advices on different aspects of rehabilitation of abandoned mines was carried out within the web-based ES-Builder Shell (*i.e.* ES-Builder©2013 McGoo Software). The stepwise procedure of the processes followed in creating the expert systems that provides guidance on different aspects of rehabilitation of abandoned mines is shown in *Figure 6.1*. Following the knowledge generation process, the respective expert systems were created within the ES-Builder. This required that for each system, Project Details page is first created. This page provides details of the expert system in terms of its name, its universe if discourse, the notes to be included in the start page of the ES, and the conclusion of the ES. This was then followed by the creation of the production rules of each expert system. As a way of verification of the functionality of the developed expert systems, they were applied to the site-specific situation of abandoned mines in the Giyani and Musina areas. The section below provides details of the expert systems development in this research.

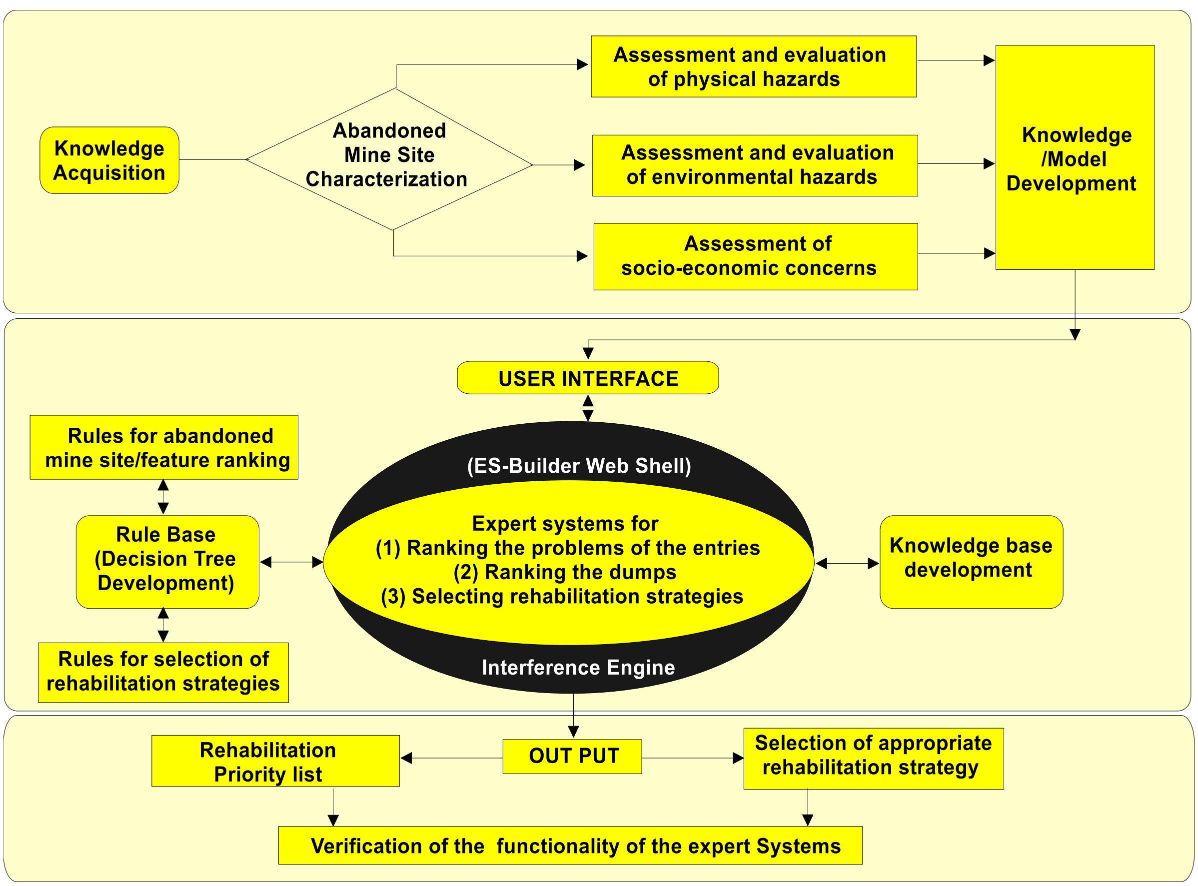


Figure 6.1: Flow of the procedures followed in the development of the expert systems.

6.2.1. An overview of development of an expert system in the ES-Builder Shell

The three expert systems that were developed to provide advice on different aspects of rehabilitation of abandoned mines or features of abandoned mines were created according to the methods and procedures that are acceptable in the ES-Builder Shell. The web based expert system shell called the ES-Builder was used to develop the production rules of the expert systems. According to Matthew *et al.* (2016), the advantages of creating expert systems in the ES-Builder Shell is the fact that the shell uses a simple web interface that can be accessed and easily used by anyone who is familiar with the internet. According to Jadhav *et al.* (2016), the ES-Builder relies on the correct specification of the logic as specified by the developer of the system and structured in the form of a decision tree. The exporting functions of the ES-Builder can create the web-page for searching the expert system, displaying the knowledge base, displaying the decision tree, displaying full decision table, listing of the attributes and values, and specifying the expert system's documentation (Zuhra *et al.,* 2016).

The process of getting access to the web-based ES-Builder Shell, required that the system developer registration and creation of the user account are conducted. This was done in the ES-Builder Shell user registration page. After registration and confirmation of the user registration, logging into the ES-Builder to begin with the creation of the production rules of the expert system being developed to advice in different aspects of rehabilitation of abandoned mines or features of abandoned mines was possible. The actual development of the expert system in this research began with defining the title of the expert system being developed. In this, the names of the expert systems being developed, and their specific information were created. The Universe of Discourse (*i.e.* the range covered by individual expert systems) of each developed expert system and the image that the start page of such expert system is to be identified with were also incorporated in the Project Details page shown in *Figure 6.2.*

Figure 6.2: Typical ES-Builder Shall project details page.

6.2.2. Creation of production rules and knowledge base

The development of an expert system requires that the knowledge base which contains the production rules for the system be created (Zuhra *et al.,* 2016; Angeli, 2010). The production rules of the expert systems developed in this research were created and captured in the knowledge base part of the ES-Builder Shell. The knowledge base is a collection of facts and rules which describe all the knowledge about the problem domain (Jadhav *et al.,* 2016). It comprises of rules structured information of the developed expert systems. The structure of the production rules of the expert systems developed in this research were created to be in the form of the condition(s) [IF] and the consequence(s) [THEN] as shown in *Figure 6.3*. In this case, once the IF statement(s) of the system is satisfied, the THEN part turn to take place (Matthew *et al.,* 2016).

In the developed expert systems, the created production rules allowed each expert system to arrive at the conclusions which provide guidance on different aspects of rehabilitation of abandoned mine sites or features. The production rules of the expert systems were manually created following the procedures of the method for ranking the environmental and physical hazards of the mine entries together with their socio-economic concerns and that of ranking the tailings for rehabilitation. These methods were developed and discussed in Chapter Three and Four of this thesis. The development of the production rules of the expert system for selection of rehabilitation strategies for abandoned mine sites or features of abandoned mines took into consideration the rehabilitation requirements of the mine features established in Chapter 5 of this thesis and the general rehabilitation requirements of mine sites specified in the Guidelines for the Rehabilitation of Mined Land (Tanner, 2007) and other published materials. A simplified illustration of the general structure of the production rules in the knowledge base of the expert system is shown in *Figure 6.3*.

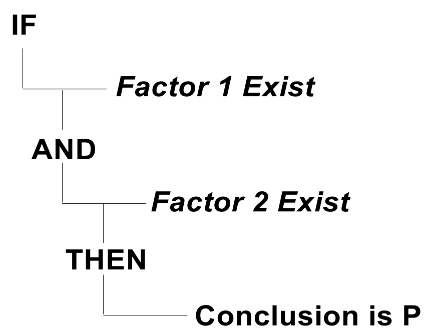


Figure 6.3: A general structure of the production rules in the knowledge base of an expert system.

6.2.3. Creation of the decision trees in the ES-Builder Shell

The ES-Builder Shell consists of a decision tree modeling process which is used for the development of the logic structure of an expert system (Jadhav *et al.,* 2016). According to Zuhra *et al.* (2016), the decision tree is basically a graphical depiction of the knowledge and production rules. The decision tree is developed within the Decision Tree View of the ES-Builder Shell. In all aspects of rehabilitation of abandoned mines for which the expert systems were developed to provide advice on, the decision trees were developed by entering the Attributes, Values, and Conclusions in the decision tree model provided by the ES-Builder Shell. The trees were created to have nodes that branches to other nodes until the conclusion is reached or until the tree is complete. In general, there are several basic rules that need to be followed when formulating acceptable decision trees in the ES Builder Shell (Matthew *et al.,* 2016). These rules are summarized and presented in *Table 6.1.* These rules were carefully considered when creating the decision trees for the expert systems developed and presented in this thesis.

In addition to the creation of the production rules and the decision tree, the Certainty Factor (Cf) (Simple Certainty Factor) was applied and it reflects in every conclusion page of the system and in the production rules within the knowledge base. This factor is used to estimate the confidence of the conclusion drawn from the expert system and the ES-Builder Shell allow the display of the Cf in every conclusion made by the expert system. According to Hatzilygeroudis *et al*. (2004) and Cruz and Beliakov (1996), the CF is basically a number that is used to measure the expert's belief (+1) and/or disbelief (-1) to the conclusion of the expert system.

Table 6.1: General rules for developing decision tree in the ES-Builder Shell (Matthew *et al.,* 2016).

Point	Rule
1	▪ The first node of the decision tree is the Universe of Discourse (UofD)
2	▪ The second node of the tree should be an Attribute that is displaying with an "A" icon.
3	▪ Each Attribute to be tested in the ES should at least have two branching nodes
4	▪ The Value nodes are mostly the only type of branch nodes that are accepted by Attribute node.
5	▪ The Value node always represent the most correct response to an Attribute for a particular conclusion
6	▪ The Value nodes have two possible types of branch node, therefore, when further Attribute needs to be tested, a branch node of a Value will be another Attribute node
7	▪ When a final conclusion has been made, the branch node of the Value will be a conclusion.
8	▪ The conclusion node must be a leaf node such that no branches are accepted from the conclusion node.
9	▪ Apart from the UofD (*i.e.* first node), about 3 data items can be added.
10	▪ Each Attribute, Value and Conclusion node may consist of a detailed definition, a paragraph of help notes, and an image to be displayed in the ES.

6.3. Description of the Developed Expert Systems

For this component of the study, three expert systems that provide guidance on different aspects of rehabilitation of abandoned mines were developed. The first system was developed to assist with the ranking of the hazards of abandoned mine entries, while the second system was developed for ranking the abandoned mine waste dumps (especially the tailings dumps) for rehabilitation. The third expert system was developed to offer advice on strategies to use in the treatment and/or rehabilitation of the different parts or features of abandoned mine sites. Presented in the section below are the details of the expert systems developed in this research. The description of these expert systems covers the issues of knowledge acquisition to develop the respective production rules of the expert systems. It also provides the general characteristics of each expert system developed and their respective application to the problems of abandoned mines in Giyani and Musina areas. The specific information of these expert systems which is also displayed on the start page of the expert systems is shown in *Table 6.2.* Such information includes the tittles of the expert system as well as their specific notes and the Universe of Discourse (UofD) of each developed expert system. The image shown on the start page of these expert systems is also presented in *Table 6.2.*

Table 6.2: Start page information of the developed expert systems.

No	Tittle of the ES	UofD	Notes	Start Page Image
31900	Expert System – Selection of strategies for rehabilitation of abandoned mines (ES-SRSAM).	Select appropriate rehabilitation strategies for abandoned mines.	This expert system will advise on which strategies to use in the rehabilitation of abandoned mine sites or features. The rehabilitation can make use of a single strategy of a combination of strategies.	 (from Abad, 2019)
32212	Expert System - Ranking of the problems of abandoned mine entries (ES-RAME)	Ranking of the problem of abandoned mine entry.	This expert system will provide the status/nature of the problems of abandoned mine entries so that appropriate strategies for addressing such problems can be identified.	 (from Olalde, 2017)
32276	Expert System - Ranking of abandoned mine tailings dumps for rehabilitation (ES-RTDR).	Ranking of abandoned mines or features for rehabilitation.	This expert system will rank the abandoned mine tailings dumps for their rehabilitation. Its application will advise the user on which dumps should be given high priority in the rehabilitation work.	 (from Olalde, 2016)

6.4. Description of the Expert System for Ranking the Problems of Abandoned Mine Entries – (ES-RAME)

The development of the expert system for ranking the problems of abandoned mine entries (ES-RAME) began with the acquisition of factual knowledge about the problems of the mine entries. This knowledge assisted in developing the production rules and the knowledge base of the expert system. These rules were developed based on the procedures of the method for ranking the hazards of abandoned mine entries developed and presented in Chapter 3 of this thesis.

The effective use of the developed expert system for ranking the problems of abandoned mine entries requires that field characterization and description of the mine entries are conducted. The purpose for such characterization of the mine entries is to establish in-depth knowledge and understanding of the physical and environmental hazards of the entries and to identify and quantify their associated socio-economic concerns. This is important for the determination of the site-specific issues of the abandoned mine entries. The generated knowledge of the problems of the mine entries is also important for accurate scoring of the factors of the identified physical and environmental hazards of the mine entries. These factors were (*i*) the source of the hazards, (*ii*) the ways of exposure/pathways of the hazards, and (*iii*) the magnitude of the potential environmental/body damage which the hazards of the mine entries are likely to cause. Based on the scoring process, the environmental and physical risks of the mine entries as well as their socio-economic concerns were quantified.

The magnitude (as were defined by the calculated scores) of the individual risks of the mine entries is then used to calculate the total hazard score which is used by the expert system to classify the problems of the mine entries into four categories, *viz*; Negligible, Low, Moderate and High. The basic framework of the method followed in the formulation of the production rules of the expert system for ranking the problems of abandoned mine entries is shown in *Figure 6.4.*

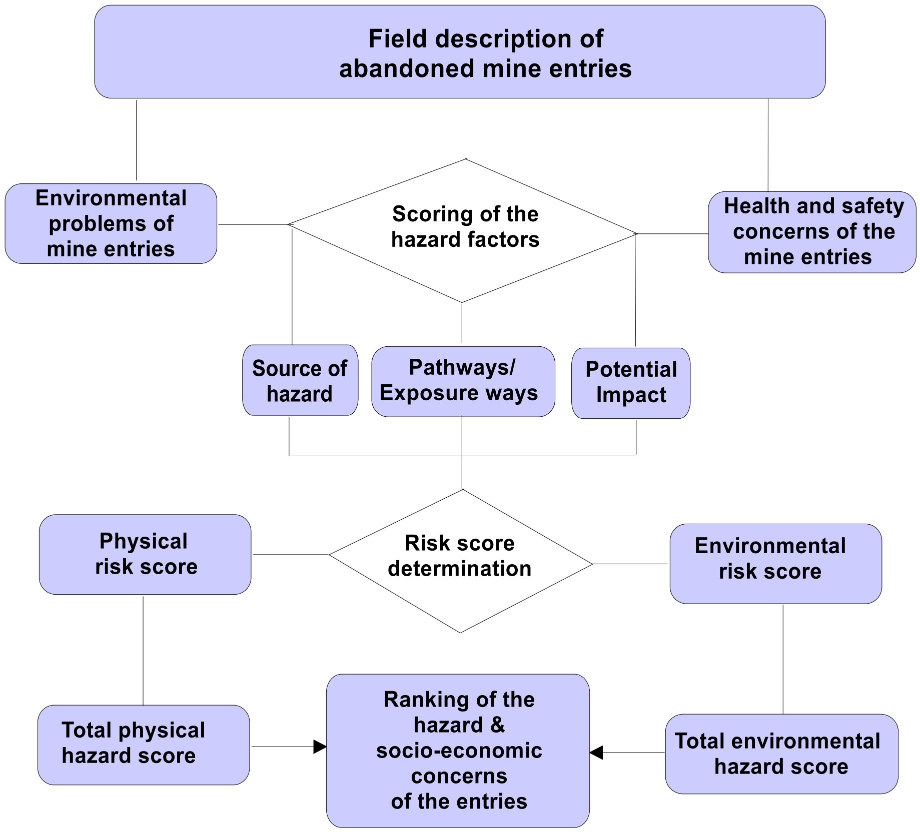


Figure 6.4: Framework of the method for evaluation of the problems of abandoned mine entries used to develop the production rules for the expert system.

6.4.1. The production rules of the ES-RAME

The decision tree created for the ES-RAME assisted in coming up with nine conclusions as shown in *Figure 6.5*. The conclusion statements given by the expert system are presented in *Table 6.3*. The production rules of this expert system made it possible that the environmental and physical hazards of the abandoned mine entries their socio-economic concerns are ranked into four categories, *viz;* High, Moderate, Low, and Negligible. This made the decision tree developed for the expert system to be broadly divided into three brunches which one rank the physical hazards and social concerns of the mine entries while the other assists with ranking the environmental and economic impact of the mine entries. The third branch of the decision tree was developed to rank the mine entries in situations where there is restricted access to the abandoned mine entries.

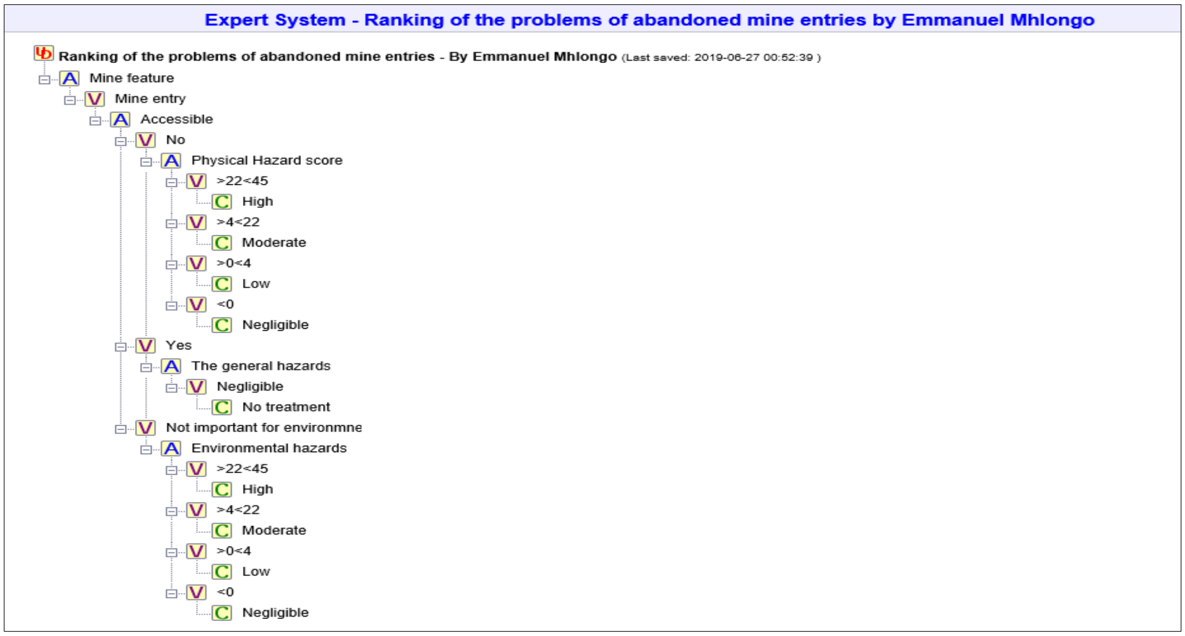


Figure 6.5: Structure of the decision tree for the ES-RAME.

Table 6.3: Decision table of the ES-RAME.

No.	Conclusion	CF	Mine feature	Accessible	Physical Hazard score	The General Hazards	Environmental Hazard Score
1	High physical hazards and social concerns	1.00	Mine entry	No	>22<45	-	-
2	Moderate physical hazards and social concerns	1.00	Mine entry	No	>4<22	-	-
3	Low physical hazards and social concerns	1.00	Mine entry	No	>0<4	-	-
4	Negligible physical hazard and social concerns	1.00	Mine entry	No	<0	-	-
5	No immediate treatment needed	1.00	Mine entry	Yes	-	Negligible	-
6	High environmental Hazard and economic concerns	1.00	Mine entry	Not important for environmental hazards	-	-	>22<45
7	Moderate environmental hazards and economic concerns	1.00	Mine entry	Not important for environmental hazards	-	-	>4<22
8	Low environmental hazard and economic concerns	1.00	Mine entry	Not important for environmental hazards	-	-	>0<4
9	Negligible environmental hazards and economic concerns	1.00	Mine entry	Not important for environmental hazards	-	-	<0

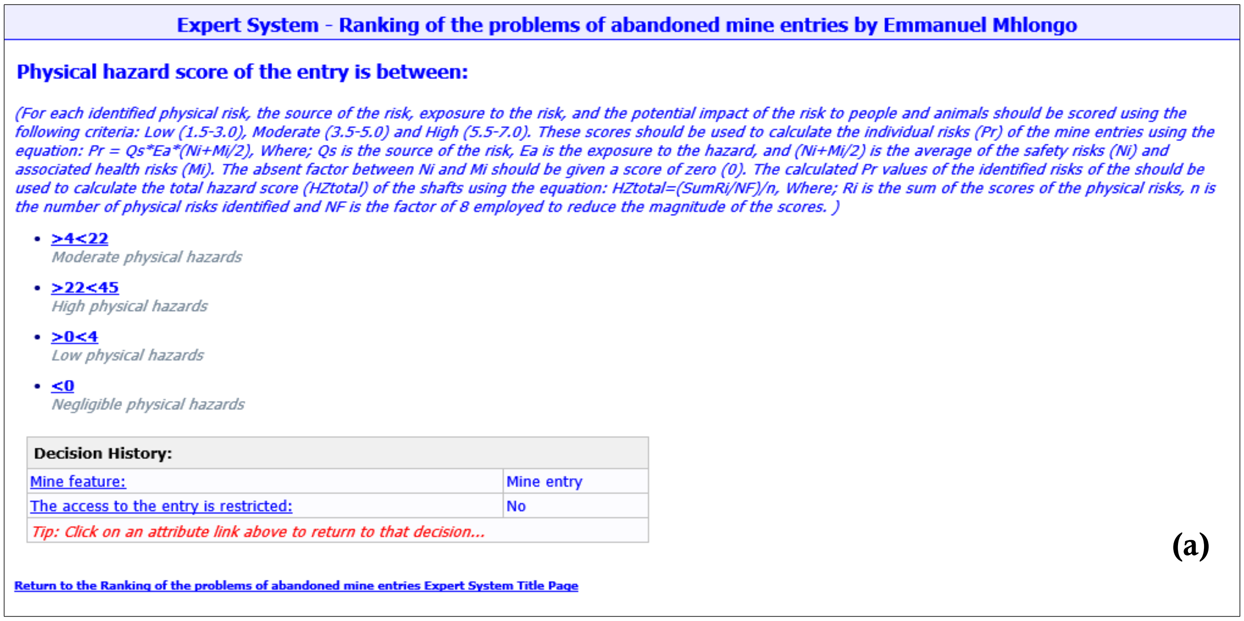
Note: - means not applicable.

In general, the developed production rules of the expert system are stored in the knowledge base of the system. The structure of the ES-RAME knowledge base with production rules is shown in *Appendix-G.* The production rules which allow the expert system user to arrive at a particular conclusion is also displayed in the conclusion page of the expert system. An image that provides the visuals of the situation that displayed by the conclusion page of the expert system is shown in each conclusion page. An example of the few selected conclusion pages of the ES-RAME can be seen in *Figure 6.6a-d*.

The implementation of the method of ranking the problems of abandoned mine entries in the expert system shell made the system to work in an interactive manner. This characteristic of the ES-RAME enabled easy use of the expert system in the manner that accommodate site-specific issues of the abandoned mine entries in to the ranking process. The method of ranking allows the user of the system to score the factors of the hazards or risks of the mine entries according to his/her field judgment of the situation. In this case, the user of the system is assisted by the expert system with the criteria for scoring the factors of the identified physical and environmental hazards of the mine entries. The expert system also provides a description of the procedure for calculation of the total physical and environmental hazard scores of the abandoned mine entries. The instruction given by the expert system on how to calculate the environmental hazard scores is shown in *Figure 6.7a* while that for calculation of the physical hazard scores is shown in *Figure 6.7b*. However, the major attributes of the ES-RAME can be seen in *Appendix-H.*

Based on the determined physical and environmental hazard scores, the expert system offers guidance on ranking of the hazards. In each category of physical and/or environmental hazards, the ES-RAME was created to provide recommendation of the aim or objective of the mine entry treatment. It is important to mention that the development of the decision tree and the production rules of the ES-RAME are based on assumption that there is relationship between the environmental and physical hazards of abandoned mines and the socio-economic concerns of these mines. This is because the environmental problems of the abandoned mines turn to result to poor economic development of the area while their physical hazards affect mostly the social well-being of the people residing around the abandoned mine sites. In view of these, the conclusion that is given by the ES-RAME combine the physical hazards with the social impact of the entries while the environmental hazards are combined with the economic impacts of the shafts. This suggest that the methods to be selected in dealing with the physical hazards of the abandoned mine entries should also contribute to improving the social status of the communities and those used to deal with the physical hazards of shafts should also address the economic situation of the abandoned mines host communities.

Figure 6.6: An illustration of the conclusion page of the ES-RAME.


Expert System - Ranking of the problems of abandoned mine entries by Emmanuel Mhlongo

Physical hazard score of the entry is between:

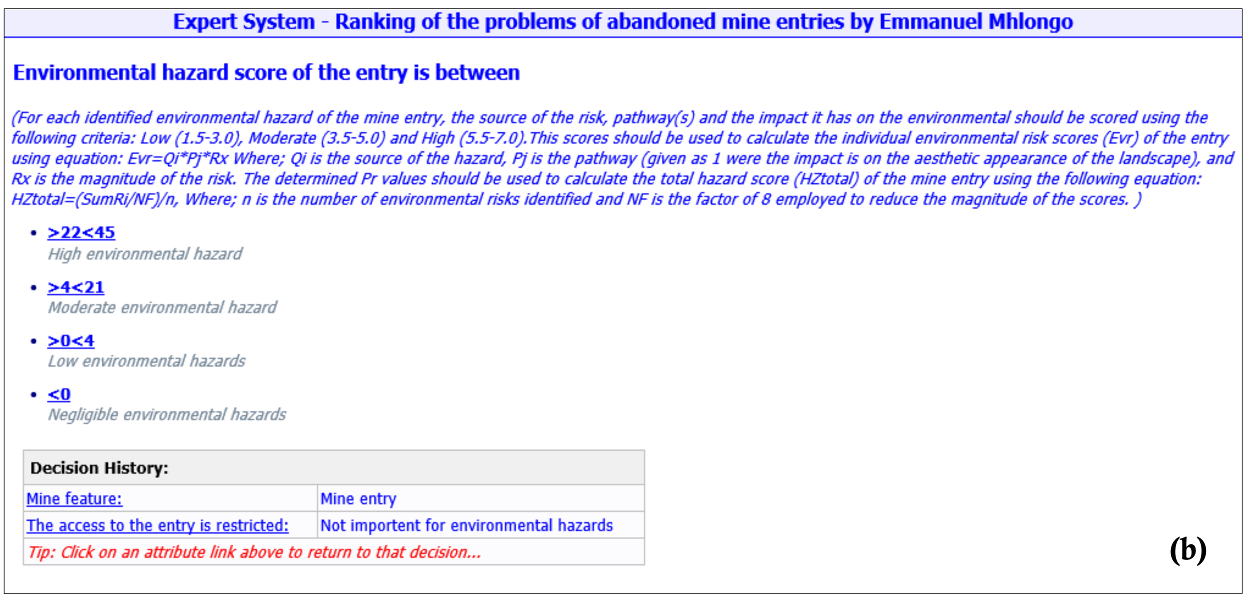
(For each identified physical risk, the source of the risk, exposure to the risk, and the potential impact of the risk to people and animals should be scored using the following criteria: Low (1.5-3.0), Moderate (3.5-5.0) and High (5.5-7.0). These scores should be used to calculate the individual risks (Pr) of the mine entries using the equation: Pr = Qs*Ea*(Ni+Mi/2), Where; Qs is the source of the risk, Ea is the exposure to the hazard, and (Ni+Mi/2) is the average of the safety risks (Ni) and associated health risks (Mi). The absent factor between Ni and Mi should be given a score of zero (0). The calculated Pr values of the identified risks of the should be used to calculate the total hazard score (HZtotal) of the shafts using the equation: HZtotal=(SumRi/NF)/n, Where; Ri is the sum of the scores of the physical risks, n is the number of physical risks identified and NF is the factor of 8 employed to reduce the magnitude of the scores.)

- >4<22
  Moderate physical hazards
- >22<45
  High physical hazards
- >0<4
  Low physical hazards
- <0
  Negligible physical hazards

Decision History:	
Mine feature:	Mine entry
The access to the entry is restricted:	No
Tip: Click on an attribute link above to return to that decision...	

(a)

Return to the Ranking of the problems of abandoned mine entries Expert System Title Page


Expert System - Ranking of the problems of abandoned mine entries by Emmanuel Mhlongo

Environmental hazard score of the entry is between

(For each identified environmental hazard of the mine entry, the source of the risk, pathway(s) and the impact it has on the environmental should be scored using the following criteria: Low (1.5-3.0), Moderate (3.5-5.0) and High (5.5-7.0).This scores should be used to calculate the individual environmental risk scores (Evr) of the entry using equation: Evr=Qi*Pj*Rx Where; Qi is the source of the hazard, Pj is the pathway (given as 1 were the impact is on the aesthetic appearance of the landscape), and Rx is the magnitude of the risk. The determined Pr values should be used to calculate the total hazard score (HZtotal) of the mine entry using the following equation: HZtotal=(SumRi/NF)/n, Where; n is the number of environmental risks identified and NF is the factor of 8 employed to reduce the magnitude of the scores.)

- >22<45
  High environmental hazard
- >4<21
  Moderate environmental hazard
- >0<4
  Low environmental hazards
- <0
  Negligible environmental hazards

Decision History:	
Mine feature:	Mine entry
The access to the entry is restricted:	Not importent for environmental hazards
Tip: Click on an attribute link above to return to that decision...	

(b)

Figure 6.7: An illustration of the instruction of the expert system about the hazard score determination. (a) is the instruction for determination of environmental hazard score and (b) is for the determination of physical hazard score.

6.4.2. Application of the ES-RAME to the mine entries of Giyani and Musina

The developed rule-based ES-RAME was applied to the situation of abandoned mines in the areas of Giyani and Musina in the Limpopo Province of South Africa. The results of the ranking of the physical and environmental hazards of the mine shafts in the study area are shown in *Figure 6.8a* and *b*. The ranking process demonstrated that the physical hazards of shafts in the two areas ranges from negligible to moderate levels. In this case, the physical hazard scores of the mine entries ranged from the minimum of 0.04 to the maximum of 15.09 (see *Figure 6.8a*). On the other hand, the environmental hazard scores ranged from 0.47 to 9.67 which resulted to the classification of these hazards ranging from low to moderate levels (see *Figure 6.8b*).

Based on the physical and environmental hazards score of the mine shafts, the ES-RAME classified the socio-economic concerns of the mine shafts in the Giyani and Musina areas to be ranging from negligible to a moderate level. In this case, the mine shafts that were recently treated or closed using both backfilling and installation of concrete plugs had negligible physical hazards while mine shafts that had minor ground movements were found to have low environmental problems. Most of the mine shafts that were treated/closed using concrete slabs and those that were found open were classified as having low and moderate socio-economic concerns respectively. The mine shafts that had relatively elevated socio-economic concerns the moderate category were the shafts with vandalized or unstable closure structure that are also on unstable grounds in Musina and the inclined shafts that the illegal gold miners use to enter the underground mines in the Giyani area. The guidance given by the expert system in terms of what should be the focus of the treatment work in these mine shafts as captured in the conclusion pages of the ES-RAME are shown in *Table 6.4.*

Table 6.4: Ranking of problems of mine entries and the objectives of their treatment in the Giyani and Musina areas.

Problems of the mine entries	Conclusion- Ranking of the issues of the mine entries	Mine shaft treatment objevtives
Physical hazards and social concerns	Negligible	Monitoring of newly treated mine entries
	Low	Maintaining or maintenance and repairing of deteriorating treatment strategies
	Moderate	Closure of mine entries using temporary structures
Environmental hazards and economic concerns	Low	Monitoring of newly treated mine entries
	Moderate	Maintaining and repairing of deteriorating treatment strategies

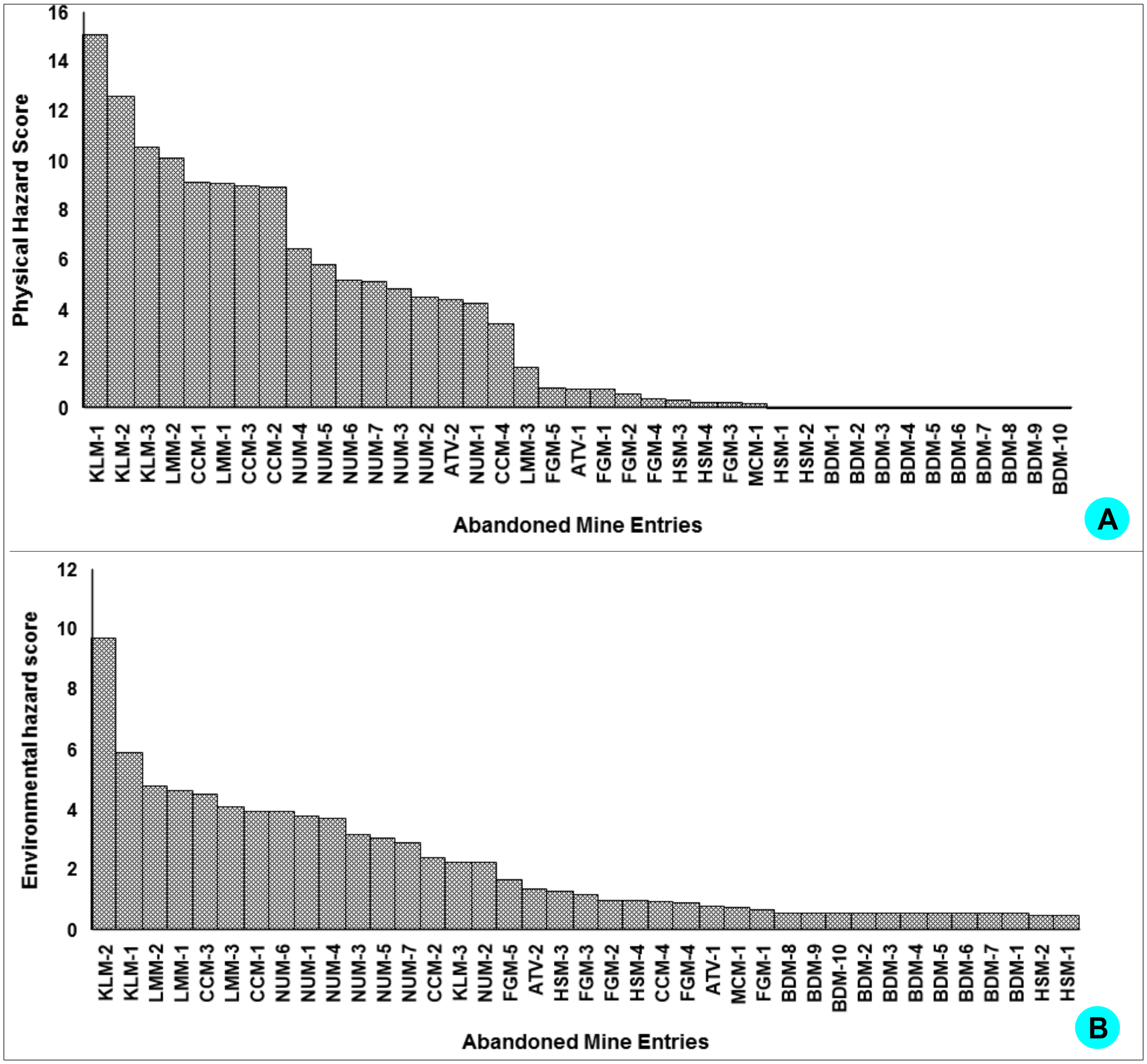


Figure 6.8: Physical (a) and environmental (b) hazards scores of the mine entries in the Giyani and Musina areas.

6.4.3. Implication for treatment of the mine entries

The analysis of the state or condition of the abandoned mine entries conducted in this research showed that these entries are generally characterized by noticeable levels of physical and environmental hazards. These hazards also have impact on the social and economic development of the host communities and/or the whole region where the abandoned mines are found. As a result, it is important that these concerns or problems of the abandoned mine entries be addressed through a progressive implementation of short- and long-term treatment strategies. Since there is generally an overlap between the categories of the problems of the mine entries, the implementation of the rehabilitation or treatment strategies can be in the manner that overlaps as shown in *Figure 6.9*.

In this case, the mine entries that have half score of the negligible category of the hazards to the half score into the category of low hazards, the treatment should focus on maintaining and repairing the failing or collapsing structures previously adopted in the treatment of the mine entries. Moving from low to moderate hazard categories, the treatment of the entries should mostly use structures that temporarily close the mine entries. The implementation of the strategies that provide permanent closure of the abandoned mine entries is to be considered in the case of mine entries that have hazard scores that are at half distance from the moderate to high category. A graphical illustration of the recommended implementation of the treatment strategies for abandoned mine entries and the focus of the treatment efforts is shown in *Figure 6.9*.

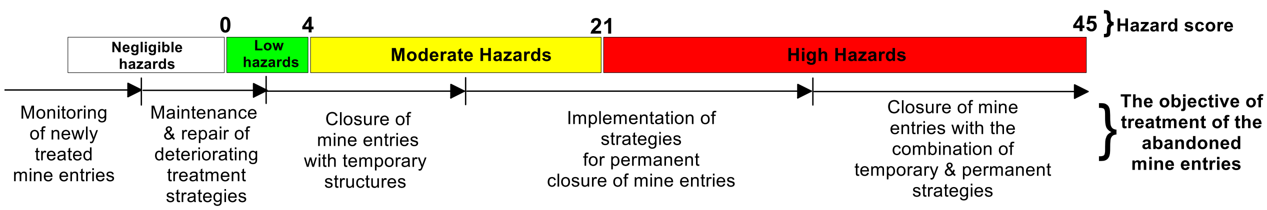


Figure 6.9: An illustration of the best approach for treatment of abandoned mine entries.

6.5. Description of the Expert System for Ranking the Mine Tailings Dumps for Rehabilitation – (ES-RTDR)

The approach used by the expert system of ranking the abandoned mine tailings dumps for rehabilitation (ES-RTDR) required that the general physical outlook of the dumps together with their potential to pollute the environment are established. Therefore, this require that the field assessment of the impact of abandoned tailings dumps on the appearance of the natural landscape is conducted. The concentration of toxic metals in tailings material and their textural properties should also be established prior to the use of the ES-RTDR. This information about the tailings material and dumps is used to determine the three indices (*viz.*, index of contamination, index of dispersion of tailings material, and the index of landscape and visual impact) that are used in the calculation of the rehabilitation priority scores (RP_{score}) of the dumps. The ES-RTDR assists with providing a step by step guidance on the determinations of these indices. Based on the determined rehabilitation priority scores of the tailing dumps, the ES-RTDR can classify the dumps as requiring Low, Moderate or High rehabilitation attention. The framework of the method for ranking the abandoned mine waste dumps for rehabilitation used in developing the production rules of the ES-RTDR is shown in *Figure 6.10*. The fact that the possibilities of the other types of mine wastes (*i.e.* waste rock dumps and spoils) to be carried to the surrounding environs thus resulting to environmental pollution are generally low, these types of mine wastes can be classified as requiring negligible attention in rehabilitation.

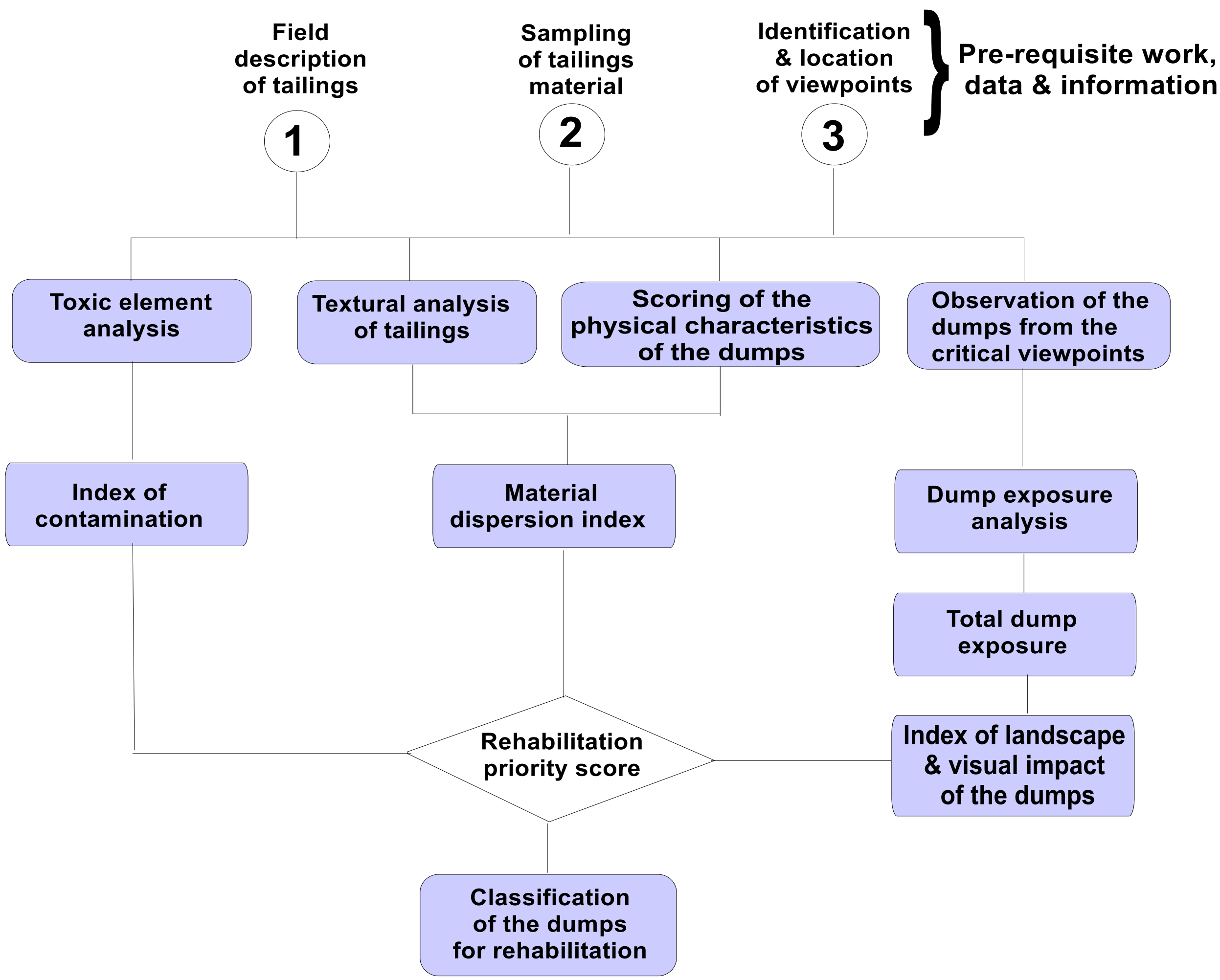


Figure 6.10: Structure of the method for ranking of abandoned mine waste dumps for their rehabilitation.

6.5.1. Production rules and the attributes of the ES-RTDR

The production rules of the ES-RTDR were created from the procedures of the method developed in this research for ranking the abandoned mine tailings dumps for rehabilitation. It basically involved the incorporation of such method in the rule-based expert system shell. In view of this, ES-RTDR provides assistances in the determination of the index values for calculation of the rehabilitation priority score of the abandoned mine waste dumps. These indices are (*i*) the index of contamination (IC), (*ii*) the index of dispersion (ID) of the tailings material to the surrounding areas, and (*iii*) the index of landscape and visual impact (ILVI)of the tailing dumps.

Based on the procedures for determination of the indices for calculation of the rehabilitation priority score developed in this research, the decision tree of the ES-RTDR was created to have five major branches which enabled the expert system to arrive to ten conclusions. The structure of the decision tree and the corresponding decision table are shown in *Figure 6.11* and *Table 6.5* respectively. In this case, the first, second and third branches of the decision tree are concerned with providing a clear guidance on how to determine the IC, ID, and ILVI values respectively. The fourth branch contained rules for determination of the rehabilitation priority scores based on the calculated IC, ID, and ILVI values. The rehabilitation priority score determined based on the guidance of the ES-RTDR is then used to rank the mine tailings dumps for rehabilitation. Based on the determined rehabilitation priority score for the dumps, the urgency or exigency of their rehabilitation can be classified as Low, Moderate or High.

In this expert system, the conclusions are presented with notes that advices on how the index values or rehabilitation priority scores of the dumps are determined or computed using the information gathered following the guidance by the expert system in different stages of the ranking process. In the process of arriving at any given conclusion, the ES-RTDR guides the user of the system on what to be done to establish the parameters required for the calculation of the index values for determination of the rehabilitation priority scores. The notes provided by the system as a way of guiding the user in different aspects of ranking the mine waste dumps for rehabilitation are shown together with other attributes of the ES-RTDR in *Table 6.6*.

Similar to the expert system developed for ranking the problems of abandoned mine entries, the ES-RTDR was also created to use forward chaining of the decision rules stores in the knowledge base to arrive in any conclusion. These rules and the applied Certainty Factors (Cf=1) are shown in the knowledge base table depicted in *Appendix-I*. In addition, the ES-RTDR was also created to work in an interactive manner. The user is guided by the ES through the processes of assigning weights in different aspects of the tailing dumps. These weights are assigned based on the information collected by means of field characterization and laboratory analysis of the tailings dumps or material. This made it possible for site-specific issues of the dumps to be easily incorporated in the ranking of the dumps for rehabilitation.

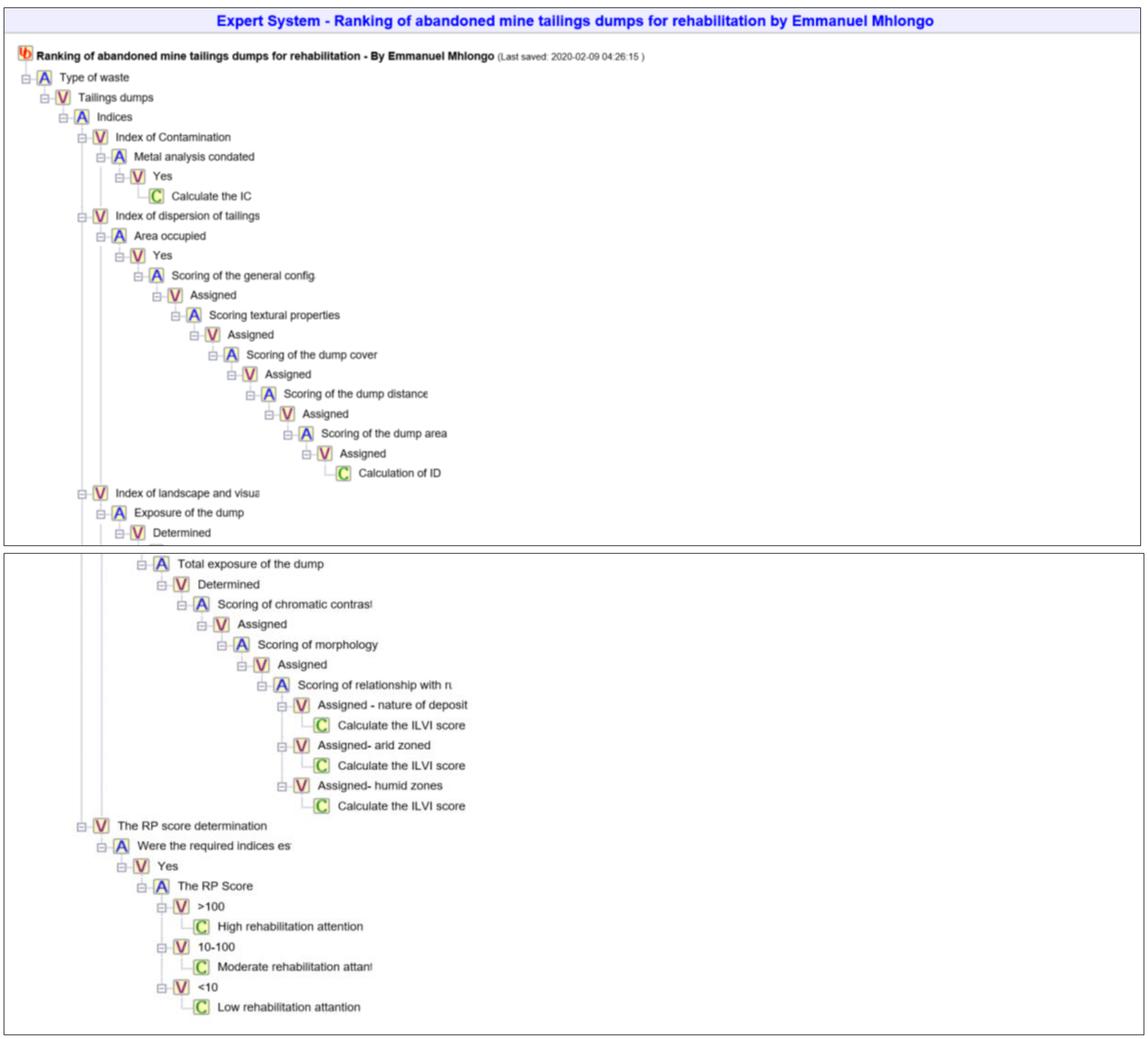


Figure 6.11: Structure of the decision tree for ranking abandoned mine waste for rehabilitation.

Table 6.5: Decision table of the ES-RTDR.

Conclusion	Type of waste	Indices	Metal analysis conducted	Area occupied	Exposure of the dump	Scoring of the general configuration	Scoring textural properties	Scoring of the dump cover	Scoring of the dump distance from water	Scoring of the dump area	Total exposure of the dump	Scoring of chromatic contrast	Scoring of morphology	Scoring of relationship with surroundings	Were the required indices established	The RP Score
Need for calculation of the mean contamination index of the tailings	Tailings dumps	Index of Contamination	Yes	-	-	-	-	-	-	-	-	-	-	-	-	-
Need for calculation of the index of dispersion of the tailing material	Tailings dumps	Index of dispersion of tailings	-	Yes	-	Assigned	Assigned	Assigned	Assigned	Assigned	-	-	-	-	-	-
Need the calculation of the index of landscape and visual impact (ILVI)	Tailings dumps	Index of landscape and visual impact	-	-	Determined	-	-	-	-	-	Determined	Assigned	Assigned	Assigned - nature of deposit	-	-
Need the calculation of the index of landscape and visual impact (ILVI)	Tailings dumps	Index of landscape and visual impact	-	-	Determined	-	-	-	-	-	Determined	Assigned	Assigned	Assigned- arid zoned	-	-
Need the calculation of the index of landscape and visual impact	Tailings dumps	Index of landscape and visual impact	-	-	Determined	-	-	-	-	-	Determined	Assigned	Assigned	Assigned- humid zones	-	-
Low rehabilitation attention	Tailings dumps	The RP score determination	-	-	-	-	-	-	-	-	-	-	-	-	Yes	<10
Moderate rehabilitation attention	Tailings dumps	The RP score determination	-	-	-	-	-	-	-	-	-	-	-	-	Yes	10-100
High rehabilitation attention	Tailings dumps	The RP score determination	-	-	-	-	-	-	-	-	-	-	-	-	Yes	

Notes: - means not applicable

Table 6.6: Attributes of the ES-RTDR.

Node	Text	Values	Notes
Type of waste	Mine waste	Tailings dump (Cf=1.00)	
Indices	Indices for rehabilitation priority score	ILVI (Cf=1.00) [This index describes the impact of the tailings dump on the landscape and the general visual appearance of the landscape. Aims to quantify the impact that the dump has on the appearance of the natural landscape.] Index of dispersion (ID) of tailings material (Cf=1.00) [This index describes the potential of the tailings material to be dispersed to the surrounding areas.] Index of contamination (Cf=1.00) [This index describes the contamination potential of the tailing material.] The rehabilitation priority score of the dump (Cf=1.00) [This is the score that classify the dump in term of the rehabilitation attention the dump deserves.]	The determination of the rehabilitation priority score require that three indices an Index of contamination (IC), Index of dispersion of the tailings (ID) and the index of landscape and visual impact (ILVI) be first determined
Metal analysis conducted	Was the toxic metal content of tailings determined?	Yes (Cf=1.00)	The toxic metal concentration in tailings material should be determined using standard analytical methods (e.g. AAS, XRF etc.).
Area occupied	Is the surface area (A) covered by the dump known?	Yes (Cf=1.00) [The area occupied by the dump should be recorded.]	The area occupied by the tailings dump should be established and recorded in hectare (ha).
Exposure of the dump	Determine the index of exposure of the dump	The IdE of each VP was determined (Cf=1.00)	The index of exposure (IdE) of the dump have to be determined for each viewpoint (VP) using the following equation: IdE=Avis/AVtotal. Where; Avis is the area of the dump visible from the viewpoint, and AVtotal is the established total surface area of the dump.
Scoring of the general configuration	Scoring of the general morphology of the dumps (id)	The score is accordingly assigned (Cf=1.00)	The score should be accordingly assigned to the following morphological characteristics of the dump: (i) Heaped fill (1.00), (ii) Side hill fill (0.80), (iii) Ridge crest fill (0.60), (iv) Valley fill (0.40), and Cross valley fill (0.20)

Table 6.6: *Continued.*

Node	Text	Values	Notes
Scoring textural properties	Scoring of textural properties of the tailing material	The score is accordingly assigned (Cf=1.00)	The texture of the tailings material should be score as follows: (i) Gravel soil - 50% or more of course fraction retained in No.4 sieve (0.10), (ii) Sandy soil - 50% or more course fraction passes the No.4 sieve (0.50), (iii) Clayey soil - 50% of fine fraction passes 2.0um (0.80), and (iv) Silt soil - 50% of fine fraction is retained between 0.6mm and 0.002mm sieves (1.00).
Scoring of the dump cover	Scoring of the cover property of the dump	The score is accordingly assigned (Cf=1.00)	The following cover property should be scored accordingly: (i) the slopes and top surface of the dump are without any cover (1.00), the top surface is covered by indigenize plant/grass (0.75), (iii) slopes are covered by indigenize plant/grass (0.50), and the dump is completely covered by indigenize plants/grass (1.25)
Scoring of the dump distance from water	Scoring of the distance of the dump from surface water bodies	The score is accordingly assigned (Cf=1.00)	The following average distances of the dump away from the surface water bodies should be accordingly scored: (i) > 100m (1.00), (ii) 100-300m (0.75), (iii) 300-600m (0.50), and (iv) 600-1000m (0.25).
Scoring of the dump area	Scoring of the surface area occupied by the tailings dump	The score is accordingly assigned (Cf=1.00)	the area occupied by the dump should be accordingly scored as follows: (i) the dump occupy an area > 625ha (1.00), (ii) the dump occupy an area of 25-625ha, (iii) the dump occupy an area of 5-25ha (0.80), (iv) the dump occupy an area of 1-5ha (0.40), and (v) the dump occupy an area <1ha (0.20)
Total exposure of the dump	Determination of the total exposure of the dump	The index of total exposure of the dump was determined (Cf=1.00)	The calculated individual viewpoint exposure (IdE) in each distance zone should be averaged and the following Equation used to calculate the total dump exposure IdEtotal=(sumIdEav/ni), Where; IdEav is the average index of exposure of the dump in a given viewing distance zone, and ni is the number of VPs considered in each distance zone.
Scoring of chromatic contrast	Scoring of chromatic contrast of the dumps	The score was accordingly assigned (Cf=1.00)	This should be scored according to the appearance of the dump: (i) visual similarity (no significant difference from over 1km) (0-1), (ii) significant chromatic contrast (yellow-brown, gray-black) (3-6), (iii) clear differences of colour-natural colour (6-8), and clear differences of colour-artificial colour (8-10)
Scoring of morphology	Scoring of morphology or shape of the physical environment	The score is accordingly assigned (Cf=1.00)	This is scored according to the shape of the deposit or dump: (i) shape of the deposit filling into the natural morphology (0-1), (ii) divergence only in shape, but not in volume (2-4), and divergence in volume and shape (4-10).

Table 6.6: *Continued.*

Node	Text	Values	Notes
Scoring of relationship with surroundings	Scoring of nature of the deposit and its relationship to the surroundings	Assigned to the nature of the deposit (Cf=1.00) [The score should be assigned as follows: (i) mining waste like natural material (0-1), and (ii) mining waste different from the natural surface material (1-4).] Assigned to dumps in arid zone (Cf=1.00) [The score should be accordingly assigned as follows: (i) dump with natural colours (1-2), (ii) dump with unnatural (anomalous) colours (3-5).] Assigned to dumps in humid zones (Cf=1.00) [The score should accordingly assigned as follows: (i) dump with natural colours (0-1), and (ii) dump with artificial colours (2-3).]	
Were the required indices established	The IC, ID and ILVI values should have been determined	Yes (Cf=1.00)	The three indices required for the calculation of the rehabilitation priority score should have been calculated. These indices are: (i) index of contamination (IC), (ii) index of dispersion of tailings material (ID), (ii) index of landscape and visual impact (ILVI).
The RP Score	Calculate the RPscore of the dump	>100 (Cf=1.00) 10-100 (Cf=1.00) <10 (Cf=1.00)	The rehabilitation priority score (RPscore) should be calculated using the following equation: RPscore=(IC*ID) +ILVI. Where; IC is the index of contamination of tailings, ID is the index of dispersion of tailings material, and ILVI is the index of landscape and visual impact

6.5.2. Application of the ES-RTDR to the tailings dumps of Giyani and Musina

In order to test the functionality of the ES-RTDR, it was applied in ranking the tailings dumps in the Giyani and Musina areas for rehabilitation. The determined index values (*i.e.* ID, IC, ILVI) for calculation of the rehabilitation priority scores for the tailings dumps are presented together with the rehabilitation scores (RP_{score}) for the dumps in Figure 6.13. The calculated rehabilitation priority scores for the tailing dumps in the study area demonstrated that the dumps that are without cover and situated in locations that are highly visible to the public should be considered first in the abandoned tailings dumps rehabilitation project. These includes the tailings dumps of Fumani and Klein Letaba mines (see *Figure 6.12*). The fact that the tailings dumps from Fumani Mine are generally having a relatively high potential to pollute the environment (IC value =19.2) resulted to them being on top of the rehabilitation priority list in the study area.

The tailing dumps that have relatively less potential to contaminate the environment but are easily eroded to the surrounding areas can be considered second in the priority list of the rehabilitation work. This includes the magnesite tailings at the Nyala Mine. Contrary, those dumps that are found in less visible areas with slopes and top surfaces that are covered by natural grasses and other form of vegetation can be considered last in the programme of rehabilitation of the tailings dumps in the study area. This is because, the vegetation growing on the dumps contribute to stabilization of the dumps while ensuring that they blend well with the surrounding vegetated landscapes. The vegetation covers also assists in reducing the effect of erosion on the dumps. This is important as it reduces the risks of tailings material being deposited in the surrounding environment in large quantities that will result to pollution of the surrounding areas. This situation of tailings dumps is comparable to that of the tailing dumps found in Mesina Copper Mine and Louis Moore Gold Mine in the study area.

Other mine waste dumps such as spoils and waste rock dumps found at abandoned mines should be considered for uses as material for backfilling the old mine workings or as building material in construction and/or civil engineering projects. For example, waste rock dumps can be crashed to produce aggregate stones used in different civil and construction engineering works. In addition, the spoils can be used without any treatment to backfill mined out areas.

The direct reuse of these mine waste materials is generally supported by the fact that they are mostly of inert nature thus free from or with little pollutants.

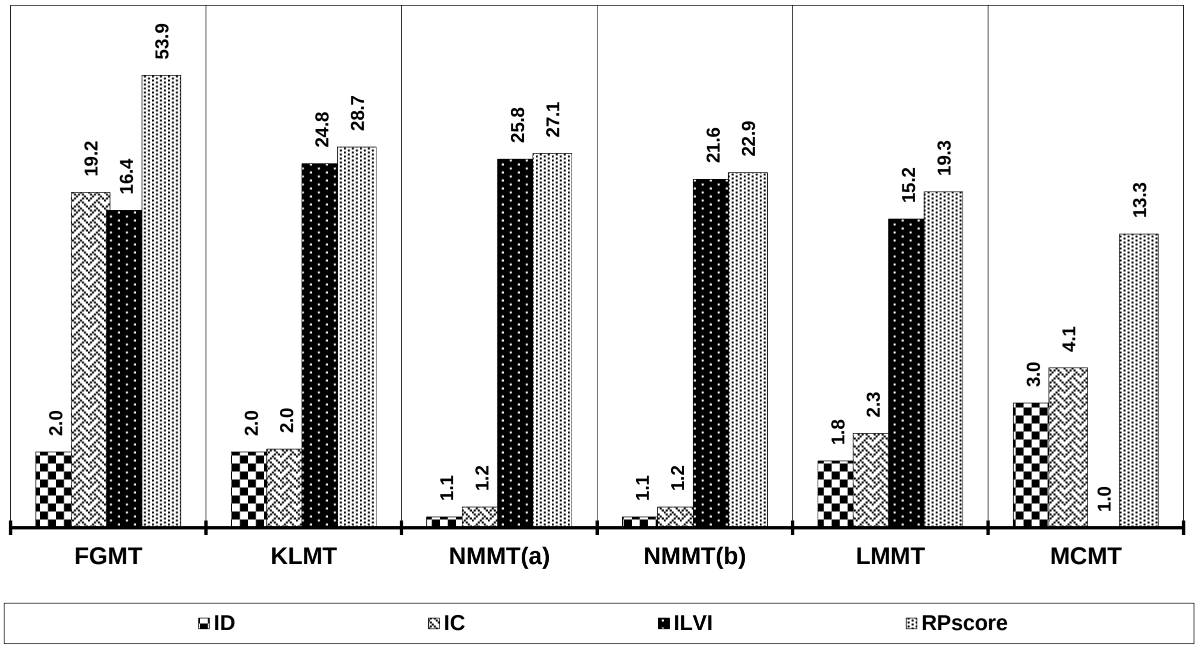


Figure 6.12: Comparison of the index values and the rehabilitation priority score of the tailing dumps.

6.5.3. Rehabilitation approach for abandoned mine waste dumps

The general objective of rehabilitation of mine waste dumps (especially tailing dumps) is to create a stable physical landform that blends well with the surrounding landscape and that is pollution free. This requires that a combination of physical, biological and chemical rehabilitation strategies is adopted in addressing the environmental problems as well as the health hazards of the tailing dumps. However, the efforts of executing these strategies may differ from one dump to the other depending on the prevailing issues of the dumps. The most important issues that require serious attention when rehabilitating the mine waste dumps include the potential of the material to pollute the environment due to high level content of toxic metals and their ease to be dispersed to the surrounding areas by the different erosion processes. Such issues also include the impact of the waste dumps on the appearance and the quality of the landscape (Favas *et al.,* 2018).

In situations where the rehabilitation of abandoned mine tailings dumps is conducted based on the results of the ranking carried out using the ES-RTDR, the rehabilitation approach to be followed can be summarized as shown in *Figure 6.13*. This approach requires that rehabilitation of tailings dumps that have less than 2.2 dispersion index values should involve the use of chemical methods to reduce the toxicity levels of the tailings to a state where they can easily support the growth of vegetation. If necessary, minor physical stabilization of the dumps can be conducted. The reason for this is the fact that tailings dumps that are resistance to erosion are mostly physically stable. In view of this, the methods for physical stabilization of the dumps may be used with limits or as a secondary method. However, as the index of dispersion of the tailings increases from 2.2. to 4.2, physical stabilization of the tailing dumps should be used as primary strategy to reduce the effect of erosion on the tailing dumps. This will assist in reducing the potential effect of erosion on tailings dumps thus minimizing their pollution of the surrounding areas. In this case, the chemical methods should be used as a secondary method after the physical stabilization of the dumps. If necessary, the chemical and physical methods of rehabilitation of the tailing dumps can be implemented concurrently.

In cases where the tailing dumps are found to be having the IC and ILVI values that are between 10 and 100, the rehabilitation efforts should primarily involve the use of physical methods together with biological techniques. The main aim of using these approaches is to ensure that the dumps are physically stable and that their high level of toxic metals are reduced. In order to promote easy growth of vegetation on such tailings, little use of chemical strategies can be considered. In situations where the dumps are found to be having IC and ILVI values that are greater than 100, all three approaches (*i.e.*, physical, biological and chemical methods) should be equally executed.

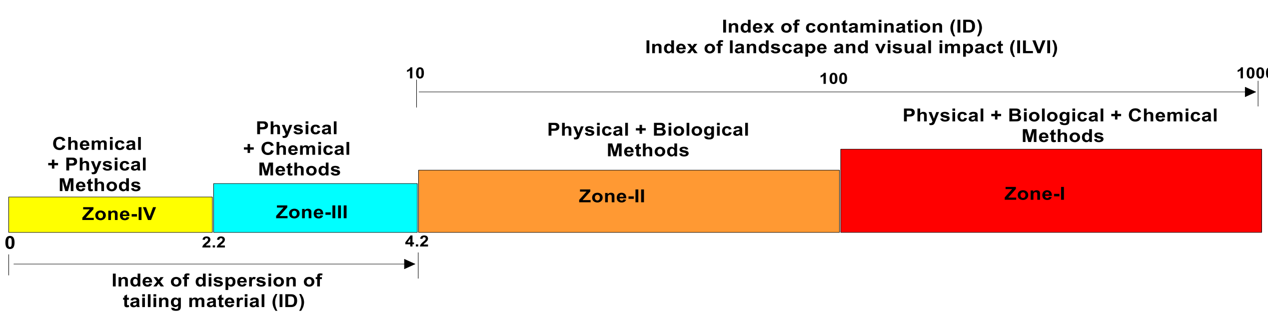


Figure 6.13: An illustration of the proposed approach for rehabilitation of abandoned mine tailings dumps.

6.6. Description of the Expert System for Selection of Rehabilitation Strategies for Abandoned Mines – (ES-SRSA)

Based on the knowledge of the environmental and physical hazards as well as the socio-economic issues of abandoned mine entries; waste dumps; surface excavations and other abandoned mine infrastructure, the objectives of the rehabilitation work for these features were developed. These objectives formed the basis for the development of the decision tree and knowledge base rules of the expert system for selection of strategies for treatment and/or rehabilitation of the abandoned mines. The approach for rehabilitation of any of the abandoned mine features can use either physical, biological and/or chemical methods (Mchaina, 2001, Festin *et al.,* 2018). However, in execution, such strategies can be accordingly combined to effectively address the issues of the abandoned mine features. *Figure 6.14* depicts the steps followed in gathering knowledge and information for the development of the production rules of the expert system of selecting rehabilitation strategies for abandoned mine sites or features.

The evaluation of the suitability of the strategies to treat and/or address the problems of abandoned mine entries was carried out using the AHP and Pugh Matrix techniques. The results of this analysis are presented, analyzed and discussed in Chapter Three of this thesis. This evaluation assisted in ensuring that the best strategies for dealing with the specific problems of abandoned mine entries while ensuring their short-term, medium-term (temporary) and long-term (permanent) closure of the shafts are identified. Based on the knowledge of treatment of abandoned mine entries generated from this process, the decision tree that contain production rules were created. These rules provide guidance on about the most appropriate strategies for addressing the problems (mainly the physical hazards, environmental problems and socio-economic issue) of the abandoned mine entries.

The approach for selecting a combination of strategies for rehabilitation of abandoned mine waste dumps (*esp.* tailings dumps) was developed based on the results of the ranking method developed in this research. Based on the results of the ranking of the waste dumps, the combination of the techniques to be used in the rehabilitation of the waste dumps can be identified. This assisted with the development of the production rules that are used by the expert system to guide on the best approaches for rehabilitation of the abandoned mine waste dumps. These rules are based on the guidance given by the procedure of the method developed in this research to define the problems of the abandoned waste dumps whole ranking them for rehabilitation.

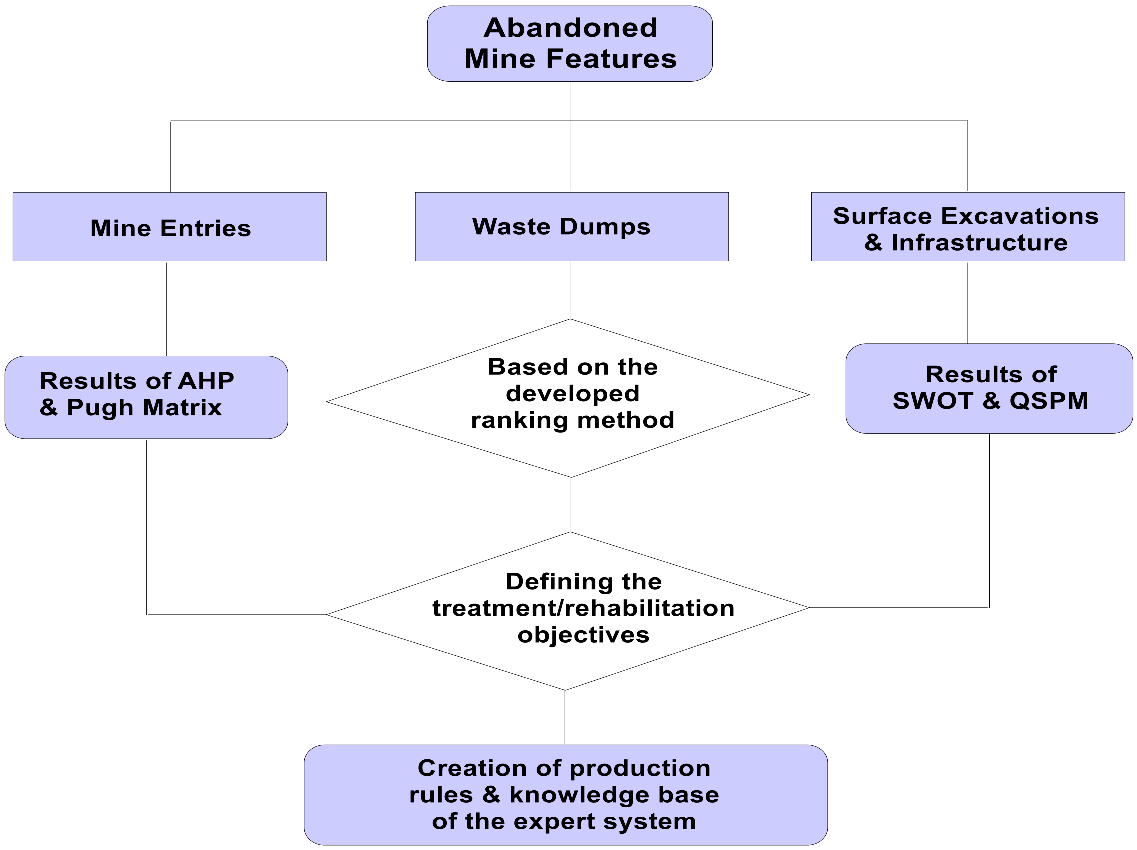


Figure 6.14: Framework for development of production rules for the expert system for selection of rehabilitation strategies for abandoned mine features.

The approaches for dealing with the issues of abandoned surface mine excavations and other abandoned mine infrastructure were identified during the field description of the abandoned mine sites in the study area. For all identified options, their SWOT analysis was performed to establish their suitability for dealing with the problems of the situation of abandoned mines. The suitability of the rehabilitation strategies was established by calculating the attractiveness scores of the different options. The QSPM method was used for this purpose. Based on this evaluation, the appropriateness of the evaluated approaches in dealing with the problems of abandoned surface mine excavations and different surface infrastructure were identified. This knowledge was very crucial in the development of the production rules and the decision tree of the expert system of selecting of appropriate strategies for the reduction or elimination of the physical and environmental hazards as well as the socio-economic concerns of the abandoned surface mine excavations and other infrastructure.

6.6.1. Production rules and attributes of ES-SRSA

In general, the selection and execution of strategies for rehabilitation of abandoned mines depend on different factors. Some of the external factors that are important in the selection of the rehabilitation strategies for abandoned mines relate to the availability of material and skills for implementation of the strategies found to be the most appropriate for the site or feature. In view of this, the production rules of ES-SRSA were created to provide guidance on what should be the focus of the rehabilitation work given the set of rehabilitation objectives or the proposed post-mining uses of the land. The set of objectives of rehabilitation of the different features of abandoned mines in the study area are presented in *Table 6.7*. This approach of reasoning of the production rules of the expert system is known as backward reasoning. According to Matthew *et al.* (2016), the backward reasoning approach involve making a hypothesis about a possible or likely outcome and then work backwards to collect the evidence that would support such conclusion. The production rules contained in the knowledge base of the ES-SRSA are presented in *Appendix-J* while the structure of the decision tree is presented in *Appendix-K* and its decision table in *Table 6.8.*

The approach used by the expert system to identify the ways of addressing the problems of abandoned mine sites is that the features responsible for the hazards should be first identified. This mostly involved locating the different features that are found in abandoned mines landscapes. In addition, the physical and environmental hazards as well as the associated socio-economic concerns of such features should be identified and quantified so that the objectives of the rehabilitation project can be developed. The production rules built into the expert system shell in this work enabled the ES-SRSA to identify a range of options that can be adopted to fulfill the objectives of the work of rehabilitation.

Table 6.7: Set of objectives of rehabilitation of abandoned mine features in the study area.

Feature	Type	Rehabilitation Objectives
Mine entries	Vertical shaft	▪ Prevention of ground movement ▪ To use simple strategies ▪ Use of strategies that require little maintenance ▪ Protect species inhabiting the shaft ▪ Prevent risks of physical injuries
	Inclined shaft	▪ Prevention of ground movement ▪ Protect species inhabiting the shaft ▪ Prevent people and animals from entering the shafts ▪ Use easy to install strategies ▪ Prevention of discharge of mine water
	Adit	▪ Protect species inhabiting the shaft ▪ Prevention of discharge of mine water ▪ Prevent people and animals from entering an adit
Mine waste	Tailings	▪ Improving the physical stability of the dump ▪ Reduce the concentration of toxic metals from tailings ▪ Improve the physio-chemical properties of tailings ▪ Removal of the dump
	Waste rock	▪ Removal of the dump
	Spoil	▪ Removal of the dump
Surface excavation		▪ Pit Lake Development ▪ Creating an acceptable landform ▪ Prevention of access of the excavation ▪ Reducing of the slopes of the pit
Other abandoned mine features	Silos and ore bins	▪ Removal from the landscape
	Mine roads	▪ Removal and rehabilitation of the land
	Concrete water reservoirs and stands	▪ Demolition and removal
	Mine houses	▪ Demolition and removal ▪ Protection and reconditioning

Table 6.8: Decision table of the ES-SRSA.

Conclusion	Mine features	Type of entry	The aim of treatment	The aim of the treatment process	The aim of the treatment process	Type of waste	The aim of the rehabilitation work	The aim of the rehabilitation work	Aim of the work	Aim of the work	Aim of the work
Prevention of access of the entry.	Mine entries	Vertical shaft	prevent risks of physical injuries	-	-	-	-	-	-	-	-
Permanent sealing of the shaft.	Mine entries	Vertical shaft	Prevention of ground movement	-	-	-	-	-	-	-	-
Use of strategies that are simple to apply	Mine entries	Vertical shaft	to use simple strategies	-	-	-	-	-	-	-	-
Apply durable strategies.	Mine entries	Vertical shaft	use of strategies that require little maintenance	-	-	-	-	-	-	-	-
Use of strategies that leave the shaft open for the movement of the species inhabiting them.	Mine entries	Vertical shaft	Protect species in the shaft	-	-	-	-	-	-	-	-
Permanent sealing of the shaft	Mine entries	Inclined shaft	-	Prevention of ground movement	Prevention of ground movement	-	-	-	-	-	-
Use of strategies leave the shaft open for the movement of the species inhabiting them.	Mine entries	Inclined shaft	-	Protection of species in shafts	Protection of species in shafts	-	-	-	-	-	-
Prevention of entry into the shaft.	Mine entries	Inclined shaft	-	prevent people and animals from entering the shafts	prevent people and animals from entering the shafts	-	-	-	-	-	-
Use of strategies that are simple to apply.	Mine entries	Inclined shaft	-	use easy to install strategies	use easy to install strategies	-	-	-	-	-	-
Use of strategies that are watertight	Mine entries	-	-	prevention of discharge of mine water	prevention of discharge of mine water	-	-	-	-	-	-
Enhance the physical stability of the dumps.	Mine waste	-	-	-	-	Tailings	-	-	Improving the physical stability of the dump	Improving the physical stability of the dump	Improving the physical stability of the dump
Use of biological methods.	Mine waste	-	-	-	-	Tailings	-	-	Reduce the levels of toxic metals from tailings	Reduce the levels of toxic metals from tailings	Reduce the levels of toxic metals from tailings
Use of chemical methods.	Mine waste	-	-	-	-	Tailings	-	-	Improve the soil physcio-chemical properties	Improve the soil physcio-chemical properties	Improve the soil physcio-chemical properties

Table 6.8: *Continued.*

Conclusion	Mine features	Type of entry	The aim of treatment	The aim of the treatment process	The aim of the treatment process	Type of waste	The aim of the rehabilitation work	The aim of the rehabilitation work	Aim of the work	Aim of the work	Aim of the work
Use as backfilling material	Mine waste	-	-	-	-	Spoil dumps	-	-	Removal of the dumps	Removal of the dumps	Removal of the dumps
Filling up of the pits with water	Surface excavations	-	-	-	-	-	Pit Lake Development	Pit Lake Development	-	-	-
Backfilling of the excavations	Surface excavations	-	-	-	-	-	Creating of an acceptable landform	Creating of an acceptable landform	-	-	-
Fencing of the excavations	Surface excavations	-	-	-	-	-	Prevention of access of the excavation	Prevention of access of the excavation	-	-	-
Recontouring and reuse of the excavation	Surface excavations	-	-	-	-	-	Reducing of the slopes of the pit	Reducing of the slopes of the pit	-	-	-
Reuse of tailings	Mine waste	-	-	-	-	Tailings	-	-	Removal or reduction	Removal or reduction	Removal or reduction
Reuse of tailings	Mine waste	-	-	-	-	Tailings	-	-	Removal or reduction	Removal or reduction	Removal or reduction
Reuse of tailings	Mine waste	-	-	-	-	Tailings	-	-	Removal or reduction	Removal or reduction	Removal or reduction
Reuse of tailings	Mine waste	-	-	-	-	Tailings	-	-	Removal or reduction	Removal or reduction	Removal or reduction
Reuse of tailings	Mine waste	-	-	-	-	Tailings	-	-	Removal or reduction	Removal or reduction	Removal or reduction
Reuse of tailings	Mine waste	-	-	-	-	Tailings	-	-	Removal or reduction	Removal or reduction	Removal or reduction
Reuse of tailings	Mine waste	-	-	-	-	Tailings	-	-	Removal or reduction	Removal or reduction	Removal or reduction
Reuse of tailings	Mine waste	-	-	-	-	Tailings	-	-	Removal or reduction	Removal or reduction	Removal or reduction
Reuse of tailings	Mine waste	-	-	-	-	Tailings	-	-	Removal or reduction	Removal or reduction	Removal or reduction
Reuse of tailings	Mine waste	-	-	-	-	Tailings	-	-	Removal or reduction	Removal or reduction	Removal or reduction
Reuse of tailings	Mine waste	-	-	-	-	Tailings	-	-	Removal or reduction	Removal or reduction	Removal or reduction
Reuse of the rock waste	Mine waste	-	-	-	-	Waste rock dumps	-	-	Removal of the dumps	Removal of the dumps	Removal of the dumps
Reuse of the rock waste	Mine waste	-	-	-	-	Waste rock dumps	-	-	Removal of the dumps	Removal of the dumps	Removal of the dumps
Other	Mine waste	-	-	-	-	Waste rock dumps	-	-	Removal of the dumps	Removal of the dumps	Removal of the dumps

Table 6.8: *Continued.*

Conclusion	Mine features	Type of entry	The aim of treatment	The aim of the treatment process	The aim of the treatment process	Type of waste	The aim of the rehabilitation work	The aim of the rehabilitation work	Aim of the work	Aim of the work	Aim of the work
Manual demolition	Silos and orebins	-	-	-	-	-	Removal from the landscape	Removal from the landscape	-	-	-
Blasting	Silos and orebins	-	-	-	-	-	Removal from the landscape	Removal from the landscape	-	-	-
Mechanical demolition	Silos and orebins	-	-	-	-	-	Removal from the landscape	Removal from the landscape	-	-	-
Protection and reconditioning of the structure	Silos and orebins	-	-	-	-	-	Reuse of the structure	Reuse of the structure	—	—	—
Cleaning up of the land	Other structures	-	-	-	-	-	-	-	-	-	-
Manual demolition and removal	Other structures	-	-	-	-	-	-	-	-	-	-
Mechanical demolition	Other structures	-	-	-	-	-	-	-	-	-	-
Manual demolition and removal	Other structures	-	-	-	-	-	-	-	-	-	-
Protection and reconditioning	Other structures	-	-	-	-	-	-	-	-	-	-
Manual demolition and removal	Other structures	-	-	-	-	-	-	-	-	-	-
Manual demolition and removal	Other structures	-	-	-	-	-	-	-	-	-	-
Protection and reconditioning	Other structures	-	-	-	-	-	-	-	-	-	-
Use of strategies that leave the shaft open for the movement of species in it	Mine entries	-	-	Protect species inhabiting the shaft	Protect species inhabiting the shaft	-	-	-	-	-	-

Table 6.8: *Continued.*

Conclusion	Purpose of demolition	Type of tailings	Type of waste	Type of structures	Compacted surfaces	Aim of rehabilitation	Location of the building	Aim of rehabilitation	Aim of rehabilitation	Aim of rehabilitation
Enhance the physical stability of the dumps.	-	-	Tailings	-	-	-	-	-	-	-
Use of biological methods.	-	-	Tailings	-	-	-	-	-	-	-
Use of chemical methods.	-	-	Tailings	-	-	-	-	-	-	-
Use as backfilling material	-	-	Spoil dumps	-	-	-	-	-	-	-
Reuse of tailings	-	Phosphate-rich tailings:	Tailings	-	-	-	-	-	-	-
Reuse of tailings	-	Manganese-rich tailings:	Tailings	-	-	-	-	-	-	-
Reuse of tailings	-	Bauxite tailings:	Tailings	-	-	-	-	-	-	-
Reuse of tailings	-	Cupper-rich tailings:	Tailings	-	-	-	-	-	-	-
Reuse of tailings	-	Sand-rich tailings:	Tailings	-	-	-	-	-	-	-
Reuse of tailings	-	Clay-rich tailings:	Tailings	-	-	-	-	-	-	-
Reuse of tailings	-	Iron-rich tailings:	Tailings	-	-	-	-	-	-	-
Reuse of tailings	-	Coal discards	Tailings	-	-	-	-	-	-	-
Reuse of tailings	-	Phlogopite-rich tailings:	Tailings	-	-	-	-	-	-	-
Reuse of tailings	-	Ultramafic tailings:	Tailings	-	-	-	-	-	-	-
Reuse of tailings	-	Potential for reprocessing	Tailings	-	-	-	-	-	-	-
Reuse of the rock waste	-	-	Waste rock dumps	-	-	-	-	-	-	-
Reuse of the rock waste	-	-	Waste rock dumps	-	-	-	-	-	-	-
Other	-	-	Waste rock dumps	-	-	-	-	-	-	-
Manual demolition	Reuse the material	-	-	-	-	-	-	-	-	-
Blasting	Demolishing of concrete silos	-	-	-	-	-	-	-	-	-
Mechanical demolition	Less cost demolition	-	-	-	-	-	-	-	-	-

Table 6.8: *Continued.*

Conclusion	Purpose of demolition	Type of tailings	Type of waste	Type of structures	Compacted surfaces	Aim of rehabilitation	Location of the building	Aim of rehabilitation	Aim of rehabilitation	Aim of rehabilitation
Cleaning up of the land	-	-	-	Mine roads	Removal and rehabilitation of the land	-	-	-	-	-
Manual demolition and removal	-	-	-	Concrete water reservoirs & stands	-	Removal and cleaning of the land	-	-	-	-
Mechanical demolition	-	-	-	Concrete water reservoirs & stands	-	New Value	-	-	-	-
Manual demolition and removal	-	-	-	Mine houses	-	-	The old mine village	Demolition and removal	Demolition and removal	Demolition and removal
Protection and reconditioning	-	-	-	Mine houses	-	-	The old mine village	Reuse of the buildings	Reuse of the buildings	Reuse of the buildings
Manual demolition and removal	-	-	-	Mine houses	-	-	In the areas of mining and mineral processing	Demolition and removal	Demolition and removal	Demolition and removal
Manual demolition and removal	-	-	-	Mine houses	-	-	Miners hostels	Demolition and removal	Demolition and removal	Demolition and removal
Protection and reconditioning	-	-	-	Mine houses	-	-	Miners hostels	Protection and reconditioning	Protection and reconditioning	Protection and reconditioning

In this research, the most possible outcome of the rehabilitation work was identified as the objective of the work, the rules then provide guidance on the strategies that can be adopted to accomplish such objective(s). The ES-SRSA gives a range of options that can be considered in the rehabilitation of the abandoned mine features in order to meet the set objective of the rehabilitation. In some cases, the most preferred strategies are presented as Category-A strategies while their alternatives are presented as Category-B strategies (see the conclusion notes in *Figure 6.15*). It is however important to mention that the rehabilitation strategies provided by the expert system in the conclusion page are merely examples of likely options for dealing with the identified problems of the abandoned mine features. Therefore, in situations where strategies that offer similar advantages as those recommended by the ES-SRSA are available, their execution is highly recommended. This is very impotent particularly in situations where the alternative strategies have proven to be cost-effective.

Expert System - Selection of strategies for rehabilitation of abandoned mine by Emmanuel Mhlongo

Based on the responses you have made:

The rehabilitation strategy of the mine feature: is **almost certainly** Permanent sealing of the shaft.

Conclusion Notes:

The strategies that completely close the open mine shaft should be used. These strategies include: Category-A [(1) Backfilling, and (2) Injection or inclusion] and Category-B [Use of self-supported or Anchored plugs, Blast Closure, Geo-synthetics]

Expert System Rule:

IF the type of the feature: mine entry
AND the type of entry: vertical shaft
AND the aim of treatment: prevention of ground movement
THEN the rehabilitation strategy of the mine feature: is **almost certainly** Permanent sealing of the shaft..

Calculated Certainty Factor: **1.00 = almost certainly**

Return to the Selection of strategies for rehabilitation of abandoned mine Expert System Title Page

Figure 6.15: An example of the conclusion page of the ES-SRSA.

6.7. The rehabilitation approaches

The current focus of rehabilitation of abandoned mines in many countries (including South Africa) has been on addressing the health and safety hazards as well as the environmental problems of these mines. In South Africa, the focus of the rehabilitation of these mines over the reuse been on those sites considered to be high risk to people and animals and then the environment (DMR, 2010). In view of this, rehabilitation of abandoned mines in South Africa has used strategies that addresses the physical and environmental hazards of abandoned mines and no efforts are made to addressing the socio-economic concerns of these mines. The current focus of abandoned mines rehabilitation is South Africa is summarized in *Figure 6.16a.* Comparatively, this research encourages that the efforts of rehabilitation of abandoned mines be such that the sustainable uses of the mine features are given the first-priority in setting the rehabilitation objectives. According to Weyer *et al.* (2017), the principles of sustainable development are impotent for the planning of mine closure and rehabilitation work. The reason being that reuse of the abandoned mine features has potential of contributing to the socio-economic development of the communities found around these mines. In cases where the abandoned mine features or sites are at the deplorable state and cannot be reused for any purpose, the focus of rehabilitation should be on addressing the physical hazards and then the environmental problems of abandoned mines. In this approach; the socio-economic issues of abandoned mines are carefully considered in the planning of the rehabilitation work than just focusing on eliminating the hazards of these mines (see *Figure 6.16b*). For example, some of the old mine shafts and underground mine workings can be used for production of electricity (hydro-power), surface excavations can be developed to pit-lakes that can benefit the communities in many ways, the mine waste can be reused for different purposes including production of building materials while mine houses or buildings can be adopted and used for different community development projects (Menendez *et al.* 2017; Lottermoser, 2011).

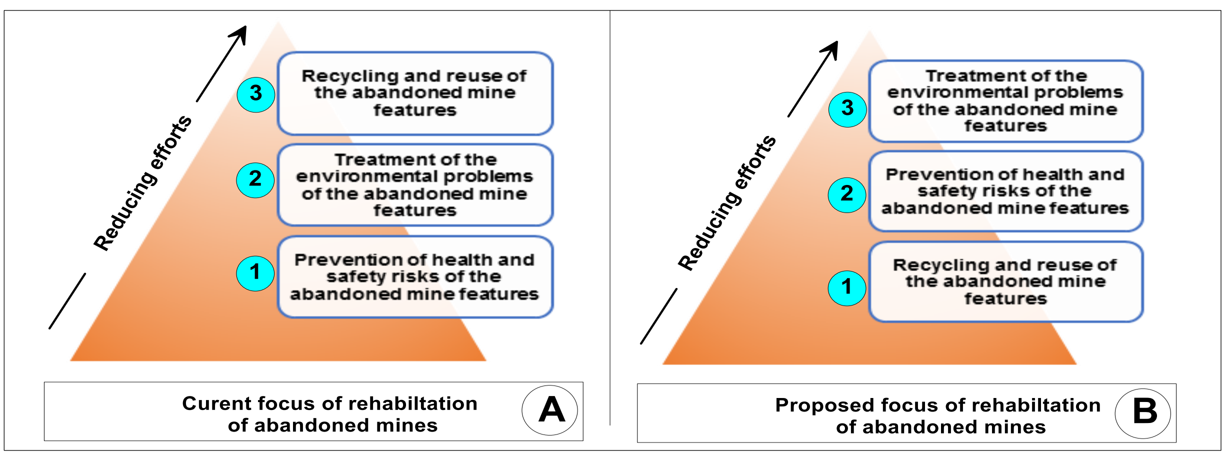


Figure 6.16. An illustration of the comparison of the existing and proposed approaches for rehabilitation of abandoned mines.

6.8. Discussion of Findings of the Study

Abandoned mines are found in all countries and regions with a long history of mining. Addressing the problems of these mines involves making several key decisions which mostly revolve around which features or sites to be rehabilitated first and which strategies are to be used in the rehabilitation of these mines. This is crucial since the rehabilitation of these mines is mostly conducted with limited resources. Therefore, the accuracy of the process of prioritization of the rehabilitation of abandoned mines coupled with the work of selecting the appropriate approaches or strategies for rehabilitation of these mines greatly assist in ensuring that sustainable management of abandoned mines is realized. As a result of this, different countries, individual researchers and organizations have been working in developing decision-making tools to assist in the rehabilitation of abandoned mines. However, not much work has been done to incorporate such tools into an expert system. The only attempt of incorporating a tool for prioritization of abandoned mines in an ES is the Abandoned Mines Hazard Ranking System – AMHAZ. According to Duszak *et al.* (1995) and Mackasey (2000), the AMHAZ used multi-criteria and pairwise comparison to rank the abandoned mines for rehabilitation. It generally used factors such as public safety and health, environmental problems and socio-economic concerns to rank the abandoned mines for rehabilitation.

In this research the method developed for ranking the problems of abandoned mine entries and the method developed for ranking the abandoned mine waste dumps for rehabilitation were incorporated into the web-based expert shell (ES-Builder©2013). Also created into the expert system shell were the production rules for selection of appropriate strategies for rehabilitation of the different features of abandoned mine sites. The creation of these expert systems in the ES-Builder©2013 McGoo Software allowed that the web-link (*i.e.* URL) for each of these expert systems are created (see *Table 6.10*). Using these web-links; each of these expert systems may be published as stand-alone expert systems. This can be done by simply sharing the link or attaching the link to the web-site specially designed for publishing these expert systems.

The methods developed in this research for ranking of the problems of the abandoned mine entries and that of prioritization of the abandoned mine tailings dumps for rehabilitation both developed in the research will assist with gathering important information for setting objectives of the work of rehabilitation of abandoned mine features. The development of these expert systems (ES-RAME and ES-RTDR) together with the ES-SRSA have significantly contributed in ensuring that the systems for abandoned mines prioritization are able to provide guidance even beyond the ranking of these mines for rehabilitation. Moreover, incorporating these methods into an expert system shell promises to reduce the risks of lack of transparency of the procedures of these ranking tools. These issues are known for contributing significantly to hindering the ease of use of the ranking methods; especially outside the areas and context which they were developed (Kubit *et al.,* 2015; Mavrommats and Menegaki, 2017). This is because procedures used by the ranking methods developed in this research are built into the expert systems as production rules and knowledge base of the expert systems. The expert systems also have an advantage of having the work of ranking and selecting the rehabilitation strategies for abandoned mines being conducted simultaneously in different areas following the same procedures incorporated into the expert system shell as production rules of the ESs. Using these expert systems in countries like South Africa that have many abandoned mines will assist in ensuring that the prioritization of rehabilitation and selection of rehabilitation strategies of these mines are effectively and quickly undertaken.

Table 6.9: Description of the developed expert systems.

Name of the ES	Description	URL:
Expert System - Ranking of abandoned tailings dumps for rehabilitation (ES-RTDR).	This expert system ranks the abandoned mine waste dumps for their rehabilitation. It provides advice to the user on which dumps should be given high priority in the rehabilitation work.	http://www.mcgoo.com.au/esbuilder/viewer/viewES.php?es=675471fca87e83c6a876199d23452e1f
Expert System - Ranking of the problems of abandoned mine entries (ES-RAME).	This expert system provides the ranks of the problems of abandoned mine entries so that appropriate strategies for addressing such problems can be identified.	http://www.mcgoo.com.au/esbuilder/viewer/viewES.php?es=008fb028150913e5e22ec4c9e936b304
Expert System - Selection of strategies for rehabilitation of abandoned mines (ES-SRSA).	This expert system provides advise on which strategies to use in the rehabilitation of abandoned mine sites or features. The rehabilitation can make use of a single strategy of a combination of strategies.	http://www.mcgoo.com.au/esbuilder/viewer/viewES.php?es=c5597a3b2dded56971ccbc6459ee444d

6.9. Summary of the Chapter

This chapter focused on creating a computer-based advisory system for rehabilitation of abandoned mines. This was done in the form of three expert systems which (i) rank the problems of abandoned mine entries (ES-RAME), (ii) rank abandoned mine tailings dumps for rehabilitation (ES-RTDR) and (iii) assist in selection of strategies for rehabilitation of abandoned mines (ES-SRSA). These expert systems were created within the ES-Builder Shell©2013 McGoo Software which is a web-based expert system shell. This make the developed expert systems to be easily assessible through or in the internet by following the respective web-link created for each of the systems. The availability of the developed expert systems in the internet is expected to assist in ensuring that the transparency of the methods for characterization and ranking of rehabilitation of abandoned mine shafts and tailings dumps (both incorporated in to the expert system shall) is maintained. This was identified as the major drawback of most of the current existing methods for prioritization of rehabilitation of abandoned mines.

CHAPTER SEVEN

FRAMEWORK FOR ESTIMATION OF REHABILITATION COSTS OF ABANDONED MINES

Once the objectives of rehabilitation of abandoned mines are set and the strategies for rehabilitation are identified, the costs of implementation of such strategies should be estimated. This chapter presents the framework for estimation of the costs of rehabilitation of abandoned mines. The scenarios of implementation of the traditional rehabilitation activities such as backfilling of surface excavations or pits, seeding and application of fertilizers and mulching on graded and backfilled areas of the abandoned mine terrain were used to test the practicality of the proposed methods of cost estimation. Moreover, the scenario of demolition of old mine buildings and closing of disused underground mine shafts with concrete plugs and slabs was also used in this study.

7.1. Background of the Study

In general, abandoned mines are considered a costly legacy of previous mining operations which were conducted with no regard of the protection of the environment. Although it is known that the rehabilitation of abandoned mines is costly, it is still not clear where the funds for carrying out the work of rehabilitation of these mines will come from. South Africa has about 5 906 documented abandoned mines and the cost of rehabilitation of these mines is estimated to be about ZAR30 billion (Cornelissen *et al.* 2019). It is important to indicate that these costs are expected to exponentially increase to a larger figure as the work of rehabilitation of these mines is delayed. According to van Druten and Bekker (2017), the rehabilitation of the documented abandoned mines in South Africa is expected to last for 800 years.

The uncertainties regarding the accuracy of the current estimate of the costs of rehabilitation of abandoned mines in South Africa make it necessary that the method for estimation of such costs is reconceptualized. For example, according to the report by the Auditor-General South Africa (2009), the ZAR30billion rehabilitation costs was made on the assumption that rehabilitation of one mine is expected to cost about ZAR5million. The same report indicated that the rehabilitation of each of the first five abandoned asbestos mines costed up to ZAR8.3 Million (which was 67% higher than the estimate cost). This and the fact that indirect cost (*e.g.* project management costs) and the cost of post-rehabilitation monitoring of the site were not considered in the estimation resulted to underestimation of the rehabilitation costs.

It is important to also note that not much has been done to develop models or methods of estimating costs for rehabilitation of abandoned mines, some researchers such as Pealta-Romero and Dagdelen (2007) and du Plessis and Brent (2006) have tried to develop approaches or tools for estimation of the costs of closure of active mines. In addition to this, there are methods that are used universally by mining companies to estimate the costs of closure of their operations. These methods are (i) financial assurance cost estimate (FACE), (ii) Life of Mine (LOM) closure cost estimate, and (iii) asset retirement obligation (ARO) cost estimate (Nehring and Cheng, 2016; Parshly *et al.,* 2009). Based on the applicability of use as well as the general requirements for use of these methods (see *Table 7.1*), they are generally not fit for use in situations of abandoned mines.

7.1.1. Objectives of this study

The main objective of the work presented in this chapter was to develop a cost estimation framework for rehabilitation of abandoned mines.

The specific objectives were:

- To identify the general activities of rehabilitation of abandoned mines,
- To develop techniques for estimation of the costs of different activities of rehabilitation of abandoned mine sites, and
- To come up with the generic framework for estimation of costs of rehabilitation of abandoned sites.

Table 7.1: Description of the popular methods for estimation of closure costs for active mines (Parshley *et al.,* 2009).

Method	Application	Requirement
1. Financial assurance cost estimate (FACE)	▪ It is used to determine the amount of financial assurance required given the laws, regulations and social-commitments. ▪ It is also applied in jurisdictions where the approved closure plan is to be implemented by the third-party.	▪ The government may add indirect costs to the estimate made to avoid possibilities of incurring some additional costs as the results of it contracting with the private entities. ▪ It does not include the additional costs that may be incurred by the mining company. ▪ Salvage value of equipment and scrap are not normally included in this method.
2. Life of mine (LOM) closure cost estimate	▪ It is used for planning, budgeting and cost tracking. It is mostly used during the prefeasibility and feasibility studies, due diligences audits, accrual allocation, annual planning and budget, and costs tracking.	▪ It assumes that the mining company will use it equipment in closure this the mining company costs are assumed excepts in the activities that will require to be contacted to a third-party. ▪ It allows the closure costs to be incorporated in to the mining operation cost model. ▪ It also allows that the revenue from the reselling and/or salvage of equipment and scrap, and residual production value are included in the cost estimation.
3. Asset retirement obligation (ARO) cost estimate	▪ The method is used for financial reporting to shareholders, IPOs	▪ The cost estimates are prepared yearly as part of the financial reporting. ▪ The cost estimate includes only of the liabilities, development, and commitments that are existing by the end of financial reporting year. ▪ The estimation does not include any activities that a third-party would not incur in meeting the legal obligations ▪ Reduction of any portion of the cost estimate may be allowed as soon as the work is complete. ▪ Like a LOM cost estimate, AROs are calculated on a cash flow basis for inclusion in the corporate financial model. ▪ Revenue from residual production, or the resale or salvage of equipment and scrap cannot be included in the cost estimate

7.2. The Research Design

The development of framework for estimation of the cost of rehabilitation of abandoned mines involved three important stages. The first stage focused on identification of common strategies for rehabilitation of abandoned mine site and their features and structures. Based on the knowledge of the problems of abandoned mines and the strategies for dealing with the problems, a conceptual framework that shows the link of the different abandoned mine features and the corresponding activities for their rehabilitation was created. This was then followed by the development of specific methods of estimating the costs of different rehabilitation activities. These methods were applied on different rehabilitation scenarios that were created using information on situation and/or condition of selected abandoned mines in Giyani and Musina areas of Limpopo province of South Africa. The rehabilitation scenarios were used in this research for both the development of the rehabilitation cost estimation techniques as well as the validation of the applicability of such developed techniques. These scenarios were:

- Rehabilitation of the land affected by surface mining at Nyala Mine through backfilling of the excavations, seeding of backfilled areas, ripping of footprints and compacted areas, and application of fertilizers and mulching of seeded areas.
- Demolition of abandoned mine structures and closing of underground mine shafts using concrete plugs and slabs.

The information created in this process on estimation of the costs of rehabilitation of abandoned mines assisted in developing and discussing a general framework for rehabilitation cost estimation. *Figure 7.1* shows the steps followed in developing the framework for estimation of the costs of rehabilitation of abandoned mine sites.

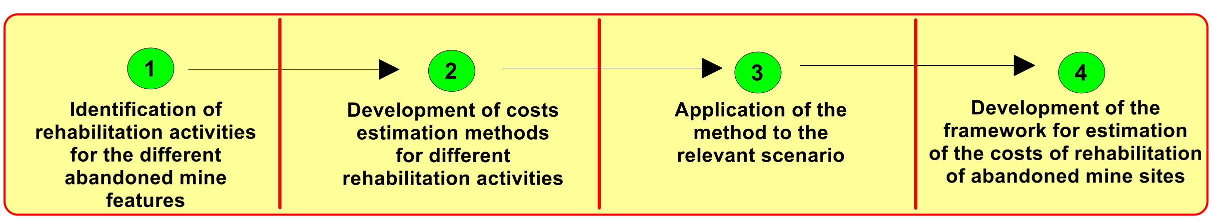


Figure 7.1: Procedure for developing abandoned mines rehabilitation cost estimation framework.

7.3. Activities of Rehabilitation of Abandoned Mines

The process of estimating the costs for rehabilitation of abandoned mine sites requires that adequate knowledge of the nature of the problems of these mines be generated. Based on this, clear objectives of the work of rehabilitation of these mines can be defined and the rehabilitation activities identified. Consequently, it is important that the features of abandoned mine sites that require rehabilitation are identified from the initial stage of the project of rehabilitation of these mines. The link of individual feature to the appropriate rehabilitation strategy(ies) should then be established. According to Peralta-Romero (2007) and Peralta-Romero and Dagdelen (2007), the process of correlating or linking the mine features to be rehabilitated with the general activities of rehabilitation is known as "closure activities mapping".

In this research, such mapping was conducted with the aim of linking the abandoned mine features to the general work of rehabilitation. The features considered in this research included (i) surface excavations (ii) mine entries or shafts (iii) mine waste (i.e. tailings, spoils and waste rock dumps), and (iv) areas where different surface infrastructures were found. Figure 7.2. show the link between the abandoned mine features as documented from the study area used for the work presented in this thesis and the traditional methods of addressing the problems of such mine features.

The section below presents and describes the approaches for estimation of the costs of implementation of the rehabilitation activities for abandoned mines. These are the methods for estimation of the (i) costs of earthworks (*i.e.,* backfilling, spreading of backfill and ripping of footprint areas), (ii) revegetation activities (*i.e.* seeding, application of fertilizers and mulching of seeded areas), and (iii) for estimation of the costs of sealing abandoned underground mine shafts and demolition of disused surface infrastructure (e.g. processing plants, workshops, old buildings, silos and ore-bins). Each of the cost estimation methods developed was applied to the relevant scenario created for this research.

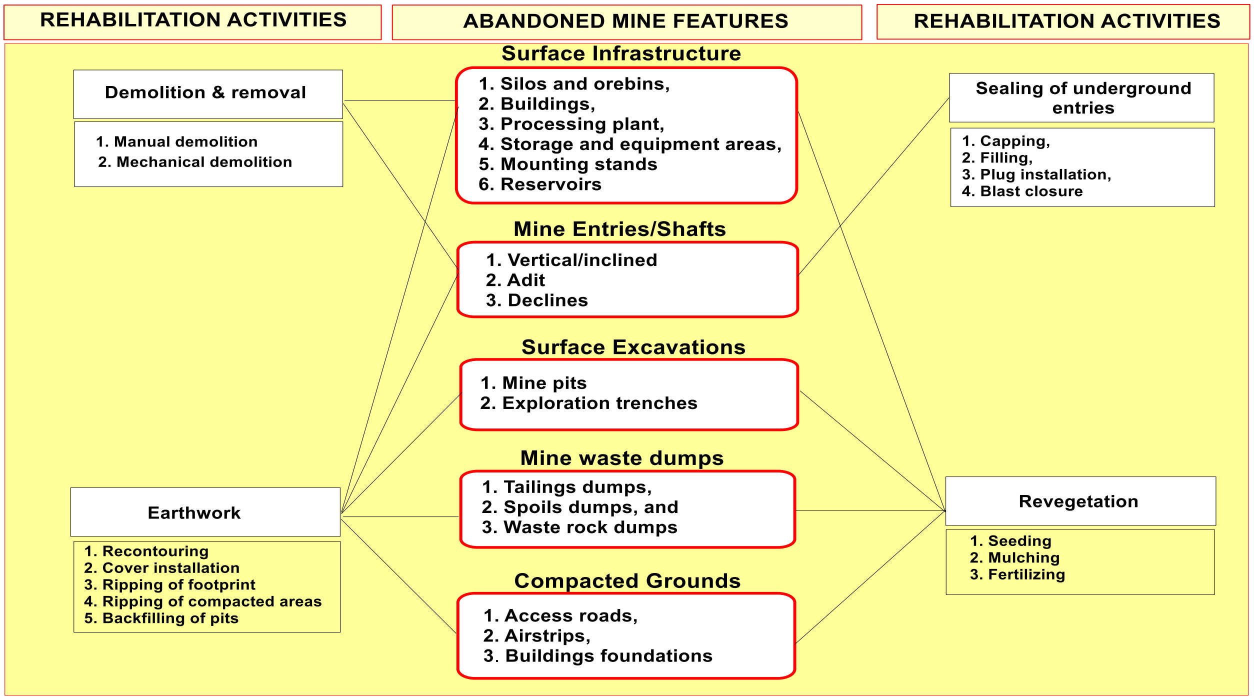


Figure 7.2: Abandoned mine features and their rehabilitation activities.

Although the rehabilitation cost estimation process is generally based on the use of a series of equations, the Microsoft Excel (MS Excel) platform was used in this research to perform the estimation of the of rehabilitation of different features of abandoned mines. The MS Excel spreadsheet of estimation of the cost of rehabilitation conducted in this research are shown in *Appendix-L*. According to Pealta-Romero and Dagdelen (2007), MS Excel have advantages that make it an important and appropriate platform for execution of the cost estimation method or model. Such advantages include the fact that MS Excel (i) is widely available and extremely used by engineers, (ii) it is clear or well understanding of the user interaction with the program, (iii) it has a rage of pre-packaged performance optimized features, and (iv) consists of visual basic for applications (VBA) programming language.

7.4. Method for Estimation of the Costs of Land Rehabilitation

The rehabilitation of land affected by surface mining activities generally require that some earthworks (*i.e.* cut and fill operations, spreading of material and ripping of compacted areas) are carried out and sometimes compaction of fill material. In some cases, these activities may be followed by seeding and applying fertilizer (Land Rehabilitation Guideline for Surface

Coal Mines, 2019). As a result of this, the estimation of the direct cost of earthworks and necessary revegetation activities for the rehabilitation of the land affected by surface mining can be achieved by using standard methods presented in *Appendix-M.* In this case, the direct costs refer to those costs which can be specifically identified with the rehabilitation activities. They include the costs of equipment hire and equipment operation which can be estimated using standard rates such as those found in the Official Rate Guide of the Contractors Plant Hire Association (CPHA). The specification of the equipment used in this research and their respective hiring and operation rates are depicted in *Table 7.2.* The estimation of the costs of rehabilitation of the land affected by mining conducted in this research, required that once the equipment for carrying out the earthworks for the rehabilitation of the abandoned mine land have been identified, their respective performance or productivity should be determined. According to Hola and Schabowicz (2010), the earthworks activities are generally highly mechanized and can be conducted using a single equipment or a set of equipment that are working together. In general, the basic equipment that are mostly needed in land rehabilitation project are tipper trucks, loaders, bulldozers and smooth-drum rollers.

As shown in *Figure 7.3*, based on the estimated direct costs of earthworks activities, the indirect costs are estimated as a percentage of the direct cost. These costs are those that are incurred by the organization for joint and/or common objectives. They cannot be identified with the specific activities of the project (Haymont, *n.d*; Environmental Sustainability Unit, 2002). The details of the indirect costs that are important to incorporate in the mine rehabilitation cost estimation project are presented and described in *Table 7.3.* They are mainly comprised of contingency cost, contractor's profit and overhead cost, the cost of post rehabilitation site monitoring and maintenance, and the cost of mobilization and demobilization of temporary structures erected to support the rehabilitation project on site. The other costs that contributes to indirect cost are those of carrying out the engineering and design studies of the rehabilitation activities.

Table 7.2: Unit rates for earthwork cost estimation (Contractors Plant Hire Association, 2011).

Equipment	Operation	Rates (ZAR)	Unit	Capacity	Equipment model/type
Bulldozer	-	225.00	/hr	-	CAT D3D, D4D, D4E; Daewoo DD80, Komatsu D31A, D31E
	Overhaul	5.00	m^3/km	-	
	Dozing	10.50	/m^3	-	
	Ripping	8,900.00	/ha	-	
Truck	Moving and dumping cut material	254.00	/hr	10m^3	Tipper trucks
Loader	Loading of cut material	245.00	/hr	1.7m^3	CAT 910, 914G, FurukawaFL310 Ball L1004D, L705D; Komatsu WA120 Volvo L30B, L40B; Michigan 35B.
Sıngle-Drum Vıbratory Rollers, Smooth	Compaction and smoothening	221.00	/hr	-	10 - 14 ton, width 2,1 m Bomag 212; CAT CS563D, Dynapac CA251SD;Simesa; NC10SD

Note: - the aspect is not applicable

The method developed in this research estimate direct and indirect costs and then used them to determine the total cost of rehabilitation project. In order to accommodate the impact of any possible increases in consumer prices, the local inflation index corresponding to the year of which the planned rehabilitation project is to be undertaken should be applied to the estimated total cost. In the case where the rehabilitation project is expected to last for or be executed after three years, the cost escalation factor should be applied from the third-year onward to obtain an escalated cost for rehabilitation of abandoned mine sites. Although, the different activities of mine rehabilitation can have varying escalation indices (du Plessis and Brent, 2006), in this research, the use of the escalation index of 10% is recommended. This escalation index is basically the rounded off average escalation index values of different activities of mine rehabilitation (du Plessis and Brent, *op cit*.). The final costs of rehabilitation of land affected by mining can be determined using *Equation 7.1* and the flow of the land rehabilitation activities is shown in *Figure 7.3.*

$$RC_{Total} = \left[\left(\sum D_{Cost} + ID_{Cost}\right) + IF_{Cost}\right] + EC_{Cost} \quad (7.1)$$

Where: RC_{Total} is the total rehabilitation cost, D_{Cost} is the direct cost of the rehabilitation work, ID_{Cost} is the indirect cost of the rehabilitation work, ES_{Cost} is the rehabilitation cost escalation which is 10% of the sum of the direct and indirect costs, and IF_{Cost} is the local inflation cost associated which depends on the estimated.

Table 7.3: Percent distribution of indirect land rehabilitation costs (Reclamation and Closure Guidance, 2013).

Items	Percentage	Description
Contractor Profit and Overhead cost	15-30	▪ The costs are estimated on the assumption that the rehabilitation work will be carried out by third party contractors. ▪ These costs include: project management (managers, superintendents and others), construction office and storage trailers, safety/personal protective equipment, temporary sanitary utilities, quality control, subcontracting costs, overtime costs, employment costs, workers' compensation, clerical support wages, office rent and utilities, insurance, performance bonds and owner's compensation (profit).
Contingency cost	5-10	▪ This cost covers both the uncertainty in the costing estimate and the possibility that some aspects of the closure and reclamation activities may be more difficult to perform.
Monitoring and maintenance cost	5-10	▪ Post-closure monitoring and maintenance costs are estimated. They should reflect the monitoring and maintenance identified in the Closure and Rehabilitation Plan.
Mobilization and/or Demobilization	5-10	▪ It is assumed that a contractor would have to mobilize all equipment and infrastructure to the site in order to carry out the closure and reclamation work. Mobilization of fuel is assumed to be necessary for every site.
Engineering and design	5-10	▪ The engineering and/or design costs are for advancing the Closure and Reclamation Plan into a scope of work that can be provided to a contractor.
Inflation	-	▪ Inflation costs are generally important for all mine rehabilitation and closure projects. These costs should be applied to the combined total of all the direct and indirect costs.
Total (%): 35 to 70 (inclusive of inflation factor)		

Note: - The local inflation rate should be applied.

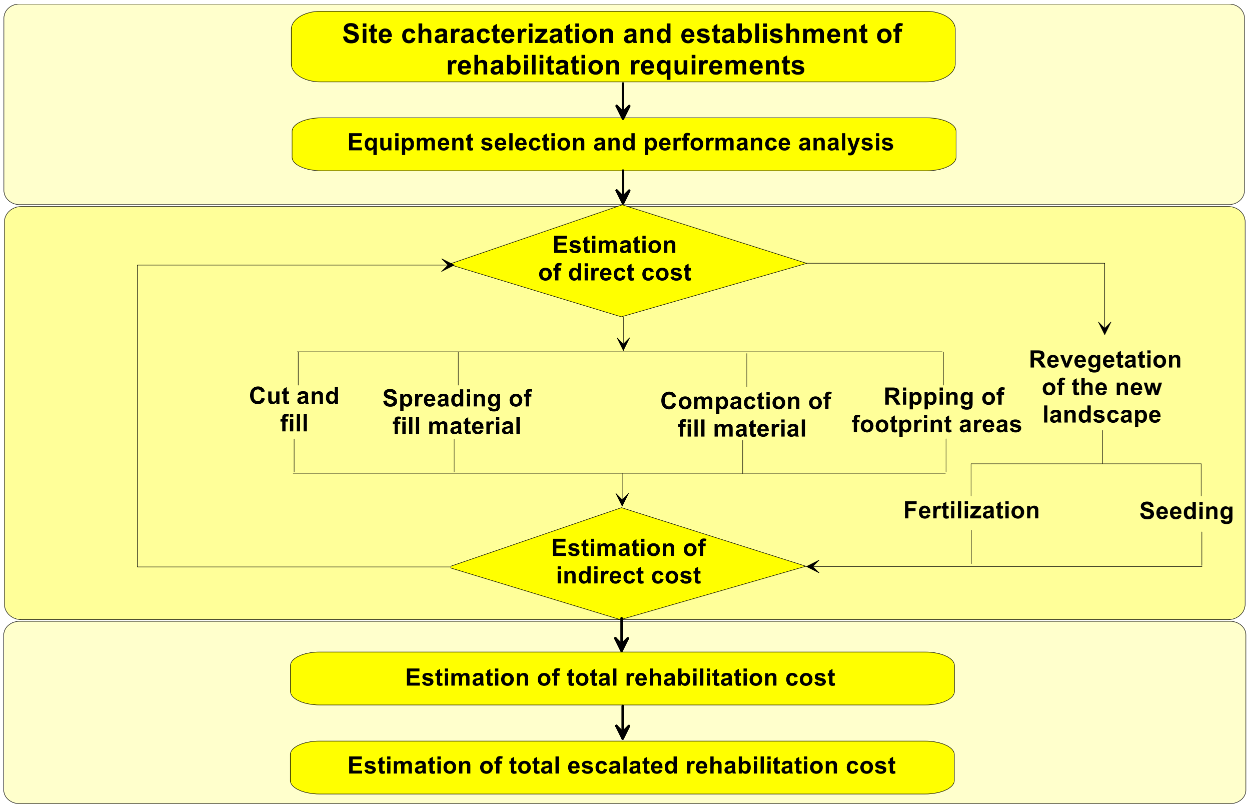


Figure 7.3: A step-wise flow diagram for cost estimation of land rehabilitation.

7.4.1. Estimation of the cost of Nyala Mine land rehabilitation

The use of a surface mining method to mine magnesite at Nyala Mine disfigured the landscape with legacy of several shallow and deep excavations as well as heaps of spoils and tailings material. This has resulted to a considerable large area (≈169ha) of the mined land being unusable and having reduced aesthetic beauty. Based on this, the rehabilitation of the Nyala Mine terrain is expected to involve grading of the mine terrain to fill the void areas (*i.e.* cut-and-fill operations), spreading of fill material, and ripping of footprint areas to prepare the soil for the natural growth of vegetation. The areas of cut-and-fill in different parts of the Nyala Mine terrain are shown in *Figure 7.4* (Mhlongo, 2012). In this case, a total volume of 2269277m^3 of material is to be cut from the areas occupied by spoils and tailings to fill an estimated void of about 2095037m^3 in areas of four surface excavations. From the terrain models of Nyala Mine shown in *Figure 7.3*, the total footprint area that require ripping to promote easy growth of vegetation was estimated to be approximately 716409m^2 (72ha) while the total area that need dozer spreading was estimated to be about 971917m^2 (97ha).

Since there is already natural vegetation (trees and shrubs) growing in different parts of the Nyala Mine landscape, it is important that dump trucks ($10m^3$) and loaders are used in loading and hauling fill material into the areas of backfill. The use of trucks is warranted due to the fact that they can easily maneuver without destroying the trees and shrubs that are already growing in different parts of the mine landscape. Using the information of the required earthworks for the rehabilitation of land affected by mining at Nyala Mine and the hiring and utilization rates of the basic equipment required to carry out such work, the minimum and maximum costs for rehabilitation of the abandoned Nyala Mine land was estimated as shown in *Table 7.4*. The costs estimate showed the costs of reshaping the mine terrain based on the cut and fill operations, spreading of fill material and ripping of compacted footprint areas to support the growth vegetation to be likely to range between ZAR5,3 million to ZAR6,6 million (Including Vat.). The individual costs of these activities (including direct and indirect costs) are depicted in *Table 7.4.* The contribution of the costs of activities to land rehabilitation to the total costs estimated are presented in percentage in *Figure 7.5.* It emerged that that the cut and fill operations which include loading, hauling and dumping of material in the areas to be filled contributes to the highest percentage (46%) to the total cost of earthworks required for rehabilitation of the land affected by mining at Nyala Mine.

Table 7.4: Estimated costs of the unit operations of abandoned Nyala Mine land rehabilitation.

Activities	Costs	Minimum Estimate (ZAR)	Maximum Estimate (ZAR)	Total land rehabilitation costs	
				Min. (ZAR)	**Max. (ZAR)**
Cut and Fill	Direct	1,493,259.18	1,493,259.18	5,299,071.95	6,590,682.07
	Indirect	522,640.71	1,045,281.43		
	Total plus VAT.	**2,413,032.17**	**3,038,633.10**		
Spreading	Direct	906,300.41	906,300.41		
	Indirect	271,890.12	543,780.25		
	Total plus VAT.	**1,410,294.07**	**1,735,746.55**		
Ripping	Direct	948,361.75	948,361.75		
	Indirect	284,508.52	569,017.05		
	Total plus VAT.	**1,475,745.71**	**1,816,302.42**		

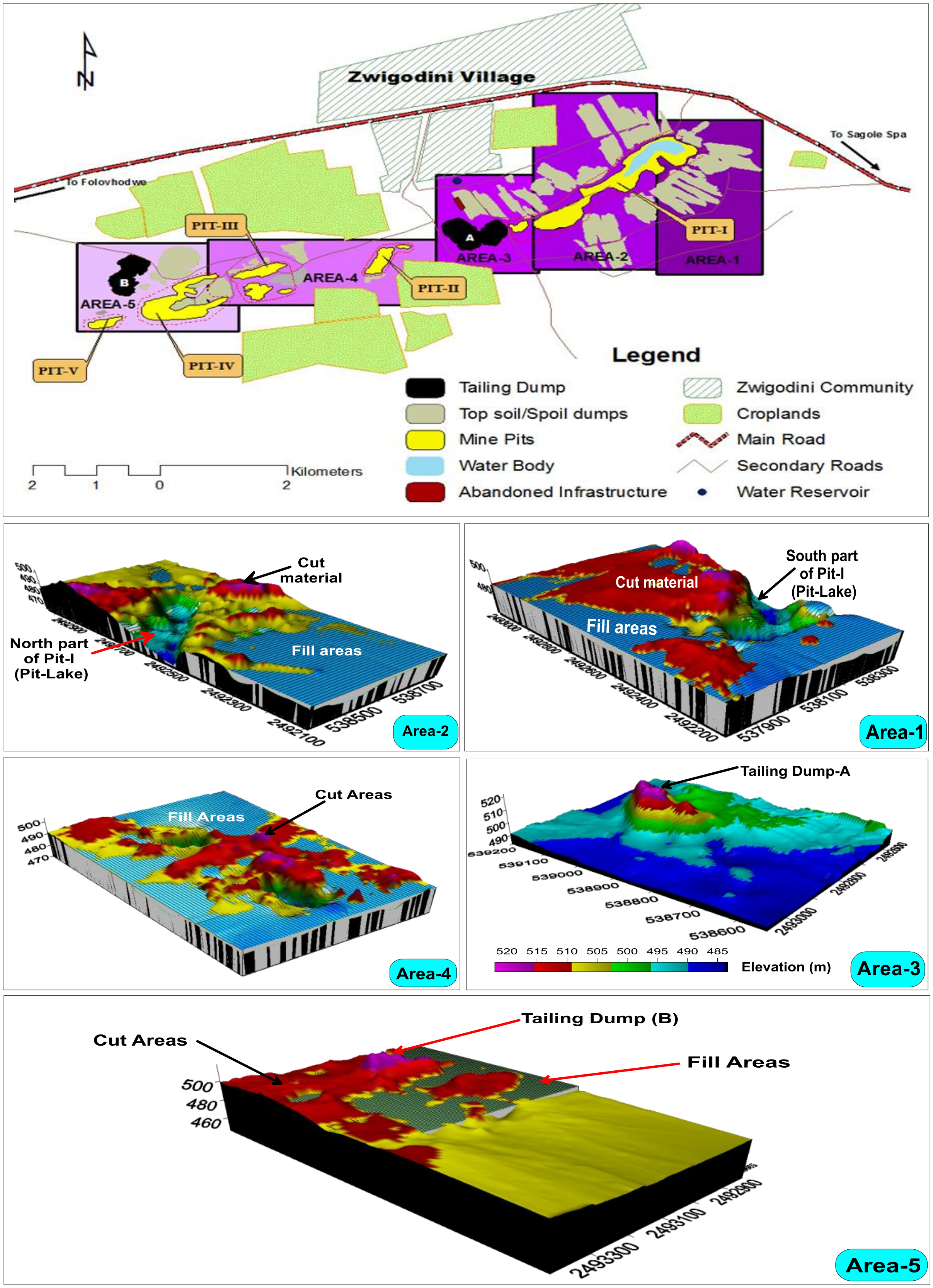


Figure 7.4: An illustration of cut and fill areas at Nyala Mine (Mhlongo, 2012).

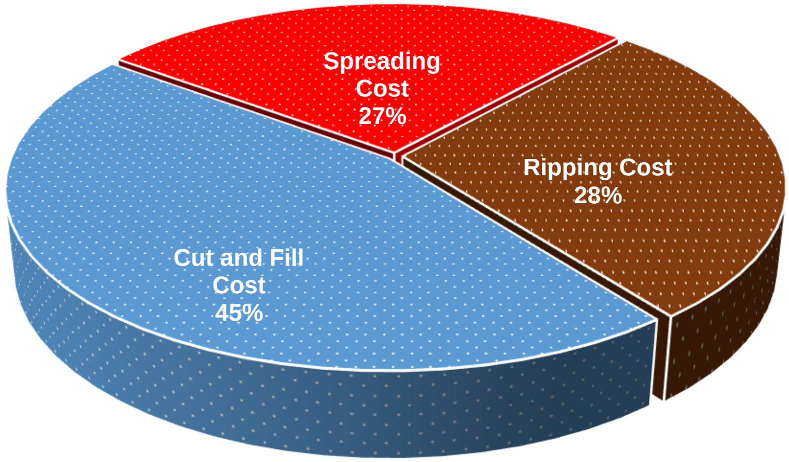


Figure 7.5: Contribution to total cost of earthwork activities of rehabilitation of Nyala Mine.

7.5. Method of estimation of the costs of revegetation of mine terrain

Revegetation of abandoned mine lands is undoubtable one of the important rehabilitation activities to be undertaken. The areas of abandoned mine sites that mostly require revegetation are those where backfilling of surface pits or excavation are to be conducted, the footprint areas where excessive material will have to be cut as well as the slopes of waste dumps and reshaped walls of the surface excavations. The properties of the geological material on which the vegetation is to be established varies from one site to the other. In view of this, the revegetation requirements also varying from one site to the other (Ogle and Reolente, 1988). For example, some sites may require fertilization and seeding after the placement of topsoil, while others may only require fertilization to promote the growth of natural vegetation. Some areas may also be able to support the growth of natural vegetation without application of fertilizers and/or mulching. Although this might be the case, according to Skousen and Zipper (2018), application of fertilizer and/or liming and the mulching of seeded land remain the important component of mined land revegetation and the rehabilitation process at large. In view of this, the method of estimation of the costs for rehabilitation of abandoned mine land developed in this research used the costs of seeding, fertilizer application, and mulching of mine land to estimate the total costs of revegetation. Therefore, the total revegetation costs (RVC_{Total}) of abandoned mine terrain can be estimated using *Equation 7.2.*

$$RVC_{Total} = S_{cost} + FL_{cost} + MC_{cost} \tag{7.2}$$

Where: S_{cost} is the cost of seeding of the abandoned mine terrain, FL_{cost} is the cost of applying fertilizers on seeded areas of abandoned mine terrains, and MC_{cost} is the costs of mulching of the seeded areas of the mine.

In this method, the direct costs of seeding, fertilization and mulching are determined by multiplying the unit prices of material by the unit area of application. The appropriate percentage of the determined direct cost is used to estimate the indirect costs of the project. The indirect cost consists of the contractor's profit, contingency costs, the costs of mobilization and/or demobilization, and the engineering and design costs shown in *Table 7.5.* Therefore, the cost of seeding, fertilization, and mulching of the seeded areas of abandoned mine lands can be determined using *Equation 7.3, 7.4* and *7.5* respectively. In *Equation 7.3*, the area of seeding refers to the areas of the mine that require seeding in hectares (ha) while the seed price (ZAR per kg) is basically the established price of the seeds that is determined from the cost of seed preparation. The percent contribution of the different indirect costs to be added on the direct costs and their symbols are presented in *Table 7.5.*

$$S_{cost} = \left[\frac{\text{ha}}{\text{Area of Seeding}} \times \left(\frac{\text{ZAR}}{\text{Seed Price}} \text{per kg} \times \frac{\text{ha}}{\text{Unit Area}}\right)\right] + (\text{CPO} + \text{C} + \text{MM} + \text{MD} + \text{ED}) \tag{7.3}$$

$$FL_{cost} = \left[\frac{\text{ha}}{\text{Area of Seading}} \times \left(\frac{\text{ZAR}}{\text{Ferilizer Price}} \text{ per ton} \times \frac{\text{ha}}{\text{Unit Area}}\right)\right] + (\text{CPO} + \text{CC} + \text{MM} + \text{MD} + \text{ED}) \tag{7.4}$$

$$MC_{cost} = \left[\frac{\text{m}^2}{\text{Area of Mulching}} \times \left(\frac{\text{ZAR}}{\text{Mulch Price}} \text{ per m}^3 \times \frac{\text{m}^2}{\text{Unit Area}}\right)\right] + (\text{CPO} + \text{C} + \text{MM} + \text{MD} + \text{ED}) \tag{7.5}$$

Table 7.5: Percent contribution of different aspects of the indirect cost.

Items	Symbol	Percentage
1. Contractor Profit and Overhead cost	CPO	15-30
2. Contingency cost	CC	5-10
3. Monitoring and maintenance cost	MM	5-10
4. Mobilization/Demobilization	MD	5-10
5. Engineering and design	ED	5-10

7.5.1. Estimated costs of revegetation of Nyala Mine

The revegetation of the land affected by mining sometimes requires that seeding and/or planting of trees/shrubs on the mine areas covered with topsoil be undertaken. In most cases, the species for revegetation of the land affected by mining should be the native species of the area where the mine is found. In this regard, it is necessary that locally available plant species are collected and processed for the revegetation of the land affected by mining (van Eeden, 2010). The following section provides the framework for estimation of the cost of seeding, fertilization and mulching of the abandoned mine lands.

The estimated cost of seeding of the mine terrain

In order to test the applicability of the revegetation cost estimation technique discussed in section 7.5 of this chapter, the scenario of revegetation of the areas of Nyala Mine terrain that required backfilling and ripping of areas that were occupied by material will be used to backfill some of the voids left by mining. In this case, the area of Nyala Mine that require revegetation was estimated to be about 169ha. These areas include those where the heaps of spoils and tailings are to be removed (*i.e.* cut) to fill up the four excavations left by surface mining of magnesite, and those were the backfilling will have been carried out. The direct cost of seeding, application of fertilizers and mulching of the seeded areas were basically estimated by multiplying the unit price of the material by the unit area and then product is multiplied by the total area of the mine to the revegetated. The unit prices of some of the seeds for revegetation of the mine terrain as established by van Eeden (2010) are shown in *Appendix-N*. For the purpose of this study, five species in *Appendix-N* were used to estimate the cost of revegetation of the Nyala Mine terrain using such species. These species were the (i) *Ehrharta villosa,* (ii) *Lebeckia spinescens*, (iii) *Trachyandra divaricate*, (iv) *Carpobrotus edulis*, and (v) *Eriocephalus racemosus*. In this regard, the costs of seeding the 169ha of the Nyala Mine terrain using these species was estimated to be about ZAR 546,013.89 (Including Vat.).

The cost of establishing the individual species used for this research on the Nyala Mine terrain are shown in *Figure 7.6a*. It can be seen in *Figure 7.6a* that the revegetation of the Nyala Mine terrain with *Lebeckia spinescens* types of species is likely to be relatively costly than the use of other species. According to van Eeden (2010), the costs of preparation of seeds for seeding of the landscapes affected by mining largely determines the unit prices of the individual seed species. Therefore, the use of seeds that are relatively inexpensive to collect and process is likely to results to relatively cheaper seeding of the land affected by mining. In the rehabilitation scenario used in the study, the relatively high unit costs or prices (ZAR769.16 per kg) of the *Lebeckia spinescens* seeds made their uses in the rehabilitation of the land affected by magnesite mining at Nyala Mine to be relatively higher than that of the other considered species. The contribution of the individual species into the total costs of rehabilitation of the Nyala Mine terrain is presented in percentages as shown in *Figure 7.6b*. In this figure, the *Lebeckia spinescens* species contributed close to half (48%) into the cost of revegetation in the scenario of Nyala Mine used in this study.

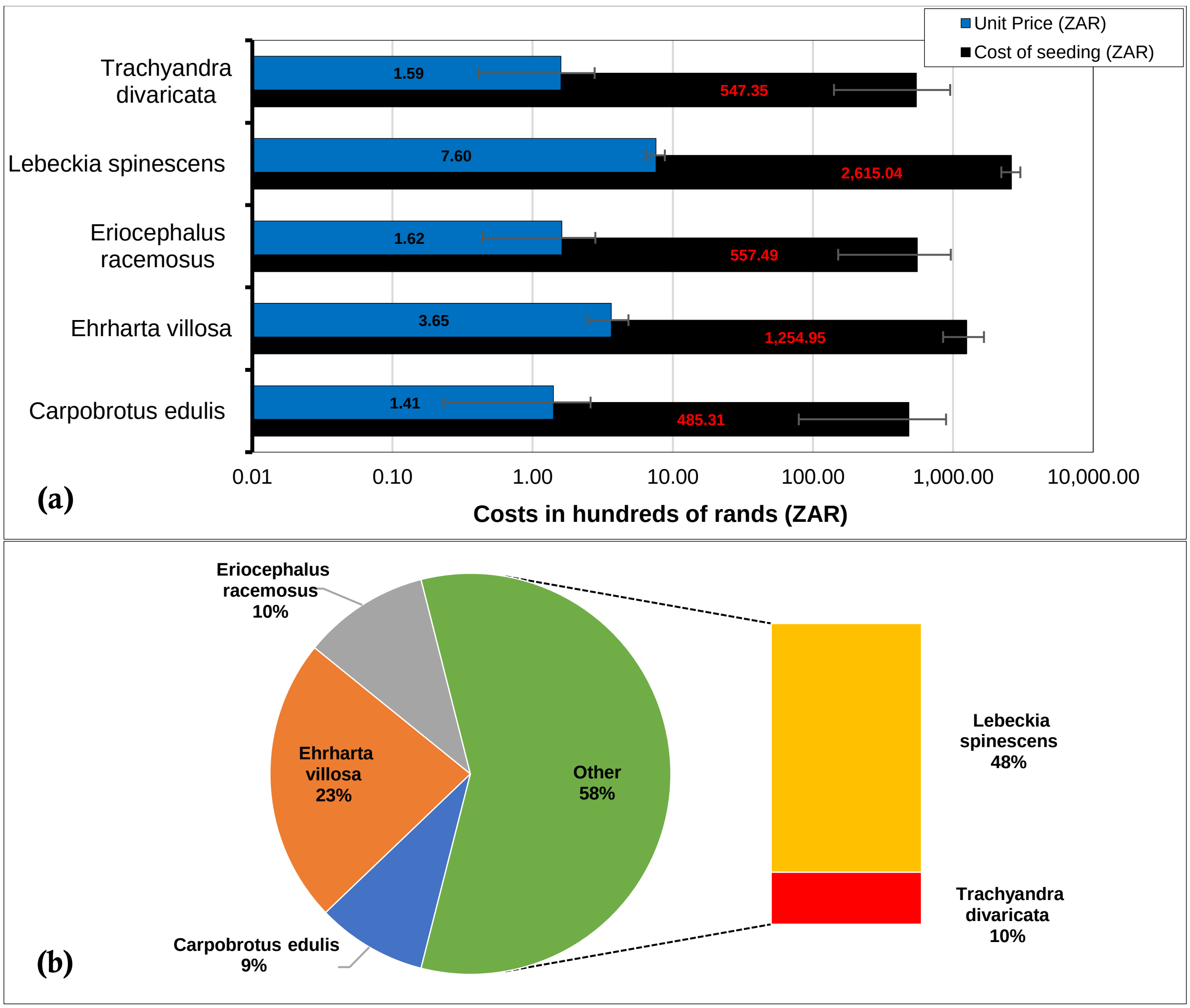


Figure 7.6: The estimate of the cost of seeding of the Nyala Mine using the selected seed species (a), and (b) illustrates the relative contribution of individual seeds used for this research.

The estimated cost of application of fertilizer

The activities of seeding of the land disturbed by mining are mostly followed by the application of fertilizers to promote the growth of vegetation of the seeded areas. The management of soil fertility is basically an important aspect of revegetation of land affected by mining and the choice of fertilizers to use is determined by factors such as the type of cover to establish, the planned post rehabilitation uses of the land, the nutrient status of the soil, and the expected production level or yield target of the soil (Tanner, 2007). In general, the fertilization of land covered by mine spoils and tailings materials is very important. This is because these materials are mostly characterized by elevated sand content, lack of moisture and low content of organic matter (Sheoran *et al.,* 2010).

This section presents the estimate of the costs of fertilization of the scenario of the Nyala Mine terrain using four different types of fertilizers. These fertilizers are Mono-Ammonium Phosphate (MAP), Potassium Chloride, Urea (46), and Limestone Ammonium Nitrate (LAN) as presented in *Table 7.6.* The use of the method of estimation of the costs of fertilization of abandoned mines presented in section 7.5 of this chapter, the costs of fertilization the 169ha of the Nyala Mine terrain were estimated as shown in *Figure 7.7.* In this case, the application of the fertilizers used for the purpose of this research at the average rate of 1 tonne per 1.5 hectares showed that the costs of applying fertilizes on the Nyala Mine terrain can be ZAR3,6 million (for LAN and Urea-46), ZAR6,4 million for MAP and ZAR3,3million for Potassium Chloride.

Table 7.6: Average unit prices for the fertilizers used in the study.

No.	Fertilizer	Cost per ton of fertilizer (ZAR)	Estimated cost (ZAR) of fertilization of Nyala Mine Terrain
1.	Mono-Ammonium Phosphate (MAP)	13,188.00	6,402,816.20
2.	Potassium Chloride	6,852.66	3,326,988.36
3.	Urea (46)	7,408.00	3,596,607.71
4.	Limestone Ammonium Nitrate (LAN)	7,408.00	3,596,607.71

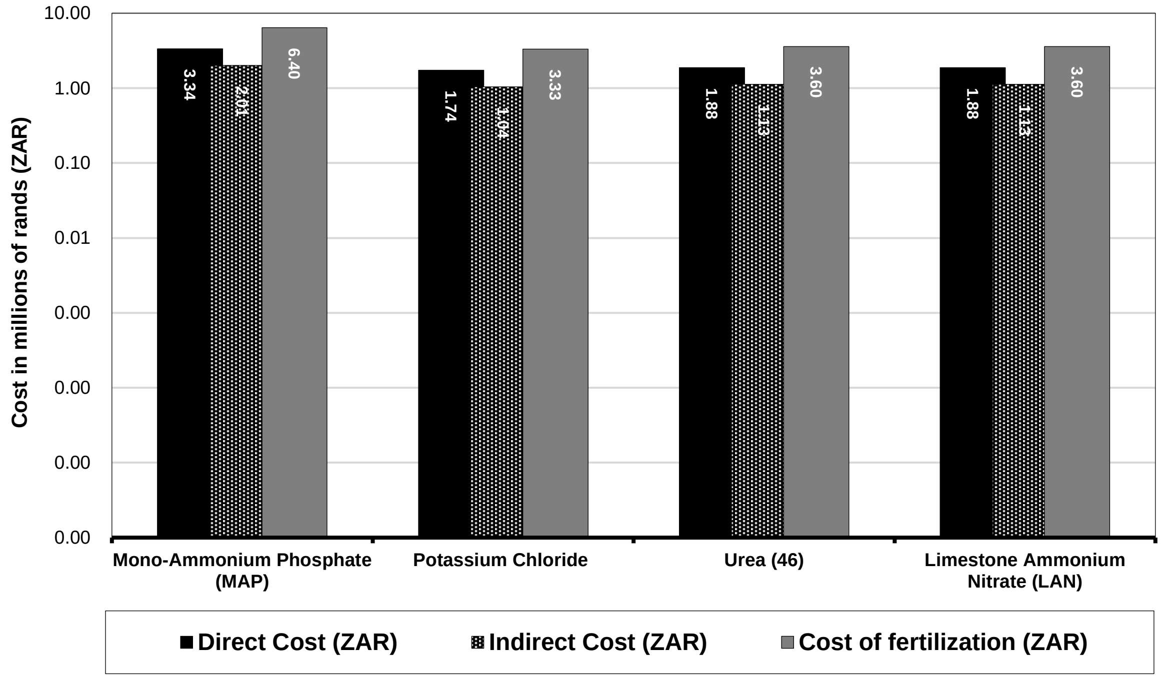


Figure 7.7: Comparison of the estimated costs of individual fertilizer application on Nyala Mine terrain.

The estimated costs of mulching of the mine terrain

In order to reduce the frequency of irrigation of the seeded areas of the abandoned mines, it is important that mulching of such area using organic mulch is conducted. The organic mulches are those that can naturally decompose, and they include those presented in Table 7.6 (Ranjan *et al.,* 2017; Bell *et al.*, 2009). However, for the purpose of this research, the use of the sawdust as mulching material was considered. This is because among all the organic mulches in *Table 7.7,* sawdust can be easily acquired in large quantities from the nearby timber processing industries. Moreover, in the case of the abandoned Nyala Magnesite Mine, the use of sawdust can be appropriate because it is generally acidic thus making its application on alkaline soils like the spoils and magnesite tailings material appropriate (Sibanda *et al.,* 2013; Mhlongo and Amponsah-Dacosta, 2015). In addition to this, the sawdust is also recommended for use in flat laying areas (like the terrain around the Nyala Mine) to avoid the easy washing away of the mulch by water during rainy days or seasons.

Table 7.7: Comparison of the characteristics of different mulches (from Bell *et al.*, 2009)

	Water conservation	Weed control	Nutrient release	Erosion control	Longevity	Cost	Ease of application
Bark dust	++	+++	+	++	++	+	+++
Bark nuggets	++	+++	+	++	+++	++	++
Wood chips	++	+++	+	++	++	++	++
Yard waste	++	+	+++	++	+	++	+++
Arborist mulch	+++	+++	+	+++	++	+	+
Tree leaves	++	++	++	++	+	+	+
Mint compost	+++	+	++	+++	+	+	+
Sawdust	++	++	+	++	++	+	+++
Nut shells	++	+++	+	++	+++	+++	+++

Note: + Low; ++ Medium, and +++ High

Given the situation at Nyala Mine, if the sawdust is sold for an average price of ZAR20.00 per cubic metre and is applied to be up to 10cm deep as recommended by Ranjan *et al.* (2019), a cubic metre of sawdust is expected to cover an area of about 10m². Based on this background, the mulching of the area of Nyala Mine (1688326m² ≈169ha) that require rehabilitation was estimated to cost about ZAR6,9 million (maximum). The direct and indirect costs of the estimated costs of mulching were up to the maximum of ZAR3.4 million and ZAR6.03million respectively (see *Figure 7.6*).

COST OF MULCHING			
MULCHING	**MATERIAL TYPE : Sawdust**		
DIRECT COST (ZAR)	Area to be seeded (m²)	Area mulched per m³	Cost of mulch per m³
	1688326	10	20.00
	168833		
Estimated Cost (ZAR)	3,376,652.00		
INDIRECT COST (ZAR)			
Contractor Profit & Overhead cost (30%)	1,012,995.60		
Contingency cost (5-10%)	337,665.20		
Monitoring & maintenance cost (5-10%)	337,665.20		
Mobilization/Demobilization (5-10%)	337,665.20		
Engineering and design (5-10%)	337,665.20		
TOTAL INDIRECT COST (ZAR)	2,363,656.40		
TOTAL DIRECT AND INDIRECT COST (ZAR)	5,740,308.40		
% Inflation	287,015.42		
TOTAL COST OF SEEDING (ZAR)	6,027,323.82		
14% VAT.	843,825.33		
TOTAL COST (INCLUDING VAT@14%)	6,871,149.15		

Figure 7.8: An illustration of the estimated costs of mulching of the Nyala Mine terrain using sawdust.

7.6. Method for Estimation of the Costs of Demolition of Surface Infrastructure and Sealing of Mine Shafts

The method for estimation of the costs of demolition of old mine buildings and other surface mine infrastructure as well as the sealing of abandoned mine shafts used the direct costs, indirect costs and the costs of labor required to determine the costs of the rehabilitation work. In this case, the direct costs are determined by multiplying the unit costs by the quantity of the work to be done. Based on the estimated direct costs, the indirect costs are estimated as the sum of the minimum contingency cost (5%), the costs of monitoring and mentioning the site after closure (5%), the costs of mobilization and demolition of temporary infrastructures developed for the project (5%), the costs of engineering and design (5%), and those of contractor profit and overheads (15%). In the case of demolition and sealing of mine shafts, the indirect costs does not include the costs of salaries of the crew. This is because the cost of salaries of the crew are determined separately and summed up with the direct and indirect costs as shown in *Equation 7.6.* The motive for this is the fact that the activities of demolition and sorting out of some materials from the demolished buildings for reuse purposes are commonly labour intensive.

$$\mathrm{RC_{Total}} = \mathrm{Inflation} + (\mathrm{D_{Cost}} + \mathrm{ID_{Cost}} + \mathrm{L_{Cost}}) \tag{7.6}$$

Where; $\mathrm{RC_{Total}}$ is the total cost of demolition of surface mine infrastructure and treatment of abandoned mine shafts. $\mathrm{D_{Cost}}$ is the direct costs which are determined using *Equation 7.7* where $\mathrm{CR_i}$ is the unit rate of carrying out the work and $\mathrm{Q_i}$ is the quantity of the work to be accomplished.

$$\mathrm{D_{Cost}} = \sum_{i=1}^{n} \mathrm{CR_i} \times \mathrm{Q_i} \tag{7.7}$$

Where; $\mathrm{ID_{Cost}}$ are the indirect costs of the project which are estimated using *Equation 7.8*. On *Equation 7.8*, $\mathrm{CPO_i}$ is the contractor's project and overhead, $\mathrm{CC_i}$ is the contingency cost, $\mathrm{MM_i}$ is the cost of monitoring and maintenance, $\mathrm{MD_i}$ is the cost of mobilization and demobilization of temporary infrastructure to be built on site for the site rehabilitation project, and $\mathrm{ED_i}$ is the cost of engineering and design studies conducted before the execution of the project.

$$\mathrm{ID}_{\mathrm{Cost}} = \sum_{i=1}^{5} \mathrm{CPO_i} + \mathrm{CC_i} + \mathrm{MM_i} + \mathrm{MD_i} + \mathrm{ED_i} \tag{7.8}$$

The cost of labor (L_{Cost}) in *Equation 7.6* are determined using *Equation 7.9* on which T is the set time of carrying out the work of demolition of surface mine infrastructure or treatment of mine shafts to address their hazards. The WDF is the sum of the four work productivity factors described in *Table 7.8*. The C_{Cost} is the hourly cost of the crew and it is determined using *Equation 7.10*.

$$\mathrm{L_{Cost}/Unit\ Quantity} = \left(\sum_{i=1}^{4} \mathrm{WDF_i}\right) + (\mathrm{T} \times \mathrm{C_{cost}}) \tag{7.9}$$

$$\mathrm{L_{Cost}/hr} = \mathrm{Crew\ Composition} \times \mathrm{Avarage\ Hour\ Rate} \tag{7.10}$$

Table 7.8: Description of the work difficulty factors (from LaGuardia, 2017).

WDF (%)	Symbol	Factors	Description
10-20	A	Accessibility	This factor intends to account for difficulty of working in difficult spaces such as ladders or scaffolding.
15-30	PC	Protective clothing	This factor is intended to account for the time the worker needs to put on protective clothing for any rehabilitation work.
5-10	WB	Work break	This factor intends to account for the time a worker needs to take a morning break, a lunch, and afternoon break during the rehabilitation work.
10-50	RP	Respiratory protection	This factor intends to account for the difficulty of a worker performing activities while wearing a full-face respirator mask.

7.6.1. Cost of demolition of unwanted infrastructure and sealing of mine shafts in selected mines in Giyani and Musina areas

The method of estimation of the costs of demolition of surface mine infrastructure and sealing of the underground mine shafts was applied in the scenarios of abandoned mines in the areas of Giyani and Musina (Limpopo province of South Africa). The situation of sealing the 28 abandoned underground mine shafts with concrete plugs and slabs was used to test the applicability of the method developed for estimation of the costs of carrying out these activities. The shaft closing scenarios used were the (i) designing and installation of the concrete plugs and (ii) installation of precast unreinforced and reinforced concrete plugs and slabs. The unit rates of carrying out the different activities of mine closure used by Jones and Wagener-Engineering and Environmental Consultants (2016) to estimate the costs of closure of Delmas Coal Mine were used in this research. The 12-man crew (including two supervisors) was adopted in the scenario of estimation of the cost of design and installation of the concrete plugs to seal the abandoned mine shafts and the scenarios of demolition of different abandoned surface mine infrastructure. On the other hand, the 6-man crew (including one supervisor) was adopted in estimation of the costs of installation of precast reinforced concrete slabs. The composition of the two crews and their estimated hourly rates are shown in *Table 7.9*. It is important to state that the hourly rate of both crews was determined as the average hourly rate of the workers and supervisors in the construction industry in South Africa.

Table 7.9: Crew hourly rate used in estimation of the cost of labour in the case study used in this research.

<table>
<tr><th rowspan="2">Operations</th><th rowspan="2">Crew Size</th><th colspan="2">Ava. Hourly Rate (ZAR)</th><th rowspan="2">Crew Hourly Rate (ZAR)</th></tr>
<tr><th>Worker</th><th>Supervisor</th></tr>
<tr><td>1. Demolition and closing the mine shafts with precast concrete plugs and slabs</td><td>5 plus supervisor</td><td rowspan="2">20.13</td><td rowspan="2">72.28</td><td>172.93</td></tr>
<tr><td>2. Design and installation of concrete plugs</td><td>10 plus two supervisors</td><td>345.86</td></tr>
</table>

In the situation of abandoned underground mine shafts in the study area, the design and installation of concrete plugs can be adopted in dealing with the physical and environmental hazards of the 14 shafts that are currently closed with temporary structures. The closing of such shafts using concrete plugs that are specially designed for the unique situations of abandoned underground mine shafts in different mines was estimated to be approximately ZAR1.2 million while sealing of 12 shafts with precast concrete slab was estimated to only cost about ZAR206,999.09 (*see Figure 7.8*).

The shafts that might require closing using concrete slabs are those that are open because the temporary structures used seal them were somehow removed by illegal miners or the mine was never closed. These cost estimates were worked out based on the assumption that the work of installation of the precast concrete slab and the design and installation of concrete plugs to address the physical and environmental hazards of the abandoned underground mine shafts in the study area can be done over a period of 24 and 42 days respectively.

The costs of demolition of the reinforced concrete wall and floors of old water reservoirs and the demolition of reinforced concrete stands were also estimated based on 24 work days period. The costs of demolition of the reinforced reservoir's concrete walls and floors of water reservoirs found in some of the mines in the study area were estimated to be about ZAR2.3 million and ZAR2.1 million respectively (see *Figure 7.8*). In addition, the cost of removal of the steel tank or silo found at Louis Moore Mine was estimated to cost about ZAR12,926.00 based on the work period of two days.

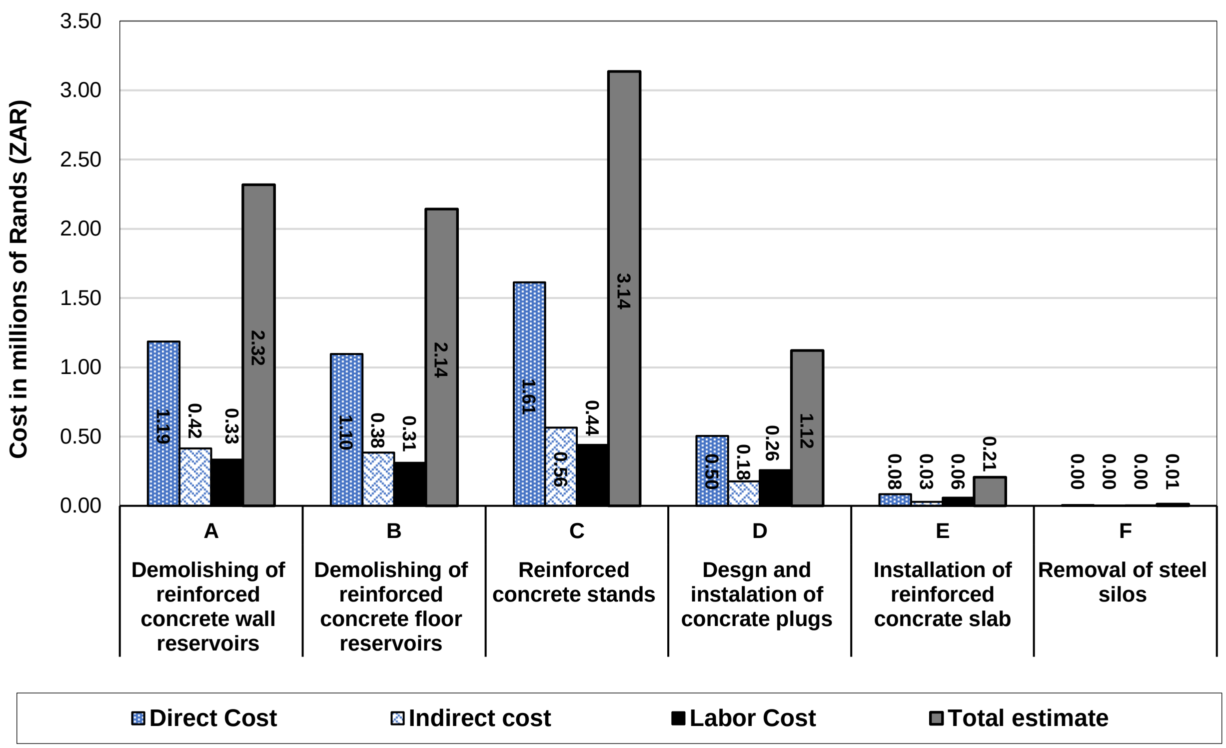


Figure 7.9: Estimated cost of demolition and closing of selected surface mine infrastructure and shafts found in some abandoned mine sites in the Giyani and Musina areas.

7.6. Discussion of the Cost Estimation Framework

Since the rehabilitation of abandoned mine sites is mostly conducted with limited funds, it is important that the costs of carrying out the rehabilitation activities are determined far in advance to avoid or reduce the possibilities of wasteful expenditure in the rehabilitation project. The estimation of closure and/or rehabilitation costs is important as it can assist in the determination of the financial liabilities of the abandoned mines in the country or region. This can then allow the government, mining companies and communities which are responsible for the rehabilitation of abandoned mines to budget and/or fundraise for the work of rehabilitation of these mines. According to Peralta-Romero and Dagdelen (2007), the estimation of mine closure costs gives the authorities, or the mining companies an idea of the financial liabilities that they face as the mine approaches the closure stage.

This research used the mine rehabilitation activities that are commonly adopted in dealing with the problems of land affected by mining using surface mining methods, closing of mine entries (shafts), and demolition of surface infrastructure to establish the best approach or framework for estimation of the costs of rehabilitation of abandoned mines. The approach of estimation of the costs of rehabilitation of abandoned mines was that the direct costs of conducting the rehabilitation work should be estimated first using the current rates of carrying out the rehabilitation activities. Based on the established direct costs, the indirect costs should then be estimated. The indirect costs should include the contractor's profit, contingency costs, monitoring and maintenance costs, mobilization and demobilization as well as the engineering and design of the rehabilitation strategies (Shen, 2012; Peralta-Romero, 2007) (*see Figure 7.10*). These costs (i.e. indirect costs) are mostly for dealing with uncertainties that may occur during the execution of the planned rehabilitation activities. According to Brodie Consultancy Ltd. (2017), incorporation into the mine rehabilitation costs estimation process should be in line with the conventional engineering practices.

Although the indirect costs are important in estimation of mine closure and rehabilitation costs, they have often been omitted in most estimations. For example, the costs of monitoring of rehabilitated abandoned mine sites in South Africa were said to have been omitted in the ZAR30 billion rehabilitation costs estimate made for these mines. As a result, there was an underestimation of the costs of rehabilitation of abandoned mines in south Africa (Auditor

General-South Africa, 2009). Internationally, the omission of indirect costs in the estimation of the costs of mine closure and rehabilitation was identified by Closure Planning Practitioners Association (CPPA) in its submission to the Parliament of Australia as one of the factors that significantly contributes to the underestimation of the rehabilitation costs by many companies. Based on the abandoned mines rehabilitation cost estimation approach used in this research, the total cost of rehabilitation can be optimized through the optimization of the indirect or labour costs of the project. In countries like South Africa where the rehabilitation of abandoned mines is the responsibility of the government, the indirect cost of the estimate can be determined or approved by the state the same way as it is done in the FACE method of closure cost estimation (Parshly *et al.,* 2009).

In labour intensive closure or rehabilitation activities, the cost of labour turn to have influence on high costs of rehabilitation. These activities include those that are associated with demolition of unused surface infrastructure and sealing of the mine shafts. In this case, the labour costs are to be summed up with the direct and indirect costs. This research proposes that the work difficulty factors (also known as work productivity factors) (LaGuardia, 2017) should be used in the estimation of the costs of labour. This is because these factors turn to slow down productivity in labour intensive activities. This is caused by difficulties of working with personal protective equipment (PPE) in difficult and hazardous conditions when conducting the rehabilitation of abandoned mines. The example of these activities includes demolition of buildings which were built with materials that contained asbestos, working above the dangerous open mine shafts as well as the removal of structures that were used to store health hazardous mining and mineral processing substances. The summarized graphical illustration of the framework for estimation of the costs of rehabilitation of abandoned mines suggested in this research is shown in *Figure 7.10.*

It is important to note that the value of salvage or resale of equipment and scrap from the abandoned mine sites can be deducted from the total estimated costs of performing the activities of rehabilitation of the abandoned mine sites. The same is also to be done in the case where repurposing of the abandoned mine sites and features is selected as the best option for dealing with the problems of abandoned mine sites. In this way, the actual cost of rehabilitation of the abandoned mine site can be determined and the financial value of the postmining uses of the sites can be deducted from the estimated actual costs of rehabilitation. However, this will require that the studies such as willingness-to-pay for the new use of the abandoned mine site should be used to establish the money value of the new use of the abandoned mine site.

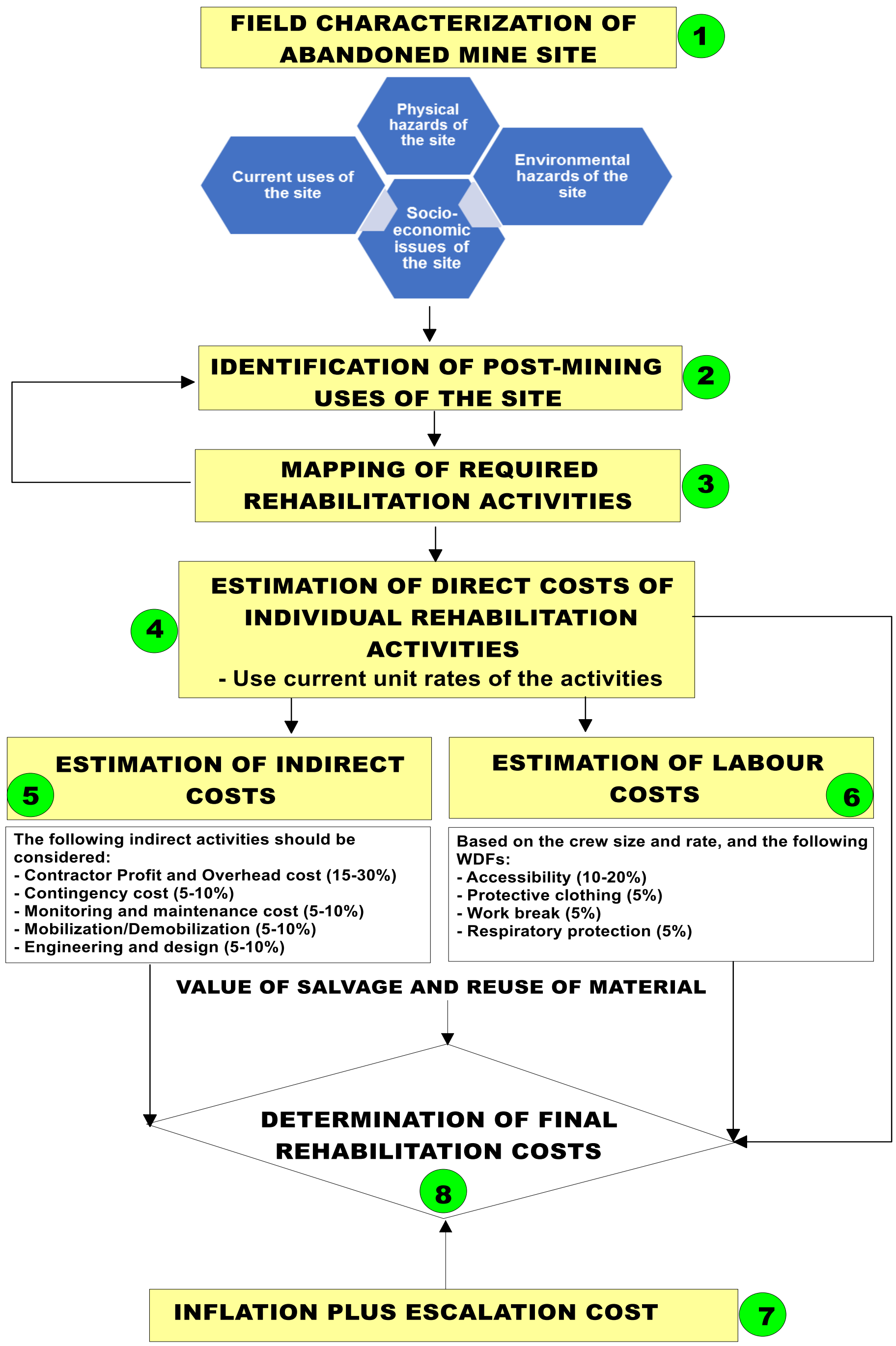


Figure 7. 10: Graphical illustration of the framework for estimation of the costs of rehabilitation of abandoned mines.

7.7. Summary of the Chapter

The success of rehabilitation of abandoned mines or features seriously depends on the availability of funds required to implement the rehabilitation work and post rehabilitation monitoring of the site. In view of this, it is important that once the strategies for rehabilitation of abandoned mines have been identified, the costs of implementation of such strategies be estimated/determined. The aim of this chapter was to develop a framework for estimation of the costs of rehabilitation of abandoned mines.

In this work the scenarios of required work of rehabilitation of selected abandoned mine sites in the Giyani and Musina areas were used to come up with costs estimation techniques and validation of their applicability. One of these scenarios was backfilling and revegetation different parts of the Nyala Mine terrain. In this case, the activities of backfilling of some of the surface excavations comprised of loading, hauling and dumping of fill material in void areas, spreading of such material using a bulldozer. The ripping of compacted areas was also considered. The activities of revegetation used were seeding, fertilization and mulching of seeded areas. The other scenario was sealing of open abandoned underground mine shafts with concrete plugs and slabs as well as the demolition of some of the surface structures found in some parts of selected abandoned mines in the study area.

The results of the study showed that the rehabilitation of the Nyala mine terrain is likely to cost between ZAR5.8million and ZAR6.6million while the cost of revegetation depends largely on the unit price of seeds, fertilizers and mulch to be used. In the same way, the costs of sealing open mine shafts will be largely influenced by the costs of the structure used to close the shafts as well as the costs of labour while that of demolition of surface structures will largely depend on labour costs.

Based on application of the cost estimation methods used in this research, a framework for estimation of the costs of rehabilitation of abandoned mine sites was developed. This framework emphasized the fact that the rehabilitation costs estimation should take into consideration the direct and indirect costs and that for labour intensive operations, the costs of labour should be separately estimated and added to the sum of the direct and indirect costs. It also recognized the fact that working in dangerous situations may slow down the productivity of labour thus the estimation of the labour costs should also make use of work difficulty factors. The use of the cost estimation framework developed in this research is expected to reduce the problems of underestimation of cost of rehabilitation of abandoned mines.

CHAPTER EIGHT

CONCLUSION AND RECOMMENDATIONS

Prioritization of rehabilitation of abandoned mines and selection of appropriate strategies for their rehabilitation are important aspects of the programme of rehabilitation of these mines. The work in this thesis was conducted with the aim of developing a computer-based advisory system for selection of rehabilitation strategies for abandoned mines. This chapter provide a summary of the research, concluding remarks, the research contribution to the body of knowledge, its limitations and the recommendations of the study.

8.1. Summary of the Study

Abandoned mines are found in all countries and regions that have a long history of mining. They are basically the result of previous mining activities that were conducted with little or no regard for the environment. Anywhere these mines are found, they present different types of physical and environmental hazards as well as socio-economic concerns. As the result of this, the government is expected to accept responsibilities of rehabilitation of these mines. However, in most cases such rehabilitation work is conducted with very limited resources. This have influenced the use of low-cost rehabilitation strategies that have not been always effective in addressing the problems of abandoned mines. In order to address the problem of using inappropriate rehabilitation strategies in rehabilitation of abandoned mines while ensuring efficient uses of resources, techniques or methods for ranking of abandoned mine sites for rehabilitation must be developed.

The main objective of this research was to develop a computer-based advisory system for selection of appropriate strategies for rehabilitation of abandoned mine sites. The other specific objectives were to carry out a characterization of the selected abandoned mines in Giyani and Musina areas in Limpopo Province of South Africa, devise methods for ranking abandoned mines for rehabilitation, create expert systems for rehabilitation of abandoned mines, and develop a framework for estimation of the costs of rehabilitation of abandoned mines.

The methodology used in this research involved carrying out a characterization of abandoned mine sites in Giyani and Musina areas. Based on the results of such characterization, new methods for ranking abandoned mine entries and the tailings dumps for rehabilitation were developed. This was followed by creation of a catalogue of appropriate strategies for rehabilitation of abandoned mines by evaluating different mine rehabilitation strategies for their appropriateness for dealing with the problems of abandoned mines. In this case, semi-quantitative methods (*i.e.* SWOT and QSPM technique) as well as Multi-Criteria Decision Making (MCDM) tools (*i.e.* AHP and Pugh Matrix) were used to carry out the evaluation of the rehabilitation strategies. Based on the developed methods for ranking of abandoned mine entries and the tailings dumps for rehabilitation as well as the knowledge of the performance of different rehabilitation strategies, three expert systems (ESs) that guides in different aspects of rehabilitation of abandoned mines were created using an ES-Builder Shell©2013 McGoo Software (version 3.0). The functionality of these ESs was verified by applying them in the situation of abandoned mines in Giyani and Musina areas. Lastly, this research used on direct costs of rehabilitation and other costs elements that were disregarded in other methods of costs estimation to develop a framework for estimation of the costs of rehabilitation of abandoned mines.

The findings of the study showed that abandoned mines present physical and environmental hazards as well as socio-economic concerns to people and animals as well as the environment in which they are found. It was observed during the field characterization stage of these research that the hazards of these mine sites vary from one site to the other and depends on the type of features and mine infrastructure that are found at the abandoned mine sites. It also emerged from the study that the physical hazards of abandoned mines were generally exacerbated by negative socio-economic status of the nearby-communities of these mines. For example, the different socio-economic issues that are associated with the closure of mines have led to these communities to engage in dangerous illegal artisanal gold mining activities. Such socio-economic issues include loss of jobs/income and increase in unemployment, depression and feelings of hopelessness in communities, and escalation in substance abuse to mention the few. These have contributed to exposure of many people (including women and children) to the physical hazards of the abandoned mine sites. Moreover, activities of washing gold-bearing sediments from abandoned gold mines in sluicing tables build on the banks of the major rivers (Nsami and Klein Letaba Rivers) in Giyani may lead to the pollution of the river by toxic metals from the mine site. Based on the study, it was found that addressing the physical and environmental hazards of abandoned mines and ignoring the socio-economic status of the host communities will not fully address the problems that these mines present.

It was also found during the field characterization of abandoned mines in Giyani and Musina areas that some of the features of these mines are at the state where they can easily be used for some other purposes. It is therefore important that the adoptive reuse of some of the abandoned mine features be considered before the decision to demolition them is taken. In this case, the characterization of such mine site or features should focus on establishing the presence and level of pollution of the site by toxic metals and other harmful substances. Therefore, the abandoned mine features should be considered for reuse when it has been established that the area or site that they are found is free from pollution. It is important to note that the commercial adoptive reuse of the abandoned mine features or site promises to contribute to the socio-economic development of the nearby-communities of these mines. This is because the new uses of the features are likely to create new opportunities that can replace those lost due to the closure and/or abandonment of the mine. It was noted that for this approach to be successfully, it is important that the infrastructure at the abandoned mines be protected from any form of vandalism or the whole site be redeveloped according to the requirements of the proposed new uses. In addition, were the demolition of abandoned infrastructure or structures is to be conducted, the value of salvage and reuse of materials from such structures should be subtracted from the estimated costs of rehabilitation.

8.2. Concluding Remarks

The field characterization of abandoned mine sites carried out in this research greatly assisted in identifying a wide range of features which include old and dilapidated buildings, surface mine excavations where mineral exploitation was conducted by surface mining method, different types of surface mine infrastructure (including silos, orebins, water reservoirs and concrete mounding stands) and old machineries. The other features that were found at the abandoned mine sites in the study area were underground mine shafts (both vertical and inclined) and mine waste deposits such as tailings dumps, spoils dumps and waste rock dumps. All these features have different types of physical and environmental hazards which turn to indirectly hamper the socio-economic development of host communities of the abandoned mines.

Analysis of practical approaches for dealing with the problems of abandoned mine features such as surface mine excavations and different surface infrastructure showed that reuse of some of the abandoned mine features and infrastructure was generally the most attractive approach compared to the use of traditional rehabilitation methods such as backfilling of the excavations and demolition of the buildings. This approach of dealing with the problems of abandoned mines will require that the existing infrastructure be protected, renovated or complete development of the site should be considered as per the requirement of the proposed reuse of the site or features.

The removal of the abandoned surface infrastructure from the site and the backfilling of open surface excavations appeared to have an advantage of making the abandoned mine sites available for other uses. This work (especially the backfilling) was identified to be potentially costly for abandoned mine sites. However, some of the cost of removal of surface infrastructure can be repaid by the fact that the material used to build such infrastructure can be recycled or reused in other construction projects. No matter the status or condition of the abandoned mine sites, a simplified conceptual model which demonstrates the benefits of implementation of the different approaches for addressing the problems of abandoned mine sites and features was created in this research. This is expected to immensely contribute to sustainable management of abandoned mine sites in different regions where they are found.

Field description and characterization of the abandoned mine shafts were conducted, and the results revealed that these features of are mostly found near communities. Therefore, it is important that they are given utmost attention using appropriate strategies for addressing their physical and environmental hazards. The treatment of these shafts will significantly improve the safety status of the abandoned mine sites and make the land they occupy available for other traditional post-mining land uses. Such productive use of abandoned mine lands will go a long way in addressing some of the socio-economic issues that prevail in communities around these mines.

The hazard ranking system for mine entries developed and used in this work has proven to be robust and reliable in providing information required to make sound decisions in the treatment of abandoned mine entries. This was showed by the ability of the method to accommodate site specific issues in the hazards ranking process and its efficiency in ranking the shafts found in different geographical settings. The results provided by the system also offer guidance on the type of treatment strategies to be considered in dealing with physical hazard and environmental problems of abandoned mine entries and the socio-economic concerns. The application of the hazard ranking system at the abandoned underground mine shafts in the Giyani and Musina areas revealed that the shafts in these areas have moderate physical and environmental hazards and corresponding socio-economic concerns. Risks of falling into the shafts and problems of ground movement which degrade the land around the shafts were found to be the dominant physical hazards and environmental problems.

The fact that the system that was developed provides ranking of the hazards based on information collected by conducting preliminary field assessment of the mine entries in the study area means that this system will be 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 entries will be effectively carried out with limited resources.

The study conducted and presented in this thesis also involved application of the Analytic Hierarchy Process and Pugh Matrix methods of Multi-Criteria Decision-Making (MCDM) techniques in finding the most suitable strategies for treatment of abandoned mine shafts in the study area. The results of preliminary field characterization and the MCDM techniques revealed that the treatment of abandoned mine shafts in these areas should make use of strategies that provide long-term close-up of the shafts and prevent risks of ground movements. The evaluation of different treatment strategies showed that backfilling, injection/inclusion, use of plugs, and blast closure were the most preferred treatment options for the abandoned mine shafts in the study area. However, the decision on which of these long-term or permanent strategies are to be used will need to take into consideration the evaluation of future use of the land as well as the future mining activities to be conducted in the area. For example, plugs can be designed such that they can be removed if the shaft is to be opened for other mining activities. However, if the surface use of the land requires that the void below the treatment structure is completely closed-up, permanent treatment of the shaft with appropriate backfilling material and use of blast closure can be considered.

Although this study was conducted in Giyani and Musina areas, the criteria for selection of treatment strategies and the priority list of shafts treatment strategies developed in this work can be used to guide decision-making in treatment of abandoned shafts in other areas. However, to ensure that strategies that address site specific issues of abandoned shafts are implemented, preliminary site characterization of the shafts is to be conducted. This will allow the objectives of the shaft treatment process to be clearly defined and provide guidance on the nature of treatment options to be considered.

This research also developed a method for characterization and selection of combination of methods for rehabilitation of abandoned tailings dumps. Its application revealed that all the tailing dumps in the Giyani and Musina areas have been affected by erosion to varying extent and that they contain different concentrations of toxic metals which include Cd, As, Cr, Ni, Pb, Zn, and Cu. The index of contamination of these dumps was determined and the high values obtained show that the dumps have potential of polluting the environment. The order of contamination of these dumps were as follows: Fumani Gold Mine Tailings > Mesina Copper Mine Tailings > Louis Moore Gold Mine Tailings > Klein Letaba Gold Mine Tailings > Nyala Magnesite Mine Tailings.

Results of the study showed that the tailings dumps affect the aesthetic beauty of the landscape differently and this significantly influenced the rehabilitation priority score for individual dumps. These dumps were classified as requiring moderate rehabilitation attention and efforts. However, their rehabilitation was identified to be requiring a mix of physical, biological and chemical techniques. It was established that the work of rehabilitation of abandoned tailings dumps in the study area be in the following order of reducing priority: Fumani Gold Mine Tailings > Klein Letaba Gold Mine Tailings > Nyala Magnesite Mine

Tailings (A) > Nyala Magnesite Mine Tailings (B) > Louis Moore Gold Mine Tailings > Mesina Copper Mine Tailings.

In developing the tailings dump rehabilitation prioritization tool, both qualitative and quantitative information were integrated and used in ranking the dumps for rehabilitation. This integrative approach allowed the rehabilitation prioritization tool to easily make use of site-specific issues and information to determine the dumps which require urgent attention and need to be prioritized for rehabilitation. Other than just creating the priority list of rehabilitation of abandoned tailings dumps, this tool also incorporated a technique for selection of most suitable rehabilitation strategies for the abandoned tailings dumps. The capability of the new rehabilitation prioritization tool to provide suitable rehabilitation strategy makes it unique and supreme to the current tools that are used in the mining industry for mine site rehabilitation endeavors.

Based on the methods of characterization of abandoned underground mine entries and tailings dumps as well as the knowledge of the techniques for dealing with the hazards of abandoned mines, three web-based expert systems were created in this research. These systems are (i) Expert System- Ranking of the Problems of Abandoned Mine Entries (ES-RAME), (ii) Expert System - Ranking of abandoned tailings dumps for rehabilitation (ES-RTDR), and (iii) Expert System - Selection of strategies for rehabilitation of abandoned mines (ES-SRSAM). They comprised of decision trees and production rules that assists in ranking of the abandoned the mine entries and tailings dumps for rehabilitation. Such rules also provide guidance on the selection of appropriate strategies for rehabilitation of abandoned mine sites.

The fact that the expert systems that were created are web-based make them available in the internet and are easily accessible. The incorporation of the abandoned mines ranking methods in the expert system shell will address the problems of lack of transparency of such methods which is the common problem of the existing techniques. The other advantage of incorporating the abandoned mines ranking systems into rule base expert system is that it provides the user with an opportunity to use fictitious information to perform preliminary or trial runs of the expert system. This can then give the user a feel and/or insight of the ranking process used by the system. Based on this exercise, the user can gain clear understanding of the type of information that is required for the actual ranking of the problems of abandoned mine entries and the ranking of the tailings dumps for rehabilitation.

One of the objectives of this research was to develop a framework for estimation of the costs of rehabilitation of abandoned mine sites. Such framework requires that in the estimation of the costs of rehabilitation of abandoned mines, the direct costs, indirect costs and the costs of labour in labour intensive rehabilitation activities are considered. The important indirect cost elements to be considered in the rehabilitation cost estimation should be: (i) contractor profit and overhead cost, (ii) contingency cost, (iii) monitoring and maintenance cost, (iv) mobilization and/or demobilization, and (v) engineering and design. The use of this framework for estimation of the costs of rehabilitation of abandoned mines will assist in eliminating or reducing the problems of under estimation of the costs of rehabilitation of these mines. It has been shown that by using this framework for estimating costs of different rehabilitation scenarios used in this research, the rehabilitation costs can be reduced by keeping the indirect cost at minimum.

8.3. Research Contribution to Knowledge

The originality of the work presented in this thesis can be measured through the contributions to the body of knowledge presented in this section.

- A detailed knowledge of physical and environmental hazards and socio-economic issues of abandoned mines has been generated in this research through the field characterization or description of abandoned mine sites in Giyani and Musina areas of South Africa.
- A catalogue of appropriate rehabilitation strategies has been created for dealing with the environmental problems and physical hazards of abandoned mine sites. This was based on methods and techniques that were developed in this research.
- An innovative technique of prioritizing rehabilitation of abandoned mine entries based on physical hazards, environmental hazards, and the socio-economic concerns was developed to identify appropriate strategies for their rehabilitation.

- A new methodological approach of ranking abandoned mine tailings dumps was developed based on their potential to pollute the environment as well as the landscape and visual impact they possess.
- Three rule-based expert systems were created to provide guidance on different aspects of rehabilitation of abandoned mines. These systems were:
  - (i) Expert System for ranking of problems of abandoned mine entries,
  - (ii) Expert System for ranking of abandoned tailings dumps for rehabilitation, and
  - (iii) Expert System for selection of strategies for rehabilitation of abandoned mines.
- A framework for estimation of cost of rehabilitation of abandoned mines was developed that takes into consideration direct costs and other very important cost elements that were neglected in existing cost estimation methods. Such framework will address the problems of underestimation of cost of rehabilitation of abandoned mines in South Africa and other countries.

8.4. Limitation of the Research

The study reported in this thesis was not conducted without some inherent limitations. This section highlights the limitations of this research.

- This research was conducted using the case study of abandoned mines found in Giyani and Musina areas of Limpopo Province of South Africa. Therefore, the problems of abandoned mines considered in this research are those specific to the abandoned mines in the study area. As a result, the creation of production rules for selection of rehabilitation strategies for abandoned mines might have been partially bias to dealing with the problems presented by the situation of abandoned mines in the study area.
- Rule-based expert systems for rehabilitation or selection of rehabilitation strategies were developed for abandoned mines. Based on the fact that the three systems are the first-of-their-kind in the fraternity of rehabilitation of abandoned mines, their performance could not be compared with other systems. Although the functionality of the developed expert systems was verified by using site-specific data and information

from abandoned mines in the Giyani and Musina areas, their performance needs to be compared with other expert systems.

- A framework for estimation of costs of rehabilitation of abandoned mines was developed in this research. The functionality of the framework was verified by applying it to the different scenarios that were created for rehabilitation of selected abandoned mine site in the study area. In view of the fact that there is lack of data sources for current and ongoing abandoned mine rehabilitation projects, it was not possible to compare the results of this framework with the actual cost of rehabilitation.

8.5. Recommendations of the Study

Based on the identified limitations of this research, the following recommendations were made.

- There is a need for continuous update of the developed expert system to incorporate the strategies for dealing with unique problems of abandoned mine sites which were not represented by the case study used in this research but exists elsewhere.
- The cost estimation framework developed in this research should be applied in active rehabilitation projects and the results of estimation be compared with the actual costs of rehabilitation of the project.
- Different categories of expert systems (e.g. rule-based, fuzzy logic or hybrid expert system) should be developed for rehabilitation of abandoned mines to enable comparative evaluation of performance attributes to be established.
- The developed framework for estimation of the costs of rehabilitation of abandoned mines should be used in influencing budgeting for rehabilitation of abandoned mines in the country.

REFERENCES

Abad, C. J. P. (2019). Environmental Recovery of Abandoned Mining Areas in Spain: Sustainability and New Landscapes in Some Case Studies. *J Sustain Res*. 1:e190003. https://doi.org/10.20900/jsr20190003

Abdollahi, F. (2010). Computational Intelligence Lecture 7: Fuzzfiers and Defuzzifiers. *Department of Electrical Engineering, Amirkabir University of Technology*. http://ele.aut.ac.ir/~abdollahi/Lec_6_10_B

Abraham, A. (2005). Rule-Based Expert Systems. In Sydenham P.H and Thorn R (editors), Handbook of Measuring Design. *John Weley and Sons Ltd*, pp. 909-919.

Adams, F. (2010). Mining Charter; Derelict and Ownerless mines: progress report by Department of Mineral Resources. https://pmg.org.za/committee-meeting/12080/

Allen, C.; Maurer, A. and Fainstein. M. (2001). Mine Site Rehabilitation - An Economic Review of Current Policy Issues. *ABARE Report Presented for the Department of Industry, Science and Resources*, Canberra, August, p 54.

Angeli, C. (2010). Diagnostic Expert Systems: From Expert's Knowledge to Real-Time Systems. Advanced Knowledge Based Systems: Model, Applications and Research (Eds. Sajja and Akerkar), 1, pp 50 – 73.

Anjaneyulu, K. S. R. (1998). Expert Systems: An Introduction, General Article, Resonance, pp. 46-58.

Arranz-Gonzalez, J.C.; Rodrıguez-Gomez, V.; Alberruche del Campo, E.; Vadillo-Fernandez, L.; Fernandez-Naranjo, F. J.; Reyes-Andres, J. and Rodrıguez–Pacheco, R. (2016). A Methodology for Ranking Potential Pollution Caused by Abandoned Mining Wastes: Application to Sulfide Mine Tailings in Mazarron (Southeast Spain). *Environ Earth Sci*. 75: 656.

Ataei, M.; Jamshidi M.; Sereshiki, F. and Jalali, S.E.M. (2008). Mining Method Selection by AHP Approach. *Journal of the southern African Institute of Mining and Metallurgy*, 108 (12), pp. 743-751.

Auditor-general South Africa (2009). Report of the Auditor-General to Parliament on a Performance Audit of the Rehabilitation of Abandoned Mines at the Department of Minerals and Energy, Auditing to Build Public Confidence, October-2009, p. 22.

Azimi, R.; Yazdani-Chamzini, A.; Fouladgar, M. M.; Zavadskas, E. K. and Basiri, M. H. (2011). Ranking the Strategies of Mining Sector Through ANP and TOPSIS in a SWOT Framework. *Journal of Business Economics and Management*, 12, pp. 670-689.

Bahnemann, K. P. (1986). The Review of the Geology of the Mesina Copper Deposits, Northern Transvaal. In: Anhaeunseh, C.R. and Maske, S. (Eds), Mineral Deposits of

Southern Africa. Vol. I and II, *Geological Society of Southern Africa.* Johannesburg, pp. 1671-1688.

Bai, Y. and Wang, D. (2006). Fundamentals of Fuzzy Logic Control – Fuzzy Sets, Fuzzy Rules and Defuzzifications. *Springer*, 115, pp 2-36.

Bandyopadhyay, L. K. and Sinha, S.K. (2002). Development of an Expert System for On-Line Ventilation Network Analysis and Graphic Representation of Mine Ventilation Parameters. *Journal of the Southern African Institute of Mining and Metallurgy*, 109, pp. 125- 130.

Barclay, A.M.D. (2014). Bat Associated with Inactive Mine Features in Southeastern Arizona. *Journal American Society of Mining and Reclamation*, 3(2), pp.1-21

Barai, S. and Pandey, P. C. (2004). Knowledge Based Expert System Approach to Instrumentation Selection. *Transport*, 16 (4), pp. 171-176.

Bell, N.; Sullivan, D.M. and Cook, T. (2019). Mulching Woody Ornamentals with Organic Materials. *EC 1629-E*, *Oregon State University*, p. 11.

Bhattacharya A.; Routh J.; Jacks G.; Bhattacharya, P. and Morth, M. (2006). Environmental Assessment of Abandoned Mine Tailings in Adak, Vasterbotten District (Northern Sweden). *Applied Geochemistry*, 21, pp. 1760–1780.

Bini, C.; Maleci, L. and Wahsha, M. (2017). Mine Waste: Assessment of Environmental Contamination and Restoration. Assessment, Restoration and Reclamation of Mining Influenced Soils, pp.89-134.

Bohanec, M and Rajkovič, V (1990). DEX: An Expert System Shell for Decision Support, A reformatted version of the article published in Sistemica, 1(1), pp. 145–157.

Boning, J. 2015. Illegal Mining in South Africa: What are the Impacts and Threats. Solidarity Union: South Africa. (03 August 2015): Available in: https://tydskrif.solidariteit.co.za/illegal-mining-in-south-africa-the-impact-and-threat/

Bolger, P. M., Duszak, Z., Koczkodaj, W. W and Mackasy, W. O. (1995). Big problems/small problems? Applying "first things first' principle towards establishing a management system (AMHAZ) for prioritizing abandoned mine hazards. Proceedings on the Sudbury 95, Conference on Mining and Environment, pp. 339–348.

Bowell R.J., Rees S.B., Parshley J.V (2000). Geochemical Predictions of Metal Leaching and Acid Generation: Geologic Controls and Baseline Assessment. in Geology and ore Deposits 2000: The Great Basin and Beyond, J.K. Cluer, J.G Price, E.M. Struhsacker, R.F Hardyman and C.L. Morris (Editors). *Geological Society of Nevada Symposium Proceedings*, *Reno/Sparks*, pp. 799-823.

Brinke, E. (2002). Costing Support and Cost Control in Manufacturing: A Cost Estimation Tool Applied in the Sheet Metal Domain. *Print Partners Ipskamp, Enschede*, the Netherlands, p 148.

Brinke E.T., Lutters E., Streppel T and Kals H (2007). Cost estimation architecture for integrated cost control based on information management. *International Journal of Computer Integrated Manufacturing,* 17 (6), pp. 534-545

Brodie Consulting LTD (2017). Reclaim 7.0 User Manual Mining Version. Government of the Northwest Territories, p. 17. Available in: https://www.enr.gov.nt.ca/sites/enr/files/resources/reclaim_user_manual_mining.pdf

Burhan, A.M. (2016). Developing an Expert System for The Investigation of Construction Failure Causes by Using ES Builder Program. *Appl. Res. J.*, *2*, pp. 43–49.

Cato, N. and Mahmud, S. (2000). Abandoned Mine Site Characterization and Cleanup Handbook. *United States Environmental Protection Agency*, p. 129.

Cervone H.F (2009). Applied digital library project management Using Pugh matrix analysis in complex decision-making situations. *OCLC Systems and services: International digital library perspectives*, 25(4), pp. 228-282.

Chamber of Mines of South Africa, (2012). Fact about South African Mining, Putting South Africa First: Mining Contribution to South Africa. p 8.

Chambers, J.; Ogilvy, R.; Wilkinson, P.; Weller, A.; Meldrum, P. and Caunt, S. (2007). Locating lost Mineshafts' Earthwise 25 British Geological Survey, *NERC*. pp. 26–27.

Christensen, R.L. (1968). The Nature of Decision Making. *Journal of Cooperative Extension*, pp. 23-28.

Chapman, A. (2011). Acid Mine Drainage in South Africa: An Emerging Environmental Problem**.** *Institute for Futures Research*, *University of Stellenbosch*, 9(1), p 4.

Chaumba, J.B.; Mundalamo, H.R.; Ogola, J.S.; Cox, J.A. and Fleisher, C.J. (2016). Petrography, Sulfide Mineral Chemistry, and Sulfur Isotope Evidence for a Hydrothermal Imprint on Musina Copper Deposits, Limpopo Province, South Africa: Evidence for a breccia pipe origin?, *Journal of African Earth Sciences*, 120, pp. 142-159.

Choi, W.; Jeong, S. and Chae, Y. (2005). Study on Recycling and Utilization of Abandoned Mine Waste. *Geosystem Engineering*, 8 (3), pp. 57-62.

Chon, H.T.; Cho, C.H.; Kim, K.W. and Moon, H.S. (1996). The Occurrence and Dispersion of Potentially Toxic Elements in Areas Covered with Black Shales and Slates in Korea. *Applied Geochemistry*, 11, pp. 69-76.

Chu, C.; Chain, W.; Lai, C.; Bludau, H.; Tshai, H.; Pai, L.; Hsieh, S.; Chu, U.; Klar. A.; Haux, R. and Wetter, T. (2009). A Bayesian Expert System for Clinical Detecting Coronary Artery Disease, *Journal of Medical Sciences*, 29 (4), pp. 187-194.

Churilov, S. (2009). Expert System for Seismic Vulnerability Assessment of Masonry Structures, *Taylor and Francis Group, London*, pp. 1449-1454.

Contractors Plant Hire Association (2011). Official Rate Guide of the Contractors Plant Hire Association (CPHA), p. 70.

Collopy, P. D. and Curran, R. (2005). The Challenge of Modeling Cost: The Problem. *1st International Conference on Innovation and Integration in Aerospace Sciences, Queen's University Belfast*, Northern Ireland, UK. 4-5 August 2005, pp 10

Coyle, G. (2004). The Analytic Hierarchy Process (AHP). Practical Strategy, Pearson Education Limited. p.11.

Crowley, J.L. (2012). Intelligent Systems: Reasoning and Recognition. ENSIMAG 2 and MoSIG M1, Lecture 2, Winter Semester 2012. p12. Available at http://www-prima.imag.fr/jlc/Courses/2011/ENSI2.SIRR/ENSI2.SIRR.S1.pdf

Cruz, G.P.A and Beliakov, G. (1996). On the Interpretation of Certainty Factors in Expert Systems. *Artificial Intelligence in Medicine*, 8, pp. 1-14.

Culshaw, M.G.; McCann, D.M. and Donnelly, L.J. (2000). Impacts of Abandoned Mine Workings on Aspects of Urban Development. *Mining Technology*, 109(3), pp.132-139.

Davenport, J. (2006). Government Allocates R70m for Rehabilitation of 8 000 Derelict Mines, Engineering News, www.engineeringnews.co.za

Davies, C.S. (1988). Abandoned Mine Shafts and Levels in the British Coalfields. *Environmental Management*, 12 (4), pp. 479-490.

Day, S. J. and Harpley, D. P. (1992). Survey of closed and abandoned mines in British Columbia for acid rock drainage I: Regional perspective. The Technical and Research Committee on Reclamation, In: *Proceedings of the 16th Annual British Columbia Mine Reclamation Symposium in Smithers*, BC, pp. 152–161

Dentoni, V.; Massacci, G. and Radwanek-Bak, B. D. (2006). Visual Impact of Quarrying in the Polish Carpathians. *Geological Quarterly*, 50, pp. 383–390.

Dentoni, V and Massacci, G (2013). Assessment of visual impact induced by surface mining with reference to a case study located in Sardinia (Italy). *Environmental Earth Sciences*, 68, pp.1485–1493.

Detyniecki, M. and Yager R. R. (2001). Ranking Fuzzy Numbers using alpha-Weighted Valuations. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, 8 (5), pp. 573-592.

Dixon, D.A. and Keto, P. (2009). Backfilling Techniques and Materials in Underground Excavations: Potential Alternative Backfill Materials in Use in Posiva's Spent Fuel Repository Concept. *Posiva OY*, Olkiluoto, p. 77.

DMR: Department of Mineral Resource (2010). Presentation to SCOPA and PPC (Mineral Resources) on the Auditor General's report on Rehabilitation of Derelict and Ownerless Mines, 1st September 2010.

Dogangun, A.; Karaca, Z.; Durmus, A. and Sezen, H. (2009). Cause of Damage and Failures in Silo Structures. *Journal of Performance of Constructed Facilities*, 23(2).

Donato, D.B.; Nichols, O.; Possingham, H.; Moore, M.; Ricci, P.F. and Noller, B.N. (2007). A Critical Review of the Effects of Gold Cyanide-Bearing Tailings Solutions on Wildlife. *Environment International*, 33, pp. 974–984.

Drummend, H. (1994). Effective Decision Making: A Practical Guide for Management, Second edition, Kogan Page, p179.

du Plessis, A. and Brent, A.C. 2006. Development of a risk-based mine closure cost calculation model. *Journal of the South African Institute of Mining and Metallurgy*, 106. pp. 443–450.

Duszak, Z.; Koczkodaj, W.W. and Mackasey, W.O. (1995). Towards better abandoned mine hazard prioritization an expert system. In: *Proceedings of the 10th National Meeting of ASSMR*, Spokane, Washington, DC, USA, 16–19 May 1995; pp. 577–590.

Eckels, R. and Bugosh, N. (2010). Natural Approach to Mined Land Rehabilitation. *FIG Congress 2010*, *Facing the Challenges – Building the Capacity Sydney*, Australia, pp. 11-16.

Edmund, O.D. (1992). Audit and Security Issues with Expert Systems AICPA: American Institute of Certified Public Accountants, Inc., p31.

Efstathhiou, J. and Rajkovic, V. (1979). Multiattibute Decision Making Using a Fuzzy Heuristic Approach. *IEEE Transaction on Systems, Man and Cybernetics*, 9, pp. 326-333.

Elkan, C. (1993). The Paradoxical Success of Fuzzy Logic. Proceedings of the Eleventh Natrona 1 Conference on Artificial Intelligence (AAA1 '93), *MIT Press*, pp 698-703.

Environmental Health Standing Committee - enHealth (2013), Asbestos: A Guide for Householders and the General Public. *Australian Health Protection Principal Committee*, Canberra, pp. 43.

Environmental Sustainability Unit, (2010). ESG1: Rehabilitation Cost Estimate Guidelines. *State of New South Wales through Department of Industry and Investment*, p 12.

Fashola, M.O; Ngole-Jeme, V.M. and Babalola, O.O. (2016). Heavy Metal Pollution from Gold Mines: Environmental Effects and Bacterial Strategies for Resistance. *Int. J. Environ. Res. Public Health*., 13, 1047

Favas P.J.C.; Martino, L.E. and Prasad, M.N.V. (2018). Abandoned mine land reclamation—challenges and opportunities (Holistic Approach). *Bio-Geotechnologies for Mine Site Rehabilitation*, pp. 3-31.

Festin, E.S.; Tigabu, M.; Cheleshe, M.N.; Syamungani, S. and Oden, P.C. (2018). Progresses in Restoration of Post-Mining Landscape in Africa. *Journal of Forest Research*, pp 381–396.

Fortier, D. and Moore, S. W. (n.d.). Abandoned Mine Site Restoration on Pine Creek, Northenr Idaho: Coeur D=Alene Basin, pp. 8.

Gallagher, C. P.; Henshaw, A. C.; Money, M. S. and Tarling, D. H. (1978). The Location of Abandoned Mine-Shafts in Rural and Urban Environments. *Bulletin of the International Association of Engineering Geology*, (18), pp. 179–185.

Ghanavati, B. (2012). A 1.5v CMOS Fuzzifier. *International Journal of Multidisciplinary Sciences and Engineering*, 3 (6), 52-55.

Giarratano, J.C and Riley, G (1998). Expert Systems: Principles and Programming (3rd edition). *PWS Pub.co: Boston,* p 597.

Gitari, M.W.; Akinyemi, S.A.; Thobakgale, R.; Ngoejana, P.C., Ramugondo, L.; Matidza M.; Mhlongo, S.E.; Dacosta, F.A. and Nemapate, N. (2018). Physicochemical and Mineralogical Characterization of Musina mine copper and New Union Gold Mine Tailings: Implications for Fabrication of Beneficial Geopolymeric Construction Materials. *Journal of African Earth Sciences*, 137, pp. 118-228.

Goldammer, W. and Nüsser A. (1999), Cost-Benefit Analyses as Basis for Decision-Making in Environmental Restoration, *WM'99 Conference*,28 February to 04 March 1999. p. 14.

Graves, J.; Kastl, M.; Suman, A. L.; Freeman, S.; Erdner, B.; Sharp, M.; Meier L.; Datin, D.; Dalgarn, J.; Garvin, M.; Keheley, E.; Rainbolt. J.; Crawford, J. (2000). Mine shaft Subcommittee Final Report to Governor Frank Keating's Tar creek superfund task force, p. 70.

Greeley, M. N. (1999). National reclamation of abandoned mine lands. SME, Retrieved from https://www3.epa.gov/npdes/pubs/amlpaper.htm

Gunn, D. A.; Deakin, M.; Ager, G. J.; Ginson, A.; Caunt, S. and Haslam, E. (2006). Thermal Infrared Survey of Mineshafts at Powfall. St. Helens: IAEG2006, *The Geological Society of London*, p. 13.

Hammerbeck, E. C. I. (1976). Copper. In: C. B. Coetzee (Ed.), The mineral resources of South Africa (5th ed). Handbook, *Geology Survey of South Africa*, pp. 125–146.

Hamner P.C.; Ringe, J.M.; Pelkki, M.H.; Graves, D.H. and Sweigard, R.J. (1999). An Economic Evaluation of Soil Bioengineering as A Method for Slope Stability on

Abandoned Mine Land in Eastern Kentucky. *International Journal of Surface Mining, Reclamation and Environment*, 13 (3), pp. 117-124.

Hargrave, P.A.; Kerschem, M.D.; Liva, G.W.; Lonn, J.D.; McDonald, C.; Metesh, J.J. and Wintergerst, R. (2000). Abandoned-inactive Mines on Lewis and Clark National Forest-Administrated Land. *Montana Bureau of Mines and Geology Abandoned–Inactive Mines Program Open-File Report MBMG 413*. Presented for the US Department of Agriculture Forest Service-Region 1, p 191.

Hatzilygeroudis I, Karatrantou A, and Pierrakeas C. (2004). PASS: An Expert System with Certainty Factors for Predicting Student Success. In: M.Gh. Negoita et al. (Eds.): KES 2004, *LNAI 3213*, pp. 292–298.

Haymont, R. (n.d). Closure Cost Estimating Methodologies: A Review of Mine Closure Cost Estimating Methodologies and for Different Reporting Purposes. Available in: *http://www.trajectory.net.au/documents/2012%20-%20Closure%20Cost%20Estimating%20Liabilities%20-%20GEMG.pdf*

Hernan, R. E. (2010). Reports, Historic Mine Sites. *Irish Environment, Environmental matters on the island of Ireland.* (05 May 2010). Available in: http://www.irishenvironment.com/reports/historic-mine-sites/

Higson, S.J.; Paul, T. and Merkle, A. (2018). Landscape and Visual Considerations in Mine Closure – An International Overview. In: Drebenstedt, C., von Bismarck, F., Fourie, A. and Tibbett, M (editors). Mine closure 2018: *Proceedings of the 12th International Conference on Mine Closure. Mine Closure*. Technical University Bergakademie Freiberg, pp. 287-300.

Hogo, M. A.; Fouad, K. and Mousa, F. (2009). Web-Based Expert System for Civil Service Regulations: RCSES. *International Journal of Computer Science and Information Security*, 6 (3), pp. 7-16.

Hola, B. and Schabowicz K. (2010), Estimation of Earthworks Execution Time Cost by Means of Artificial Neural Networks. *Automation in Construction*, 19, pp. 570-579.

Holl G. W and Fairon E. G (1973). A Review of Some Aspects of Shaft Design. *Journal of the South African Institute of Mining and Metallurgy*, pp. 309-324.

Holmes, D. (2008). The Investigation of Statutory Nuisance Mineshafts: A Project to Establish Awareness and Actions Amongst Local Authority Environmental Health Departments. *Chartered Institute of Environmental Health,* 7(1). Retrieved from http:// www.cieh.org/JEHR/statutory_nuisance_mineshafts.

Hoskin, W.M.A. (2012). Mine Closure – The 1st Century Approach Avoiding Future Abandoned Mines, p 10.

Houben, G.; Lenie, K. and Vanhoof, K. (1999). A Knowledge-Based SWOT-Analysis System as an Instrument for Strategic Planning in Small and Medium Sized Enterprises, Decision Support Systems, 26, pp. 125–135.

Hutchison, I. and Dettore, R. (2011). Statistical and Probabilistic Closure Cost Estimating. *Proceedings Tailings and Mine Waste, Vancouver,* BC, 6 - 9 November 2011, pp 13.

Iacovidou, E. and Purnell, P. (2016). Mining the Physical Infrastructure: Opportunities, Barriers and Interventions in Promoting Structural Components Reuse. *Science of the Total Environment*, 557–558, pp. 791–807.

Ianca, E. and Buta, S. (2011). Potential Developments of Expert Systems Using Information about Explicit and Tacit Knowledge, *IJRRAS*, 9, pp. 420-426.

Jadhav, J.S.; Nalawade, K.M.; Bapat M.M. (2016). Rule Based Expert System Prototype Application for Crime Against Women Law in Indian Legislation System. IOSR *Journal of Computer Engineering*, 18 (6), pp. 1-7.

Johnston, D.; Potter, H.; Jones, C.; Rolley, S.; Watson, I. and Pritchard, J. (2008). Abandoned Mines and the Water Environment: Science Project SC030136-41, *Environment Agency* – August 2008, p 40.

Johnson, B. and Carroll, K.C. (2007). Waste Rock Backfill of Open Pits: Design, Optimization, and Modelling Considerations. In: Fourie, A.; Tibbett, M. and Wiertz, J. (eds), Mine Closure 2007, *Australian Centre for Geomechanics*, Perth, pp. 701- 708.

Jordan, G. and Abdaal, A. (2013). Decision Support Methods for the Environmental Assessment of Contamination at Mining Sites. *Environmental Monitoring and Assessment*, 185, pp. 7809–7832.

Kadhim, M. A.; Alam, M.A. and Kaur, H. (2011). Design and Implementation of Fuzzy Expert System for Back pain Diagnosis. *International Journal of Innovative Technology and Creative Engineering*, 1(9), pp 16-22.

Kamunda, C.; Mathuthu, M. and Madhuku, M. (2016). Health risk assessment of heavy metals in soils from Witwatersrand Gold Mining Basin, South Africa. *International Journal of Environmental Research and Public Health*, 13, 663.

Kappes. S.F.; Kim. S.S.; Tanner, P.J.; Williams, R.J. and Cohn. L.F. (1990). Employing Expert System Technologies to Real Property Management Decision-making. *USACERL Technological Report*, p 40.

Keshwani D.R.; Jones, D.D.; Meyer G. E.; Brand, R. M. (2007). Rule-based Mamdani-type Fuzzy Modeling of Skin Permeability. *Applied Soft Computing*, 8, pp. 285–294.

Kilian, J.M. (2008). Addressing the Social Impact of Mining Activities on Communities for Sustainability. Civil Engineering, 16, pp.22-24.

Kim, M. and Jung, Y. (2004). Vertical Distribution and Mobility of Arsenic and Heavy Metals in and around Mine Tailings of an Abandoned Mine. *Journal of Environmental Science and Health: Part A - Toxic/Hazardous Substances and Environmental Engineering*, A39 (1), pp. 203–222.

Kirmanli, C. and Erceleni, S.G. (2009) An Expert System for Hydraulic Excavator and Truck Selection in Surface Mining. The Journal of the Southern African Institute of Mining and Metallurgy, 109, pp. 727-739.

Kivinen, S. (2017). Sustainable Post-Mining Land Use: Are Closed Metal Mines Abandoned or Re-Used Space?. *Sustainability,* 9, pp. 1-18.

Kubit, O. E.; Pluhar, C. J. and De Graff, J. V. (2015). A model for prioritizing sites and reclamation methods at abandoned mines. *Environment Earth Sciences*, 73 (12), pp. 7915–7931.

LaGuardia, T.S. (2017). The Real Costs of Decommissioning. In: Advances and Innovations in Nuclear Decommissioning. *Woodhead Publishing Series in Energy*, pp. 91-129

Land Rehabilitation Society of Southern Africa, Coaltech, Minerals Council of South Africa (2018). Land Rehabilitation Guidelines for Surface Coal Mines, p. 189.

Laurence, D. (2011). Establishing a Sustainable Mining Operation: An Overview. *Journal of Cleaner Production*, 19(2–3), pp. 278-284.

Lecomte, A. and Niharra, A. M. (2013). Handbook to Best Practices for Mine Shafts Protection: Project Deliverable D4, *MISSTER*, p. 45.

Lee, C.C. (1990). Fuzzy Logic in Control Systems: Fuzzy Logic Controller-Part I. *IEE Transaction of systems, Man, and Cybernetics*. 20(2), pp 404-418.

Lehohla, P. (2014). Provincial profile: Limpopo Census 2011. Report No. 03-01-78 (2011). *Statistics South Africa*. p. 58.

Li, X. and Huang, L. (2015). Toward a New Paradigm for Tailings Phytostabilization—Nature of the Substrates, Amendment Options, and Anthropogenic Pedogenesis, Critical Reviews in Environmental Science and Technology, 45(8), 813-839.

Liefferink, M. (2006). Registration Number: 2006/217972/23 NPO NUMBER: 062986-NPO. *Federation for a Sustainable Environment*. Randburg, Republic of South Africa. p.

Limpitlaw, D. and Briel A. (2014). Post-Mining Land Use Opportunities in Developing Countries–A Review. *The Journal of The Southern African Institute of Mining and Metallurgy*, 114, pp. 899-903.

Lonmo, L. and Muller, G. (2014). Concept Selection Applying Pugh Matrices in the Subsea Processing Domain. p.16

Lottermoser, B.G. (2011). Recycling, Reuse and Rehabilitation of Mine Wastes. *Elements*. 7, pp. 405–410.

Luger, G.F. and Chakrabarti, C. (2009). Knowledge-Based Probabilistic Reasoning from Expert Systems to Graphical Models. *Technical Report –UNM Computer Science*, pp. 22.

Luodes, N.M. (2013), Inventory of Closed and Abandoned Mines Methods for Performing the Inventory and for Risk Classification with Diverse Data Availability Levels. Thesis Environmental Engineering, *Mikkelin Ammattikorkeakoule, Mikkeli University of Applied Sciences*, p. 83.

Macharia, J. (2009). More than 60 illegal miners killed at SA gold mine. Mail and Gardenia. http://mg.co.za/article/2009-06-02-more-than-60-illegal-miners-killed-at-sa-gold-mine

Mackasey, W.O (2000). Abandoned Mines in Canada. WOM Geological Associates Inc. Sudbury, Ontario. p 14.

Madke, P.B. and Jaybhaye, M.D. (2016). Application of Pugh Selection Matrix for Fuel Level Sensing Technology Selection. *International Journal of Engineering Research,* 5 (2), pp. 368-370.

Magary, J. (1997). Artificial Intelligence and PLC Systems. In: Programmable Controllers Theory and Implementation 2nd edition. Bryan L.A and Bryan E.A (Editors). *Industrial Text Company*. pp. 774-788.

Magodi, R. (2017). Assessment and Management of Environmental and Socio-Economic Impacts of Small-Scale Gold Mining at Giyani Greenstone Belt (Unpublished MSc. Dissertation). Department of Geography and Geo-Information Systems, School of Environmental Sciences, *University of Venda*, p 100.

Mahaman, B.D.; Passam, H.C.; Sideridis, A.B and Yialouris, C.P. (2002). DIARES-IPM: a Diagnostic Advisory Rule-Based Expert System for Integrated Pest Management in Solanaceous Crop Systems, *Agricultural Systems*, 76, pp. 1119–1135.

Maher, M. L.; Longinos, P. and Carnegie, M. (1986). Development of an Expert System Shell for Engineering Design. University Engineering Design Research Center. *Department of Civil and Environmental Engineering. Paper 1*, p. 20.

Makgae, M. (2012). The Status and Implication of the AMD Legacy Facing South Africa. In: McCullough, Lund and Wyse (Editors). *International Mine Water Association, Annual Conference*. pp. 327 – 334.

Mendel, J.M. (1995). Fuzzy Logic Systems for Engineering: A Tutorial. *Proceedings of the IEEE*, 83 (3), pp 345-377

Menéndez. J.; Loredo J.; Fernandez, J.M. and Galdo, M. (2017). Underground Pumped-Storage Hydro Power Plants with Mine Water in Abandoned Coal Mine. In:

Wolkersdorfer C, Sartz L, Sillanpää M, Häkkinen A (Editors), *Proceedings of the 13th International Mine Water Association Congress, Mine Water and Circular Economy*, Lappeenranta, Finland, pp. 6-13.

Mani, D. and Kumar, C. (2014). Biotechnological Advances in Bioremediation of Heavy Metals Contaminated Ecosystems: An Overview with Special Reference to Phytoremediation. *International Journal of Science and Technology,* 11(3), pp. 843-872.

Masannat, Y.M (1980) Development of Piping Erosion Conditions in the Benson area, Arizona, U.S.A. *Quarterly Journal of Engineering Geology and Hydrogeology*, 13, pp. 53-61.

Matshusa, K. and Makgae, M. (2014). Overview of Abandoned Mines in the Limpopo Province, South Africa: Rehabilitation challenges. *Journal of Environmental Science and Engineering B*, 3, pp. 156–161.

Matthew, O.; Buckley, K.; Garvey, M. and Moreton, R. (2016). Multi-tenant Database Framework Validation and Implementation into an Expert System. International *Journal of Advanced Studies in Computer Science and Engineering,* 5 (8), pp. 13-21.

Mavrommats, E. and Menegaki, M. (2017). Setting Rehabilitation Priorities for Abandoned Mines of Similar Characteristics According to their Visual Impact: A case of Milos Island, Greece. *Journal of Sustainable Mining*, 16, pp. 104–113.

Maynard, E. (2013). Ten Steps to an Effective Bin Design. *American Institute of Chemical Engineers (AIChE),* pp. 25-32.

Mazzini, G. (1997). Chapter Seventeen: Fuzzy Logic, Industrial Text and Video Company, pp 199-845.

McArdle P. and Kelly M., Historic mine sites inventory and risk classification non-technical summary, *Geological Survey of Ireland and the Environmental Protection Agency*, p. 28.

McCarthy T.S (2011). The Impact of Acid Mine Drainage in South Africa. *South African Journal of Science.,* pp. 107-712.

McCullough, C.D.; Schultze, M. and Vandenberg, J. (2020). Realizing Beneficial End Uses from Abandoned Pit Lakes. *Minerals,* 10, 133

Mchaina D.M (2001). Environmental Planning Considerations for the Decommissioning, Closure and Reclamation of a Mine Site. *International Journal of Surface Mining, Reclamation and Environment*. 15 (3), pp. 163-176.

Mhlongo S.E. (2012). Development of a Modeling Framework for Design of Low-Cost and Appropriate Rehabilitation Strategies for Nyala Abandoned Mine. Unpublished MSc. Dissertation, Department of Mining and Environmental Geology, *University of Venda*, p. 156

Mhlongo, S.E.; Amponsah-Dacosta, F. and Mphephu, N.F. (2013). Rehabilitation prioritization of abandoned mines and its application to Nyala Magnesite Mine. *Journal of African Earth Sciences*, 88, pp. 53-61.

Mhlongo, S.E.; Amponsah-Dacosta, F.; Magodi R. and Sithole K.C. (2018). Artisanal Gold Mining and its Environmental Stress at Abandoned Louis Moore Mine in the Limpopo Province of South Africa. ASM Conference 2018 "Fostering a Regional Approach of ASM Transformation in Sub-Saharan Africa". *The Southern African Institute of Mining and Metallurgy,* Johannesburg, 10-11 September 2018, pp. 181-193.

Mhlongo, S.E and Amponsah-Dacosta, F. (2015). Rehabilitation of Abandoned open Excavation for Beneficial use of the pit Lake at Nyala Magnesite Mine, *International Journal of Environmental Research,* 9(1), pp. 303-308.

MINEO, (2003). Assessing and monitoring the environmental impact of mining activities in Europe using advanced Earth Observation techniques. Project funded by the European Community under the "Information Society Technology" Programme (1998-2002), April 2003, p40.

Misthos, L.M, Pavlidis, A.; Karabassakis, E.; Menegaki, M, Krassanakis, V. and Nakos, B. (2019) Exploring the Visual Impact from Open Pit Mines Applying Eye Movement Analyses on Mining Landscape Photograph. *International Journal of Mining, Reclamation and Environment*, pp.1-17.

Mitchel, A. and Mackasey, W.O. (1995). The Identification, Location and Assessment of Abandoned Mine Hazards – The First Step toward Rehabilitation, *Conference on Mining and the Environment,* Sudburg, Ontario, May 28th – June 1st, 1995: p. 289 – 298.

Miyabe, Y.; Baba, T.; Dairiki, O.; Matsuo, Y. and Mizuno, S. (1993). A Very Fast Rule-Based Inference Engine for Expert Systems. *NIPPON Steel Technical Report No. 56 January 1993*, pp. 23-29.

Mohutsiwa, M. and Musingwini, C. (2015). Parametric Estimation of Capital Costs for Estimating a Coal Mine: South Africa Case Study. *The Journal of the South African Institute of Mining and Metallurgy,* 115, pp. 789-797.

MMSD: Mining, Minerals and Sustainable Development (2002). Mining for the Future Appendix C: Abandoned Mines Working Paper, *IIED and WBCSD 28*, pp. 1-25.

Moosavirad, S. M. and Behnia, B. (2016). Suitability evaluation for land reclamation in mining areas: Gol-eGohar Iron Ore Mine of Sirjan, Kerman, Iron. *International Journal of Mining, Reclamation and Environment*, pp. 1-14.

Munnik, V.; Hochmann G.; Hlabane, M. and Law, S. (2010). The Social and Environmental Consequences of Coal Mining in South Africa: A Case Study, *Environmental Monitoring Group,* p 24.

Musztyfaga, M. and Skolud, B. (2007). Advisory System Assisting Selection of Project Structures and Project Team. *Journal of Achievements in Materials and Manufacturing Engineering*, 20, 1-2, pp 551-554.

Musingwini, C. and Minnitt, R.C.A. (2008). Ranking the Efficiency of Selected Platinum Mining Methods Using the Analytic Hierarchy Process (AHP). 3rd International Platinum Conference 'Platinum in Transformation'. *The Southern African Institute of Mining and Metallurgy*, pp. 319 - 326.

Muzerengi, C. (2015). Heavy Metal Concentration of Soils in the Vicinity of Louis Moore Gold Mine, South Africa. In: Jorge Chavez and Fernando Valenzuela (eds), Proceedings of the 4th International Seminar on Environmental Issues in Mining (Environmine2015), *Gecamin*, Chile, pp. 111-120.

Navarro-Pedreño, J.; Belén Almendro-Candel, M.; Gómez, I.; Jordán M.M.; Pardo, F (2017). Organic Mulching to Improve Mining Soil Restoration. *Assessment, Restoration and Reclamation of Mining Influenced Soils,* pp. 375- 386.

Nehring, M. and Cheng, X. (2016). An Investigation into the Impact of Mine Closure and its Associated Cost on Life of Mine Planning and Resource Recovery. *Journal of Cleaner Production*, 127(20), pp. 228-239.

Newton. G.; Reynolds. S.; Newton-Reed. S.; Tuffly. M.; Miller. E.; Reeves. S.; Mistchenko. J. and Bailey, J. (2000). California's Abandoned Mines, A Report on the Magnitude and Scope of the Issue in the State Volume I. *Department of Conservation Office of Mine Reclamation Abandoned Mine Lands Unit*, p. 66.

Niazi, A.; Dai J.S.; Balabani S. and Seneviratne, L. (2006). Product Cost Estimation: Technique Classification and Methodology Review. *Journal of Manufacturing Science and Engineering.* 128, pp. 563- 575.

Nimick, D. A. and Moore, J. M. (1991). Prediction of water-soluble metal concentrations in fluvially deposited tailing sediments, Upper Clark Fork Valley, Montana, USA. *Appl. Geochem.* 6, pp. 635–646.

Noran, O.S (2003). The Evolution of Expert Systems, Griffith University, School of Computing and Information Technology, Queensland, Australia. Available: http://www.cit.gu.edu.au/~noran

Nordstrom, D.K. and Alpers C.N. (1999). Geochemistry of Acid Mine Waters. In: Plumlee, G.S. and Logsdon, M.J. (Eds.). The Environmental Geochemistry of Mineral Deposits, Part A: Processes, Techniques and Health Issues, Reviews in Economic Geology Vol. 6A, *Society of Economic Geologists*, *Inc*., pp. 133-160.

Nurcahyo, G. W. and Shamsuddin, S. M. (2003). Selection of Defuzzification Method to obtain Crisp Value for Representing Uncertain Data in a Modified Sweep Algorithm. *The Journal of Computer Science and Technology*, 3(2), pp. 22-28.

Oelofse, S. (2008). Mine Water Pollution – Acid Mine Decant, Effluent and Treatment: A Consideration of Key Emerging Issues That May Impact the State of the Environment. In: Sri Krishna (eds), Mining: Environment and Health Concerns. *The Icfai University Press*. pp 83-91

Ogbeide, S.O.; Adejuyigbe, S.B. and Kareem, B. (2010). An Expert System for Determining Machines Capacity in Cement Industries. *Journal of Emerging Trends in Engineering and Applied Sciences*, 1 (1), pp. 52-59.

Ogle, P.R. and Redente, E.F. (1988). Plant Succession on Surface Mined Lands in the West. *Rangelands*, 10(1), pp. 37-42.

Olalde, M. (2016). Leaving the Poor to Cope Alone: South Africa's Failed System of Mine Closure. The Star (IOL). https://pulitzercenter.org/reporting/leaving-poor-cope-alone-south-africas-failed-system-mine-closure. Date viewed: 08 July 2019

Olalde, M. (2017). SA Coal Mines Leave Legacy of Ruin. Fun24. https://www.fin24.com/Companies/Mining/sa-coal-mines-leave-legacy-of-ruin-20170419, Date viewed: 08 July 2019

Olobatoke, R.Y. and Mathuthu, M. (2016). Heavy Metal Concentration in Soil in the Tailing Dam Vicinity of an Old Gold Mine in Johannesburg, South Africa. *Can. J. Soil. Sci.,* 96, pp. 299–304.

Ozkan S. and Ipekoglu B, (2002). Investigation of Environmental Impacts of Tailings Dams. *Environmental Management and Health*, 13 (3), pp. 242-248.

Parnham, D. (n.d). Creating share value in South Africa and Canada, Unlocking Value in the Limpopo Provence. *Giyani Gold Corp*. p. 21

Paruma, O.A.L. (2004). A Forward-Chaining Inference Rule Engine for a Prototype-Based Language. MSc. Thesis, *Vrije Universiteit Brussel, Faculty of Sciences*, p. 96.

Parshley, J.V.; Bauman, W. and Blaxland, D. (2009). An Evolution of the Methods for and Purposes of Mine Closure Cost Estimating. In: A.B. Fourie, M. Tibbett (eds), Mine Closure 2009. *Australian Centre for Geomechanics*, pp. 187-200.

Patel, A.V. (2005). Simplest Fuzzy PI Controllers under Various Defuzzification Methods. *International Journal of Computational Cognition*. 3, (1), pp 21-34

Pealta-Romero, A and Dagdelen, K. (2007). A New Model for Estimation of Mine Closure Costs. In: Fourie A, Tibbett M, and Wiertz J (eds), *Proceedings of the Second International Seminar on Mine Closure*, 16-19 October 2007, pp. 393-404.

Peralta-Romero, A. (2007). Development of a cost estimation model for mine closure. Arthur Lakes Library, *Colorado School of Mines*, p.185.

PGeo, E.G.S.; Gallagher, V.; Mhairtín, F. N.; Brogan, J.; Lally, P.; PGeo, E.E.D. and PGeo, E.L.F. (2009). Geochemical Characterization and Environmental Matters Historic Mine Sites – Inventory and Risk Classification: A Joint Study Carried out by the Environmental Protection Agency and The Geological Survey of Ireland. Volume I, p. 170

Pioneer Technical Services Inc (1994). Abandoned hard rock mine priority sites 1994 summary report (Engineering Services Agreement DSL-AMRB No. 94-006), *Montana Department of State Lands Abandoned Mine Reclamation Bureau*, p. 148.

Power, B. A.; Tinholt, M. J.; Hill, R. A.; Fikart, A.; Wilson, R. M.; Stewart, G.G.; Sinnett, G. and Runnells, J. L. (2009). Risk Ranking Methodology for Prioritizing Historic, Potentially Contaminated Mine Sites in British Columbia. *Integrated Environmental Assessment and Management*, 6, pp. 145–154

Pratt S.E (2011). All that glitters... Acid mine drainage: The toxic legacy of gold mining in South Africa. *American Geosciences Institute*, Friday, September 23, 2011 - 19:00

Priscu, D.M.; Armitt, E. and Priscu, C. (2010). Manitoba's Orphaned and Abandoned Mine Site Rehabilitation Programme -10 years in the Making. Proceedings of the Fifth International Conference on Mine Closure. *Australian Centre for Geomechanics*, Perth, pp. 609-622.

Ranjan, V.; Sen, P.; Kumar, D and Sarsawat, A. (2015). A Review on Dump Slope Stabilization by Revegetation with Reference to Indigenous Plant. *Ecological Processes*, 4 (14), p. 11.

Ranjan, P.; Patle, G.T.; Prem, M and Solanke K.R (2017) Organic Mulching - A Water Saving Technique to Increase the Production of Fruits and Vegetables. *Current Agriculture Research Journal*, 5 (3), pp. 371- 380.

Reclamation and Closure Guidance (2013). Reclamation and Closure Planning for Quartz Mining Projects Plan Requirements and Closure Costing Guidance. August 2013, p 41.

Reffat, R. and Hardness, E.L. (2001). Expert System for Environmental Quality Evaluation. *Journal of Performance of Constructed Facilities,* pp. 109-114.

Reinhardt, C. (2008). Heap Leaching and the Water Environment – Does Low Cost 396 Recovery Come at a High Environmental Cost? In: Rapantova, N. and Hrkal, Z., *397 Mine Water and the Environment*. pp. 395-398.

Reichardt, M (2012). A History of Mine Wastes Rehabilitation Techniques in South Africa: A Multi-Disciplinary Overview of Mine Waste Rehabilitation and the Non-Scientific Drivers for its Implementation 1950s – 1980s. *University of Witwatersrand: Botany Department*, p. 47.

Reis, A. P.; Ferreira da Silva, E.; Cardoso Fonseca, E.; Patinha, C.; Barrosinho, C. and Matos, J. (2012). Environmental Assessment of the Caveira Abandoned Mine (Southern Portugal): Part 1: Characterization of Metal Contaminated Soil. *Soil and Sediment Contamination: An International Journal,* 21 (2), pp. 227-254.

Rethman, N. (2000), Approaches to Biodiversity on Rehabilitated Minelands in South Africa, *Trop. Grassland*. 34, pp. 251–253.

Riley, S.J. and East, T.J. (1990). Investigation of the Erosion Stability of Waste Rock Dumps under Simulated Rainfall, A Proposal. *Technical Memorandum, Australian Government Publishing Service,* Canberra, p. 57.

Rodrıguez, R.; Dıaz, M.B.; Vigil, H. and Rodrıguez, A. (2011). Development of a user-Friendly Method to Assess the Present Condition of Old Abandoned Mining Waste Dumps in Asturias (Spain). *International Journal of Mining, Reclamation and Environment*, 25 (1), pp. 6–31.

Ross, T. J. (2004). Properties of Membership Functions, Fuzzification, and Defuzzification. Fuzzy Logic with Engineering Applications, Second Edition, *John Wiley & Sons, Ltd*, pp 90-119.

Rudas, I.J., Pap, E and Fodor, J (2013). Information Aggregation in Intelligent Systems: An Application Oriented Approach. *Knowledge-Based Systems*, 38, pp 3–13.

Rupprecht S.M. (2012). Mine Development – Access to Deposit. Platinum 2012, *The Southern African Institute of Mining and Metallurgy,* pp. 101- 122.

Rupprecht S.M (2015). Safety Aspects and Recommendations for Surface Artisanal Mining. *The Southern African Institute of Mining and Metallurgy,* 115, pp. 1007-1012.

Saade, J.J. and Diab, H. B. (2004). Defuzzification Methods and New Techniques for Fuzzy Controllers. *Iranian Journal of Electrical and Computer Engineering,* 3(2), pp 161-174.

Sahu, H. B. and Dash, S. (2011). Land Degradation due to Mining in India and its Mitigation Measures. *Proceedings of Second International Conference on Environmental Science and Technology- February 26-28*, 2011.

Salgado, I. (2011). Mines Threaten Water Catchment Areas. Business report, 21 February 2011; at 06:00am. http://www.iol.co.za/business/markets/commodities/mines-threaten-water-catchment-areas-1.1029384?showComments=true

Salim, M.D.; Villavicencio, A.; and Timmerman, M.A. (2003). A Method for Evaluating Expert System Shells for Classroom Instruction. *Journal of Industrial Technology*, 19 (1), p 11.

Salmon, R. and Degas, M. (2003). Mine shafts in Nord and Pas-de-Calais coalfield, France: risk assessment and treatment technique' mining technology. *Transactions of the Institutions of Mining and Metallurgy: Section A*, 112(1), pp. 1-8.

Saving Water SA (Cape Town, South Africa) and Partnered with Water Rhapsody Conservation Systems (2010). Slow pace of abandoned mine clean up leads to environmental disaster – 01 September 2010. http://www.savingwater.co.za/2010/09/01/18/pace-of-mine-clean-up-leads-to-disaster/

Scanlan, J.; Hill, T.; Marsh, R.; Bru, C.; Dunkley, M. and Cleevely, P. (2002). Cost Modeling for Aircraft Design Optimization. *Journal of Engineering Design.* 13, 2, pp 261 – 269

Schmoldt, D.L. (2001). Application of Artificial Intelligence to Risk Analysis for Forested Ecosystems, In: von Gadow, K (Ed.), Risk Analysis in Forest Management. Kluwer Academic Publishers, Netherlands, pp. 49–74.

Segal, N. and Malherbe, S. (2000). A Perspective on the South African Mining Industry in the 1st Century. An Independent Report Presented for The Chamber of Mines of South Africa by the Graduate School Business of the University of Cape Town in Association with Genesis Analytics, p. 74.

Seram, N. (2013). Decision Making in Product Development – A Review of the Literature. *International Journal of Engineering and Applied Sciences*, 2(4), pp. 1-11.

Sharma, T., Tiwari, N and Kelkar, D. (2012). Study of Difference between Forward and Backward Reasoning. *International Journal of Emerging Technology and Advanced Engineering*, 2(10), pp. 271-273.

Shehab, E.M. and Abdalla, H.S. (2001). Manufacturing Cost Modelling for Concurrent Product Development. *Robotics and Computer Integrated Manufacturing*, 17, pp 341-353.

Shen, B. (2012). Study on Financial Assurance and Closure Cost for Mine Reclamation. Master of Applied Science Thesis, Faculty of Graduate and Postdoctoral Studies, *The University of British Columbia*, p. 139.

Sheoran, V.; Sheoran, A. S. and Poonia, P. (2010). Soil Reclamation of Abandoned Mine Land by Revegetation: A Review. *International Journal of Soil, Sediment and Water*, 3(2), p. 21.

Shi, Y. and Sen, P.C. (2000). A New Defuzzification Method for Fuzzy Control of Power Converters. Paper 1, p 8.

Shinno, H.; Yoshioka, H.; Marpaung, S. and Hachiga, S. (2006). Quantitative SWOT analysis on global competitiveness of machine tool industry. *Journal of Engineering Design*, 17, pp. 251–258.

Sibanda, Z., Amponsah-Dacosta, F. and Mhlongo, S. E. (2013). Characterization and Evaluation of Magnesite Tailings for their Potential Utilization: A Case Study of Nyala Magnesite Mine, Limpopo Province of South Africa. *ARPN Journal of Engineering and Applied Sciences*, 8 (8), 606-613.

Siler, W. and Buckley, J.J (2005). Fuzzy Expert Systems and Fuzzy Reasoning. *John Wiley and Sons*, Inc, Hoboken, New Jersey, p. 422.

Spitz, K. and Trudinger, J. (2009), Mining and Environment from Ore to Metal, *Taylor and Francis Group*, London, p. 819.

Steenkamp, N.C. and Clark-Mostert, V. (2012). Impact of Illegal Mining at Historic Gold Mine Locations, Giyani Greenstone Belt area, South Africa, 9th International Mining History Congress. 17 – 20 April 2012, p. 10.

Stylianoun, A.C., Madey, G.R., and Smith, R.D. (1992). Selection Criteria for Expert System Shells: A Socio-technical Framework. *Communications of the ACM*, 35 (10), pp 30-48

Skinner, E. H. and Beckett, L. A (1994). A Field Trial for Sealing Abandoned Mine Shafts and Adits with Lightweight Concrete. Report of Investigations 9495, *U. S, Department of the Interior*, pp. 32.

Skousen J and Zipper C (2018), Powell River Project—Revegetation species and practices. *Virginia Cooperative Extension 460-122, Blacksburg, VA*. http://pubs.ext.vt.edu/460/460-122/460-122.html

Smith, S. (2009). Mining and The Environment - Briefing Paper No 6/09**.** NSW Parliamentary Library Research Service, p 36.

Swart, E. (2003). The South African legislative framework for mine closure, Proceedings of the Colloquium on Mine Closure for Sustainable Development. *South African Institute of Mining and Metallurgy*, Johannesburg, pp. 489-492.

Tahernejad, M. M.; Ataei, M. and Khalokakaei R. A. (2013). Strategic Analysis of Iran's Dimensional Stone Mines Using SWOT Method. *Arab J Sci Eng*., 38, pp. 149–154.

Tanner, P. (2007). Guidelines for the Rehabilitation of Mined Land. *Chamber of Mines of South Africa/COALTECH*, p.167.

Tsolaki-Fiaka. S, Bathrellos, G.D and Skilodimou, H.D. (2018). Multi-Criteria Decision Analysis for an Abandoned Quarry in the Evros Region (NE Greece). *Land,* 7 (43), pp. 1-16.

Tremblay, G. A. and Hogan, C.M. (2009). Approaches for the Remediation of Abandoned Mines and NOAMI. DÉCHETS - Revue Francophone D'écologie Industrielle - N° 54 - 2è, Reproduction Interdite, pp.3-9.

Turban, E. and Watkins, P. R. (1986). Integrating Expert Systems and Decision Support Systems. Management Information Systems Research Center, University of Minnesota. *MIS Quarterly*, 10 (2) (Jun. 1986), pp. 121-136.

Turpin, S. M. and Marais, M. A. (2004). Decision-making: Theory and practice. *ORiON*, 20(2), pp. 143–160.

Uitenbroek, H. (2003). The Accuracy of the Center-Of-Gravity Method for Measuring Velocity and Magnetic Field Strength in the Solar Photosphere. The Astrophysical Journal, 592 (1), pp. 1225–1233.

UNEP and COCHILCO (2001). Abandoned Mines Problems, Issues and Policy Challenges for Decision Makers, 1st Pan-American Workshop, Santiago, Chile 18 June 2001, pp 30.

Van de Graaff. S., Unger, C and Evans, R (2012). AusIMM Abandoned Mines Survey Report. *The AusIMM Sustainability committee,* February 2012, p 23.

Van der Schyff, E. (2012). South African Mineral Law: A Historical Overview of the State's Regulatory Power Regarding the Exploitation of Minerals, New Contree, No. 64, July 2012, pp. 131-153.

Van Druten, E.S. and Bekke, M.C. (2017). Towards an inclusive model to address unsuccessful mine closures in South Africa. *The Southern African Institute of Mining and Metallurgy*, 117, pp. 485-490.

Van Eeden, E.S.; Liefferink, M. and Durand, J.F. (2009). Legal Issues Concerning Mine Closure and Social Responsibility on the West Rand. TD: *The Journal for Transdisciplinary Research in Southern Africa*, 5 (1), pp. 51-71

Van Eeden J.D (2010). Cost Effective, Post-Mining Environmental Restoration of an Open-Cast Phosphate Mine at Langebaanweg, South Africa. Master of Science Thesis, *Rhodes University*, South Africa. p. 263.

Van Leekwijck, W. and Kerr, E.E. (1999). Defuzzification: Criteria and Classification. *Fuzzy Sets and Systems* 108, pp. 159-178.

van Rensburg D.; Melis L (2012). The Development of a Remote-Controlled Highwall Rockbroom–A World First for The Open-Pit Mining Industry. *The Journal of The Southern African Institute of Mining and Metallurgy*, 112, pp. 755-759.

Van Zyl, D.; Sassoon, M.; Digby, C.; Fleury, A.-M. and Kyeyune, S. (2002). Mining for the Future, Main Report. Mining, *International Institute for Environment and Development (IIED) and World Business Council for Sustainable Development (WBCSD)*, p. 31.

Van Zyl, H.; Bond-Smith, M.; Minter, T.; Botha, M.; and Leiman A. (2012) Financial Provisions for Rehabilitation and Closure in South African Mining: Discussion Document on Challenges and Recommended Improvements (Summary), *WWF-World Wide Fund for Nature (Formerly World Wildlife Fund)*, Cape Town, 2012. p. 108.

Vesser, D.J.L. (1989). Explanation of the 1:1 000 000 Geological Map 4th edition, 1984: The geology of the Republic of South Africa, Transkei, Bophuthatwana, Venda and Ciskei and the Kingdom of Lesotho and Swaziland. *Geological Survey*, Republic of South Africa, p. 491

Venter, A. and Senne, W. (2014). Rehabilitation of an Abandoned Open Cast Mined Area: From an Open Cast Pit to a Waste Disposal Facility - A Case Study. Proceedings of the 20th WasteCon Conference 6-10 October 2014. Somerset West, Cape Town. *Institute of Waste Management of Southern Africa*, pp. 195-202.

Vieira, J.D. and Stefenon, V.M. (2017). Soil Bioremediation in Heavy Metal Contaminated Mining Areas: A Microbiological/Biotechnological Point of View. *Journal of Advances in Microbiology,* 4(1), pp. 1-10.

Waterman, D. (1986). A Guide to Expert Systems. Reading, MA: Addison-Wesley. *Artificial Intelligence,* 1 (1), pp. 62-63.

Weyer V.D.; Truter, W F. Lechner, A.M. Unger, C.J. (2017). Surface-strip coal mine land rehabilitation planning in South Africa and Australia: Maturity and opportunities for improvement. Resources Policy, pp.117-129

Wilson, M. G. C. (1998). Copper. In: M. G. C. Wilson and C. R. Anhaeusser (Eds.), The mineral resources of South Africa (6th ed.). Handbook 16, Pretoria, Republic of South Africa: *Council for Geoscience*, pp. 209–229

Winde F (2010). Uranium pollution of the Wonderfonteinspruit, 1997-2008 Part 2: Uranium in Water – Concentrations, Loads and Associated Risks. *Water SA,* 36 (3), pp. 257-278.

Wirth P, Mali BC, Fischer W (2012). Problems and Potentials of Post-Mining Regions: In: Wirth P, Mali B C, Fischer W (Editors), Post-Mining Regions in Central Europe Problems, Potentials, Possibilities. Rhodes Barrett, Berlin, pp. 1-30.

Woehrle, S.L. (2011). Decision Classification Enhances Case-Based Reasoning. *International Business and Economics Research Journal*, 1(1), pp1-6.

Word, J.H.W and Wilson M.G.C. (1998). Gold Outside Witwatersrand Basin, [In] Wilson, M.G.C. and Anhaeusser, C.R., The Mineral Resources of South Africa, *Council for Geosciences*, pp. 350-386.

Wrona, P.; Rozanski, Z.; Pach, G, Suponik, T, and Popczyk, M. (2016). Closed Coal Mine Shaft as a Source of Carbon Dioxide Emissions. *Environ Earth Sci*., 75 (1139), pp. 1-12.

Yirenkyi, S. (2008). Surface Mining and Its Socio-Economic Impacts and Challenges. *The South African Institute of Mining and Metallurgy*, pp. 181-202.

Yogi, P.; Rizal, O.; Ahmadi, S. and Suharyo, O.S. (2017). Feasibility Analysis of Naval Base Relocation Using SWOT and AHP Method to Support Main Duties Operation. *Journal of Defense Management*, 7, p. 160.

Zuhra, F.T.; Arai, A.A.; Tuni, M.A. (2016). An Implementation of Expert System for Orthopedic Patient Diagnosis. *Quaid E Awam Univ. Res. J. Eng. Sci. Technol.*, *15*, pp. 40–45.

APPENDICES

APPENDIX-A: Results of scoring and ranking of abandoned underground mine shafts.

The scoring and ranking of physical hazards

Shaft ID	Risk type	Source of hazards	Exposure to the Risk	Health problems	Safety problems	Impact	Risk score	Total shaft hazard score		Description
Musina Copper Mine Shafts										
MCM-1	Falling into the shaft	1.50	1.50	0.00	1.50	0.75	1.69	1.195	0.149	The shaft is closed with a concrete slab, fenced and monitored. It is less than 15m away from the extension of the Musina shaping mall. There is very low risk of falling into the mineshaft, however risks of ground movement are high.
	Drowning in contaminated water in the shaft	1.00	1.50	0.00	1.50	0.75	1.13			
	Rock fall	1.50	1.50	0.00	1.50	0.75	1.69			
	Mine gases	1.50	1.30	1.00	0.00	0.50	0.98			
	Intake of contaminated water	1.00	1.00	1.00	0.00	0.50	0.50			
ATV-1	Falling into the shaft	6.5	6.5	0.0	5.0	2.5	15.5	6.1	0.763	The shaft id sealed with a concrete slab. A small portion of the shaft collar/lining has collapsed leaving the shaft slightly open (450cm²). The drive way around the mine is developed above the shaft (concrete slab). The shaft is in the busy site of the mine. The car that drive above the shaft treatment increase the risk of falling into the shaft
	Drowning in contaminated water in the shaft	1.5	1.5	0.0	1.5	0.8	3.8			
	Rock fall	1.5	1.5	0.0	1.5	0.8	3.8			
	Mine gases	2.0	1.5	3.0	0.0	1.5	5.0			
	Intake of contaminated water	1.0	1.0	1.0	0.0	0.5	2.5			
ATV-2	Falling into the shaft	7.0	6.5	0.0	7.0	3.5	159.3	34.8	4.345	The attempt of closing the shaft were made by the sealing concrete slab was found damaged. The shaft is in a remote site of the mine, however it present serious hazard of falling into the shaft. The open part of the slab is about 45x30cm (1350cm²). The shaft caller is still intact.
	Drowning in contaminated water in the shaft	1.5	1.5	0.0	1.5	0.8	1.7			
	Rock fall	1.5	1.0	0.0	1.5	0.8	1.1			
	Mine gases	2.5	3.0	3.0	0.0	1.5	11.3			
	Intake of contaminated water	1.0	1.0	1.0	0.0	0.5	0.5			
CCM-1	Falling into the shaft	7.0	7.0	0.0	7.0	3.5	171.5	72.65	9.081	The mine treatment structure (concrete slab) was used to close the shaft however the shaft collar/lining has completely collapsed living the shaft completely open (1.5 x1m = 1.5m²). The shaft in in serious unstable ground conditions. It is the promises of the newly opened stone aggregate producing operation in the area. It present serious risk of falling into the shaft and the land around the shaft can't be used for another use without farther treatment
	Drowning in contaminated water in the shaft	2.0	2.0	1.5	1.5	1.5	6.0			
	Rock fall	7.0	7.0	0.0	7.0	3.5	171.5			
	Mine gases	3.0	3.0	3.0	0.0	1.5	13.5			
	Intake of contaminated water	1.0	1.0	1.5	0.0	0.8	0.8			
CCM-2	Falling into the shaft	7.0	7.0	0.0	7.0	3.5	171.5	71.1	8.888	The shaft is in unstable ground and it is with high risk of falling into the shaft. The collar and lining structure are constantly falling. The ground around the shaft can't be used for any other land uses without treatment. The hazards of falling into the mine shaft if not an obvious one. The shaft is within the aggregate production site.
	Drowning in contaminated water in the shaft	2.0	2.0	1.5	1.5	1.5	6.0			
	Rock fall	7.0	7.0	0.0	7.0	3.5	171.5			
	Mine gases	2.0	2.0	3.0	0.0	1.5	6.0			
	Intake of contaminated water	1.0	1.0	1.0	0.0	0.5	0.5			
CCM-3	Falling into the shaft	7.00	7.00	0.00	7.00	3.50	171.5	71.64	8.955	This the huge sinkhole (±60m diameter) that it up to the mine workings deep. The hole in within the aggregate production operations. It present serious safety hazard and it is with highly unstable walls and at approximately 30m away from the busiest part of the aggregate mine operation. The hole is not fenced therefore open to the public.
	Drowning in contaminated water in the shaft	2.00	2.00	1.50	1.50	1.50	6.0			
	Rock fall	7.00	7.00	0.00	7.00	3.50	171.5			
	Mine gases	2.00	2.50	3.00	0.00	1.50	7.5			
	Intake of contaminated water	1.50	1.50	1.50	0.00	0.75	1.7			
CCM-4	Falling into the shaft	5.5	5.5	0.0	6.0	3.0	90.8	27.05	3.381	The shaft about 300m away from the aggregate mining site. It is threated with a concrete and it is on a relatively more stable ground. The shaft sealing structure was observed to be competent and seriously reducing the risk of falling into the shaft.
	Drowning in contaminated water in the shaft	2.0	2.0	1.5	1.5	1.5	6.0			
	Rock fall	4.0	4.0	0.0	4.0	2.0	32.0			
	Mine gases	2.0	2.0	3.0	0.0	1.5	6.0			
	Intake of contaminated water	1.0	1.0	1.0	0.0	0.5	0.5			

APPENDIX-A: *Continued.*

Shaft ID	Risk type	Source of hazards	Exposure to the Risk	Health problems	Safety problems	Impact	Risk score	Total shaft hazard score		Description
Giyani Gold Mine Shafts										
KLM-1	Falling into/interring the shaft	7.0	6.5	0.0	3.0	1.5	68.3	120.6	15.070	Inclined shaft with destroyed treatment structure (concrete slab). Illegal miners enter the shaft to collect metal objects to sale to scrape metal traders. The mines used the concrete steps constructed as manway to descend to the deeper parts of the mine. In this shaft there are increased risk of rock fall and falling due to slippery floor/steps.
	Drowning in water of undefined pollutants	5.5	6.5	5.5	6.0	5.8	205.6			
	Rock fall	7.0	7.0	0.0	7.0	3.5	171.5			
	Mine gases	6.0	7.0	5.0	0.0	2.5	105.0			
	Intake of contaminated water	5.0	6.0	3.5	0.0	1.8	52.5			
KLM-2	Falling into the shaft	6.5	7.0	0.0	6.5	3.3	147.9	100.6	12.580	It is a vertical shaft that was found closed/treated using the wire grate (5x5m = 25m²). It is filled with water that is pumped and used for irrigation and other domestic uses. The grate used to close the shaft is removable thus making the risks of falling and drowning into the shaft high. This shaft if less than 30m away from the main access road in the area
	Drowning in water of undefined pollutants	7.0	5.0	5.0	6.0	5.5	192.5			
	Rock fall	1.5	1.5	0.0	2.5	1.3	2.8			
	Mine gases	1.5	1.0	1.0	0.0	0.5	0.8			
	Intake of contaminated water	7.0	6.5	7.0	0.0	3.5	159.3			
KLM-3	Falling into the shaft	7.0	7.0	0.0	7.0	3.5	171.5	84.2	10.525	It is a vertical shaft that was never closed or treated. It is without shaft collar or lining structure. The shaft is in the vicinity of a densely vegetated part of the mine area. The risk of people and animal falling into this shaft are high and exacerbated by the fact that the shaft id characterized by collapsing walls and it is not visible to the public. Although this is the case, this shaft is in the area that is abstemiously accessible to illegal miners and other members of the community.
	Drowning in contaminated water in the shaft	5.0	4.5	5.0	6.0	5.5	123.8			
	Rock fall	6.5	3.5	0.0	7.0	3.5	79.6			
	Mine gases	3.5	4.5	2.5	3.0	2.8	43.3			
	Intake of contaminated water	1.5	1.5	1.5	1.0	1.3	2.8			
HSM-1	Falling into the shaft	0.0	7.0	0.0	0.0	0.0	0.0	0.3	0.042	The shaft is treated using a concrete plug. There is no evidence of ground movement. The shaft is less than 30m away from the settlement areas. The sealing/treatment structure is well marked thus the area of old mine shafts are is visible.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
HSM-2	Falling into the shaft	0	7	0.0	0.0	0.0	0.0	0.3	0.042	The shaft is treated using a concrete plug. There is no evidence of ground movement. The shaft is less than 30m away from the settlement areas. The sealing/treatment structure is well marked thus the area of old mine shafts are is visible.
	Drowning in contaminated water in the shaft	0	0	0.0	0.0	0.0	0.0			
	Rock fall	0	0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0	0	0.0	0.0	0.0	0.0			
HSM-3	Falling into the shaft	2.0	7.0	0.0	1.5	0.8	10.5	2.4	0.305	The mineshaft was backfilled and treated using a concrete plug which moved downward for about 1.5m. The shaft has very low risk of physical injury. It is situated at less than 50m distance from the settlement area.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
HSM-4	Falling into the shaft	1.5	6.5	0.0	1.5	0.8	7.3	1.8	0.225	The mineshaft was backfilled and treated using a concrete plug which moved downward for about 0.5m. The shaft has very low risk of physical injury. It is situated at less than 50m distance from the settlement area.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
FGM-1	Falling into the shaft	2.0	7.0	0.0	3.0	1.5	21.0	6.1	0.764	The shaft is closed/treated using an approximately 20cm concrete slab (2x3m = 6m² slab). A very small (≈600cm²) portion of the slab was destroyed. In generally, the shaft treatment structure is still stable and effectively eliminating the risk of falling into the mineshaft. However, risks of ground movement is still presented by the shaft. This shaft is less than 10m away from the nearest foot path frequently used by the people from the nearby village.
	Drowning in contaminated water in the shaft	2.0	1.5	1.5	1.5	1.5	4.5			
	Rock fall	1.5	1.5	0.0	1.5	0.8	1.7			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	1.5	1.5	1.5	0.0	0.8	1.7			

APPENDIX-A: *Continued.*

Shaft ID	Risk type	Source of hazards	Exposure to the Risk	Health problems	Safety problems	Impact	Risk score	Total shaft hazard score		Description
FGM-2	Falling into the shaft	2	7	0	2	1.0	14.0	4.5	0.561	The shaft is well sealed using an 8m² concrete slab. The treatment structure is not tempered with. The haft is about 15m away from the foot path and access road frequently used by the villages. Therefore, the shaft is easily accessible but well-sealed. Ground movement are the only potentials hazards of this shafts.
	Drowning in contaminated water in the shaft	1.5	1.5	1.5	1.5	1.5	3.4			
	Rock fall	1.5	1.5	0	1.5	0.8	1.7			
	Mine gases	1.5	1.5	1.5	0	0.8	1.7			
	Intake of contaminated water	1.5	1.5	1.5	0	0.8	1.7			
FGM-3	Falling into the shaft	1.5	4.0	0.0	1.5	0.8	4.5	1.6	0.197	toward the river (last shaft)
	Drowning in contaminated water in the shaft	1.5	0.0	1.5	0.0	0.8	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	3.0	0.0	1.5	3.4			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
FGM-4	Falling into the shaft	2.0	6.0	0.0	1.5	0.8	9.0	2.8	0.352	Closed by debris (about 10m away from the road)
	Drowning in contaminated water in the shaft	1.5	1.5	1.5	1.5	1.5	3.4			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0	0.0	0.0	0.0			
FGM-5	Falling into the shaft	1.5	7.0	1.5	1.5	1.5	15.8	6.3	0.788	Well closed ventilation shaft
	Drowning in contaminated water in the shaft	3.0	1.5	2.0	2.0	2.0	9.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	3.0	3.0	0.0	1.5	6.8			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
BDM-1	Falling into the shaft	0.0	5.0	0.0	0.0	0.0	0.0	0.3	0.042	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
BDM-2	Falling into the shaft	0.0	5.0	0.0	0.0	0.0	0.0	0.3	0.042	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
BDM-3	Falling into the shaft	0.0	5.0	0.0	0.0	0.0	0.0	0.3	0.042	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
BDM-4	Falling into the shaft	0.0	5.0	0.0	0.0	0.0	0.0	0.3	0.042	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			

APPENDIX-A: *Continued.*

Shaft ID	Risk type	Source of hazards	Exposure to the Risk	Health problems	Safety problems	Impact	Risk score	Total shaft hazard score		Description
BDM-5	Falling into the shaft	0.0	5.0	0.0	0.0	0.0	0.0	0.3	0.042	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
BDM-6	Falling into the shaft	0.0	5.0	0.0	0.0	0.0	0.0	0.3	0.042	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
BDM-7	Falling into the shaft	0.0	5.0	0.0	0.0	0.0	0.0	0.3	0.042	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
BDM-8	Falling into the shaft	0.0	5.0	0.0	0.0	0.0	0.0	0.3	0.042	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
BDM-9	Falling into the shaft	0.0	5.0	0.0	0.0	0.0	0.0	0.3	0.042	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
BDM-10	Falling into the shaft	0.0	5.0	0.0	0.0	0.0	0.0	0.3	0.042	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Drowning in contaminated water in the shaft	0.0	0.0	0.0	0.0	0.0	0.0			
	Rock fall	0.0	0.0	0.0	0.0	0.0	0.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
NUM-1	Falling into the shaft	5.0	6.5	1.5	5.0	3.3	105.6	33.6	4.197	Unclosed inclined shaft-surrounded by vegetation –currently used to dump waste- with an extent of 2.5m×4.5 m
	Drowning in contaminated water in the shaft	1.5	2.0	1.5	4.0	2.8	8.3			
	Rock fall	5.0	4.0	0.0	5.0	2.5	50.0			
	Mine gases	2.0	2.0	2.0	0.0	1.0	4.0			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			

APPENDIX-A: *Continued.*

Shaft ID	Risk type	Source of hazards	Exposure to the Risk	Health problems	Safety problems	Impact	Risk score	Total shaft hazard score		Description
NUM-2	Falling into the shaft	6.0	7.0	0.0	5.0	2.5	105.0	35.6	4.450	Closing structure Completely removed –inclined shaft collared with steel rod and concrete-covers surface extent of 3.2m×2.5m –used as dumping site – located 10 meters from the road.
	Drowning in contaminated water in the shaft	2.0	4.0	1.5	4.0	2.8	22.0			
	Rock fall	5.0	3.0	0.0	5.0	2.5	37.5			
	Mine gases	3.0	3.0	3.0	0.0	1.5	13.5			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
NUM-3	Falling into the shaft	7.0	7.0	0.0	7.0	3.5	171.5	38.4	4.800	-ventilation shaft within some old building-located 5 meters from the road
	Drowning in contaminated water in the shaft	2.0	2.0	1.5	2.0	1.8	7.0			
	Rock fall	2.0	2.0	0.0	2.0	1.0	4.0			
	Mine gases	2.5	2.5	2.5	0.0	1.3	7.8			
	Intake of contaminated water	1.5	1.5	1.5	0.0	0.8	1.7			
NUM-4	Falling into the shaft	7.0	7.0	0.0	7.0	3.5	171.5	51.2	6.394	Wide open (15m×15m) vertical uncollared shaft surrounded by dense vegetation –located 5 meters from the road
	Drowning in contaminated water in the shaft	3.0	3.0	1.5	3.0	2.3	20.3			
	Rock fall	4.0	5.0	0.0	6.0	3.0	60.0			
	Mine gases	2.0	2.0	2.0	0.0	1.0	4.0			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
NUM-5	Falling into the shaft	7.0	6.0	0.0	7.0	3.5	147.0	46.4	5.800	Widely open (8m×8m) vertical uncollared shaft –surrounded by dense vegetation
	Drowning in contaminated water in the shaft	2.0	2.0	1.5	3.0	2.3	9.0			
	Rock fall	4.0	6.0	0.0	6.0	3.0	72.0			
	Mine gases	2.0	2.0	2.0	0.0	1.0	4.0			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
NUM-6	Falling into the shaft	7.0	7.0	0.0	7.0	3.5	171.5	41.3	5.163	Shaft closing structure Completely removed-timber collared shaft (2.5×3.5)-used for dumping waste-located 5 meters from the road
	Drowning in contaminated water in the shaft	2.0	2.0	1.5	2.0	1.8	7.0			
	Rock fall	4.0	3.0	0.0	4.0	2.0	24.0			
	Mine gases	2.0	2.0	2.0	0.0	1.0	4.0			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
NUM-7	Falling into the shaft	7.0	7.0	0.0	7.0	3.5	171.5	40.8	5.105	The shaft was never closed, and it is in the area where it is camouflage by vegetation.
	Drowning in contaminated water in the shaft	2.0	2.0	1.5	2.0	1.8	7.0			
	Rock fall	4.0	3.0	0.0	4.0	2.0	24.0			
	Mine gases	1.5	1.5	1.5	0.0	0.8	1.7			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
LMM-1	Falling into the shaft	7.0	7.0	0.0	7.0	3.5	171.5	72.3	9.038	The shaft is closed with concrete slab that was later destroyed by artisanal miners. It is an inclined shaft.
	Drowning in contaminated water in the shaft	4.0	6.0	1.5	5.0	3.3	78.0			
	Rock fall	6.0	6.0	0.0	6.0	3.0	108.0			
	Mine gases	2.0	2.0	2.0	0.0	1.0	4.0			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			

APPENDIX-A *Continued.*

Shaft ID	Risk type	Source of hazards	Exposure to the Risk	Health problems	Safety problems	Impact	Risk score	Total shaft hazard score		Description
LMM-2	Falling into the shaft	7.0	7.0	0.0	7.0	3.5	171.5	80.7	10.088	The shaft was closed with concrete slab, but the artisanal miners have destroyed the brick made shaft lining and left the mine shafts open once again.
	Drowning in contaminated water in the shaft	6.0	6.0	1.5	7.0	4.3	153.0			
	Rock fall	5.0	5.0	0.0	6.0	3.0	75.0			
	Mine gases	2.0	2.0	2.0	0.0	1.0	4.0			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			
LMM-3	Falling into the shaft	4.0	7.0	0.0	4.0	2.0	56.0	13.0	1.627	The shaft is closed with the concrete and steel screen. It is now covered by debris or waste material from artisanal mining operations that are ongoing on the site.
	Drowning in contaminated water in the shaft	1.5	1.5	1.5	1.5	1.5	3.4			
	Rock fall	1.5	1.5	0.0	1.5	0.8	1.7			
	Mine gases	2.0	2.0	2.0	0.0	1.0	4.0			
	Intake of contaminated water	0.0	0.0	0.0	0.0	0.0	0.0			

The scoring and ranking of environmental hazards

Shaft ID	Risk type	Source of hazards	Exposure to the Risk	Impact to the environmental	Risk score	Total shaft hazard score	Reduced score	Description
Musina Copper Mine Shafts								
MCM-1	Aesthetic appearance	1.5	1.0	1.5	2.3	5.875	0.7	The shaft is closed with a concrete slab, fenced and monitored. It is less than 15m away from Musina shaping mall. They are very low risk of falling into the mineshaft, however risks of ground movement are high.
	Land degradation	3.0	1.0	4.0	12.0			
	Pollution problems	1.5	1.5	1.5	3.4			
ATV-1	Aesthetic appearance	1.5	1.0	1.5	2.25	7.2	0.9	The shaft id sealed with a concrete slab. A small portion of the shaft collar/lining has collapsed leaving the shaft slightly open (450cm²). The drive way around the mine is developed above the shaft (concrete slab). The shaft is in the busy site of the mine. The car that drive above the shaft treatment increase the risk of falling into the shaft
	Land degradation	4.0	1.0	4.0	16.00			
	Pollution problems	1.5	1.5	1.5	3.38			
ATV-2	Aesthetic appearance	3.0	1.0	3.0	9.00	10.8	1.3	The attempt of closing the shaft were made by the sealing concrete slab was found damaged. The shaft is in a remote site of the mine, however it present serious hazard of falling into the shaft. The open part of the slab is about 45x30cm (1350cm²). The shaft collar is still intact.
	Land degradation	5.0	1.0	4.0	20.00			
	Pollution problems	1.5	1.5	1.5	3.38			
CCM-1	Aesthetic appearance	6.0	1.0	7.0	42.00	31.5	3.9	The mine treatment structure (concrete slab) was used to close the shaft however the shaft collar/lining has completely collapsed living the shaft completely open (1.5 x1m = 1.5m²). The shaft in in serious unstable ground conditions. It is the yard of the newly opened stone aggregate production operation in the area. It presents serious risk of falling into the shaft and the land around the shaft can't be used for another use without farther treatment
	Land degradation	7.0	1.0	7.0	49.00			
	Pollution problems	1.5	1.5	1.5	3.38			
CCM-2	Aesthetic appearance	5.0	1.0	4.0	20.00	19.1	2.4	The shaft is in unstable ground and it is with high risk of falling into the shaft. The collar and lining structure are constantly falling. The ground around the shaft can't be used for any other land uses without treatment. The hazards of falling into the mine shaft if not an obvious one. The shaft is within the aggregate production site.
	Land degradation	5.0	1.0	7.0	35.00			
	Pollution problems	1.5	1.0	1.5	2.25			
CCM-3	Aesthetic appearance	7.00	1.00	7.00	49.00	34.2	4.3	This the huge sinkhole (±60m diameter) that it up to the mine workings deep. The hole in within the aggregate production operations. It presents serious safety hazard and it is with highly unstable walls and at approximately 30m away from the busiest part of the aggregate mine operation. The hole is not fenced therefore open to the public.
	Land degradation	7.00	1.00	7.00	49.00			
	Pollution problems	1.50	2.00	1.50	4.50			
CCM-4	Aesthetic appearance	2.0	1.0	1.5	3.00	7.5	0.9	The shaft about 300m away from the aggregate mining site. It is threated with a concrete and it is on a relatively more stable gradient. The shaft sealing structure was observed to be competent and seriously reducing the risk of falling into the shaft.
	Land degradation	4.0	1.0	4.0	16.00			
	Pollution problems	1.5	1.5	1.5	3.38			

APPENDIX-A. *Continued.*

Shaft ID	Risk type	Source of hazards	Exposure to the Risk	Impact to the environmental	Risk score	Total shaft hazard score	Reduced score	Description
Giyani Gold Mine Shafts								
KLM-1	Aesthetic appearance	6.0	1.0	5.0	30.00	47.0	5.9	Inclined shaft with destroyed treatment structure (concrete slab). Illegal miners enter the shaft to collect metal objects to sale to scrape metal traders. The mines used the concrete steps constructed as manway to descend to the deeper parts of the mine. In this shaft there are increased risk of rock fall and falling due to slippery floor/steps.
	Land degradation	6.0	1.0	6.0	36.00			
	Pollution problems	3.0	5.0	5.0	75.00			
KLM-2	Aesthetic appearance	4.0	1.0	4.0	16.00	77.3	9.7	It is a vertical shaft that was found closed/treated using the wire grate (5x5m = 25m²). It is filled with water that is pumped and used for irrigation and other domestic uses. The grate used to close the shaft is removable thus making the risks of falling and drowning into the shaft high. This shaft if less than 30m away from the main access road in the area
	Land degradation	6.0	1.0	6.0	36.00			
	Pollution problems	6.0	5.0	6.0	180.00			
KLM-3	Aesthetic appearance	5.0	1.0	5.0	25.00	17.8	2.2	It is a vertical shaft that was never closed or treated. It is without shaft collar or lining structure. The shaft is in the vicinity of a densely vegetated part of the mine area. The risk of people and animal falling into this shaft are high and exacerbated by the fact that the shaft id characterized by collapsing walls and it is not visible to the public. Although this is the case, this shaft is in the area that is abstemiously accessible to illegal miners and other members of the community.
	Land degradation	5.0	1.0	5.0	25.00			
	Pollution problems	1.5	1.5	1.5	3.38			
HSM-1	Aesthetic appearance	2.0	1.0	2.0	4.00	3.8	0.5	The shaft is treated using a concrete plug. There is no evidence of ground movement. The shaft is less than 30m away from the settlement areas. The sealing/treatment structure is well marked thus the area of old mine shafts are is visible.
	Land degradation	2.0	1.0	2.0	4.00			
	Pollution problems	1.5	1.5	1.5	3.38			
HSM-2	Aesthetic appearance	2.0	1.0	2.0	4.00	3.8	0.5	The shaft is treated using a concrete plug. There is no evidence of ground movement. The shaft is less than 30m away from the settlement areas. The sealing/treatment structure is well marked thus the area of old mine shafts are is visible.
	Land degradation	2.0	1.0	2.0	4.00			
	Pollution problems	1.5	1.5	1.5	3.38			
HSM-3	Aesthetic appearance	4.5	1.0	4.0	18.00	10.3	1.3	The mineshaft was backfilled and treated using a concrete plug which moved downward for about 1.5m. The shaft has very low risk of physical injury. It is situated at less than 50m distance from the settlement area.
	Land degradation	3.0	1.0	3.5	10.50			
	Pollution problems	1.5	1.5	1,5	2.25			
HSM-4	Aesthetic appearance	3.5	1.0	3.0	10.50	7.6	1.0	The mineshaft was backfilled and treated using a concrete plug which moved downward for about 0.5m. The shaft has very low risk of physical injury. It is situated at less than 50m distance from the settlement area.
	Land degradation	3.0	1.0	3.0	9.00			
	Pollution problems	1.5	1.5	1.5	3.38			
FGM-1	Aesthetic appearance	3.0	1.0	2.0	6.00	5.1	0.6	The shaft is closed/treated using an approximately 20cm concrete slab (2x3m = 6m² slab). A very small (≈600cm²) portion of the slab was destroyed. In generally, the shaft treatment structure is still stable and effectively eliminating the risk of falling into the mineshaft. However, risks of ground movement is still presented by the shaft. This shaft is less than 10m away from the nearest foot path frequently used by the people from the nearby village.
	Land degradation	3.0	1.0	2.0	6.00			
	Pollution problems	1.5	1.5	1.5	3.38			
FGM-2	Aesthetic appearance	3.0	1.0	3.0	9.00	7.8	1.0	The shaft is well sealed using an 8m² concrete slab. The treatment structure is not tempered with. The haft is about 15m away from the foot path and access road frequently used by the villages. Therefore, the shaft is easily accessible but well-sealed. Ground movement are the only potentials hazards of this shafts.
	Land degradation	3.0	1.0	4.0	12.00			
	Pollution problems	1,5	1.5	1.5	2.25			
FGM-3	Aesthetic appearance	3.0	1.0	4.0	12.00	9.1	1.1	toward the river (last shaft)
	Land degradation	3.0	1.0	4.0	12.00			
	Pollution problems	1.5	1.5	1.5	3.38			
FGM-4	Aesthetic appearance	3.0	1.0	3.0	9.00	7.1	0.9	closed by debris (about 10m away from the road)
	Land degradation	3.0	1.0	3.0	9.00			
	Pollution problems	1.5	1.5	1.5	3.38			
FGM-5	Aesthetic appearance	5.0	1.0	4.0	20.00	13.1	1.6	Well closed ventilation shaft
	Land degradation	4.0	1.0	4.0	16.00			
	Pollution problems	1.5	1.5	1.5	3.38			

APPENDIX-A. *Continued.*

Shaft ID	Risk type	Source of hazards	Exposure to the Risk	Impact to the environmental	Risk score	Total shaft hazard score	Reduced score	Description
Giyani Gold Mine Shafts								
BDM-1	Aesthetic appearance	2.0	1.0	2.0	4.00	4.1	0.5	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Land degradation	2.5	1.0	2.0	5.00			
	Pollution problems	1.5	1.5	1.5	3.38			
BDM-2	Aesthetic appearance	2.0	1.0	2.0	4.00	4.1	0.5	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Land degradation	2.5	1.0	2.0	5.00			
	Pollution problems	1.5	1.5	1.5	3.38			
BDM-3	Aesthetic appearance	2.0	1.0	2.0	4.00	4.1	0.5	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Land degradation	2.5	1.0	2.0	5.00			
	Pollution problems	1.5	1.5	1.5	3.38			
BDM-4	Aesthetic appearance	2.0	1.0	2.0	4.00	4.2	0.5	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Land degradation	2.0	1.0	2.0	4.00			
	Pollution problems	2.0	1.5	1.5	4.50			
BDM-5	Aesthetic appearance	2.0	1.0	2.0	4.00	4.2	0.5	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Land degradation	2.0	1.0	2.0	4.00			
	Pollution problems	2.0	1.5	1.5	4.50			
BDM-6	Aesthetic appearance	2.0	1.0	2.0	4.00	4.2	0.5	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Land degradation	2.0	1.0	2.0	4.00			
	Pollution problems	2.0	1.5	1.5	4.50			
BDM-7	Aesthetic appearance	2.0	1.0	2.0	4.00	4.2	0.5	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Land degradation	2.0	1.0	2.0	4.00			
	Pollution problems	2.0	1.5	1.5	4.50			
BDM-8	Aesthetic appearance	2.0	1.0	2.0	4.00	4.2	0.5	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Land degradation	2.0	1.0	2.0	4.00			
	Pollution problems	2.0	1.5	1.5	4.50			
BDM-9	Aesthetic appearance	2.0	1.0	2.0	4.00	4.2	0.5	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Land degradation	2.0	1.0	2.0	4.00			
	Pollution problems	2.0	1.5	1.5	4.50			
BDM-10	Aesthetic appearance	2.0	1.0	2.0	4.00	4.2	0.5	The shaft was backfilled and treated or closed using a concrete plug. Warning sign engraved on the granite slab was attached plug landmark. No risk of ground movement was identified.
	Land degradation	2.0	1.0	2.0	4.00			
	Pollution problems	2.0	1.5	1.5	4.50			
NUM-1	Aesthetic appearance	6.0	1.0	6.0	36.00	30.0	3.8	Unclosed inclined shaft-surrounded by vegetation –currently used to dump waste- with an extent of 2.5m×4.5 m
	Land degradation	6.0	1.0	6.0	36.00			
	Pollution problems	3.0	2.0	3.0	18.00			
NUM-2	Aesthetic appearance	5.0	1.0	5.0	25.00	17.8	2.2	Closing structure completely removed –inclined shaft collared with steel rod and concrete-covers surface extent of 3.2m×2.5m –used as dumping site – located 10 meters from the road.
	Land degradation	5.0	1.0	5.0	25.00			
	Pollution problems	1.5	1.5	1.5	3.38			
NUM-3	Aesthetic appearance	6.0	1.0	6.0	36.00	25.1	3.1	Ventilation shaft within ventilation duct found near old building-located 5 meters from the road
	Land degradation	6.0	1.0	6.0	36.00			
	Pollution problems	1.5	1.5	1.5	3.38			

APPENDIX-A. *Continued.*

Shaft ID	Risk type	Source of hazards	Exposure to the Risk	Impact to the environmental	Risk score	Total shaft hazard score	Reduced score	Description
Giyani Gold Mine Shafts								
NUM-4	Aesthetic appearance	7.0	1.0	7.0	49.00	29.5	3.7	Widely open (15m×15m) vertical uncollared shaft surrounded by dense vegetation –located 5 meters from the road
	Land degradation	6.0	1.0	6.0	36.00			
	Pollution problems	1.5	1.5	1.5	3.38			
NUM-5	Aesthetic appearance	5.5	1.0	6.0	33.00	24.1	3.0	Widely open (8m×8m) vertical uncollared shaft –surrounded by dense vegetation
	Land degradation	6.0	1.0	6.0	36.00			
	Pollution problems	1.5	1.5	1.5	3.38			
NUM-6	Aesthetic appearance	7.0	1.0	7.0	49.00	31.5	3.9	Shaft closing structure Completely removed-timber collared shaft (2.5×3.5)-used for dumping waste-located 5 meters from the road
	Land degradation	7.0	1.0	6.0	42.00			
	Pollution problems	1.5	1.5	1.5	3.38			
NUM-7	Aesthetic appearance	5.5	1.0	6.0	33.00	23.1	2.9	The shaft was never closed, and it is in the area where it is camouflage by vegetation.
	Land degradation	5.5	1.0	6.0	33.00			
	Pollution problems	1.5	1.5	1.5	3.38			
LMM-1	Aesthetic appearance	6.5	1.0	5.0	32.50	36.8	4.6	The shaft is closed with concrete slab that was later destroyed by artisanal miners. It is an inclined shaft.
	Land degradation	6.0	1.0	5.0	30.00			
	Pollution problems	4.0	3.0	4.0	48.00			
LMM-2	Aesthetic appearance	6.0	1.0	6.0	36.00	38.0	4.8	The shaft was closed with concrete slab, but the artisanal miners have destroyed the brick made shaft lining and left the mine shafts open once again.
	Land degradation	5.0	1.0	6.0	30.00			
	Pollution problems	4.0	3.0	4.0	48.00			
LMM-3	Aesthetic appearance	5.0	1.0	5.0	25.00		4.1	The shaft is closed with the concrete and steel screen. It is now covered by debris or waste material from artisanal mining operations that are ongoing on the site.
	Land degradation	5.0	1.0	5.0	25.00			
	Pollution problems	4.0	3.0	4.0	48.00	32.7		

APPENDIX-B: Results of the evaluation of the abandoned mine shafts treatment strategies using Pugh Matrix.

Criteria	*Rating (1-10): Based on AHP evaluation*	*Fencing*	*Backfilling*	*Blast closure (adits)*	*Signage*	*Fencing & Signage*	*Backfill & Signage*	*Blast Closure & Signage*	*Steel capping*	*Steel grate*	*Concrete slab*	*Self-supported plug*	*Anchored plug*	*Surface cab*	*Streel wire*	*Barrier sealing*	*Dams sealing*	*Geo-synthetics*	*Vent*	*Injection / inclusion*
Ability to address physical injury	8	s	+	+	-	+	+	+	s	s	+	+	+	+	s	+	-	s	-	+
Ability to address risk of ground movement	6	-	+	s	-	-	+	s	-	-	-	s	s	-	-	-	-	s	-	+
Ability to address the risk of gas emission	4	-	+	+	-	-	+	+	-	-	-	+	+	-	-	-	-	-	+	s
The cost saving ability	5	+	s	s	+	+	s	s	s	s	s	-	-	s	s	-	s	s	s	-
Simplicity of implication	2	s	s	s	+	+	s	s	+	s	s	-	-	-	+	+	s	+	+	+
Maintenance requirements	1	s	s	s	-	-	s	s	+	s	s	+	+	+	-	s	s	s	+	+
Duration of the strategy	7	-	+	s	-	-	+	s	-	-	-	+	+	+	-	-	-	-	s	+
Protection of species in the shafts	3	+	-	-	+	+	-	-	-	+	-	-	-	-	s	+	+	-	-	-
Sum of Positives		2	4	2	3	4	4	2	2	1	1	4	4	3	1	3	1	1	3	5
Sum of Negatives		3	1	1	5	4	1	1	4	3	4	3	3	4	4	4	4	3	3	2
Sum of the Sames		3	3	5	0	0	3	5	2	4	3	1	1	1	3	1	3	4	2	1
Weighted Sum of Positives		8	25	12	10	18	25	12	3	3	8	20	20	16	2	13	3	2	7	24
Weighted Sum of Negatives		17	3	3	26	18	3	3	20	17	20	10	10	15	18	22	25	14	17	8

APPENDIX-C: Results of landscape and visual impacts analysis.

Landscape impact of tailings dumps in the study area

	Tailings Dump	Scoring of factors				Area-A (m^2)					Exposure per viewpoint				View Zone		IdE (total)	ILVI
		Appearance	Morphology	Deposit & Surrounding	LI	Dump	VP-1	VP-2	VP-3	VP-4	VP-1	VP-2	VP-3	VP-4	A	B		
1	KLMT	8	10	5	23	62279.6	23275.0	41044.4	40195.7	29606.9	0.4	0.7	0.6	0.5	0.4	0.7	1.1	24.8
2	LMMT	7	3	3	13	55378.4	16005.7	32729.5	42533.3	41239.0	0.3	0.6	0.8	0.7	0.7	0.5	1.2	15.2
3	FGMT	8	10	5	23	68358.1	3691.4	45161.2	-	-	0.1	0.7	-	-	0.1	0.7	0.7	16.4
4	MCMT	8	7	5	20	877703.1	42875.0	0.0	0	-	0.05	0	0	-	0.00	0.05	0.05	1.0
5	NMMT(a)	9	10	5	24	29437.1	9134.9	13723.9	20157.5	-	0.3	0.5	0.7	-	0.7	0.4	1.1	25.8
6	NMMT(b)	9	10	5	24	25654.8	16468.4	14294.1	15319.0	-	0.6	0.6	0.6	-	0	0.9	0.9	21.6

Dispersion of the tailings dumps material to the surrounding areas

Damp Area (ha)	Scoring of the waste dispersion factors				ID	RP_{score}
	i_d	i_f	i_e	i_a		
0.60	1.00	1.00	0.5	0.75	2.0	28.7
0.60	1.00	0.75	0.5	0.75	1.8	19.3
0.60	1.00	1.00	0.5	0.75	2.0	53.9
1.00	1.00	1.00	0.5	0.5	3.0	13.3
0.40	1.00	1.00	0.5	0.25	1.1	27.1
0.40	1.00	1.00	0.5	0.25	1.1	22.9
1.00	1.00	1.00	1.3	1.00	4.3	0.0
0.20	1.00	0.25	0.1	0.25	0.3	0.0

APPENDIX-D: The distribution of abandoned mine features in different sites.

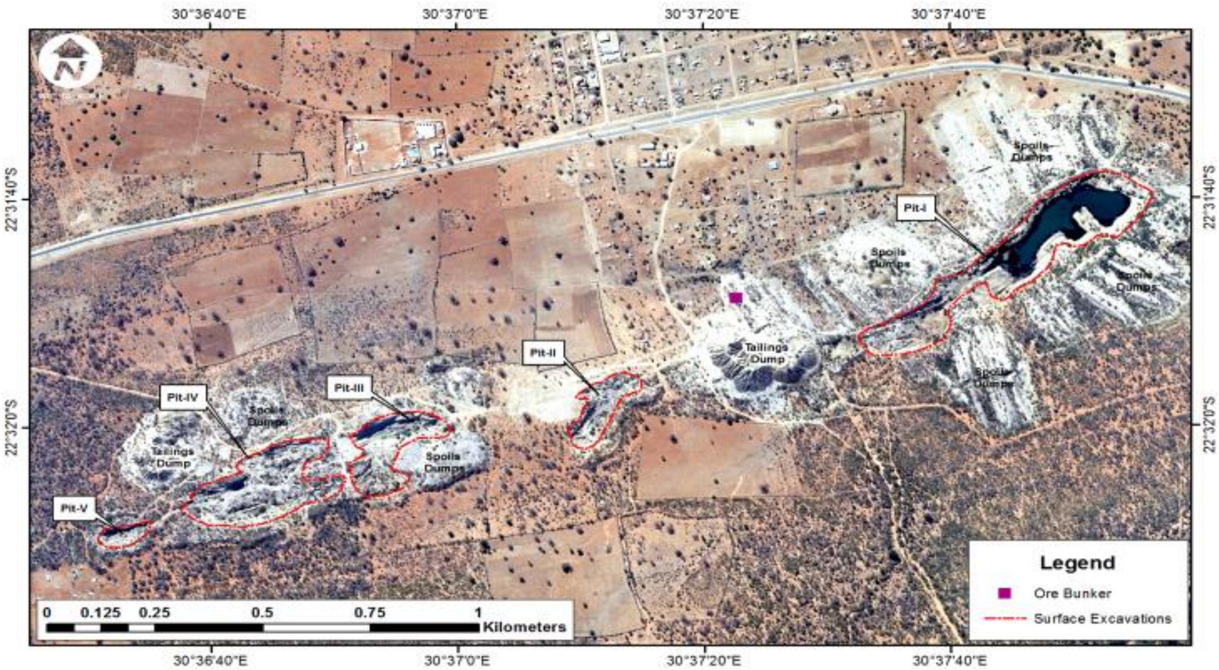


Figure-I. The abandoned Nyala Magnesite Mine landscape

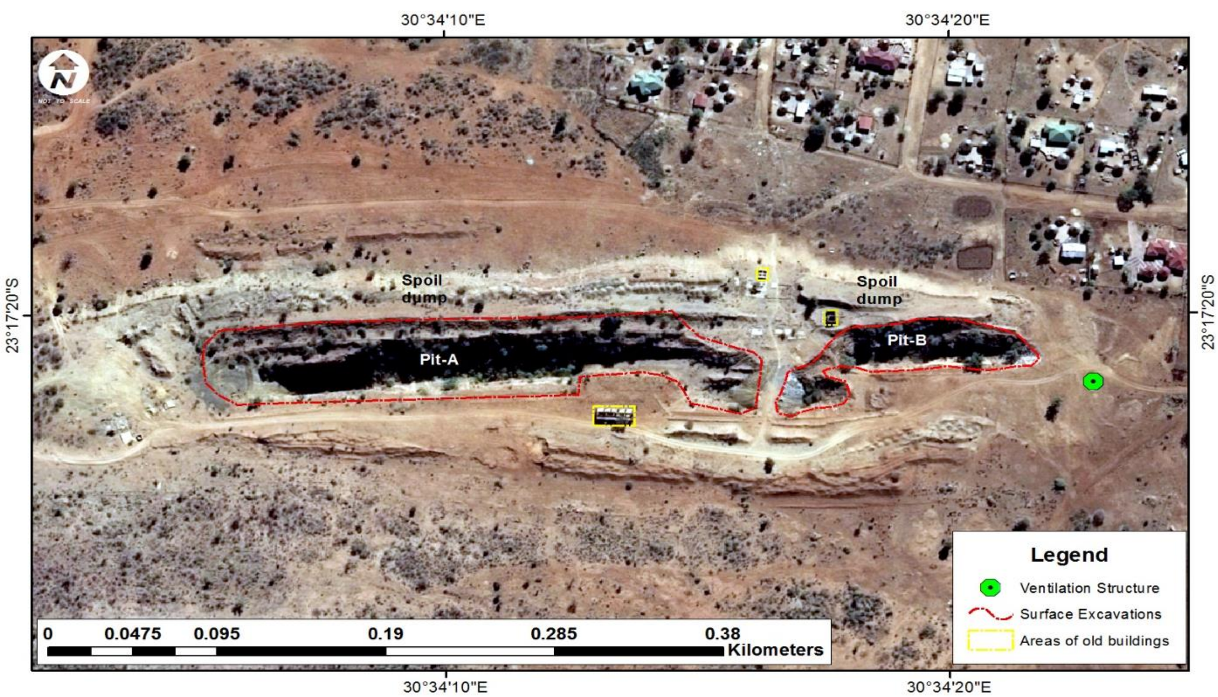


Figure-II. The abandoned Frankie Gold Mine landscape

APPENDIX-D *Continued.*

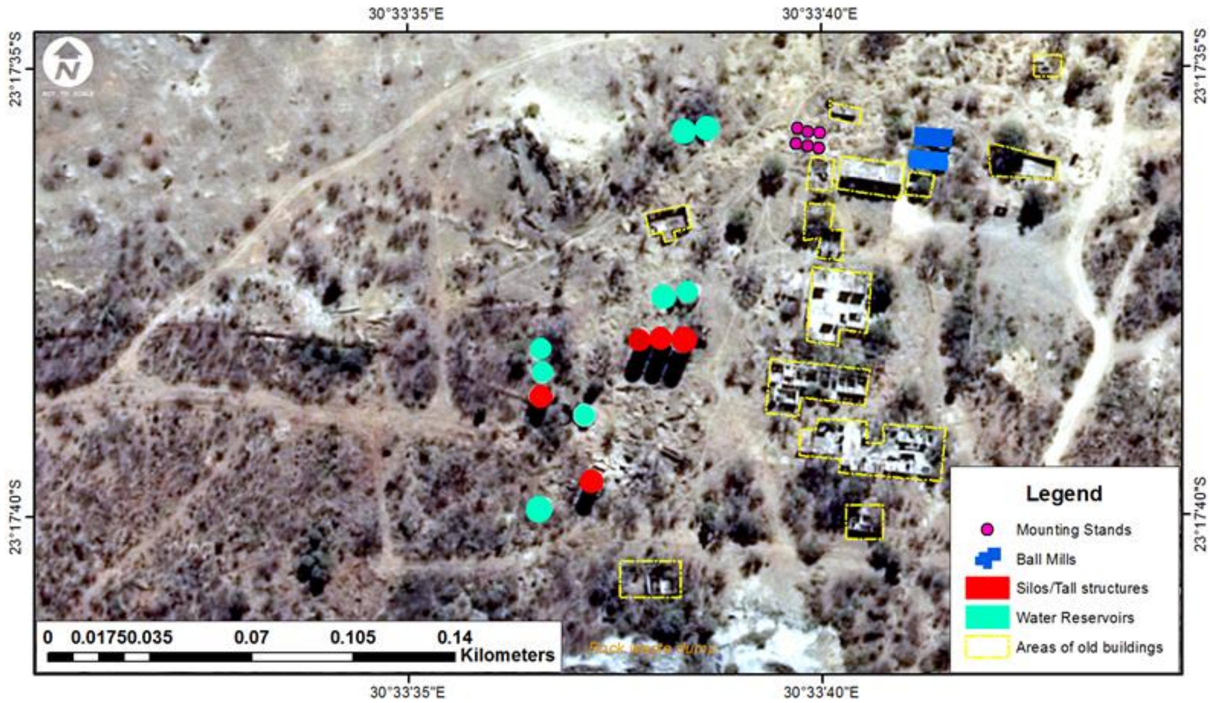


Figure-III. The abandoned Klein Letaba Mine landscape.

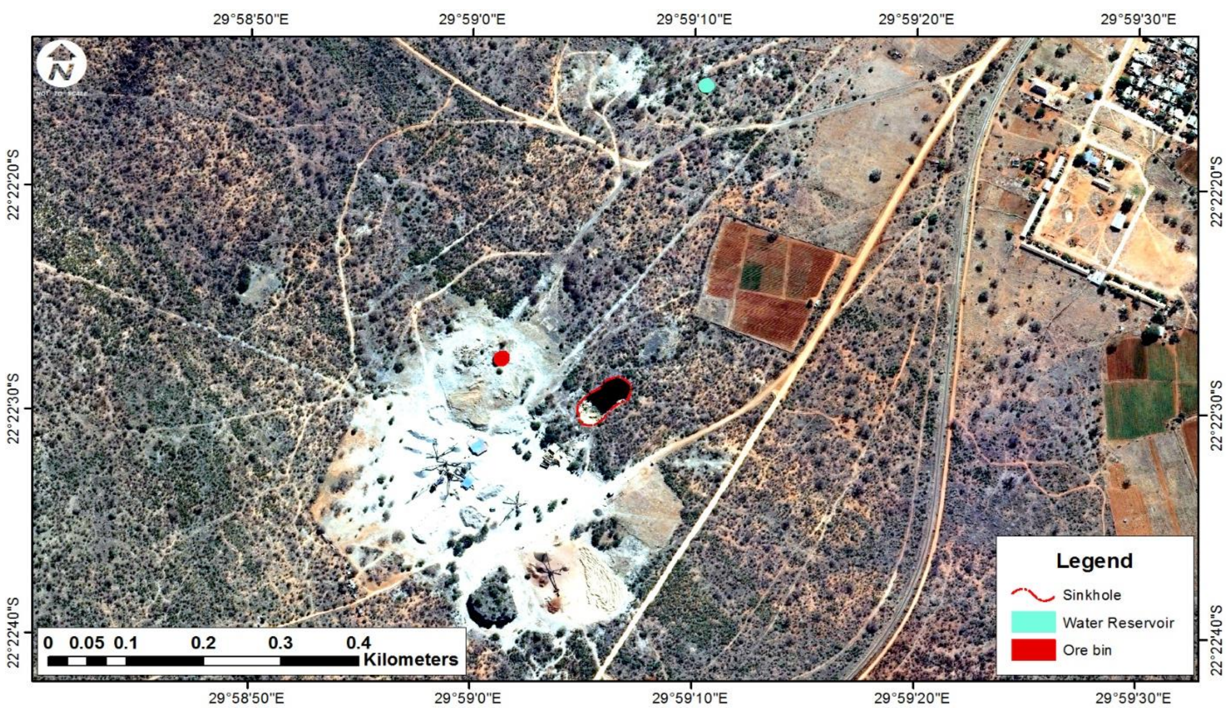


Figure-IV. The abandoned Campbell Copper Mine landscape.

APPENDIX-D *Continued.*

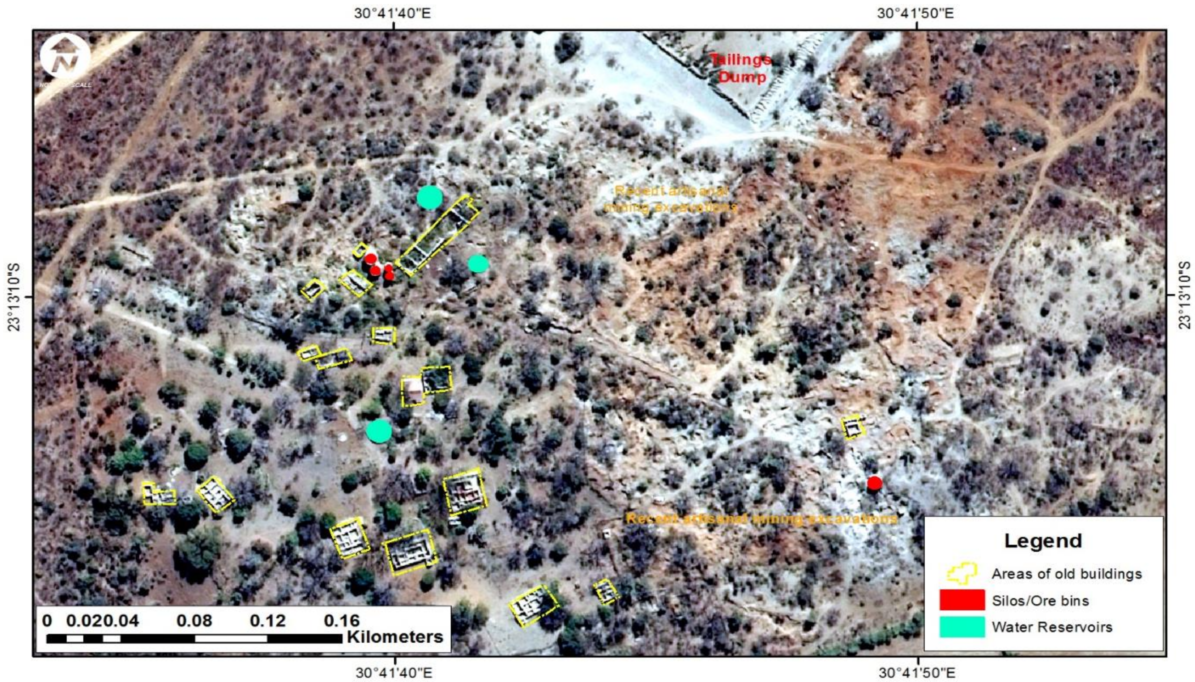


Figure-V. The abandoned Louis Moore Mine landscape.

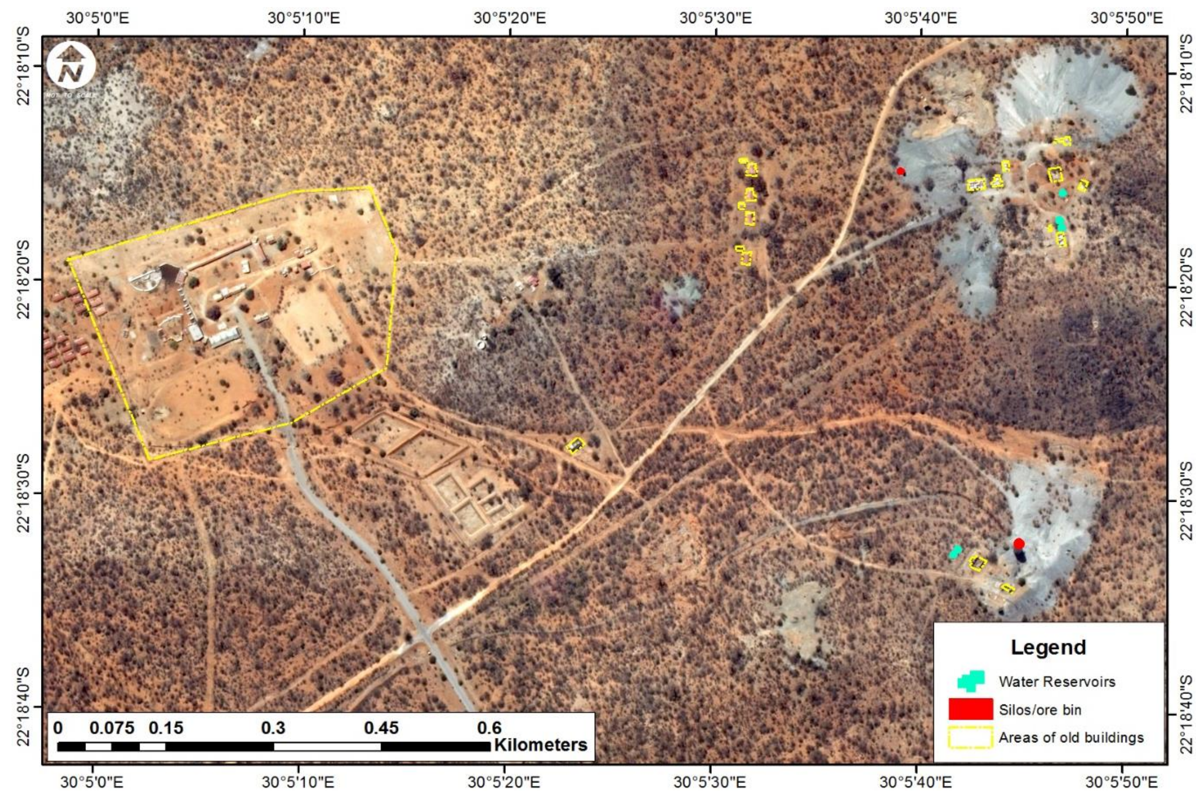


Figure-VI. The abandoned Artonvilla Copper Mine landscape.

APPENDIX-E: SWOT analysis of the strategies of dealing with the problems of abandoned surface infrastructure and excavations.

Mine feature	SWOT Parameters	Strength	Weaknesses	Opportunities	Threats
Excavations with water throughout all reasons	Backfilling	▪ Elimination of all risks of the pits and the water ▪ Creation of flat topography	▪ Intense earthworks required ▪ Require large volumes of soil	▪ Large land can be made available other land-uses	▪ The backfill material might not be always enough ▪ The cost of earthworks is mostly high. ▪ Opportunities for beneficial use of the pit will completely be eliminated
	Fencing	▪ Exposure to hazards of the pit will be eliminated ▪ The installation of the fence is mostly less costly	▪ Not all land occupied by the pits can be used for other uses	▪ The current use of the water in the pit can will be still possible.	▪ Constant maintenance of the fence will be required. ▪ Does not remove the risks associated with the pits ▪ The current informal uses of the pit will be eliminated
	Reduction of highwalls and reuse of the pit	▪ Eliminates the risks of falling from the highwalls. ▪ Reduced earthworks requirement ▪ Relatively low cost of rehabilitation ▪ Relatively less maintenance of rehabilitation work required	▪ Does not address the risks of drowning and being trapped in mud at the pit floor.	▪ Other commercial uses of the pit can be explored. ▪ The pit can be developed to a complete pit lake.	▪ The approach can be easily supported by the host community
	No action	▪ No or very little earthwork requirement ▪ Extremely reduced cost of rehabilitation ▪ There can be little, or no maintenance required	▪ The risks of highwalls might be not addressed ▪ The risks of using water in the pit might remain ▪ Promotion of the beneficial use of the pit and its waters	▪ Other uses of the pit and land can be later explored	▪ The approach will not address the current risks of the pit.
	Use of combined strategies (reduction of highwall, fencing and reuse of the pit)	▪ The majority of the risks of the pits will be addressed. ▪ The aesthetic appearance of the mine landscape can be improved	▪ Relatively high cost of rehabilitation and maintenance	▪ New opportunities of the use of the pit can be identified. ▪ The current land can be transported to support the nearby community	▪ Longer and costly maintenance of the site might be required

APPENDIX-E. *Continued.*

Mine feature	SWOT Parameters	Strength	Weaknesses	Opportunities	Threats
Seasonally flooded excavations	Backfilling	▪ Elimination of all risks of the pits and the water ▪ Creation of flat topography	▪ Intense earthworks required ▪ Require large volumes of soil	▪ Large land can be made available other land-uses	▪ The backfill material might not be always enough ▪ The cost of earthworks is mostly high. ▪ Opportunities for beneficial use of the pit will completely be eliminated
	Fencing	▪ Exposure to hazards of the pit will be eliminated. ▪ The installation of the fence is mostly less costly	▪ Not all land occupied by the pits can be used for other uses	▪ Future use of the pit can be conceptualized	▪ Constant maintenance of the fence will be required. ▪ Does not remove the risks associated with the pits ▪ The current informal uses of the pit will be eliminated
	Reduction of highwalls and reusing the pit	▪ Eliminates the risks of falling from the highwalls. ▪ Reduced earthworks requirement ▪ Relatively low cost of rehabilitation ▪ Relatively less maintenance of rehabilitation work required	▪ Does not address the risks of drowning and being trapped in mud at the pit floor during rainy days.	▪ Other beneficial uses of the pit can be later identified and implemented.	▪ The approach can be easily supported by the host community
	No action	▪ No or very little earthwork requirement ▪ Extremely reduced cost of rehabilitation ▪ There can be little, or no maintenance required	▪ The risks of highwalls might be not addressed ▪ The risks of using water in the pit might remain	▪ Other uses of the pit and land can be later explored	▪ The approach will not address the current risks of the pit.
	Use of combined strategies (reduction of highwall, fencing and reuse of the pit)	▪ The majority of the risks of the pits will be addressed. ▪ The aesthetic appearance of the mine landscape can be improved	▪ Relatively high cost of rehabilitation and maintenance	▪ New opportunities of the use of the pit can be identified. ▪ The current land can be transported to support the nearby community	Longer and costly maintenance of the site might be required

APPENDIX-E. *Continued.*

Mine feature	SWOT Parameters	Strength	Weaknesses	Opportunities	Threats	Driver for end land-uses
Old buildings	Renovation or establishment of residential houses in areas of old mine settlements	▪ This will ensure that the building contribute to housing development of the abandoned mine host community ▪ The work of demolishing the building and removal of concrete rabbles	▪ The hostel buildings might require extensive reconfiguration and renovation.	▪ The old mine settlement can be mentioned. ▪ The history of mining in the area can be mentioned	▪ Some buildings may be in remote areas were attracting occupancies might be a challenge. ▪ Conflicts regarding surface land ownership might arise	Renovation or establishment of residential houses in areas of old mine settlements
	Uses of mine workers hostels for commercial or community development projects	▪ The approach can contribute to the socio-economic development of the host community. ▪ Will promote that the existing buildings are maintained and that the work of their removal is avoided	▪ Renovation and repurposing of the structure will be required. ▪ A detailed analysis of the structural integrity of the buildings will be required.	▪ New economic opportunities for the host community can be identified. ▪ Economic development of the area can improve. ▪ The history of mining in the area can be preserved.	▪ The location and the stability of the mine hostel buildings might not fully support their use thus requiring demolishing. ▪ Conflicts regarding surface land ownership might arise	Uses of mine workers hostels for commercial or community development projects
	Removal of the buildings	▪ Their removal will improve the aesthetic appearance of the landscape.	▪ The history of mining in the area will be removed too.	▪ The land occupied by the buildings can be used for other uses. ▪ New economic use of the land can be identified.	▪ The removal might disable the new habitat for animals.	Removal of the buildings

APPENDIX-E. *Continued.*

Mine feature	SWOT Parameters	Strength	Weaknesses	Opportunities	Threats
Mounting stands and water reservoirs	Reuse of the structure	▪ The structures can be of beneficial use to the host communities ▪ The reuse will reduce the cost requirement of removal of the structures	▪ The renovation or repurposing of the structures might be required.	▪ The structures can contribute to the socio-economic demands of the host communities	▪ Finding appropriate reused that can benefit the host communities can be difficult
	Removal of the structure	▪ Eliminate the hazards of the features. ▪ Will enhance the natural beauty of the landscape.	▪ The removal of the structures will be relatively costly than reusing them.	▪ The land occupied by the structures can be made available for other uses.	▪ The removal will contribute to the removal of the history of mining in the area.
Tall cylindrical structures	Uses for commercial advertisement	▪ Preservation of the history of mining in the landscape. ▪ Relatively low cost for conversion of the feature than demolishing it. ▪ The physical appearance of the structure will be enhanced	▪ The stability of the feature will need to be investigated.	▪ Other recreational uses of the structures can be identified ▪ The structures can be attractive features on the landscape thus enhancing tourism in the area	▪ The structures might not be always in the strategical location for advertisement and recreational uses.
	Removal of the structure	▪ Clear the land for other uses. ▪ Eliminate all hazards associated with the feature.	▪ Remove a part of the landmark of mining in the area ▪ The removal will be done at relatively high cost compared to the repair of the new use	▪ The land occupied by the features can be used for other purposes. ▪ The natural beauty of the landscape will be enhanced.	▪ In urban areas or highly developed sites, the demolishing might be difficulty and costly ▪ Will contribute to the removal of the history of mining in the area.

APPENDIX-F: QSPM analysis of strategies of dealing with the problems of abandoned surface infrastructure and excavations

Excavations with water throughout all reasons

Backfilling

Strength	Weight	Attractiveness Score	Total attractiveness score
▪ Elimination of all risks of the pits and the water	0.30	4.00	1.20
▪ Creation of flat topography	0.25	3.00	0.75
Weaknesses			
▪ Intense earthworks required	0.25	1.00	0.25
▪ Require large volumes of soil	0.20	1.00	0.20
Sum weight	1.00		2.40
Opportunities			
▪ Large land can be made available other land-uses	0.30	4.00	1.2
Threats			
▪ The backfill material might not be always enough	0.20	1.00	0.20
▪ The cost of earthworks is mostly high.	0.25	1.00	0.25
▪ Opportunities for beneficial use of the pit will completely be eliminated	0.25	1.00	0.25
Sum Weight	1.00		1.90
Sum Total Attractiveness Score	**4.30**		

Fencing

Strength	Weight	Attractiveness Score	Total Attractiveness Score
▪ Exposure to hazards of the pit will be reduced	0.4	4.00	1.60
▪ The installation of the fence is mostly less costly	0.35	3.00	1.05
Weaknesses			
▪ Not all land occupied by the pits can be used for other uses	0.25	2.00	0.50
Sum weight	1.00		3.15
Opportunities			
▪ The current use of the water in the pit can will be still possible	0.55	3.00	1.65
Threats			
▪ Constant maintenance of the fence will be required.	0.20	2.00	0.40
▪ Does not remove the risks associated with the pits	0.15	1.00	0.15
▪ The current informal uses of the pit will be eliminated	0.10	1.00	0.10
Sum Weight	1.00		2.30
Sum Total Attractiveness Score	**5.45**		

APPENDIX-F. *Continued.*

Reduction of highwalls and reuse of the pit

Strength	**Weight**	**Attractiveness Score**	**Total Attractiveness Score**
▪ Eliminates the risks of falling from the highwalls.	0.30	4	1.20
▪ Reduced earthworks requirement	0.30	2	0.60
▪ Relatively low cost of rehabilitation	0.20	1	0.20
▪ Relatively less maintenance of rehabilitation work required	0.10	1	0.10
Weaknesses			
▪ Does not address the risks of drowning and being trapped in mud at the pit floor.	0.10	1	0.10
Sum Weight	1.00		2.20
Opportunities			
▪ Other commercial uses of the pit can be explored.	0.40	4	1.60
▪ The pit can be developed to a complete pit lake.	0.40	4	1.60
▪ The approach can be easily supported by the host community	0.10	2	0.20
Threats			
▪ New risks might manifest	0.10	1	0.1
Sum Weight	1.00		3.50
Sum Total Attractiveness Score	**5.70**		

No action

Strength	**Weight**	**Attractiveness Score**	**Total Attractiveness Score**
▪ No or very little earthwork requirement	0.20	2	0.4
▪ Extremely reduced cost of rehabilitation	0.20	2	0.4
▪ There can be little, or no maintenance required	0.30	1	0.3
Weaknesses			
▪ The risks of highwalls might be not addressed	0.10	1	0.1
▪ The risks of using water in the pit might remain	0.10	1	0.1
▪ Promotion of the beneficial use of the pit and its waters	0.10	1	0.1
	1.00		1.4
Opportunities			
▪ Other uses of the pit and land can be later explored	0.6	3	1.8
Threats			
▪ The approach will not address the current risks of the pit.	0.20	1	0.2
▪ The risks of the pit might escalate	0.20	1	0.2
Sum Weight	1.00		2.2
Sum Total Attractiveness Score	**3.6**		

APPENDIX-F. *Continued.*

Use of combined strategies (reduction of highwall, fencing and reuse of the pit)

Strength	Weight	Attractiveness Score	Total Attractiveness Score
▪ The majority of the risks of the pits will be addressed.	0.50	4.00	2.00
▪ The aesthetic appearance of the mine landscape can be improved	0.40	3.00	1.20
Weaknesses			
▪ Relatively high cost of rehabilitation	0.10	1.00	0.10
Sum Weight	1.00		3.30
Opportunities			
▪ The current land can be transported to support the nearby community	0.40	4.00	1.6
▪ New opportunities of the use of the pit can be identified.	0.40	4.00	1.6
Threats			
▪ Longer and costly maintenance of the site might be required	0.20	1.00	0.2
Sum Weight	1.00		3.4
Sum Total Attractiveness Score	**6.70**		

Seasonally flooded excavations

Backfilling

Strength	Weight	Attractiveness Score	Total Attractiveness Score
Elimination of all risks of the pits and the water	0.40	4.00	1.60
Creation of flat topography	0.30	3.00	0.90
Weaknesses			
Intense earthworks required	0.15	1.00	0.15
Require large volumes of soil	0.15	1.00	0.15
Sum Weight	1.00		2.80
Opportunities			
Large land can be made available other land-uses	0.40	4.00	1.6
Threats			
The backfill material might not be always enough	0.20	1.00	0.20
The cost of earthworks is mostly high.	0.20	1.00	0.20
Opportunities for beneficial use of the pit will completely be eliminated	0.20	1.00	0.20
Sum Weight	1.00		2.20
Sum Total Attractiveness Score	**5.00**		

APPENDIX-F. *Continued.*

Reduction of highwalls and reusing the pit

Strength	Weight	Attractiveness Score	Total Attractiveness Score
▪ Eliminates the risks of falling from the highwalls.	0.40	4.00	1.60
▪ Reduced earthworks requirement	0.30	3.00	0.90
▪ Relatively low cost of rehabilitation	0.10	3.00	0.30
▪ Relatively less maintenance of rehabilitation work required	0.10	3.00	0.30
Weaknesses			
▪ Does not address the risks of drowning and being trapped in mud at the pit floor during rainy days.	0.10	1.00	0.10
Sum Weight	1.00		3.20
Opportunities			
▪ Other beneficial uses of the pit can be later identified and implemented.	0.80	2.00	1.6
Threats			
▪ The community will be still exposed to their hazards of the pit	0.20	2.00	0.40
Sum Weight	1.00		2.00
Sum Total Attractiveness Score	**5.20**		

Fencing

Strength	Weight	Attractiveness Score	Total Attractiveness Score
▪ Exposure to hazards of the pit will be eliminated.	0.50	4.00	2.00
▪ The installation of the fence is less costly	0.30	2.00	0.60
Weaknesses			
▪ Not all land occupied by the pits can be used for other uses	0.20	2.00	0.40
Sum Weight	1.00		3.00
Opportunities			
▪ Future use of the pit can be conceptualized and implemented	0.60	3.00	1.8
Threats			
▪ Constant maintenance of the fence will be required.	0.15	1.00	0.15
▪ Does not remove the risks associated with the pits	0.15	1.00	0.15
▪ The current informal uses of the pit will be eliminated	0.10	1.00	0.10
Sum Weight	1.00		2.20
Sum Total Attractiveness Score	**5.20**		

APPENDIX-F. *Continued.*

No action

Strength	Weight	Attractiveness Score	Total Attractiveness Score
▪ No or very little earthwork requirement	0.20	2.00	0.40
▪ Extremely reduced cost of rehabilitation	0.20	2.00	0.40
▪ There can be little, or no maintenance required	0.20	2.00	0.40
Weaknesses			
▪ The risks of highwalls might be not addressed	0.20	1.00	0.20
▪ The risks of using water in the pit might remain	0.20	1.00	0.20
Sum Weight	1.00		1.60
Opportunities			
▪ Other uses of the pit and land can be later explored	0.50	2.00	1
Threats			
▪ The approach will not address the current risks of the pit.	0.50	1.00	0.50
Sum Weight	1.00		1.50
Sum Total Attractiveness Score	**3.10**		

Use of combined strategies (reduction of highwall, fencing and reuse of the pit)

Strength	Weight	Attractiveness Score	Total Attractiveness Score
▪ The majority of the risks of the pits will be addressed.	0.40	4.00	1.60
▪ The aesthetic appearance of the mine landscape can be improved	0.40	4.00	1.60
Weaknesses			
▪ Relatively high cost of rehabilitation and maintenance	0.20	2.00	0.40
Sum Weight	1.00		3.60
Opportunities			
▪ New opportunities of the use of the pit can be identified.	0.40	4.00	1.6
▪ The current land can be transported to support the nearby community	0.40	4.00	1.6
Threats			
▪ Longer and costly maintenance of the site might be required	0.20	1.00	0.20
Sum Weight	1.00		3.40
Sum Total Attractiveness Score	**7.00**		

APPENDIX-F. *Continued.*

Dealing with tall structures such as silos, agitation tanks and ore bins

Reuse of the tall structures

Strength	Weight	Attractiveness Score	Total Attractiveness Score
▪ Preservation of the history of mining in the landscape.	0.30	3.00	0.90
▪ The physical appearance of the structure will be enhanced	0.30	4.00	1.20
▪ Relatively low cost for conversion of the feature than demolishing it.	0.20	2.00	0.40
Weaknesses			
▪ The structures might not be always in the strategical location for advertisement and recreational uses.	0.10	2.00	0.20
▪ The structure might not be structurally stable	0.10	2.00	0.20
Sum Weight	1.00		2.90
Opportunities			
▪ Other recreational uses of the structures can be identified	0.40	4.00	1.60
▪ The structures can be attractive features on the landscape thus enhancing tourism in the area	0.35	4.00	1.40
Threats			
▪ The stability of the feature will need to be investigated.	0.25	1.00	0.25
Sum Weight	1.00		3.25
Sum Total Attractiveness Score	**6.15**		

Removal of the tall structures

Strength	Weight	Attractiveness Score	Total Attractiveness Score
▪ Clear the land for other uses.	0.40	4.00	1.60
▪ Eliminate all hazards associated with the feature.	0.40	4.00	1.60
Weaknesses			
▪ Remove a part of the landmark of mining in the area	0.10	2.00	0.20
▪ The removal will be done at relatively high cost compared to the repair of the new use	0.10	2.00	0.20
Sum Weight	1.00		3.60
Opportunities			
▪ The land occupied by the features can be used for other purposes.	0.30	3.00	0.90
▪ The natural beauty of the landscape will be enhanced.	0.30	3.00	0.90
Threats			
▪ In urban areas or highly developed sites, the demolishing might be difficulty and costly	0.20	2.00	0.40
Will contribute to the removal of the history of mining in the area.	0.20	1.00	0.20
Sum Weight	1.00		2.40
Sum Total Attractiveness Score	**6.00**		

APPENDIX-F. *Continued.*

Dealing with mounting stands and water reservoirs

Reuse of mounting stands and water reservoirs

Strength	Weight	Attractiveness Score	Total Attractiveness Score
▪ The structures can be of beneficial use to the host communities	0.40	4.00	1.60
▪ The reuse will reduce the cost requirement of removal of the structures	0.20	3.00	0.60
Weaknesses			
▪ The renovation or repurposing of the structures might be required.	0.40	2.00	0.80
Sum Weight	1.00		3.00
Opportunities			
▪ The structures can contribute to the socio-economic demands of the host communities	0.65	3.00	1.95
Threats			
▪ Failure to find appropriate reuses that can benefit the host communities can be difficult	0.35	2.00	0.70
Sum Weight	1.00		2.65
Sum Total Attractiveness Score	**5.65**		

Removal of the mounting stands and water reservoirs

Strength	Weight	Attractiveness Score	Total Attractiveness Score
▪ Eliminate the hazards of the features.	0.40	4.00	1.60
▪ Will restore the natural beauty of the landscape.	0.40	4.00	1.60
Weaknesses			
▪ The removal of the structures will be relatively costly than reusing them.	0.20	2.00	0.40
Sum Weight	1.00		3.60
Opportunities			
▪ The land occupied by the structures can be made available for other uses.	0.70	3.00	2.10
Threats			
▪ The removal will contribute to the removal of the history of mining in the area.	0.30	2.00	0.60
Sum Weight	1.00		2.70
Sum Total Attractiveness Score	**6.30**		

APPENDIX-G: Knowledge base rules of the ES-RAME.

No.	Rule	Notes	Image
1	**IF** mine feature: mine entry **AND** the access to the entry is restricted: no **AND** physical hazard score of the entry is between: >22<45 **THEN** the rank of the problems of the abandoned mine entry is **almost certainly** (Cf=1.00) ***High physical hazards and social concerns .***	The objective of treatment of the mine entry is to eliminate or reduce the risk of falling into the shaft or intended intrusion of the mine entry by people and animals. Strategies that provide permanent or long-term closure of the entry should be considered.	
2	**IF** mine feature: mine entry **AND** the access to the entry is restricted: no **AND** physical hazard score of the entry is between: >4<22 **THEN** the rank of the problems of the abandoned mine entry is **almost certainly** (Cf=1.00) ***Moderate physical hazards and social concerns .***	The objective of treatment of the mine entry is that moderate efforts should be put on addressing the physical hazards and social concerns of partially closed mine entries. This is when the abandoned mine entry was first treated with temporal structures which overtime got removed, destroyed or vandalized by the members of the community or illegal artisanal mines. A closure of the shaft using permanent or long-term strategies should be considered.	
3	**IF** mine feature: mine entry **AND** the access to the entry is restricted: no **AND** physical hazard score of the entry is between: >0<4 **THEN** the rank of the problems of the abandoned mine entry is **almost certainly** (Cf=1.00) ***Low physical hazards and social concerns.***	The objective of treatment requires that strategies that address the little physical hazards of these entries be used. The work of treatment of the mine entries involve conducting repairs and maintenance of structures used to treat these shafts but later got vandalized or destroyed by illegal artisanal miners.	
4	**IF** mine feature: mine entry **AND** the access to the entry is restricted: no **AND** physical hazard score of the entry is between: <0 **THEN** the rank of the problems of the abandoned mine entry is **almost certainly** (Cf=1.00) ***Negligible physical hazard and social concerns.***	The objective of the mine entry treatment is to monitor the performance of the newly installed treatment structure.	
	IF mine feature: mine entry **AND** the access to the entry is restricted: yes **AND** the general hazards can be considered: negligible **THEN** the rank of the problems of the abandoned mine entry is **almost certainly** (Cf=1.00) ***No immediate treatment needed.***	The objective of treatment is that there is no required immediate treatment of the mine entry. The protection of the entry from the public might be necessary to reduce or eliminate exposure to the environmental or physical hazards of the shafts.	

APPENDIX-G. *Continued.*

No	Rule	Notes	Image
6	**IF** mine feature: mine entry **AND** the access to the entry is restricted: not important for environmental hazards **AND** environmental hazard score of the entry is between >22<45 **THEN** the rank of the problems of the abandoned mine entry is **almost certainly** (Cf=1.00) ***High environmental Hazard and economic concerns.***	The objective of the treatment of the entry involve elimination of environmental hazards which include excessive ground movement and discharge of contaminated water by the entry. The use of strategies that provide permanent closure of the shaft should be considered.	
7	**IF** mine feature: mine entry **AND** the access to the entry is restricted: not important for environmental hazards **AND** environmental hazard score of the entry is between >4<21 **THEN** the rank of the problems of the abandoned mine entry is **almost certainly** (Cf=1.00) ***Moderate environmental hazards and economic concerns.***	The objective of treatment of the mine entry is that moderate efforts should be on addressing the manner environmental problems such as the impact of the entry on the aesthetic appearance of the landscape, and the treatment of water discharged by the entry. In this case, the problems of ground movement are not of concern. The treatment can use permanent or temporal strategies.	
8	**IF** mine feature: mine entry **AND** the access to the entry is restricted: not important for environmental hazards **AND** environmental hazard score of the entry is between >0<4 **THEN** the rank of the problems of the abandoned mine entry is **almost certainly** (Cf=1.00) ***Low environmental hazard and economic concerns.***	The objective of the treatment of the entry should be put on addressing the little identified environmental concerns to alleviate the economic status of the abandoned mine shaft and its surroundings.	
9	**IF** mine feature: mine entry **AND** the access to the entry is restricted: not important for environmental hazards **AND** environmental hazard score of the entry is between <0 **THEN** the rank of the problems of the abandoned mine entry is **almost certainly** (Cf=1.00) ***Negligible environmental hazards and economic concerns.***	The closure or treatment work is mostly about monitoring the newly implemented treatment strategy(ies) to address the environmental concerns of the mine entry or implemented for the use of the entry for alternative economic benefit.	

APPENDIX-H: Attributes of the ES-RAME.

Node	Text	Values	Notes	Image
Mine feature	Mine feature:	Mine entry (Cf=1.00) [This includes all openings that connect with the abandoned underground mine workings. They may be vertical or inclined shafts, edits or declines, tunnels and even sinkholes.]	Underground features which can be a vertical or inclined openings-shafts, adits and tunnels.	
Accessible	The access to the entry is restricted:	Yes (Cf=1.00) [The mine entry cannot be easily accessed by people and animals] No (Cf=1.00) [The entry and/or the whole of the abandoned mine site is open to the public.] Not important for environmental hazards (Cf=1.00) [The environmental problems of the abandoned mine entry are of concern in this case.]	This refer to the openness of the mine entry to the members of the public. In this case the mine entry might have been treated/closed with different structures or still open.	
Physical Hazard score	Physical hazard score of the entry is between:	>4<22 (Cf=1.00) [Moderate physical hazards] >22<45 (Cf=1.00) [High physical hazards] >0<4 (Cf=1.00) [Low physical hazards] <0 (Cf=1.00) [Negligible physical hazards]	For each identified physical risk, the source of the risk, exposure to the risk, and the potential impact of the risk to people and animals should be scored using the following criteria: Low (1.5-3.0), Moderate (3.5-5.0) and High (5.5-7.0). These scores should be used to calculate the individual risks (Pr) of the mine entries using the equation: Pr = Qs*Ea*(Ni+Mi/2), Where; Qs is the source of the risk, Ea is the exposure to the hazard, and (Ni+Mi/2) is the average of the safety risks (Ni) and associated health risks (Mi). The absent factor between Ni and Mi should be given a score of zero (0). The calculated Pr values of the identified risks of the should be used to calculate the total hazard score (HZtotal) of the shafts using the equation: HZtotal=(SumRi/NF)/n. Where; Ri is the sum of the scores of the physical risks, n is the number of physical risks identified and NF is the factor of 8 employed to reduce the magnitude of the scores.	

APPENDIX-H. *Continued.*

Node	Text	Values	Notes	Image
The general hazards	The general hazards can be considered:	Negligible (Cf=1.00) [This because there is no exposure to the hazards of the abandoned mine entry]	The risks of the mine entry are extremely reduced by prevention of access. These is a mine entry in a well fenced and protected abandoned mine site. Mostly the entry is protected because there is a hope for reuse of the mine entry for future mining activities.	
Environmental hazards	Environmental hazard score of the entry is between	>22<45 (Cf=1.00) [High environmental hazard] >4<21 (Cf=1.00) [Moderate environmental hazard] >0<4 (Cf=1.00) [Low environmental hazards <0 (Cf=1.00) [Negligible environmental hazards]	For each identified environmental hazard of the mine entry, the source of the risk, pathway(s) and the impact it has on the environmental should be scored using the following criteria: Low (1.5-3.0), Moderate (3.5-5.0) and High (5.5-7.0).This scores should be used to calculate the individual environmental risk scores (Evr) of the entry using equation: Evr=Qi*Pj*Rx. Where; Qi is the source of the hazard, Pj is the pathway (given as 1 were the impact is on the aesthetic appearance of the landscape), and Rx is the magnitude of the risk. The determined Pr values should be used to calculate the total hazard score (HZtotal) of the mine entry using the following equation: HZtotal=(SumRi/NF)/n, where; n is the number of environmental risks identified and NF is the factor of 8 employed to reduce the magnitude of the scores.	

APPENDIX-I: Knowledge base rules of the ES-RTDR.

No.	Rule	Notes	Image
1	**IF** mine waste: tailings dump **AND** indices for rehabilitation priority score index of contamination **AND** was the toxic metal content of tailings determined? yes **THEN** the rank of the rehabilitation of the tailings dump is **almost certainly** (Cf=1.00) ***Need for calculation of the mean contamination index of the tailings.***	The calculation of the IC involves dividing the concentration (mg/kg) of toxic metals in tailings by their respective allowable limit in soils. The sum of the quotient values obtained should be then divided by the number of metals considered. This is explained by the equation in the picture.	
2	**IF** mine waste: tailings dump **AND** indices for rehabilitation priority score index of dispersion (ID) of tailings material **AND** is the surface area (A) covered by the dump known? yes **AND** scoring of the general morphology of the dumps (id) the score is accordingly assigned **AND** scoring of textural properties of the tailings material the score is accordingly assigned **AND** scoring of the cover property of the dump the score is accordingly assigned **AND** scoring of the distance of the dump from surface water bodies the score is accordingly assigned **AND** scoring of the surface area occupied by the tailings dump the score is accordingly assigned **THEN** the rank of the rehabilitation of the tailings dump is **almost certainly** (Cf=1.00) ***Need for calculation of the index of dispersion of the tailing material.***	The index of dispersion of tailings material (ID) should be calculated using the Equation: ID=A*(ie+if+id+ia) where; A = the area occupied by the dump in hectares, ie = the score assigned to the textural property of the tailings material, if = the score assigned to the cover property of the dump, id = the score assigned to the general morphology of the dump, and ia = the score assigned to the area coverage of the dump.	
3	**IF** mine waste: tailings dump **AND** indices for rehabilitation priority score ILVI **AND** determine the index of exposure of the dump the IdE of each VP was determined **AND** determination of the total exposure of the dump the index of total exposure of the dump was determined **AND** scoring of chromatic contrast of the dumps the score was accordingly assigned **AND** scoring of morphology or shape of the physical environment the score is accordingly assigned **AND** scoring of nature of the deposit and its relationship to the surroundings assigned to the nature of the deposit **THEN** the rank of the rehabilitation of the tailings dump is **almost certainly** (Cf=1.00) ***Need the calculation of the index of landscape and visual impact (ILVI).***	The index of landscape and visual impact (ILVI) should be calculated using the Equation: ILVI=IdEtotal*(ic+ir+in), Where; ic = the dump appearance (chromatic contrast of the dump), ir = the shape of the dump (morphological and shape of the physical environment), and in= the nature of the deposit (relationship with the surroundings)	
4	**IF** mine waste: tailings dump **AND** indices for rehabilitation priority score ILVI **AND** determine the index of exposure of the dump the IdE of each VP was determined **AND** determination of the total exposure of the dump the index of total exposure of the dump was determined **AND** scoring of chromatic contrast of the dumps the score was accordingly assigned **AND** scoring of morphology or shape of the physical environment the score is accordingly assigned **AND** scoring of nature of the deposit and its relationship to the surroundings assigned to dumps in arid zone **THEN** the rank of the rehabilitation of the tailings dump is **almost certainly** (Cf=1.00) ***Need the calculation of the index of landscape and visual impact (ILVI).***	The index of landscape and visual impact (ILVI) should be calculated using the Equation: ILVI=IdEtotal*(ic+ir+in), Where; ic is the dump appearance (chromatic contrast of the dump), ir is the shape if the dump (morphological and shape of the physical environment), and in is the nature of the deposit (relationship with the surroundings).	

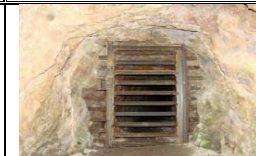
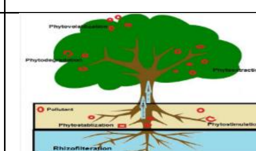
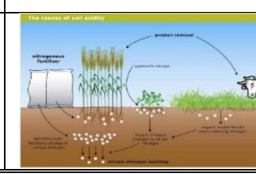
APPENDIX-I. *Continued.*

No.	Rule	Notes	Image
5	**IF** mine waste: tailings dump **AND** indices for rehabilitation priority score ILVI **AND** determine the index of exposure of the dump the IdE of each VP was determined **AND** determination of the total exposure of the dump the index of total exposure of the dump was determined **AND** scoring of chromatic contrast of the dumps the score was accordingly assigned **AND** scoring of morphology or shape of the physical environment the score is accordingly assigned **AND** scoring of nature of the deposit and its relationship to the surroundings assigned to dumps in humid zones **THEN** the rank of the rehabilitation of the tailings dump is **almost certainly** (Cf=1.00) ***Need the calculation of the index of landscape and visual impact*.**	The index of landscape and visual impact (ILVI) should be calculated using the following Equation: ILVI=IdEtotal*(ic+ir+in). Where; ic is the dump appearance (chromatic contrast of the dump), ir is the shape of the dump (morphological and shape of the physical environment), and in is the nature of the deposit (relationship with the surroundings)	
6	**IF** mine waste: tailings dump **AND** indices for rehabilitation priority score the rehabilitation priority score of the dump **AND** the IC, ID and ILVI values should have been determined yes **AND** calculate the RPscore of the dump >100 **THEN** the rank of the rehabilitation of the tailings dump is **almost certainly** (Cf=1.00) ***High rehabilitation attention*.**	The rehabilitation of tailings dumps should focus on creation of a stable landscape with improved soil physic-chemical qualities for easy growth of vegetation. The is a need for removal and mobilization of toxic metals using equal efforts of biological and chemical methods.	
7	**IF** mine waste: tailings dump **AND** indices for rehabilitation priority score the rehabilitation priority score of the dump **AND** the IC, ID and ILVI values should have been determined yes **AND** calculate the RPscore of the dump 10-100 **THEN** the rank of the rehabilitation of the tailings dump is **almost certainly** (Cf=1.00) ***Moderate rehabilitation attention*.**	The tailing dump require physical stabilization and removal of toxic metals using biological methods. Chemical methods can be also used.	
8	**IF** mine waste: tailings dump **AND** indices for rehabilitation priority score the rehabilitation priority score of the dump **AND** the IC, ID and ILVI values should have been determined yes **AND** calculate the RPscore of the dump <10 **THEN** the rank of the rehabilitation of the tailings dump is **almost certainly** (Cf=1.00) ***Low rehabilitation attention*.**	The tailings dump requires chemical improvement of the soil quality to improve vegetation growth following miner physical stability of the slopes of the dump	

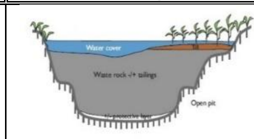
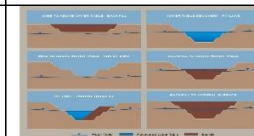
APPENDIX-J: Knowledge base rules of the ES-SRSA.

No.	Rule	Notes	Image
1	IF the type of the feature: mine entry AND the type of entry: vertical shaft AND the aim of treatment: prevention of ground movement THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Permanent sealing of the shaft.*	The strategies that completely close the open mine shaft should be used. These strategies include: Category-A [(1) Backfilling, and (2) Injection or inclusion] and Category-B [Use of self-supported or Anchored plugs, Blast Closure, Geo-synthetics]	
2	IF the type of the feature: mine entry AND the type of entry: vertical shaft AND the aim of treatment: to use simple strategies THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Use of strategies that are simple to apply.*	The strategies that are simple to apply should be used. These strategies may include (1) fencing of the entry with or without the use of signage; (2) steel capping, (3) concrete slab, (4) steel wire, (5) barrier sealing, (6) geo-synthetics, (7) vent, and (8) injection or inclusion.	
3	IF the type of the feature: mine entry AND the type of entry: vertical shaft AND the aim of treatment: use of strategies that require little maintenance THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Apply durable strategies..*	The strategies that require little or no maintenance should be used. These strategies may include (1) backfilling, (2) steel capping, (3) self-supported or anchored plugs (4) surface cab, (5) vent, and (5) injection or inclusion.	
4	IF the type of the feature: mine entry AND the type of entry: vertical shaft AND the aim of treatment: protect species inhabiting the shaft THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Use of strategies that leave the shaft open for the movement of the species inhabiting them..*	The strategies that ensures that species inhabiting the shafts are protected should be used. These strategies may include (1) fencing with or without signage, (2) steel grate, (3) barrier sealing, (4) dams sealing	
5	IF the type of the feature: mine entry AND the type of entry: vertical shaft AND the aim of treatment: prevent risks of physical injuries THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Prevention of access of the entry.*	The strategies that seals the shaft or prevent access to the shaft should be used. These strategies may include: Category-A [(1) backfilling, (2) steel capping, (3) steel grate, (4) concrete slab, (5) plugs (self-supported or anchored plugs, (6) surface cab, (7) barrier sealing, and (8) injection or inclusion] and Category-B [(1) steel capping, (2) steel grate, (3) steel wire, (4) geo-synthetics, and (5) fencing]	
6	IF the type of the feature: mine entry AND the type of entry: inclined shaft AND aim of treatment: prevention of ground movement THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Permanent sealing of the shaft .*	The strategies that completely seal the shaft should be used. These strategies may include: (1) backfilling, (2) blast closure, (3) use of geo-synthetic methods, and (4) appropriate designs of concrete plugs	

APPENDIX-J. *Continued.*

No.	Rule	Notes	Image
7	IF the type of the feature: mine entry AND the type of entry: inclined shaft AND aim of treatment: protect species inhabiting the shaft THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Use of strategies leave the shaft open for the movement of the species inhabiting them.*	The strategies that ensures that species inhabiting the shafts are protected should be used. These strategies may include (1) fencing with or without signage, (2) steel grate, (3) barrier sealing, (4) dams sealing	
8	IF the type of the feature: mine entry AND the type of entry: inclined shaft AND aim of treatment: prevent people and animals from entering the shafts THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Prevention of entry into the shaft.*	The strategies that prevent people and animals from entering the abandoned mine shafts should be used. These strategies may include; (1) backfilling, (2) blast closure, (3) use of barrier sealing strategies, (4) use of steel grate, and (5) fencing coupled with the use signage.	
9	IF the type of the feature: mine entry AND the type of entry: inclined shaft AND aim of treatment: use easy to install strategies THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Use of strategies that are simple to apply.*	The strategies that are generally not difficult to implement should be used. These strategies may include installation of (1) steel capping, (2) installation of steel grate, and (3) fencing with or without signage etc.	
10	IF the type of the feature: mine entry AND the type of entry: adit AND the aim of treatment: prevention of discharge of mine water THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Use of strategies that are watertight .*	The strategies that seals the edits in a way that prevent possible discharge of contaminated mine water should be used. These strategies may include the use of (1) concrete barriers, (2) blast closure, (3) backfilling, (4) dams sealing and (5) use of geo-synthetics etc.	
11	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: improving the physical stability of the dump THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Enhance the physical stability of the dumps..*	The methods that improves the physical stability of the tailing dumps can be used. These methods may include use of (1) retaining wall, (2) loose rock or stone check dam, (3) pole or log check dam, (4) gabions, (5) wire-bound loose stone or rock check dam, (6) rock gabions, (7) riprap or stone terrace, (8) bench terraces, (9) mulch spreading, (10) topsoil cover, (11) reshaping of the dump etc.	
12	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: reduce the concentration of toxic metals from tailings THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Use of biological methods.*	The biological techniques such as (1) phytostabilization, (2) biomineralization, (3) hyperaccumulation, (4) dendroremediation, (5) cyanoremediation, (6) biomineralization, (7) genoremediation, (8) rhizoremediation, (9) biostimulation, (10) mycoremediation, (11) biosorption may be used.	
13	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: improve the physio-chemical properties of tailings THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Use of chemical methods..*	The chemical methods such as (1) use of nanoparticles, (2) adding of synthetic chelates, (3) adding of fertilizer, and (4) application of lime may be used.	

APPENDIX-J. *Continued.*

No.	Rule	Notes	Image
14	IF the type of the feature: mine waste AND type of waste: spoil dumps AND the aim of rehabilitation: removal of the dump THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Use as backfilling material.*	The spoil materials can be used to fill up the abandoned mine excavations.	
15	IF the type of the feature: surface excavations AND the aim of rehabilitation: Pit Lake development THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Filling up of the pits with water.*	The abandoned mine excavations can be flooded with water to create a pit lake that can be used by the public for different purposes.	
16	IF the type of the feature: surface excavations AND the aim of rehabilitation: creating an acceptable landform THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Backfilling of the excavations.*	The surface mine excavations or pits can be filled up with different types of mine waste which include tailings, waste rock dumps and spoils material or overburden.	
17	IF the type of the feature: surface excavations AND the aim of rehabilitation: prevention of access of the excavation THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Fencing of the excavations.*	Guard against danger to persons at person and animals	
18	IF the type of the feature: surface excavations AND the aim of rehabilitation: reducing of the slopes of the pit THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Re-contouring and reuse of the excavation.*	The walls of shallow excavation need to be graded to maintain a safe profile.	
19	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: removal of the dump AND type of tailings: ultramafic tailings THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of tailings .*	This type of tailings can be used in the production of glass and rock wool; carbon dioxide sequestration in ultramafic tailings can also be considered.	
20	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: removal of the dump AND type of tailings: phosphate-rich tailings THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of tailings .*	This type of tailings can be used for the extraction of phosphoric acid.	

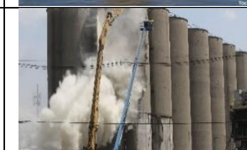
APPENDIX-J. *Continued.*

No.	Rule	Notes	Image
21	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: removal of the dump AND type of tailings: phlogopite-rich tailings THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of tailings* .	This type of tailings can be used for sewage treatment.	
22	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: removal of the dump AND type of tailings: coal discards THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of tailings* .	Energy recovery from compost - coal tailings mixtures.	
23	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: removal of the dump AND type of tailings: iron-rich tailings THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of tailings* .	This type of tailings can be mixed with fly ash and sewage sludge for lightweight ceramics.	
24	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: removal of the dump AND type of tailings: cupper-rich tailings THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of tailings* .	This type of tailings can be used as extenders for paints.	
25	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: removal of the dump AND type of tailings: bauxite tailings THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of tailings* .	This type of tailings can be considered for use as sources of alum	
26	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: removal of the dump AND type of tailings: manganese-rich tailings THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of tailings* .	This type of tailings can be used in agro-forestry, building and construction materials, coatings, cast resin products, glass, ceramics and glazes.	

APPENDIX-J. *Continued.*

No.	Rule	Notes	Image
27	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: removal of the dump AND type of tailings: clay-rich tailing THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of tailings .*	This type of tailings can be used as an amendment to sandy soils. They can also be use in the manufacturing of bricks, cement, floor tiles, sanitary ware and porcelains.	
28	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: removal of the dump AND type of tailings: sand-rich tailings THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) Reuse of tailings .	This type of tailings can be mixed with cement and used to backfill the old underground mine working.	
29	IF the type of the feature: mine waste AND type of waste: tailings AND the aim of rehabilitation: removal of the dump AND type of tailings: potential for reprocessing THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of tailings .*	Reprocessing to extract minerals and metals - reprocessing of tailings for extraction of valuable minerals.	
30	IF the type of the feature: mine waste AND type of waste: waste rock dumps AND the aim of rehabilitation: removal of the dump AND type of rock waste dump: inert (chemically inactive): THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of the rock waste .*	The use of waste rock dumps in the followings should be considered: (1) backfill for open voids; (2) landscaping material; (3) capping material for waste repositories; (4) substrate for vegetation at mine sites; (5) aggregate in embankment, road, pavement, foundation and building construction	
31	IF the type of the feature: mine waste AND type of waste: waste rock dumps AND the aim of rehabilitation: removal of the dump AND type of rock waste dump: sulphidic waste rock: THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Reuse of the rock waste .*	This type of waste rock dumps can be used as soil additive to neutralize infertile alkaline agricultural soils	
32	IF the type of the feature: mine waste AND type of waste: waste rock dumps AND the aim of rehabilitation: removal of the dump AND type of rock waste dump: other THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Other.*	The mine waste rocks can also be used as (1) source of minerals and metals; (2) asphalt component; (3) feedstock for cement and concrete	

APPENDIX-J. *Continued.*

No.	Rule	Notes	Image
33	IF the type of the feature: silos and orebins AND the aim of rehabilitation: removal from the landscape AND purpose of demolition: reuse the material or avoid risk of property damage THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Manual demolition .*	This will require the use of simple hand tools such as crowbars, sledgehammers, cutting torches, and saws. Most often used at sites where high salvage value exists, liability and risk of property damage is high, or heavy equipment access is limited.	
34	IF the type of the feature: silos and orebins AND the aim of rehabilitation: removal from the landscape AND purpose of demolition: demolishing of concrete silos THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Blasting.*	This method is primarily used to reduce concrete or masonry structures. requires specialized expertise.	
35	IF the type of the feature: silos and orebins AND the aim of rehabilitation: removal from the landscape AND purpose of demolition: less cost demolition THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Mechanical demolition.*	This method uses wrecking cranes, jackhammers, and bulldozers. It is generally less costly than manual demolition. It is used where sufficient access and working area is available, and as required by structural strength, mass, and extent of structures.	
36	IF the type of the feature: silos and orebins AND the aim of rehabilitation: reuse of the structure THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Protection and reconditioning of the structure .*	If the decision has been made to preserve the site and the silos, temporary barriers should be erected to prevent access until permanent upgrade of the features for its new use is undertaken.	
37	IF the type of the feature: other features AND details of the feature: mine roads AND compacted surfaces removal and rehabilitation of the land THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Cleaning up of the land.*	Rehabilitation of the areas occurred by mine roads may be done in the following steps: (1) remove road surface and sub-base (the gravel material can be salvaged for other uses), (2) remove culverts, (3) rip on contour to reduced compaction, (4) use a large bulldozer to restore original contours of on hillslopes (up to 40% slopes), (5) roads on hillslopes greater than can be restored to or near original profile with large backhoes or draglines, and (6) pull berm and outside shoulder up the cut slope as far as possible using a backhoe or dragline.	
38	IF the type of the feature: other features AND details of the feature: concrete water reservoirs and stands AND aim of rehabilitation: demolition and removal THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Manual demolition and removal .*	This method requires the use of simple hand tools such as crowbars, sledgehammers, cutting torches, and saws. Most often used at sites where high salvage value exists, liability and risk of property damage is high, or heavy equipment access is limited.	

APPENDIX-J. *Continued.*

No.	Rule	Notes	Image
39	IF the type of the feature: other features AND details of the feature: concrete water reservoirs and stands AND aim of rehabilitation: demolition and removal THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Mechanical demolition.*	This method uses wrecking cranes, jackhammers, and bulldozers. It is generally less costly than manual demolition. It is used where sufficient access and working area is available, and as required by structural strength, mass, and extent of structures.	
40	IF the type of the feature: other features AND details of the feature: mine houses AND location: the old mine village AND aim of rehabilitation: demolition and removal THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Manual demolition and removal .*	This method requires the use of simple hand tools such as crowbars, sledgehammers, cutting torches, and saws. Most often used at sites where high salvage value exists, liability and risk of property damage is high, or heavy equipment access is limited.	
41	IF the type of the feature: other features AND details of the feature: mine houses AND location: the old mine village AND aim of rehabilitation: protection and reconditioning THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Protection and reconditioning .*	If the decision has been made to preserve the site and its buildings, temporary barriers should be erected to prevent access until permanent upgrade of the buildings for its new use is undertaken.	
42	IF the type of the feature: other features AND details of the feature: mine houses AND location: in the areas of mining and mineral processing AND aim of rehabilitation: demolition and removal THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Manual demolition and removal .*	This method requires the use of simple hand tools such as crowbars, sledgehammers, cutting torches, and saws. Most often used at sites where high salvage value exists, liability and risk of property damage is high, or heavy equipment access is limited.	
43	IF the type of the feature: other features AND details of the feature: mine houses AND location: miner's hostel AND aim of rehabilitation: demolition and removal THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Manual demolition and removal .*	This method requires the use of simple hand tools such as crowbars, sledgehammers, cutting torches, and saws. Most often used at sites where high salvage value exists, liability and risk of property damage is high, or heavy equipment access is limited.	
44	IF the type of the feature: other features AND details of the feature: mine houses AND location: miner's hostel AND aim of rehabilitation: protection and reconditioning THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Protection and reconditioning .*	If the decision has been made to preserve the site and its buildings, temporary barriers should be erected to prevent access until permanent upgrade of the buildings for its new use is undertaken.	
45	IF the type of the feature: mine entry AND the type of entry: adit AND the aim of treatment: protect species inhabiting the shaft THEN the rehabilitation strategy of the mine feature: is almost certainly (Cf=1.00) *Use of strategies that leave the shaft open for the movement of species in it.*	The strategies that ensures that species inhabiting the shafts are protected should be used. These strategies may include (1) fencing with or without signage, (2) steel grate, (3) barrier sealing, (4) dams sealing	

APPENDIX-K. Structure of the decision tree of the ES-SRSA

APPENDIX-K. *Continued.*

APPENDIX-K. *Continued.*

- V Surfce excvations
  - A The aim of the rehabilitation v
    - V Pit Lake Development
      - C Filling up of the pits with wate
    - V Creating of an acceptable lar
      - C Backfilling of the excavations
    - V Prevention of access of the e
      - C Fancing of the excavations
    - V Reducing of the slopes of the
      - C Recontouring and reuse of th
- V Silos and orebins
  - A The aim of the rehabilitation v
    - V Removal from the landscape
      - A Purpose of demolition
        - V Reuse the material
          - C Manual demolition
        - V Demolishing of concrete silos
          - C Blasting
        - V Less cost demolition
          - C Mechanical demolition
    - V Reuse of the structure
      - C Protection and reconditioning
- V Other structures
  - A Type of structures
    - V Mine roads
      - A Compacted surfaces
        - V Removal and rehabilitation of
          - C Cleaning up of the land

- V Concrete water reservoirs & :
  - A Aim of rehabilitation
    - V Removal and cleaning of the
      - C Manual demolition and remov
    - V New Value
      - C Mechanical demolition
- V Mine houses
  - A Location of the building
    - V The old mine village
      - A Aim of rehabilitation
        - V Demolition and removal
          - C Manual demolition and remov
        - V Reuse of the buildings
          - C Protection and reconditioning
    - V In the areas of mining and mi
      - A Aim of rehabilitation
        - V Demolition and removal
          - C Manual demolition and remov
    - V Miners hostels
      - A Aim of rehabilitation
        - V Demolition and removal
          - C Manual demolition
        - V Protection and reconditioning
          - C Protection and reconditioning

Return to the Selection of strategies for rehabilitation of abandoned mine Expert System Title Page

APPENDIX-L: MS excell spreadsheets of abandoned mine cost estimation methods

COST OF LOADING IN EARTHWORK					
Loading Time per Truck					
	Basic Cycle Time	Mixed Material Type	Pile Type: Truck Dumped	Miscellaneous	Wheel Loader Mininmum Travel
	24	1	1	2	15
LCT (min)	43	0.72			
	passes/Truck	(LMC)	Loading Time/Truck (min)		
Truck Capacity (m^3)	10	10.0	4.2		
Loader Bucket Net Capacity (m^3)	1.7				
Passess	5.9				
Corrections of Loader Operator and Job Efficiencies			Calculation of Loader Operation Cost		
Correction Facter	0.75		(ZAR)	245.00	
Upareter Efficiance Correction	0.96		Cost of Loader Operating/min	4.08	
Job Efficiance Correction	1.27		Loader Cost/m^3 (ZAR)	3.06	
Time/m^3	0.75				
Total Direct Loading cost (ZAR)					
Volume to be loaded (m^3)	226277.0				
Direct Loading cost (ZAR)	692,470.06				
REQUIRED TRUCK HOURS AND THE PRODUCTION RATE					
	Haul Time (sec.)	Return Time (sec.)	Dump and least manuever time	Loading Time	Truck Cycle Time (sec.)
	23	23	12	258	316
Truck Cycle Time (Min.)	5.3				
	Truck Cycle Time	Total loading Time	Truck(s)		
Number of Trucks Needed	5.3	4.2	1		
	Net Truck Capacity	Number of Trucks	Truck Cycle Time (min)	Rate (LCM/min)	
Production Rate	10.0	1	5.3	2.37	
	Production Rate (LCM/I	Track Cycle Time (min)	Production (LCM/hr)		
Hourly Production	142.3	5.3	749.6		
	Volume to be moved	Hourly Production	Hours		
Hours Required	226277.0	749.6	169,613,029.40		
Correction of driver efficiency					
	Truck Cycle Time	Correction Factor	Correction		
Driver Efficiency Correction	5.3	0.75	7.0		
	Driver Efficiency Time	Correction Factor	Correction		
Job Efficiency Correction	7.0	0.84	8.4		
	Job Efficiency	Truck Capacity	Time/m^3		
Truck Time/m^3	8.4	10.0	0.84		
Determination of the cost per cubic metre					
	Rate (ZAR)				
Truck Driver Cost	254.0				
	Truck Driver Cost (ZAR)				
Track Operation/min	4.23				
	Time /m^3	Truck Operation Cost	Cost per m^3		
Truck Cost/m^3	0.84	4.23	3.54		
Volume for trucking (m^3)	226277.0				
TOTAL HAUL COST (ZAR)	800,789.11				
TOTAL DIRECT LOADING AND HAUL COST (ZAF	1,493,259.18				
INDIRECT COST					
	Cost (ZAR)				
Contractor Profit & and Overhead cost (15-30%)	447,977.75				
Contingency cost (5-10%)	149,325.92				
Monitoring & maintenance cost (5-10%)	149,325.92				
Mobilization/Demobilization (5-10%)	149,325.92				
Engineering and design (5-10%)	149,325.92				
TOTAL INDIRECT COST (ZAR)	1,045,281.43				
TOTAL DIRECT AND INDIRECT COST (ZAR)	2,538,540.60				
% Inflation	126,927.03				
TOTAL CUT AND FILL COST (ZAR)	2,665,467.63				
14% VAT.	373,165.47				
TOTAL COST (INCLUDING VAT@14%)	3,038,633.10				

(a)

COST OF LOADING IN EARTHWORK					
Loading Time per Truck					
	Basic Cycle Time	Mixed Material Type	Pile Type: Truck Dumped	Miscellaneous	Wheel Loader Mininmum Travel
	24	1	1	2	15
LCT (min)	43	0.72			
	passes/Truck	(LMC)	Loading Time/Truck (min)		
Truck Capacity (m^3)	10	10.0	4.2		
Loader Bucket Net Capacity (m^3)	1.7				
Passess	5.9				
Corrections of Loader Operator and Job Efficiencies			Calculation of Loader Operation Cost		
Correction Facter	0.75		(ZAR)	245.00	
Upareter Efficiance Correction	0.96		Cost of Loader Operating/min	4.08	
Job Efficiance Correction	1.27		Loader Cost/m^3 (ZAR)	3.06	
Time/m^3	0.75				
Total Direct Loading cost (ZAR)					
Volume to be loaded (m^3)	226277.0				
Direct Loading cost (ZAR)	692,470.06				
REQUIRED TRUCK HOURS AND THE PRODUCTION RATE					
	Haul Time (sec.)	Return Time (sec.)	Dump and least manuever time	Loading Time	Truck Cycle Time (sec.)
	23	23	12	258	316
Truck Cycle Time (Min.)	5.3				
	Truck Cycle Time	Total loading Time	Truck(s)		
Number of Trucks Needed	5.3	4.2	1		
	Net Truck Capacity	Number of Trucks	Truck Cycle Time (min)	Rate (LCM/min)	
Production Rate	10.0	1	5.3	2.37	
	Production Rate (LCM/I	Track Cycle Time (min)	Production (LCM/hr)		
Hourly Production	142.3	5.3	749.6		
	Volume to be moved	Hourly Production	Hours		
Hours Required	226277.0	749.6	169,613,029.40		
Correction of driver efficiency					
	Truck Cycle Time	Correction Factor	Correction		
Driver Efficiency Correction	5.3	0.75	7.0		
	Driver Efficiency Time	Correction Factor	Correction		
Job Efficiency Correction	7.0	0.84	8.4		
	Job Efficiency	Truck Capacity	Time/m^3		
Truck Time/m^3	8.4	10.0	0.84		
Determination of the cost per cubic metre					
	Rate (ZAR)				
Truck Driver Cost	254.0				
	Truck Driver Cost (ZAR)				
Track Operation/min	4.23				
	Time /m^3	Truck Operation Cost	Cost per m^3		
Truck Cost/m^3	0.84	4.23	3.54		
Volume for trucking (m^3)	226277.0				
TOTAL HAUL COST (ZAR)	800,789.11				
TOTAL DIRECT LOADING AND HAUL COST (ZAF	1,493,259.18				
INDIRECT COST					
	Cost (ZAR)				
Contractor Profit & and Overhead cost (15-30%)	223,988.88				
Contingency cost (5-10%)	74,662.96				
Monitoring & maintenance cost (5-10%)	74,662.96				
Mobilization/Demobilization (5-10%)	74,662.96				
Engineering and design (5-10%)	74,662.96				
TOTAL INDIRECT COST (ZAR)	522,640.71				
TOTAL DIRECT AND INDIRECT COST (ZAR)	2,015,899.89				
% Inflation	100,794.99				
TOTAL CUT AND FILL COST (ZAR)	2,116,694.89				
14% VAT.	296,337.28				
TOTAL COST (INCLUDING VAT@14%)	2,413,032.17				

(b)

Figure-I. The minimum (a) and maximum (b) estimated costs of cut and fill operations towards the rehabilitation of abandoned Nyala Mine.

APPENDIX-L. *Continued.*

ESTIMATION OF RIPPING COST				
Cycle Time	Cut length (m) 100	Average Speed (m/min) 26.8	Fixed Turn Time 0.25	Time 3.98
Passes/hr	Ave. Operator work minutes 45	Cycle Time 3.98	Per Hour 11.30	
Volume to be Ripped	Cut length (m) 100	Rip Spacing (m) 0.9	Ripper Penetration (m) 0.5	BCM/Pass 45
Hourly Production	Vol. Ripped /Pass (BCM) 45	Passes/hr 11.30	BCM 508.62	
Hours Required	Bank Vol. to be Ripped 413593	Hourly Production (BCM/Hr) 508.62	Hours 813.16	
Dozor oparation cost (ZAR)	Dozer Hire Rate (ZAR)/ha 225.00	Cost (ZAR)/hr 182,961.75		
Ripping cost (ZAR)/ha	Dozing Rate (ZAR)/ha 8,900.00	Ripping area (ha) 86	Cost (ZAR)/ha 765,400.00	
TOTAL DIRECT RIPPING COST (ZAR)	948,361.75			

INDIRECT COST	Cost (ZAR)
Contractor Profit & and Overhead cost (15-30%)	284,508.52
Contingency cost (5-10%)	94,836.17
Monitoring & maintenance cost (5-10%)	94,836.17
Mobilization/Demobilization (5-10%)	94,836.17
Engineering and design (5-10%)	94,836.17
TOTAL INDIRECT COST (ZAR)	569,017.05
TOTAL DIRECT AND INDIRECT COST (ZAR)	1,517,378.79
% Inflation	75,868.94
TOTAL RIPPING COST (ZAR)	1,593,247.73
14% VAT.	223,054.68
TOTAL COST (INCLUDING VAT@14%)	1,816,302.42

(a)

ESTIMATION OF RIPPING COST				
Cycle Time	Cut length (m) 100	Average Speed (m/min) 26.8	Fixed Turn Time 0.25	Time 3.98
Passes/hr	Ave. Operator work minutes 45	Cycle Time 3.98	Per Hour 11.30	
Volume to be Ripped	Cut length (m) 100	Rip Spacing (m) 0.9	Ripper Penetration (m) 0.5	BCM/Pass 45
Hourly Production	Vol. Ripped /Pass (BCM) 45	Passes/hr 11.30	BCM 508.62	
Hours Required	Bank Vol. to be Ripped 413593	Hourly Production (BCM/Hr) 508.62	Hours 813.16	
Dozor oparation cost (ZAR)	Dozer Hire Rate (ZAR)/ha 225.00	Cost (ZAR)/hr 182,961.75		
Ripping cost (ZAR)/ha	Dozing Rate (ZAR)/ha 8,900.00	Ripping area (ha) 86	Cost (ZAR)/ha 765,400.00	
TOTAL DIRECT RIPPING COST (ZAR)	948,361.75			

INDIRECT COST	Cost (ZAR)
Contractor Profit & and Overhead cost (15-30%)	142,254.26
Contingency cost (5-10%)	47,418.09
Monitoring & maintenance cost (5-10%)	47,418.09
Mobilization/Demobilization (5-10%)	47,418.09
Engineering and design (5-10%)	47,418.09
TOTAL INDIRECT COST (ZAR)	284,508.52
TOTAL DIRECT AND INDIRECT COST (ZAR)	1,232,870.27
% Inflation	61,643.51
TOTAL RIPPING COST (ZAR)	1,294,513.78
14% VAT.	181,231.93
TOTAL COST (INCLUDING VAT@14%)	1,475,745.71

(b)

Figure-II. The maximum (a) and minimum (b) estimated costs of compacted areas in the rehabilitation of the abandoned Nyala Mine terrain.

APPENDIX-L. *Continued..*

SPREADING OF MATERIAL									
Operation Adjustment Factor	Operator Factor 0.75	Material Factor 0.80	Efficiency 0.83	Grade 0.95	Weight Correction 0.93	Production 1.00	Visibility 1.00	Elevation 1.00	Factor 0.44
Net Hourly Production	Normal Hourly 458	Operating Adjustment 0.44	Prodaction 201.9						
Hours Required	Volume to be Moved 812523	Net Hourly Production 201.9	Work Hours 4023.5						
	Spreading rate/ha	Dozer Work Hours	Cost (ZAR)						
Dozar Hire	10.50	97.0	1,018.50						
	Dozer Hire rate/hr	Dozer Work Hours							
Dozar Oparation	225.00	4023.5	905,281.91						
TOTAL DIRECT COST (ZAR)	906,300.41								

INDIRECT COST	Cost (ZAR)
Contractor Profit & and Overhead cost (15-30%)	271,890.12
Contingency cost (5-10%)	90,630.04
Monitoring & maintenance cost (5-10%)	90,630.04
Mobilization/Demobilization (5-10%)	90,630.04
Engineering and design (5-10%)	90,630.04
TOTAL INDIRECT COST (ZAR)	543,780.25
TOTAL DIRECT AND INDIRECT COST (ZAR)	1,450,080.66
% Inflation	72,504.03
TOTAL SPREADING COST (ZAR)	1,522,584.69
14% VAT.	213,161.86
TOTAL COST (INCLUDING VAT@14%)	1,735,746.55

(a)

SPREADING OF MATERIAL									
Operation Adjustment Factor	Operator Factor 0.75	Material Factor 0.80	Efficiency 0.83	Grade 0.95	Weight Correction 0.93	Production 1.00	Visibility 1.00	Elevation 1.00	Factor 0.44
Net Hourly Production	Normal Hourly 458	Operating Adjustment 0.44	Prodaction 201.9						
Hours Required	Volume to be Moved 812523	Net Hourly Production 201.9	Work Hours 4023.5						
	Spreading rate/ha	Dozer Work Hours	Cost (ZAR)						
Dozar Hire	10.50	97.0	1,018.50						
	Dozer Hire rate/hr	Dozer Work Hours							
Dozar Oparation	225.00	4023.5	905,281.91						
TOTAL DIRECT COST (ZAR)	906,300.41								

INDIRECT COST	Cost (ZAR)
Contractor Profit & and Overhead cost (15-30%)	135,945.06
Contingency cost (5-10%)	45,315.02
Monitoring & maintenance cost (5-10%)	45,315.02
Mobilization/Demobilization (5-10%)	45,315.02
Engineering and design (5-10%)	45,315.02
TOTAL INDIRECT COST (ZAR)	271,890.12
TOTAL DIRECT AND INDIRECT COST (ZAR)	1,178,190.54
% Inflation	58,909.53
TOTAL SPREADING COST (ZAR)	1,237,100.06
14% VAT.	173,194.01
TOTAL COST (INCLUDING VAT@14%)	1,410,294.07

(b)

Figure-III. The maximum (a) and minimum (b) estimated costs of spreading of backfill material at Nyala Mine.

APPENDIX-L. *Continued.*

COST OF INITIAL SEEDING			
SEEDING	**SPECIES OF SEEDS:**	***Carpobrotus edulis***	
DIRECT COST (ZAR)	Area to be seeded (ha)	Quantity of seeds per ha (kg)	Cost of Seed per kg
	169	1	141.12
Estimated Cost (ZAR)	23,849.28		
INDIRECT COST (ZAR)			
Contractor Profit & Overhead cost (30%)	7,154.78		
Contingency cost (5-10%)	2,384.93		
Monitoring & maintenance cost (5-10%)	2,384.93		
Mobilization/Demobilization (5-10%)	2,384.93		
Engineering and design (5-10%)	2,384.93		
TOTAL INDIRECT COST (ZAR)	16,694.50		
TOTAL DIRECT AND INDIRECT COST (ZAR)	40,543.78		
% Inflation	2,027.19		
TOTAL COST OF SEEDING (ZAR)	42,570.96		
14% VAT.	5,959.94		
TOTAL COST (INCLUDING VAT@14%)	48,530.90		

(a)

COST OF INITIAL SEEDING			
SEEDING	**SPECIES OF SEEDS:**	***Ehrharta villosa***	
DIRECT COST (ZAR)	Area to be seeded (ha)	Quantity of seeds per ha (kg)	Cost of Seed per kg
	169	1	364.92
Estimated Cost (ZAR)	61,671.48		
INDIRECT COST (ZAR)			
Contractor Profit & Overhead cost (30%)	18,501.44		
Contingency cost (5-10%)	6,167.15		
Monitoring & maintenance cost (5-10%)	6,167.15		
Mobilization/Demobilization (5-10%)	6,167.15		
Engineering and design (5-10%)	6,167.15		
TOTAL INDIRECT COST (ZAR)	43,170.04		
TOTAL DIRECT AND INDIRECT COST (ZAR)	104,841.52		
% Inflation	5,242.08		
TOTAL COST OF SEEDING (ZAR)	110,083.59		
14% VAT.	15,411.70		
TOTAL COST (INCLUDING VAT@14%)	125,495.29		

(b)

COST OF INITIAL SEEDING			
SEEDING	**SPECIES OF SEEDS:**	***Eriocephalus racemosus***	
DIRECT COST (ZAR)	Area to be seeded (ha)	Quantity of seeds per ha (kg)	Cost of Seed per kg
	169	1	162.11
Estimated Cost (ZAR)	27,396.59		
INDIRECT COST (ZAR)			
Contractor Profit & Overhead cost (30%)	8,218.98		
Contingency cost (5-10%)	2,739.66		
Monitoring & maintenance cost (5-10%)	2,739.66		
Mobilization/Demobilization (5-10%)	2,739.66		
Engineering and design (5-10%)	2,739.66		
TOTAL INDIRECT COST (ZAR)	19,177.61		
TOTAL DIRECT AND INDIRECT COST (ZAR)	46,574.20		
% Inflation	2,328.71		
TOTAL COST OF SEEDING (ZAR)	48,902.91		
14% VAT.	6,846.41		
TOTAL COST (INCLUDING VAT@14%)	55,749.32		

(c)

COST OF INITIAL SEEDING			
SEEDING	**SPECIES OF SEEDS:**	***Lebeckia spinescens***	
DIRECT COST (ZAR)	Area to be seeded (ha)	Quantity of seeds per ha (kg)	Cost of Seed per kg
	169	1	760.41
Estimated Cost (ZAR)	128,509.29		
INDIRECT COST (ZAR)			
Contractor Profit & Overhead cost (30%)	38,552.79		
Contingency cost (5-10%)	12,850.93		
Monitoring & maintenance cost (5-10%)	12,850.93		
Mobilization/Demobilization (5-10%)	12,850.93		
Engineering and design (5-10%)	12,850.93		
TOTAL INDIRECT COST (ZAR)	89,956.50		
TOTAL DIRECT AND INDIRECT COST (ZAR)	218,465.79		
% Inflation	10,923.29		
TOTAL COST OF SEEDING (ZAR)	229,389.08		
14% VAT.	32,114.47		
TOTAL COST (INCLUDING VAT@14%)	261,503.55		

(d)

Figure-IV. The estimated costs of seeding the Nyala Mine terrain using (a) *Carpobrotus edulis*, (b) *Ehrharta villosa*, (c) *Eriocephalus raemosus* and (d) *Lebeckia spinescens* seed species.

APPENDIX-L. *Continued.*

COST OF FERTILAZATION			
FERTILAZATION	TYPE OR NAME:	Mono-Ammonium Phosphate (MAP)	
DIRECT COST (ZAR)	Area to be seeded (ha)	Unit area to fertilaze with 1 ton fertiliser (ha)	Cost of fertilizer per tonne
	169	1.5	13,188.00
Estimated Cost (ZAR)	3,343,158.00		
INDIRECT COST (ZAR)			
Contractor Profit & Overhead cost (30%)	1,002,947.40		
Contingency cost (5-10%)	167,157.90		
Monitoring & maintenance cost (5-10%)	334,315.80		
Mobilization/Demobilization (5-10%)	334,315.80		
Engineering and design (5-10%)	167,157.90		
TOTAL INDIRECT COST (ZAR)	2,005,894.80		
TOTAL DIRECT AND INDIRECT COST (ZAR)	5,349,052.80		
% Inflation	267,452.64		
TOTAL COST OF SEEDING (ZAR)	5,616,505.44		
14% VAT.	786,310.76		
TOTAL COST (INCLUDING VAT@14%)	6,402,816.20		

(a)

COST OF FERTILAZATION			
FERTILAZATION	TYPE OR NAME:	Potassium Chloride	
DIRECT COST (ZAR)	Area to be seeded (ha)	Unit area to fertilaze with 1 ton fertiliser (ha)	Cost of fertilizer per tonne
	169	1.5	6,852.66
Estimated Cost (ZAR)	1,737,149.31		
INDIRECT COST (ZAR)			
Contractor Profit & Overhead cost (30%)	521,144.79		
Contingency cost (5-10%)	86,857.47		
Monitoring & maintenance cost (5-10%)	173,714.93		
Mobilization/Demobilization (5-10%)	173,714.93		
Engineering and design (5-10%)	86,857.47		
TOTAL INDIRECT COST (ZAR)	1,042,289.59		
TOTAL DIRECT AND INDIRECT COST (ZAR)	2,779,438.90		
% Inflation	138,971.94		
TOTAL COST OF SEEDING (ZAR)	2,918,410.84		
14% VAT.	408,577.52		
TOTAL COST (INCLUDING VAT@14%)	3,326,988.36		

(b)

COST OF FERTILAZATION			
FERTILAZATION	TYPE OR NAME:	Urea (46)	
DIRECT COST (ZAR)	Area to be seeded (ha)	Unit area to fertilaze with 1 ton fertiliser (ha)	Cost of fertilizer per tonne
	169	1.5	7,408.00
Estimated Cost (ZAR)	1,877,928.00		
INDIRECT COST (ZAR)			
Contractor Profit & Overhead cost (30%)	563,378.40		
Contingency cost (5-10%)	93,896.40		
Monitoring & maintenance cost (5-10%)	187,792.80		
Mobilization/Demobilization (5-10%)	187,792.80		
Engineering and design (5-10%)	93,896.40		
TOTAL INDIRECT COST (ZAR)	1,126,756.80		
TOTAL DIRECT AND INDIRECT COST (ZAR)	3,004,684.80		
% Inflation	150,234.24		
TOTAL COST OF SEEDING (ZAR)	3,154,919.04		
14% VAT.	441,688.67		
TOTAL COST (INCLUDING VAT@14%)	3,596,607.71		

(c)

COST OF FERTILAZATION			
FERTILAZATION	TYPE OR NAME:	Limestone Ammonium Nitrate (LAN)	
DIRECT COST (ZAR)	Area to be seeded (ha)	Unit area to fertilaze with 1 ton fertiliser (ha)	Cost of fertilizer per tonne
	169	1.5	7,408.00
Estimated Cost (ZAR)	1,877,928.00		
INDIRECT COST (ZAR)			
Contractor Profit & Overhead cost (30%)	563,378.40		
Contingency cost (5-10%)	93,896.40		
Monitoring & maintenance cost (5-10%)	187,792.80		
Mobilization/Demobilization (5-10%)	187,792.80		
Engineering and design (5-10%)	93,896.40		
TOTAL INDIRECT COST (ZAR)	1,126,756.80		
TOTAL DIRECT AND INDIRECT COST (ZAR)	3,004,684.80		
% Inflation	150,234.24		
TOTAL COST OF SEEDING (ZAR)	3,154,919.04		
14% VAT.	441,688.67		
TOTAL COST (INCLUDING VAT@14%)	3,596,607.71		

(d)

Figure-V. The estimate of the costs of using (a) mono-ammonium phosphate (MAP), (b) potassium chloride, (c) Urea (46), and (d) limestone ammonium nitrate fertilizers.

APPENDIX-L. *Continued.*

COST OF DEMOLITION OF SURFACE INFRASTRUCTURE AND TREATMENT OF MINE SHAFTS

Item	Item activities	Rate (R)	Unit	Quantity	DIRECT COST (ZAR)	Planned Work Hr	Average cost of crew	Accessibility (10-20%)	Protective clothing (5%)	Work break (5%)	Respiratory protection (5%)	LABOUR COST (ZAR)
Demolising of surface infrastructure	Removal of rainforced foundations	696.54	m³		-			-	-	-	-	-
	Demolising of unrainforced concrate foundations	696.54	m²		-			-	-	-	-	-
	Removal of raiforced concrate walls	624.48	m³		-			-	-	-	-	-
	Demolising of concrate-brick walls	102.08	m²		-			-	-	-	-	-
	Demolishing of reinforced concrete wall reservoirs	624.48	m³	1900	1,186,512.00	216	37,352.88	118,651.20	59,325.60	59,325.60	59,325.60	333,980.88
	Demolishing of reinforced concrete floor reservoirs	576.44	m³	1900	1,095,236.00	216	37,352.88	109,523.60	54,761.80	54,761.80	54,761.80	311,161.88
	Reinforced concrete stands	504.39	m³	3200	1,614,048.00	216	37,352.88	161,404.80	80,702.40	80,702.40	80,702.40	440,864.88
	Breaking and removal of concrete paving	27.62	m²		-			-	-	-	-	-
	Breaking and removal of asphalt surfaces	16.81	m²		-			-	-	-	-	-
	Removal of steel tanks	7,205.55	N/A		-			-	-	-	-	-
	Removal of steel silos	4,803.70	N/A	1	4,803.70	18	3,112.74	480.37	240.19	240.19	240.19	4,313.67
Closing of mine entries	Desgn and instalation of concrate plugs	36,027.75	N/A	14	504,388.50	378.00	130,735.08	50,438.85	25,219.43	25,219.43	25,219.43	256,832.21
	Installation of reinforced concrate slab	576.44	m²	147	84,736.68	216	37,352.88	8,473.67	4,236.83	4,236.83	4,236.83	58,537.05
	Installation of unreinforced concrate plugs	3,482.68	m²		-			-	-	-	-	-
	Backfilling of the shaft	96.07	m²		-			-	-	-	-	-
				TOTAL:	4,489,724.88	1,260.00	245,906.46	440,498.82	220,249.41	220,249.41	220,249.41	1,405,690.56

Contractor Profit & Overhead cost (15%)	Contingency cost (5%)	Monitoring & maintenance cost (5%)	Mobilization/ Demobilization (5%)	Engineering & design (5%)	INDIRECT COST (ZAR)	TOTAL DIRECT, INDIRECT AND LABOR COST (ZAR)	% Inflation	TOTAL DEMO & TREATMENT COST (ZAR)	14% VAT.	TOTAL COST (PLUS VAT@14%)
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
177,976.80	59,325.60	59,325.60	59,325.60	59,325.60	415,279.20	1,935,772.08	96,788.60	2,032,560.68	284,558.50	2,317,119.18
164,285.40	54,761.80	54,761.80	54,761.80	54,761.80	383,332.60	1,789,730.48	89,486.52	1,879,217.00	263,090.38	2,142,307.38
242,107.20	80,702.40	80,702.40	80,702.40	80,702.40	564,916.80	2,619,829.68	130,991.48	2,750,821.16	385,114.96	3,135,936.13
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
720.56	240.19	240.19	240.19	240.19	1,681.30	10,798.66	539.93	11,338.59	1,587.40	12,926.00
75,658.28	25,219.43	25219.425	25219.425	25219.425	176,535.98	937,756.68	46,887.83	984,644.51	137,850.23	1,122,494.75
12710.502	4,236.83	4236.834	4236.834	4236.834	29,657.84	172931.568	8,646.58	181,578.15	25,420.94	206,999.09
0	-	0	0	0	-	0	-	-	-	-
0	-	0	0	0	-	0	-	-	-	-
673,458.73	224,486.24	224,486.24	224,486.24	224,486.24	1,571,403.71	7,466,819.15	373,340.96	7,840,160.11	1,097,622.41	8,937,782.52

Figure-VI. The spreadsheet of estimating the costs of demolition of abandoned surface mine infrastructure and treatment of underground mine entries.

APPENDIX-M: Formulas for calculation of the direct costs of earthworks.

Calculation of dump-truck performance parameters

Calculation of Truck required Hours

$$\text{Truck Cycle Time} = \frac{23\text{ sec}}{\substack{\text{Haul}\\\text{Time}}} + \frac{23\text{sec}}{\substack{\text{Return}\\\text{Time}}} + \frac{258\text{sec}}{\substack{\text{Loading}\\\text{Time}}} + \frac{12\text{ sec}}{\substack{\text{Dump and least}\\\text{manuever time}}} = 316\text{ sec} \approx 5.26\text{ min}\ldots\ldots\ldots\text{i}$$

$$\text{No. Trucks requered} = \frac{5.2}{\substack{\text{Truck}\\\text{Cycle Time}}}\text{min} \div \frac{4.3}{\substack{\text{Total loading}\\\text{Time}}}\text{min} = 1\text{ Truck}\ldots\ldots\ldots\text{ii}$$

$$\text{Production Rate} = \frac{10.2}{\substack{\text{Net Truck}\\\text{Capacity}}}\text{LCM} + \frac{1}{\substack{\text{Number of}\\\text{Trucks}}}\text{Trucks} \div \frac{5.2\text{min}}{\substack{\text{Truck Cycle}\\\text{Time}}} = 2.15\text{ LCM/min}\ldots\ldots\ldots\text{iii}$$

$$\text{Hourly Production} = \frac{2.15\text{ LCM/min}}{\substack{\text{Production}\\\text{Rate}}} \times 60\text{ min/hr} \times \frac{5.2\text{min}}{\substack{\text{Track Cycle}\\\text{Time}}} = 670.8\text{ LCM/hr}\ldots\ldots\ldots\text{iv}$$

$$\text{Hours Required} = \frac{x}{\substack{\text{Volume to be}\\\text{moved}}}\text{LCM} \div \frac{670.8}{\substack{\text{Hourly}\\\text{Production}}}\text{LCM/hr} = \_\_\_\_\_\text{ hr}\ldots\ldots\ldots\text{v}$$

Calculation of Truck Operator and Job Efficiencies

$$\text{Driver Efficiency Correction} = \frac{5.26}{\substack{\text{Truck Cycle}\\\text{Time}}} \div \frac{0.75}{\substack{\text{Correction}\\\text{Facter}}} = 7.01\text{ min}\ldots\ldots\ldots\text{vi}$$

$$\text{Job Efficiency Correction} = \frac{7.01}{\substack{\text{Driver Efficiency}\\\text{Time}}} \div \frac{0.84}{\substack{\text{Correction}\\\text{Facter}}} = 8.44\text{ min}\ldots\ldots\ldots\text{vii}$$

$$\text{Truck Time/Cubic Meter} = \frac{8.44}{\text{Job Efficiency}} \div \frac{10}{\text{Truck Capacity}} = 0.84\text{ min}\ldots\ldots\ldots\text{viii}$$

Calculation Truck of Operation Cost

$$\text{Cost of Truck \& Driver} = \text{R}254.00\text{/hr}\ldots\ldots\ldots\text{ix}$$

$$\text{Track Operation/min} = \frac{\text{R}254.00}{\substack{\text{Truck Driver}\\\text{Cost}}} \div 60 = \text{R}4.23/\text{m}^3\ldots\ldots\ldots\text{x}$$

$$\text{Truck Cost/Cubic Meter} = \frac{0.84}{\text{Time/Cubic Meters}} \times \frac{4.23}{\text{Truck Operation Cost}} = \text{R}3.55/\text{m}^3 \ldots\ldots\ldots\ldots\ldots\ldots\text{xi}$$

Calculation of Bull Dozer Performance Parameters

Hours required for ripping of footprint areas

$$\text{Cycle Time} = \left[\frac{100\text{ m}}{\text{Cut Lenght}} \div \frac{26.8\text{m/min}}{\text{Average Speed}}\right] + \frac{0.25\text{ m}}{\text{Fixed Turn Time}} = 3.98\text{ min/pass} \ldots\ldots\ldots\ldots\ldots\ldots\text{i}$$

$$\text{Passes/hr} = \frac{45\text{ min}}{\text{Average Opareter work minutes}} \div \frac{3.98}{\text{Cycle Time}} = 11.30\text{ passes/hr} \ldots\ldots\ldots\ldots\ldots\ldots\text{ii}$$

$$\text{Volume to be Ripped} = \frac{100\text{ m}}{\text{Cut lenght}} \times \frac{0.9\text{ m}}{\text{Rip Spacing}} \times \frac{0.5\text{ m}}{\text{Ripper Panetration}} = 45\text{ BCM/pass} \ldots\ldots\ldots\ldots\text{iii}$$

$$\text{Hourly Production} = \frac{45}{\text{Vol.Ripped/Pass}}\text{BCM} \times \frac{11.30}{\text{Pass/Hour}} = 508.5\text{ BCM} \ldots\ldots\ldots\ldots\ldots\ldots\text{iv}$$

$$\text{Hours Requered} = \frac{\text{X}}{\text{Bank Vol. to be Ripped}}\text{BCM} \div \frac{508.5}{\text{Hourly Production}}\text{BCM/hr} = \_\_\_\_\_\_\text{hr} \ldots\ldots\ldots\ldots\text{v}$$

Hours required for spreading of footprint areas

$$\text{Operation Adjustment Factor} = \frac{0.75}{\text{Operater Factor}} \times \frac{0.80}{\text{material Factor}} \times \frac{0.83}{\text{Efficiency Factor}} \times \frac{0.95}{\text{Grade Fector}} \times \frac{0.932}{\text{Weight Correction Factor}} \times \frac{1.0}{\text{production method/blade factor}} \times \frac{1.0}{\text{Visibility Factor}} \times \frac{1.0}{\text{Eveltion Factor}} = 0.441 \ldots\ldots\ldots\ldots\ldots\ldots\text{vi}$$

$$\text{Net Hourly Production} = \frac{458}{\text{Normal Hourly Production}}\text{LCM/hr} \times \frac{0.441}{\text{Operating Adjustment Factor}} = 201.98\text{ LCM/hr} \ldots\ldots\ldots\text{vii}$$

$$\text{Hours Required} = \frac{\text{x}}{\text{Volume to be Moved}}\text{LCM} \div \frac{201.98}{\text{Net Hourly Production}}\text{LCM/hr} = \_\_\_\_\_\_\text{ hr} \ldots\ldots\ldots\ldots\text{viii}$$

APPENDIX-N: Estimated prices of mine site rehabilitation species (Van Eeden, 2010).

Number	Name	Cost per kg of seeds (ZAR)
1	*Amellus tenuifolius*	142.31
2	*Athanasia crithmifolia*	202.66
3	*Athanasia trifurcate*	145.75
4	*Carpobrotus edulis*	141.12
5	*Chaetobromus dregeanus*	217.12
6	*Chrysanthemoides incana*	266.86
7	*Dimorphotheca pluvialis*	249.31
8	*Ehrharta calycina*	184.50
9	*Ehrharta villosa*	364.92
10	*Eriocephalus racemosus*	162.11
11	*Euryops multifidus*	310.53
12	*Foveolina tenella*	169.32
13	*Juncus krausii*	224.68
14	*Lebeckia spinescens*	760.41
15	*Lessertia frutescens*	323.82
16	*Leysera gnaphalodes*	692.62
17	*Lycium ferocissimum*	191.30
18	*Metalasia muricata*	149.42
19	*Oncosiphon grandiflorum*	131.18
20	*Onsosiphon suffruticosum*	138.51
21	*Omithogalum cooperi*	325.59
22	*Omithogalum thyrsoides*	179.42
23	*Othonna cylindrica*	177.99
24	*Pelargonium capitatum*	381.97
25	*Prenia pallens*	158.52
26	*Rhus glauca*	174.33
27	*Senecio elegans*	268.10
28	*Senecio litoreus*	192.01
29	*Sylapterus micranthus*	129.48
30	*Trachyandra divaricata*	159.16
31	*Zygophyllium morgsana*	287.74