DEVELOPMENT OF A MODELING FRAMEWORK FOR DESIGN OF LOW-COST AND APPROPRIATE REHABILITATION STRATEGIES FOR NYALA ABANDONED MINE

Name : Mhlongo Sphiwe Emmanuel
Student number: 11542669

Supervisor : Dr. F. Amponsah-Dacosta
Co-supervisor : Dr. N.F. Mphephu

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A Dissertation submitted to the Department of Mining and Environmental Geology, University of Venda, in fulfillment of the requirements for the degree of Master of Earth Science in Mining and Environmental Geology

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DECLARATION

I (the undersigned) declare that this dissertation, which is presented to the Department of Mining and Environmental Geology, University of Venda, is my own work. All the assistance and reference material cited has been fully acknowledged. This work has not previously been submitted for degree purposes at this or any other university.

Mhlongo Sphiwe Emmanuel

02/11/2012
Date

Supervisor

02 NOV. 2012
Date

DEDICATION

This dissertation is lovingly dedicated to my parents and to the living memory of my grandparents, Doctor "Mlungudodi" Mhlongo and Vinah Shongwe.

ABSTRACT

The issue of abandoned mine sites is a major environmental and social problem for the mining industry, communities and governments. A legacy associated with historical mining is significant degradation of the environment since these operations were not subject to current environmental protection laws. The impacts of abandoned mines include a range of health and safety problems, and extensive economic impacts due to resource degradation and water pollution. So far, there are only a small number of systematic programmes to deal with the issue and in many instances there is a rapidly growing population encroaching on areas of historic mining activities thereby creating a greater potential for adverse effects to human health and the environment.

The main purpose of this research was to develop a modeling framework for the design of inexpensive and suitable rehabilitation plans for the abandoned Nyala Magnesite Mine. The specific objectives were to conduct a detailed site characterization of the abandoned mine site, create surface terrain models for the development of different rehabilitation landforms, design low-cost and appropriate rehabilitation plans for addressing the problems at the mine site, and estimate cost of alternative rehabilitation strategies. The research approach used involved site examination and characterization to establish the environmental conditions of the mine. Hazards at the mine were identified, scored, and rated using modified Historical Mine Site Scoring System. Terrain models were generated using RTK-GPS data and this assisted in developing rehabilitation design alternatives ranging from doing nothing to rehabilitating various sections of the mine to approximate original contour. The alternatives were evaluated for expense, attractiveness in terms of site stabilization and aesthetics, and mitigation of public safety hazards. A comparative economic evaluation of the three most promising rehabilitation alternatives was conducted in order to select the most suitable option for the abandoned Nyala Mine site.

The mine site characterization assisted in determining the nature and extent of environmental problems at the study area. The site was found to be extremely degraded with most surface alterations resulting from extensive diggings, tailings material and overburden spoil dumps. Dangerous abandoned highwalls, exploration trenches, deep erosion gullies and dilapidated ore bunker were identified to be major physical hazards

in the area. In addition, the pit lake presents a drowning hazard and the exposed and rusted empty metal containers, drums, scraps, and nails represent safety hazards. The conceptual site model developed for the abandoned Nyala Mine has provided an increased understanding of the physical features of the site, a description of chemical migration pathways, and an outline of human and ecological populations that may be exposed to identified hazards at the mine.

The results of the physical characterization of the mine waste showed that both tailings and spoil materials are generally well-graded sands and are suitable for engineering purposes. The different surface models generated for the mine site assisted in making informed decisions with regard to the area of the terrain to be cut and the voids to be filled. Based on Strengths, Weaknesses, Opportunities, and Threats (SWOT) and Quantitative Strategic Planning Matrix (QSPM) analysis and cost estimates the three most promising rehabilitation options were evaluated. These options were scenario I which focused on developing the mine site for crop farming; pit lake and construction of inert landfill site with an estimated cost of R68.8 million, scenario II aimed at developing the mine site for settlement and industrial purposes; pit lake; livestock grazing site and pit lake associated with the picnic site and the estimated cost was R72.6 million, and scenario III with the estimated implementation cost of R47.6 million. The lowest cost and the most appropriate rehabilitation option was scenario III. This plan focused on rehabilitation design for residential area, development of BMX dirt park, and construction of landfill site for inert waste and pit lake.

The cost estimates and the escalating costs will assist in budgeting for the rehabilitation of the abandoned mine site. This research has revealed that site characterization and terrain modeling are robust scientific techniques for making sound decision on selection of economical and appropriate rehabilitation plans for abandoned mine sites. The modeling framework developed in this study will serve as a blueprint for developing low-cost and appropriate rehabilitation strategies for other abandoned mines within the province and/or the country.

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GLOSSARY OF ABBREVIATION AND ACRONYMS

AMD	-Acid Mine Drainage
ARD	-Acid Rock Drainage
CDS	-Cold Dry Season
CGS	-Council for Geosciences
CGS	-Council for Geosciences
CSIR	-Council for Scientific and Industrial Research
CSM	-Conceptual Site Model
CNS	-Central Nervous System
Dc	-Direct Cost
DEM	-Digital Elevation Model
DME	-Department of Minerals and Energy
DTM	-Digital Terrain Model
EC	-Electrical Conductivity
ESP	-Exchangeable Sodium Percentage
GIS	-Geographical Information System
FAAS	-Flame Atomic Absorption Spectrometer
GPS	-Geographical Positioning System
HMS-SS	-Historic Mine Site Scoring System
IC	-Ion Chromatograph
Ic	-Indirect Costs
LMB	-Limpopo Mobile Belt
L.O.I	-Loss on Ignision
MMSD	-Mining, Minerals and Sustainable Development
NMZ	-North Marginal Zone
PGM	-Platinum Group Minerals
pH	-Potential of Hydrogen
QSPM	-Quantitative Strategic Planning Matrix
SMZ	-South Marginal Zone
SWOT	- Strengths, Weaknesses, Opportunities, and Threats
RTK	-Real time kinetics
TDS	-Total Dissolved Solids

TSS	-Total Suspended Solids
WDS	-Wet Dry Season
XRF	-X-Ray Fluorescence

LIST OF ELEMENTS AND COMPOUNDS

Al	-Aluminium
Al_2O_3	-Aluminum oxide
Ca	-Calcium
CaO	-Calcium oxide
Cr	-Chromium
Cl^-	-Chlorine
CO_2	-Carbon dioxide
Fe	-Iron
F^-	-Fluorine
Fe_2O_3	-Iron (III) Oxide
FeO	-Ferric Oxide
H_2O	-Water
K	-Potassium
Mg	-Magnesium
MgO	-Magnesia
Mn	-Manganese
Na	-Sodium
NO_3^-	-Nitrate
P	-Phosphorus
PO_4^{3-}	-Phosphate Ion
Si	-Silicon
SiO_2	-Silica
SO_4^{2-}	-Sulfate Ion
Ti	-Titanium

GLOSSARY OF UNITS OF MEASURE

cm	-centimeter
µS/cm	-microSiemens per centimeter
m	-metre
m^2	-square metre
m^3	-cubic metre
mS/cm	-millisiemens per centimetre
mm	-millimetre
ppm	-parts per million
%	-persent
°	-degree
kg	-kilometer
hr	-hour
ha	-hectare
l	-litre
min	-minutes
R	-rand

CHAPTER ONE

INTRODUCTION

1.1 Statement of the Research Problem

South Africa has a large and well established mining industry with approximately 860 000 employees. Its economy has been dominated by its mineral wealth for more than a century (SouthAfrica.info, 2010). The country's mining sector is characterized by a wide range of commodities such as Platinum Group Metals (PGM), manganese, gold, chromium, vanadium, zirconium and titanium.

In the Limpopo Province, mining is considered to be a premier economic sector with not less than 136 mining operations (Trade and Investment Limpopo, 2008). Commodities mined in the province include diamond, iron ore, copper, middle-grading coking coal and phosphate. According to Cradit-Guarantee (2010), Limpopo province employed 13% (64118 employees) of the overall South Africa's mining labour force. Other important minerals found in the province include platinum group metals (PGM), chromium, and antimony. In addition, emeralds, scheelite, magnetite, vermiculite, silicon, and mica mineral reserves as well as base commodities such as black granite, corundum and feldspar are also found in this province. However, if mining sites are poorly rehabilitated or abandoned; they tarnish the reputation of the industry and this is considered a legacy of mining (MMSD, 2002; Australian Government, 2006).

Abandoned mines are commonly the result of lack of care and planning in the past practices and they are linked directly to regulations which were inadequate as a result of the lack of detailed understanding. These mines are commonly found in all regions with a long history of mining such as South Africa with a history of mining that span for more than 120 years (MMSD, 2002; Davenport, 2006). According to Montgomery (2003), reclamation is more costly to mining companies than leaving spoils banks behind and in some cases even if reclamation measures are made; it may be difficult to achieve the anticipated end results. The costs and the liabilities of conducting proper closure and rehabilitation are normally inherited by the government, host community and the society

at large; that the mines are suddenly derelicted (Australian Government, 2006; Trembay and Hogan, 2006).

Abandoned mines throughout the world remain a major concern due to their associated physical, environmental and public safety concerns. The physical concerns include public health and safety, visual impacts, stability issues and dust emission problems. On the other hand, environmental issues range from abandoned spoil heaps and tailing facilities, contaminated aquatic sediments, subsidence, burning coal waste dumps and working, derelict work sites with compacted and polluted soil, and change in vegetation (MMSD, 2002).

Although abandoned mines in South Africa pose noticeable threats to the environment and public health and safety, very little has been done. Consequently, these old orphaned/abandoned mine sites have mounted as potential site for small scale mining practices with severe environmental impacts; especial the abandoned gold mines. Increases in environmental stresses raise public safety issues, environmental concerns and social risks problems. Like all countries with long history of mining, South Africa has a large number of abandoned mines (MMSD, 2002).

Currently, the government through integrated and co-operative approach embarks on rehabilitation of hazardous asbestos mines; waste dumps facilities and hazardous abandoned gold mines shafts in the Witwatersrand goldfields. In the year 2004 and 2005, the Department of Minerals and Energy rehabilitated about 60% of the 578 existing asbestos dumps located around Limpopo, Northern Cape, and North West provinces (GCIS, 2005). Generally, the rehabilitation of the abandoned mines in South Africa is on the health hazards priority base, where most hazardous abandoned mines receive more attention on rehabilitation. Despite the rehabilitation of asbestos and gold mines, the rehabilitation of abandoned uranium mines was initiated in the Karoo and Free State between 2006 and 2007 (GCIS, 2007).

Generally, insufficient understanding of the problems associated with the abandoned mines has led to lack of effective designs for their rehabilitation. There is, therefore, a pressing need for development of modeling framework that will create low-cost and appropriate rehabilitation strategies for abandoned mines. Such an approach will serve as guidelines for future land use in the area.

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1.2 Objectives of the Research

1.2.1 Main objective

The primary objective of this research was to develop a modeling framework for the design of low-cost and appropriate rehabilitation strategies for the abandoned Nyala Magnesite Mine.

1.2.2 Specific objectives

This research specifically aims:

- to conduct a comprehensive site investigation and characterization of the abandoned mine site.
- to create terrain models for the development of optimum rehabilitation land form designs.
- to design low-cost and appropriate engineering strategies for controlling the environmental impacts and physical hazards at the mine site.
- to estimate cost of alternative rehabilitation strategies.

1.3 Research Questions

Abandoned mines are associated with severe environmental stresses that vary across the different mining methods and the commodities mined. Therefore, there is a pressing need for this research to address the following principal research questions.

- What is the nature and extent of the physical and environmental hazards associated with Nyala Mine?
- What are the chemical and physical properties of the tailing materials that directly or indirectly affect the vegetation growth hence influencing the material dispersion to the surrounding environs?
- Are there existing means of public exposure to the hazards presented by the abandoned mine site?
- Can digital terrain models of the mine site be developed from the RTK-GPS height data?
- What are the appropriate strategies for rehabilitation of the abandoned Nyala Mine?

- Can low-cost rehabilitation strategies be developed from the current surface model of the mine site?
- What will be the volume of waste materials to be cut and the size of voids to be filled for rehabilitation of the rugged terrain of the mine?
- What will be the cost of the alternative rehabilitation strategies for the mine?

1.4 Hypothesis

This research focused on assessing in detail the environmental stresses and development of rehabilitation strategies of the Nyala abandoned mine. It was aimed at satisfying the following hypothetical statements.

- The nature and extent of physical and environmental hazard associated with the abandoned Nyala Mine can be determined using site investigation and characterization technique and scoring of individual mine features.
- Terrain model of the mine site can be developed using the RTK-GPS height data for the analysis of different landform designs for rehabilitation of the mine site.
- Through detailed site characterization and development of the mine site terrain models, low-cost rehabilitation strategies can be developed.
- The total cost of rehabilitation work of the Nyala Mine can be determined by identifying and determining the costs of the various rehabilitation elements.

1.5 Significance of the Study

This study was aimed at developing a framework for the design of appropriate rehabilitation strategies for the derelicted Nyala Mine. This will have several benefits to both the public and the environment. The assessment of environmental stresses and physical hazards of the Nyala Mine will assist in determining the nature and extent of environmental problems due to historical magnesite mining operations in the area.

Development of rehabilitation strategies for the mine site will have positive impacts on the neighboring or host community and the state as it will provide alternatives for addressing the problems associated with the mine, hence appropriate post mining land-use plans may be developed for the site. One of the objectives of this research was to

establish the cost of alternative rehabilitation approaches for the derelict mine. This will assist in budgeting for the rehabilitation of the abandoned mine site once funds are made available for this purpose.

There are so many abandoned mines in the province and not much information with regard to the nature and extent of the problems they present are known. There is no doubt that they are in deplorable state and will certainly need to be given attention. In this regard similar study will be conducted in future so as to compile a comprehensive inventory of abandoned mines in the province. Considering that funds are not even available for this purpose and other resources are limited, scoring of historical mine sites will assist in prioritizing rehabilitation of these mines.

This study will also contribute to the national abandoned mines rehabilitation programme in that the designed models and knowledge generated will serve as a framework or guideline for selection of appropriate rehabilitation strategies at other abandoned mined sites in the country.

1.6 Description of the Study Area

This section provides description of the selected study area in terms of geographical location, the topographical relief and drainage pattern, land-use and vegetation cover, climatic condition, and regional geology.

1.6.1 Geographical location of the study area

The study area is located at Zwigodini Village at the co-ordinates of 22° 45' S to 22° 33' S (latitude) and 30° 36' E and 30° 39' E (longitude). It is situated at approximately 50 km North East of Thohoyandou and 31 km South East of Musina town. The Nyala Magnesite Mine is generally situated in the north-eastern corner of the Limpopo Province at about 65 km from the Pafuri gate of the Kruger National Park. Figure 1.1 illustrates the geographical location of the study area and some of the major towns of the Limpopo province of South Africa.

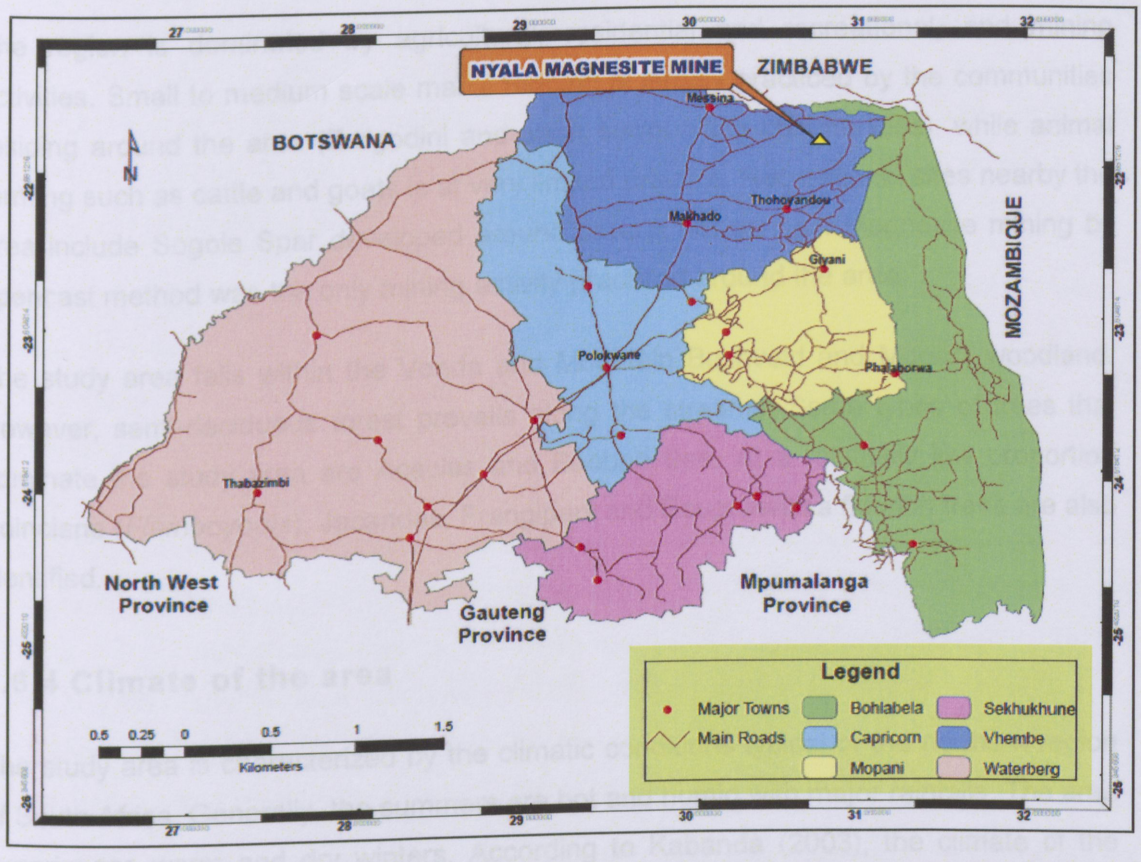


Figure 1.1: *Geographical location on the study area.*

1.6.2 Topography and drainage pattern

The topographical relief of the study area is fairly flat and characterized by scattered outcrops of relatively small hills towards the West and the South. Gently-undulating slopes occurring as an influence of development of valleys around the area also prevails. The altitude at Zwigodini village and the surrounding areas ranges between 460 to 667 m above the main sea level.

The study area falls under Mutele River catchment and is characterized by very few perennial tributaries that flow next to the abandoned Nyala Magnesite Mine (Among others, they include Mbodi and Klein Tshipise). The community around the mine, wild life and domestic livestock depends on water from Mutele River, boreholes and other reservoirs providing water throughout the year. During rainy seasons, small tributaries recharge the aquifers with enough water which later on discharges by fountains as ground water (Nemakundani, 2009).

1.6.3 Land-use and vegetation cover

The region is dominated by agricultural, residential and recreational, and mining activities. Small to medium scale maize farming is largely practiced by the communities residing around the area (Zwigodini and other surrounding communities), while animal farming such as cattle and goats is at very limited practice. Recreational sites nearby the area include Sogole Spar developed around natural hot springs. Magnesite mining by opencast method was the only mining activity practiced around the area.

The study area falls within the Venda arid Mountain Bushveld and Mopani woodland. However, semi-deciduous forest prevails along the streams. Some types of trees that dominate the study area are Acacias and Baobab tree. At a relatively low proportion Poinciana (*Flamboyouts*), Jacandas, Frangipani and Bougainvillea flourish trees are also identified.

1.6.4 Climate of the area

The study area is characterized by the climatic conditions typical of the northern region of South Africa. Generally, the summers are hot and humid with major rainfalls. The area experiences warm and dry winters. According to Kabanda (2003), the climate of the study area and the Soutpansberg region as a whole can be categorized into Warm Wet Season (WWS) and Cool Dry Season (CDS). The WWS is characterized by warn temperatures that range from 16 °C to 40 °C and the maximum rainfall that span for approximately 182 days (from April to October). The CDS is characterized by temperatures ranging from 12 °C to 22 °C and maximum rainfall of 2000 mm (Kabanda, 2003). Generally, the semi-arid areas of the Soutpansberg experiences wind erosion in August.

1.6.5 General geology

The area falls within the Tshipise Straightening Zone at the southern periphery of the Central Zone of the Limpopo Mobile belt (LMB). Generally, the Central Zone comprise dominantly of high grade metasediments which are interlayered with quartzofeldspathic gneisses and mafic rocks (collectively known as Beit Bridge Complex). These rocks are lithologically subdivided into three groups; namely, Mount Dowe, Malala Drift and Gumbu Groups in their order of younging. The Mount Dowe Group mainly consists

dominantly of quartzite, magnetite quartzite and metapelitic gneiss, with intercalations of quartzofeldsphic gneiss. Comparatively, the Malala Drift is dominated by quartzofeldspathic gneisses with minor quartzite, magnesite quartzite and metapelite, while the Gumbu Group is characterized predominantly of marbles and calc-silicate rocks with minor fine-grained metapelite and metapsammite (Kramers *et al.,* 2006).

The other two domains of the belt are Northern and Southern Marginal Zones as presented in Figure 1.2. The NMZ is dominated by granulite facies orthogneises comprising dominantly of quartz diorite to trondhjemite and grano-diorite rocks (collectively referred to as charnockite-enderbite gneisses) (Kamber *et al.,* 1998; Ridley, 1992). Along the south, the SMZ is characterized by high grade grannelite facies of the Bandelierkop Complex consists of quartz, plagioclase, orthoclase, garnet, biotite, and cordierite, with less common K-feldspar, spinel, sillimanite and kyanite. Generally, the rocks of the Limpopo belt attain a maximum width and length of approximately 200 km and 700 km respectively. It is sandwiched between the Zimbabwe and Kaapvaal Cratons as shown in Figure 1.2 and both eastern and western ends of the belt are masked by Precambrian and Phanerozoic cratonic cover sequences (Kramers *et al.,* 2006).

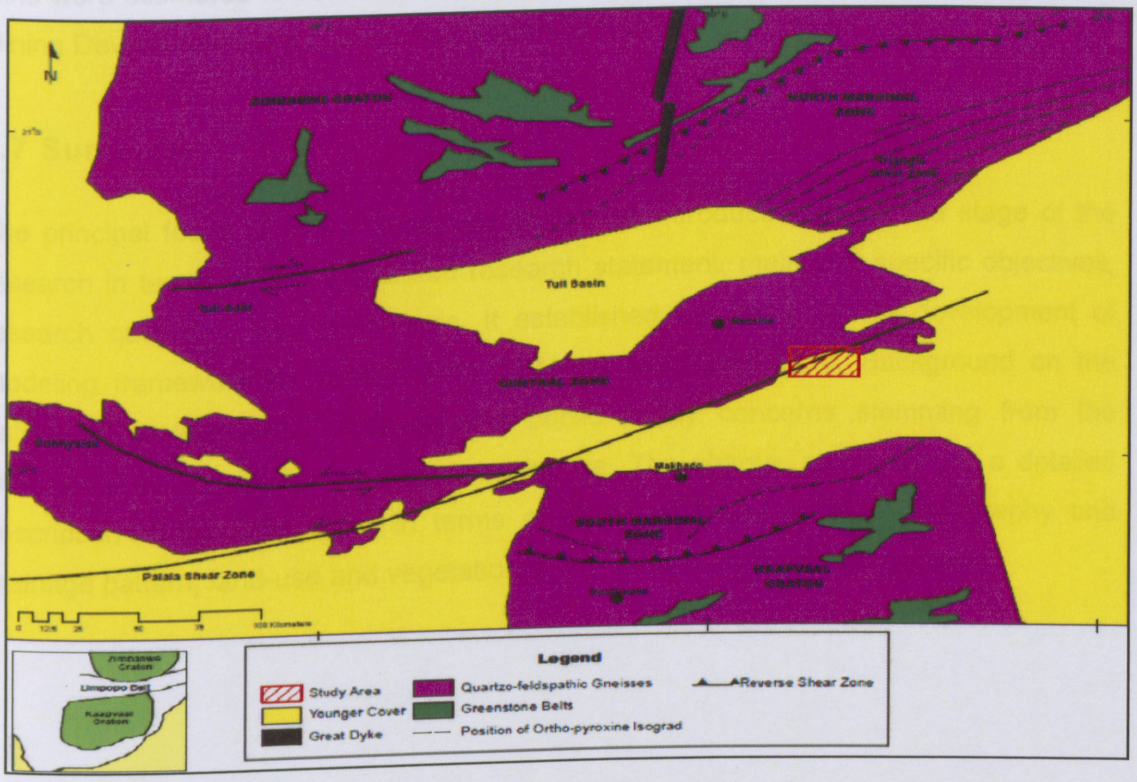


Figure 1.2: *Simplified geological map of the Limpopo Belt and its adjacent craton (modified after Kramers et al., 2006 and Chinoda et al., 2009).*

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According to Kramers *et al.* (2006), the Tshipise Zone over its length is covered by Soutpansberg sediments (1800 Ma) and Karoo basalts. The rocks of the Soutpansberg rest unconformably on archaean granulite-grade gneisses, Blouberg Formation and possible on the Mogalakwena Formation of the Waterberg Group. Towards the east and along the periphery at the north, these rocks are overlain unconformably by the rocks of the Karoo Suppergroup (Barker *et al.,* 2006). Lithostratigraphically, the Soutpansberg rocks can be divided into Tshifhefhe, Sibasa, Fundudzi, Wyllie's Pllrt, Musekwa, Ngwanedzi and Nzhelele Formations (SACS, 1980; Brandl, 1999).

The magnesite deposit in the study area is hosted by metamorphosed ultrabasic and calcareous rocks of the Limpopo Belt. This deposit covers an area extending for about 50 km east-north of Tshipise. It is of amorphous in nature and occurs as veins and irregular masses that were derived by weathering from olivine-rich rocks; these area limburgite rocks of the Drakensburg Stage of the Stormberg Group of the Karoo. Other similar deposits of little economic importance occurring around the area includes the deposits occurring within pyroxinite and veins of crystalline, within the vicinity of Musina and Mopane districts. However, most of the magnesite deposits of the country are of amorphous in nature (Herzberg, 1976). In addition, the magnesite reserves at Nyala Mine were estimated to be about 270 000 tons at 21 m depth in 1965 (The Mineral and Mining Development in the Black Homelands of South Africa, 1977).

1.7 Summary

The principal focus of this chapter was to provide introduction to set the stage of the research in terms of well articulated research statement, main and specific objectives, research questions, and hypothesis. It established the need for the development of modeling framework for rehabilitation of Nyala Magnesite Mine. Background on the nature of environmental stresses and public safety concerns stemming from the abandoned mining sites was given prominence. The chapter also provides a detailed description of the study area in terms of its geographical location, topography and drainage pattern, land-use and vegetation cover, climate, and general geology.

1.8 Operational Definitions

An easy understanding of the work presented in this dissertation depends on clear understanding of some terms and concepts as they are used in the research. This section therefore presents the definitions of the key terms and concepts that form part of this dissertation.

- *Abandoned/orphaned mine:* a mine is 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 indefinitely advanced exploration, mining, or mine production on the site, without rehabilitating the site.

- *Inactive mine:* a mine is considered inactive if there is an identifiable owner or operators of the facility, but the facility is not currently operating and there are no approved authorization or permits to operate.

- *Rehabilitation:* refers to the measures and actions used to remediate land disturbed by mining operations and/or exploration activities. It can also be defined as the process of making a former mine site safe, stable and self-sustaining.

- *Indirect costs:* indirect costs are those costs incurred by an organization for common or joint objectives, and which cannot be identified specifically with a particular activity or project.

- *Direct costs:* direct costs are any cost that can be specifically identified with a particular project or activity, including salaries, travel, equipment and supplies directly benefiting the project or activity.

- *Physical hazards:* a factor within the environment that can harm the body without necessarily touching it.

- *Spoil:* the overburden and non-ore material that has been removed during excavation to gain access to the mineral deposit.

- *Dirt Park:* an area of land designed for bicycle racing on a dirt track with berms and jumps made up of loose earth or soil.

1.9 Organization and Structure of the Dissertation

This dissertation is arranged into seven (7) chapters all contributing to the objectives of this research. *Chapter One* serves as an introduction of the dissertation, while *Chapter Two* presents the synthesis of the literature relevant to the main aims of this research. The description of the methods, tools and procedures employed during data acquisition aspect of this research is presented in *Chapter Three. Chapter Four* is earmarked for the presentation and interpretation of the mine site characterization data. Terrain modeling and design of the abandoned Nyala mine rehabilitation strategies is presented in *Chapter Five* whilst *Chapter Six* focuses on the development of engineering cost estimated of various rehabilitating alternatives. *Chapter Seven* presents the conclusion and recommendations for further research and development.

CHAPTER TWO

LITERATURE REVIEW

Modeling framework as well as design of rehabilitation strategies for an abandoned mine requires general overview of environmental and physical impact associated with both mining and processing activities. Consequently, the principal focus of this chapter is to synthesize the literature relevant to the research. The literature review is broadly organized into the nature and the description of South Africa's magnesite deposits, general description of magnesite mining techniques, legislative framework, environmental issues associated with abandoned mines, health issues associated with exposure to magnesite dust, environmental assessment strategies, approach for rehabilitation of open pit mines, rehabilitation cost estimation, and digital terrain modeling.

2.1 Nature and the Distribution of Magnesite Deposits in South Africa

Magnesite makes up some portion of rocks; it is commonly formed from the alteration of magnesium-rich rocks during the low grade metamorphism. Although it shares the same crystal structure with calcite, it differs in one respect; the magnesium ion does not allow the Carbon ion (CO_3) to interact easily with cold acids, as the Calcium ion does in calcite. It is theoretically composed of 47.7% magnesia (MgO) and 52.4% (CO_2) (Kramer, 2006; Cardavelli, 2008). Pure magnesite is dead white. However, the presence of impurities might change its colour to yellow, grayish white or brown. Economical deposits of this mineral are mainly found occurring in two forms namely; compact/amorphous or spathic/crystalline. Generally the amorphous magnesite occurs in veins, pocket and irregular masses as the decomposition product of ultrabasic rocks, notably serpentinised rocks (Kogel *et al.,* 2006). However, other deposits in the Ntabayezulu area (KwaZulu-Natal) occur as encrustations within the lavas of the Lebombo Group (Mintek, 2007). Magnesite is characterized by the hardness of 3.5 to 5 and the specific gravity of about 3 (Herzberg, 1976).

South Africa's economically viable deposits; mainly found in Mpumalanga (in the vicinity of Malelane area) and Limpopo (mostly in the area to the north of Soutpansberg,

Burgersfort, and Giyane district) Province. Magnesite occurs as weathering product of rocks with high magnesium content. Most of these deposits are mined and sold as crude material (80%) to the local farmers as farm feed or fertilizer additives; in the north of Soupansberg, while the rest (20%) is exported (Ratlabala, 2003). The country's overall annual production range was at 65 kt in 1994 to 2000 and it dropped to 35 kt in 2001 (Ratlabala, 2003; Kogel *et al.,* 2006). Currently the South Africa major magnesite producers include Strathmare, Syfenrtein mines and Magnesite Mining; respectively producing various magnesite products at Malelane, Waterberg and Thohoyandou. The magnesite obtained from main magnesite fields of the country comprise of the major oxides presented in Table 2.1. These include quartz (SiO_2), Aluminum Oxide (Al_2O_3), Iron Oxide (Fe_2O_3), Iron Oxide or Ferrous Oxide (FeO), Magnesium Oxide (MgO), CaO, water (H_2O), and Carbon dioxide (CO_2).

Table 2.1: *Composition of main magnesite deposits in South Africa (Modified From Herzberg, 1976).*

Composition	Magnesite Main Producing Areas			
	Lydenburg Area (%)	*Kaapmuiden Area (%)*	*North of Soutpansburg (%)*	*Letaba District (%)*
SiO_2	1.44	2.43	2.01	1.89
Al_2O_3	0.67	0.53	0.25	0.27
Fe_2O_3	–	–	0.18	0.07
FeO	–	–	0.08	–
MgO	45.30	45.88	45.10	46.21
CaO	1.48	0.10	1.34	0.88
H_2O	0.40	0.40	51.00	50. 03
CO_2	51.71	50.66		
Total (%)	*101.00*	*100.00*	*99.96*	*99.40*

2.2 Magnesite Mining and Processing Techniques

Mining can be defined as an activity, occupation, and industry concerned with the extraction of any naturally occurring mineral substance (solid, liquid, and gas) from the earth or other heavenly bodies for utilitarian purposes. This practice involves the use of underground and surface mining techniques. Generally, the overall sequence of activities in modern mining is often compared with the five stages in the life cycle of the

mine: namely, prospecting, exploration, development, exploitation, and reclamation. The closure and reclamation stage was added as one of the necessary part of the life cycle of the mine because of the demands of society for a cleaner environment and present stricter laws regulating the abandonment of mines.

The nature of the deposit determine the type of mining method to be adopted, for example large, massive, near surface deposits are usually worked by surface mining method (open pit or open cast), while the narrow and deep deposits are worked by underground drifts and stopes. Magnesite deposits of economic potential around Venda area (Folovhodwe) were described by Paul *et al.* (1997), to be suitable for artisanal mining due to its occurrence as soft clay-like matrix above the water table. However, according to Mintek (2007) magnesite deposits throughout the country are generally mined by open cast method.

2.2.1 Magnesite mining

Depending on the anticipated reserves, kind of ore body, overburden, geological conditions and many more; magnesite mining can be either by underground or surface methods. However, in some cases combined methods are employed. Underground mining method has been used to some extent in the early development of many magnesite mines throughout the world. Lately, the use of this method is at minimal level. It is only identified in places such as Australia and former Yogoslavia (Slovenia, Macedonia, Croatia, Montenegro, Kosovo, and Bosnia) where the mountain topography and the thickness of the overburden do not support surface mining (Wicken, 1990). Generally, underground mining methods employed in magnesite mining (in the case of large magnesite bodies) largely resemble those used in limestone mining. Room and Pillar underground mining techniques with power loaders and trucks are mostly used in underground magnesite mines (Wicken, 1990).

Open pit mining is the most preferred method for magnesite deposits which are at shallow depth. According to Lackner *et al.* (1997), the occurrence of magnesite deposits as large shallow bodies extending over a wide area while reaching greater depth making it possible to mine by deep open pits. The stripping of overburden, establishment of benches, and the patterns of ore removal are guided by the information from exploration and mapping programs. Power shovels, trucks, scrapers, and front-end loaders are used in carrying out stripping and ore removal. For example, tractor loader backactors (TLBs)

were used to expose the magnesite seams to the collectors who gathered the materials in piles of about 2 t which were eventually transported by trailer to the bunkers (40 and 100 t) at Venmag Magnesite Mine in the vicinity of the Folovhodwe northwards of Thohoyandou (Paul *et al.,* 1997).

Open pit mining method is highly adopted where the ratio of waste and overburden to ore is moderate (Wicken, 1990). According to Cardavelli (2008), all magnesite deposits are mined by open pit mining method at a relatively high stripping ratio. According to Ratlabala (2003), currently South Africa has only two operating magnesite mines namely, Strathmore (owned by Chamotte Holdings) at Malelane and Syferfontein (owned by Syferfontein Calcite) in the vicinity of Soutpansberg district. In both Syferfontein and Strathmore mines, magnesite is mined by surface mining methods.

According to Kogel *et al.* (2009), the mined magnesite ore is rarely shipped or used as crude form. It is normally processed near the mine site to yield magnesia products. Inventably some degree of sorting or beneficiation is applied to the ore prior to heat treatment.

2.2.2 Magnesite processing

The simplified unit operations in magnesite processing can be divided into crushing, sizing and beneficiation (Shand, 2006). The magnesite hoisted to the surface is normally hand-cobbed by the work force of about 25 to 30% of the total labor. The hand-sorting includes trimming of the ore from siliceous impurities and of remnant of serpentine that adhere to the magnesite. However, the ore is furthermore broken up into lumps of the required sizes (Paul *et al.,* 1997). Since gas works require magnesite grains that range between 50.8 to 101.6 mm in diameter. Generally, the processing of magnesite ore begins with crushing, screening and washing (Cardavelli, 2008).

2.2.3 Magnesite ore calcinations

Calcination is the decomposition endothermic reaction by which chemically combined water of hydration and carbon dioxide is removed. This process is carried out for many commercially important materials such as dolomite (calcium carbonate), bauxite, magnesite, and phosphate rocks. It is normally carried out in a shaft kiln or rotary kiln (Gupta and Sathiyamoothy, 1999). According to Paul *et al.* (1997), Venmag Magnesite

Mine which is adjacent the Nyala Magnesite Mine used two methods in obtaining calcined magnesite products. The first method includes firing of kilns filled with washed and upgraded material with coal while, the second adopted method included the labour intensive primitive method mostly used in bricks firing. In this second method the magnesite and coal are piled in layers into a box-shaped heap and sealed with clay prior to the ignition at the bottom of the heap.

The theory of limestone calcinations is applied in magnesite due to that the magnesium carbonate calcinations has not been studied in detail. The heating of magnesite results into the release of CO_2 and the formation of magnesium oxide as shown in equation 2.1:

$$MgCO_3 \rightarrow MgO + CO_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

Important factors in magnesite decomposition kinetics are the magnesite rock has to be heated to the decomposition temperature, this minimum temperature must be maintained for a certain duration; until the magnesite has been essentially decomposed to magnesium oxide, and the CO_2 gas evolves during the decomposition has to be removed from the kiln to increase the rate of decomposition (Shand, 2006).

2.3 Causes of the Abandoned Mines

The MMSD (2002) stated the economic, technical, national security and others such as regulation, loss of mine data, politics unrest, and small scale mining listed by the WOM Geological Associates (2000) to be having created the legacy of abandoned mines in Canada. This section presents the contribution of these factors on the abandonment of mines in Canada as stated by the MMSD (2002).

According to Moon *et al.* (2006), the opposition from environmentalists to exploration and mining operations contributed to the abandonment of a major copper mining project in the Snowdonia National Park in the vicinity of Wales during 1973. The other serious factor that contributed in the abandonment of most gold-shafts on the Witwatersrand was the depletion of a resource or change in market conditions that led to mines not being financially viable (Davenport, 2006). However, the majority of officially listed abandoned mines in South Africa ceased operation prior to 2002 when Mineral and Petroleum Resources Development (MPRD) Act 28 of 2002 came into effect (Auditor-General South Africa, 2009). Mines can be abandoned due to natural processes such as flooding. Mining operations along the Gulf of Maxico (state of Louisiana), dry mines in

Larraine (France) and potash mines in the northern Germany are typical examples of mine abandonment as a consequence of flooding (Berest *et al.,* 2004).

2.4 Abandoned Mines Issues in South Africa

South Africa with its long history of mining that span for more than a century has a number of mines that were improperly closed and even abandoned (Sustainable Development Through Mining, 2007). According to Davenport (2006), the abandoned mines, quarries and small scale operations scattered throughout the country add up to 8000. Following the dedicated verification; owners of some of this mines were identified, others became operational, while some were duplications. Consequently the database consisting of 8000 entries was reduced to 5445 (Sustainable Development Through Mining, 2007).

The Auditor-General South Africa (2009) mentioned that as per the report submitted to DME by the Council for Geosciences (CGS) the official listed abandoned mines in South Africa were 5906 by May 2008 and about 1730 of them were classified as high risk mines. In addition, Munnik *et al.* (2009) also mentioned that the abandoned mines of the country are approximately 6000. Limpopo Province abandoned gold, platinum, diamond, ferrous and base metals, and industrial minerals add up to 729 as presented in Figure 2.1.

According to Auditor-General South Africa (2009), CGS estimated that the required cost of cleaning-up the abandoned mines in the country is R 35 billion. The contraction and operation of plants as well as the long term treatment of acid mine drainage was estimated to take 5 billion of this amount, while approximately 28.5 billion was estimated to be required for the rehabilitation of 1730 high-risk abandoned (Auditor-General South Africa, 2009).

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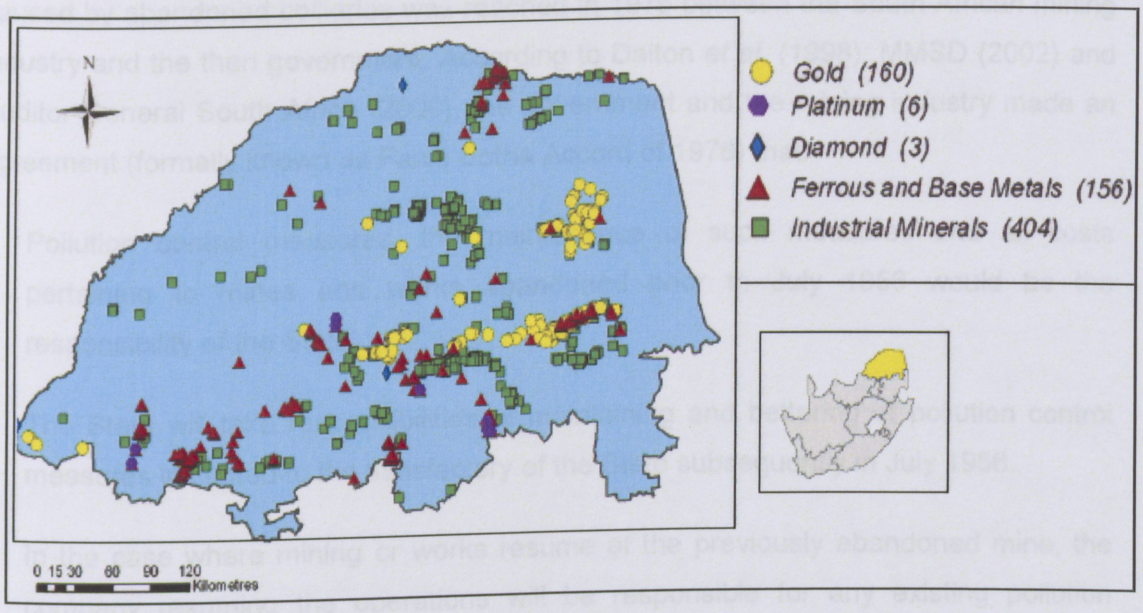


Figure 2.1: *Relative position of the abandoned mines in Limpopo (From Development Through Mining, 2007).*

2.4 Legislative Framework

There are numerous factors that contribute to abandonment of mines. In South Africa the abandonment of mines was primary influenced by previous legislations which rarely placed emphasis on the need for environmental management and rehabilitation (Davenport, 2006 and Auditor-General South Africa, 2009). These laws did not give clear understanding on the requirements for environmental management and mine closure. The provision for mine rehabilitation and closure in terms of the old Mines and Works Act of 1956 did not address the environmental rehabilitation of mines rather; it focused on making the mines safe to protect the public against the hazards that may arise from prospecting and mining operations (Davenport, 2006). Historically, the abandonment of mine sites after the mineral extraction has ceased was a common practice which resulted in these sites being left un-vegetated and exposed, while waste materials were left in piles or haphazardly dumped into mine cavities and pits (MMSD, 2002).

In South Africa many mines were left ownerless prior to the promulgation of the Water Act 54 in 1956. The provision for control of abandoned mines was also provided in the Water Amendment Act 58 of 1997 (MMSD, 2002). According to Limpitlaw *et al.* (2005), before 1956, mine closure was not subjected to any regulative closure requirements.

However, the agreement on the responsibilities and the cost of controlling pollution caused by abandoned collieries was reached in 1976 between the South African mining industry and the then government. According to Dalton *et al.* (1998); MMSD (2002) and Auditor-General South Africa (2009), the government and the mining industry made an agreement (formally known as Fanie Botha Accord of 1976) that:

- Pollution control measures, the maintenance of such measures and all costs pertaining to mines and works abandoned prior to July 1956 would be the responsibility of the State.
- The State will take responsibilities of maintaining and bettering of pollution control measures instituted to the satisfactory of the State subsequently in July 1956.
- In the case where mining or works resume at the previously abandoned mine, the company resuming the operations will be responsible for any existing pollution control measures on the portion which is to be reworked and for any additional pollution control measures required in terms of the resumed operations

Some countries including South Africa have started some means of addressing the problems of abandoned mines. Currently the South African government through the Department of Minerals and Energy (DME) in partnership with Council for Scientific and Industrial Research (CSIR), the Council for Geosciences (CGS) and Mintek has established the Sustainable Development through Mining Progremme as a means of finding solutions for long-term rehabilitation and environmental management of abandoned mines. This programme aims at addressing the derelict and ownerless mines database, the regional mine closures for the Witwatersrand Water Basin, the sustainable development strategy for minerals and mining, mine environmental management guidelines for implementation, monitoring and mine closure, and instruments and tools to assist with decision-making (GCIS, 2008).

Mineral and Petroleum Resources Development Act (28 of 2002) is the main regulation governing mine closure in South Africa. Prior to the passing of this Act, mine closure was governed by the Mineral Act 50 of 1991 which provided a basis for environmental management for the first time (Limpitlaw *et al.,* 2005). Swart (2003) mentioned that prior to this Act many companies used irresponsible mining methods with no regards towards

protecting the environment and dragged rehabilitation until their time of leaving the country.

The promulgation of Mineral and Petroleum Resources Development Act 2002, Act 28 of 2002 led to the creation of Mineral Development Branch comprising of Mineral Regulatory, Mineral Promotion, and Mineral Policy Formulation branches. The principal functions of the Mineral Regulation subdivision is to address past legacies with regard to derelict and ownerless mines and enforce legislation regarding mine rehabilitation by means of regulated environmental management plans which forms an integral part of the mineral-resource management. On the other hand, the principal focus of the Mineral Promotion and Policy Formulation branches is to formulate and promote mineral related policies that will encourage investment into the mining and mineral industry thus making South Africa attractive to investors. The Mineral Promotion branch; furthermore, promotes mineral development and advice on trends in the mining industry to attract investors (DMR, 2011).

The Mine Environmental Management which forms a section or integral part of the management of mineral and petroleum resources; primarily focuses on the approval and monitoring of the execution of environmental management plan and the environmental management programmes (GCIS, 2010). It also aim at strengthening the enforcement of preventing the occurrence of mining legacies, and identifying mine-pollution 'hot-spot' and implementation of appropriate additional measures, norms and standards for addressing and managing pollution within such areas. Finally, to address issues pertaining to rehabilitation of abandoned and ownerless mines (GCIS, 2007).

2.5 Environmental Impacts of Abandoned Mines

The problems of abandoned mines take two significant dimensions; which are environmental impact, and the cost of environmental protection (Chao and Peck, 1999). Generally, abandoned mine sites (regarded as the negative legacy of mining) always emerge as major environmental, social and economic problems in all countries with long and rich history of mining. Common physical impacts associated with abandoned surface mine sites include altered landscape; unused pits; altered soil quality (pH) or slopes; abandoned tailings dumps; changes in groundwater regime; contaminated soils and aquatic sediments; and changes in vegetation cover. These problems also have associated social and economic impacts on affected countries and communities. This

arises as the consequence of loss of productive land, degradation of both ground and surface water by sediments or salts; negative impact of contaminated sediments to aquatic species; changes in river regimes; air pollution from dust or toxic gases; risk of falls into derelicted pits; and occurrence of landslides. It is widely acknowledged that abandoned surface and underground mines have severe impact on local communities and the environment. Although the impact of the abandoned mines varies from one site to the other in terms of the type and degree and the commodity mined. The most common impacts of these mines on the environment include reduction of water (both surface and ground) and air quality; and contamination of the soil (MMSD, 2002).

2.5.1 Impacts of abandoned mining sites on water quality

Water is regarded as the main conduits by which pollutants from abandoned sites can get carried away; consequently abandoned mines emerges as major source of reduced water quality. The chemistry of mine water varies greatly and their effect differs. For example; drainage from the mine may be alkaline, moderately or high saline, alkaline and ferruginous, or acidic and ferruginous (National River Authority, 1994). Generally, increased levels of metals, suspended solids, hydrocarbons, and brine leaching as common mine water pollutants also pose severe threats to surface and ground water. A common water problem in all derelicted mines in sulphide deposits is Acid Mine Drainage (AMD). It is produced where iron sulphide minerals (among others pyrite, chalcopyrite, chalcocile and galena) are exposed to air in the present of water. This exposure converts the relatively salable sulphide materials into soluble sulphuric acid and iron compound. The use of the water from the abandoned magnesite mine site for irrigation purposes turn to have potentials for aggravating the process of salinization, which is the alteration of soil to alkaline. The alkaline soil consisting of sodium carbonate (Na_2CO_3), sodium bicarbonate ($NaHCO_3$) and sodium silicate ($NaSiO_3$) is normally characterized by EC (electric conductivity) greater than 400 $mS*m^{-1}$, ESP (Exchangeable Sodium Percentage) (von der Meden, 1969; Jozef, 2002).

South Africa has many operating and abandoned mines of which water drainage from them pose serious negative effect on the receiving surface and underground water bodies thus affecting the aquatic ecosystem. These sites expose materials that alter the originally harmless water to hazardous waste that pollute both surface and ground water (Griffith *et al.* 1995). Common water quality changes include increased total dissolved solids (TDS), total suspended solids (TSS), sulphate, and hardness and trace metals,

and reduction in dissolved oxygen and pH. Some of these effects can be evidenced at a significant distance from the source of pollution even some years after the mining has ceased.

2.5.2 Impacts of abandoned mines on air quality

The environment around either active or abandoned mine is often characterized by air-borne dust which emerge as a primary air pollutant. In abandoned mines, the disturbed land, spoil dumps, and tailing dumps are the major sources of dust. This is due to strong winds blowing finer particles from exposed surface of the land and eventually disposes them at relatively extensive areas. The public exposures to excessive dust from the mining sites give rise to the problem of pneumoconiosis diseases. Most old tailings dumps; especially in semi arid areas in south Africa are associated with highest levels of dust thus they provide highest wind erosion (Blight, 2007). The severity of these diseases depends largely on the quantity, quality and size distribution of air-borne dust, period of exposure and susceptibility of the individual subjected to exposure (Manoj and Prasannakumar, 2002). Dust settling out also affect the crops (especial cotton and chilly crops) cultivated around the mining area. According to Prasannakumar and Manaj (1998), dust particles interfere with the process of photosynthesis by obstructing the incident rays from the sun required for the process. Dust dispersion can be a serious nuisance and health hazard to inhabitants as well as animals nearby settlements. It is also associated with other environmental problems such as degradation of crops, pollution of soil; surface; and ground water (Blight, 2007).

2.5.3 Land degradation due to surface mining

Land degradation is a major direct environmental impact of mining. Apart from air, water and other pollution problems caused by surface mining, it also renders the problem of land degradation unless it is restored or rehabilitated (Poithanker, 2000). According to Singh *et al,* (2007) deforestation, siltation, excavations, waste dumps, and soil quality are causes of land degradation associated with surface mining. Changes in topography associated with surface drainage with the potential for increased soil erosion, long-term compaction, reduced agricultural capacity is one of the environmental changes associated with surface mining that were identified by Brink *et al.* (1990) to be associated with surface mining (MMSD, 2001).

Generally, topography changes are the result of digging of open pits and dumping of overburden rock mass in the form of the heap (Singh *et al.*, 2007). However, the process of construction, erection and commissioning new mining infrastructure often results in large-scale alteration of the environment, particularly at landscape (MMSD, 2001). Consequently, the extensively mined terrains usually do not possess sufficient surface soil to anchor plants, hence even when plant growth does take place; it is inhibited by the presence of toxic metals.

2.6 Public Health and Safety Hazards Associated With Abandoned Mines

2.6.1 Safety Hazards of Abandoned Mines

Most abandoned mines are located relatively close to residential areas and therefore they pose a certain degree of hazard to their host communities. Figure 2.2 illustrates the correlation between the South African abandoned mine site and the population density.

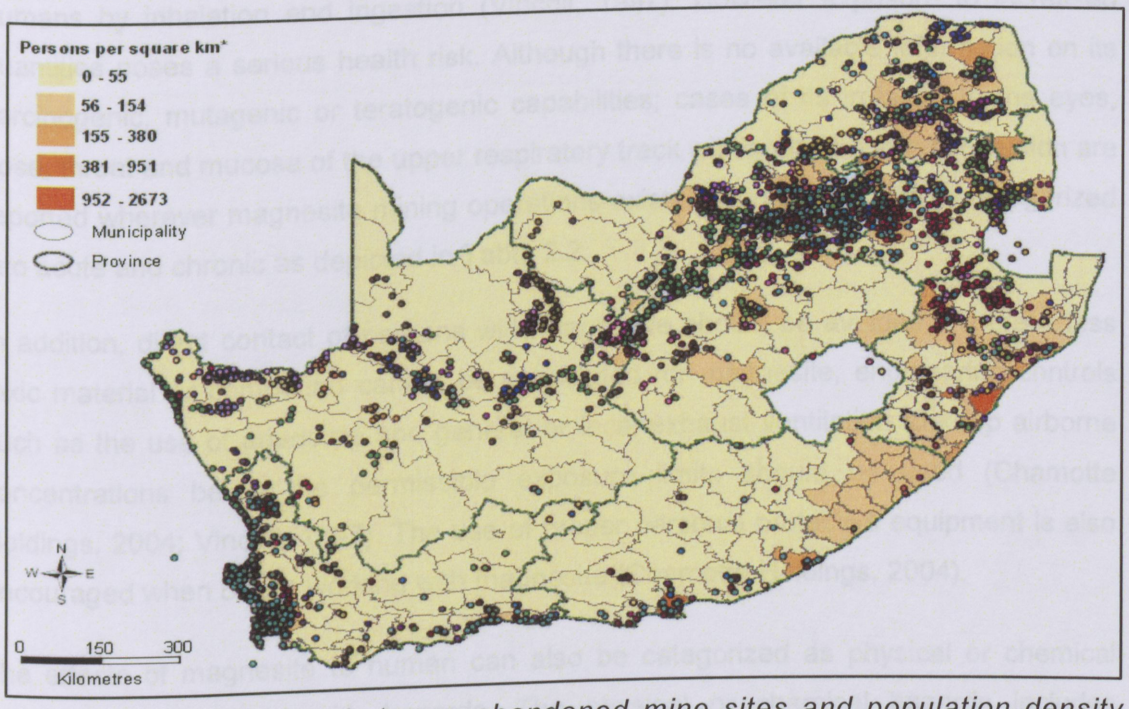


Figure 2.2: *Correlation between abandoned mine sites and population density (From Auditor-General South Africa, 2009).*

Dangers and hazards of abandoned mines include poisonous or explosive gases, oxygen deficiencies, flooded sections, unstable roofs, hard-to-see vertical shafts, venomous fauna and disorienting mazes of mine workings. These might lead to injuries

or death of adventurer who enters abandoned underground mine workings. In the case of open pit or cast dangerous conditions are associated with highwalls; dumps, stockpiles and spoil heaps; and water hazards. The abandoned highwalls and dumps, stockpiles or spoil heaps pose threats to the public thus their slopes are unstable and prone to collapse. On the other hand, derelicted pits can be flooded and conceal sharp objects, drop-offs and other abandoned equipment (Knee, 1999, MMSD; 2002). According to Masondo and Lelliot (2010), many abandoned mines kill and injure scores of people every year. Although the media continuously reports on abandoned mines fatalities, South Africa and the continent at large still lack a formal way of reporting all fatal accidents arising from the abandoned mines. According to the US Department of Labor, about 30 people die in abandoned mines related accidences yearly. An example of fatalities in South Africa is the Eland Inactive Gold Mine shaft accident, where the death of 61 illegal miners was reported (Bryson, 2009).

2.6.2 Health issues associated with exposure to magnesite

Magnesite is considered a nuisance particulate due to its relatively low toxicity in humans by inhalation and ingestion (Vincoli, 1997). However exposure to increased quantities poses a serious health risk. Although there is no available information on its carcinogenic, mutagenic or teratogenic capabilities; cases of its irritation to the eyes, nose, throat and mucosa of the upper respiratory track with coughing and congestion are reported wherever magnesite mining operations exist. These effects can be categorized into acute and chronic as depicted in Table 2.2.

In addition, direct contact of persons with magnesite should be avoided. Where a less toxic material or compound cannot be substituted for magnesite, engineering controls such as the use of adequate and general or local exhaust ventilation to keep airborne concentrations below the permissible exposure limits should be used (Chamotte Holdings, 2004; Vincoli, 1997). The use of proper personal protective equipment is also encouraged when one is working with magnesite (Chamotte Holdings, 2004).

The effects of magnesite to human can also be categorized as physical or chemical hazards and human health hazards. The physical or chemical hazards includes depression of the central nervous system (CNS), disturbances of the cardiac, eye and skin irritation, respiratory and digestion track irritation, and other silica related diseases. On the other hand a human health hazard includes irritation of the respiratory track and

coughing when inhaled. However, when magnesite is ingested it is likely to cause irritation of the digestive track, diarrhea, while an excess exposure course central nervous system depression and cardiac abnormalities (Chamotte Holdings, 2004).

Table 2.2: *Health effects of exposure to magnesite (Modified From Vincoli, 1997).*

Acute Health Effect	Skin Contact	▪ May cause mild irritation, depending on the conditions and length of exposure
	Eye Contact	▪ Mild to moderate irritation
	Inhalation	▪ Irritation of the mucosa of the eyes, nose, throat, and respiratory track, and cough.
	Ingestion	▪ Ingestion of excessive quantities of magnesite can cause gastrointestinal effect, kidney problems, and depression of the central nervous system that can lead to death.
Chronic Health Effect	Cancer Hazards	▪ Magnesite site has not been shown to cause cancer in animals
	Reproductive Hazards	▪ There are no reports of any teragenic or reproductive effect from exposure to magnesite

2.7 Challenges of Rehabilitation of Abandoned Mines

Mining is one activity that is characterized by severe environmental impacts. According to Azam (2008), the main environmental issues associated with mining industry include greenhouse gas emission, energy consumption, waste use and recycling, metal leaching, and acid rock drainage (ARD), and the geotechnical stability of large volumes of solid waste. Even where mining operations have been discontinued, environmental problems associated with mining frequently continue. For example, contaminated water emanating from abandoned or "orphaned" mines continue to cause the pollution of both surface and groundwater, while dust from the abandoned dumps, soil erosion (especially in the case of abandoned opencast mines), and the impoundment of solid or liquid waste; constitute further environmental problems that continues even after actual mining has ceased (Strydom *et al.,* 2009).

Generally, abandoned mine sites present numerous challenges and these include the following (Tasmania Geological Survey, 2007):

- the absence of any planning for rehabilitation during the original operation;
- the degraded state of the sites (early miners did not conserve topsoil and sites are often completely bare with denuded expanses of regolith, bedrock and tailings emplacement, which present hostile environments for vegetation);
- remaining soils are often contaminated and may be acidic after long term exposure to site pollution;
- inadequate documentation of the operations may present hazards, including unmarked workings, unstable embankments, and unexpected chemical contamination;
- acidic water coupled with the uncertain extent of workings; make sealing workings to prevent further water entry or escape, difficult and sometimes impossible;
- mining and processing methods which have often spread the impact of activities beyond the precincts of the original site;
- the sites often have heritage and scientific significant;
- sites may have become the habitat for native fauna and relict populations of native flora, sometimes as a direct result of mine disturbance;
- most sites are isolated from major settlements so that in many cases cost recovery through subsequent sale of remediated land is not generally feasible; and
- the presence of exotic plants is also common.

The main challenges of abandoned mine site rehabilitation in most countries with long mining history of private sector are: having only very general policy and legislation for mine closure, providing for mine closure on a negotiation "mine-to-mine" basis, a high degree of state responsibility for both abandoned and some operational mines, and few (if any) bonding procedures to ensure comprehensive mine closure (Clark and Clark, 2005).

2.8 General Approach of Mine Rehabilitation

The final stage in the operation of the mine is reclamation or rehabilitation of the disturbed land. Generally, the best recommended time to begin reclamation process of a mine is before the first excavations are initiated. The unit operations of reclamation or rehabilitation of the mine differ from one mining method to the other. The major difference between strip mining, open pit and quarries is that the strip mine tends to be developed promptly to its full depth and then progresses horizontally as the resource is

recovered. As mining progresses, considerable land surface is disturbed and large strip excavation result. The mined-out areas or pits are used as storage locations for the spoil being generated in the adjacent mining area. This practice has led to the need for backfilling and recontouring of the mined out areas. Several unit operations such as backfilling, leveling, development of stable outside spoil areas, topsoil handling, seeding and lastly the maintenance of the reclaimed sites are carried out simultaneously in the reclamation of strip mining and this makes the process to be complex. These unit operations impact directly on each other from a cost, parathion and planning stand-point (Phelps, 1990).

Reclamation is more costly to mining companies than leaving spoils banks behind. In some cases even if reclamation efforts are made it may be difficult to achieve the anticipated end results. However, it is recommended by DME that at any given mine, the rehabilitation plan should aim at addressing the safety concerns of the mine site (especially, if the area is open to the general public). These include the removal of office buildings, processing facilities, transportation equipment, utilities, and other surface structure, all the shafts, adits and other openings that may present physical hazards should be sealed, provide mitigations to prevent injuries or death due to failure of highwalls and other geological structures. The second issue that needs to be addressed during reclamation of a mine site is restoration of the land surface, the water quality, and the waste disposal areas. According to Rainbow (1987), effective rehabilitation of an open pit mine depends mainly on the climate and the hydrology of the area, for example; the pit can be allowed to fill with water provided it is accepted for recreational or fishing purpose.

Different organizations, associations, and agencies throughout the world use different prioritization criteria in rehabilitation of abandoned mines. However, these criteria tend to be similar in one respect; they all consider public health and safety as the first priority (MMSD, 2002). Generally, the rehabilitation activities should pay more focus on all facilities that pose safety and health hazards to the citizens.

In many countries (including South Africa) priority of rehabilitation of abandoned mine is first given to public safety and then the environment. For instance the abandoned mines rehabilitation programme in South Africa has for the past years focused on health hazardous abandoned asbestos mines (constitutes 3.84% of the total population of the country's abandoned mines) throughout the country as well as the safety threatening

abandoned vertical shafts in the vicinity of Witwatersrand (MMSD, 2002; Davenport, 2006; and Auditor-General South Africa, 2009). According to Sonjica (2007), a database for derelict and ownerless mines and a ranking system are employed in the prioritization of the rehabilitation of the abandoned mines in the country. In addition, the communities directly impacted by the derelict and ownerless mines should be in the forefront in the making of decisions relevant to these mines and identification of optimal land uses (The Federation for a Sustainable Environment, 2009).

2.9 Rehabilitation Cost Estimation

Cost estimation is a fundamental stage of project management and it can be achieved by making use of various relationships of the project's unit operations. It establishes the baseline of the project cost at different stages of the project development. There are various methods for estimating direct and indirect cost. According to Stewart (1991), the basic ingredients for cost estimation are labor-hours, material and subcontracts, travel cost, direct and indirect cost, labor rating administration cost, and fee or profit.

The holistic way of cost estimation starts with work breakdown structure (WBS). No estimate is guaranteed to be accurate, however relying on prior experience and making assumptions might improve the level of confidence of the estimate. The fundamental goal of estimation is to gauge honest, well-informed opinions of the effort required to do a task from those people in the organization who have most applicable training and knowledge (Stellman and Greene, 2006). The four basic techniques employed in cost estimation include parametric, expert opinion, analogy, and engineering cost estimation methods (Nicholas and Steyn, 2008; Greves and Schreiber, 1995).

2.9.1 Statistical and parametrical cost estimation method

This cost estimating techniques rely mostly on relationships between item characteristics and the associated item cost. The parametric cost estimate uses cost estimation relationship and associated mathematical algorithms to establish the cost estimate for a project. Generally, the method correlates cost and manpower information with parameters that describe the system to be costed (Greves and Schreiber, 1995). It can be developed internally by the organization for unique estimation needs; this is because some organizations have specific estimation needs that cannot be achieved by using a

commercial parametric model, or they can be obtained commercially. The method can be applied to develop an estimate before design is complete (Anderson *et al.,* 2007). According to Nicholas and Steyn (2008), it can be used when preliminary design characteristics are being set for the first time and cost estimate is immediately needed. In addition, parametric estimates using statistical techniques can produce a range of probable costs rather than a single deterministic cost (Anderson *et al.,* 2007).

2.9.2 Engineering cost estimation technique

This refers to detailed cost analyses of individual cost categories at the work package or task level. Nicholas and Steyn (2008) described this method as most accurate and time consuming. The method requires considerable work-definition information which is often obtained at a later stage of the project. Engineering cost estimate (bottom-up) involves breaking down the project into activities or work packages which are later on divided into cost categories. The source and structure of this method provide much more detailed estimate than the one given by analogy or parametric. However, its major drawback is that producing an engineering cost estimate is labor intensive, slow and expensive. Consequently the method is recognized as the most costly method as it reflects the detailed build-up of labor, material and overhead cost.

2.9.3 Analogy-based cost estimation algorithm

Analogy-based cost estimation is a useful method that provides sound estimates and it is accepted and trusted by practitioners. Although its accuracy and consistency depends on the quality of the existing data, it is more accurate in estimation than other methods (Auer *et al.,* 2006). When it is used in estimating cost for features of new projects, the analogy-based estimation tries to find projects with similar features in the historical feature database (Bibi and Stamelos, 2008; Auer *et al.,* 2006). Consequently, the cost adjustment normally takes a mathematical expression form thus considered a formula based method (Creese *et al.,* 1992).

This method can be used at all levels of the project. The overall project cost can be estimated from the cost of an analogous project; work-package cost can be estimated from other analogous work-packages; and the task cost can be estimated from analogue tasks (Nicholas and Steyn, 2008).

It is mostly useful where the new system/project is primarily a new combination of existing subsystems for which recent historical cost data are available. The steps of carrying out the analogy-based estimation include, measuring the observable features of the new project at the time of estimation, identification of projects with similar feature values from the historical feature database, and finally; determination of the new estimate using the known costs of the chosen historical project (Auer *et al.,* 2006). Common limitations of analogy method is that the estimates tend to be based on static technology, as such if there is any change in the facility technology; the analogy estimating relationship would need to be modified to reflect such technical changes. The method also lack important details that make costs considerably higher than the original cost estimates (Creese *et al.,* 1992).

2.9.4 Expert opinion cost estimation method

An expert opinion method is an estimate provided by experts. Its application is usually limited to estimate cost during the conception phase of the project and also for poorly defined or unique project (Nicholas and Steyn, 2008). It is commonly used where project historical data is scarce or non-existent. There are numerous major disadvantages of an expert opinion estimate and among others they include the fact that the estimate is subject to biasness; the estimate cannot be substantiated or quantified; and the estimate generally does not lead to an information base that can be developed for future estimates (Creese *et al.,* 1992). Despite these disadvantages, the opinion estimate can be used as a verification method for other methods of conceptual estimation (Creese *et al.,* 1992).

2.10 Terrain Modeling

Digital terrain model (3D-DTM) also known as digital elevation model (DEM) is understood as the continuous surface consisting of a height value. The elevation value (height) is attributed to each square cell of the grid. According to Ervin (2001), simple elevation faction ($z = f(x, y)$) is sufficient to describe the landform or terrain surface. The approach of interpreting these elevations can be either by assuming that each cell represents the discrete area thus the entire cell area consists of the same value with changes occurring along the cell edges. The second approach being by assuming that the area between the cell centers is having the same intermediate value. The common

elements that describe the DEM are slope, aspect, curvature, gradient, skeleton (pit, thalwegs, saddles, ridges, peaks) and others (Podobnikar, 2008).

Modeling and analysis of spatially referenced data set using GIS and other associated software have gained more attention over the past decades and the technique has been adopted in diverse field of science. Since 1950s DTMs have gained wide application on disciplines such as mapping, remote sensing, civil engineering, geology, geomorphology, military engineering, land planning, communication, environmental sciences, ecological systems, digital terrain cartography, computer experiments, and public health (Maune *et al.,* 2001; Banerjee and Finley, 2009). According to Li *et al.* (2004), DTM can be applied in planning and landscape design as well as visual impact analysis. DTM became widely used in mining, following the pioneering work carried out by Robert in 1957 on its application to civil engineering (highway design) (Li *et al.,* 2004).

2.10.1 Application of GIS in 3D Modeling

Applications of GIS span a wide range from sophisticated analysis and modeling of spatial data to simple inventory and management (environmental management) (Goodchild, 1993). Fisher (1993) explained the 3D GIS as an emergent branch of science that offers a new set of tools to the field of environmental modeling. However, different 3D GIS models are characterized by numerous limitations and strong points which makes them suitable for different applications.

Table 2.3 depicts the advantages, disadvantages and the application of different 3D GIS models. The 3D spatial data models are divided into two types; namely, geographical special object modeling referring to constructions on the ground, and the geological special objects modeling (subdivided into surface model, solid models and integrate model) referring to humanized engineering bodies. These models include TIN model, Grid model, Block model, Tetrahedral network model (TEN), Pyramid model, Wireframe model, GTP model, TEN + Octree, and TIN + Octree (Yanbing *et al.,* 2007; Fisher, 1993). However the integration of geographical and geological models form the third division as depicted in Table 2.3.

Table 2.3: *Advantages and disadvantages of different types of 3D GIS models (Yanbing et al., 2009).*

Type	Name	Using	Advantages	Disadvantages
Geographical Model	3DFDS	3D City model	Easy make the adjacent between spatial and non spatial objects	Difficult to compress complex spatial objects
	n Tuple model	Geology, Complex buildings	Easy maintenance of topological expression	Difficult to express complex spatial objects
	SSM	Web-oriented, Visualization, Query	Easy abstract primitives, small storage	Update dynamically and modify are complex, constructive objects are multi-value
	UDM	City Visualization	Easy abstract primitives, small storage, facial visualize	Update dynamically and modify are complex
	OO3D	City Visualization	Complex object, LOD, Visualization	Indistinct topology, little 3D spatial analysis function
Geological Model	3D-TIN	Geology, Terrain	Facial visualization	No Attribute in object
	Grid	Terrain	Facial visualization	Massive data
	TEN	Geo-information, Pollution Cloud	Facial visualization, complex body and face	Difficult to visualize complex objects, great storage
	Octree	CAD/CAM, Geology, Sea	Simple structure, inside attribute transformation expression	Difficult to express geological objects' geometrical boundary, massive data, data redundancy
	Solid Model	Geology, Mine	Fit for complex structure inside expression	Great manual work
	GTO[20]	Geological Engineering	Topology completely, 3D expression of geology, based on drill hole data	Difficult to express the complex geological object
Integrated Model	TIN+CSG	3D City model	Two models integrate in a user windows	Difficult to express the complex geological object such as faults, folds, fissure etc
	TIN+Octree	3D City model, Geological Engineering	Topology expression, query easily	Octree data changed with the change of TIN, easily disturbed by the pointer
	TEN+Octree	Geological Engineering	Improve the precision of objects, reduce data storage	Difficult to build topology of spatial object

2.10.2 Other modeling tools

Commonly used engineering software for DTM includes DATAMINE (mine design system STUDIO), Vulcan as well as Surfer 8 Software. DTM by DATAMINE is based on the fact that it employs tools for surface interpolation from GPS points and triangulation tools. For example, the topographic data established by RTK (Real Time Kinetic) was manipulated using DATAMINE packages to create a terrain model for monitoring and appraisal of slopes for China Clay Open-Pit Mine (Coggan *et al.*, 2001).

Vulcan has been widely used in Post-Mine Topography (PMT) design by superimposing regarded post-mining surface on the disturbed mining landscape. This promotes easy calculation of required cut and fills work for final PMT. The accuracy and efficiency of a design PMT is assured by interactively viewing and analyzing Vulcan's triangulated surface model against each other. The computation of cut and fill is checked for 3D volumetric accuracy giving both Vulcan and DATAMINE highlights over traditional computation methods (Kapageridis and Tavoularis, 2002). Surfer 8 Software is also widely used in digital terrain modeling for engineering practices. It uses point and block kriging which offers a variation of drift parameters and variogram models. The software variograms include linear, Gaussian, quadratic, spherical and cubic variogram models (Fencik and Vajsablova, 2006).

CHAPTER THREE

METHODOLOGY AND MATERIALS

In order to achieve the objectives of this study relevant data was collected. This chapter presents all the methods, tools and procedures adopted in the collection and processing of the data. The research approach comprised of desktop study, reconnaissance survey, site characterization, topographic or terrain data collection and analysis. A brief discussion on the relevance of the collected data and methods used are also given in this chapter. The steps, tools and procedures of data acquisition are presented in Figure 3.1.

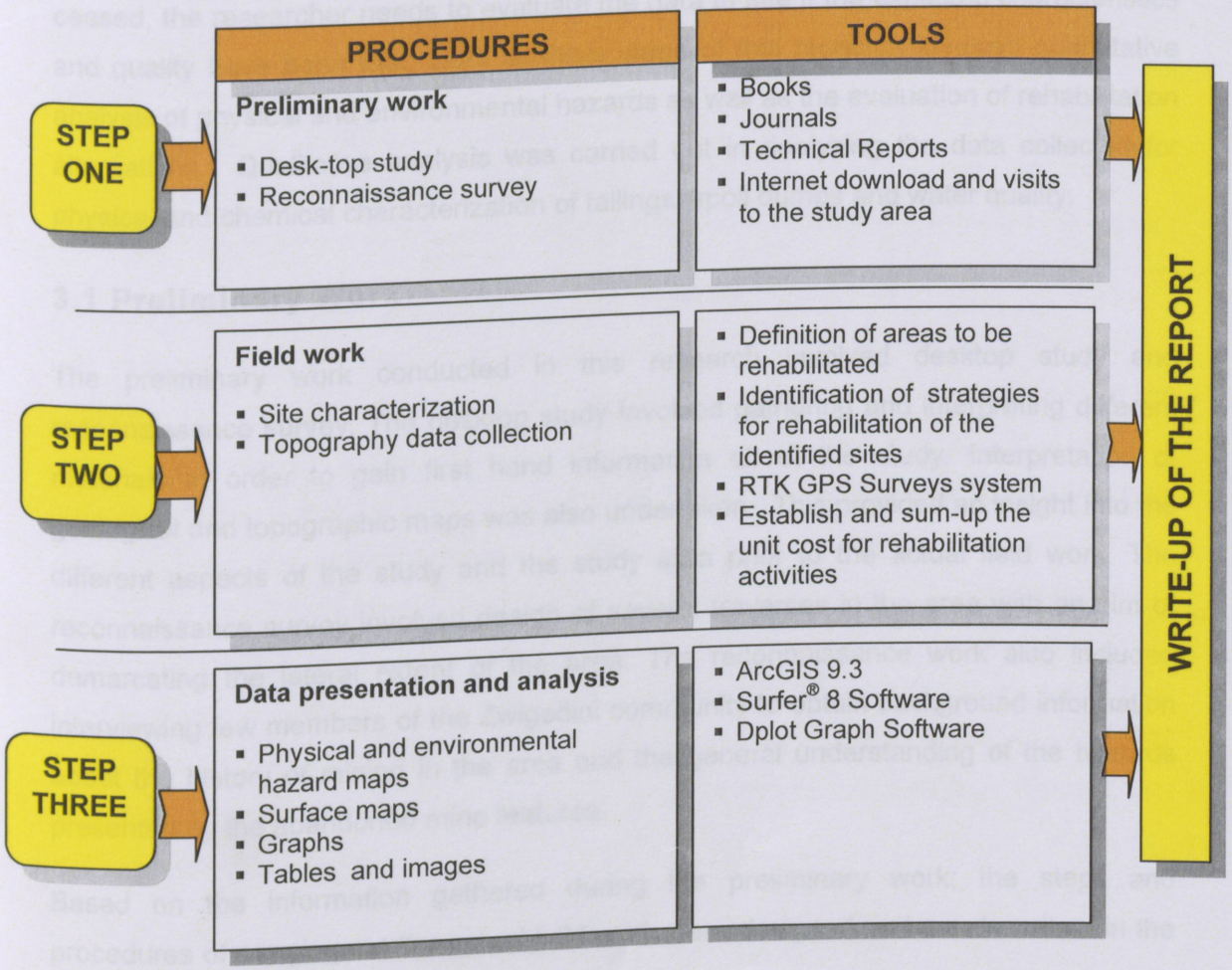


Figure 3.1: *Simplified flow-chat showing steps, procedures and materials used in the collection and processing of data.*

The initial stage of collecting the necessary data to meet the objectives of this research was carrying out preliminary work. This is the work generally carried out in the office or on site prior to actual field work. The preliminary work conducted in this research involved carrying out desktop study in the office and reconnaissance survey in the field.

Fieldwork is generally any practical work that is carried out in the field for the purpose of researching or collecting data. Field work conducted in this research involved collection of data for mine site characterization, topography data for surface modeling, and data on the different characteristics of the environment for the design of appropriate rehabilitation strategy.

Data analysis is an endeavour that is more than number crunching or an activity that permeates all stages of the research. Once the data collection stage of the study has ceased, the researcher needs to evaluate the data to see if the expected characteristics and quality have been met. Data analysis stage of this research involved quantitative analysis of physical and environmental hazards as well as the evaluation of rehabilitation alternatives. Qualitative analysis was carried out in analyzing the data collected for physical and chemical characterization of tailings, spoil dumps and water quality.

3.1 Preliminary Work

The preliminary work conducted in this research involved desktop study and reconnaissance survey. The desktop study involved gathering and interpreting different materials in order to gain first hand information about the study. Interpretation of geological and topographic maps was also undertaken. This provided an insight into the different aspects of the study and the study area prior to the actual field work. The reconnaissance survey involved design of several traverses in the area with an aim of demarcating the lateral extent of the area. The reconnaissance work also included interviewing few members of the Zwigodini community to obtain background information about the history of mining in the area and the general understanding of the hazards presented by the abandoned mine features.

Based on the information gathered during the preliminary work; the steps and procedures of carrying out the actual field work were designed and are described in the following section.

3.2 Mine Site Characterization

The first stage in the characterization of Nyala Mine site was to develop a physical and environmental hazard conceptual model. This involved identification of all the hazards at the mine site followed by scoring of the identified hazards to determine their seriousness. The following sections describe the procedures followed in the development of the hazards conceptual model, and presents scoring and rating of the identified hazards.

3.2.1 Development of hazard conceptual model

The development of the Nyala Mine conceptual model began with identification and location of all abandoned features at the mine site. The identification of the abandoned mine features was achieved through systematic traversing around the mine area. The identified features were located and marked on the topographic map using handheld Garmin GPS 60. The sketch map produced in the field was superimposed on the 2004 orthophotographs covering the study area. The information from field investigation and orthophotographic interpretation was traced out on the tracing table. The manually compiled feature map was then scanned and digitized using GIS 9.3 software packages.

Detailed field description of the features was made with the aim of establishing the ways and manner at which they pose environmental and physical threats to the nearby communities. Some of the tools used for gathering information for description of the different features of the mine included clino-ruler, Garmin GPS 60, tape measure and high resolution digital camera. Through the description of the mine site features, pathways and the possible means of exposure to the hazards presented by the abandoned mine were established. In the case of the tailings dumps; their release and chemical influence to the surrounding environs was established through textural and chemical characterization of the tailings dump materials. This looked more precise on the composition of tailings that directly or indirectly impact on the fertility of soil. Physical properties of tailings and top soil banks was investigated to measure their susceptibility to wind and water erosion.

3.2.2 Compilation of physical hazard map

Physical hazard map of the abandoned mine site was constructed by classifying and demarcating extremely hazardous, moderately hazardous and less hazardous zones of

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the mine. The physical hazard map depicts scores and rating of the physical hazards identified at the mine sites.

Scoring of hazards

The method used to score the hazardous features was based on the magnitude of physical and environmental hazard they present and was the modified Historic Mine Site Scoring System (HMS-SS). Generally, the use of the method involved identification of all hazards prone features at the mine site, description of these physical and environmental hazards, scoring of identified hazards, and amalgamation of individual scores in order to determine the entire score for the feature. The approach used is presented in Figure 3.2.

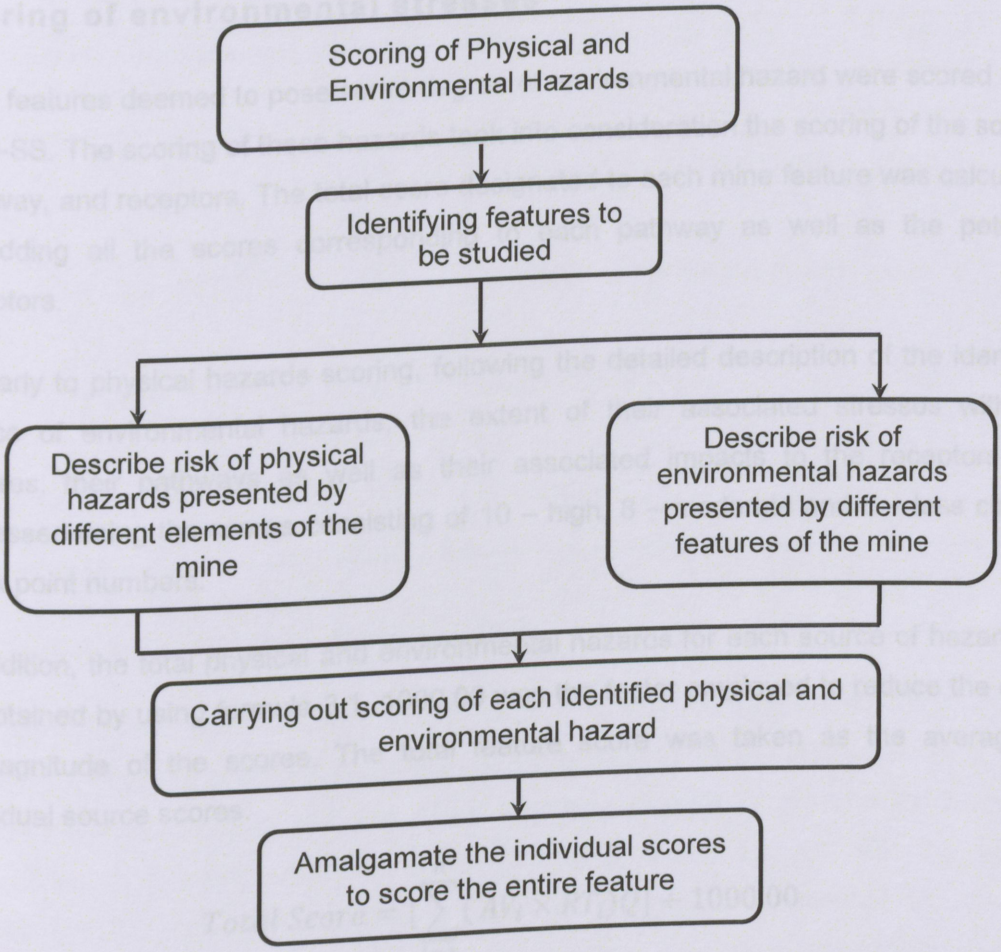


Figure 3.2: *HMS-SS approach for scoring physical and environmental hazards (Modified from PGeo et al., 2009).*

Scoring of physical hazards

Features of the mine site which were identified as physical hazards were assessed for potential risk they pose to both human and animals. The scoring of these features focused more on the primary source of physical hazards and the ways at which the victims get exposure to the identified hazards.

Based on the field description of mine features, the extant of physical hazard, seriousness of exposure and possible damage to the victims were expressed using the scores of 10 – high, 8 – moderate and 6 – less.

Scoring of environmental stresses

Mine features deemed to pose some degree of environmental hazard were scored using HMS-SS. The scoring of these hazards took into consideration the scoring of the source, pathway, and receptors. The total score designated to each mine feature was calculated by adding all the scores corresponding to each pathway as well as the potential receptors.

Similarly to physical hazards scoring, following the detailed description of the identified source of environmental hazards, the extent of their associated stresses with the features, their pathways as well as their associated impacts to the receptors was expressed using the scores consisting of 10 – high, 8 – moderate and 6 – less chosen break point numbers.

In addition, the total physical and environmental hazards for each source of hazard will be obtained by using formula 3.1. 1000.00 was the factor employed to reduce the order of magnitude of the scores. The total feature score was taken as the average of individual source scores.

$$Total\ Score = [\sum_{i=1}^{n} (AV_i \times RT_i)Q] \div 1000.00 \quad \text{.....(3.1)}$$

where: AV_i = Quantity of the mine feature score

RT_i = The total hazard score for each receptor/victim

Q = Total score for each receptor/victims of the hazards

3.2.3 Rating of hazards at mine site

Based on the intense and detailed field description of hazardous feature of the mine, different physical hazards at Nyala Mine were scored and rated as extreme, moderate, less and reduced hazards. The zones of the mine characterized by extreme hazards were coded red while those presenting moderate and less hazards were respectively coded purple and blue. Areas of reduced hazard were not assigned any colour code. Table 3.1 presents physical and environmental hazards ranking and classification guideline used at Nyala Mine.

Table 3.1: *Physical and environmental hazard ranking and classification guideline (Modified from PGeo et al., 2009).*

Physical Hazard Ranking and Classification	*Value of the class*	*Description of the class*	*Colour coding*
≥90	A	Extremely hazardous zones	Red
61-99	B	Moderately hazardous zones	purple
31-60	C	Less hazardous	Blue
≤30	D	Negligible	None

3.3 Sample Collection Procedures

As recommended by Mackasey (2000), the inventory of abandoned mines should incorporate physical and chemical sites characterization so as to address both physical and chemical instability of the site. Thus, sampling of water bodies on the bottom of excavations and waste materials (mine waste) was carried out with the aim of establishing the chemical composition and determines the potential influence of magnesite mining to other elements of the environment. Textural characteristic of tailings was also analyzed to determine some of the factors that influence their ease of release to the surrounding environment by wind and water. Physical properties of tailings were also analyzed to define the material support of vegetation adaptation.

3.3.1 Sample collection

Representative samples of tailings dump and top soil materials were collected using the random sampling approach. The approach involved delineation of the different waste dumps into meaningful segments on which sampling points were selected. Despite sampling of the solid was material (tailings and topsoil dumps), the water contained by abandoned excavations was also sampled. Figure 3.3 presents the relative position of the sampled materials to the water body in the vicinity of the Nyala Mine and Zwigodini village.

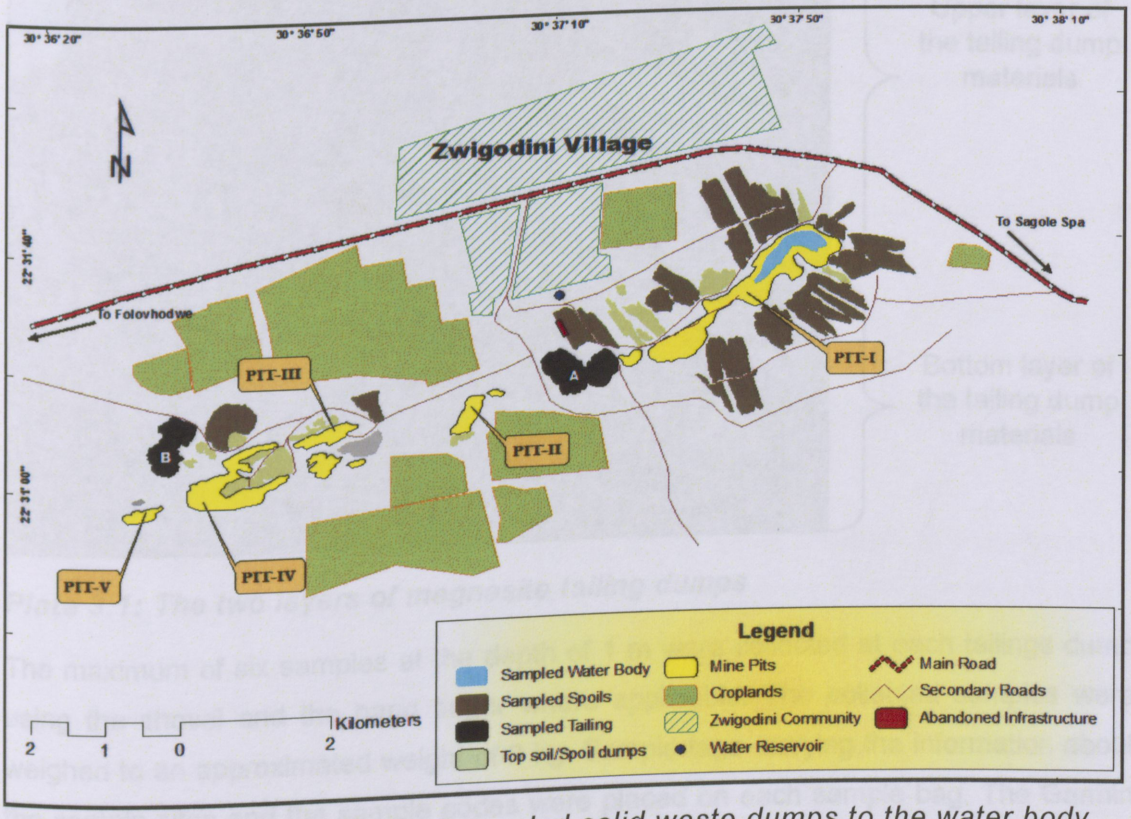


Figure 3.3: *Relative position of sampled solid waste dumps to the water body.*

The section below present procedures followed in tailing dump sampling, top soil dump sampling, and water sampling at the Nyala Magnesite Mine.

3.3.2 Tailing dumps sampling

The representative samples of tailing dumps were obtained randomly along the two layers characterizing the magnesite tailing dump materials in the study area. The random sampling approach used in sampling both tailing dumps (denoted as Tailing-A

and Tailing-A) at Nyala Mine involved dividing the dumps into segments. The sampling points were then selected along the visible layers of different materials exposed along deeply developed erosion gullies on the dumps. The sampling in this case was primarily focused on sampling both layers of the dumps. However, a material eroded by water from these layers to be base of the dumps was also sampled. The two tailing material layers are shown on Plate 3.1.



Plate 3.1: *The two layers of magnesite tailing dumps*

The maximum of six samples at the depth of 1 m were collected at each tailings dump using the shovel and the hand auger where applicable. The collected samples were weighed to an approximated weight of 2 kg. Sample tags carrying the information about the sample sites and the sample codes were placed on each sample bag. The Garmin GPS 60 type of Global Positioning System was used to locate each sample collected.

3.3.3 Spoil banks sampling

Similar to tailing dumps sampling, the top soil pills in the study area were divided into meaningful segments along which representative samples were collected. The top soil dumps were identified to be characterized by courser materials (boulders) at the base. Therefore, most top soil samples were strategically collected at the depth greater than 50 cm on the upper surface of the dumps. The hand auger and shovel were the tools

used to extract the desired samples. The total number of 20 top soil samples with the maximum of two to three samples at each dump was collected.

The spoil banks samples of an approximated weight of 2 kg were marked SDA-001 and SDB-001 while the tailing damps samples for Tailing-A were labeled TA-01 to TA-06 and those for Tailing-B were labeled TB-01 to TB-06.

3.3.4 Procedure for water sampling

Large volumes of water contained in abandoned excavations in the study area were sampled using direct sampling method. The method involved collection of water samples direct to the sample bottles. The sampling sites were selected randomly along the perimeter of the water body.

Prior to taking the samples, sample bottles were rinsed with deionizered water to decontaminate the bottles. The decontaminated water bottles were kept closed until the time of collecting the samples. Other precautions taken in water sample collection included careful holding the water bottle in one hand near the base while the other hand was holding the bottle lid. This was done to avoid touching the inside part of the screw cap hence avoiding contamination of the sample.

The actual sampling involved careful lowering of the sample bottles to predetermined depth while avoiding sampling the surface of the water as well as bottom disturbances. The first content of the bottle was discharged to clear potential contaminants while the second was taken as the representative sample of the water body. The total number of five water samples was collected and coded SW-01 to SW-05.

3.4 Laboratory Analysis of Samples

The collected samples were all taken to the laboratory for analysis, where both chemical and physical properties of tailings dumps were determined. The top soil bank material was only analyzed for their textural properties, pH and electrical conductivity (EC). This section is earmarked for description of methods, procedures and equipments used in analyzing both water and soil samples. The pH, electrical conductivity and the associated cations and anions were the investigated chemical properties of water.

3.4.1 Physical classification of tailings and spoils materials

The particle size classification was the employed technique for physical characterization of the samples. The technique includes measuring the grain size distribution of the wastes by passing them through a series of different sizes sieves. The sizes of sieves refer to the size of the sieves openings. In this research sieves of sizes ranging from 4, 3.15, 2, 1 mm; 500, 250, 125, 63, 32 µm were used. A pan was placed at the bottom of the stack of sieves. The procedure included determination of the weight of each empty sieve. Thereafter, the solid soil sample (dried at 110 ºC for more than 9 hours) of known weight was passed through the set of sieves. Material retained on each sieve was weighed and expressed as a percentage of the whole sample. The sieve stack was placed on the motorized mechanical shaker and shaken for 1 hour.

The percentage passing on each sieve was plotted on the grain size distribution graph. From the gradational curve, grain size of the sample passing at 10% (D_{10}), 30% (D_{30}) and 60% (D_{60}) were determined. These values were used to calculate both coefficient of uniformity (C_u) and curvature (C_c) as presented by the following equations.

$$C_u = \frac{D_{60}}{D_{10}} \quad \text{and} \quad C_c = \frac{D_{30}^2}{D_{10} \times D_{60}} \qquad \text{.....3.2}$$

where:

C_u = Coefficient of uniformity,

C_C = Coefficient of curvature,

D_{10} = grain size corresponding to 10% passing,

D_{30} = grain size corresponding to 30% passing, and

D_{60} = grain size corresponding to 60% passing

3.4.2 Determination of pH and conductivity of samples

Mine water and magnesite waste materials were analyzed for pH and their corresponding conductivity. The soil pH was determines using an electronic pH meter (Crison pH basic 20). The samples from the field were manually homogenized through the use of stainless still spoon and bucket. The stainless riffle splitter was used to split and reduce the homogenized samples to a fraction less than 50 g. The content of one bin of the splitter was placed aside while the other content was passed through the chutes of the splitter until the required size of the sample was obtained.

Slurry was prepared by adding 20 ml of deionizered water to the 20 g scoop of clay and silt particles of the sieved sample in the beaker. Each sample was vigorously stirred for 15 minutes with a glass stirring rod and let to stand for 30 minutes. The pH meter was then calibrated over the appropriate alkaline range of pH 7.00 to pH 9.00 using the buffer standard solution and thereafter immersed to the beaker with slurred samples. The pH of the soil and its corresponding electrical conductivity (EC) was then recorded from the pH meter and the electrical conductivity meter.

The pH of water samples collected from the site was measured by immersing the pH rod in 40 ml in water for a minute. Prior to that, the water sample was vigorously stirred and let to stand for at least 60 minutes.

3.4.3 Analysis of anions and cations in water

The water samples were analyzed for anions and cations using Ion Chromograph (IC) and AAS in the Department of Chemistry, University of Venda. The analysis of anions in the water samples was carried out through the use of 850 professional Ion Chromatograph (IC) as illustrated in Plate 3.2.

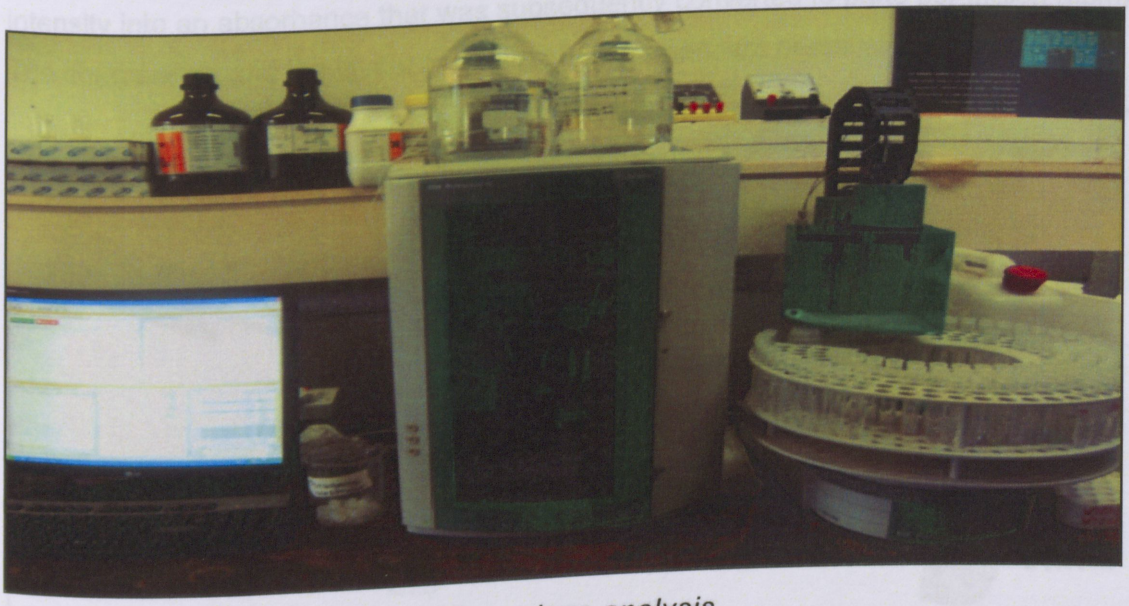


Plate 3.2: *Iron chromatography for anions analysis*

The instrument has a capacity to measure concentrations of major anions and cations in the range of parts-per-billion (ppb) to parts-per-million (ppm). For the analysis of anions, the mobile phase of the instrument was equipped with two litres solution of 168 g sodium

carbonate ($NaHCO_3$) and 678 g disodium carbonate (Na_2CO_3). The water samples were passed through the pressurized Metrosep A Supp 5 anions column at 0.8 ml/minute flow rate. The standards used for instrument calibration are 1 ppm, 5 ppm, 10 ppm and 20 ppm.

Alkali metals (catoins) in water ware analyzed using a Flame Atomic Absorption Spectrometry (FAAS) (Perkin Elmer AAnalyst 400). Sodium, calcium, magnesium, potassium and iron were detected in water samples by plotting non-linear calibration curve using well prepared standard solutions for each metal under investigation. Prior to the instrument calibration, optimization was done to obtain the best response of the instrument. The instrument was calibrated with 1, 2, 5, 10 and 20 ppm standard solution of each desired elements.

The analysis involved introducing a water sample to the instrument aspirator where it was then aspirated to flame in the form of aerosol. The beam of ultraviolet light at a specific wavelength was focused to the flame prior to sample aspiration. The machine detected the metal existence in water by measuring the change in intensity of each metal under investigation. The computer system then converted the measured change in intensity into an absorbance that was subsequently converted to parts per million (ppm). The components and the layout of the FAAS instrument are presented in Figure 3.4.

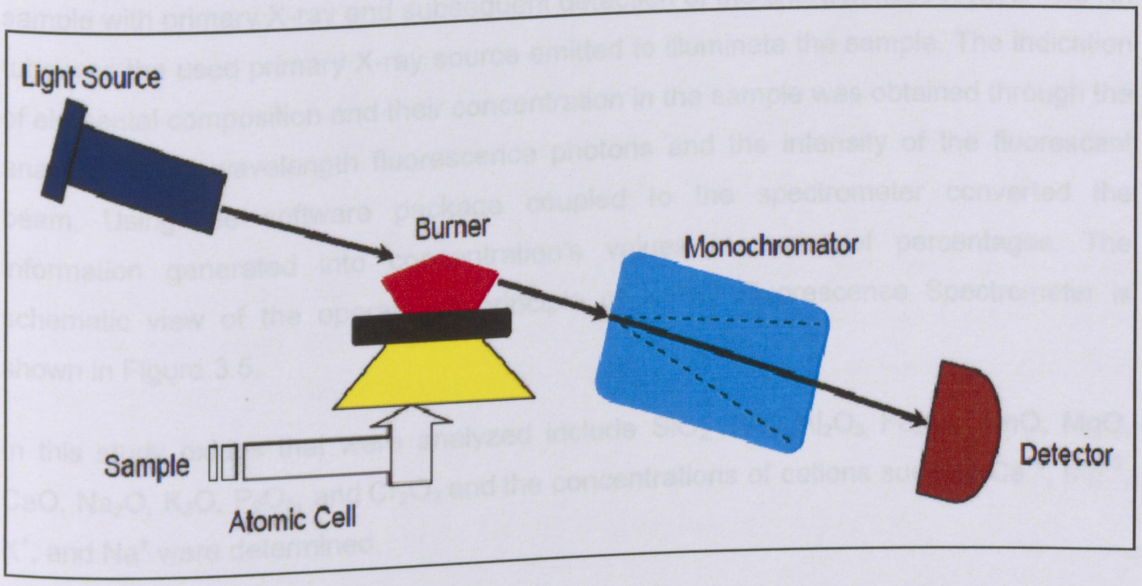


Figure 3.4: *Component and layout of AAS instrumental (Modified from Ma and Gonzlez, 1997).*

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3.4.4 Tailings sample preparation for XRF analysis

Magnesite tailings samples were prepared to allow direct X-ray fluorescence spectrometer (XRF) analysis on solid powdered spacimen. This made the sample preparation process simpler and more accurate without the risk of contamination.

The procedure for samples preparation involved milling of fine grain tailings materials to the fraction less than 75 µ. The Retsch RS 200 vibratory disk milling machine set at 1500 min^{-1} motor speed for 5 minutes was used.

The milled spacimen was then roasted at 1000 °C for at least 3 hours to oxidize ion (Fe^{2+}) and Sulfur (S). This was also done to determine the Loss of Ignition (L.O.I) of the samples. For the analysis of major oxides by XRF required the preparation of glass disks. This was prepared by fusing 1 g roasted sample and 8 g (12-22) flux consisting of 35% alkali borate ($LiBO_2$) and 64.71% lithium tetraborate ($Li_2B_4O_7$) at 1050 °C. The glass disks were then analyzed by a PANanalytical Axios X-ray fluorescence spectrometer equipped with a 4 kW Rhodium (Rh) tube.

3.4.5 Operation of X-Ray Fluorescence Spectrometer

The working principle of the XRF spectrometer involves atom excitation by irradiating the sample with primary X-ray and subsequent detection of the characteristic X-rays. The Rh tube was the used primary X-ray source emitted to illuminate the sample. The indication of elemental composition and their concentration in the sample was obtained through the analysis of the wavelength fluorescence photons and the intensity of the fluorescent beam. Using the software package coupled to the spectrometer converted the information generated into concentration's values in terms of percentages. The schematic view of the operational principle of X-Ray Fluorescence Spectrometer is shown in Figure 3.5.

In this study oxides that were analyzed include SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, and Cr_2O_3 and the concentrations of cations such as Ca^{+2}, Mg^{+2}, K^+, and Na^+ were determined.

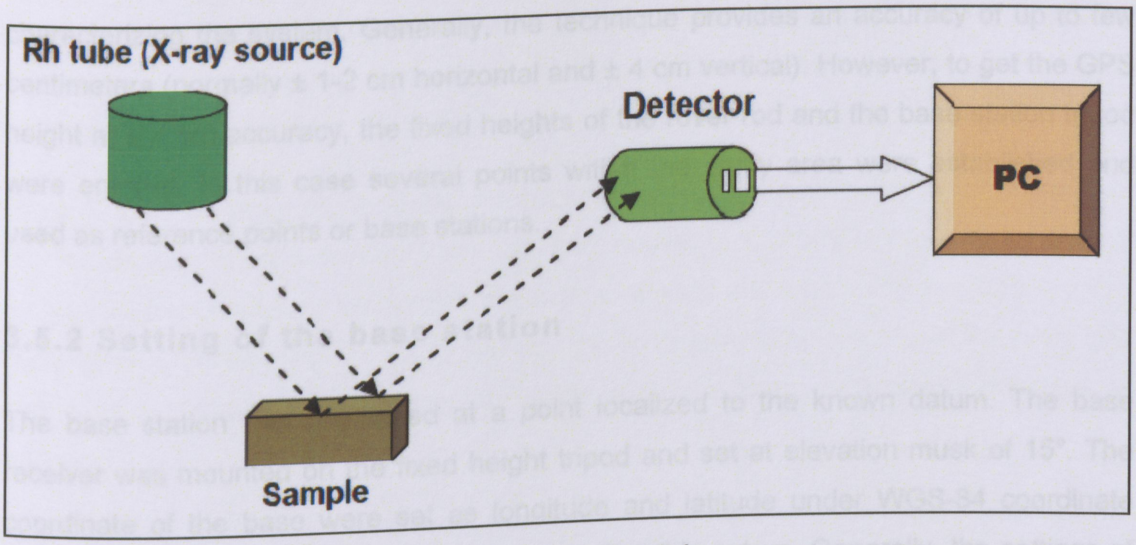


Figure 3.5: *A schematic view of the XRF principle*

3.5 Mine Site Terrain Modeling

One of the specific objectives of this research was to create 3D digital terrain model of the study area. Such a model depicts the extent of the land degradation and also to assists in designing engineering strategies for rehabilitation of such sites. For a 3D digital terrain model to be useful as a tool for making sound decision on best mine rehabilitation strategy, there is a need to first create terrain model of the existing topography of the area and compare with models of different rehabilitation alternatives. Terrain design (3D Modeling) has been recommended by a number of researchers such as Massad and Bango (2006) and Visockiene *et al.* (2008) as a significant and vigorous tool mostly applied in solving problems in the field of surveying, geology, mining engineering, reverse engineering and environmental engineering.

This section provides description of procedures, equipment and tools used in the collection, processing and presentation of the height data required as input for digital terrain modelling. The height data was obtained through the use of Hi-Target V9 GNSS RTK Surveying system.

3.5.1 Operational principle of RTK surveying system

The RTK system employs two GPS receivers with one set over the known point (Base or Reference point), while the other is placed on the roving platform. The operation process of both base and rover is instructed by the sound navigation operation technology

characterizing the system. Generally, the technique provides an accuracy of up to few centimeters (normally ± 1-2 cm horizontal and ± 4 cm vertical). However, to get the GPS height at ± 4 cm accuracy, the fixed heights of the rover rod and the base station tripod were entered. In this case several points within the study area were established and used as reference points or base stations.

3.5.2 Setting of the base station

The base station was positioned at a point localized to the known datum. The base receiver was mounted on the fixed height tripod and set at elevation musk of 15°. The coordinate of the base were set as longitude and latitude under WGS-84 coordinate system, while the height (H) was kept at an ellipsoids set-up. Generally, the settings of the base station involved setting of the base station work parameters which included base station coordinates convention parameter, and data link of the reference point. In addition, the base was set on the site with clear view of the sky at a radius of more than 50 m away from the high voltage power lines.

3.5.3 Setting of the rover receiver

The rover was set such that it allows the recording of vertical data (X, Y and H) at every 5 m interval along the designed traverse lines of 15 m spacing. These denser grids were designed with the purpose of improving the information content of the digital surface representation. The receiver was mounted on the fixed height rover rod (2 m) and set at elevation musk of 10º to enhance the positioning accuracy. The settings of the rover deferred only in information input from those of the base or reference point.

3.5.4 Surface model development

The RTK GPS points were used in developing a grid surface representation model of the study area. The surfer® 8 software (Contouring and 3D Surface Mapping for Scientists and Engineers) package using linear interpolation methods was employed in carrying out this task. Prior to the creation of the actual surface; the height data was processed to make it compatible for the software. Kriging interpolation method was used to produce visual maps from irregularly spaced height data. The software uses two Kriging types,

namely; Point Kriging (the value of the point was estimated at the grid nodes) and Block Kriging (the average value of the rectangular blocks was estimated on the center on the grid nodes.

Block Kriging is generally a spatial interpolation which estimates the average value of the rectangular blocks centered on the grid nodes that promotes the generation of smooth surface contours. Generally, the interpolation of any type involves creating a fine rectangular grid covering the study region, and then estimating the height for every grid cell. The grid value is established by using a simple linear expression indicated as equation 3.3.

$$H_j = \sum_{i=1}^{n} \lambda_i H_i \qquad \text{..... (3.3)}$$

where:

H_i= the H value to be estimated for location j

λ_i= are a set of estimated weight

H_i = the known value at points (x, y)

Adjustments on the topographic data set were made for the creation of an engineering surface model. The two surfaces (the surface representation of the site and the designed engineering surface) were superimposed to give the final surface representation of the site post rehabilitation.

3.6 Estimation of Cut and Fill Quantities

In conducting rehabilitation at a mine site, it is often necessary to adjust the terrain. Various sections of the mine site will require bringing in earth whilst other sections will require earth to be removed. Earth that is brought in is considered Fill while earth that is removed is considered Cut. Generally, Cut and Fill diagrams are generated which illustrate the cut and fill present at any site. To determine the amount of earthwork to occur on a given site, the volumes need to be calculated.

The approximate volume of the material to be cut and the area to be filled was computed using surfer® 8 software. The method of volume calculation involved extended Trapezoidal rule, extended Simpson's rule, and extended Simpson's 3/8 as expressed mathematically in equation 3.4, 3.5 and 3.6. In these equations, Δx represents the grid column spacing, Δy represents the grid row spacing, and $G_{i,j}$ represents the grid node value in row i and column j.

$$A_i = \frac{\Delta x}{2}[G_{i,1} + 2G_{i,2} + 2G_{i,3} \ldots + 2G_{i,nCol-1} + G_{i,nCol}]$$

$$Volume \approx \frac{\Delta y}{2}[A_1 + 2A_2 + 2A_3 + \cdots + 2A_{nCol-1} + A_{nCol}] \quad \ldots\ldots\ldots\ldots 3.4$$

where: the pattern of coefficients is: 1, 2, 2, 2,..., 2, 2, 1

$$A_i = \frac{3\Delta x}{3}[G_{i,1} + 4G_{i,2} + 2G_{i,3} + 4G_{1,4} + \cdots + 2G_{i,nCol-1} + G_{i,nCol}]$$

$$Volume \approx \frac{\Delta y}{3}[A_1 + 4A_2 + 2A_3 + 4A_3 \ldots + 2A_{nCol-1} + A_{nCol}] \quad \ldots\ldots\ldots 3.5$$

where: the pattern of coefficients is: 1, 4, 2, 4, 2, 4, 2,..., 4, 2, 1

$$A_i = \frac{3\Delta x}{8}[G_{i,1} + 3G_{i,2} + 3G_{i,3} + 2G_{1,4} + \cdots + 2G_{i,nCol-1} + G_{i,nCol}]$$

$$Volume \approx \frac{3\Delta y}{8}[A_1 + 3A_2 + 3A_3 + 3A_3 + \cdots + 2A_{nCol-1} + A_{nCol}] \quad \ldots\ldots\ldots 3.6$$

where: the pattern of coefficients is 1, 3, 3, 2, 3, 3, 2,..., 3, 3, 2, 1

The difference in the volume computed by the three methods was used to measure the accuracy of the estimate. In the cases where the three volume estimates were reasonable close, the three volumes were considered to be close to the computed values. The net volume of the material to be cut as well as the void to be filled was considered to be the average of the three values.

3.7 Selection of Appropriate Mine Rehabilitation Strategies

Based on the site characterization outcomes and the developed terrain models, several rehabilitation alternative strategies for each modeled landform area were selected. The most appropriate alternatives were identified through the use of SWOT analysis. Quantitative Strategic Planning Matrix (QSPM) for each strategy was developed and used to evaluate the selected alternatives in terms of their relative attractiveness. On this, both internal (strengths and weaknesses) and external (opportunities and threats)

factors of each strategy were assigned weights (at a scale of 0.00 to 1.00) indicating their significance and attractiveness score (ranging from 1-not acceptable to 4-most acceptable and 0-not relevant).

3.8 Cost Estimation of Rehabilitation Options

Although rehabilitation cost-benefit analysis is considered difficult (Baxter and Wicomb, 2000), it was one of the objectives of this research to provide cost estimate for execution of rehabilitation practices in the area. The procedure for engineering cost estimation method involved the establishment of an inventory for individual sites or elements of the area to be rehabilitated and assigning unit cost for the designed rehabilitation strategy for individual sites. Finally, the total rehabilitation cost model was presented as the sum of all estimated costs for individual sites rehabilitation (as expressed in equation 3.7).

$$C_{TR} = \sum_{i=1}^{n} C\,x_i \qquad \text{.....3.7}$$

where; C_{TR} = Total site rehabilitation cost

Cx_i = Cost of individual site rehabilitation

Where; the cost of rehabilitation of individual C_x comprises of the sum of all the direct and indirect cost together with the estimated labor cost at a specified time estimate as presented in equation 3.8. Direct cost included costs that can be specifically identified with a particular activity, while indirect cost are all costs incurred by an organization for common or joint objectives, and which cannot be identified specifically with a particular activity or project.

$$C_x = \sum L.T + Dc + Ic \qquad \text{.....(3.8)}$$

where; L = Labor Cost (R);

T = Estimated Time in hours;

Dc = Estimated Direct Cost; and

Ic = Estimated Indirect Costs

Depending on the complexity and the size of each identified unit task, the major activities required further breakdown so as to achieve more accurate costs estimate. The breakdown took into account the effects resulting from too little and too much breakdown. Figure 3.6 presents the sequence of practices in the estimation of the whole site rehabilitation cost estimation.

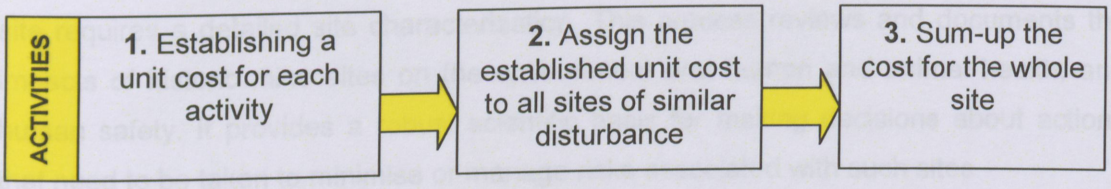


Figure 3.6: *Method of estimation of rehabilitation cost*

The method that integrates cost engineering estimation and expert opinion cost estimation strategy was used in carrying out the rehabilitation cost estimate. The method was applied by assigning unit cost of each suggested rehabilitation strategy on individual site or environmental elements. The estimated unit costs were used to provide the overall site cost rehabilitation or reclamation cost estimate. In order to achieve the most accurate and detailed estimate further breakdown of some activities was considered. The costing of the unit operations was then achieved by considering the cost of the similar or related activities in other projects, for example, similar practices in civil work, agriculture and forestry, and mining and mineral exploration. In the case where a new and unique activity has to be conducted, opinions from experts were considered in costing such activities. Finally, all the sub-estimates were summed-up to obtain the whole site estimate.

CHAPTER FOUR

CHARACTERIZATION OF ABANDONED MINE SITE

The development of sound engineering strategies for rehabilitation of abandoned mine site requires a detailed site characterization. This process reviews and documents the impacts of historic mine sites on the environment and human and animal health, and human safety. It provides a robust scientific basis for making decisions about actions that need to be taken to minimise or manage risks associated with such sites.

This chapter describes the sources of physical and environmental hazards identified at the study area, establishes the hazard exposure pathways and pinpoints the possible receptors, and highlights the main elements of the mine site conceptual model. In addition, it discusses the physical and chemical characteristics of the types of solid waste found at the mine site, provide discussion on the quality of water contained in the pits, and presents physical and environmental hazard maps of the abandoned mine site.

4.1 Sources of Hazards at the Mine Site

The abandoned Nyala Mine is generally characterized by extremely rugged terrain due to presence of extensive excavations and piles of tailings and spoil dumps at the mine site. The tailings and spoil dumps together with excavation areas were left unrehabilitated with increased potential to cause hazards. These abandoned pits contained water and the chemical characteristics of the water may present hazards.

The highwalls of the pits, erosion gullies on the tailings dumps and the ore bunker were identified to be the major sources of risk of injury from a fall that might occur as a result of their height, slope angle, and stability. Figure 4.1 presents the relative position of Zwigodini community to various mine features. All features of the abandoned Nyala Mine were identified and described in detail so as to indicate the extent or seriousness of physical and environmental hazards they present. Identified abandoned pits were denoted as Pit-I, Pit-II, Pit-III, Pit-IV and Pit-V as shown in Figure 4.1.

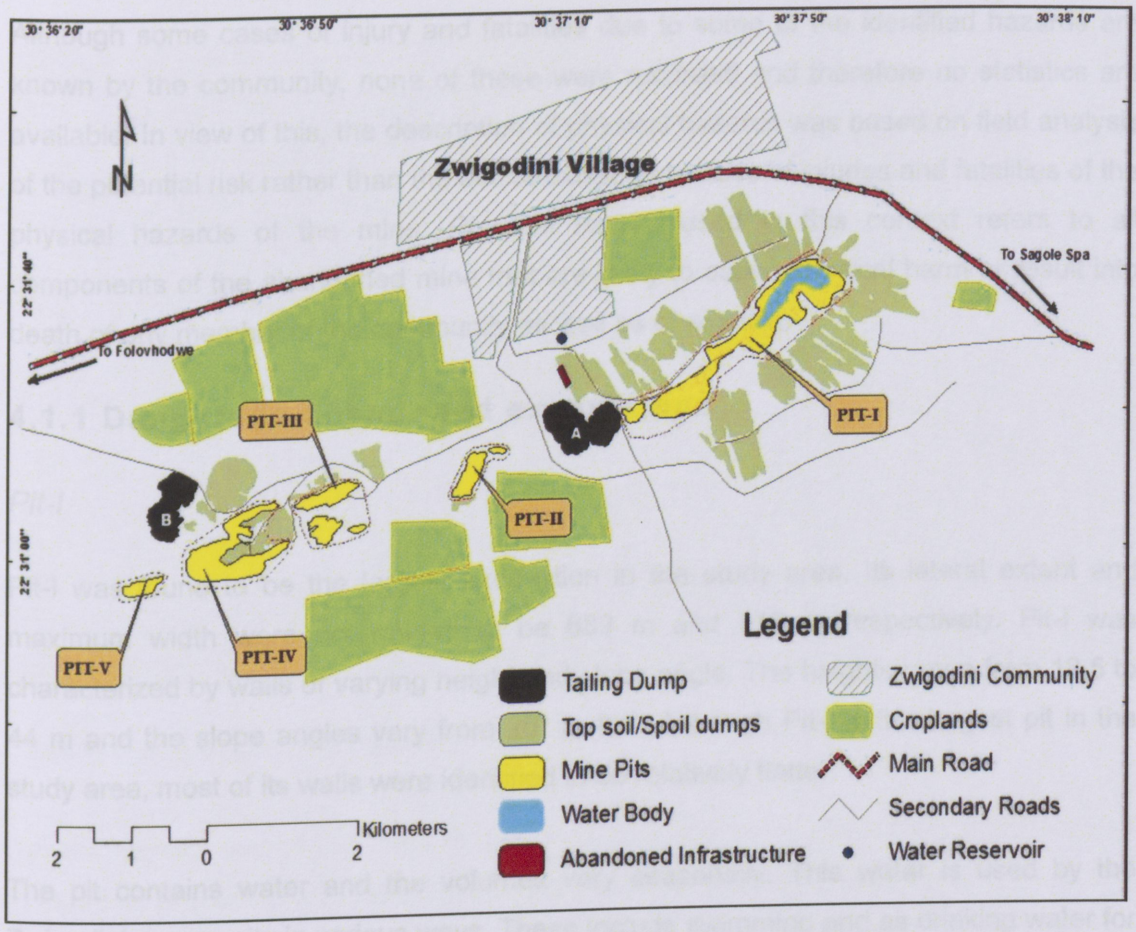


Figure 4.1: *Layout of existing features of abandoned Nyala Mine.*

Based on the field investigation the source of physical hazards identified at the mine site were dilapidated ore loading platform, large volumes of water contained in pits, and pit highwalls, exploration trenches as well as unstable and dangerous erosion gullies formed on the tailings dumps. Hazards identified to be associated with the pit lakes includes drowning risks, working hazards associated with water saturated sands in the pit floor and potential health effects of water. Objects dumped in the pit and covered by water might create a potential risk of cut and injury due to swimming in the water lake.

In addition, potential physical hazards identified to be associated with tailing material included falling from the unstable pit slopes, cut and injury by metal objects imbedded in the tailings and potential health hazards of the materials. Potential walking and tripping hazards were identified to be sharp metal edges and nails or packs identified within the study area.

Although some cases of injury and fatalities due to some of the identified hazards are known by the community, none of these were recorded and therefore no statistics are available. In view of this, the description of physical hazards was based on field analysis of the potential risk rather than the actual existing statistics of injuries and fatalities of the physical hazards of the mine. *Physical hazard* used in this context refers to all components of the abandoned mine that are likely to cause physical harm or result into death of any member of the community as well as of animals.

4.1.1 Dangerous abandoned excavations

Pit-I

Pit-I was found to be the largest excavation in the study area. Its lateral extent and maximum width were determined to be 689 m and 113 m respectively. Pit-I was characterized by walls of varying height and slope angle. The heights range from 12.5 to 44 m and the slope angles vary from 20° to 87°. Although Pit-I is the largest pit in the study area, most of its walls were identified to be relatively flatter.

The pit contains water and the volumes vary seasonally. This water is used by the Zwigodini community in various ways. These include swimming and as drinking water for livestock. In addition, fishing activities are also carried out in Pit-I water lake. The existence of fish and the fact that the water in Pit-I is daily consumed by domestic animals such as cows, donkeys, goats and others from the neighboring communities is evident that the water is less health hazardous for animals consumption. Fatal cases due to drawning as well as death of cattle as a consequence of mud trap on the pit bottom were reported to be common at Pit-I. Plate 4.1 shows the part of skeleton of an animal within the water body during dry seasons.

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Plate 4.1: *part of an animal skeleton within the water body*

Several metres east of the main Pit-I, the smaller extension of Pit-I was identified and mapped as one entity with Pit-I. This part of Pit-I was about 55.7 m in length and 35.5 m wide. In addition, the walls of this portion of Pit-I were measured to be about 2.3 to 3.0 m, while the slope angle was vertical to near vertical (ranges between 75° and 90°). There were evidence of mud cracks in some portions of the pit floor. The area can be described as semi-arid without sufficient surface waters.

Pit-II

Pit-II was located at a very close proximity to Pit-I (towards the west). This pit is about 183 m^2 with extremely hazardous walls. The most dangerous walls of this pit extend for about 159 m and attain a maximum height of approximately 15 to 20 m. The characteristics of part of the wall such as the height, steep slope angle (ranging from 82° to 104°) and instability raises serious concerns. Generally, the hazardous walls of Pit-II are caved-in (see Plate 4.2) with extensive cracks prevailing along the face and the upper surfaces of the wall.



Plate 4.2: *The hazardous cave-in highwalls of Pit-II*

Comparatively, the rest of the walls of Pit-II attain the slope angle of 32° to 55° making them relatively less hazardous. The pit floor is characterized by shrubs of acacia. In addition, the accumulation of rain water in the pit during rainy season is evidenced by mud cracks that prevail on the pit bottom.

Other Pits

Magnesite mining along the central part of the mine area was by open pit comprising of three benches of 12.5 m, 3.7 m and 6.5 m respectively from the upper bench to be bottom. This pit was denoted as Pit-III. The maximum height of highwalls of Pit-III was approximately 22.7 m. The slope angles of the benches range from 74° to 110° with 45° and 59° (prevailing only along the backfilled parts) of the pit. The width of the upper bench is approximately 3.1 m while the middle one was measured to be 11.7 m. Plate 4.3 shows the hazardous wall of Pit-III.



Plate 4.3: *High angle and unprotected hazardous walls of Pit-III.*

The pit is generally accessible to humans and animals. Animals use the water in the pit as source of drinking water and they at times get trapped in mud and eventually die. Part of the skeleton of animal which died as a result of mud trap is shown in Plate 4.4.



Plate 4.4: *Skeleton of the dead animal trapped in mud at the pit floor*

The walls of Pit-III are characterized by joints, cracks (width of cracks 15 cm) and loose blocks of rock and these present serious hazards. Evidence of toppling was identified along the walls. Generally the highwall strata in the study area consist of unconsolidated soil material, underlain by Zebra type low grade magnesite ore with intensive bedding planes that may be weak zones that can result in easy falling of rocks and soil from above.

Pit-IV is the second largest pit in the study area. The pit has relatively low walls with the height of the pit walls ranging between 5.2 to 8 m. The slope angles of the walls vary from 65° to 79°. Pit-IV was identified to be less hazardous because the pit walls are more stable and the pit is shallow. However, a section of the area was found to be having pit wall of height ranging from 16 to 18 m and attaining a near vertical angle of 86°. This was considered to be a dangerous wall and that it is located at close proximity to a foot path.

Very close to Pit-IV towards the far western part of the study area, Pit-V was identified. The height of the walls range from 7.5 m to 13 m and the slope angles vary from 78° to 86°. In addition, week zones or cracks of about 20 to 35 cm wide characterize the dangerous walls of Pit-IV as well as Pit-V; and these make the walls to be unstable.

4.1.2 Dilapidated ore bunker

The main abandoned surface infrastructure at Nyala Mine is the ore loading platform or the ore bunker. This structure was found to be 7.5 m high while both the width and breath were measured to be of equal length of 4.5 m. The structure is made up of steel frame on which the feeder box in the form of an inverted pyramid with the bottom discharge is attached. Treated *eucalyptus* logs tightly supported by large boulders against the frame were used to line walls of this structure.

The dangerous part of this structure results from the fact that most of the timbers are currently in a decayed state; resulting to the instability of the walls. The feeder box that was left at its highest point on the structure during the time the mine was abandoned was observed in the field to be gradually moving to lower positions. The feeder box current position on the structure can be seen in Plate 4.5.

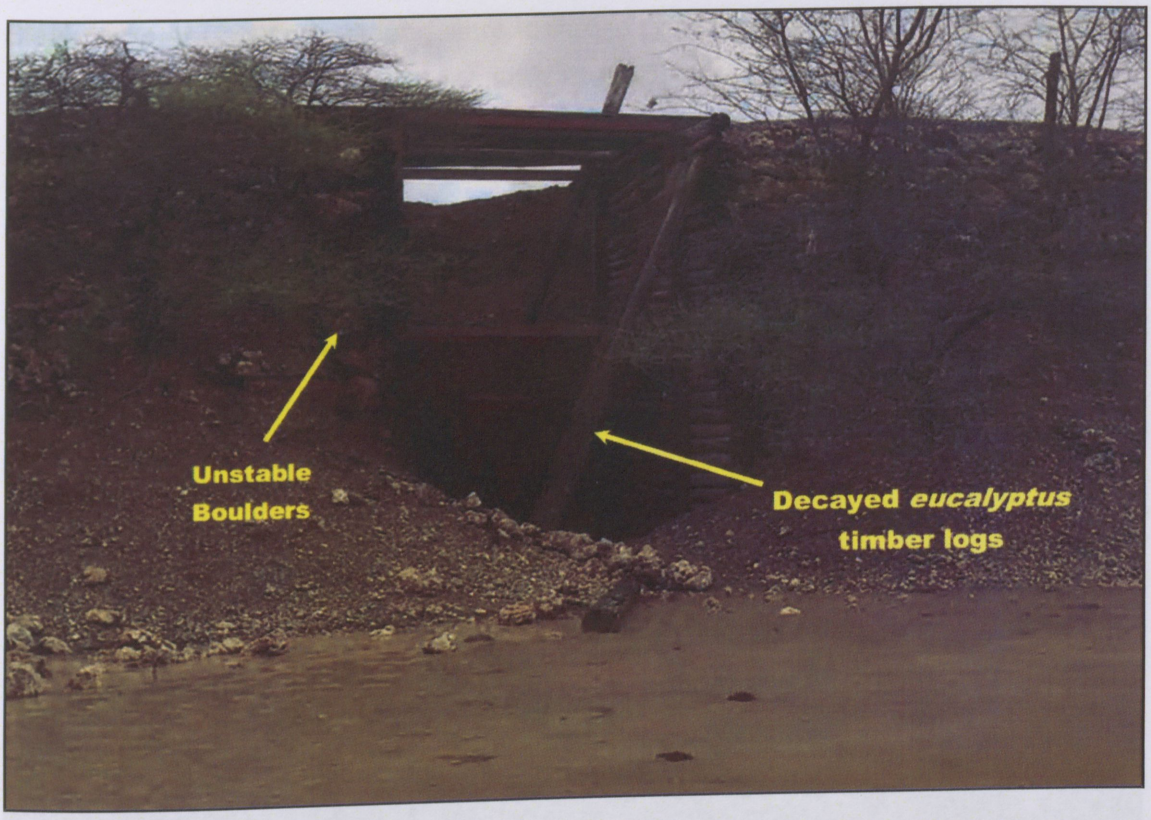


Plate 4.5: *Dilapidated magnesite ore bunker at Nyala Mine*

Generally; this structure presents risk of injuries or fatalities due to a fall of human and animals from its high walls. These risks also stem from the unstable feeder box, decaying timber logs and large unstable boulders supporting the logs. The structure poses a certain level of physical hazards to the public and because these hazards are quite visible they are relatively easier to be avoided. However children do play on the structure and therefore the risks of injury and death are high.

4.1.3 Metal containers and exposed metal edges

Scrap materials such as metal containers which are scattered all over the mine premises present risk of physical injuries. These empty drums and containers, mostly imbedded within tailing materials, present increased risk of injury as children subsequently skate down the dumps. These containers may be contaminated by unidentified chemicals and may create inhalation or skin exposure hazards.

Steel packs of about 30 cm long were identified at certain areas within the study area. Most of them occur along low laying area where rain water normally accumulates (see Plate 4.6). As a result, these exposed metal edges and nails create walking and tripping hazards in these areas.



Plate 4.6: *Exposed metal edges in water accumulated area*

4.1.4 Pit Lake

Most pits in the study area contain water during rainy seasons and dry up during dry seasons. However, Pit-I is identified with water throughout the year. The volume of water in this pit lake varies seasonally. Plate 4.7 shows the volume of water in Pit-I during rainy season.

The deep water in the pit lake (mainly during rainy days) create a drowning potential. Working hazards in the pit like are created by saturated sediments in the pit floor as they may be slippery or unstable. In addition, the rainwater that accumulate in the pit may be acidified or extremely alkaline resulting in corrosive hazard when contacted with skin and eyes. Swimming in this water presents increased physical risks as the water can hide scrape metals and rock ledges. In addition, potentially unstable pit highwalls can result in falling of rocks and loose soils from above.

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Plate 4.7: *Deep water in the pit lake during rainy seasons*

4.1.5 Tailings dumps

The study area consists of two magnesite tailing dumps covering an area of 129818 m^2. These dumps were left unrehabilitated; as a result no attempt of tailings surface protection was put in place. The tailings dumps were identified as potential source of inhalation hazards as they produce significant amount of dust during windy days. The fact that the tailings material is subsequently get carried away by wind and water, create a potential soil fertility hazard. These materials might be acidic or highly alkaline and/or contaminated by unidentified chemicals that creating inhalation, ingestion or skin exposure hazard. This also creates a potential soil degradation hazard.

4.1.6 General hazards

Confined spaces in abandoned mines turn to be excellent habitat for most reptiles (such as snakes) and dangerous insects (such as spiders, honeybees and scorpions), creating biological hazards from getting in contact with wildlife. These hazards are mostly found associated with abandoned infrastructure, old machineries/equipments and holes or ledges. These features can be as well habitat to bets, mice and rates which sometimes carry airborne diseases such as hantavirus that are fatal to human.

The other general hazard in the study area can be created by windblown dusts as they can come into contact with an eye and result into the irritation of eyes. If inhaled, these

dusts have potential to cause irritation of the throat. Continuous exposure to these dusts may lead to chronic lung diseases.

4.2 Hazard Exposure and Receptors

4.2.1 Exposure pathways

Human and living natural resources exposure to mine–related contaminants can be through direct and indirect routes. Direct exposure may include direct or dermal contact with contaminated water and mine waste on site. Accidental or intentional ingestion of sediments, drinking of water in the pit lake, and direct inhalation of fine windblown dusts particles on the atmosphere presents a potential direct exposure route to both human beings and animals.

Indirect exposure might include consumption of fish, birds, mammals and amphibians that feeds and get into contact with contaminated grounds and drink contaminated water.

4.2.2 Potential receptors

Human – tailing particles carried by water and wind may be contacted by villages, hunters any other adventurous and/or researching personas through inhalation on the atmosphere, drinking water contaminated by chemical on the atmosphere. Children playing at the mine site, especial on tailing dumps may be victims of potential skin contact hazards with the tailings materials and chemical contains imbedded within these materials. Swimming and fishing in the pit lake also expose people to skin and eye contact hazards. Risks of accidental ingestion of contaminated water during swimming in the pit lake waters are also high.

Animals- domestic animals grazing within the abandoned mine has potential of up taking the contaminants through drinking water in the pit lakes and also from grazing on the contaminated fields. Birds, amphibians and reptiles (such as monitor lizards identified at Nyala mine) has found habitat on the site, thus get exposed to the mine hazards presented by contaminated water, sediments and tailing soils.

Terrestrial plants- abandoned mines; especial tailing dumps can have detrimental effects on plants. This is due to the fact that plants get their nutrients directly from the soil and

as a result, any change in the soil chemical characteristics and structure directly affect the plant growth in the area.

Aquatic species- contaminates from different parts of the mine are carried to pit lakes where they have potential to affect aquatic species (both plants and animals). These species get to be exposed to this hazards as they inhabit within in the water in the pits. The exposure can be also through food contact with sediments at the pit floor. The roots of aquatic plants on the other hand take up chemical contaminates from sediments.

Agricultural fields- the Nyala Mine area is surrounded by a number of crop farming fields. Therefore, the dispersion of tailing materials to these fields may have severe effect on soils thus reducing the productiveness of these fields.

4.3 Conceptual Site Model of the Abandoned Mine

A conceptual site model (CSM) is a valuable analytical framework that provides visual summaries of the current understanding of the physical features of the site including known and potential sources of mine-related contamination, describes known and potential chemical migration pathways, and outlines human and ecological populations that may contact mine-related contamination or be exposed to physical hazards presented by the features of the mine. The CSM elements related to exposure media, exposure routes, and populations of concern are used to develop exposure scenarios.

The sources of environmental problems identified at Nyala Mine were large volumes of magnesite tailing dumps, spoil dumps, top soil piles as well as large volume of water contained in excavations. Generally, the site is extremely degraded with most profound surface alterations resulting from extensive diggings, tailings material and overburden spoil dumps that continuously get carried away to the surounding environs through wind and surface run-off routes. Sepage of surface water was considered to be the primary potantial pathway or route for ground water contamination.

Dengerous abandoned highwalls, exploration trenches, ore loading platform together with mine litter (such as metalic chamical containers and steel packs) left exposed to the general public were identified to be major physical hazards in the area.

Solid waste and contaminated mine water enter the environment and eventualy taken up by members of the public through ingestion, inhalation, direct contact and dermal contact. Fine magnesite dust from tailings and the rest of the extensively degraded mine

site is carried by wind for a long distance to the surrounding environs, thus infuencing the pH of soils in these areas. However, cases of animals and human drowning in some of these water bodies were reported by members of the public and remains of especially the animals were found at the site. The environmental and physical hazards of the abandoned Nyala Magnesite Mine can be conceptualised schamatically as shown in Figure 4.2.

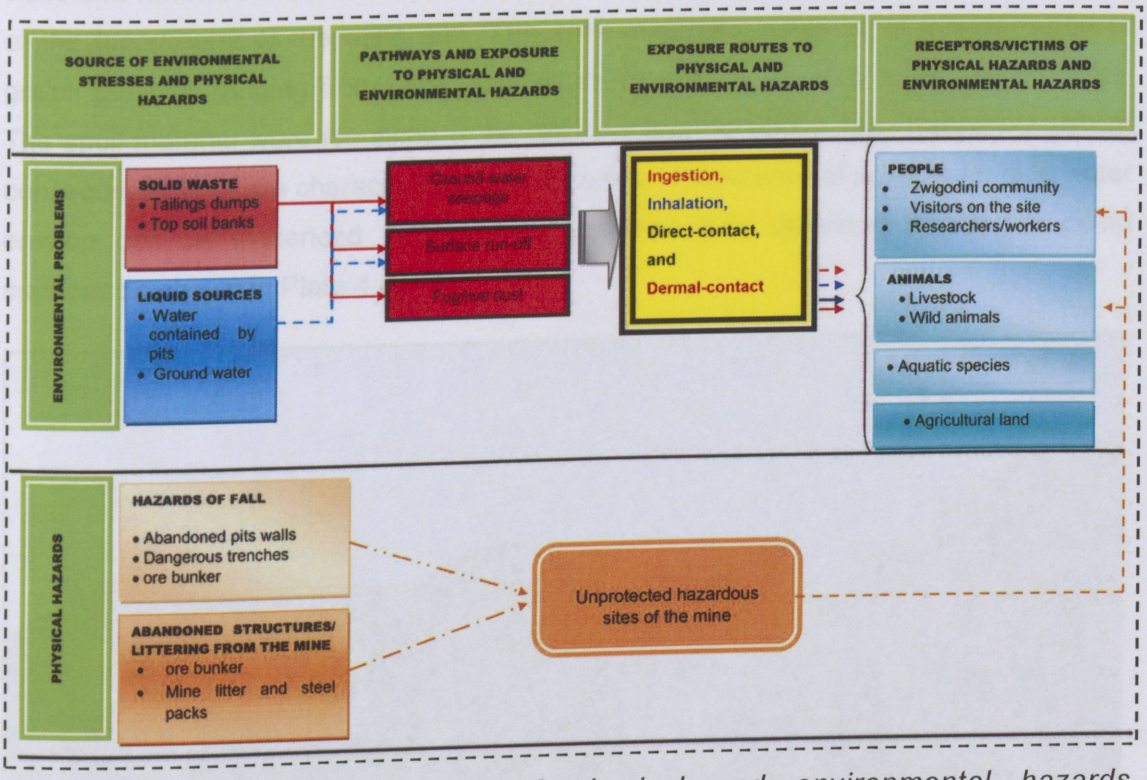


Figure 4.2: *Conceptual model of physical and environmental hazards associated with Nyala Magnesite Mine*

4.4 Characterization of Mine Wastes

4.4.1 Types of waste deposits

The site has two large-volume tailings dumps (denoted as Tailing-A and Tailing-B) and several spoil dumps. The calculated volumes of Tailing-A and Tailing-B materials were found to be 132579 m^3 and 647238 m^3 respectively. About 86% (111120 m^2) of the 129818 m^2 total area covered by tailings material was found to be overlaid by Tailing-A while Tailing-B was found to be occupying an estimated area of about 14.4% (18698 m^2) of the total. Measured slope angle of the tailing dumps at Nyala Mine ranges from 30° to 35°. The average height of Tailing-A and Tailing-B were 23 m and 20 m respectively.

The surfaces of these tailing dumps are characterized by gully formation as a result of extensive erosion and rapid run-off reoccurrence during rainy seasons. The maximum width and depth of the gullies on the dumps were found to be 8 m and 6 m respectively.

Spoil materials were observed to be covering an extensive part of the study area; especially zones around the excavations. These materials constitute piles of different sizes and were found all over the mine site. These piles have influenced the ruggedness of the topography of the mine site. The spoil materials comprise of a wide range of grains particles ranging from lager cobbles size grains to fine clay and/or silt particles. The spoil material were identified to be reach in organic matter than magnesite tailing, consequently they are characterized by dark colour. Resistance of spoil material to water erosion can be evidenced by extremely reduced gully development on the dump surfaces as shown in Plate 4.8.

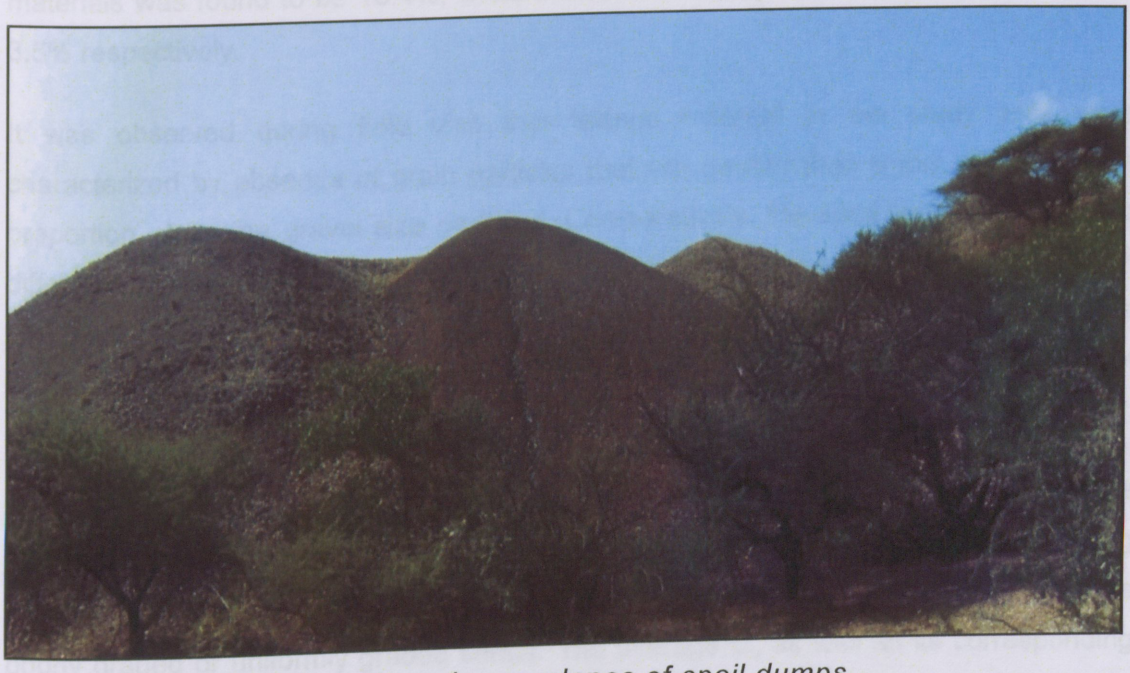


Plate 4.8: *Limited effect of erosion on slopes of spoil dumps.*

Apart from the fact that this material showed evidence of resisting water erosion better than magnesite tailing materials, it also promotes vegetation growth better. There is evidence of growth of *aristida-congesta-subsp* grasses at the toe of the slopes of the spoil dumps. Generally, the growth of grasses and few acacia trees were identified in areas completely covered by spoil materials or where these materials are found mixed with tailings materials such as along the base of magnesite tailings.

4.4.2 Physical characterization of mine wastes

Physical characterization of abandoned waste materials in the study area was carried out to establish their physical properties in terms of their grain size distribution. This section describes the physical properties of both tailing and spoils heaps a material in terms of the grain size distribution curves as well as the calculated coefficient of uniformity and curvature. A summary of the computations for this purpose is presented in Appendix-B.

The gain size analysis for both tailings and spoil materials comprised of grains spanning from fine gravel, sand and silt to clay particles. The calculated average percentage for gravel in tailings was found to be 18.2% while the average sand and clay particles were found to be 84.5% and 3.2% respectively. The average gravel percentage in spoil materials was found to be 18.4%, while the sand and clay was found to be 78.0% and 3.5% respectively.

It was observed during field visit that tailings material in the study area were characterized by absence of grain particles that are greater than 8 mm with very little proportion of coarse gravel size particles. Comparatively, the spoil material showed to differ from tailings dumps in one respect; this was that they appeared to comprise of high percentage of grains that are greater than 11 mm (coarse gravel, cobbles and large boulders). These large boulders and cobbles were mostly observed along the base of the spoil dumps.

Grain size distribution curves of the mine wastes are presented in Figure 4.3. The interpretation of the steep slope gradient of the plotted gradational curves for both tailing and spoil materials (see Figure 4.3) qualified the classification of these materials as poorly graded or uniformly graded sands. The average C_u as well as its corresponding C_c values for tailing material ware found to be 10.97 and 1.09, while those of spoil material were found to be 9.97 and 1.14 respectively.

According to Unified Soil Classification System (USCS) classification criteria; the computed average C_u values for both materials was found to be greater than 6 and C_c values found to be ranging between 1 and 3 (below 4) justified the classification of these materials as well-graded sands. This was also supported by the fact that both materials comprise of less than 5% silt to clay particle sizes (those are particles that were able to

pass through 63 m sieves). The similarity of grains comprising both tailings and spoil materials at the study area can be interpreted from the grain size distribution curves lying almost parallel to each other (see Figure 4.3).

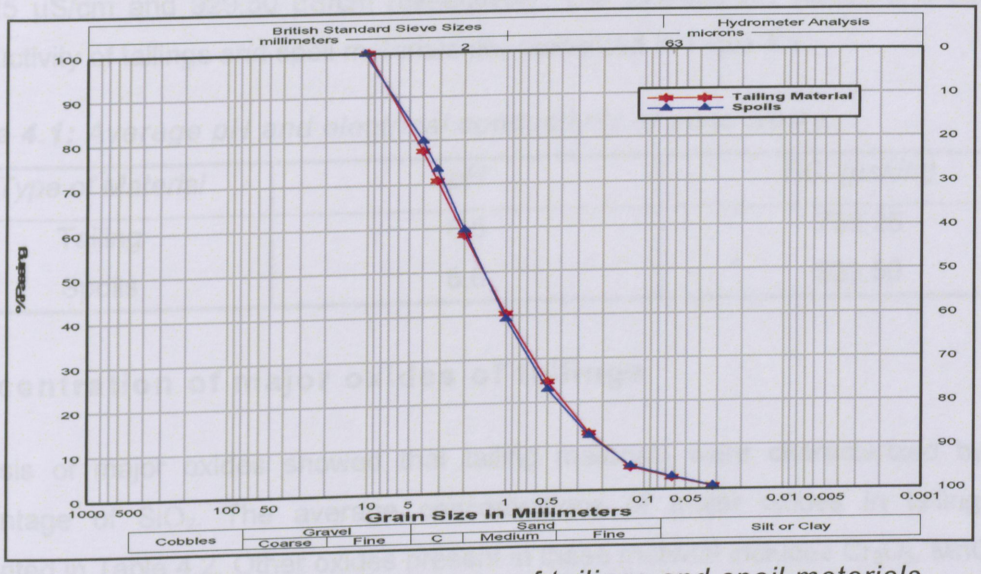


Figure 4.3: *Grain size distribution curves of tailings and spoil materials.*

Although both materials were classified as well-graded sand, field inspection revealed that the spoils consist of high organic matter than tailing materials. Generally, the dark brown colour characterizing the spoils suggests the presence of organic matter in these soils; while magnesite tailings possess white colour suggesting their deficiency of organic matter.

These slight differences of physical properties of the waste materials required that strategic backfilling be adopted. These will involve systematic backfill of deeper voids with tailing materials then overlaying them with spoil materials. However, the backfilled and disturbed areas will require that suitable cost effective fertilizers such as livestock manure is applied to improve the soil structure and balance plant nutrient for easy adaptation of vegetations.

4.4.3 Chemical characterization of mine waste

Results of pH and electrical conductivity of tailings and spoil

Generally, pH has very little direct but increased nutrition effects to plant growth. Both tailing and spoil materials in the study area were analyzed based on their measured pH values as well as their corresponding electrical conductivity.

The pH analysis of the samples collected from tailings and spoil dumps revealed that both materials are alkaline; characterized by average pH values of 8.5 (tailings) and 8.6 (spoil). The average electrical conductivity for tailings and spoils ware found to be 738.25 µS/cm and 929.50 µS/cm respectively. The average pH values and electrical conductivity of tailings and spoil materials are presented in Table 4.1.

Table 4.1: *Average pH and electrical conductivity of mine waste.*

Type of Material	*pH*	*EC. (µs/cm)*
Tailing	8.5	738.25
Spoils	8.6	929.50

Concentration of major oxides of tailings

Analysis of major oxides showed that tailing materials were characterized by high percentage of SiO_2. The average concentrations of major oxides in tailings are presented in Table 4.2. Other oxides present in these material includes Cr_2O_3, MnO, and Na_2O respectvely contributing less than a percent of the composition. In addition, about 13.70% of the composition was found to be corresponding L.O.I properties of the material.

Table 4.2: *Avarage concentration of majer oxides in tailing.*

Sample	*Major oxides concentrations in tailings (%)*		
	Tailing-B	Tailing-A	Average
SiO_2	45.82	40.82	43.32
TiO_2	2.25	2.20	2.22
Al_2O_3	4.10	3.88	3.99
Fe_2O_3(t)	10.90	11.97	11.43
MnO	0.14	0.15	0.15
MgO	19.02	22.11	20.56
CaO	3.82	3.66	3.74
Na_2O	0.12	0.12	0.12
K2O	0.48	0.37	0.42
P_2O_5	0.13	0.16	0.15
Cr_2O_3	0.19	0.21	0.20
L.O.I.	13.05	14.34	13.70
Total %	*100.02*	*99.97*	*100.00*

Concentration of major elements of tailings

The analysis of major element concentrations in tailings material was found to be mostly consisting of Si, Mg, and Fe and relatively small amount of Ti, Al, and Ca. Very little concentrations of P, Cr. Mn and K were obseved in all samples. The avarage concentrations of these elements are presented in Table 4.3. Reduced average levels of P (0.03 ppm), Cr (0.07 ppm) and K (0.18 ppm) were identified characterizing these materials.

Table 4.3: *Average concentrations of major elements in tailings*

Major Elements	*Concentration of major elements in tailings (ppm)*		
	Tailing – A	Tailing – B	Average
Si	20.74	19.75	20.24
Ti	1.51	1.15	1.33
Al	1.10	1.01	1.05
Fe	4.39	3.61	4.00
Mn	0.12	0.11	0.11
Mg	11.89	12.88	12.39
Ca	2.43	2.91	2.67
Na	0.05	0.03	0.04
K	0.18	0.17	0.18
P	0.03	0.03	0.03
Cr	0.08	0.06	0.07

4.5 Interpretation of Soil Fertility

The analysis of magnesite tailings indicated that these materials have average pH level of 8.5 and the EC of 739.25 µ/cm. Generally, the soil pH has direct influence on the availability of significant amount of plant nutrients in soils. According to Moody (2006), alkaline soils are commonly characterized by problems of micronutrients deficiency such as zinc, copper, iron, boron and manganese. Major element analysis showed much reduced iron and manganese concentrations. Although the total Mn concentration cannot be used to predict plants respond, magnesite tailings were found to be far below the 4.00 ppm total Mn worldwide soil concentration. According to Ross (1992), any less

than 1.0 ppm of Mn concentration in soil is at the deficiency range for plant growth, while greater than 2.0 ppm but less than 4.5 ppm Fe concentrations are considered marginal.

Soil pH also has effect on the availability of major nutrients for plant growth on soils. These nutrients include phosphorous (P), nitrogen (N) and potassium (K). The effects of soil pH to nutrients availability can be attributed to the availability of P and this availability depends much on the way and manner at which it reacts with other minerals, mostly macronutrients such as Fe, Ca and Al. For alkaline soils of greater than 7.5 pH levels, phosphates ions are known of reacting quickly with Ca and Mg to form less soluble compounds. The relative abundance of Fe (4.00 ppm), Ca (2.67 ppm) and Al (1.05 ppm) on magnesite tailing soils has potential of promoting this reaction with P (0.03 ppm); thus fixing it to make it unavailable to plants.

Despite the pH level, the infertility of the tailings and spoil materials can be also related to the textural characteristics of these materials. Generally, the soil texture has effect on the ability of soils to retain nutrients and water. The textural analysis of both tailings and spoils proved these materials to be sandy in nature. This is because the spoils materials were found to be comprising of 78% sand, 18.45% gravel and 3.5% silt/clay particles; while the tailings materials were characterized by 78.7% sand, 18.2% gravel and 3.2% silt/clay. According to Troeh and Thompson (1993), sandy soils have limits of low water holding capacity, thus leading to easy leaching or washing away of nutrients from the soils.

4.6 Results of Water Quality Analysis

The pH analysis of water samples from Pit-I revealed that the water is strongly alkaline in nature; with pH values ranging from 9.3 to 9.9. The average pH of this water was found to be 9.2. The comparison of the average pH values with standards for domestic use of water as prescribed by DWAF was found to be above the target water quality as shown in Table 4.4. According to this standard the average water pH level of 9.2 has increased potentials of toxic effects associated with deprotonated species such as ammonium and to cause the water to taste bitter.

The electrical condictivity of the water in Pit-I was found to be in the range of 2.26 mS/cm to 2.39 mS/cm with an avarage of 2.30 mS/cm. this avarage electrical condactivity was found to be within the reccomended water quality range for domestic

use (see Table 4.4). As a result, no health and aesthetic and/or economic effect associated with the measured avarage EC was identified.

Table 4.4 : *pH and EC of water in abandoned excavetions*

	pH	*EC (mS/cm)*
Avarage values	9.2	2.30
DWAF standards for domestic use	*6.0 - 9.0*	*0 - 70*

The result of analysis of anions concentrations in water are presented in Table 4.5. The analysis of anions included Fluoride (F^-), Chloride (Cl^-), Nitrate (NO_3^-), Phosphate (PO_4^{3-}) and Sulphate (SO_4^{2-}) for which their average concentrations levels were detected at 1.09 ppm, 169.63 ppm, 0.63 ppm, -0.04 ppm, and 0.71 ppm respectively. These average values were compared with presented standards by DWAF. Generally all samples showed elevated concentrations of Cl^- (ranging from 163.99 ppm to 180.22 ppm), while F^- were within the range of 1.04 ppm to 1.12 ppm. Highly reduced concentrations of NO_3^- (0.60 ppm to 0.99 ppm) and SO_4^{2-} (0.50 ppm to 1.05 ppm) were detected in all five samples. With an exception of SW-05 (-0.21 ppm) all water samples indicated the absence of PO_4^3 (see Table 4.5). Although the Cl^- concentration (169.63 averages) in this water is above 0-100 ppm targeted range for domestic use, the water has no aesthetic or health effects but it may increase corrosion rate in domestic appliances (Department of Water Affairs and Forestry, 1996). The 1.09 ppm fluoride concentration generally has potential to cause slight mottling of dental enamel in sensitive persons.

Table 4.5: *Anions concentration in water samples*

Sample No:	*Concentration of anions (ppm)*				
	F^-	Cl^-	NO_3^-	PO_4^{3-}	SO_4^{2-}
WS-01	1.07	180.22	0.60	-	1.05
WS-02	1.12	168.48	0.61	-	0.58
WS-03	1.04	170.77	0.99	-	0.50
WS-04	1.09	163.99	0.69	-	0.84
WS-05	1.12	164.68	0.91	-0.21	0.61
Average	*1.09*	*169.63*	*0.76*	*-0.04*	*0.71*
DWAF standards for domestic use	*0-1.0*	*0-100*	*0-6*	-	*0-200*

The concentration of cations in Pit-I water was also analyzed. This included the analysis of Sodium (Na^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Potassium (K^+), and Iron (Fe^{3+}). The results of the analysis are presented on Table 4.6. Generally, all the five samples showed elevated concentrations of Mg and K with average values recoded as 67.85 ppm and 87.16 ppm. These values were found to be above the recommended concentration range for domestic use prescribed by DWAF. Comparatively, the Na and Ca concentrations were found to be at relatively low levels (within the recommended standard range); that is 8.22 ppm and 15.67 ppm respectively (see Table 4.6).

Extremely reduced Fe^{3+} levels in this case can be explained as a result of the elevated measured pH of water. This is due to the fact that pH plays a significant role in Fe^{3+} precipitation in water. The lower the pH values the more iron is precipitated and vice versa. Therefore, strong alkaline pH of water presented conditions that were not favorable for iron precipitation, thus the average concentration obtained from the analysis was -0.27 ppm (see Table 4.6).

Table 4. 6: *Cations concentrations in water samples*

Sample No:	*Concentration of cations (ppm)*				
	Na^+	Ca^{2+}	Mg^{2+}	K^+	Fe^{3+}
WS-01	7.61	9.86	63.50	86.00	-0.03
WS-02	8.03	15.08	67.50	84.00	-0.03
WS-03	8.30	16.92	70.75	86.80	-1.21
WS-04	8.27	17.38	68.00	85.80	-0.03
WS-05	8.87	19.10	69.50	93.20	-0.03
Average	8.22	15.67	67.85	87.16	-0.27
DWAF standards for domestic use	*0-100*	*0-32*	*0-30*	*0-50*	*0-0.1*

With reference to the Department of Water Affairs and Forestry (1996), the measured average potassium concentration (87.16 ppm) in this water has no aesthetic and health effect to adults. However, this concentration is undesirable for infants or persons with renal diseases. Full contact with this water can cause severe eye, skin, ear and mucous membrane irritation with advanced aesthetic taste when accidentally swallowed.

These problems can be attributed to be the result of elevated pH values (average of 9.23). This pH value is also out of the 6.5 – 9.0 recommended or target pH for

successful fish health and reproduction. On the other hand, the 67.85 ppm magnesium concentration has no health problems or bitter taste of water, but it can lead to the development of scaling problems. In addition, the growth of algae in the water presents slight limits in the use of this water for recreational purposes thus it makes the water to be visually unappealing with increased unpleasant odour due to algae decaying in water.

4.7 Hazard Map of Abandoned Nyala Mine

Based on the method of physical and environmental hazard classification and rating presented in the previous chapter; individual hazards (physical or environmental hazards) identified in the study area were ranked and placed into different classes which were then used to construct the Nyala Mine site hazard maps. The hazard rating of the features took into consideration the magnitude of danger they present, the level of attention they require and the complexity of strategies to be adopted to resolve the problems.

4.7.1 Classification of physical hazards

The seriousness of the hazards presented by the features identified at the abandoned mine site were determined in terms of the score and classification procedure described in chapter 3. Based on the score the mine features were assigned into four classes namely A, B, C and D. The classification was as follows: Class-A (≥ 90), Class-B (61-89), Class-C (31-60) and Class-D (≤30). Class-A involved features that require special rehabilitation design while Class-B consist of those features of the mine that require general mitigation approaches of all identified physical hazard sources. Class-C involves features that are characterized with reduced hazards that can be easily avoided whilst Class-D comprises of those features that carry a negligible level of physical hazards (this includes excavations with only portion of unstable hazardous walls. A summary of calculations of scores and the nature of identified hazards is presented in Appendix-A1.

The two mine features classified as extremely hazardous were Pit-I and Pit-III both categorized under Class-A as shown in Table 4.7. Major risks of physical hazards at Pit-I were found to be the volume and quality of water contained by the pit. In the case of Pit-III the major source of physical hazards was identified to be the unstable highwalls as well as the water body and its associated sticky mud at the pit bottom.

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The ore bunker, Pit-II and topsoil piles or spoil materials were assigned to Class-B. The risk of falling off from the unstable highwalls and falling off of the walls themselves due to their instability were the identified major physical hazards of Pit-II. The hazard of exposure to fine magnesite dust generated from the surface of the spoil together with the risk of falling from the steep slopes of these dumps were the identified hazards associated with the overburden waste materials in the study area.

The magnesite tailing dumps (both Tailing-A and Tailing-B) were categorized as less hazardous features of the mine and were assigned to Class-C. Pit-IV and Pit-V were assigned to Class-D due to the very low physical hazard total scores. The major hazard of these pits included the risks of falling from highwalls or falling off of the unstable highwalls. There was no evidence of large volume water accumulation on the floor of these pits.

Table 4.7: *Abandoned mine site physical hazards classification*

Abandoned Site features	*Physical Hazards Total Score*	*Class*	*Risks Identified*	*Colour*
Pit-I	93.66	A	6	Red
Pit-III	110.27	A	6	Red
Pit-II	63.00	B	6	Purple
Ore Bunker	88.18	B	4	Purple
Topsoil/Spoils	85.90	B	3	Purple
Tailing-A	49.87	C	6	Blue
Tailing-B	41.67	C	6	Blue
Pit IV	8.82	D	6	None
Pit-V	13.61	D	6	None

Based on the field description of the mine site features as well as the scoring of their associated physical hazards, the hazard map of the abandoned Nyala Magnesite Mine was constructed and is shown in Figure 4.4. The map shows the relative position of each mine feature. The magnitude of physical hazard they present is shown by different

colour codes; where extreme hazard were shown by red colour, moderate hazard with purple colour and the low hazard were coded blue. Extremely reduced or negligible hazards were not assigned any colour code.

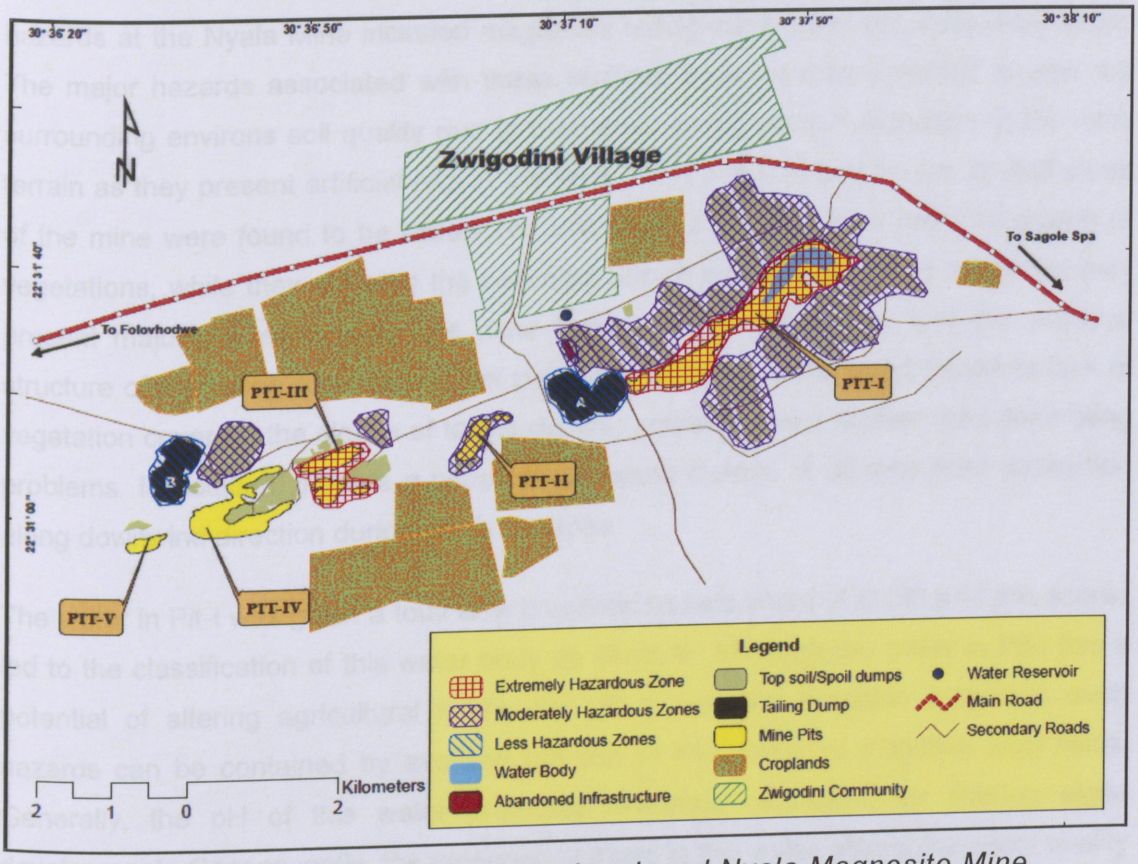


Figure 4.4: *Physical hazard map of an abandoned Nyala Magnesite Mine*

4.7.2 Categorization of environmental hazards

The environmental hazards scores were assigned to each of the identified major mine features to determine seriousness of the problem and their corresponding classes. Similar to physical hazard classification, the break point numbers of 10, 8 and 6 were used as indicated in Chapter Three.

The classification of hazards categorized all mine features that extremely reduces the capabilities of the mine site environment as Class-A. Mine features characterized by containable hazards fell under Class-B while those with slight influence to the environment were classified under Class-C. The environmental hazard scores assigned to various Nyala Mine features and their respective classes are shown in Figure 4.6. According to the classification system, the abandoned ore bunker was the only feature

with negligible level of environmental hazards. Summarized calculations of environmental hazard scores are presented in Appendix-A2.

The mine features assessed to be carrying extremely high levels of environmental hazards at the Nyala Mine included magnesite tailing dumps and the excavated areas. The major hazards associated with these features included their potential to alter the surrounding environs soil quality due to their easy erodibility and alteration of the mine terrain as they present artificial hills in the area. On the other hand the excavated areas of the mine were found to be associated with lack of fertile soils to promote growth of vegetations, while they are also the consequence of ruggedness of the terrain as they present major depressions on the mine terrain. The geochemistry and the physical structure of the tailing materials do not promote vegetation growth and therefore lack of vegetation cover on the slopes of tailing dumps, presents major fugitive dust generating problems. In addition, there is a potential increased chance of alkaline soils deposition along downwind direction during windy seasons.

The water in Pit-I was given a total environmental hazard score of 69.95 and this scores led to the classification of this water body as Class-B. Although the water in Pit-I has a potential of altering agricultural field's soil pH if used for irrigation purposes, such hazards can be contained by avoiding the use of this water for irrigating crop fields. Generally, the pH of this water promotes favorable conditions for floating algae development. Consequently, the presence of algae in this water affects the water quality and gives the water an unpleasant look and odour. Despite the limited use of this water for domestic, recreational and agricultural purposes; the algae in the water also reduces fish reproduction level as it prevents sun from reaching certain areas of the water, a requirement for maximum fish reproduction.

The spoil dumps in the study area were classified to be less hazardous. The major hazards associated with the spoils included in-situ soil pH alteration and change in topography. The spoil material also presents risks of erosion by water and wind erosion.

The abandoned ore bunker was classified under Class-D and was considered to have low level of environmental hazards. The only main environmental problem associated with the ore bunker in the study area was that it occupies an area for further development. The type of environmental hazards identified, their corresponding scores and classes are presented in Table 4.8.

Table 4.8: *Abandoned mine site environmental hazards classification*

Abandoned Site features	*Total Hazard Score*	*Class*	*Risks Identified*	*Colour*
Tailing dumps	130.41	A	7	Red
Excavations	104.31	A	5	Red
Water body	69.95	B	3	Purple
Spoil dumps	50.62	C	3	Blue
Ore bunker	5.60	D	2	None

The average scores assigned to each mine feature was use in the construction of an environmental hazard map of the mine as presented in Figure 4.7. The degree of impact associated with each feature can be described by the assigned colour codes.

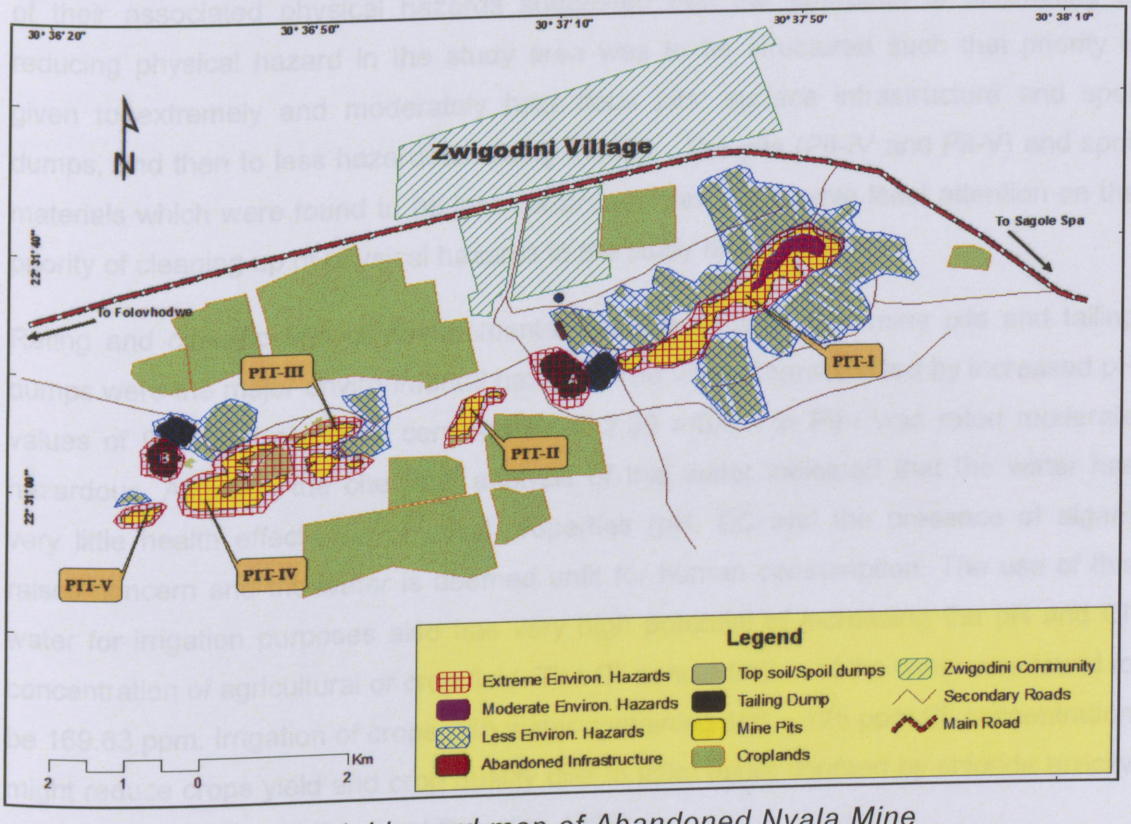


Figure 4.7: *Environmental hazard map of Abandoned Nyala Mine*

4.8 Summary

The site characterization component of this study showed that the Nyala Mine is characterized by extremely rugged terrain with pronounced level of physical and

environmental hazards. Generally, mining operation in the area has created a landscape of wasteland with extremely reduced capacity to support various land uses. According to the developed conceptual site model (CSM), the identified environmental stresses at the abandoned mine site were spoils and tailing dumps, and abandoned ore bunker. The physical hazards at the mine site comprised of highwalls of the abandoned pits together with deep erosion gullies of the tailing surfaces, ore loading platform and mine litter.
The rating of the identified physical hazards in the study area showed that Pit-I, Pit-II and Pit-III were moderately to extremely hazardous. Other mine features such as spoil dumps with metal edges, and abandoned infrastructure (that is the ore bunker) were rated as moderate physical hazards. In addition, tailing dumps characterized with wide and deep unstable erosion gullies and empty chemicals metal containers; were classified as less hazardous. The rating and classification of the mine features in terms of their associated physical hazards suggested that the approach of eliminating or reducing physical hazard in the study area was to be structured such that priority is given to extremely and moderately hazardous pits; surface infrastructure and spoil dumps, and then to less hazardous tailing dumps. The pits (Pit-IV and Pit-V) and spoil materials which were found to be less hazardous were to receive least attention on the priority of cleaning up of physical hazards in the study area.

Rating and classification of environmental hazards showed that mine pits and tailing dumps were the major environmental hazards. The water characterized by increased pH values of 9.23 and electrical conductivity of 2.30 mS/cm in Pit-I was rated moderate hazardous. Although the chemical analysis of this water indicated that the water has very little health effects, its physical properties (pH, EC and the presence of algae) raises concern and the water is deemed unfit for human consumption. The use of this water for irrigation purposes also has very high potential of increasing the pH and Cl^- concentration of agricultural or crop field. The Cl^- concentration of the water was found to be 169.63 ppm. Irrigation of crops with water containing 100 – 175 ppm Cl^- concentration might reduce crops yield and crop quality due to foliar injury coursed by chloride toxicity (Department of Water Affairs and Forestry, 1996).

According to the Department of Water Affairs and Forestry (1996), pH levels that are greater than 9 are not recommended for successful fish health and production. Therefore the water in Pit-I could only be used by domestic and wild animals as drinking water since there is no alternative stream or water body nearby Zwigidini area.

CHAPTER FIVE

SURFACE MODELING AND DESIGN OF REHABILITATION STRATEGIES

The method described in Chapter Three was used to collect the elevation data for estimation of the surface model of the abandoned Nyala Magnesite Mine. The final surface of the mine was developed in five (5) meaningful segments covering the mine landscape. Figure 5.1 shows the portions of the mine site covered by these segments as denoted as Area-1 to Area-5.

This section is earmarked for development of terrain models as well as the simulation of the different landform designs for the development of cost-effective rehabilitation strategies for the site. The summary of results for the evaluation of appropriate rehabilitation strategies is presented in Appendix-C.

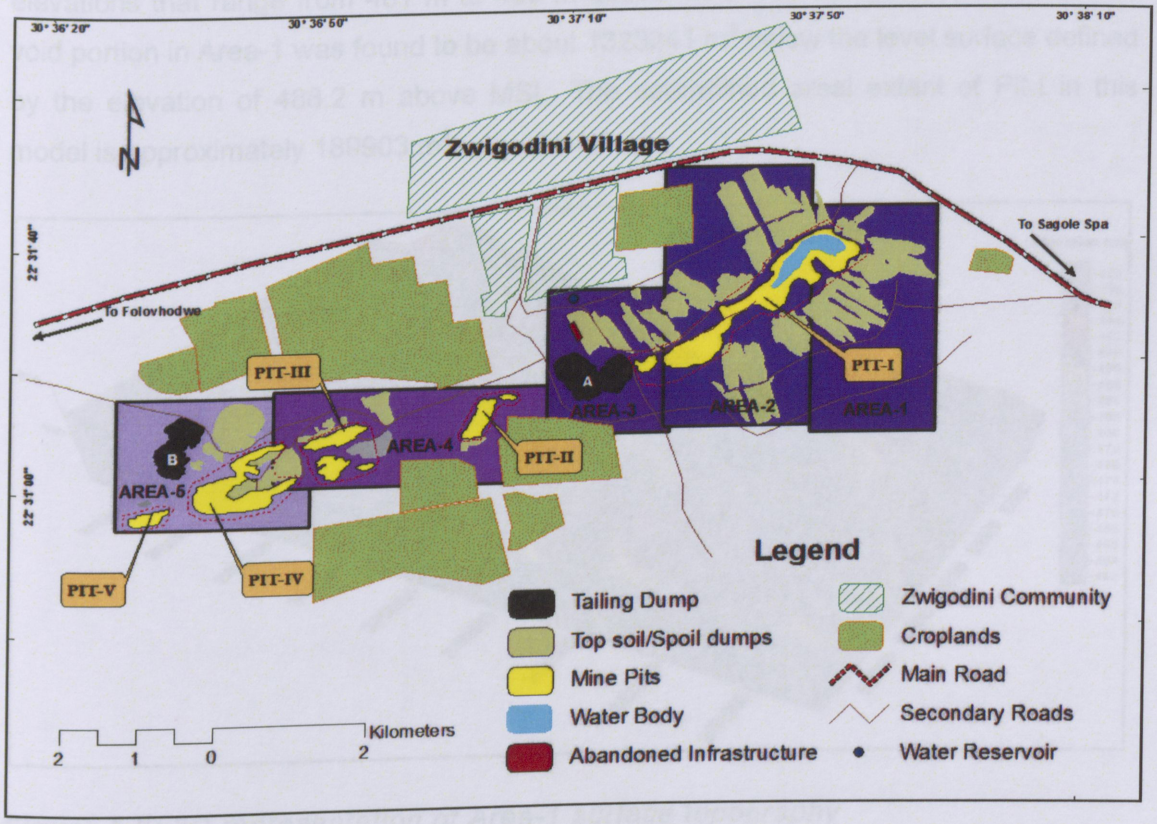


Figure 5.1: *Areas delineated for landform modeling and simulation*

5.1 Surface Model of Area-1

Area-1 model covers a plane area of about 558103 m^2 along the southern part of Pit-I which is the only main feature covered in the model. This terrain model was produced using grid consisting of 948 points. The surface model of Area-1 is shown in Figure 5.2.

The analysis of terrain slopes showed that Pit-I portion covered in the model ranges between 14° (minimum) to 44° (maximum) (24.9% - 96.6 % grades). They attain the maximum height of approximately 29 m. The spoil dumps directly above the south east facing walls added about 14 m extra height of the wall. As a result, some part of Pit-I in the model reaches the depth of up to 43 m. An extensive portion of the model northward of grid line 2492500 and the Pit-I zone of the model was recognized to be dominated by grounds of greater than 489 m above MSL. These portions of the terrain consist of the maximum elevation of up to 501 m above MSL. The same elevation (> 489 m) was also identified on the far western part of Pit-I.

Generally, the larger area of Area-1 surface model is dominated by areas of the elevations that range from 481 m to 489 m above MSL. The computed volume of Pit-I void portion in Area-1 was found to be about 1323241 m^3 below the level surface defined by the elevation of 488.2 m above MSL. The determined areal extent of Pit-I in this model is approximately 189903 m^2.

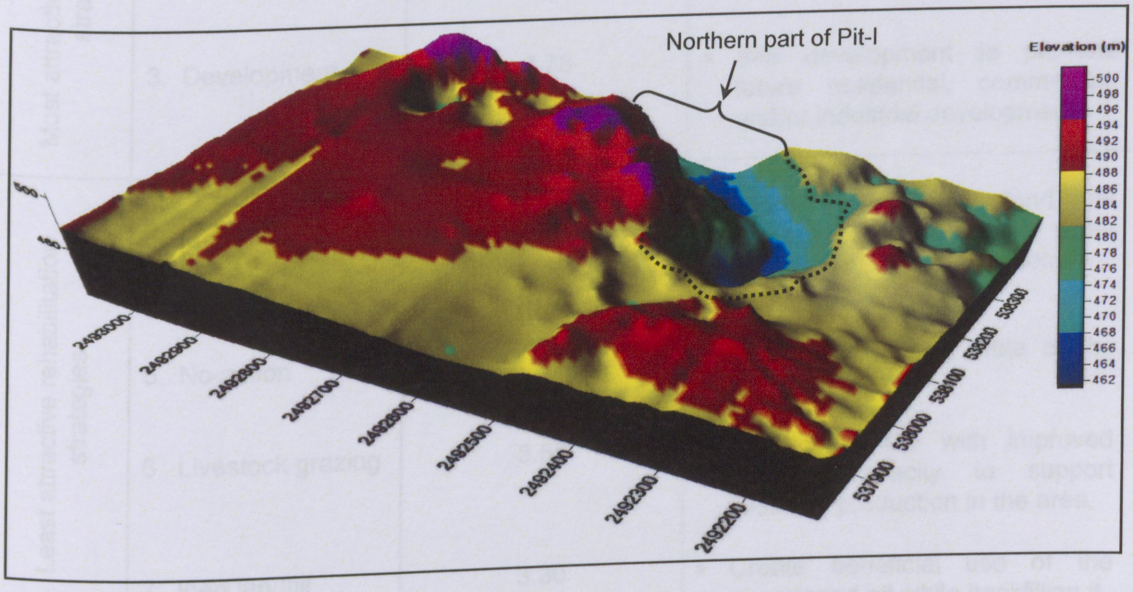


Figure 5.2: *3D representation of Area-1 surface topography*

5.1.1 Rehabilitation alternatives for Area-1

Seven rehabilitation strategies were selected for Area-1 modeled portion of the mine that cover the southern portion of Pit-I. These rehabilitation strategies ranged from doing nothing (no-action) to the rehabilitation of the mine to beneficial use of the land. Table 5.1 presents all the seven selected rehabilitation strategies and their computed sum total attractiveness scores.

The computed sum total attractiveness score of the selected rehabilitation alternative as presented in Table 5.1 showed that crop farming alternative is the most attractive strategy with the highest score of 5.70, followed by the development of pit lake, and development of the site for settlement purposes carrying the scores of 4.95 and 4.75 respectively.

Table 5.1: *Selected and evaluated strategies for rehabilitation of Area-1*

	Rehabilitation alternatives	*Sum Total Attractiveness Score*	*Driver for end land use*
Most attractive rehabilitation strategies	1. Agriculture: crop farming	5.70	▪ Strive to create stable crop lands.
	2. Pit lake	4.95	▪ Create the lake and native animal habitat
	3. Development	4.75	▪ Site development to promote future residential, commercial, and/or industrial development
Least attractive rehabilitation strategies	4. Recreational: Dirt park construction	4.55	▪ Strive to develop a land that support both inland and water based recreational activities.
	5. No-action	3.55	▪ Retain the current state of the site
	6. Livestock grazing	3.55	▪ Develop a site with improved grazing capacity to support livestock production in the area.
	7. Inert landfill	3.30	▪ Create beneficial use of the abandoned pit while backfilling it.

The implementation of the three most attractive rehabilitation strategies will require grading and reshaping of the spoil dumps around Pit-I portion of the surface model. These will involve the development of smooth surface with a capacity to support crop farming, development of the land for settlement purposes, and the development of picnic facilities around the proposed pit lake.

The terrain model for rehabilitation of Area-1 surface was designed as illustrated in Figure 5.3. The design involved defining the volume of material required to fill the void areas below the adopted level surface of 488.2 m above MSL. According to the surface rehabilitation simulation model in Figure 5.3 the development of a relatively flat landscape of Area-1 will require grading of about 550757 m^3 high grounds materials to fill the void of approximately 276440 m^3.

The plane area occupied by Cut material was found to be 39413 m^2 while the surface area of the pit was found to be 32878 m^2. The surface areas corresponding to the above mentioned plane areas were measured to be 39446 m^2 and 327932 m^2 respectively. Large volume Cut material will be graded from the portion of the model northward of Pit-I to fill low laying grounds along the west and southern part of the rehabilitation terrain model (see Figure 5.3).

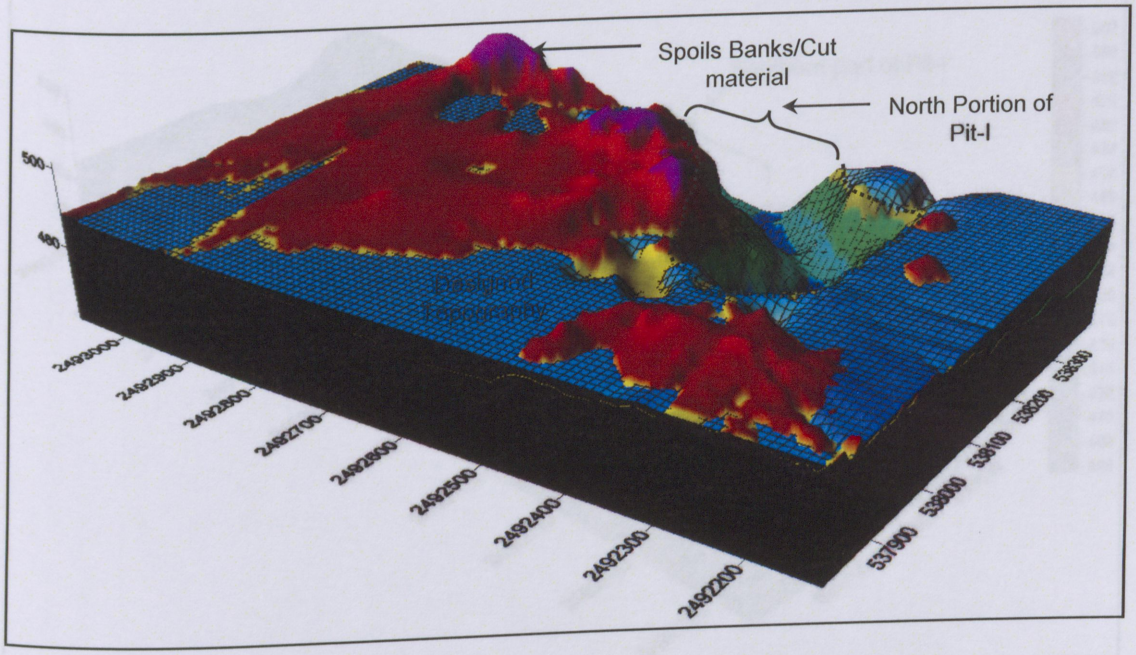


Figure 5.3: *3D illustration of Area-1 rehabilitation surface*

5.2 Surface Model of Area-2

The 3D surface model of Area-2 of the mine extends over the plane area of 379141 m^2 while covering the south west portion of Pit-I and its surrounding terrain. Area-2 surface model was developed using 1181 points grid file. The model shows extremely rugged terrain around Pit-I portion and this is due to relatively small excavations as well as the carelessly dumped overburden and/or spoils material found in the area. The portion of Pit-I covered in the model is characterized by steep highwalls (ranging from 8° to 50°; that is 14.1% to 119.2% steepness) that attains the average height of approximately 20 m. The spoil dumps directly above the north facing highwalls of the pit extended the wall height to about 36 m.

Generally, the larger portion of this section of the mine is characterized by elevations that range between 484 m to 491 m above MSL. Despite Pit-I section of Area-2, the model shows the dominance of relatively small zones of 478 m to 484 m above MSL along the south; that is between the grid of 2492100 and 2492500 (see Figure 5.4). Consequently, zones of greater than 491 m above MSL are identified along the north west and south east of the south west; north east trending Pit-I.

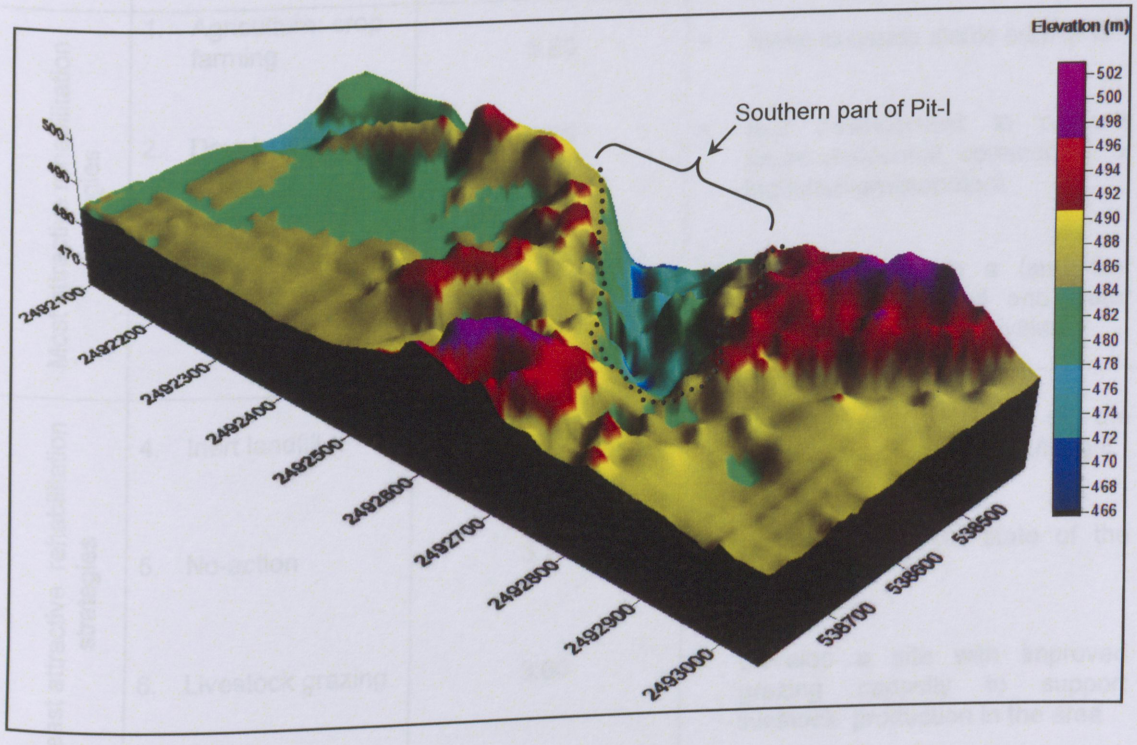


Figure 5.4: *3D representation of Area-2 current surface*

5.2.1 Rehabilitation options for Area-2

Similar post mining land-uses selected for rehabilitation of Area-1 were as well selected and evaluated for Area-2. It was observed that Area-2 portion of Pit-I covered in the model rarely contain water and as a result the construction of pit-lake alternative was not selected for evaluation. The six evaluated rehabilitation strategies are presented in Table 5.2. Based on the attractiveness scores, crop farming, site development for settlement purposes and construction of Dirt Park for cycling purpose were found to be the most attractive alternatives.

The computed sum total attractiveness score for the use of Pit-I portion as landfill site for inert waste, the alternative of retaining the current state of the site (no-action alternative) as well as the utilization of the land as livestock grazing site were found to be least attractive rehabilitation strategies.

Table 5.2: *Selected and evaluated rehabilitation strategies for Area-2*

	Rehabilitation alternatives	*Sum Total Attractiveness Score*	*Driver for end land use*
Most attractive rehabilitation strategies	1. Agriculture: crop farming	5.60	▪ Strive to create stable crop land
	2. Development	4.95	▪ Site development to promote future residential, commercial, or industrial development
	3. Recreational: dirt park construction	4.85	▪ Strive to develop a land that support both inland and water based recreational activities
Least attractive rehabilitation strategies	4. Inert landfill	3.74	▪ Create beneficial use of the abandoned pit while backfilling it.
	5. No-action	3.70	▪ Retain the current state of the site
	6. Livestock grazing	3.60	▪ Develop a site with improved grazing capacity to support livestock production in the area

The SWOT analyses of these alternatives revealed that Cut and Fill operations will be necessary in the development of agricultural field and the site with capacity for residential and industrial development. The dirt park construction will require redesign of spoil dumps to develop bicycle dirt dumps. The estimation of the volume of Cut material and Fill voids in Area-2 were made using the 3D model in Figure 5.5.

The flat laying terrain of this portion of the mine will be developed by cutting a reasonable amount of the waste material forming the high grounds to fill relatively low sections around Pit-I. As a result, the horizontal plane at 486 m above MSL was developed on the grid fill to define the Cut and Fill volumes.

The 486 m above MSL horizontal plane was critically selected to ensure effective leveling of the spoil dumps high grounds. Consequently, the designed rehabilitation terrain model for Area-2 shown in Figure 5.5 require cutting of about 715935 m^3 waste material over plane and surface area of 186311 m^2 and 189602 m^2 respectively. The 3D surface model of the designed rehabilitation topography in Figure 5.5 shows cut material of about 186311 m^3 above the wire framed level surface. The estimated Fill volume of the terrain designed was found to be approximately 333824 m^3 at a plane area of 13104 m^2. The corresponding cut surface area on the other hand was computed to be about 134900 m^2.

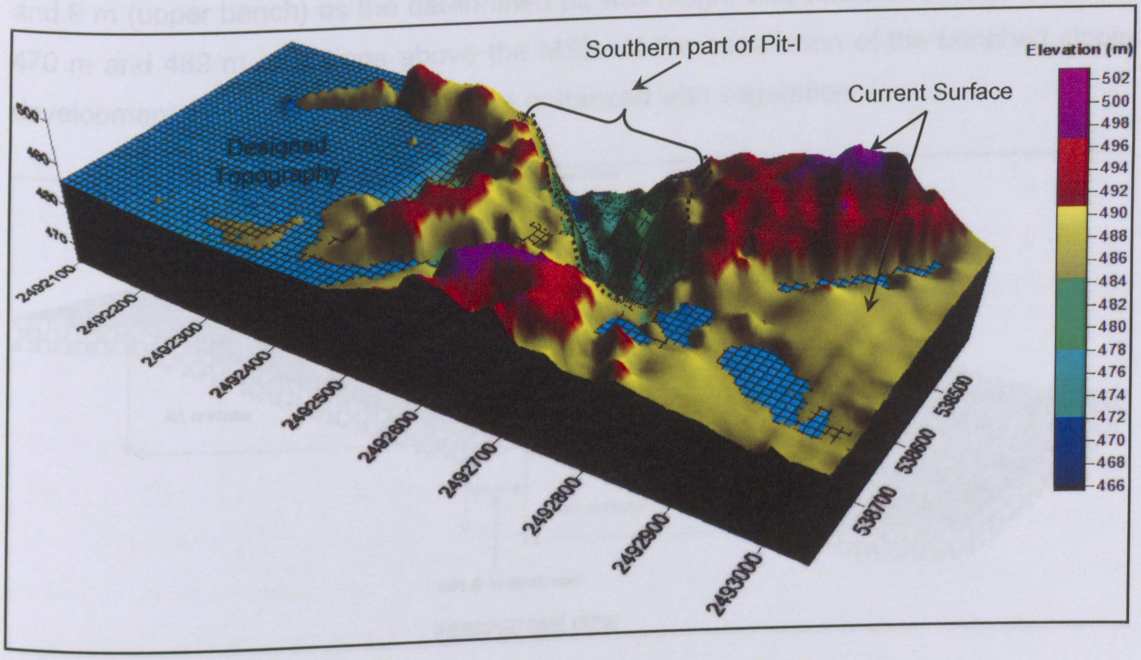


Figure 5.5: *3D illustration of Area-2 rehabilitation surface model*

5.2.2 Erosion and sedimentation control in Pit-I

Physical and environmental hazards associated with high walls characterizing Pit-I will be reduced by reducing the slope angles of the walls, while fine sediments deposition at the pit floor will be minimized through the installation of appropriate erosion control measures. Erosion control will also assists in the reduction of development of gullies on the pit walls thus minimizing environmental problems associated with erosion effects on slopes.

Pit Slope Design

The proposed slope design of Pit-I is 4:1 (horizontal: vertical ratio) 14° (24.99% grade). The sketch of the proposed walls design is shown in Figure 5.6. This wall design encouraged the installation of the reverse bench of not less than 101.6 cm width at one half slope length to reduce runoff speed. The reverse bench will also serve as a runoff route to the designed stable water outlet (Gabion protected inflow). Consequently, the reverse bench will be designed with the inclination of 2% to 3% towards the installed outlet (see Figure 5.6).

Generally, this pit wall design will break the bench slope length into 10 m (lower bench) and 9 m (upper bench) as the determined pit wall height was found to be 19 m between 470 m and 489 m elevations above the MSL. At the completion of the benched slopes development, the slopes stability will be enhanced with vegetation.

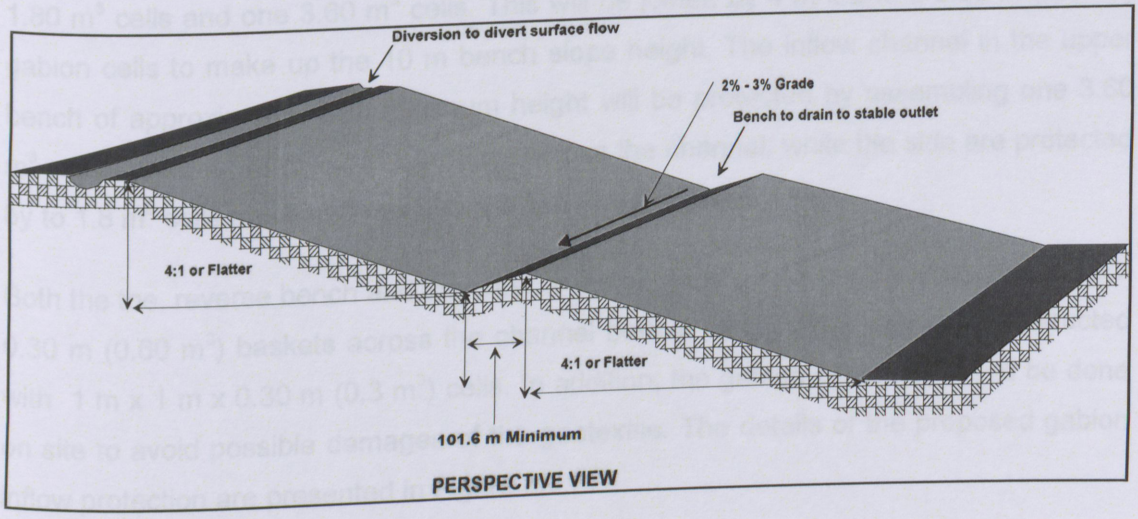


Figure 5.6: *Sketch diagram of Pit-I slope design not on scale (Modified from Maryland Department of the Environment, 1994)*

Drainage and erosion control

Runoff from the drain bench (reverse bench) shall be conveyed to the pit bottom by gabion protected inflow channel. The gabion inflow protection (GM) was recommended by the Maryland Department of the Environment (1994) as an appropriate erosion control measure within the channel in areas of up to 2:1 slope steepness. Due to the fact that the grading of pit walls in the study area will involve reducing the slopes to 4:1 (14°), the gabion inflow protection was identified as most convenient and effective measure for conveying surface runoff to the pit bottom at minimum degree of erosion.

Proposed Gabion Inflow protection design

The construction of gabion inflow protection will involve placing the wire baskets (made up of either hexagonal, triple-twist mesh with galvanized steel) on the filter fabric cloth (commonly known as geotexine). The placing of these baskets will be from the crest to the toe of the pit/basin as shown in Figure 5.7.

Average gabion size stones; that are 10 mm to 150 mm in diameter will be collected and used to fill the baskets. Although the gabion installation is largely according to manufacturer's specification, it is recommended that in this case 6 m x 2 m x 0.30 m (3.60 m^3) gabion baskets are placed across the bottom of the trapezoidal channel. The sides of the channel will be kept at the slope of 4:1 and they will be protected by 6 m x 1 m x 0.30 m (1.80 m^3) gabion cells. The 10 m long lower bench of the pit will require two 1.80 m^3 cells and one 3.60 m^3 cells. This will be joined by 4 m x 2 m x 0.30 m (2.4 m^3) gabion cells to make up the 10 m bench slope height. The inflow channel in the upper bench of approximately 9 m minimum height will be protected by assembling one 3.60 m^3 cell and 1.8 m^3 (3 m x 2 m x 0.30 m) across the channel; while the side are protected by to 1.8 m^3 cells and two 3 m x 1 m x 0.3 m (0.9 m^3) cells.

Both the toe, reverse bench and the crest of the pit walls will be protected by 1 m x 2 m x 0.30 m (0.60 m^3) baskets across the channel bottom width, while they are constructed with 1 m x 1 m x 0.30 m (0.3 m^3) cells. In addition, the gabion construction will be done on site to avoid possible damages of the geotextile. The details of the proposed gabion inflow protection are presented in Figure 5.7.

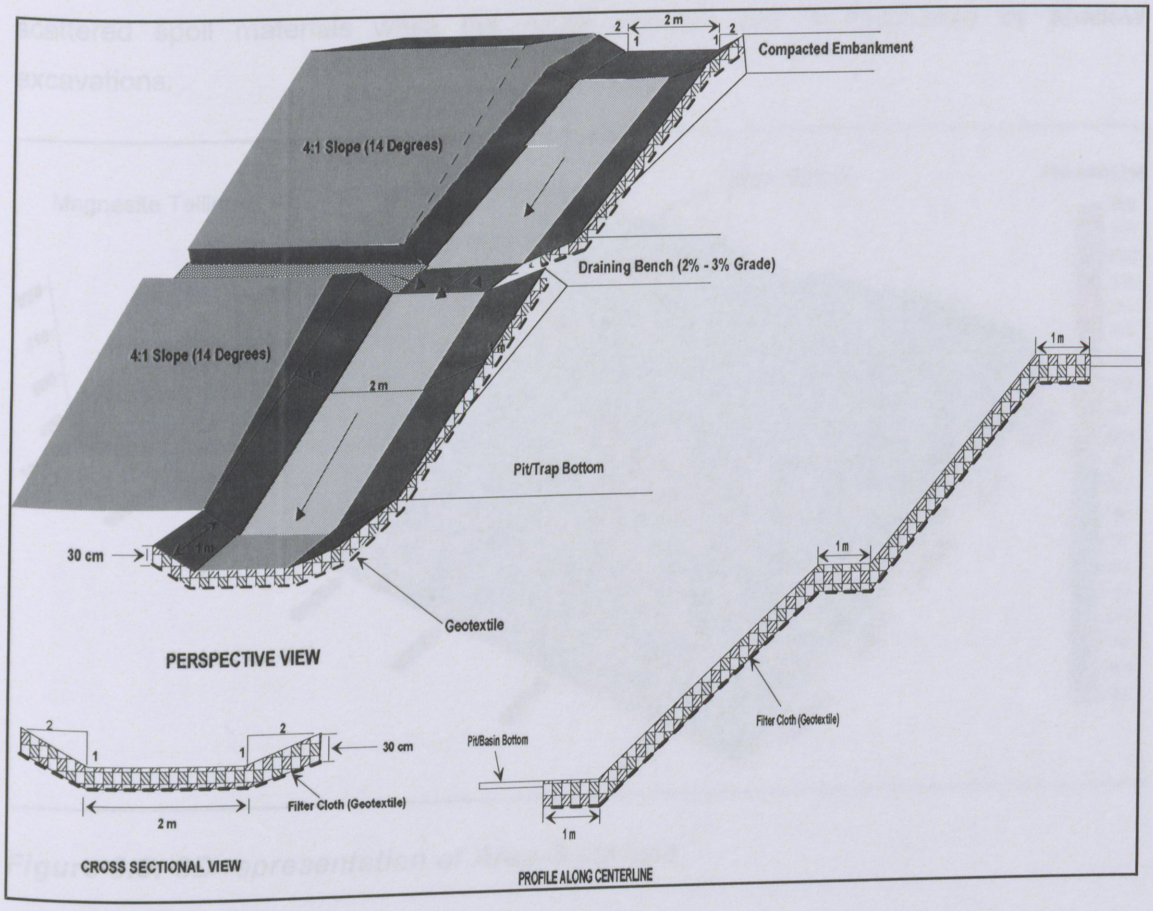


Figure 5.7: *Gabion Inflow protection details, not on scale (Modified after Maryland Department of the Environment, 1994)*

5.3 Surface Model of Area-3

The central part of the study area is overlain by a large volume of magnesite tailings (Tailing-A) and spoil materials as shown on the terrain model in Figure 5.8. This surface model was developed using the grid of 332 points and the areal extent of the model was estimated to be about 331269 m^2.

Generally, the tailings and the spoil materials cover surface area of about 56660 m^2 and plane area of 56152 m^2 above the estimated elevation of 499 m above MSL. The estimated dump height was about 23 m. The highest 522 m and points of the deep were estimated to be approximately 499 m above MSL respectively. The slope angles of the tailing dumps were determined and found to be ranging from 14.1% to 78.1% grades (8° to 38°). The relief at the north east of this tailing dump appears rugged due to the

scattered spoil materials while the south western part is dominated by shallow excavations.

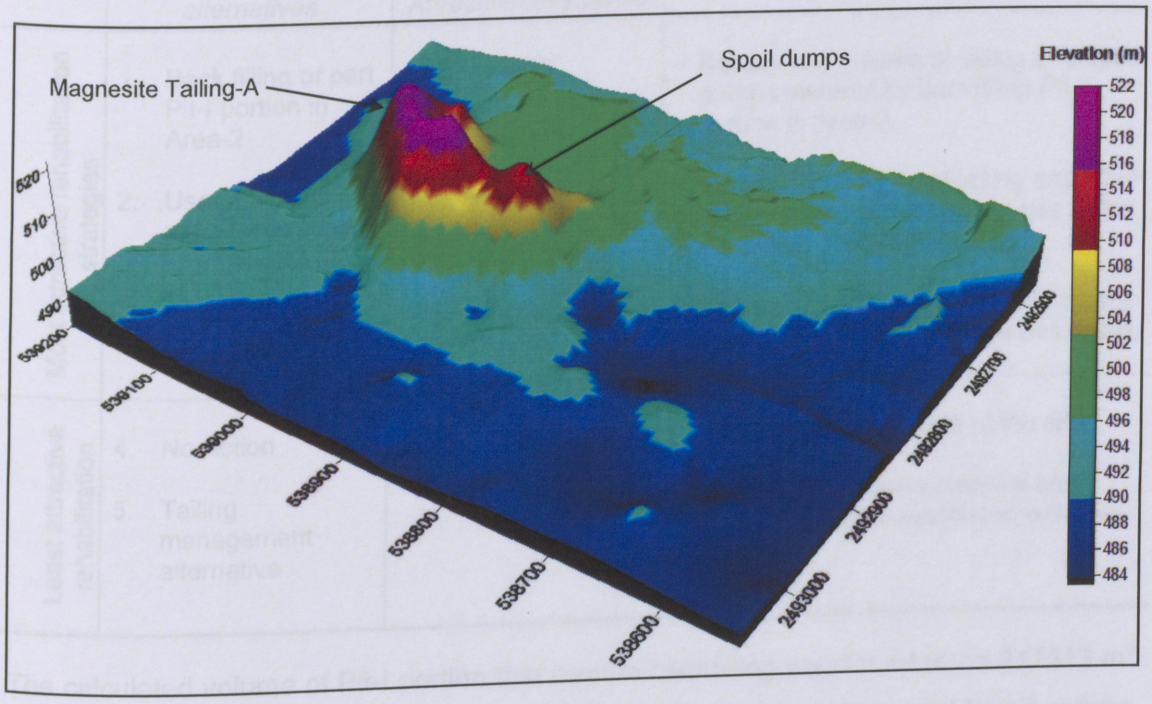


Figure 5.8: *3D representation of Area-3 surface*

5.3.1 Rehabilitation strategies for Area-3

Area-3 rehabilitation strategies were selected with the aim focus of addressing environmental stresses and physical hazards associated with large volume tailings and spoil materials dominating the area. Five rehabilitation alternatives were selected ranging from doing nothing (no-action alternative), removal of the dump by means of evaluating alternative use of the tailings, and management of the dumps as an alternative strategy for containing the hazards.

SWOT analysis of the selected rehabilitation options enabled identification of three most attractive land uses for Area-3. These were: (1) removal of the tailings material and its subsequent use to backfill part of Pit-I portion covered in Area-2, (2) utilization of the tailings material as fill material in road construction and (3) use of the material as replacement of river sand in making of blocks or bricks. The no-action option and tailings management alternatives were not found to be attractive strategies (see Table 5.3).

Table 5.3: *Selected rehabilitation options for Area-3*

	Rehabilitation alternatives	*Sum Total Attractiveness Score*	*Driver for end land use*
Most attractive rehabilitation strategies	1. Back filling of part Pit-I portion in Area-2	5.50	▪ Reduce the volume of tailing and spoil dumps material by backfilling Pit-I portion in Area-2.
	2. Use of tailings in road construction	4.80	▪ Reduce the volume of tailing and spoil dumps material through the use of the material in road construction.
	3. Use of tailing for block making	4.10	▪ Reduce the volume of tailing and spoil dumps material through the use of the material for brick making.
Least attractive rehabilitation	4. No Action	3.75	▪ Retain the current state of the site
	5. Tailing management alternative	3.15	▪ To contain the environmental and physical hazards associated with the dumps.

The calculated volume of Pit-I portion that require backfilling was found to be 217613 m^3 over the plane area of 219905 m^2. This volume of material if used as backfill will reduce the tailing and spoil dump volume from the estimated 223906 m^3 (above the level surface of 500 m above the MSL) to 6293 m^3. Figure 5.9 shows the anticipated size and shape of Pit-I after filling of the southern portion of the pit. The filing will reduce Pit-I volume by 15.8% (from 100% to 84.2% over the surface of 486 above MSL).

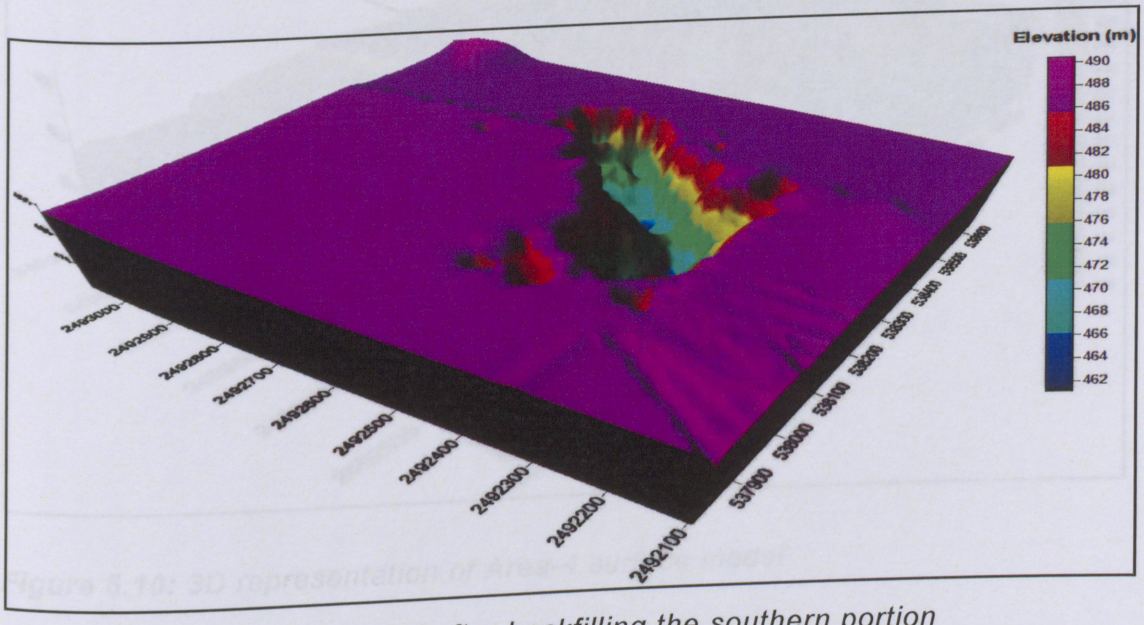


Figure 5.9: *Illustration of Pit-I after backfilling the southern portion*

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5.4 Terrain Model of Area-4

Area-4 portion of the Nyala Mine is relatively flat with minimum excavations and spoil dumps as illustrated in Figure 5.10. This model covers an area of approximately 551292 m^2 and it was developed using a grid file of about 1628 points. The major excavations in Area-4 terrain model include Pit-II, Pit-III and part of Pit-IV (see Figure 5.10). Portions of high grounds were only identified along central part of the model; that is between Pit-I and Pit-III. The larger part of Area-4 consists of the areas characterized by elevation of 486 m to 493 m above MSL. However portions of up to 504 m above MSL were identified between the grid lines of 2493000 to 2493300 and 539400 to 539950 (see Figure 5.10).

The maximum depth of Pit-II was determined to be approximately 20 m thus the pit bottom is at 473 m above MSL while the terrain right above the pit walls is at a maximum elevation of 493 m above MSL. Comparatively Pit-III was computed to be up to the depth of 29 m. The elevation of Pit-III at the pit bottom was approximately at 469 m above MSL, while the ground above the walls was at 496 m above MSL. However, the waste dump directly above some zones of the north wall of Pit-III added about 12 m on the height of these walls giving them the maximum height of 27 m.

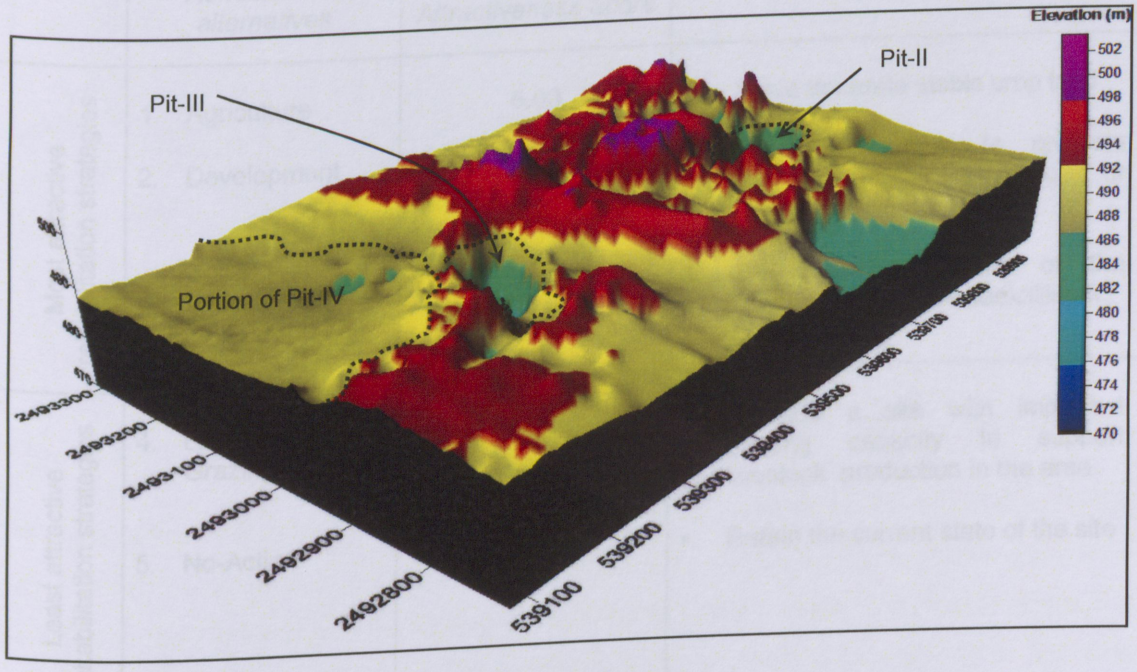


Figure 5.10: *3D representation of Area-4 surface model*

5.4.1 Rehabilitation options for Area-4

Based on the site characterization and interpretation of the developed terrain model, five possible strategies for rehabilitation of area-4 were selected and evaluated. These included maintaining the current state of the site, development of the site for agricultural and residential purposes as well as the use of the site for livestock grazing purposes. The alternative of using Pit-I as landfill site for inert waste was also considered (see Table 5.4).

The calculated sum total attractiveness score revealed that the three most attractive strategies for rehabilitation of Area-4 was found to be the use of the site for agricultural and development purposes as well as the use of Pit-II as landfill site for inert waste. These alternatives carried the sum total attractiveness scores of 5.00, 4.95 and 4.10 respectively in their order of decreasing attractiveness meanwhile, the no-action alternative as well as the use of the area as grazing site were found to be least attractive with 3.65 and 4.30 score respectively (see Table 5.4).

Table 5.4: *Selected rehabilitation alternatives for Area-4*

	Rehabilitation alternatives	*Sum Total Attractiveness Score*	*Driver for end land use*
Most attractive rehabilitation strategies	1. Agriculture	5.00	▪ Strive to create stable crop land
	2. Development	4.95	▪ Site development to promote future residential, commercial, or industrial development
	3. Use of pits as Inert landfill	4.10	▪ Create beneficial use of the abandoned pit while backfilling it.
Least attractive rehabilitation strategies	4. Livestock Grazing	4.30	▪ Develop a site with improved grazing capacity to support livestock production in the area
	5. No-Action	3.65	▪ Retain the current state of the site

Although Area-4 portion of the study area is characterized by relatively flat landscape the need for leveling spoil dumps around Pit-II and Pit-III to fill and level the rugged portion of Pit-IV and Pit-III was identified.

Figure 5.11 shows the portion of the ground to be cut above the designed level surface around Pit-II to completely fill both Pit-III and Pit-IV portion covered in the surface model. The level surface that defines the Cut and Fill volumes was developed at 491 m above MSL. It was computed from the model that approximately 451949 m^3 (over the level surface of 491.5 m above MSL) of material will be moved to fill the relatively low grounds around Pit-II. The total estimated Fill volume was found to be 971529 m^3. The plane surface area occupied by the Cut volume was measured to be approximately 206637 m^2 while the Fill volume area was estimated to be 344655 m^2.

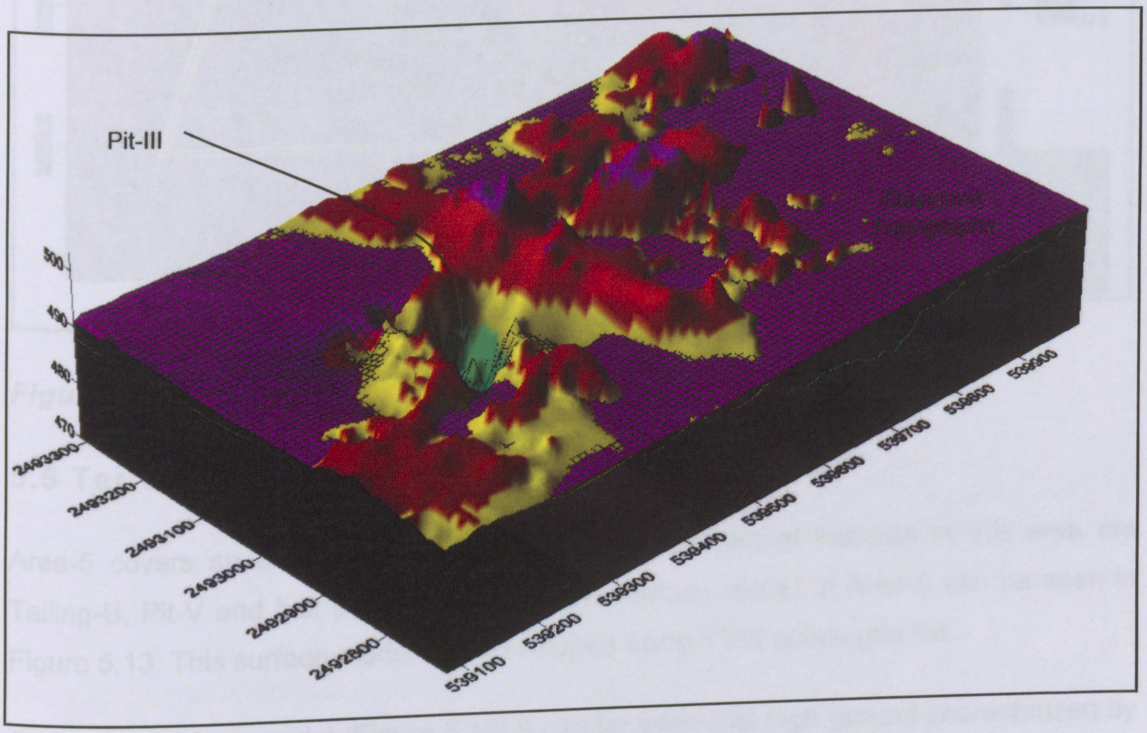


Figure 5.11: *3D representation of terrain rehabilitation of Area-4*

Pit-II was identified to be at relatively shallow depth and always dry (except other during rainy days); it was therefore proposed that the pit be used by Zwigodini community as a landfill site for inert waste. The design of Pit-II for landfill purposes will involve reshaping of the pit walls to ensure stability. The north eastern wall need to be reduced to serve as a pit entry while ensuring easy access to the pit bottom. Prevention of animal (wide

animals and livestock) access to the pit will be ensured by installing a fence and an access gate around the pit (see Figure 5.12).

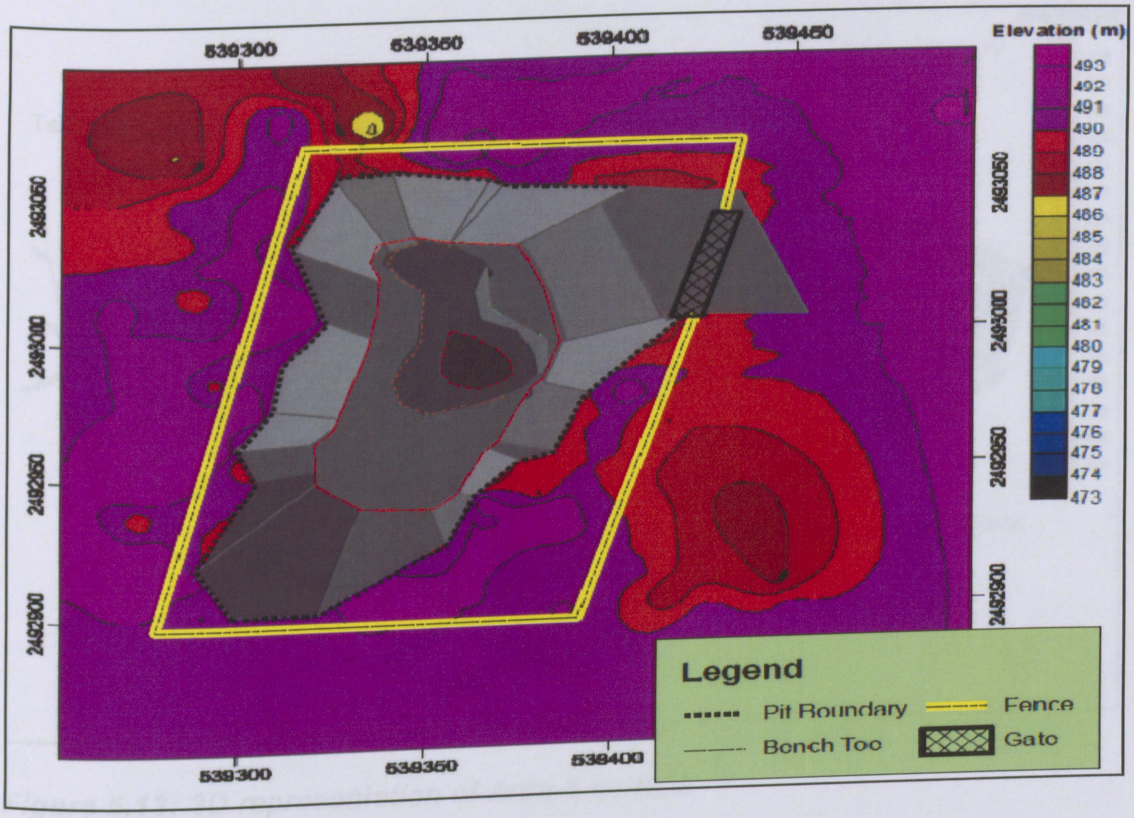


Figure 5.12: *Designed of Pit-II for inert landfill site*

5.5 Terrain Model of Area-5

Area-5 covers an area of about 297997 m^2 and prominent features in this area are Tailing-B, Pit-V and half portion of Pit-IV. The surface model of Area-5 can be seen in Figure 5.13. This surface model was developed using 1252 points grid file.

On Area-5 surface model (Figure 5.13) it can be seen that high ground characterized by the red colour are made up of spoil materials while the low grounds are dominated by shallow excavations. This includes Pit-IV and other areas adjacent to Tailing-B. Magnesite tailing dump and its surrounding waste and/or spoils attain an elevation greater than 507 m above MSL.

At a level surface of 495 m above MSL, the height of Tailing-B was determined to be about 26 m. Pit-V was identified to be the deepest pit in this area of the mine. However, a relatively small portion of Pit-IV in Area-5 terrain model was observed to be about 25 m

deep. That is from the surface of 492 m elevation above the pit bottom at 465 m above the MSL.

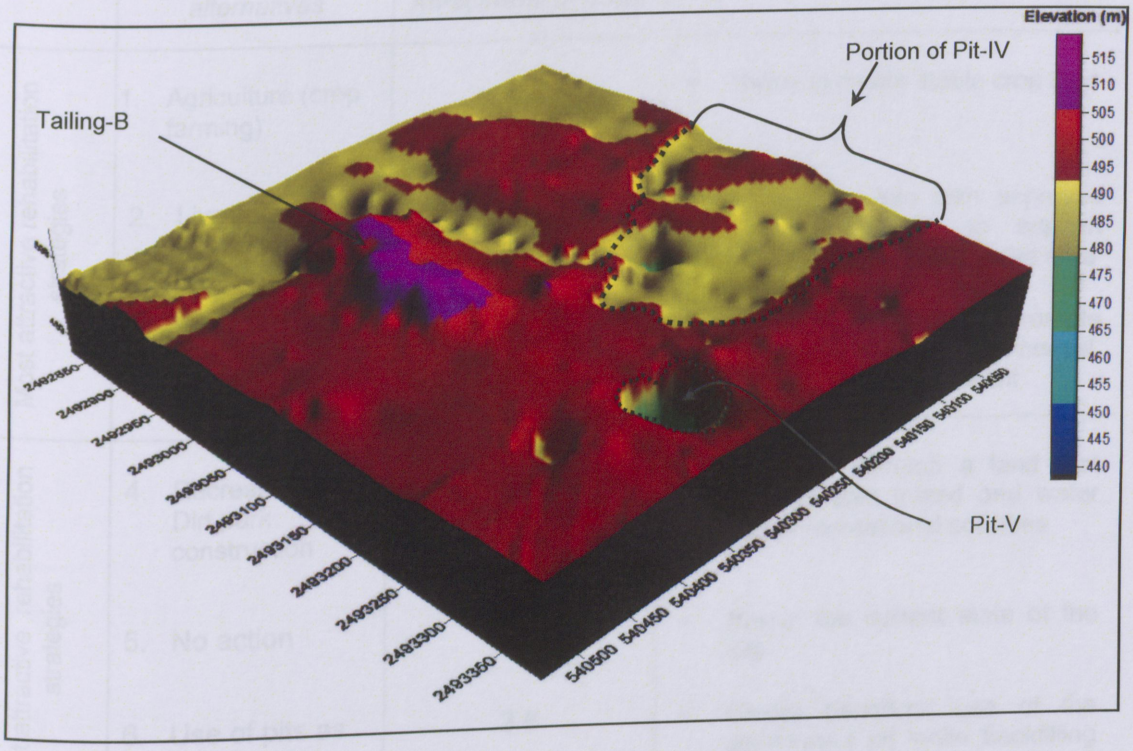


Figure 5.13: *3D representation of Area-5 surface*

5.5.1 Rehabilitation strategies for Area-5

The rating of alternative rehabilitation strategies for Area-5 showed the use of the site for livestock grazing, agricultural purposes (crop land) and development of the site for residential purposes are the most attractive rehabilitation strategies.

The other three alternatives evaluated were found to be less attractive and these were no-action strategy, use of Pit-IV and Pit-V as landfill site for inert waste and construction of a dirt park. Table 5.5 shows the respective total attractiveness scores calculated for the six rehabilitation strategies for Area-5.

Table 5.5: *Selected rehabilitation alternatives for Area-5*

	Rehabilitation alternatives	Sum Total Attractiveness Score	Driver for end land use
Most attractive rehabilitation strategies	1. Agriculture (crop farming)	5.1	▪ Strive to create stable crop land
	2. Livestock Grazing	4.3	▪ Develop a site with improved grazing capacity to support livestock production in the area
	3. Development	3.9	▪ Site development to promote future residential, commercial, or industrial development
Least attractive rehabilitation strategies	4. Recreational: Dirt park construction	3.8	▪ Strive to develop a land that support both inland and water based recreational activities
	5. No action	3.7	▪ Retain the current state of the site
	6. Use of pits as Inert landfill	3.6	▪ Create beneficial use of the abandoned pit while backfilling it.

Rehabilitation of Area-5 terrain was designed such that a Cut volume of 862747 m^3 is to be graded to fill a void of about 513244 m^3. Without material compaction operation, about 349503.42 m^3 of this material was determined as an extra Cut volume material. Figure 5.15 shows, the ground above the plane wire framed surface that represents the current topography that requires grading. The wire framed topography represents the designed rehabilitation topography.

Generally, the landscape rehabilitation in Area-4 involved complete filling of Pit-IV and Pit-V with Tailing-B and its surrounding spoils. The material to be graded or cut occupied a plane and surface areas of 188183 m^2 and 185127 m^2. On the other hand, the area occupied by the Fill volume material was estimated to be 117813 m^2 (plane area) and 124960 m^2 (surface area).

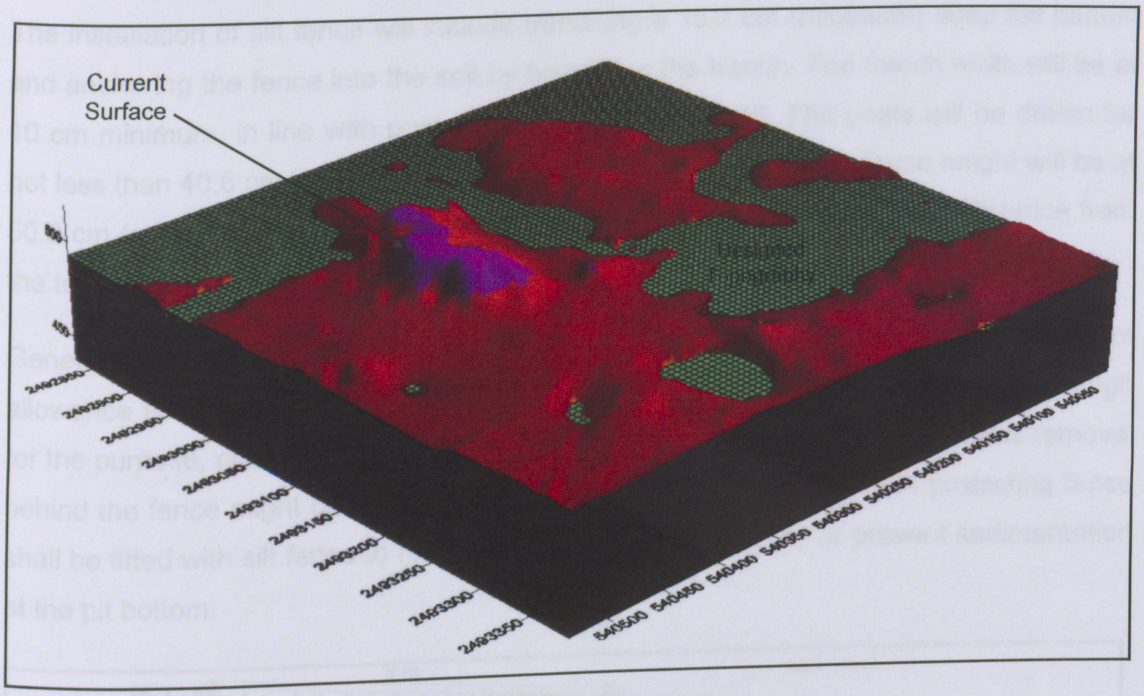


Figure 5.15: *3D representation of the Area-5 rehabilitation terrain*

5.6 Sedimentation and Erosion Control at the Mine Site

The Nyala Mine is generally located in the semi-arid region of the province with very little support of growth of vegetation (especially grasses). Consequently, control of sedimentation at the pit bottom and erosion of the vulnerable soil will be through the use of pragmatic and cost effective engineering measures. As a result, silt fence will be employed as a sedimentation control measure in slope of less than 5:1 (< 10°) thus the mine topography will have to be leveled to less than 4 (< 6.99% grade). Table 5.6 presents the maximum allowable slope length contributing runoff to the silt fence placed on recommended slopes in practice.

Table 5.6: *Considerations for use of silt fence (from Minnesota Pollution Control Agency, 2000).*

Slope Steepness	*Maximum slope length (m)*
2:1	7.6
3:1	15.2
4:1	22.9
5:1 or flatter	30.5–61.0

The installation of silt fence will include trenching a 15.2 cm (minimum) deep flat bottom and anchoring the fence into the soil by backfilling the trench. The trench width will be at 10 cm minimum, in line with post as shown in Figure 5.16. The posts will be driven for not less than 40.6 cm into the ground and their height or the whole fence height will be at 50.8 cm (see Figure 5.16). The spacing between the posts as well as the distance from the toe of the slope to the fence shall be maintained at 3 m minimum.

Generally, the silt face will be installed perpendicular to the slope of the land. The 3 m allowance space for sediments accumulation at the slope toe was judged to be enough for the purpose, given the general topography slope grade. However, sediments removal behind the fence might be necessary. Moreover, about 91.4 cm of Pit-I protecting fence shall be fitted with silt fence to reduce the amount of sediments or prevent sedimentation at the pit bottom.

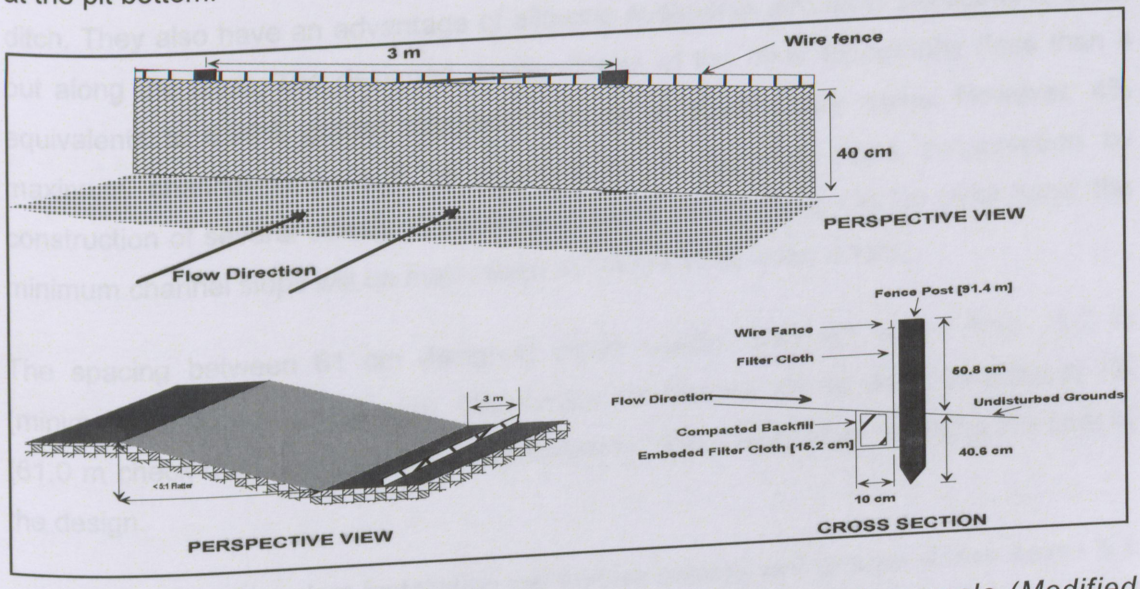


Figure 5.16: *Typical illustration of silt fence installation, not on scale (Modified after Maryland Department of The Environment, 1994).*

5.7 Storm Water Management

Runoff will be diverted from the most vulnerable areas of the mine by ditches which will convey it to Pit-I. This will be done in order to minimize erosion in these areas until the full adaptation of the permanent erosion control measures while ensuring that enough water is conveyed to the pit for community use. The channel sizes for this purpose will differ from one place to another, depending on grounds or channel slope length and steepness. This is due to the fact that longer slopes tend to deliver more runoff to the

base of the slopes and steeper slopes increase runoff velocity. As a result, these conditions have potentials to enhance erosion effects on slopes or ditches and accelerate deposition of sediments downstream or pit bottom.

Stone check dam shall be constructed within collector channels/ditch to reduce and/or eliminate erosion and sedimentation potential of the runoff in the ditch. Easy installation of the dumps and the fact that the stones can be easily obtained around the mine has potential for reducing the cost of erecting stone check dumps in the study area.

5.7.1 Design and installation of stone check dams

Stone check dams are generally inexpensive, easy to construct, and effective engineering measure in reducing runoff speed, erosion and gulling within the channel or ditch. They also have an advantage of allowing sediments and other pollutants to settle out along the ditch. The designed terrain slopes of the mine topography (less than 4 equivalents to 6.99% grade) supports the use of stone check dams. However, 4% maximum channel slope will be encouraged to minimize stone consumption by construction of several closely spaced dams along the channel. On the other hand, the minimum channel slope will be maintained at 1% grade in flatter areas.

The spacing between 61 cm designed stone checks dam will range from 15.2 m (minimum) to 61.0 m (maximum). Once more, preference will be given to slope of 1% (61.0 m check dam spacing) to ensure minimum stone use; while reducing the cost of the design.

In this case the stone dam installation will involve placing well graded stones matrix 5.1 m to 22.9 cm on top of the filter fabric to 0.6 m height in 1 m deep ditch. The central part of the channel dam shall be maintained at 22.9 cm lower than the outer edges m (see Figure 5.17). Proper installation of the stone check dam will be judged by keeping the toe of the upstream dam at the same elevation as the top of the downstream dam (see Figure 5.17).

Growing of grass along the upstream dam will be encouraged as it will serve as a permanent channel lining material. Prior to the full establishment of the grass linings, sediments behind the dam will be continuously removed once they reach one half of the dam height (30.5 cm) (see Figure 5. 17).

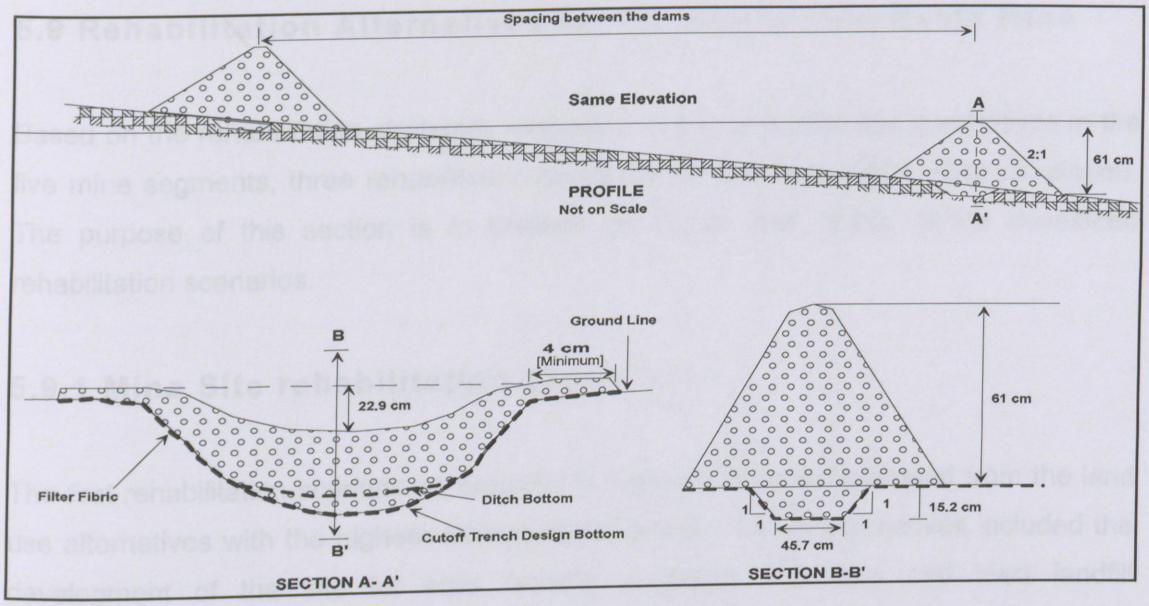


Figure 5.17: *Details of stone check dam design (Modified from Minnesota Pollution Control Agency, 2000).*

5.8 Restoration of Soil Productivity

Due to the fact that soil is an important and limited resource, there will be a need for soil rehabilitation in the study area (especially in areas overlain by alkaline spoils and tailing material). Generally, limitation in the productivity of the soil could be attributed to both physical and chemical properties of the soil.

Physical analysis of fill material in the study area showed that the materials are generally sandy soils with poor physical structure. Therefore, to improve the conditions suitable for increased vegetation growth, application of organic fertilizers was found to be economical and cost effective due to the fact that they can be obtained at relatively little or no cost. These organic fertilizers include cow, sheep, poultry, hoarse/donkey and any other biodegradable waste that can be easily obtained in abundance from the neighboring Zwigodini community and other nearby livestock farms. Despite these economic benefits, fertilizers have advantages of effectively improving water holding capacity of sandy soils. This can also be a distinct advantage of organic fertilizers application at the study area characterized by semi-arid climatic conditions. These fertilizers also have improved ability to add and balance some of the essential primary plants nutrients such as potassium and phosphorus, and some secondary plant nutrients.

5.9 Rehabilitation Alternatives for the Abandoned Nyala Mine

Based on the rehabilitation strategies evaluated to be most attractive alternatives in the five mine segments, three rehabilitation scenarios for the Nyala Mine were developed. The purpose of this section is to present the layout and details of the developed rehabilitation scenarios.

5.9.1 Mine Site rehabilitation scenario I

The first rehabilitation scenario as depicted in Figure 5.18 was developed from the land use alternatives with the highest attractiveness scores. Those alternatives included the development of the site for crop farming purposes, Pit Lake and inert landfill construction.

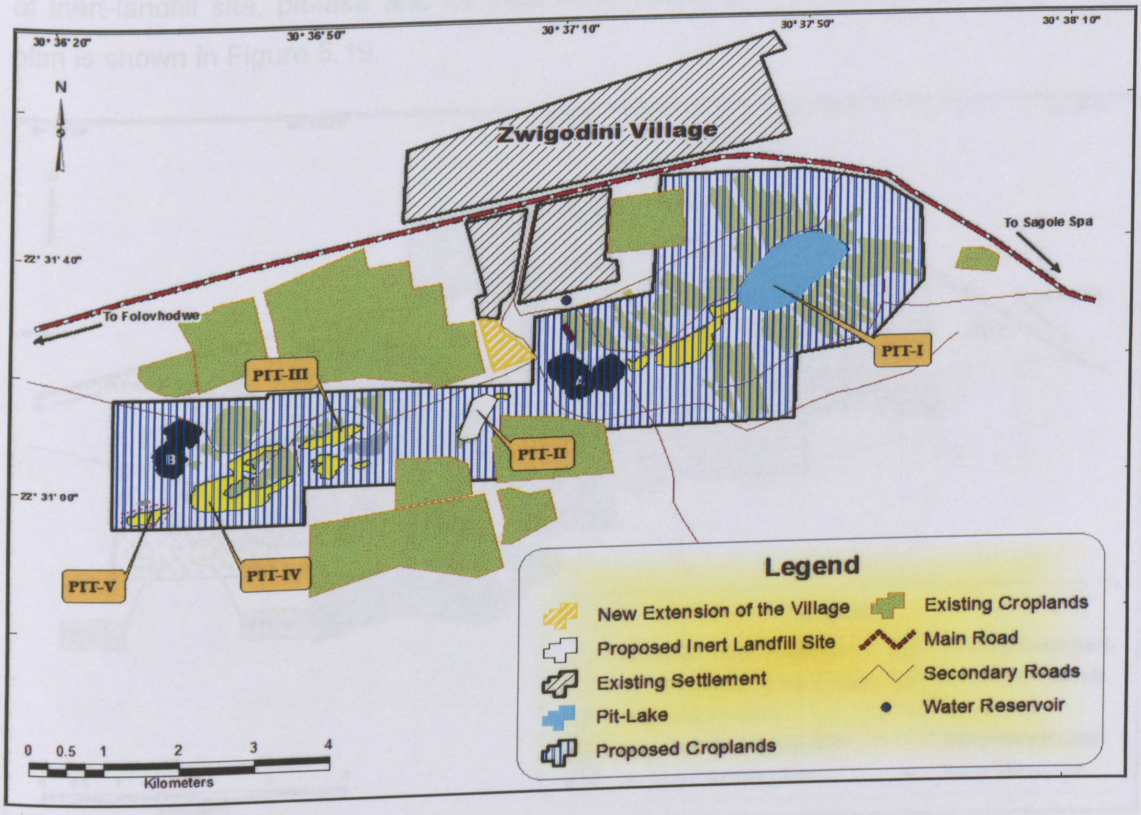


Figure 5.18: *Proposed mine site rehabilitation Plan I.*

The calculated total surface area to be occupied by the proposed land use alternatives was found to be 1644 ha. The surface areas corresponding to each proposed land use are presented in Table 5.7.

Table5.7: *Surface areas of rehabilitation strategies in the first scenario*

Rehabilitation Alternatives	*Surface Area of Total (ha)*	*Percentage of Total (%)*
1. Proposed Crop land	1593	97
2. Pit-lake	41	2.5
3. Inert landfill site	10	0.5
Total area	*1644*	*100*

5.9.2 Mine site rehabilitation scenario II

The second mine site rehabilitation scenario of the abandoned Nyala Mine was developed using the second most attractive rehabilitation options for individual mine terrain segments. The rehabilitation strategies suggested include cleaning up of the land for settlement and industrial development purposes, livestock grazing and construction of inert-landfill site, pit-lake and its associated picnic site. The proposed rehabilitation plan is shown in Figure 5.19.

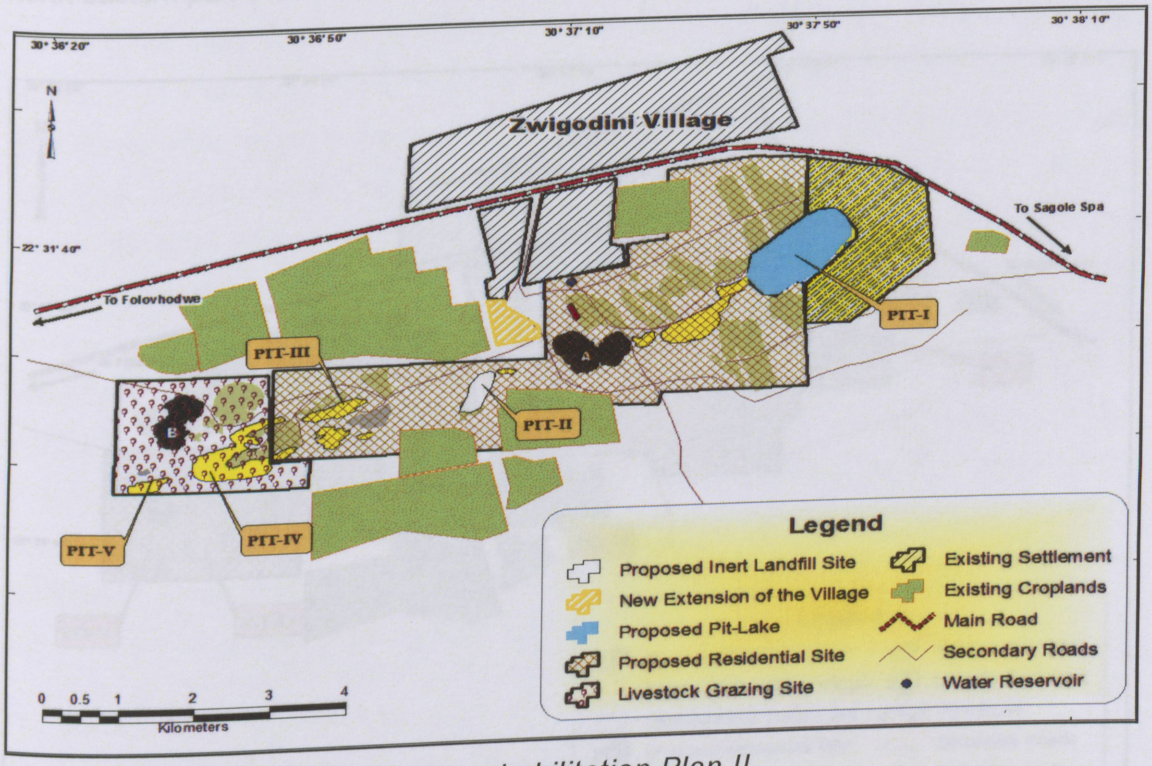


Figure 5.19: *Proposed mine site rehabilitation Plan II.*

The areal extent of land mass evaluated to support each selected rehabilitation option was calculated and the results are presented in Table 5.8. The total area to be occupied by these alternatives was found to be 2144 ha.

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Table 4.8: *Surface areas for rehabilitation alternatives in the second scenario*

Rehabilitation Alternatives	*Surface Area of Total (ha)*	*Percentage of Total (%)*
1. Pit-lake	41	1.9
2. Inert landfill site	10	0.5
3. Proposed residential site	1329	61.9
4. Picnic park	339	15.8
5. Livestock grazing site	425	19.8
Total area	*2144*	*100*

5.9.3 Mine site rehabilitation scenario III

The third rehabilitation scenario was mainly developed using rehabilitation alternatives selected as less attractive operations. The most prominent option was the rehabilitation of the site to support development and the construction of earth ramp dirt pack along the north eastern part of the mine area as shown in Figure 5.20.

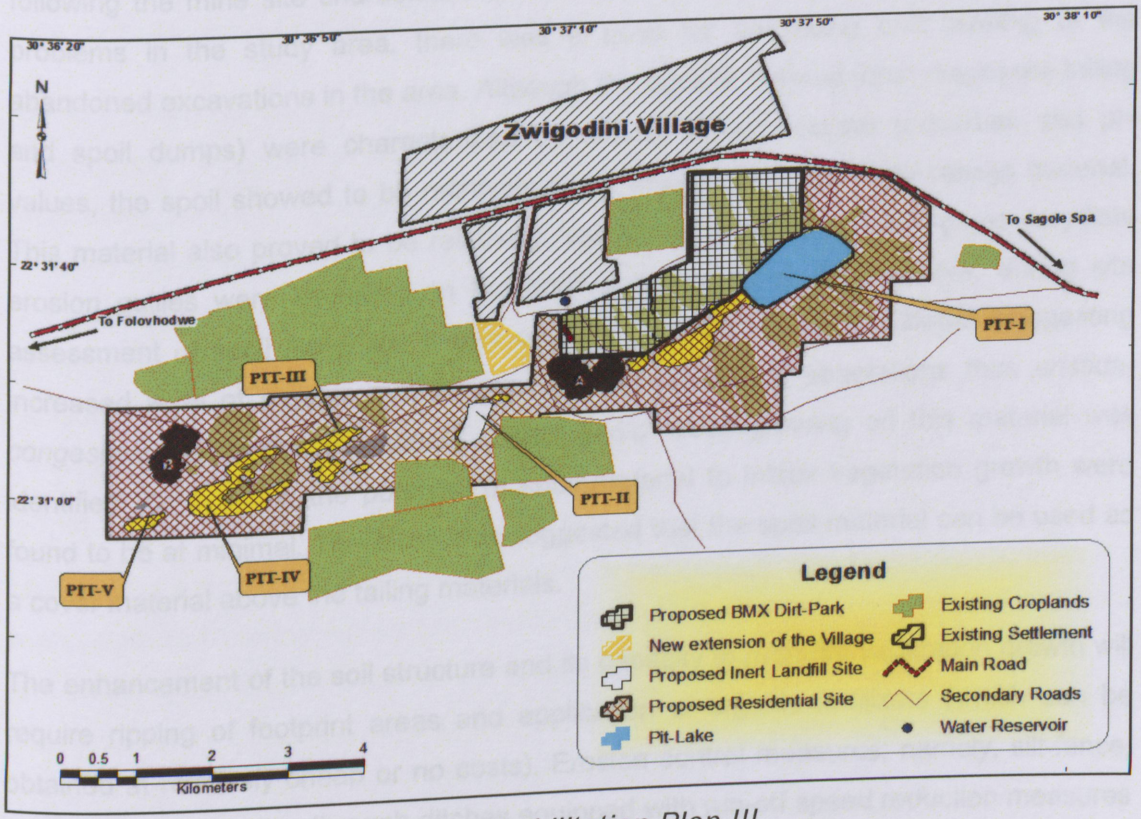


Figure 5.20*: Proposed mine site rehabilitation Plan III.*

Table 5.9 presents the total area of each of the selected rehabilitation alternatives in the total surface area of about 1982 ha.

Table5.9: *Surface areas for rehabilitation options in the third scenario.*

Rehabilitation Alternatives	*Surface Area of Total (ha)*	*Percentage of Total (%)*
1. Proposed residential site	1541	77.8
2. BMX Dirt Park construction site	390	19.6
3. Pit Lake	41	2.0
4. Inert landfill site	10	0.5
Total Area	*1982*	*100*

5.10 Summary

The attempt of developing sound and cost effective rehabilitation strategies was made following the mine site characterization. An approach of eliminating the environmental problems in the study area, there was a need for backfilling and leveling of the abandoned excavations in the area. Although the backfill material (both magnesite tailing and spoil dumps) were characterized by almost similar textural properties and pH values, the spoil showed to be relatively richer in organic matter than tailings material. This material also proved to be relatively resistant to erosion than tailings as very little erosion gullies were identified on the spoil dump surfaces. Furthermore, during site assessment of spoil materials, it was observed that darker spoil material (suggesting increased level of organic matter) promotes the growth of vegetations thus *aristida-congesta subsp* grass and acacia shrubs and/or trees growing on this material was identified. As a result, the potential of spoil material to inhibit vegetation growth were found to be at minimal. Therefore, this suggested that the spoil material can be used as a cover material above the tailing materials.

The enhancement of the soil structure and its capacity to promote vegetation growth will require ripping of footprint areas and application of organic fertilizers (which can be obtained at relatively cheap or no costs). Erosion control measures; namely, silt-fence, storm water channeling through ditches equipped with run-off speed reduction measures such as stone check dumps were proposed. This also involved the use of protected

inflow channels (gabion protected inflow channel) to discharge run-off water in the proposed pit lake. Generally, the filling of voids, reshaping of spoils and removal of tailings dumps required that the significant volume of these materials be cut and subsequently used to level certain portions of the mine.

The SWOT and QSPM analysis of different possible land use for the rehabilitation of the abandoned Nyala Mine showed that the construction of the Pit Lake, inert landfill site, bicycle Dirt Park and animal grazing site, development of croplands and cleaning up of the mine site for residential purposes were found to be favorable. The utilization of tailings material for road construction and brick making purposes was found to be very attractive alternative as well.

The evaluation and rating of different options for rehabilitation of the Nyala Mine revealed that about 97% of the total mine area was found to be suitable for use as cropland and 77.8% for the development of residential areas; three rehabilitation scenarios were designed. The second scenario was designed with about 62% of the area proposed residential purposes. The picnic site extending over about 16% of the total rehabilitation area was proposed adjacent to the Pit Lake along the east.

On the other hand, about 78% of the rehabilitation area was designated for the development of residential areas in conjunction with the dirt BMX Park. The use of the spoil materials as dirt rumps was found to be appropriate and the BMX Cycling was selected due to its minimum noise and dust emission. BMX dirt parks require high level of maintenance, care and greater risk management control because of the erodability potential of the dirt jumps. According to Bellinger Foster Steinmetz Landscape Architecture (2002), erosion concerns can be addressed through careful design of berms jumps and tracks of the pack and restricted use of the pack, for example restricting use during winter seasons.

Moreover, it was proposed that Pit-II be used as inert landfill site for earth and earth-like waste such as concrete, bricks, yard trimmings, land cleaning debris, tiles and ceramics, and waste glass-based fibrous material without organic binder. These wastes do not dissolve; burn or otherwise physically or chemically react, biodegrade or adversely affect other matter with which it comes into contact in a way that may give rise to environmental problems and/or affect human health (Environment Agency, 2010).

CHAPTER SIX

REHABILITATION COST ESTIMATION

This chapter presents the estimate of cost required to carry out or implement rehabilitation scenarios developed in the previous chapter. The costs estimate for each scenario included direct cost of physical site rehabilitation, their associated indirect cost and costs of required labour.

6.1 Unit Rates for Equipment Operation

The cost of land leveling and reshaping of the rugged Nyala Mine terrain was estimated from the cost of equipment per their hours of operation. Cut and Fill operation involved loading and tipping of filling material in the void areas using standard ten wheeler (10 m^3 volumes) dump trucks. This type of trucks was selected based on the fact that they have more maneuverability than others. The loading of the trucks will be carried out through the use of a loader equipped with 1.7 m^3 volume bucket.

The work of spreading and/or leveling the fill material will be carried out by the use of the bulldozer. According to Chamber of Mines of South Africa and Coaltech (2007), the use of bulldozer to spread the truck dumped soils is recommended due to the fact that the bulldozer tracks exert a lower bearing and as a result they compact less than wheeled systems or machinery. Despite spreading of backfill material; the bulldozer will be used to loosen or rip footprint areas, as a result the dozer equipped with the ripper tiners will be employed for this purposes.

The cost of earthmoving operations aimed at reshaping the spoils material and tailing dumps and fill the void areas for the development of a smooth topography was established using the unit rates presented in Table 6.1. These rates were obtained from Golder's Associates documents and the 2011 official rate of the Constructor's Plant Hire Association (CPHA). The estimation of earthwork cost was directly established from the cost of loading, transportation, and spreading of every cubic metre of backfill material in fill areas. The cost of ripping footprint areas to alleviate compaction (per h) was also part of the estimate.

Table 6.1: *Unit rates for earthwork cost estimation*

Cost item	*Unit Rate*	*Units*	*Capacity*	*Description/models*
Equipment rates				
▪ Bulldozer	R225.00	/hr		▪ CAT D3D, D4D, D4E; Daewoo DD80, Komatsu D31A, D31E
▪ Tipper Trucks	R254.00	/hr	10 m^3	▪ 10 m^3, Tipper trucks
▪ Loader	R245.00	/hr	1.7 m^3	▪ CAT 910, 914G, FurukawaFL310 Ball L1004D, L705D; Komatsu WA120 Volvo L30B, L40B; Michigan 35B.
Operations rates				
▪ Extra rate for overhaul	R5.00	m^3/km	-	▪ Outside the free haul distance
▪ Bulk dozing of material	R10.50	/m^3	-	▪ Bulk dozing operations
▪ Ripping of footprint areas	R8,900.00	/ha	-	▪ 3 Ripper tiners to 500 mm
▪ Establishment of vegetation	R18,130.00	/ha	-	▪ General

6.2 Cost Estimate of Earthwork at Nyala Mine

Earthwork in the context of this research include the work of adjusting the terrain by cutting various sections of the terrain to fill certain section of the mine to create a smooth topography with capacity to support a wide range of land uses. It includes digging, loading, transportation, dumping and spreading of materials in fill areas. It also includes the work of ripping the footprint areas to alleviate compaction thus improving the soil structure to support easy adaptation of vegetation. This section presents the estimated costs of earthworks to be carried out in each proposed rehabilitation scenario in the study area. The rates used for cost estimation are exclusive of VAT and fuel cost. However they include wages of truck driver and machine operators.

6.2.1 Earthwork costs estimation parameters

The cost of terrain reshaping operations at Nyala Mine was established by first determining the number of hours required to move the Cut material to the void areas using 10 cubic metres tipper trucks. These required that parameters such as loader cycle time (LCT), number of loader passes per truck, net truck capacity, loading time per truck, truck cycle time (TCT), the number of trucks required and the truck hourly production rate at 100% efficiency are determined. The summary of calculations of these parameters is presented in Appendix-D1 and Appendix-D2.

The calculated loader cost per cubic metre of materials to be loaded was used to estimate the cost of loading. Generally, the loading cost was determined as product of loader cost per cubic metre (R3.59/m^3) and the volume to be moved in each scenario. The site operation costs of the loader were determined by multiplying the machine estimated work hours by the hourly rate of R245.00/hr. The total loading cost for each rehabilitation scenario was determined as a sum of site operation cost of the loader or loader hiring costs and the cost of loading per cubic metres moved.

The total costs of moving the cut material to fill void areas was considered to be a sum of estimated overhaul volume cost and the truck site operation cost. The total trucking costs was determined by multiplying the truck hourly rate of R254/hr by the estimated number of work hours for each truck. The overhaul volume cost was taken as a product of the estimated truck cost per cubic metres to be moved and the volume of the material to be moved. These parameters were computed based on the machine performance (loader) and truck 100% efficiency as estimated from the Caterpillar Handbook.

6.2.2 Cut and Fill costs estimate

The cost of Cut and Fill operations of the three designed rehabilitation scenarios designed in the previous chapter were estimated as depicted in Table 6.2. The cost of reshaping the Nyala Mine topography was found to be up to R22, 116,617.16 in the case of the first and second rehabilitation scenarios. The cost of reshaping in the third scenario was R16, 834,894.50 which was about 24% reduction. This was due to the fact that in the third scenario about 19.65% (390 hectors) of the total surface area was reserved for the construction of the dirt park in the third scenario. The area designated

for dirt park construction will require minimum reshaping of spoils to design the dirt tracks and ramps.

Table 5.2: *Cost estimate of Cut and Fill operations*

Rehabilitation scenario I and II		**Rehabilitation scenario III**	
Estimation Variables		Estimation Variables	
1. Material to be moved	2805294 m³	1. Material to be moved	2135375 m³
2. Required work hours	4182	2. Required work hours	3183
1. Loader Hiring Rate/hr	R245.00	3. Truck hiring rate/hr	R254.00
2. Loader cost/m³	R3.59	4. Trucking cost/m³	R3.55
Truck Loading Cost		**Truck Loading Cost**	
▪ Loader Site Operation	R1,024,590.00	▪ Loader Site Operation	R779,835.00
▪ Loading Costs	R10,071,005.46	▪ Loading Costs	R7,665,996.25
▪ Total Truck Loading Costs	R11,095,595.46	▪ Total Truck Loading Costs	R8,445,831.25
Trucking Cost		**Trucking Cost**	
▪ Truck Site Operation	R1,062,228.00	▪ Truck Site Operation	R808,482.00
▪ Load Moving	R9,958,793.70	▪ Load Moving	R7,580,581.25
▪ Total Material Transportation Costs	R11,021,021.70	▪ Total Material Transportation Costs	R8,389,063.25
Total costs of Cut & Fill operations: R22,116,617.16		**Total costs of Cut & Fill operations: R16,834,894.50**	

6.3 Compaction Alleviation Costs

The preparation of the site for crop farming, as it was a main land use selected for rehabilitation of the Nyala Mine area in the first scenario, will require ripping of footprint areas. Ripped soils have increased potential for promoting easy infiltration of water to be taken up by plants than compacted soils. The second rehabilitation scenario will require ripping the area of 19.8% and 15.8% of the total area reserved for livestock grazing and picnic site construction purposes respectively. The land uses selected in the third rehabilitation scenario will generally not require any ripping operations. Therefore, the

costs of ripping activities presented in this section are for the first and second rehabilitation scenarios.

Soil compaction in filled areas will be minimized through the use of shovel and truck method for which the dozer will be used to spread the truck dumped material. The bulldozer equipped with three ripper tiners that can penetrate the ground up to the minimum depth of approximately 500 mm will be used to spread the material and rip the footprint areas to alleviate compaction. This section is earmarked for the presentation of the cost of ripping the footprint areas and that of spreading the truck dumped material in backfilled areas.

6.3.1 Parameters for estimation of bulldozer ripping cost

Prior to the calculation of the costs of ripping the footprint areas in the study area, the calculation of the hours required for the bulldozer to successfully complete the ripping operations was determined. The required bulldozer work-hours were determined after the average cycle time or ripping time per dozer pass was calculated. The number of dozer passes per hour was calculated based on the assumption that the minimum operator average work time was 45 min per hour. This is the standard approximation operator efficiency designed for calculation purposes in case of unavailability of job data (Caterpillar, 1998).

The volume of material to be ripped per single dozer pass (BCM/pass) was calculated by multiplying the average proposed cut length of 100 m, the ripper tiners spacing and the desired 500 mm (≈0.5 m) ripper penetration. The volume of the material to be ripped was then used to compute the bulldozer hourly production that was then employed in the computation of the number of hours required to rip an estimated bank volume footprint material. The calculations of dozer cycle time, number of passes per hour, volume of material to be ripped, dozer hourly production and the hours required to rip the entire footprint areas in the study area are presented in Appendix-D3.

The bulldozer operation cost was determined by multiplying the estimated hectares of rip area by the ripping cost rate of R8,900.00 per hour, while the bulldozer cost per hour of operation was estimated as a product of the dozer work-hours and its hire rate of R225.00/hr.

6.3.2 Ripping cost estimate

The estimated total costs of ripping the footprint area in the first rehabilitation scenario was found to be R919,188.04 as presented in Table 6.3. This cost was reduced by 46% to R420,129.04 in the second scenario (see Table 6.3). The areas that require ripping in the second rehabilitation scenario includes footprint areas in the section of the mine designated for the construction of the picnic site and that selected for livestock grazing purposes.

Table 6.3: *Estimated costs of compaction eluviations at Nyala Mine*

Rehabilitation Scenario I		**Rehabilitation Scenario II**	
Estimation Variables		Estimation Variables	
1. Footprint Area (m^2)	827186 (83 ha)	1. Footprint Area (m^2)	189043 (38 ha)
2. Volume to be ripped	413593 m^3	3. Volume to be ripped	94092 m^3
3. Required ripping hours	813	4. Required ripping hours	372
4. Ripping rate/ha	R8,900.00	5. Ripping rate/ha	R8,900.00
5. Dozer Hire rate/hr	R225.00	6. Dozer Hire rate/hr	R225.00
Footprint Ripping Costs		**Footprint Ripping Costs**	
▪ Dozer site operation	R182,992.50	▪ Dozer site operation	R83,632.50
▪ Dozer ripping costs	R736,195.54	▪ Dozer ripping costs	R336,496.54
Total ripping costs: R919,188.04		**Total ripping costs: R420,129.04**	

6.3.3 Spreading of fill material

The cost of spreading the material used to fill the void areas was determined by first calculating the volume of the material to be spread out, that was computed with an assumption that the material height will be approximately 0.836 m (average dozer blade height). Consequently, the volume of the material to be spread was estimated by multiplying the average blade height by the estimated plane backfill area. In order to determine the number of hours required to spread the fill material in the backfill areas, there was a need to calculate the dozer net hourly production using the operation adjustment factor and the normal hourly dozer production (see Appandix-D3). As a

result, dividing the volume of material to be leveled by the determined net hourly production gave an estimate of the number of hours required for the completion of the work of spreading the fill material.

The cost of bulldozing and spreading of fill material in the study area was estimated as a product of volume of material requiring spread and the bulldozer rate per cubic metre volume of material (R10.50/m^3). The cost of dozer hire was estimated by multiplying the dozer hire rate of R225.00/hr by the estimated number of dozer work-hours. Consequently, the total cost of spreading the fill material was determined to be comprising of the bulk material bulldozing cost and the dozer hiring cost. Thus the total estimated cost of spreading these materials was estimated to be R9,436,437.43 in the first and second rehabilitation scenarios as depicted in Table 6.4. In the case of the third rehabilitation scenario, this cost was slightly reduced by 1.6% to R9,309,260.51 (see Table 6.4).

Table 6.4: *Estimated costs of spreading the fill material*

Rehabilitation Scenario I and II		**Rehabilitation Scenario III**	
Estimation Variables		*Estimation Variables*	
1. Spread Area (m^2)	971917 (97 ha)	1. Spread Area (m^2)	958813 (96 ha)
2. Spread Volume	812523 m^3	2. Spread Volume	801568 m^3
3. Spreading rate/ha	R10.50	3. Spreading rate/ha	R10.50
4. Dozer work hours	4022	4. Dozer work hours	3968
5. Dozer Hire rate/hr	R225.00	5. Dozer Hire rate/hr	R225.00
Dozer Spread Costs		**Dozer Spread Costs**	
▪ Dozer site operation	R904,950.00	▪ Dozer site operation	R892,800.00
▪ Dozer spreading costs	R8,531,487.43	▪ Dozer spreading costs	R8,416,460.51
Total spreading costs: R9,436,437.43		**Total spreading costs: R9,309,260.51**	

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6.4 Cost of Security Fence Erection

In order to prevent and/or control animal access to Pit-I (pit lake) and Pit-II (proposed landfill site) erection of security fence around these pits will be necessary. The fence corner post coordinates were established as presented on Table 6.5. These coordinates were used to calculate the length (m) of each side of the area to be fenced. The sketch diagrams of the established fence line around Pit-I and Pit-II are presented in Figure 6.1.

The determined total fence length and the R130.00/m rate of security fence erection was used to estimate the total cost of fencing the pit lake and the landfill site in the study area. The cost of erecting the fence of about 1969.10 m around Pit-I was estimated to be R255,983.00 and that of erecting the 678.04 m around Pit-II was found to be R88,145.20. The total fence length and fencing cost were determined to be 2647.14 m and R344,128.20 respectively (see Table 6.5).

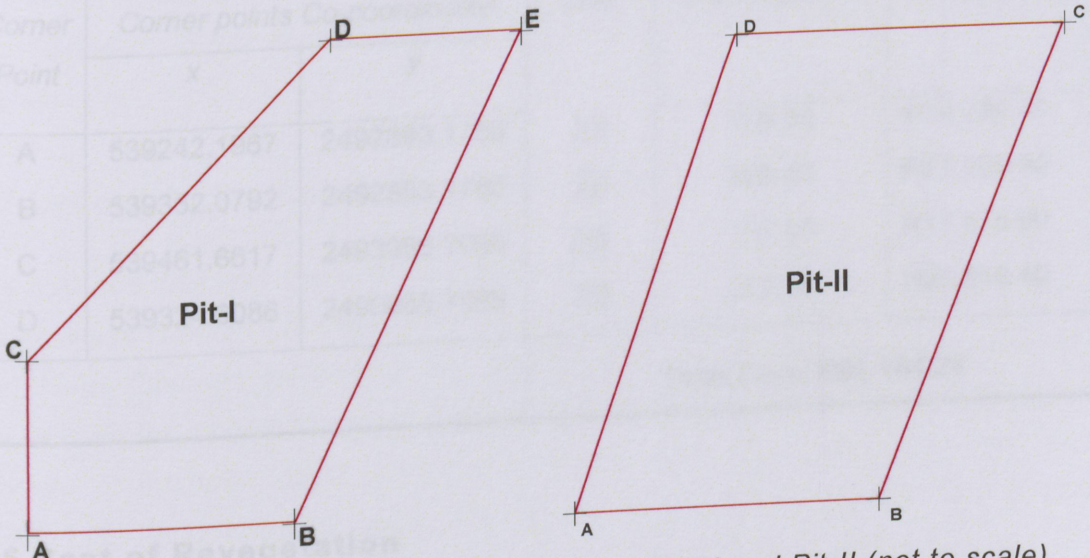


Figure 6.1: *Sketch diagram of fence boundary in Pit-I and Pit-II (not to scale)*

Table 6.5: *Estimated unit cost of fencing the abandoned pits at Nyala Mine*

Fencing of Pit-I					
Corner Point	*Corner points Co-coordinates*		*Line*	*Line length (m)*	*Fencing Cost*
	x	*y*			
A	538006.0183	2492288.0802	$\overleftrightarrow{AB}$	439.44	R57,127.20
B	538445.5484	2492288.0802	$\overleftrightarrow{AC}$	165.02	R21,452.60
C	538006.0183	2492453.1070	$\overleftrightarrow{DC}$	584.33	R75,962.90
D	538582.9015	2492838.1696	$\overleftrightarrow{DC}$	192.29	R24,997.70
E	538775.1910	2492810.6651	$\overleftrightarrow{BE}$	588.02	R76,442.60
Fencing of Pit-II			**Total Cost: R255,983.00**		
Corner Point	*Corner points Co-coordinates*		*Line*	*Line length (m)*	*Fencing Cost*
	x	*y*			
A	539242.1967	2492893.1785	$\overleftrightarrow{AB}$	109.88	R14,284.40
B	539352.0792	2492893.1785	$\overleftrightarrow{AD}$	209.43	R27,225.90
C	539461.6617	2493085.7098	$\overleftrightarrow{CD}$	137.05	R17,816.50
D	539324.6086	2499085.7098	$\overleftrightarrow{DE}$	221.68	R28,818.40
			Total Cost: R88,145.20		

6.5 Cost of Revegetation

The cost of planting grass on disturbed landscape was estimated and considered as the product of the number of hectors that require revegetation and the standard rate of revegetation cost per hectares (R18,130.00/ha). The identified areas that require establishment of vegetation cover include footprint areas in the portions of the mine to be developed for livestock grazing purposes and that reserved for the construction of a picnic site. As a result, the revegetation operations will be only carried out in the third rehabilitation scenario with the estimated costs of R1,400,250.61. The total surface area to be revegetation was found to 77 ha.

6.6 Machinery Fuel Costs Estimate

The diesel cost for trucks and other machinery (loader and dozer) were estimated using their average hourly fuel consumption. The ten cubic metres Mercedes-Benz tipper truck maximum consumption of 7.51l per hour on site job was used to get average costs of fuel needed by trucks. The used site job dozer and loader fuel efficiency were 29.147l per hour and 13.5l per hour respectively (see Appendix-D4).

In order to compute the final fuel cost estimate of landscaping work in the study area required that the litres of diesel per equipment be calculated by multiplying the hourly fuel consumption by the estimated work hours. Consequently, the dozer; truck; and loader fuel requirement in all the three scenarios was multipled by the current diesel price to obtain the estimate of each equipment fuel costs as presented in Appendix-D4. As a result, the calculated fuel cost for loading, transportation, spreading and ripping operations in the study area were found to be R2,191,874.22 in the first scenario, R2,182,114.11 in the second scenario and R1,858,156.68 in the case of the third scenario.

6.7 Labour Costs Estimation

The cost of labour was estimated using the adopted hourly rate of R17.66/hr; which is the minimum rate for civil engineers in South Africa. On this, the assumption that the work hours (8hr/day) will add up to 4182 and 3183 hours which were the estimated timelines for the longest Cut and Fill operations of the three scenarios. As a result, the estimate of the total labour cost of R73,854.12 (first and second scenarios) and R56,211.78 (third scenario) were obtained by multiplying the hourly rate by the maximum labour work hours.

6.8 Total Rehabilitation Costs

The estimate of the total direct cost was made by adding the unit cost of various operations constituting the rehabilitation work, namely: earthmoving or earthwork operations, material spreading and footprint ripping cost, revegetation, labour costs and the cost of security fence installation. The estimated direct costs for the implementation of the three designed rehabilitation scenarios are presented in Table 6.6. The estimated

total direct cost in each rehabilitation scenario was inflated by incorporating the adopted inflation rate of 10% (average inflation rate for the previous 30 years, 1981-2011).

Indirect cost such as the mobilization/demobilization was estimated as 5% of the inflated direct cost, the contractor profit as 27% of the inflated cost, and the project management fees as 5% of the inflated direct cost. On the other hand, the fuel cost was separately estimated (as presented in the previous section) and inflated to obtain the costs presented in Table 6.6. The costs of BMX dirt park design and construction was estimated as 16% of the inflated direct cost for rehabilitation strategies in the third scenario. Financial provision for erosion control measures were calculated in the form of contingency fees was made.

Table 6.6: *Total rehabilitation costs*

Direct Cost Estimate	**Rehabilitation Scenario Cost Estimates**		
	Scenario I	*Scenario II*	*Scenario III*
1. Earthmoving Costs	R33,212,212.62	R33,212,212.62	R16,834,894.50
2. Ripping & Spreading Cost	R10,355,625.47	R9,856,566.47	R9,309,260.51
3. Revegetation Costs	-	R1,400,250.61	-
4. Fencing Costs	R344,128.20	R344,128.20	R344,128.20
5. Labour Costs	R73,854.12	R73,854.12	R56,211.78
6. Total Direct Costs	R43,985,820.41	R44,887,012.01	R26,544,494.99
7. Inflated Total Direct Costs	R48,384,402.45	R49,375,713.21	R29,198,944.49
Indirect Cost Estimate	**Rehabilitation Scenario Costs Estimates**		
	Scenario I	*Scenario II*	*Scenario III*
8. Mobilization/Demobilization	R2,419,220.12	R2,468,785.66	R1,459,947.23
9. Contractor Profit/Overhead	R13,063,788.66	R13,331,442.57	R7,883,715.01
10. Diesel Cost	R2,411,061.64	R2,400,325.52	R2,043,972.35
11. Project Management Fees	R2,540,181.13	R2,592,224.94	R1,532,944.59
12. Contingencies Fees	R2,419,220.12	R2,468,785.66	R1,459,947.23
13. Redesign & Construction BMX Dirt Park	-	-	R4,087,852.23
14. Total Indirect Cost	R20,434,251.55	R23,261,564.36	R18,468,378.63
Total Rehabilitation Costs	**R68,818,654.00**	**R72,637,277.57**	**R47,667,323.12**

6.9 Projected Rehabilitation Costs

The unit costs for individual rehabilitation activities were escalated for the development of the ten years rehabilitation costs projection as presented in Table 6.7. The escalation was done using the most likely escalation values of 13.5% for escalation of fuel costs, 9.9% labour costs and 8.4% fencing costs escalation as determined by du Plessis and Brent (2006). From the escalated direct rehabilitation costs, the escalated indirect costs were calculated to get the overall escalated rehabilitation costs.

Table 6.7: *Escalated cost of Nyala Mine rehabilitation*

Year	Escalated Rehabilitation Costs		
	Scenario I	*Scenario II*	*Scenario III*
2013	R123,476,995.04	R126,006,820.13	R79,187,537.46
2014	R135,684,861.10	R138,465,138.86	R87,009,925.41
2015	R149,099,920.74	R152,155,446.00	R95,605,837.53
2016	R163,841,568.80	R167,199,591.07	R105,050,960.14
2017	R180,041,010.21	R183,731,476.68	R115,429,436.00
2018	R197,842,428.42	R201,898,251.06	R126,833,557.44
2019	R217,404,469.31	R221,861,618.40	R139,364,709.13
2020	R238,900,652.22	R243,799,278.84	R153,134,299.79
2021	R262,522,920.50	R267,906,511.20	R168,264,753.43
2022	R288,481,345.63	R294,397,911.81	R184,890,599.69
2023	R317,006,999.63	R323,509,305.83	R203,159,665.90

6.10 Summary

The implementation costs of the designed rehabilitation strategies were estimated based on the determined direct and indirect costs. The estimation of total rehabilitation costs showed that the first rehabilitation scenario can be implemented at an initial cost of R68,818,654.00. This costs were made up of R48,384,402.45 inflated direct costs and R20,434,251.55 indirect costs. The direct costs comprised of the costs of loading and moving about 2805294 m^3 of cut materials, spreading of 812523 m^3 material in fill areas and ripping of 83 hectares footprint areas. It also included the cost of labour and the costs of security fence installation around the pit lake and the landfill site proposed for dumping of inert waste.

It was estimated that the work of implementation of the second rehabilitation scenario can be carried out with an initial cost of R72,637,277.57. This cost estimate was about 5.5% higher than the first rehabilitation scenario. This increase in the rehabilitation cost can be attributed to the proposed revegetation work of an area of about 47 hectares which is designated for picnic site construction and 31ha footprint areas of the mine to serve as animals/livestock grazing site.

The cost estimate of the third scenario was found to be least costly rehabilitation strategy for the Nyala Mine. The implementation costs of this scenario was estimated at R47.667,323.12 made up of R29.198,944.49 inflated direct costs and R18.468,378.63 indirect costs. Scenario III rehabilitation unit operations used for direct cost estimation are earthmoving, ripping and spreading operations, fencing and labour costs. About 22.1% (R4.087,852.23) of direct cost was estimated as typical cost for redesign and construction of the proposed BMX dirt park. Estimated direct costs were all inflated to accommodate possible future changes of goods and service prices into the estimation.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATIONS

The main purpose of this chapter is to present the summary, concluding remarks and recommendations of the study to develop modeling framework for design of economical and appropriate rehabilitation plans for abandoned magnesite mine site.

7.1 Summary of the Study

Abandoned mines are a major concern due to their associated physical, environmental and public safety concerns. The concerns include public health and safety, visual impacts, stability issues, dust emission problems, erosional unstable waste rock dumps and tailings deposits, contaminated aquatic sediments, derelict work sites with compacted and polluted soil, and change in vegetation. Although abandoned mines in South Africa pose noticeable threats to the environment and public health and safety, very little has been done in terms of management of the problems and rehabilitation of the mine sites. In addition, inadequate understanding of the physical and environmental problems of the abandoned mines has led to ineffective rehabilitation designs.

The main purpose of this research was to develop a modeling framework for the design of inexpensive and suitable rehabilitation plans for the abandoned Nyala Magnesite Mine. The specific objectives were to carry out a comprehensive site examination and characterization of the abandoned mine site, generate surface terrain models for the development of different rehabilitation landforms, design economical and appropriate rehabilitation strategies for controlling environmental impacts and physical hazards at the mine site, and estimate cost of alternative rehabilitation strategies.

The research approach used in accomplishing these objectives involved conducting a comprehensive site investigation and characterization of the mine in order to identify and assess the environmental and physical hazards at the mine site. The identified hazards were scored and rated using modified Historical Mine Site Scoring System approach. The outcome of these endeavors was the compilation of physical and environmental hazard maps of the study area.

Following the site characterization process, terrain models were developed using RTK-GPS coordinates to guide the selection of appropriate rehabilitation alternatives for the site. The identified rehabilitation strategies were evaluated for their attractiveness. The three most attractive alternatives were used to develop three post-mining land use maps. The costs of implementing the three most promising rehabilitation alternatives were determined.

7.2 Conclusions

The assessment of environmental and physical hazards of the historical magnesite mine site assisted in determining the nature and extent of environmental problems at the study area. The sources of environmental problems identified at Nyala Mine were large volumes of magnesite tailing dumps, spoil dumps, top soil piles as well as large volume of water contained in excavations. The site was extremely degraded with most surface alterations resulting from extensive diggings, tailings material and overburden spoil dumps. Dangerous abandoned highwalls, exploration trenches, deep erosion gullies and dilapidated ore bunker were identified to be major physical hazards in the area. In addition, the pit lake presents drowning hazard and the exposed and rusted empty metal containers, drums, scraps, and nails represent safety hazards.

The rating and classification of the mine features in terms of their associated physical and environmental hazards provided credence that the best approach of effectively stamping out or reducing these hazards in the study area was to give priority to extremely and moderately hazardous pits; surface infrastructure and spoil dumps, and then to less hazardous tailing dumps. The pits and spoil materials which were found to be less hazardous were to receive least attention on the priority of cleaning up of physical hazards in the study area.

The identification of the hazards at the mine site provided an impetus for the development of the conceptual site model. The direct contact with mine waste, water in pit lakes and chemical containers were identified as the major pathways for human, animal, aquatic species and terrestrial plants. Consumption of fish, birds, mammals and amphibians that feeds; get into contact with contaminated grounds and drink contaminated water were identified as indirect exposure to the hazards.

The conceptual site model developed for the abandoned Nyala Mine has provided an increased understanding of the physical features of the site, a description of chemical

migration pathways, and an outline of human and ecological populations that may contact mine-related contamination or be exposed to physical hazards at the mine. Such a complete and detailed conceptual model is essential for making sound professional judgement on developing and optimizing rehabilitation designs. It can help identify the pros and cons of various rehabilitation activities and it is an important communication tool for regulators, rehabilitation parties and stakeholders.

The physical characterization of the mine waste showed that both tailings and spoil materials are generally well-graded sands. These materials were found to be suitable for engineering purposes such as road construction, brick- and block-making, and as fill material in foundation building due to their uniform size gradation. The high silica (SiO_2) content in the tailing materials coupled with the fact that silica is one of the hardest minerals makes this resource more suitable for engineering purposes.

The physical structure coupled with lack of nutrients of the tailings and the spoil were detrimental to vegetation growth. The failure of the mine wastes to support vegetation establishment was attributed to the high pH values recorded. The high average pH value of 8.5 of tailings and spoil materials could have possibly been the main reason for deficiency of Mn and marginal concentration of Fe for plant growth. This pH level also contributed to unavailability of major nutrients such as P, N and K required for plant growth and this led to the failure of waste materials to promote vegetation growth.

Laboratory analysis of certain parameters of the water samples from the pit lake showed that the water can be used as drinking water for domestic and wild animals. The measured pH value of 9 of the water exceeded the recommended DWAF standard for domestic use and the presence of algae made the water unfit for human consumption. The measured chloride concentration of 169.63 ppm was found to be at the toxic range (100-175 ppm) for crop irrigation and above the recommended (0-100 ppm) range for domestic use of the water.

Three-dimensional surface models were successfully generated using 5340 RTK-GPS coordinates. These surface models assisted in making informed decisions with regard to the area of the terrain to be cut and the voids that need to be filled. The quantity of Cut and Fill were accurately computed from the 3D terrain surface models and these estimates provided invaluable data for making strategic rehabilitation designs and creating different landforms.

Based on the site characterization outcomes and the developed terrain models, several rehabilitation alternative strategies for each modeled landform area were selected. The most appropriate alternatives were identified through the use of SWOT analysis. Quantitative Strategic Planning Matrix (QSPM) tool was used to evaluate the selected alternatives in terms of their relative attractiveness.

Results of the SWOT and QSPM analysis indicated that about 97% of the total rehabilitation area in the first rehabilitation scenario was favorable for cropland development. It also emerged that about 62% and 78% of the total area will be more appropriate for development of residential areas in the second and third scenarios respectively. The alternative use of Pit-I as pit lake (in conjunction with picnic site in scenario II) and Pit-II as a landfill site for inert waste were proposed in all the rehabilitation scenarios.

Development of rehabilitation strategies for the mine site using these decision-making tools will have positive impacts on the neighboring or host community in that it will provide most appropriate rehabilitation options for effectively addressing the problems and establishing sound post-mining land-use plans at the mine site.

Estimation of the cost of implementation of the three most promising rehabilitation scenarios was successfully made based on the direct and indirect unit costs of the selected rehabilitation options. The lowest cost and the most appropriate rehabilitation option was scenario III. This will involve rehabilitation design for residential area and development of BMX dirt park, construction of landfill site for inert waste and pit lake. The estimated cost for implementation of this rehabilitation plan was found to be R47.6 million. The attractiveness of scenario III is that it presents an opportunity for alternative use of the minesite with little disturbance of the current landscape of the mine. The most costly and least appropriate scenario was scenario II with the estimated cost of R72.6 million.

It was further established that any delay in the implementation of the rehabilitation plans will lead to sky-high rehabilitation costs. For example, the cost of rehabilitation of the best practicable option will escalate to R203.1 million by the year 2023. The cost estimates of the alternative rehabilitation approaches and the corresponding escalating costs will assist in budgeting for the rehabilitation of the abandoned mine site with the premise that funds will be made available for this purpose.

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This research has revealed that site characterization and terrain modeling are robust scientific techniques for making sound decision on selection of economical and appropriate rehabilitation plans for abandoned mine sites. The modeling framework developed in this study can be adopted in developing low-cost and appropriate rehabilitation strategies for other abandoned mines within the province and/or the country.

7.3 Recommendations

In the light of the main objectives of this research and on the bases of the above concluding remarks, the following recommendations are made:

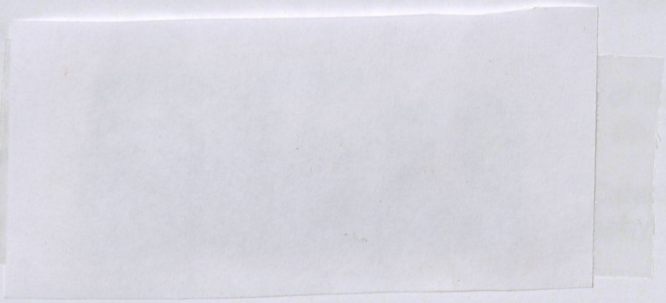
- It is recommended that cost-benefit study be conducted to determine both the environmental and social cost benefits of the selected rehabilitation options. The analysis of the cost-benefits of these alternatives will ensure that strategies with benefits that exceed the estimated costs of starting up the rehabilitation work of the abandoned Nyala mine are implemented. This will serve as justification of the need for rehabilitation of the Nyala Mine.

- Terrain models in this study were developed from independent GPS height measurements which might present uncertainties due to inaccessibility of some parts of the mine. If the similar study is conducted elsewhere, integration of more than one height data sets is recommended for enhancement of the quality and accuracy of the model.

- Further studies aimed at assessing and evaluating the best suitable crop species for rehabilitation of the Nyala Mine is also recommended. This will assist in ensuring that only appropriate crops with potentials of excellent yield are considered for farming in the study area.

- Limpopo province is endowed with mineral resources and there are also many abandoned mines in the province. There is paucity of information on the current environmental status of these mines. There is no doubt that they are in appalling condition and that a more appropriate rehabilitation strategies need to developed and implemented to correct the devastating impacts of these historic mine sites. In this regard similar studies need to be conducted in future so as to compile a

comprehensive inventory of abandoned mines in the province. Considering that funds are not even available for this purpose and other resources are limited, scoring of historical mine sites will assist in prioritizing rehabilitation of these mines.



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APPENDICES

Appendix-A1: Physical Hazards Scoring

Pit-I	Source of Hazards	Potential Risk Types	Source Scores	Exposure Scores	Physical Hazard	Victim Score	Scores Amalgamation	Individual Hazard Score	Individual Source Score	Total Mine Feature Score
	High walls	Falling from the high walls	4.50	8.50	38.25	6.60	2145.83	9656.21	17.28	93.66
		Falling of unstable walls	5.00	6.60	33.00	7.00	1524.60	7623.00		
	Water body	Drowning	9.00	9.60	86.40	9.80	8128.51	73156.61	170.04	
		Potential Health problems	6.40	9.00	57.60	9.00	4665.60	29859.84		
		Mud trap	9.00	8.50	76.50	8.50	5527.13	49744.13		
		Object in the pits bottom	6.00	8.00	48.00	7.50	2880.00	17280.00		
Pit-II	High walls	Falling from the high walls	9.60	8.50	81.60	8.40	5826.24	55931.90	116.47	63.00
		Falling of unstable walls	9.70	8.70	84.39	8.50	6240.64	60534.21		
	Water body	Drowning	0.00	1.50	0.00	0.00	0.00	0.00	9.52	
		Health related problems	5.00	6.00	30.00	4.50	810.00	4050.00		
		Mud trap	0.50	2.50	1.25	4.50	14.06	7.03		
		Object in the pits floor	4.50	6.00	27.00	7.50	1215.00	5467.50		
Pit-III	High walls	Falling from the high walls	9.80	9.50	93.10	8.50	7517.83	73674.69	101.45	110.27
		Falling of unstable walls	7.70	7.70	59.29	7.90	3606.61	27770.90		
	Water bodies	Drowning	9.50	8.90	84.55	7.00	5267.47	50040.92	119.10	
		Potential Health problems	8.00	8.40	67.20	6.40	3612.67	28901.38		
		Mud trap	7.90	8.60	67.94	8.70	5083.27	40157.84		
		Object at the pits floor	2.00	2.00	4.00	0.00	0.00	0.00		
Pit-IV	High walls	Falling from the high walls	6.00	6.00	36.00	6.00	1296.00	7776.00	16.90	8.82
		Falling of unstable walls	6.00	6.50	39.00	6.00	1521.00	9126.00		
	Water bodies	Drowning	0.00	6.00	0.00	6.00	0.00	0.00	0.73	
		Potential Health problems	0.50	3.00	1.50	5.00	22.50	11.25		
		Mud trap	0.00	0.50	0.00	3.00	0.00	0.00		

		Object at the pits floor	3.00	4.00	12.00	5.00	240.00	720.00		
Pit-V	High walls	Falling from the high walls	7.70	7.80	60.06	6.00	2810.81	21643.22	26.97	13.61
		Falling of unstable walls	6.50	6.00	39.00	3.50	819.00	5323.50		
	Water body	Drowning	0.00	4.00	0.00	1.00	0.00	0.00	0.25	
		Potential Health problems	1.50	3.40	5.10	4.00	69.36	104.04		
		Mud trap	3.00	0.00	0.00	1.00	0.00	0.00		
		Object in the pits floor	2.00	5.00	10.00	1.50	75.00	150.00		
Ore bunker	Structure	Falling- walls of the structure	6.40	8.50	54.40	9.30	4300.32	27522.05	88.18	88.18
		Falling of unstable walls	7.00	7.00	49.00	8.50	2915.50	20408.50		
		Frame Stability	8.40	8.00	67.20	6.50	3494.40	29352.96		
		Object at the floor	6.50	6.30	40.95	6.50	1676.90	10899.87		
Magnesite Tailings	Tailing-A	Falling from the slopes	5.00	7.00	35.00	6.50	1592.50	7962.50	48.56	49.87
		Falling of unstable walls	4.00	6.00	24.00	6.00	864.00	3456.00		
		Objects within the dump material	3.50	6.40	22.40	6.50	931.84	3261.44		
		Potential Health problems	7.00	8.40	58.80	9.80	4840.42	33882.91		
	Erosion Gullies	Falling from the Gully walls	8.40	7.00	58.80	8.00	3292.80	27659.52	51.18	
		Falling of unstable walls	8.00	7.00	56.00	7.50	2940.00	23520.00		
Magnesite Tailings	Tailing-B	Falling from the Slopes	2.50	6.00	15.00	3.00	270.00	675.00	24.31	41.67
		Falling of unstable tailings	2.50	6.00	15.00	6.80	612.00	1530.00		
		Objects within the dump material	4.50	7.50	33.75	6.40	1620.00	7290.00		
		Potential Health problems	6.00	7.00	42.00	8.40	2469.60	14817.60		
	Erosion Gullies	Falling from the Gully walls	8.00	7.50	60.00	6.50	2925.00	23400.00	59.03	
		Falling of unstable walls	8.30	7.80	64.74	8.50	4292.26	35625.77		
Spoil banks		Potential Health problems	8.00	9.80	78.40	9.40	7222.21	57777.66	85.90	85.90
		Object in the spoils	1.50	8.50	12.75	9.00	975.38	1463.06		
		Falling from the steep slopes	7.00	8.00	56.00	8.50	3808.00	26656.00		

Appendix–A2: Environmental Hazard Scoring

Water body	Source Hazards	Potential Risks Types	Source Scores	Pathway Scores	Environ. Hazard	Receptors Score	Amalgamation of Scores	Individual Env. Hazard Score	Individual Env. Hazard source Scores	Total Feature Scores
	Water Quality	Influence on agricultural land	8.50	4.50	38.25	8.00	1377.00	11704.50	69.59	69.59
		Effect on aquatic pieces	6.50	9.00	58.50	7.00	3685.50	23955.75		
		Effect on livestock & human	8.50	8.50	72.25	6.50	3991.81	33930.41		
Tailing Material	Soil structure	Sedimentation	9.50	8.00	76.00	8.50	5168.00	49096.00	174.83	130.41
		Poor structure to support vegetarian	9.90	6.00	59.40	8.50	3029.40	29991.06		
		Damage to Land	8.00	7.50	60.00	7.00	3150.00	25200.00		
		Dust generation	9.00	8.00	72.00	8.40	4838.40	43545.60		
		Damage to water	7.50	8.00	60.00	7.50	3600.00	27000.00		
	Geochemistry	Influence on agricultural land	9.00	8.70	78.30	9.00	6130.89	55178.01	85.98	
		Influence on surface water	9.00	6.50	58.50	9.00	3422.25	30800.25		
Spoil banks	Physical structure	Effect of Erosion	5.00	6.00	30.00	5.00	900.00	4500.00	50.62	50.62
		Change of soil pH levels	6.50	6.00	39.00	6.00	1404.00	9126.00		
		Damage to Landscape	8.50	8.00	68.00	8.00	4352.00	36992.00		
Excavations		Effect on soil quality	9.00	6.00	54.00	6.00	1944.00	17496.00	104.31	104.31
		Sedimentation	8.50	7.00	59.50	7.00	2915.50	24781.75		
		Dust generation	8.00	8.50	68.00	6.40	3699.20	29593.60		
		Damage to water	7.00	5.00	35.00	6.00	1050.00	7350.00		
		Damage to Land	7.00	8.00	56.00	8.00	3584.00	25088.00		
Ore bunker		Alteration of the landscape	4.00	5.00	20.00	5.00	500.00	2000.00	5.60	5.60
		Sterilization of the land for development	7.50	4.00	30.00	4.00	480.00	3600.00		

APPENDIX-B: SUMMARY OF CALCULATIONS FOR GRAIN SIZE DISTRIBUTION CURVES

Appendix-B1: Tailing Material

Sieve sizes	Sieve wt	Sieve + Sample	Sample wt	Cumulative wt	Cumulative %	% Retained	% Passing	Error wt	Error in %
4mm	398.78	734.02	335.24	335.24	22.38	22.38	77.62	2.27	0.45
3.15mm	357.50	459.18	101.68	436.92	29.16	8.22	91.78		
2mm	326.60	513.00	186.40	623.32	41.61	12.44	87.56		
1mm	298.30	567.11	268.81	892.13	59.55	17.94	82.06		
500µm,	291.70	526.74	235.04	1127.17	75.24	15.69	84.31		
250µm	243.70	420.66	176.96	1304.13	87.05	11.81	88.19		
125µm	237.20	355.50	118.30	1422.43	94.95	7.90	92.10		
63µm	252.00	288.21	36.21	1458.63	97.37	2.42	97.58		
32µm	251.20	281.50	30.30	1488.93	99.39	2.02	97.98		
Pan	329.46	338.59	9.13	1498.07	100.00	0.61	99.39		

Appendix-B2: Spoil Dumps Material

Sieve sizes	Sieve wt	Sieve + Sample	Sample wt	Cumulative wt	Cumulative %	% Retained	% Passing	Error wt	Error in %
4mm	395.54	705.39	309.85	309.81	20.78	20.78	79.22	7.83	0.52
3.15mm	357.50	457.25	99.75	409.56	27.48	8.21	91.79		
2mm	326.60	545.06	218.46	628.01	42.18	14.70	85.30		
1mm	298.30	599.22	300.92	928.93	62.41	20.23	79.77		
500µm,	291.70	523.85	232.15	1161.08	78.02	15.61	84.39		
250µm	243.70	393.94	150.24	1311.32	88.12	10.10	89.90		
125µm	237.20	336.19	98.99	1410.31	94.77	6.65	93.35		
63µm	252.00	286.58	34.58	1444.88	97.15	2.32	97.68		
32µm	251.20	283.84	32.64	1477.52	99.29	2.19	97.81		
Pan	330.25	340.84	10.59	1488.11	100.00	0.71	99.29		

APPENDIX-C: SWOT AND QSPM ANALYSIS FOR SELECTION OF APPROPRIATE REHABILITATION STRATEGIES

Area-1 SWOT analysis

SWOT Parameters (AREA-1)	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
No Action	▪ No disturbance of the recovering sites ▪ No rehabilitation cost required	▪ No reduce or eliminate the environmental hazards ▪ No reduction or elimination of physical hazards	▪ Opportunity of vegetation recovery in some portion of the area	▪ No beneficial use of the site	▪ Retain the current state of the site
Development	▪ Provision of new residential site ▪ Elimination of environmental problems of spoils	▪ Require reshaping of spoil materials. ▪ Fencing of Pit-I will be necessary.	▪ Opportunity for further southward expansion of Zwigodini village.	▪ Residence close to Pit-I might lid to the use of the pit as domestic waste dump site.	▪ Site development to promote future residential, commercial, or industrial development
Agriculture: crop farming	▪ Good soil chemistry stability	▪ Require contouring of spoil materials to provide suitable slopes for this purpose. ▪ Improvement of soil quality will be necessary	▪ The water contained in Pit-I can be used for irrigation purpose, with little treatment.	▪ Attempt to use water in Pit-I for irrigation without treatment might have effect on soil quality	▪ Strive to create stable crop land
Recreational: Dirt park construction	▪ Minimum reshaping of spoil materials for bicycle dirt jump ▪ The site is easily accessible by road for this purpose.	▪ No solution to the environmental and physical stresses associated with the Pit-I portion of the model ▪ The spoil materials comprise mostly of boulders, therefore ripping and sieving out of lager soil particles ▪ Removal of the few vegetation growing on the site	▪ Introduction of new sporting activity in the area. ▪ The park can attract many bicycle dirt jumping fans as it also at close proximity to Pafuri gate to Kruger National Park and Big-Tree tourist destinations.	▪ The facility my not receive full support of the community.	▪ Strive to develop a land that support both inland and water based recreational activities
livestock grazing	▪ No disturbance of the recovering sites. ▪ Reduced rehabilitation cost.	▪ Not eliminate the physical hazards of Pit-I portion. ▪ Minimum vegetation growth.	▪ Development of livestock enterprise	▪ Increasing number of livestock per hector my lid to extensive site degradation.	▪ Develop a site with improved grazing capacity to support livestock production in the area
Pit wetland	▪ Stabilization of the pit wall and minimize hazards associated with them and the water in the pit.	▪ Require revegetation of the site with native species around the pit ▪ The pit walls are too high ▪ The water volume in the pit reduces significantly during winter. ▪ The pit walls are generally of consolidated low grade magnesite ore.	▪ The site can also concurrently be used for animal grazing and water base recreational purpose. ▪ Development of picnic facilities around the site.	▪ Community reluctance to the land use ▪ The pitwalls might not support the growth of native spices	▪ Create a lake and native animal habitat
Inert landfill	▪ Filling the pit with inert waste has no effect on ground water	▪ The pit is extensive and contains water.	▪ Improve the quality of the backfill soil in the pit ▪ The filled pit can support a range of land uses.	▪ The back filling of the pit will lid to the drying up of the water in the pit. ▪ High potentials of use of the site as domestic waste disposal site.	▪ Create beneficial use of the abandoned pit while backfilling it.

Area-2 SWOT analysis

SWOT Parameters (AREA-2)	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
No Action	▪ No disturbance of the recovering sites ▪ No rehabilitation cost required	▪ No elimination of physical and environmental hazards associated with Pit-I and spoil dumps.	▪ Opportunity of vegetation recovery in some portion of the area	▪ No beneficial use of the site	▪ Retain the current state of the site
Development	▪ Provision of new residential site ▪ Elimination of environmental problems of spoils dumps	▪ Require reshaping of spoil materials. ▪ Fencing of Pit-I will be necessary.	▪ Opportunity for further southward expansion of Zwigodini village.	▪ Residence close to Pit-I might lid to the use of the pit as domestic waste dump site.	▪ Site development to promote future residential, commercial, or industrial development
Agriculture: crop farming	▪ Site geochemical stability ▪ Growth of crops can minimize dust generation from spoil dumps	▪ Require contouring of spoil materials ▪ Improvement of soil quality will be necessary	▪ Opportunity for increased crop production in the area	▪ No water for irrigation of crops. ▪ The area is covered by large volume spoil dumps which might not support crop growth.	▪ Strive to create stable crop land
Recreational: Dirt park construction	▪ Require minimum reshaping of spoil materials for bicycle dirt jump ▪ The site is easily accessible by road for this purpose.	▪ No solution to the environmental and physical stresses associated with the Pit-I portion of the model ▪ The spoil materials comprise mostly of boulders, therefore ripping and sieving out of lager soil particles ▪ Removal of few vegetation growing on the site	▪ Introduction of new sporting activity in the area. ▪ The park can attract many bicycle dirt jumping fans as it also at close proximity to Pafuri gate to Kruger National Park and Big-Tree tourist destinations.	▪ The facility my not receive full support of the community.	▪ Strive to develop a land that support both inland and water based recreational activities
Livestock grazing	▪ No disturbance of the recovering sites. ▪ Reduced cost of rehabilitation.	▪ No elimination of physical and environmental hazards associated with Pit-I portion. ▪ Minimum growth of vegetation for livestock grazing.	▪ Development of new livestock enterprises	▪ Increasing number of livestock per hector my lid to extensive site degradation.	▪ Develop a site with improved grazing capacity to support livestock production in the area
Inert landfill	▪ Filling the pit with inert waste has no effect on ground water	▪ The pit is extensive.	▪ Improve the quality of the backfill soil in the pit as the grass has potential to improve soil organic matter ▪ The filled pit can support a range of land uses.	▪ High potentials of use of the site as domestic waste disposal site.	▪ Create beneficial use of the abandoned pit while backfilling it.

Area-3 SWOT analysis

SWOT Parameters (AREA-3)	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
No Action	▪ No disturbance of the recovering sites ▪ No rehabilitation cost required	▪ No reduce or eliminate the environmental hazards ▪ No reduction or elimination of physical hazards	▪ Use of the dump as study site for university students.	▪ No beneficial use of the site	▪ Retain the current state of the site
Use of tailing for block making	▪ Significantly reduce the amount of in the tailing dump. ▪ The material has good engineering properties for this purpose.	▪ Very little material can be used for such purpose ▪ Minimum construction being carried out in the study area	▪ Development of new brick/blocks making enterprises.	▪ River sand abundance in the area can reduce the attractiveness of the strategy	▪ Reduce the volume of tailing and spoil dumps material through the use of the material for brick making.
Use of tailing as fill material in road construction	▪ Reduce the amount of in the tailing dump. ▪ Loading of the material won't require the use of excavator.	▪ Not less than 5 km distance from potential site for read construction	▪ Reduce risks of feather damage of the environment due to excavations material for road construction.	▪ Alternative site closer to the road construction site can be identified	▪ Reduce the volume of tailing and spoil dumps material through the use of the material in road construction.
Back filling of part Pit-I portion in Area-2	▪ Extremely reduce the amount of in the tailing dump. ▪ Will eliminate physical and environmental hazards associated with the tailing dump as well as those associated with Pit-I portion in Area-2	▪ The material is characterized by poor soil structure.	▪ The backfilled area can support a wide range of land uses	▪ Increase salinity of water Pit-I due to magnesite leaching from tailing material	▪ Reduce the volume of tailing and spoil dumps material by backfilling Pit-I portion in Area-2.
Tailing management alternative	▪ The environmental and physical hazards can be contained.	▪ The tailing does not support vegetation growth used mostly to prevent excessive erosion of tailings ▪ Budget for continuous tailing management will be required.	▪ Non was found	▪ No easy and cost effective strategy for water and wind erosion control of tailings can be found.	▪ To contain the environmental and physical hazards associated with the mine.

Area-4 SWOT analysis

SWOT Parameters (AREA-4)	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
No Action	▪ No disturbance of the recovering sites ▪ No rehabilitation cost required	▪ No elimination of physical and environmental hazards associated with Pit-III, Pit-IV and spoil dumps.	▪ Opportunity of vegetation recovery in some portion of the area	▪ No beneficial use of the site	▪ Retain the current state of the site
Development	▪ Provision of new residential site ▪ Elimination of environmental problems of spoils dumps	▪ Require reshaping of spoil materials. ▪ Fencing of the pits will be necessary.	▪ Opportunity for further southward expansion of Zwigodini village.	▪ Residence close to Pit-III and Pit-IV might lid to the use of the pit as domestic waste dump site.	▪ Site development to promote future residential, commercial, or industrial development
Agriculture: crop farming	▪ Site geochemical stability in filled areas ▪ Growth of crops can minimize dust generation from spoil dumps ▪ Very small portion of the area was disturbed by mining	▪ Require filling of Pit-III and Pit-III by few spoil dumps found around the area	▪ Opportunity for increased crop production in the area ▪ Opportunity to connect the southern crop field with the northern one	▪ No water for irrigation of crops. ▪ Agricultural activities might disturb extensive area that was not disturbed by mining.	▪ Strive to create stable crop land
Livestock grazing	▪ No disturbance of the recovering sites. ▪ Reduced cost of rehabilitation.	▪ No elimination of physical and environmental hazards associated with Pit-III and Pit-IV portion. ▪ Minimum growth of vegetation for livestock grazing.	▪ Development of new livestock enterprises.	▪ Increasing number of livestock per hector my lid to extensive site degradation.	▪ Develop a site with improved grazing capacity to support livestock production in the area
Use of pits as Inert landfill	▪ Filling the pit with inert waste has no effect on ground water ▪ Both pits (Pit-III and IV) are shallow with above the water table. ▪ Pit-I is at less than 100 m distance from the current expunction of Zwigodini village ▪ The pit of reasonable size for this purpose	▪ Fencing of Pit-I to provide controllable access to the pit is necessary.	▪ Improve the quality of the backfill soil in the pit as the grass has potential to improve soil organic matter ▪ The filled pit can support a wide range of land uses.	▪ High potentials of use of the site as domestic waste disposal site.	▪ Create beneficial use of the abandoned pit while backfilling them.

Area-5 SWOT analysis

SWOT Parameters (AREA-5)	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
No Action	▪ No disturbance of the recovering sites. ▪ No rehabilitation cost required.	▪ No elimination of physical and environmental hazards associated with Pit-IV, Pit-V, and tailing dumps.	▪ Opportunity of vegetation recovery in some portion of the area	▪ No beneficial use of the site	▪ Retain the current state of the site
Development	▪ Provision of new residential site ▪ Elimination of environmental problems of spoils dumps	▪ Require reshaping of tailings and spoil materials.	▪ Opportunity for further southward expansion of Zwigodini village.	▪ The area is far from the existing residential area, thus the strategy might receive little support.	▪ Site development to promote future residential, commercial, or industrial development
Agriculture: crop farming	▪ Site geochemical stability in filled areas ▪ Growth of crops can minimize dust generation from spoil dump	▪ Require filling of Pit-IV and Pit-V by tailing material from Tailing Dump-B	▪ Opportunity for increased crop production in the area	▪ No water for irrigation of crops.	▪ Strive to create stable crop land
Livestock grazing	▪ No disturbance of the recovering sites. ▪ Reduced cost of rehabilitation.	▪ No elimination of physical and environmental hazards associated with tailing, Pit-IV portion and Pit-V. ▪ Minimum to medium growth of vegetation for livestock grazing.	▪ Development of new livestock enterprises.	▪ Increasing number of livestock per hector my lid to extensive site degradation.	▪ Develop a site with improved grazing capacity to support livestock production in the area
Use of pits as Inert landfill	▪ Filling the pit with inert waste has no effect on ground water ▪ Both pits (Pit-IV and V) are shallow with above the water table.	▪ Pit-IV is extensive and shallow. ▪ Pit-V is far from the community.	▪ Improve the quality of the backfill soil in the pit as the grass has potential to improve soil organic matter ▪ The filled pit can support a wide range of land uses.	▪ High potentials of use of the site as domestic waste disposal site.	▪ Create beneficial use of the abandoned pit while backfilling them.
Recreational: Dirt park construction	▪ Require minimum reshaping of spoil materials for bicycle dirt jump ▪ The site is easily accessible by road for this purpose.	▪ No solution to the environmental and physical stresses associated with the pits and tailing dumps portion of the model ▪ The spoil materials comprise mostly of boulders, therefore ripping and sieving out of lager soil particles ▪ Removal of few vegetation growing on the site	▪ Introduction of new sporting activity in the area. ▪ The park can attract many bicycle dirt jumping fans as it also at close proximity to Pafuri gate to Kruger National Park and Big-Tree tourist destinations.	▪ The facility my not receive full support of the community.	▪ Strive to develop a land that support both inland and water based recreational activities

Quantitative Strategic Planning Matrix for Area-1 Rehabilitation Alternatives

QSPM for No-Action Rehabilitation alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ No disturbance of the recovering sites	0.35	3	1.05
▪ No rehabilitation cost required	0.25	2	0.50
Weaknesses			
▪ Not reduce or eliminate the environmental hazards	0.20	1	0.20
▪ No reduction or elimination of physical hazards	0.20	1	0.20
Sum Weights	*1.00*		*1.95*
Opportunities			
▪ Vegetation recovery in some portions of the mine	0.60	2	1.20
Threats			
▪ No beneficial use of the site	0.40	1	0.40
Sum Weights	*1.00*		*1.60*
Sum Total Attractiveness Score		3.55	

QSPM for Development Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Provide new residential site	0.30	4	1.20
▪ Eliminate environmental problems of spoils	0.30	4	1.20
Weaknesses			
▪ The terrain is too rugged due to spoil dumps	0.20	2	0.40
▪ Pit-I highwalls will pose physical hazards to the community	0.20	2	0.40
Sum Weights	*1.00*		*3.20*
Opportunities			
▪ Southward expansion of Zwigodini village.	0.55	2	1.10
Threats			
▪ Residence close to Pit-I might lid to the use of the pit as domestic waste dump site.	0.45	1	0.45
Sum Weights	*1.00*		*1.55*
Sum Total Attractiveness Score		4.75	

QSPM for Recreational (Dirt Park Construction) Development Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Minimum reshaping of spoil materials for bicycle dirt jump	0.20	4	0.80
▪ The site is easily accessible by road	0.25	3	0.75
Weaknesses			
▪ Pit-I environmental and physical hazards remain	0.10	1	0.10
▪ Presence of boulders in spoils dumps	0.15	2	0.30
▪ Removal of some vegetation growing on the site	0.30	2	0.60
Sum Weights	*1.00*		*2.55*
Opportunities			
▪ Introduction of new sporting activity in the area.	0.40	2	0.80
▪ The park can attract many bicycle dirt jumping fans as it also at close proximity to Pafuri gate to Kruger National Park and Big-Tree tourist destinations.	0.30	2	0.60
Threats			
▪ The facility my not receive full support of the community.	0.30	2	0.60
Sum Weights	*1.00*		*2.00*
Sum Total Attractiveness Score		4.55	

QSPM for Animal Grazing Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ No disturbance of the recovering sites.	0.30	3	0.90
▪ Reduced rehabilitation cost.	0.25	2	0.50
Weaknesses			
▪ Not eliminate the physical hazards of Pit-I portion.	0.25	1	0.25
▪ Minimum vegetation growth	0.20	2	0.40
Sum Weights	1.00		2.05
Opportunities			
▪ Development of livestock enterprise	0.50	2	1.00
Threats			
▪ Increasing number of livestock per hector my lid to extensive site degradation.	0.50	1	0.50
Sum Weights	*1.00*		*1.50*
Sum Total Attractiveness Score		3.55	

QSPM for Agriculture Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Site chemistry stability	0.40	4	1.60
Weaknesses			
▪ Require contouring of spoil materials to provide suitable slopes for this purpose.	0.30	4	1.20
▪ Improvement of soil quality will be necessary	0.30	3	0.90
Sum Weights	*1.00*		*3.70*
Opportunities			
▪ The water contained in Pit-I can be used for irrigation purpose, with little treatment.	0.50	2	1.00
Threats			
▪ Attempt to use water in Pit-I for irrigation without treatment might have effect on soil quality	0.50	2	1.00
Sum Weights	*1.00*		*2.00*
Sum Total Attractiveness Score		5.70	

QSPM for Pit-Wetland Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Stabilization of the pit wall and minimize hazards associated with them and the water in the pit.	0.30	4	1.20
Weaknesses			
▪ Require revegetation of the site with native species around the pit	0.30	4	1.20
▪ The pit walls are too high	0.00	2	0.00
▪ The water volume in the pit reduces significantly during winter.	0.20	1	0.20
▪ The pit walls are generally of consolidated low grade magnesite ore.	0.20	2	0.40
Sum Weights	*1.00*		*3.00*
Opportunities			
▪ The site can also concurrently be used for animal grazing and water base recreational purpose.	0.35	2	0.70
▪ Development of picnic facilities around the site.	0.20	3	0.60
Threats			
▪ Community reluctance to the land use	0.20	2	0.40
▪ The pitwalls might not support the growth of native spices	0.25	1	0.25
Sum Weights	*1.00*		*1.95*
Sum Total Attractiveness Score		4.95	

QSPM for Inert landfill Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ No effect on ground water	0.55	4	2.20
Weaknesses			
▪ The pit is extensive and contains water.	0.45	0	0.00
Sum Weights	*1.00*		*2.20*
Opportunities			
▪ Improve the quality of the backfill soil in the pit	0.30	2	0.60
▪ The filled pit can support a range of other land uses.	0.20	2	0.40
Threats			
▪ The back filling of the pit will lid to the drying up of the water in the pit.	0.30	1	0.30
▪ High potentials of use of the site as domestic waste disposal site.	0.20	1	0.20
Sum Weights	*1.00*		*1.50*
Sum Total Attractiveness Score		3.30	

Quantitative Strategic Planning Matrix for Area-2 Rehabilitation Alternatives

QSPM for No-Action Rehabilitation alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ No disturbance of the recovering sites	0.40	3	1.20
▪ No costs of rehabilitation	0.30	2	0.60
Weaknesses			
▪ No elimination of physical and environmental hazards associated with Pit-I and spoil dumps.	0.30	1	0.30
Sum Weights	*1.00*		*2.10*
Opportunities			
▪ Vegetation recovery in some portions of the mine	0.60	2	1.2
Threats			
▪ No beneficial use of the site	0.4	1	0.4
Sum Weights	*1.00*		*1.6*
Sum Total Attractiveness Score		3.70	

QSPM for Development Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Provision of new residential site	0.30	4	1.20
▪ Elimination of environmental problems of spoils dumps	0.30	4	1.20
Weaknesses			
▪ Require reshaping of spoil materials.	0.20	3	0.60
▪ Fencing of Pit-I will be necessary.	0.20	2	0.40
Sum Weights	*1.00*		*3.40*
Opportunities			
▪ Southward expansion of Zwigodini village.	0.55	2	1.10
Threats			
▪ Residence close to Pit-I might lid to the use of the pit as domestic waste dump site.	0.45	1	0.45
Sum Weights	*1.00*		*1.55*
Sum Total Attractiveness Score		4.95	

QSPM for Agriculture Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Site geochemical stability	0.30	4.00	1.20
▪ Growth of crops can minimize dust generation from spoil dumps	0.30	3.00	0.90
Weaknesses			
▪ Require contouring of spoil materials	0.20	4.00	0.80
▪ Improvement of soil quality will be necessary	0.20	3.00	0.60
Sum Weights	*1.00*		*3.50*
Opportunities			
▪ Opportunity for increased crop production in the area	0.40	3	1.20
Threats			
▪ No water for irrigation of crops.	0.30	2	0.60
▪ The area is covered by large volume spoil dumps which might not support crop growth.	0.30	1	0.30
Sum Weights	*1.00*		*2.10*
Sum Total Attractiveness Score		5.60	

QSPM for Recreational (Dirt Park Construction) Development Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Require minimum reshaping of spoil materials for bicycle dirt jump	0.20	4	0.80
▪ The site is easily accessible by road for this purpose.	0.25	3	0.75
Weaknesses			
▪ No solution to the environmental and physical stresses associated with the Pit-I portion of the model	0.10	1	0.10
▪ The spoil materials comprise mostly of boulders, therefore ripping and sieving out of lager soil particles	0.15	2	0.30
▪ Removal of few vegetation growing on the site	0.30	2	0.60
Sum Weights	*1.00*		*2.55*
Opportunities			
▪ Introduction of new sporting activity in the area.	0.40	2	0.80
▪ The park can attract many bicycle dirt jumping fans as it also at close proximity to Pafuri gate to Kruger National Park and Big-Tree tourist destinations.	0.30	3	0.90
Threats			
▪ The facility my not receive full support of the community.	0.30	2	0.60
Sum Weights	*1.00*		*2.30*
Sum Total Attractiveness Score		4.85	

QSPM for Livestock Grazing Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ No disturbance of the recovering sites.	0.30	3	0.90
▪ Reduced cost of rehabilitation.	0.25	3	0.75
Weaknesses			
▪ No elimination of physical and environmental hazards associated with Pit-I portion.	0.25	1	0.25
▪ Minimum growth of vegetation for livestock grazing.	0.20	1	0.20
Sum Weights	*1.00*		*2.10*
Opportunities			
▪ Development of new livestock enterprises	0.50	2	1.00
Threats			
▪ Increasing number of livestock per hector my lid to extensive site degradation.	0.50	1	0.50
Sum Weights	*1.00*		*1.50*
Sum Total Attractiveness Score		3.60	

QSPM for Inert landfill Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Filling the pit with inert waste has no effect on ground water	0.55	4	2.20
Weaknesses			
▪ The pit is extensive.	0.45	0	0.00
Sum Weights	*1.00*		*2.20*
Opportunities			
▪ Improve the quality of the backfill soil in the pit as the grass has potential to improve soil organic matter	0.45	2	0.90
▪ The filled pit can support a range of land uses.	0.25	2	0.50
Threats			
▪ High potentials of use of the site as domestic waste disposal site.	0.30	1	0.30
Sum Weights	*1.00*		*1.70*
Sum Total Attractiveness Score		3.74	

Quantitative Strategic Planning Matrix for Area-3 Rehabilitation Alternatives

QSPM for No-Action Rehabilitation alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ No disturbance of the recovering sites	0.30	3	0.90
▪ No rehabilitation cost required	0.30	3	0.90
Weaknesses			
▪ No reduce or eliminate the environmental hazards	0.20	1	0.20
▪ No reduction or elimination of physical hazards	0.20	1	0.20
Sum Weights	*1.00*		*2.20*
Opportunities			
▪ Opportunity of vegetation recovery in some portion of the area	0.55	2	1.10
Threats			
▪ No beneficial use of the site	0.45	1	0.45
Sum Weights	*1.00*		*1.55*
Sum Total Attractiveness Score		3.75	

QSPM for use of tailing for block/brick making alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Significantly reduce the amount of in the tailing dump.	0.30	3	0.90
▪ The material has good engineering properties for this purpose.	0.30	3	0.90
Weaknesses			
▪ Very little material can be used for such purpose	0.20	1	0.20
▪ Minimum construction being carried out in the study area	0.20	1	0.20
Sum Weights	*1.00*		*2.20*
Opportunities			
▪ Development of new brick/blocks making enterprises.	0.45	3	1.35
Threats			
▪ River sand abundance in the area can reduce the attractiveness of the strategy	0.55	1	0.55
Sum Weights	*1.00*		*1.90*
Sum Total Attractiveness Score		4.10	

QSPM for Use of tailing as fill material in road construction alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Reduce the amount of in the tailing dump.	0.40	3	1.20
▪ Loading of the material won't require the use of excavator.	0.30	2	0.60
Weaknesses			
▪ Not less than 5 km distance from potential site for read construction	0.30	3	0.90
Sum Weights	*1.00*		*2.70*
Opportunities			
▪ Reduce risks of feather damage of the environment due to excavations material for road construction.	0.55	3	1.65
Threats			
▪ Alternative site closer to the road construction site can be identified	0.45	1	0.45
Sum Weights	*1.00*		*2.10*
Sum Total Attractiveness Score		4.80	

QSPM for Back filling of part Pit-I portion in Area-2 alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Extremely reduce the amount of in the tailing dump.	0.40	4	1.60
▪ Will eliminate physical and environmental hazards associated with the tailing dump as well as those associated with Pit-I portion in Area-2	0.30	4	1.20
Weaknesses			
▪ The material is characterized by poor soil structure.	0.30	2	0.60
Sum Weights	*1.00*		*3.40*
Opportunities			
▪ The backfilled area can support a wide range of land uses	0.55	3	1.65
Threats			
▪ Increase salinity of water Pit-I due to magnesite leaching from tailing material	0.45	1	0.45
Sum Weights	*1.00*		*2.10*
Sum Total Attractiveness Score		5.50	

QSPM for management of tailing alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ The environmental and physical hazards can be contained.	0.35	3	1.05
Weaknesses			
▪ The tailing does not support vegetation growth used mostly to prevent excessive erosion of tailings	0.35	2	0.70
▪ Budget for continuous tailing management will be required.	0.30	1	0.30
Sum Weights	*1.00*		*2.05*
Opportunities			
▪ Non was found	0.45	0	0.00
Threats			
▪ No easy and cost effective strategy for water and wind erosion control of tailings can be found.	0.55	2	1.10
Sum Weights	*1.00*		*1.10*
Sum Total Attractiveness Score		3.15	

Quantitative Strategic Planning Matrix for Area-4 Rehabilitation Alternatives

QSPM for Inert landfill Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Filling the pit with inert waste has no effect on ground water	0.20	3	0.60
▪ Both pits (Pit-III and IV) are shallow with above the water table.	0.20	2	0.40
▪ Pit-I is at less than 100 m distance from the current expansion of Zwigodini village	0.20	3	0.60
▪ The pit of reasonable size for this purpose	0.20	2	0.40
Weaknesses			
▪ Fencing of Pit-I to provide controllable access to the pit is necessary.	0.20	2	0.40
Sum Weights	*1.00*		*2.40*
Opportunities			
▪ Improve the quality of the backfill soil in the pit as the grass has potential to improve soil organic matter	0.30	2	0.60
▪ The filled pit can support a wide range of land uses.	0.40	2	0.80
Threats			
▪ High potentials of use of the site as domestic waste disposal site.	0.30	1	0.30
Sum Weights	*1.00*		*1.70*
Sum Total Attractiveness Score		4.10	

QSPM for No Action Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ No disturbance of the recovering sites	0.40	3	1.20
▪ No rehabilitation cost required	0.30	2	0.60
Weaknesses			
▪ No elimination of physical and environmental hazards associated with Pit-III, Pit-IV and spoil dumps.	0.30	1	0.30
Sum Weights	1.00		2.10
Opportunities			
▪ Opportunity of vegetation recovery in some portion of the area	0.55	2	1.10
Threats			
▪ No beneficial use of the site	0.45	1	0.45
Sum Weights	*1.00*		*1.55*
Sum Total Attractiveness Score		3.65	

QSPM for livestock Grazing Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ No disturbance of the recovering sites.	0.30	3	0.90
▪ Reduced cost of rehabilitation	0.25	3	0.75
Weaknesses			
▪ No elimination of physical and environmental hazards associated with Pit-III and Pit-IV portion.	0.25	1	0.25
▪ Minimum growth of vegetation for livestock grazing.	0.20	2	0.40
Sum Weights	1.00		2.30
Opportunities			
▪ Development of new livestock enterprises.	0.50	3	1.50
Threats			
▪ Increasing number of livestock per hector my lid to extensive site degradation.	0.50	1	0.50
Sum Weights	1.00		2.00
Sum Total Attractiveness Score		4.30	

QSPM for Agriculture Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Site geochemical stability in filled areas	0.30	3	0.90
▪ Growth of crops can minimize dust generation from spoil dumps	0.30	3	0.90
▪ Very small portion of the area was disturbed by mining	0.20	3	0.60
Weaknesses			
▪ Require filling of Pit-III and Pit-III by few spoil dumps found around the area	0.20	2	0.40
Sum Weights	1.00		2.80
Opportunities			
▪ Opportunity for increased crop production in the area	0.30	3	0.90
▪ Opportunity to connect the southern crop field with the northern one	0.30	3	0.90
Threats			
▪ No water for irrigation of crops.	0.20	1	0.20
▪ Agricultural activities might disturb extensive area that was not disturbed by mining.	0.20	1	0.20
Sum Weights	1.00		2.20
Sum Total Attractiveness Score		5.00	

QSPM for Development Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Provision of new residential site	0.30	4	1.20
▪ Elimination of environmental problems of spoils dumps	0.30	4	1.20
Weaknesses			
▪ Require removal of spoil materials.	0.20	3	0.60
▪ Fencing of the pits will be necessary.	0.20	2	0.40
Sum Weights	*1.00*		*3.40*
Opportunities			
▪ Southward expunction of Zwigodini village.	0.55	2	1.10
Threats			
▪ Residence close to Pit-III and Pit-IV might lid to the use of the pit as domestic waste dump site.	0.45	1	0.45
Sum Weights	*1.00*		*1.55*
Sum Total Attractiveness Score		4.95	

Quantitative Strategic Planning Matrix for Area-5 Rehabilitation Alternatives

QSPM for No Action Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ No disturbance of the recovering sites.	0.40	3	1.20
▪ No rehabilitation cost required.	0.30	2	0.60
Weaknesses			
▪ No elimination of physical and environmental hazards associated with Pit-IV, Pit-V, and tailing dumps.	0.30	1	0.30
Sum Weights	*1.00*		*2.10*
Opportunities			
▪ Opportunity of vegetation recovery in some portion of the area	0.55	2	1.10
Threats			
▪ No beneficial use of the site	0.45	1	0.45
Sum Weights	*1.00*		*1.55*
Sum Total Attractiveness Score		3.65	

QSPM for Development Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Provision of new residential site	0.35	2	0.70
▪ Elimination of environmental problems of spoils dumps	0.35	3	1.05
Weaknesses			
▪ Require reshaping of tailings and spoil materials.	0.30	2	0.60
Sum Weights	1.00		2.35
Opportunities			
▪ Southward expansion of Zwigodini village.	0.55	2	1.10
Threats			
▪ The area is far from the existing residential area, thus the strategy might receive little support	0.45	1	0.45
	1.00		1.55
Sum Total Attractiveness Score		3.90	

QSPM for Agriculture Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
Site geochemical stability in filled areas	0.35	3	1.05
Growth of crops can minimize dust generation from spoil dump	0.35	3	1.05
Weaknesses			
Require filling of Pit-IV and Pit-V by tailing material from Tailing Dump-B	0.30	3	0.90
Sum Weights	*1.00*		*3.00*
Opportunities			
Opportunity for increased crop production in the area	0.55	3	1.65
Threats			
No water for irrigation of crops.	0.45	1	0.45
Sum Weights	*1.00*		*2.10*
Sum Total Attractiveness Score		5.10	

QSPM for livestock Grazing Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ No disturbance of the recovering sites.	0.30	3	0.90
▪ Reduced cost of rehabilitation.	0.25	3	0.75
Weaknesses			
▪ No elimination of physical and environmental hazards associated with tailing, Pit-IV portion and Pit-V.	0.25	1	0.25
▪ Minimum to medium growth of vegetation for livestock grazing.	0.20	2	0.40
Sum Weights	*1.00*		*2.30*
Opportunities			
▪ Development of new livestock enterprises.	0.50	3	1.50
Threats			
▪ Increasing number of livestock per hector my lid to extensive site degradation.	0.50	1	0.50
Sum Weights	*1.00*		*2.00*
Sum Total Attractiveness Score		4.30	

QSPM for Inert landfill Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Filling the pit with inert waste has no effect on ground water	0.30	2	0.60
▪ Both pits (Pit-IV and V) are shallow with above the water table.	0.30	2	0.60
Weaknesses			
▪ Pit-IV is extensive and shallow.	0.20	1	0.20
▪ Pit-V is far from the community.	0.20	1	0.20
Sum Weights	*1.00*		*1.60*
Opportunities			
▪ Improve the quality of the backfill soil in the pit as the grass has potential to improve soil organic matter	0.35	2	0.70
▪ The filled pit can support a wide range of land uses.	0.35	2	0.70
Threats			
▪ High potentials of use of the site as domestic waste disposal site.	0.30	2	0.60
Sum Weights	*1.00*		*2.00*
Sum Total Attractiveness Score		3.60	

QSPM for Recreational (Dirt Park Construction) Development Rehabilitation Alternative

Strengths	Weight	Attractiveness score	Total Attractiveness Score
▪ Require minimum reshaping of spoil materials for bicycle dirt jump	0.20	2	0.40
▪ The site is easily accessible by road for this purpose.	0.15	2	0.30
Weaknesses			
▪ No solution to the environmental and physical stresses associated with the pits and tailing dumps portion of the model	0.20	1	0.20
▪ The spoil materials comprise mostly of boulders, therefore ripping and sieving out of lager soil particles	0.15	2	0.30
▪ Removal of few vegetation growing on the site	0.30	2	0.60
Sum Weights	*1.00*		*1.80*
Opportunities			
▪ Introduction of new sporting activity in the area.	0.40	2	0.80
▪ The park can attract many bicycle dirt jumping fans as it also at close proximity to Pafuri gate to Kruger National Park and Big-Tree tourist destinations.	0.30	2	0.60
Threats			
▪ The facility my not receive full support of the community.	0.30	2	0.60
Sum Weights	*1.00*		*2.00*
Sum Total Attractiveness Score		*3.80*	

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APPENDIX-D: SUMMARY OF CALCULATIONS FOR REHABILITATION COST ESTIMATION

Appendix-D1: Calculation of Loader Performance Parameters

a) Calculation of Loading Time per Truck

$$\text{LCT} = \underbrace{\frac{24\ \text{sec}}{}}_{\substack{\text{Basic}\\\text{Cycle}\\\text{Time}}} + \underbrace{\frac{1\ \text{sec}}{}}_{\substack{\text{Mixed}\\\text{Material}\\\text{Type}}} + \underbrace{\frac{1\ \text{sec}}{}}_{\substack{\text{Pile Type:}\\\text{Truck}\\\text{Dumped}}} + \underbrace{\frac{2\ \text{sec}}{}}_{\text{Miscellaneous}} + \underbrace{\frac{15\ \text{sec}}{}}_{\substack{\text{Wheel Loader}\\\text{Mininmum}\\\text{Travel Time}}} = 43\ \text{sec} \approx 0.71\ \text{min} \quad \text{.....i}$$

$$\text{No. Loader passes/Truck} = \underbrace{\frac{10}{}}_{\substack{\text{Truck}\\\text{Capacity}}}\ \text{m}^3 + \underbrace{\frac{1.7}{}}_{\substack{\text{Loader Bucket}\\\text{Net Capacity}}}\ \text{m}^3 = 6\ \text{passes} \quad \text{.....ii}$$

$$\text{Net Truck Capacity} = \underbrace{\frac{1.7}{}}_{\substack{\text{Loader Bucket}\\\text{Net Capacity}}}\ \text{m}^3 \times \underbrace{\frac{6}{}}_{\substack{\text{No.Loader}\\\text{Passes/Truck}}}\ \text{passes} = 10.2\ \text{LCM} \quad \text{.....iii}$$

$$\text{Loading Time/Truck} = \underbrace{\frac{43\text{sec}}{}}_{\substack{\text{Loader Cycle}\\\text{Time}}} \times \underbrace{\frac{6}{}}_{\substack{\text{No.Loader}\\\text{Passes/Truck}}}\ \text{passes} = 258\ \text{sec} \approx 4.3\ \text{min} \quad \text{.....iv}$$

b) Corrections of Loader Operator and Job Efficiencies

$$\text{Opareter Efficiance Correction} = \frac{0.71}{\text{LCT}} \div \underbrace{\frac{0.75}{}}_{\substack{\text{Correction}\\\text{Facter}}} = 0.94\ \text{mim} \quad \text{.....v}$$

$$\text{Job Efficiance Correction} = \underbrace{\frac{0.94}{}}_{\substack{\text{Opareter}\\\text{Efficiance}}} \div \underbrace{\frac{0.75}{}}_{\substack{\text{Correction}\\\text{Facter}}} = 1.25\ \text{min} \quad \text{.....vii}$$

$$\text{Time/Cubic Meter} = \frac{1.25}{\text{Job Efficiance}} \div \frac{1.7}{\text{Loader Capacity}} = 52.8\ \text{sec} \approx 0.88\ \text{min} \quad \text{.....vii}$$

c) Calculation of Loader Operation Cost

$$\text{Cost of Loader \& Operater} = \text{R}245.00/\text{hr} \quad \text{.....ix}$$

$$\text{Loader Operating/min} = \underbrace{\frac{\text{R}245.00}{}}_{\substack{\text{Loader } \textit{and Operater}\\\text{Cost}}} \div 60 = \text{R}4.08/\text{min} \quad \text{.....x}$$

$$\text{Loader Cost/Cubic meter} = \frac{0.88}{\text{Time/m}^3} \times \underbrace{\frac{4.08}{}}_{\substack{\text{Operating}\\\text{Cost/min}}} = \text{R}3.59/\text{m}^3 \quad \text{.....xi}$$

Appendix-D2: Calculation of Dump-Truck Performance Parameters

a) Calculation of Truck required Hours

$$\text{Truck Cycle Time} = \underset{\text{Haul Time}}{\frac{23\text{ sec}}{}} + \underset{\text{Return Time}}{\frac{23\text{sec}}{}} + \underset{\text{Loading Time}}{\frac{258\text{sec}}{}} + \underset{\text{Dump and least manuever time}}{\frac{12\text{ sec}}{}} = 316\text{ sec} \approx 5.26\text{ min} \quad \text{.....i}$$

$$\text{No. Trucks requered} = \underset{\text{Truck Cycle Time}}{\frac{5.2}{}}\text{ min} \div \underset{\text{Total loading Time}}{\frac{4.3}{}}\text{ min} = 1\text{ Truck} \quad \text{.....ii}$$

$$\text{Production Rate} = \underset{\text{Net Truck Capacity}}{\frac{10.2}{}}\text{ LCM} + \underset{\text{Number of Trucks}}{\frac{1}{}}\text{ Trucks} \div \underset{\text{Truck Cycle Time}}{\frac{5.2\text{min}}{}} = 2.15\text{ LCM/min} \quad \text{.....iii}$$

$$\text{Hourly Production} = \underset{\text{Production Rate}}{\frac{2.15\text{ LCM/min}}{}} \times 60\text{ min/hr} \times \underset{\text{Track Cycle Time}}{\frac{5.2\text{min}}{}} = 670.8\text{ LCM/hr} \quad \text{.....iv}$$

$$\text{Hours Required} = \underset{\text{Volume to be moved}}{\frac{x}{}}\text{ LCM} \div \underset{\text{Hourly Production}}{\frac{670.8}{}}\text{ LCM/hr} = _____\text{ hr} \quad \text{.....v}$$

b) Calculation of Truck Operator and Job Efficiencies

$$\text{Driver Efficiency Correction} = \underset{\text{Truck Cycle Time}}{\frac{5.26}{}} \div \underset{\text{Correction Facter}}{\frac{0.75}{}} = 7.01\text{ min} \quad \text{.....vi}$$

$$\text{Job Efficiency Correction} = \underset{\text{Driver Efficiency Time}}{\frac{7.01}{}} \div \underset{\text{Correction Facter}}{\frac{0.84}{}} = 8.44\text{ min} \quad \text{.....vii}$$

$$\text{Truck Time/Cubic Meter} = \underset{\text{Job Efficiency}}{\frac{8.44}{}} \div \underset{\text{Truck Capacity}}{\frac{10}{}} = 0.84\text{ min} \quad \text{.....viii}$$

c) Calculation Truck of Operation Cost

$$\text{Cost of Truck \& Driver} = \text{R}254.00\text{/hr} \quad \text{.....ix}$$

$$\text{Track Operation/min} = \underset{\text{Truck Driver Cost}}{\frac{\text{R}254.00}{}} \div 60 = \text{R}4.23/\text{m}^3 \quad \text{.....x}$$

$$\text{Truck Cost/Cubic Meter} = \underset{\text{Time/Cubic Meters}}{\frac{0.84}{}} \times \underset{\text{Truck Operation Cost}}{\frac{4.23}{}} = \text{R}3.55/\text{m}^3 \quad \text{.....xi}$$

Appendix-D3: Calculation of Bull Dozer Performance Parameters

a) Hours required for ripping of footprint areas

$$\text{Cycle Time} = \left[\frac{100\text{ m}}{\text{Cut Lenght}} \div \frac{26.8\text{m/min}}{\text{Average Speed}}\right] + \frac{0.25\text{ m}}{\text{Fixed Turn Time}} = 3.98\text{ min/pass} \quad \text{.....i}$$

$$\text{Passes/hr} = \frac{45\text{ min}}{\text{Average Opareter work minutes}} \div \frac{3.98}{\text{Cycle Time}} = 11.30\text{ passes/hr} \quad \text{.....ii}$$

$$\text{Volume to be Ripped} = \frac{100\text{ m}}{\text{Cut lenght}} \times \frac{0.9\text{ m}}{\text{Rip Spacing}} \times \frac{0.5\text{ m}}{\text{Ripper Panetration}} = 45\text{ BCM/pass} \quad \text{.....iii}$$

$$\text{Hourly Production} = \frac{45}{\text{Vol.Ripped/Pass}}\text{ BCM} \times \frac{11.30}{\text{Pass/Hour}} = 508.5\text{ BCM} \quad \text{.....iv}$$

$$\text{Hours Requered} = \frac{X}{\text{Bank Vol. to be Ripped}}\text{ BCM} \div \frac{508.5}{\text{Hourly Production}}\text{ BCM/hr} = _____\text{hr} \quad \text{.....v}$$

b) Hours required for spreading of footprint areas

$$\text{Operation Adjustment Factor} = \frac{0.75}{\text{Operater Factor}} \times \frac{0.80}{\text{material Factor}} \times \frac{0.83}{\text{Efficiency Factor}} \times \frac{0.95}{\text{Grade Fector}} \times \frac{0.932}{\text{Weight Correction Factor}} \times \frac{1.0}{\text{production method/blade factor}} \times \frac{1.0}{\text{Visibility Factor}} \times \frac{1.0}{\text{Eveltion Factor}} = 0.441 \quad \text{...vi}$$

$$\text{Net Hourly Production} = \frac{458}{\text{Normal Hourly Production}}\text{ LCM/hr} \times \frac{0.441}{\text{Operating Adjustment Factor}} = 201.98\text{ LCM/hr} \quad \text{.....vii}$$

$$\text{Hours Required} = \frac{x}{\text{Volume to be Moved}}\text{ LCM} \div \frac{201.98}{\text{Net Hourly Production}}\text{ LCM/hr} = _____\text{ hr} \quad \text{.....viii}$$

Appendix-D4: Estimated Fuel Costs

Scenario I

	Bulldozer Work Hours	Truck Work Hours	Loader Work Hours	Diesel Price (R/Liter)
	4835	4182	3183	
Truck Fuel Use/Hr	29.147	7.51	13.5	10.18
Machinery	Bulldozer	Truck	Loader	Total
Diesel Requirement (*l*)	140934.49	31406.82	42970.50	215311.81
Diesel Cost (R)	R1,434,713.10	R319,721.43	R437,439.69	R2,191,874.22

Scenario II

	Bulldozer Work Hours	Truck Work Hours	Loader Work Hours	Diesel Price (R/Liter)
	4340	4182	4182.00	
Track Fuel Use/hr	29.147	7.51	13.5	10.18
Machinery	Dozer	Truck	Loader	Total
Diesel Requirement (*l*)	126489.24	31406.82	56457.00	214353.06
Diesel Cost (R)	R1,287,660.42	R319,721.43	R574,732.26	R2,182,114.11

Scenario III

	Bulldozer Work Hours	Truck Work Hours	Loader Work Hours	Diesel Price (R/Liter)
	3968	3183	3183	
Track Fuel Use/hr	29.147	7.51	13.5	10.18
Machinery	Dozer	Truck	Loader	Total
Diesel Requirement (*l*)	115655.30	23904.33	42970.50	182530.13
Diesel Cost (R)	R1,177,370.91	R243,346.08	R437,439.69	R1,858,156.68