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包括的枠組みの開発

2024

**Graduate School of Environmental Science
Hokkaido University**

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by

KAWISHA MUTIMBA

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Abstract

Mining industry significantly contributes to government revenues and job creation. In regions such as Africa, the mining sector is of utmost importance, with nations such as, Zambia, relying heavily on it for its GDPs. Considering the growing global emphasis on sustainable development, it is essential to consider mining from a sustainability perspective. When a mine reaches unprofitable production levels, it is necessary to close it. Historically, mine closures have been conducted in an environmentally harmful manner, leading to long-lasting negative consequences. However, modern sustainable development principles and integrated into Zambian legislation aim to enhance the environmental sustainability of mine closure.

To address this question, this study examines sustainability principles in international and Zambian mining and closure policies. The analysis revealed that Zambia's mine closure legislation was reasonably robust in terms of incorporating sustainability principles. The next step was to survey a group of experts on environmental sustainability indicators and current and best mine closure practices in the Copperbelt Province. Participants were recruited using purposive sampling. This study employed a mixed-format questionnaire and utilized both qualitative narrative analysis and quantitative analysis when appropriate. Furthermore, Land Use Land Cover (LULC) changes associated with mining activities were mapped using the Google Earth Engine (GEE) from 1990 to 2020 to comprehend the dynamics of LULC change associated with mining activities.

This research aimed to evaluate the environmental principles and sustainable development indicators of mine closures in the province, with a focus on the experiences and work environments of the respondents, the current status of mining environmental indicators in the province, mine closure and closure planning, and the awareness and opinions of the Zambian mine closure legislation. The results revealed that the majority of mine closure professionals in the province work in the private sector (92.4%), 70% employed at mine sites, 12.9 % serving as consultants, 6.3% in corporate roles, and 3.3% in legal positions. The top five economic minerals in Zambia account for 90% of closure experts' experiences. This study also found that mine closure practices in the province cover a range of aspects throughout the mine lifecycle. However, there are several challenges, including inconsistent environmental monitoring data, insufficient baseline studies, and a lack of commitment from senior management. Some progress has been made, such as an emphasis on proactive planning for end-use objectives for land and water.

This study assessed the Land Use Land Cover (LULC) modifications that occurred due to mining activities. The LULC classification for 2020 achieved an overall accuracy of 82.47% and a kappa coefficient of 0.78. The primary LULC classes comprised bare land, built-up area, forest,

grassland/pasture/agricultural land, and water. The proportion of each class's area in 1990, 2000, 2010, and 2020 revealed that grassland/pasture/agricultural land occupied the largest space in 1990, accounting for 46.2% (369.43 km²) of the total LULC categories assigned. This class experienced a significant increase of 51.7% (412.96 km²) in 2020. In general, 45.2% of the district area (360.92 km²) underwent LULC changes from 1990 to 2020. The overall change indicates that the areas of built-up area, bare land, and grassland/pasture/agricultural land expanded by 35.84 km², 14.67 km², and 43.53 km², respectively. Meanwhile, forest experienced a loss of 95.30 km², with the primary driver being the privatization of mining companies. However, the forest loss was highest between 1990–2000 and 2010–2020 (42.04 and 43.86 km², respectively).

The third study identified significant inadequacies and ineffectiveness in the Zambia's legal framework for mine closure. It found a scarcity of detailed sustainability indicators and insufficient consideration of socioeconomic factors. The current legislation mainly focuses on environmental aspects in the EIA process, mandating mine developers to submit Environment Impact Statement (EIS) or Environment Project Brief (EPB) containing some closure-related information but falls short in comprehensive sustainability practices. The Mines and Minerals (Environmental) Regulations (1997) and the Environmental Protection Fund Regulations (1998) exist but do not adequately enforce rehabilitation and post-closure obligations. These regulatory gaps coupled with inadequate public and stakeholder engagement in altering mine closure procedures highlight the need for a more robust legal framework that ensures comprehensive and sustainable mine closure practices, aligns with international best practices and addresses environmental, social, and economic impacts.

This study explored the discrepancy between Zambia's mine closure regulations and their practical implementation, advocating for an environmental sustainability indicator framework tailored to Zambia's mine closures. The framework aims to assist the mining industry in assessing and managing a mine's progression towards sustainable closure. This study highlights the importance of stabilizing Zambia's mining legislation and proposes a conceptual framework for sustainable mine closure. The focus is on developing environmental sustainability indicators that combine global best practices with local contexts to evaluate current practices and legislative benchmarks, identify gaps, and propose measurable indicators. The aim is to guide the Zambian mining industry towards sustainable operations and a positive environmental legacy. The findings and methodology of this study can serve as a model for sustainable mine closure in other mining regions.

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Abbreviations & Acronyms

AMD	Acid Mine Drainage
APEC	Asia-Pacific Economic Cooperation
BOZ	Bank of Zambia
CO ₂	Carbon Dioxide
CESR	Center for Economic and Social Rights
CSO	Central Statistics Office
CNMM	China Nonferrous Metal Mining
CSR	Corporate Social Responsibility
DMP	Department of Mines and Petroleum
ECZ	Environmental Council of Zambia
EIA	Environmental Impact Assessment
EMA	Environmental Management Act
EMP	Environmental Management Plan
EMS	Environmental Management System
EPFR	Environmental Protection Fund Regulations
EIR	Extractive Industries Review
FAO	Food and Agriculture Organization
GDACE	Gauteng Department of Agriculture, Conservation and Environment
GMI	Global Mining Initiative
GEE	Google Earth Engine
GHG	Greenhouse Gases
IRMA	Initiative for Responsible Mining Assurance
ICLG	International Comparative Legal Guides
ICMM	International Council on Mining and Metals.
IFC	International Finance Corporation
IIED	International Institute for Environment and Development

IUCN	International Union for Conservation of Nature
JPOI	Johannesburg Plan of Implementation
KPMG	Klynveld Peat Marwick Goerdeler
KCM	Konkola Copper Mine
LULC	Land Use Land Cover
LCA	Life Cycle Assessment
LCM	Lubambe Copper Mine
MMDA	Mines and Mineral Development Act
MMR(EPF)	Mines and Minerals (Environmental Protection Fund) Regulations
MMR(Env)	Mines and Minerals (Environmental) Regulations
MSD	Mines Safety Department
MMSD	Mining, Minerals and Sustainable Development
MMMD	Ministry of Mines and Mineral Development
MWDSEP	Ministry of Water Development, Sanitation and Environmental Protection
MCM	Mopani Copper Mines
NRSC	National Remote Sensing Centre
NIR	Near-Infrared
NGO	Non-Governmental Organization
NDVI	Normalized Difference Vegetation Index
OLI	Operational Land Imager
OECD	Organization for Economic Co-operation and Development
PM10	particulate matter 10 micrometers
PMRC	Philippine Mineral Reporting Code
RFC	Random Forest Classifier
SWIR	Short Wave Infrared
SVM	Support Vector Machines
SDG	Sustainable Development
SDG	Sustainable Development Goals
TM	Thematic Mapper

TCZ	Tropical Convergence Zone
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFAO	United Nations Food and Agriculture Organization
UNFCCC	United Nations Framework Convention on Climate Change
WB	World Bank
WBCSD	World Business Council for Sustainable Development
WSSD	World Summit on Sustainable Development
ZCCM	Zambia Consolidated Copper Mines Ltd
ZEMA	Zambia Environmental Management Agency
ZAFFICO	Zambia Forestry and Forest Industries Corporation
ZSA	Zambia Statistics Agency

1. Introduction and background

1.1 Background to Research

Mining is an important economic sector in the world, and it provides vital materials for infrastructure, technology, and other products. This industry (metals and minerals) contributes significantly to national economic development worldwide, through its contribution to government revenues and the creation of employment (Ericsson & Löf, 2019). Therefore, mining significantly leads to economic development in low- and middle-income nations (ICMM, 2016). Mining also leads to progress in socioeconomic development indicators of low- to middle-income mineral-rich countries (Ericsson & Löf, 2019).

Globally, mining activities are spread across various continents with countries such as Australia, Canada, Russia, and Brazil leading in the production of various important minerals and metals (KPMG International, 2022). However, the benefits of mining come with extensive environmental, social, and governance challenges that impose sustainable practices to mitigate adverse impacts such as pollution, habitat destruction, and community displacement (Haddaway et al., 2019).

In Africa, the mining industry is a major economic driver with significant deposits of copper, gold, diamonds, platinum, and uranium among others. Countries such as South Africa, Zambia, Ghana, and the Democratic Republic of Congo have well-established mining sectors that contribute to their GDP (Signé, 2021). Despite this, the sector often faces challenges related to political instability, regulatory uncertainties, and infrastructural deficiencies which hinder growth and sustainable development.

The drive for environmental sustainability in mining globally involves the adoption of practices that reduce the environmental impact of mining operations. These practices include improved waste management, the use of renewable energy sources, and the rehabilitation of mining areas. Countries such as Canada and Australia are at the forefront of implementing sustainable mining practices (Gorman & Dzombak, 2018). For example, Canada has introduced regulations that ensure mines are planned with closure in mind, which includes the managing of waste rock and tailings, water treatment, and ecosystem rehabilitation post-mining activities (Gorman & Dzombak, 2018).

Conversely, in some African nations, the lack of stringent environmental regulations and enforcement challenges has led to significant ecological damage (Agbor, 2018). Countries like the

Democratic Republic of Congo and Ghana have struggled with pollution and deforestation linked to mining activities (Agbor, 2018). These issues are compounded by illegal mining which often neglects environmental, safety, and health regulations (Emmanuel et al., 2018). Despite abundant mineral resources, these countries face severe challenges in harnessing these resources sustainably without causing long-term environmental degradation (Emmanuel et al., 2018).

On a positive note, some African countries are making strides toward sustainable mining practices. For example, South Africa has implemented several initiatives aimed at promoting sustainable development in the mining sector. These include legislative frameworks that mandate the minimization of environmental impact and encourage community involvement in mining decisions (Muswaka, 2017). Furthermore, South Africa has established the concept of mine closure certificates, which are granted after a mine is closed and rehabilitated to a satisfactory standard (Muswaka, 2017).

Botswana is another African country that has shown commendable progress in sustainable mining practices. The country has a well-established regulatory framework that governs mining operations, ensuring that environmental sustainability is a core component of all mining activities (KPMG International, 2014). Botswana's approach to mining includes comprehensive environmental impact assessments and the use of modern technologies to minimize ecological disruption.

Looking forward, the future of sustainable mining globally hinges on collaboration between governments, mining companies, and communities. Initiatives such as the United Nations Sustainable Development Goals (SDGs) provide a valuable framework for addressing the environmental impacts of mining (UN, 2022). Embracing technologies that reduce emissions, improve waste management, and restore ecosystems are essential for the transition to sustainable mining practices.

One country that has a particularly rich mining history is Zambia. Located in southern Africa, Zambia is home to some of the world's largest copper and cobalt deposits, making it a significant player in the global mining industry (Zambia Development Agency, 2013). Zambia has an abundance of mineral resources; with the largest known reserves of emeralds in the world. Zambia also mines coal, diamonds, and gold amongst many other mineral resources (Barry, 2023). The Zambian mining industry has come a long way since the construction of the first commercial mine in 1928, a copper mine in Luanshya District, in the Copperbelt Province although copper had been produced at Kansanshi and Bwana Mkubwa mines in 1908 and 1911 respectively (Sikamo et al., 2016a). Zambia was once ranked second in world copper production (Fraser & Larmer, 2010b). Currently, it is the second-largest producer of copper in Africa and the seventh in the world

(Extractive Industries Transparency Initiative, 2014). The mining industry has been pivotal in the development of Zambia and remains instrumental in the country's economy.

Mining has been the main economic stay of Zambia from as early as the 1920s and is predominantly private sector-led. There was a significant investment in the industry which included mine development and operation, processing facilities and infrastructure and the building of new towns around the mines (Fraser & Larmer, 2010b). Although mining is an industry that has the potential to provide significant economic benefits to countries and communities, it may also have detrimental effects on the environment and society if it is not carefully managed (Worlanyo & Jiangfeng, 2021). Therefore, it is important to approach mining from a sustainable development perspective to ensure that it contributes to economic development while minimizing its negative impacts. By its very nature, mining is a temporary land use, as it involves extracting finite resources from the earth's crust (Segura-Salazar & Tavares, 2018). Mining companies must identify and locate mineral deposits and then extract and process, which ultimately results in the depletion of the deposit. Once a mine is no longer profitable or the mineral deposit is depleted, the mining company will typically close the mine and begin the process of decommissioning and reclamation (Segura-Salazar & Tavares, 2018). The closure has a history of being environmentally negligent and having detrimental long-term effects. In general, abandoned mines continue to produce environmental risks such as Acid Mine Drainage (AMD), the related mobilization of heavy metals, reduced soil fertility, unstable surfaces, and airborne PM10 particles, sometimes virtually eternally (Cottard, 2001; McCarthy, 2011; van Tonder et al., 2008). Moreover, abandoned mines frequently prevent future land use that would be beneficial to human health and prosperity as well as ecosystem function (Gankhuyag & Gregoire, 2018; Robertson et al., 1999).

These negative effects should be mitigated following closure with the help of contemporary sustainable development principles, and mine closure should contribute positively by leaving a sustainable land use legacy for future development (Stacey et al., 2010). The principle of sustainable development is most frequently characterized as "filling the demands of the present without sacrificing the ability of future generations to fulfill their own needs," which is in direct opposition to the effects mentioned above (Pavlovskaja, 2013). Conversely, in reality, especially in most African countries Zambia included, mine closure is often inadequately planned for with immitigable environmental impacts remaining.

1.2 Problem statement

This research problem identified is focused on the tension between sustainable development and environmental mine closure impacts. This is a complex and multifaceted issue, and there are several different avenues to explore it further.

Zambia is one of the countries that have subscribed to the principle of sustainable development and has integrated it into its governance framework. The country has, therefore, put in place various policies and strategies that aim at promoting sustainable development across the spectrum of the economy (Ministry of National Development Planning, 2020). For instance, the country's Seventh National Development Plan (7NDP) prioritizes sustainable economic growth and job creation, social development, and environmental protection. This is based on the fact that the plan has at the center of its focus sustainable economic growth and job creation, social development, and environmental protection (Ministry of National Development Planning, 2017).

Zambia has also put in place several institutions and legal frameworks that moderate the policies associated with sustainable development. For example, the Environmental Management Act (EMA) defines the mechanisms of the country for the management and protection of the environment, while the National Climate Change Policy (NCCP) is about understanding the great challenge that is climate change and developing a sustainable development approach (Republic of Zambia, 2023). Besides, Zambia is a signatory to quite many international treaties and conventions that relate to sustainable development, among them being the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Convention to Combat Desertification (UNFCCC). In general, Zambia has committed to the promotion of sustainable development and is taking huge steps towards the realization of this goal (Government of the Republic of Zambia, 2002; UN, 2022).

1.3 Research aims and objectives

The main aim of this research is to develop a theoretical framework for environmental sustainability indicators specifically for tracking progress and promoting sustainable mine closure practices. According to Dong & Hauschild (2017) and Mamat et al. (2016), environmental sustainability indicators are key tools used to evaluate the impact of human activities on the natural environment and measure progress towards sustainability goals. These indicators help in evaluating the effectiveness of policies and practices aimed at reducing negative environmental externalities such as pollution, resource depletion, and habitat loss. Common environmental sustainability indicators include metrics for tracking energy use, water consumption, waste generation, carbon emissions (including Scope 1, 2, and 3 emissions), and the extent of land use.

This framework seeks to integrate global best practices with local Zambian contexts, ensuring that mine closure contributes positively to both environmental conservation and socio-economic development. The human face of this research lies in its approach to carefully document current practices and legislative benchmarks and then to measure these against the established principles of the environment to identify gaps and propose, therefore, practical and measurable indicators that could guide the mining industry in Zambia towards more sustainable operations. This is a very noble initiative that ensures every mining activity leaves behind a positive activity. This, in return, shall promote the well-being of future generations by conserving and, otherwise, restoring the natural environment.

The above-mentioned aim of this research shall be achieved by completing the following set of chronological objectives:

1. Evaluate Zambian mine closure legislation against environmental principles and indicators of sustainable development.
2. Examine land use and land cover changes associated with mining in the Copperbelt Province, Zambia: A case study of Kitwe District due to mining activities.
3. Analyze the legal issues related to mine closure in Zambia to identify regulatory gaps in the legal framework.
4. Define the gap between Zambian mine closure legislation (objective 3) and the Zambian mine closure status quo (objective 1), within the context of sustainable development principles (objective 1) and propose a theoretical framework of environmental sustainability indicators to address the gap defined.

To achieve the objectives mentioned above, the following methodologies are proposed for each objective:

To achieve the objective (1):

- a. Conduct a literature review to establish current global and Zambian best practices regarding environmental principles and indicators of sustainable development in mining.
- b. Conduct a literature review to determine the extent of Zambian legislation that pertains to mine closure.
- c. The results of this Zambian mine closure legislation review (1) (b) will be compared to the review of world and Zambian sustainable development principles and environmental indicators in mining (1) (a).
- d. With the comparative knowledge gained in (1) (b), the sustainable development principles and environmental indicators embedded in Zambian legislation will be documented and made explicitly.

- e. Draft an appropriate survey based on learnings from (1). This will seek to question what the Zambian mining industry is seeking to achieve, and how are they going about it, concerning environmental indicators, mine closure, and sustainable development.
- f. The survey compiled in (1) (e) will then be circulated to relevant mining professionals/experts.
- g. Based upon the responses to the survey conducted, a summary of the status quo regarding environmental indicators, mine closure, and sustainable development in Zambia will be detailed.

To achieve the objective (2):

- a. Conduct a comprehensive remote sensing analysis using satellite imagery to track changes in land use and land cover over time in Kitwe District, focusing on areas affected by mining activities.
- b. Perform field surveys and collect ground truth data to validate and enhance the accuracy of the remote sensing analysis, ensuring a robust assessment of LULC changes directly attributable to mining operations.

To achieve the objective (3):

- a. Conduct an exhaustive review of all current legal documents, statutes, and regulations that govern mine closure in Zambia.
- b. Analyze these documents to understand the legal requirements for mine closure, the responsibilities of mining companies, penalties for non-compliance, and provisions for environmental conservation.

To achieve the objective (4):

- a. Perform gap analysis, in the context of sustainable development principles, between the practice ‘on-the-ground’, based on the results of the survey (objective 1) and the legislative closure requirement as defined by.
- b. Propose a set of environmental sustainability indicators that will seek to address the gap between, sustainable development principles and Zambian legislation, and the current status quo (as defined in (3)).

1.4 Limits of study

This study will research and investigate the themes, topics, gaps, and interrelationships between mine closure, sustainability, and environmental sustainability indicators within the context

of Zambia. It takes an understanding of the global development of sustainable development, both as a broader concept and concerning mining. This is done to better frame the ‘sustainable development and mining’ discourse within a Zambian context. Sustainable development is commonly understood as having three key components operating within a governance framework: social, environmental, and economic dimensions (Barbier et al., 1987). However, this study's primary focus is on the development of indicators for assessing the 'environmental' aspect of sustainable development, specifically within the context of mine closure. While the economic and social dimensions are not the central focus of this study, they will be discussed as relevant within the context. If, in the text, the specific type or nature of the impacts is not explicitly mentioned, it should be assumed that the impacts being referred to are environmental. Moreover, it must be noted that this study takes the stance of interrogating mine closure from a position of ‘strong sustainability’; defined by Neumayer (2013) as being when: “*Natural capital is considered irreplaceable, not by the production or consumption of goods, its ability to absorb pollution, or by serving as a direct source of value through environmental benefits*” (Neumayer, 2013).

This contrasts with the concept of 'weak sustainability,' which asserts that the environmental impacts of growth can be addressed through technological innovation and the use of manufactured products, allowing for the substitution of natural capital with man-made capital (Barinaga-Rementería & Etxano, 2020). Regarding mine closure, this study exclusively focuses on specific key Zambian minerals and provides comprehensive discussions of only the major mining methods. As justified in Table 1, this focus on these particular minerals and mining methods ensures a broad yet representative investigation. It is important to acknowledge that much of the literature which discusses sustainability principles in mining, is authored by institutional sources in form of reports. Lastly, it's important to recognize that the study's scope is constrained by the nature and depth of the responses received from specialists in the Zambian mining closure sector who willingly participated in the survey.

1.5 Thesis structure

This thesis is organized systematically into eight comprehensive chapters, each with a different heading supporting the overall objective of the research. Chapter 1, the general introduction, sets the stage by outlining this thesis's scope, objectives, and significance, providing a solid foundation for the subsequent analysis. Chapter 2 focuses on the literature review that unfolds an explicative examination of existing scholarly work on mine closure, environmental sustainability, and the specific context of mining in Zambia. Chapter 3 Methodology and study area. The chapter gives a method and tools used while conducting the research, together with the study area description to

bring out a clear picture of how the research was conducted. Chapter 4 compares Zambian mine closure practices with established environmental principles and indicators of sustainable development to provide a critical evaluation of current practices. Chapter 5 shows a case of land use and land cover change in the Kitwe District of the Copperbelt Province to demonstrate the impacts of mining activities on the area. Chapter 6 addresses the legal issues related to mine closure in Zambia, providing an in-depth analysis of the legal framework governing mine closure and its implications. Chapter 7, the general discussion, synthesizes results from the previous chapters, discussing the implications and integrating the research into a broader context. Finally, Chapter 8 presents the summary of the results, conclusion, and recommendations for further research, with, capturing the research journey and its academic contributions.

2. Literature review

2.1 Introduction

In the literature review, an attempt shall be made to investigate the interrelationships between sustainable development, mine closure, and environmental indicators within the Zambian context. Its objective is to offer a comprehensive understanding of the existing research and knowledge on these subjects and pinpoint areas that demand additional investigation. This literature review attempted to critically discuss seminal scholarly articles, reports, and studies on issues, best practices, and strategies for sustainable development, mine closure management, and the environmental indicators of sustainability. These were addressed on a global, regional, and specifically Zambian scale, insofar as they relate to the mining sector.

2.2 The Zambia context, mining and minerals

Covering a surface area of 752,618 square kilometers, Zambia is abundantly endowed with mineral resources, including copper, cobalt, zinc, lead, coal, emeralds, and various precious gemstones (Cross Border Road Transport Agency, 2020). The soil composition varies in the different regions, whereby some have fertile valleys and river basins, while others have sandy or clayey soils in their upland areas (Brammer, 1976). The climate is generally warm and dry, with mean temperature ranges of 25-35 degrees Celsius (77-95 degrees Fahrenheit), varying between regions and altitudes. While the northern and eastern parts receive rainfall annually between 1,000 to 1,400 millimeters (39 to 55 inches), in the southwestern and western regions of the country, the same occurs at an amount of between 700 to 1,000 millimeters (27 to 39 inches) in a year (Tomalka et al., 2022).

Despite occupying a small percentage of the Earth's surface, Zambia is globally acknowledged for its exceptional biodiversity. In addition to that, the impressive richness of Zambia's different ecosystems displays about 1.5% of the world's plant species and around 2% of the world's animal species (Ministry of Lands Natural Resources and Environmental Protection, 2015). As of the 2022 national census, the total population stood at 19 million people. However, the country struggles with challenges in poverty reduction, with an estimated 58% of the population living below the poverty line. Initiatives led by the government and various organizations are ongoing to tackle poverty through social programs and economic development (Zambia Statistics Agency, 2022).

Zambia has made progress in improving literacy rates, with a current estimate of approximately 70%. The country still embarks on increasing the level of education for every

Zambian (Zambia Statistics Agency, 2022). Another most basic and still chronic is unemployment, standing at 18%. The government is also taking initiatives in different forms to promote economic growth, boost the inflow of investment, and soundly support skills development to be able to curb unemployment (Rajaram et al., 2022).

2.2.1 Mineral resources in Zambia

Zambia is richly blessed with a variety of minerals that take a very fundamental role in the country's economy, the foremost being copper. Zambia is ranked among the world's largest producers of this metal (World Bank, 2011). Copper mining has been the backbone of the country's economy for many years and has continued to contribute to the country's GDP and its export earnings. It is estimated that Zambia has approximately 5-7% of the world's copper reserves (World Bank, 2011).

The other valuable mineral found in Zambia is cobalt. Cobalt is an essential resource mined as a by-product of copper deposits and holds a particular significance. Zambia is ranked as one of the leading producers of cobalt globally, contributing to the world's cobalt supply significantly (Gulley, 2022). The additional economically important minerals produced in Zambia include zinc, lead, coal, emeralds, gold, silver, uranium, and gemstones. In Zambia, the methods applied to mining are quite varied. Commonly, the country uses open-cast (surface mining) and underground mining methods and the choice of method generally considers the nature of the mineral deposit, geological conditions, and economic viability (Mutambo & Njamba, 2022).

The ore/minerals processing is also a crucial aspect, with a significant portion of 'Run of Mine' products experiencing a secondary processing process (Zambia Development Agency, 2013). Therefore, mining rises as a complicated, deeply rooted, and expansive activity within the socio-economic fabric of Zambia, exerting significant impacts on the natural environment (Fraser & Larmer, 2010b).

2.2.2 The economics performance of the mining industry in Zambia

The mining sector contributes to Zambia's economic landscape by approximately 12% of the GDP, with copper and cobalt mining being the primary minerals. Various studies report that the employment opportunities accruing from this sector have contributed to economic growth and development since it is the backbone of Zambia's economy and offers both direct and indirect employment opportunities (Oxfam International, 2021). Zambia prides itself on being among the highest producers of copper on the global scene. The contribution of Zambia to the world, in terms of copper, is remarkable and, importantly, enhances foreign exchange earnings through the export

of copper (World Bank, 2011). Beyond direct mining roles, the industry creates job opportunities in other related sectors, hence contributing significantly to economic growth (PMRC, 2023). Foreign investments in mining bring capital, technology, and expertise that foster infrastructure development and diversification (OECD, 2002). Moreover, the contribution of the industry extends to government revenues that fund public infrastructure, social programs, education, and health, besides poverty reduction initiatives (World Bank, 2015). It is noted that in these positive contributions come challenges such as environmental impacts and social issues that they admit and aim to take corrective measures through sustainable practices and community engagement (Fraser, 2021). Overall, responsible and sustainable mining practices are emphasized to ensure continuing benefits for Zambia and its population (World Bank Group, 2016a).

2.2.3 Major minerals mined in Zambia

Zambia boasts a rich collection of mineral resources, including copper, cobalt, gold, coal, and emerald. In the copper sector, Zambia is currently second in Africa after the Democratic Republic of the Congo (PMRC, 2023). Although copper production was affected by low copper prices and the privatization of the mines in the 1990s, production has been increasing since 2000, as shown in Figure 1 (Barry, 2023; Kangwa & Mutambo, 2018; Sikamo et al., 2016a; World Bank, 2017). Further, the Zambian cobalt industry is allied to copper mining and is placed at the thirteenth position in the world, with growth recorded at 5% in 2021 (Cobalt Institute, 2023). Although faced with a decline in production leading up to 2021, projections indicate a potential rise with a 4% compound annual growth rate between 2022 and 2026 (Barry & Plaza-Toledo, 2022; GlobalData, 2023). Further, the gold production in Zambia, which began in the year 2004, has shown remarkable growth. The Kansanshi Mine showed growth of 12% in terms of gold output in the year 2019, for example. The industry involves both large-scale and artisanal mining, with government initiatives, for example, the Bank of Zambia's gold purchase plan, aimed at formalizing the sector, addressing environmental concerns, and providing competitive prices in the domestic market (Barry, 2023; First Quantum Minerals Ltd, 2020; ZCCM, 2020).

Other than that, Zambia has a historical coal industry dating back to 1967, with contributors such as Maamba Collieries Limited and Collume Coal Mine (Baruya, 2013). Despite a decline in production due to restructuring efforts and challenges for example, labor disputes, Zambia expects an increase in coal production with improved investment and new power station constructions (Baruya, 2013; BBC, 2013; Nulacha, 2012). Additionally, the country has established itself as a major global emerald producer, contributing approximately 40% to the world's emerald production. Gemfield's earnings from Zambian emerald auctions highlight the sector's significant promise,

particularly in the Musakashi and Kafubu regions, where large-scale open-pit mining operations make Zambia one of the leading producers of gem-grade emerald worldwide (Barry, 2023; Behling & Wilson, 2010; Gao et al., 2023). However, despite all these fluctuations, including great difficulties in lowering the groundwater level, Kagem emerges as the largest open-pit colorful gemstone mine in the world, forming the basis for strength in the international emerald market for Zambia (Gao et al., 2023; Barry, 2023).

2.2.4 Rationale for reviewed minerals

There is a global concern that over 25% of active mining and exploration sites are located within or overlapping with strictly protected regions, with nearly one-third existing in areas of high conservation value and in watersheds that are stressed (Miranda et al., 2003). In Zambia, the study focuses on copper, cobalt, coal, gold, and emerald as key minerals in mine closure, each showing different environmental impacts. Apart from the common problems such as Acid Mine Drainage (AMD) and habitat disruption, coal mining includes spontaneous combustion and more air pollution, while copper, cobalt, and gold mining release heavy metals, cause siltation, and produce toxic elements, respectively (Křibek et al., 2023). The selected minerals, therefore, represent a wide range of massive environmental impacts from intensive mining in Zambia and hence give due weight to the importance of addressing its legacy (Lindahl, 2014a; Miranda et al., 2003).

Hamrin (1980) identifies financial aspects, particularly regarding ore-related conditions, as a great influence on the viability of a mine and hence as a great influence on problems of mine closure. The mineralogy of the ore, the grade, and the impurities all have direct impacts on potential chemical reactions with bearing on the release of pollutants during exposure to water and oxygen (Brown & Calas, 2011). Closing large-scale mines involves addressing topographical changes and waste dumps, as highlighted by Laing and Trines (2011). In contrast, Cabalda et al. (2002) advocate allocating 10% of capital and operating costs for best practices in new mining ventures to prevent environmental accidents and promote efficient resource use. This proactive approach internalizes the environmental costs at the planning stage and leads to a long-term benefit in the form of regulatory compliance, environmental liability reduction, and good relationships with the stakeholders. This implies that mining should strive to be a worthy contributor to sustainable development through proactive environmental measures that cover the mine's lifecycle (Brown & Calas, 2011; Cabalda et al., 2002; Hamrin, 1980; Laing & Trines, 2011).

Table 1. Minerals and environmental impact of the reviewed minerals in this study

Mineral	Copper	Cobalt	Gold	Coal	Emerald
Government classification	Base metal	Base metal	Precious	Bulky	Precious
Mining Method	Underground	Underground	opencast	opencast	opencast
Lifecycle stage	mature	mature	mid	mid	mid
Production 2022	763,550 Mt	251.8 Mt	2,773 kg	823,450 Mt	22,381kg
Environmental impacts of minerals reviewed in this study					
Environmental aspect	Environmental impacts				
Air	Dust during operations and from waste rock & tailing dumps; Spontaneous combustion & associated gasses				
Water	Disruption of streams & aquifers & water balance; AMD & consequent heavy metals & radioactivity; increased TDS, sulphate & sediment loads				
Land	Land-use loss, surface sinking, and abandoned shafts.				
Ecosystem	Fracturing & destruction of habitat esp. riverine; Vegetation clearing				
Other	Cumulative impacts; Waste dumps; Noise & vibration; Accidental chemical spills; Visual; Increased resource use; Contribution to greenhouse gasses				

2.2.5 The history and transformation of Zambia's mining industry

The Zambian mining industry has undergone significant transformations over the decades, particularly in its ownership structure and economic contributions (Sikamo et al., 2016a). These changes have been marked by shifts from private to nationalized control and back to privatization, reflecting broader economic and political trends both domestically and globally (Sikamo et al., 2016a; Simutanyi, 2008a).

In the early 20th century, Zambia's mining sector was predominantly in private hands, largely controlled by foreign companies. The industry was the backbone of the country's economy, with copper accounting for the majority of its export earnings (Sikamo et al., 2016a). The post-colonial era, particularly in the 1960s and 1970s, saw significant changes. Following independence in 1964, Zambia's first president, Kenneth Kaunda, implemented widespread nationalization policies. By 1973, the government had nationalized the copper mines, consolidating them under the

state-controlled Zambia Consolidated Copper Mines (ZCCM) (Fraser & Lungu, 2007; Sikamo et al., 2016a). This move was part of a broader trend in Africa where governments sought to gain control over their natural resources from colonial powers and foreign corporations (Sikamo et al., 2016a).

The nationalization aimed at leveraging the country's mineral wealth to foster national economic development and reduce foreign dependence. Initially, this approach yielded positive results, as high copper prices on the global market translated to substantial revenue for the Zambian government. However, the situation began to deteriorate in the late 1970s due to a combination of factors, including declining copper prices, increased international competition, and high operational costs. The ZCCM became increasingly unprofitable and reliant on government subsidies (Fraser & Lungu, 2007). The economic difficulties faced by ZCCM and the broader Zambian economy led to a shift in policy in the 1990s. With support from international financial institutions such as the World Bank and the International Monetary Fund (IMF), Zambia began a process of privatizing its copper mines (Lungu, 2008a). By the early 2000s, the majority of the mines were sold to private investors, including multinational corporations (Chamber of Mines of Zambia & ICMM, 2014; Fraser & Lungu, 2007; Lungu, 2008a; Sikamo et al., 2016a; Simutanyi, 2008a).

This transition aimed to attract foreign investment, reduce public sector borrowing, and increase efficiency within the mines. Privatization was also expected to introduce new technologies and management expertise (Fraser & Lungu, 2007; Lungu, 2008a). Following privatization, there was a resurrection in production and investment in the sector. Copper output, which had fallen dramatically by the late 1990s, started to recover, and by the 2010s, Zambia was again one of the top copper producers in the world (Fraser & Larmer, 2010b).

Today, Zambia's mining sector is a critical component of its economy, with copper still constituting the majority of its export earnings. However, the sector faces several challenges, including fluctuating global commodity prices, disputes over taxation and royalties between mining companies and the government, and concerns over environmental impact and sustainability (Noyoo, 2021). The Zambian government continues to seek a balance between attracting foreign investment and ensuring that the mining sector contributes fair economic benefits to the country. Recent debates have focused on issues such as increasing the government's stake in mining operations, improving regulatory frameworks, and ensuring that mining benefits local communities (African Development Bank, 2022; Noyoo, 2021).

In terms of production, Copper reached its peak of 720000 tons in 1969. The talks on nationalization accelerated in this same year (Sikamo et al., 2016a). By 1973, when nationalization was coming to an end, production had decreased to 700000 tons. This came about as a result of the

mining industry's investment beginning to decline as soon as nationalization talks began. Following nationalization, production declined further, reaching 250000 tons by 2000, 24 years after nationalization (Fraser & Lungu, 2007; Fraser & Larmer, 2010b; Sikamo et al., 2016a). Production levels started to rise when the new mine owners made significant investments in green field projects and the renovation of the mines that had received no prior funding. By 2013, production had reached 763,000 tons (Figure 1) and the industry was employing over 90000 direct employees from the low of 22000 at the time that privatization was completed. It is important to note that, before re-privatization, mines were jointly owned, overhead services were shared, and higher-grade copper led to higher unit labor productivity. As a result, the quantity of copper produced per person in 2013 was less than in 1972 (Fraser & Lungu, 2007; Fraser & Larmer, 2010b; Sikamo et al., 2016a). In 2020, the production increased to 882061 tons (BOZ, 2020).

Generally, Zambia's mining industry has experienced significant changes in its ownership and management structures over the past several decades, with corresponding impacts on its performance and role in the national economy. The ongoing challenge for Zambia will be to manage this sector in a way that maximizes its contributions to national development while addressing environmental and social concerns which is commonly known as sustainable Mining.

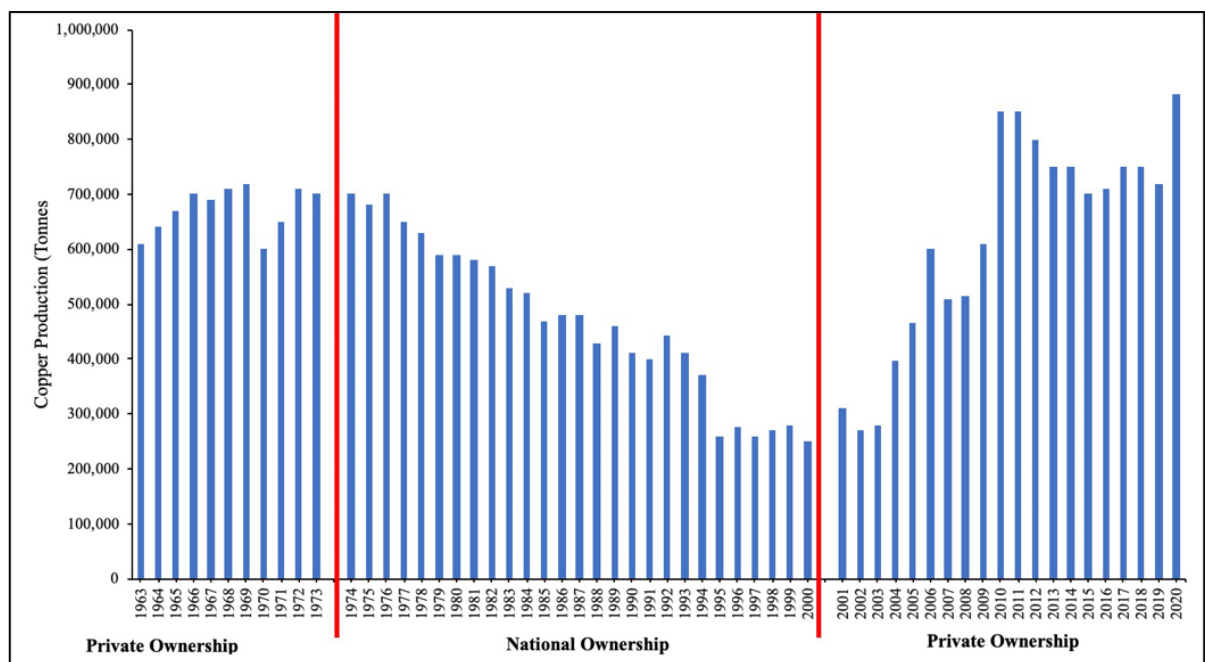


Figure 1. Zambia's Copper production from 1963 - 2020 during the different ownerships (Source: Fraser & Lungu, 2007; Fraser & Larmer, 2010b; Sikamo et al., 2016a; BOZ, 2020).

2.3 Principles of sustainable development in mining

2.3.1 Introduction

The mining sector became aware of new emerging principles of sustainable development in the late 1990s and new challenges in adapting its operations to meet new requirements. These were about public, governmental, and shareholder expectations (Pedro et al., 2017). They were related to the industry's reputation, and thus, they presented risks to it through market acceptance and social approval. Despite recognizing these imperatives, the mining sector lacked a unified approach, addressing sustainable development in an unconnected and incremental manner (Danielson, 2006). The following part of the literature review explores the underpinning of sustainable development within the mining industry through a range of policy analyses and key historical initiatives. It will provide a chronological story of the sustainable development initiative through the examination of the idea, goals, principles, and relevant reports of mine closure. The review will also explore the discourse on sustainable development and mining in Zambia, concluding with a consolidated section on 'sustainable development principles in mining' derived from the literature (Danielson, 2006).

2.3.2 The origin and progression of sustainable development's concept

The concept of sustainable development builds on some of the very early concepts presented in the 1970s and 1980s. The concept that developed into the popular definition was brought out by the Brundtland Commission report of 1987, titled "Our Common Future." It emphasized meeting the present needs without compromising the next generations' needs; it signaled the guiding principle for global entities (Brundtland, 1987). Accordingly, Sustainable Development (SD) became of great importance to be inscribed in treaties and conferences that focus on the balance between keeping the environment and enhancing socio-economics (Lélé, 1991). The 1992 Earth Summit in Rio de Janeiro marked a significant milestone, producing binding agreements, the Rio Declaration, and Agenda 21, which Zambia voluntarily endorsed, outlining action plans for sustainable development. The UN Millennium Declaration in 2000 further embedded sustainable development into the international policy framework, indicating growing accommodation in goal-setting exercises (CSD, 2009; Drexhage & Murphy, 2010; IUCN et al., 1980; UN, 1972, 2000; UNECE, 1987).

2.3.3 The responses of the international mining sector to sustainable development

In the late 1990s, it became clear that the mining industry, which had been well aware of the new principles of sustainable development, was dealing for some time with challenges resulting from the changing public and government reputation, market acceptance, and shareholder expectations affecting social licenses (Danielson, 2006). Guided by Danielson (2006), the review offers a chronological account of major sustainable development initiatives in mining, consolidating different principles across initiatives to serve as a benchmark for subsequent gap analysis (Danielson, 2006; OECD, 2008).

The Global Mining Initiative (GMI), established in 1999 by the Mining and Minerals Working Group of the World Business Council for Sustainable Development, aimed to understand the positive role of mining in transitioning to sustainable development. The GMI, consisting of the Mining, Minerals and Sustainable Development (MMSD) project, Resourcing the Future conference, and the International Council on Mining and Metals (ICMM), wanted to explore the industry's contribution to sustainable development (CESR, 2003; ICMM, 2014; MMSD, 2002). The MMSD project was a sincere independent initiative that involved all stakeholders in the assessment of the role that would be played by the mining industry in the attainment of the global sustainable development goals (ICMM, 2002). The subsequent 2002 report, *Breaking New Ground*, influenced positive developments in mining legislation and projects in Zambia, demonstrating the project's impact on shaping industry standards (Chibbabbuka et al., 2021; MMSD, 2002).

The Johannesburg Plan of Implementation (JPOI), emerging from the 2002 Johannesburg World Summit on Sustainable Development, laid down the action plans in the context of sustainable development, pointing at the mining sector as one of the prime movers to economic and social development the world over (WSSD & UN, 2003). The JPOI recommendations came in line with continuous efforts in Zambia, therefore, to mainstream sustainability in mining practices and call for stakeholder involvement and a holistic approach to considering the environmental, social, and economic aspects (Gankhuyag & Gregoire, 2018; World Bank Group, 2016a). Built on the shoulders of the MMSD, the Extractive Industries Review (EIR) was a comprehensive analysis of the mining industry that sought to determine the effectiveness with which poverty reduction goals, set by the World Bank Group, can be achieved through mining investments (World Bank, 2002, 2003). The Framework for Responsible Mining (FRM) recommended in the JPOI emphasized stakeholder participation, especially in local communities and women, and called for developing country support in sustainable mining practices and site restoration (World Bank, 2003). Finally, the APEC report on "Balancing Mining and Sustainable Development" in 2010 stressed the need for a net benefit across economic, social, and environmental dimensions in mining, advocating a

systematic methodology for sustainable development in the Asia-Pacific region (Azapagic, 2004; Mining Task Force, 2010).

2.3.4 The impact of sustainable development policy on the Zambian mining sector

In Zambia, sustainable development has become a main point of national policy, reflecting a global shift toward environmental conservation and responsible resource management. The realization of the extent to which the mining sector means to the economy, the government of Zambia, has put in place several legislative and policy frameworks that would harmonize mining practices with the SDGs (Ministry of National Development Planning, 2020). This is the commitment underlined by the Environmental Management Act of 2011—one of strong sensibility toward preserving and promoting natural resources for present and future generations, with consideration also directed to appropriate social and economic development (Government of Zambia, 2011a). Further, the Act outlines an elaborate framework of environmental management, reflecting the policies of similar South African legislation, though modified to serve the specific ecological and sociological needs peculiar to Zambia (Government of Zambia, 2011a).

Important implications throughout the world, including Zambia, were realized through the 2002 Johannesburg World Summit on Sustainable Development and thus saw it fit to come up with the Sixth National Development Plan and the Zambia Vision 2030 (Ministry of Finance and National Planning, 2006, 2022). The strategic documents are anchored in the sustainable development principles that guide them towards transforming Zambia into a "prosperous middle-income nation by 2030," (Ministry of Finance and National Planning, 2006). In other words, the response of the Zambian government to the call for immediate action by the summit entails very specific strategies that must be undertaken to make mining environmentally sustainable while boosting economic growth.

The government of Zambia further followed up on these issues in 2007 by drafting its National Policy on Environment. The National Policy on Environment highlights the vision that the nation maintains its ecological integrity through fostering economic development (Ministry of Tourism, 2007). This policy highlights the need for a balanced approach that does not compromise the ability of future generations to meet their needs. The strategy emphasizes the importance of community participation, the use of clean technologies, and the rehabilitation of mining areas as key components of sustainable mining practices (Ministry of Tourism, 2007). It includes the Johannesburg Plan of Implementation, which stresses having developed the indicators that should measure sustainability in general and more particularly within the mining sector.

Despite these policies, challenges remain in fully implementing sustainable practices within Zambia's mining industry. Issues such as environmental degradation and the need for more effective regulatory frameworks are still prevalent (Wambwa et al., 2023). Further, the government continues working to make these frameworks more enhanced to ensure that mining contributes to the max of its potential in sustainable development. Part of these continued efforts includes revising mining legislation, promoting engagement of stakeholders, and raising transparency in environmental management. The objective is to be in the cycle, in fact, not only with global sustainability standards but also to ensure that mining operations are a positive contribution to both the economy and environment in Zambia.

2.3.5 Sustainable development principles and modes

The aim of examining different global and Zambian sustainable development initiatives is to obtain a consolidated set of principles to guide sustainable development in mining. This includes finding key principles from the literature, with a focus on the environmental dimension. While the literature mainly articulates what the mining industry should undertake, it recognizes the interconnectedness of social and economic aspects within sustainable development. The resulting list of 'sustainable development principles in mining,' presented below, is a product of combining and extracting insights collected from the literature discussed above.

- a. Precautionary principle:** Employing precaution in the presence of uncertainties, requires representing responsible and forward-thinking environmental management of natural resources. It involves considering factors such as the environmental carrying capacity, addressing intergenerational considerations, and managing cumulative and unquantified impacts, even in the face of pressing social and economic development needs.
- b. Ethical corporate responsibility, community engagement, and reporting:** Mining companies should demonstrate high ethical standards and take responsibility for their actions, including engaging stakeholders through transparent communication and consultations. Sustainability reporting should be a key tool, subject to independent reviews for credibility.
- c. Subsidiarity principle and underpinning decision making:** Decision-making should occur at the most relevant level, ensuring community involvement and prioritizing sustainable development goals throughout mining processes. The integration and prioritization of sustainable development principles and goals must guide decision-making and governance, emphasizing their significance across the entire mining process and relevant decision-making structures.

- d. **Extensive Risk Management:** Comprehensive identification, mitigation, and management of risks should be continuously revisited, integrating social, environmental, and economic factors, including provisions for redundancies, disaster management, and climate change impacts.
- e. **Internalization of costs:** All costs, including financial, social, and environmental impacts, should be considered within mining activities to reflect true production costs, guiding assessments of mining feasibility and operations.
- f. **Iterative planning, monitoring, and continual improvement:** Engage in long-term planning focused on continuous improvement, regularly revising and adjusting mining plans based on environmental, social, and cost monitoring.
- g. **Investment in research, development, and capacity building:** The mining industry should lead in supporting research and development concerning environmental and social effects, investing in human capital within mining operations, local communities, government agencies, and academic institutions to transform resource extraction into human capital development.
- h. **Rehabilitation, appropriate land use, and local sustainability:** With mining as temporary land use, its legacy must be positive, appropriate, and sustainable within the bio-physical locality and for its inhabitants. Rehabilitation must be undertaken as mining progresses and in line with the final sustainable land use. Persistent environmental and social impacts must be tackled to bring about sustainable development outcomes at closed and legacy mining sites.
- i. **Systems approach and interconnectedness of principles:** Mining should aim for efficiency by achieving more with less; however, it should merely reduce negative impacts and actively contribute to sustainable development. Embracing a paradigm of sustainable development involves holistic thinking, considering social, environmental, and economic aspects as an interconnected and complex whole. Applying systems thinking in the conceptualization and design of mining operations leads to resilient solutions that can adapt to change. Recognizing and applying the interconnectedness of these principles can have a multiplying effect on the positive outcomes of sustainable development.

- j. **Waste as a resource: Greening a circular economy:** Sustainable mining efforts should transform mining waste into valuable resources for other processes or reintegrate it back into natural systems, promoting a circular economy.

As mining certainly leads to closure, the argument arises that the objective at this concluding stage should involve making a well-rounded contribution to sustainable development at both the national and local levels. While these principles and approaches are presented as guidelines for the mining sector to guide its operations toward sustainability, the inquiry persists regarding how the industry can assess this progression. Nevertheless, a comprehensive discussion on the processes, objectives, and actualities of mining and mine closure is imperative before a proper assessment can be undertaken.

2.4 Mining methods and mine closure

2.4.1 Mining methods

Mineral resources are spread across geographical areas and structures, necessitating the development of different mining methods. Mining operations are chiefly conducted in four geographical settings: underground, open-pit (opencast), alluvial, and marine environments (Gogolewska, 2011). This discussion provides an overview of the mining methods used in these different contexts. It is important to clarify that this overview does not aim to be comprehensive; rather, it focuses on explaining the most dominant mining methods.

2.4.2 Historical mining methods

The first historical mining techniques applied to the minerals that have been eroded and, therefore, got exposed on the surface; for example, the mineral ore found on hillsides. The other would be a pit or tunnel that would be increasingly bored into the deeper realms of the hillside as mining activities expanded (Twitty & Fell, 2010). The other primitive method was picking through alluvial deposits. This method had been mined on mineral deposits, which would have been worn away, and carried downwards by the river currents as shown in figure 2. Inside the river, the minerality has a concentration by many mechanisms of physical separation produced from differences in density and flow rates, all of which favor obtaining a high concentration of minerals (Hammel et al., 2000). The process yields the formation of placers, probably containing the mineral nuggets (Figure 2). Thus, the process resulted in the formation of placers and their further development, which, in this case, could contain chunks of the mineral. These chunks were then classically secluded using the panning technique, as detailed by Hammel et al in 2000.

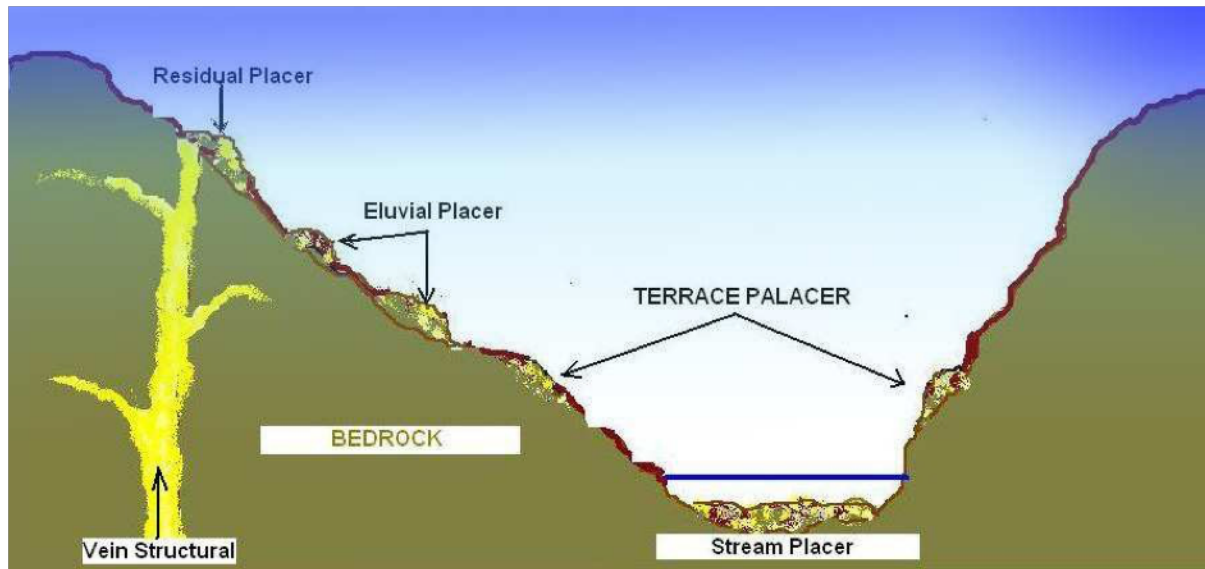


Figure 2. Placer deposits. (Source: Earth Science Australia, 2004).

2.4.2.1 Underground mining methods

In the industrial revolution period, large quantities of coal and iron ore were extracted from the mines, using sophisticated underground mining technologies to achieve the goals of mechanization and industrialization. The ore deposits, whose location is more than 60 meters below the surface, are considered uneconomical for mining in today's world (Clark & Jacks, 2007). Currently, the underground method is used when the site of ore deposits is deeper than 60m below the surface. All the underground mines require a shaft for access, whether inclined or vertical, and often the management of water underground is an essential activity in mining (Gogolewska, 2011) (Figure 3). The work of Hamrin (1980) describes four main methods of underground ore extraction: board and pillar, caving, stopping, and longwall mining. The latter is probably one of the most common ones with different variations, which is also quite possible due to the distinct characteristics of every ore deposit. It is a general summary of the main methods without specifying them, giving particular emphasis on the fact that financial considerations and efficient access to ore continued to dominate the contemporary practice of underground mining (Hamrin, 1980).

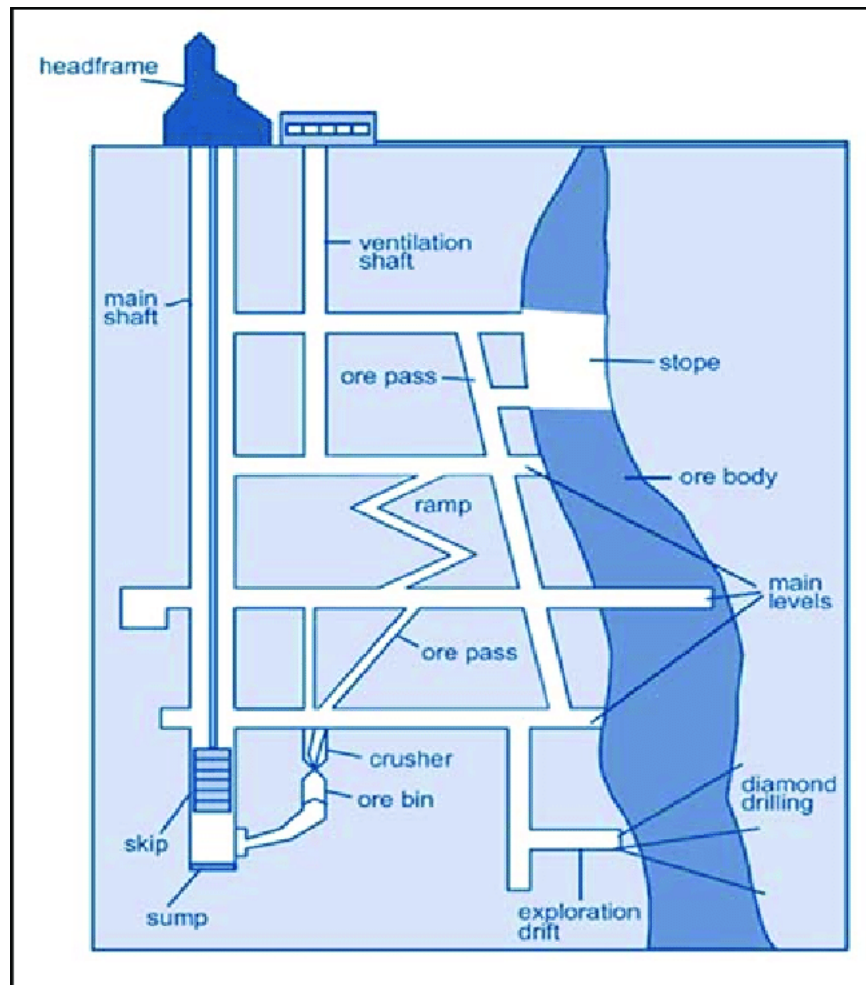


Figure 3. A cross-section through a typical underground mine. (Source: Erdogan & Yayuz, 2017).

2.4.2.1.1 Underground mining environmental impacts

As presented under section 2.2.4, mining has the potential to be linked to environmental impacts. This includes impacts on land aspects, ranging from loss of land use to the footprint of the waste stockpile (Gogolewska, 2011). Furthermore, this may lower the air quality due to the generation of dust and fumes. Ecosystems may also be affected due to habitat loss and a decrease in biodiversity; water bodies may suffer from serious adversities such as AMD, changes in aquifers, and changes to drainage systems (Vinayagam et al., 2024). This is a result of a low environmental impact from underground mines since overburden is not stripped off totally in the process of gaining access to the resource. Surface subsidence, however, may create an environmental hazard process that changes the natural surface water drainage pattern (Guzy & Malinowska, 2020). This involves changes in geohydrological flows and water chemistry. The effects related to water can be compounded by the interconnectedness of neighboring underground operations. Additionally, underground mines can also result in other surface impacts such as tailings dams, and mine

infrastructure, which in turn can disrupt land use, contaminate soil, or generate dust emissions (GDACE, 2008; IFC, 2012; Smith, 2009).

2.4.2.2 Surface mining methods

Bullivant, in 1987, categorizes three common surface mining methods that are selectively employed according to the prevailing geological characteristics of the mineral deposit: strip mining, terrace mining, and open-pit mining (Bullivant, 1987). The expansion of surface mining has been driven by the integration of large-scale mechanized equipment, such as draglines, hydraulic excavators, and high-capacity trucks. However, the economic viability of open-cast mining is dependent on the depth of the mineral deposit from the Earth's surface (Bullivant, 1987).

One of the strip-mining methods is applied to deposits of minerals, especially coal, which are flat and broad, allowing for effective costs, both cost-effective and effective volume production (Kalt, 1983; Klishin & Klishin, 2010). The process involves the removal of topsoil and overburden, followed by drilling, blasting, and mineral extraction. A critical economic factor is the stripping ratio, with strip mining becoming impractical if the mineral lies more than 60 meters below the surface (Bullivant, 1987). Terrace mining is one of the strip-mining methods, whereby modifications are made that fit conditions where either the ore body depth or the inclination is too great. The method involves benching with a slow increase to reach the deposit and presumes the use of excavators with a bucket wheel in the truck and shovel operations during overburden handling removal (Bullivant, 1987; Gogolewska, 2011).

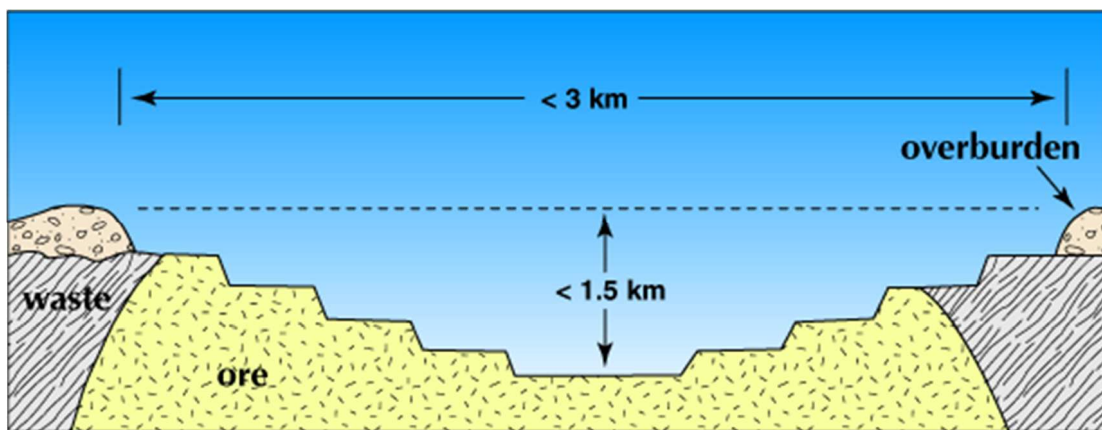


Figure 4. Cross section of an open pit mine (Source: Myers, 2010).

Finally, the open-pit mining approach is applied to dome or tube deposits that are large. The method involves cut-stepping bench preparation to expose the valuable ore together with the waste material. The movements of trucks and shovels with materials facilitate the deposition of waste in

the designated stockpiles (Bullivant, 1987). The schematic cross-section of the described open-pit mining method is depicted in Figure 4.

2.4.2.2.1 Surface mining environmental impacts

As outlined in Section 2.2.8 and Table 1, there are many potential environmental impacts associated with mining operations. The impacts of surface mining differ from those of underground mining due to the evident change in the landscape of the surface. This change, exemplified by the methods of mining mentioned above, frequently induces marked changes in the topographic and surficial drainage patterns, resulting subsequently in higher salt and silt loading of surface water resources (Younger & Wolkersdorfer, 2003). The outcome of mining is visible, taking the form of visible scars such as waste rock deposits on the surface, scars left by ramps, and final voids (Park et al., 2018). The occurrence of AMD in both surface and underground waters is dependent on the mineral composition of the deposit, surface stripping, and oxidizing conditions. Surface habitats are largely modified, usually broken, or destroyed and post-closure efforts to restore them to pre-mining state often fail (Park et al., 2018). Dust released from open-pit operations poses a more significant challenge compared to underground mining. All these activities, including, blasting, loading, hauling, dumping, and spoiling of ore or waste rock, are contributory factors towards the massive generation of dust (GDACE, 2008; IFC, 2017).

2.4.2.3 Waste dumps and tailings

Most of the mining operations result in the production of large mineral waste, which is further divided into waste rock dumps and tailings. Waste rock dumps result from removing upper layers during open-pit mining and basic beneficiation processes, containing relatively intact rock material (Charbonnier, 2001). The tailings, on the other hand, emerge from extensive beneficiation and smelting, possessing elevated moisture levels, additional chemicals, and either acidic or alkaline properties. Tailings release sulfates and heavy metals, impacting the environment through issues such as AMD and heavy metal presence (Qaidi et al., 2022). Both the chemical composition and physical characteristics of tailings and waste rock dumps, including risks such as slumping, dam failures, erosion, dust emissions, and loss of land utility, contribute to environmental concerns (Charbonnier, 2001; Hudson-Edwards et al., 2011; Wei et al., 2013).

2.4.3 Impacts of mining on LULC

The LULC change has emerged as one of the critically important aspects in changing monitoring and natural resource management strategies (Twisa & Buchroithner, 2019; White et al.,

2014). Earth's land surface experiences large-scale alterations, which are greatly accelerated by human activities, particularly their economic activities, influencing the global systems and depletion of vital resources such as water, soil, and vegetation (Twisa & Buchroithner, 2019). Local causes of LULC changes, such as mining economic activities, get intensified attention due to their adverse impacts on land resources and the ecological environment (Lv et al., 2019).

Mining, driven by economic and social development, is identified as a major factor responsible for LULC changes, with notable impacts on the environment, including land loss, occupation, vegetation degradation, and soil erosion (Xiao et al., 2020). These harmful effects of mining and urbanization on natural ecosystems have led many governments to request the reclamation of degraded mining areas (Mensah, 2019). Therefore, in place of this, continued monitoring of LULC changes is advocated for understanding their long-term environmental impacts and providing bedrock knowledge to devise land reclamation and ecological restoration strategies with environmental sustainability and green practices (Carvalho, 2017; Schladweiler, 2018; Song et al., 2020).

Singh et al. (2018) further emphasize the global concern regarding LULC changes resulting from mining, particularly in developing countries for example, Zambia, where mining leads to urban growth and subsequent alterations in LULC (Singh et al., 2018). The collective impact of these activities should be accurately monitored and assessed for their effects on ecological, environmental, and socioeconomic grounds (Wu et al., 2019).

2.4.4 Mine closure

Legacy mines, a result of historical mining practices and inadequate consideration of environmental and social consequences, continue to impact surrounding areas despite being inactive. This remains a challenge for governments, the general public, and mining companies equally, to the pursuit of sustainable development of mining (OECD, 2020; UNEP, 2001). Heikkinen et al. (2008) regard mine closure as ceasing all operations, including the decommissioning of necessary infrastructures and termination of the right to mine. It can be planned or premature due to factors such as ore reserve depletion, economic shifts, social unrest, political instability, and environmental degradation. This is highlighted in the contemporary literature by the temporary nature of the land use for sustainable development, considering that the post-closure planning consists of post-mining land use (Gankhuyag & Gregoire, 2018). However, challenges arise, with some mining operations rendering portions of land unsuitable for other purposes. Worrall (2009) points out that some of the existing frameworks are simply not sensitive enough to be operational in their application, causing complications both in the mine-closure state and anticipation of remediation measures and adapting

to the ever-evolving legislative expectations. This, therefore, makes decentralized mining accommodate the facts of environmental management at the regional scale being complex, requiring government strategy and cooperative planning among mining companies (Gankhuyag & Gregoire, 2018; Heikkinen et al., 2008; Worrall et al., 2009).

2.4.4.1 Whole of mine life phases

This section examines the relationship of closure with the various phases in the life cycle of a mining project. Mine closure planning should be a progressive procedure that transpires over the life of an operation. The complexity level would differ with a shift towards some specific issues being addressed at different phases. Therefore, effective mine closure planning requires that mine management incorporates it from project inception and not treat it as an afterthought when the mine reaches its end-of-life (IIED & WBCSD, 2002). In most cases activities during the exploration phase influence how successful and efficient the closure planning will be. Continuous consultation with the local community and other stakeholders is, therefore, necessary to achieve better results at every stage of mine-closure planning.

The first phase is the exploration phase. In the initial phase of mineral exploration, the uncertainty of establishing a mine is accompanied by significant environmental and societal consequences. Despite the low possibility of exploration leading to mine development, critical tasks such as community engagement plan formulation, stakeholder identification, conducting socio-economic studies, and environmental baseline assessment are important (Commonwealth of Australia, 2006; DMP & EPA, 2015a). Proactive engagement at the exploration stage sets the stage for both future planning and the mine closure process, with an emphasis placed on making connections with effective stakeholders and carrying out comprehensive assessments (IRMA, 2019).

The second phase is the feasibility phase which comes after identifying a mineral resource. The feasibility stage involves project assessments to evaluate the economic, environmental, and societal implications of mining. Feasibility studies, including scoping, pre-feasibility, and final studies, justify ongoing investments and initiate Environmental Impact Assessment (EIA) and Social Impact Assessment (SIA) (Al-Bakri et al., 2023; Equinox Copper Ventures Limited, 2005). Social and economic development concerns are important to this stage, emphasizing local business initiatives and complete mine closure planning (IIED & WBCSD, 2002). The decisions taken during the feasibility phase have implications for a long time on the environment, land use, community health, and mine closure (Commonwealth of Australia, 2006).

The third phase is planning and design. Mine planning and design focuses on developing a complete strategy for mining operations, considering economic, environmental, and social factors.

Collaborating across disciplines, decisions during mine planning have long-term implications, necessitating a risk-centered strategy to assess potential environmental and closure responsibilities (Rahnema et al., 2023; Wambwa et al., 2023). The construction phase denotes a vital change in the environment and community; hence, in its context, reduction in the site disturbance needs to be paid attention to and ultimate community comfort ensured against the temporality of these impacts (Mononen et al., 2022).

The operational phase, spanning from five to over 50 years, requires gradual activity, coordination with higher-level goals, and implementation of closure works. Operational stages include Operations Commissioning, Mature Operations, and Pre-Closure Planning, occurring five or more years before ore depletion (Department of Mines, 2023). Closure involves executing plans established earlier, conducting investigations, demolishing infrastructure, and reshaping mining landforms (Department of Mines, 2023). Post-closure sustainable land use focuses on responsible and strategic land utilization after closure, considering environmental restoration, economic opportunities, community engagement, long-term monitoring, regulatory compliance, innovation, collaboration, and education (Tuija et al., 2022). It aims to turn mine closure challenges into opportunities for environmental renewal, economic development, and community well-being (Young et al., 2022). Success and sustainability require continually human-planned, reviewed, and appropriate actions throughout the life of the mine (IFC, 2007; MMSD, 2002; Robertson et al., 1999).

The need for mine closure plans requires integration into all phases of mining so that the application of sustainability principles remains continuous, as shown in Figure 5 below, adapted from Bell et al. (2006).

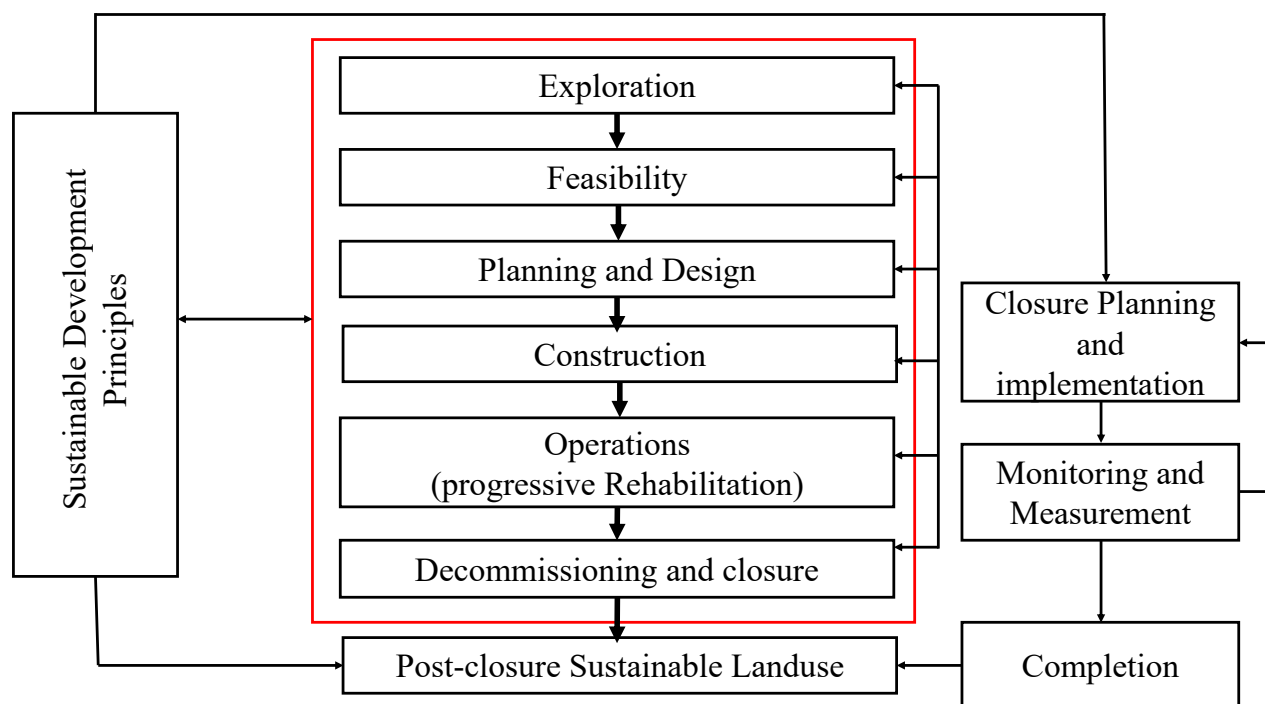


Figure 5. Phases of a mine life cycle with consideration given to sustainable closure throughout. (Source: Commonwealth of Australia, 2006).

If such iterative closure planning and attendant actions are implemented from the outset, then the final closure liability (legacy) will be minimized and closure objectives more likely to be met. Figure 6 depicts the consequences of such progressive closure planning practice versus weak closure planning in which unforeseen closure risks and thus costs arise at the end of the life of mine (Fleury & Parsons, 2006).

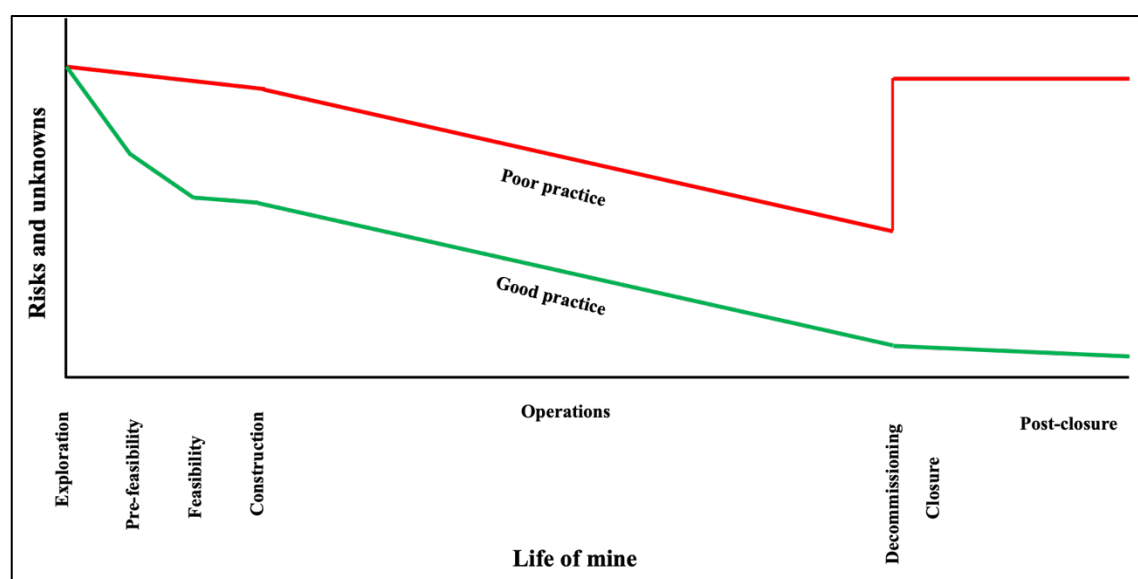


Figure 6. Closure consequences of good vs. poor life of mine planning and practices. (Source: ICMM, 2006).

According to Limpitlaw & Hoadly (2006), post-closure monitoring tests the end result of a mine's contribution to sustainable development, both during and after closure, whether it is good or negative. This demonstrates once more how important the study is—that is, how to create environmental sustainability indicators to help with sustainable mine closure (Limpitlaw & Hoadley, 2006). If advancement toward the environmental aspect of sustainable development is better tracked throughout the mine life cycle, then the final stage of mining, closure, can be directed towards leaving a positive legacy.

2.4.4.2 Environmental impacts and objectives of closure

In the context of sustainable development, mine closure's environmental aspects and impacts play a crucial role. While social aspects are beyond this study's scope, various challenges related to mine closure were identified. The environmental impacts summarized by minerals tend to persist beyond the mine's operating life (Bainton & Holcombe, 2018). Robertson et al. (1999) categorize closure impacts as physical stability, geochemical stability, land use, and sustainable development. Targeted closure objectives, according to MMSD (2002), IFC (2007a), and Heikkinen et al. (2008), include physical, chemical, and biological stability, consideration of geographical and climatic influences, land use and aesthetics, natural resource preservation, financial preparedness, and positive socio-economic legacy. These objectives align with sustainable mine closure goals, such as reverting to a pre-mining state, securing future land use, permitting varied ecosystems, ensuring public health, preventing resource degradation, maximizing positive socioeconomic effects, and minimizing negative socioeconomic effects. Developing indicators aligned with these sustainability principles is essential for measuring and managing a mine's contribution to sustainable development throughout its life cycle. This iterative process aims to ensure that the site's actual condition closely aligns with the closure's sustainable goals at the end of the mining tenure (Gankhuyag & Gregoire, 2018).

3. Methodology and study area

3.1 Introduction

Mine closure is the subject of a lot of theory and debate, as the previous chapter showed. The "on-the-ground" component, on the other hand, is likewise highly distinct and is extremely practical in its considerations and application. In this dissertation, the gap(s) between mine closure policy, legislation, and the 'on-the-ground' status quo in Zambia will be investigated. This chapter covers the methodology (datasets) and study area used in this study. The study area is precisely described, providing insights into its geographical, socio-economic, and environmental attributes that make it an important choice for this research.

3.2 Datasets

This research employed a thorough strategy to acquire insights into the procedures involved in closing mines in Zambia. Utilizing a well-structured questionnaire, participants were requested to assess their familiarity with mine closure procedures specific to Zambia. The questionnaire aimed to gather metadata about diverse aspects of mining operations in Zambia, covering information about industries, the types of mining activities, the variety of minerals involved, and the scale of mining operations. Furthermore, the study examined the current status of environmental indicators in mining and the existing practices of mine closure in Zambia. Participants were also urged to express their opinions on both the current practices and the ideal strategies for mine closure within the Zambian mining sector. Furthermore, this research examined the utilization of remote sensing data for monitoring the environmental impacts linked with mining activities, specifically employing Landsat and PlanetScope data. This comprehensive methodology sought to provide an all-encompassing comprehension of the dynamics of mine closure, environmental indicators, and the potential integration of remote sensing technology in the Zambian mining setting.

3.3 Study area

Copperbelt Province, located in the heart of Zambia, holds a pivotal position in the country's economic landscape. Renowned for its rich mineral deposits, particularly copper, the province has been a cornerstone of Zambia's mining industry and it covers the total area of 31328

km² (Aurélien et al., 2022). The province is divided into 10 districts and Ndola is the provincial headquarters (Figure 7). The other districts include Kitwe, Chingola, Mufulira, Luanshya, Chililabombwe, Kalulushi, Masaiti, Mpongwe, and Lufwanyama. Each district contributes uniquely to the economic and mining landscape of the province (Aurélien et al., 2022).

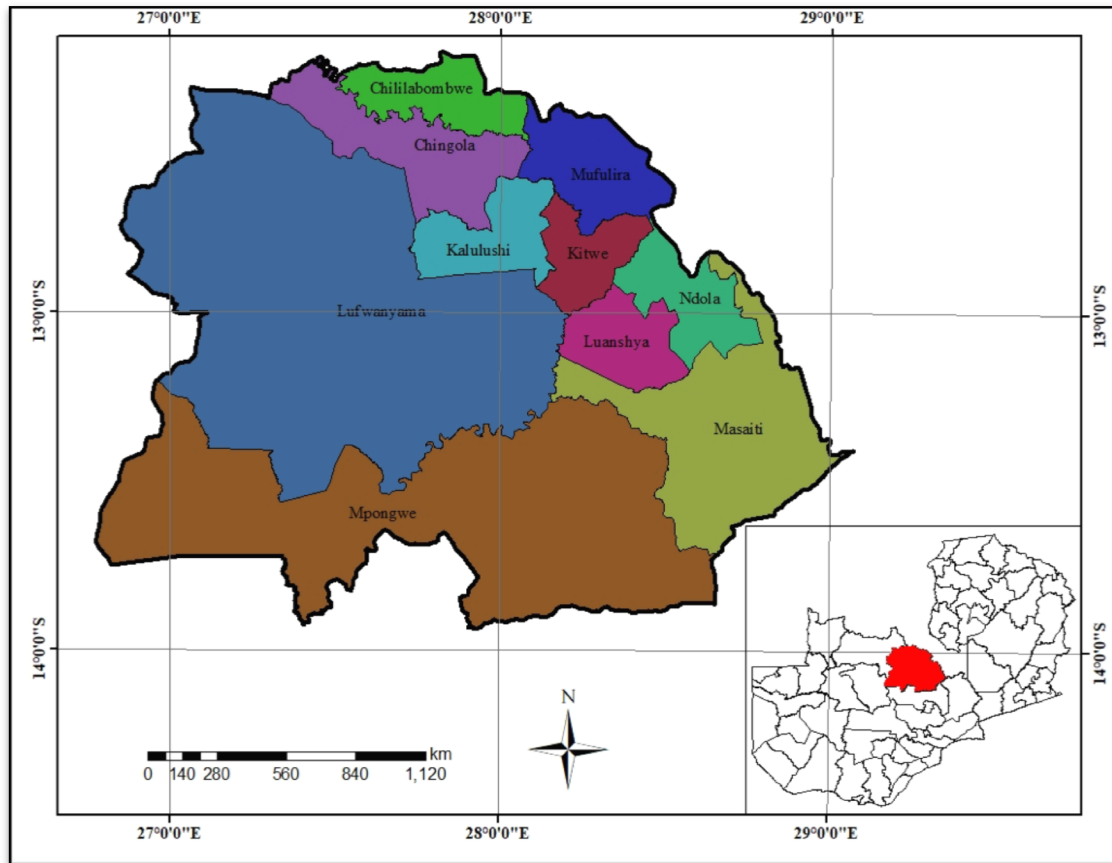


Figure 7. Map of the study area, Copperbelt Province.

The Copperbelt Province is the home of Mopani Copper Mines (MCM), Konkola Copper Mines (KCM), Lubambe Copper Mine, Chibuluma Mines, NFC Africa Mining, CNMC Luanshya, Chambishi Copper Smelting Company, Sino-Metals, Chambishi Metals, Nchanga (Open Pit and Underground Mine), Baluba Mine, and Muliashi Mine (Aurélien et al., 2022; Chadwick, 2013). It is bounded by the North-Western province (to the west) and Central province (south) and by the Democratic Republic of the Congo (to the north and east) (Aurélien et al., 2022).

3.4 Population distribution in Copperbelt Province

In 2010, Zambia had a population of 13,046,508 made up of 6,394,455 males and 6,652,053 females (CSO, 2012a). An estimated 7,978,274 people (61%) resided in rural areas whereas 5,068,234 (39%) resided in urban areas. The Copperbelt Province, with the second largest population after Lusaka Province, had 1,958,623 people out of which 973,770 are males and 984,853 are females (CSO, 2012c). The average annual population growth rate in the 1990-2010 intercensal period for the Copperbelt Province was 2.0% for males and 2.3% for females. One of the districts in the Copperbelt Province is Kitwe district (CSO, 2012c).

In terms of population growth, Copperbelt's population has increased from 1,458,459 (739,519 males and 718,940 females) in 1990 to 1,972,317 (981,887 males and 990,430 females) in 2010 and it rose to 2,757,539 by 2022 (Table 2) (ZSA, 2022b).

Table 2. Population in Copperbelt Province, 1990–2022. Source: (CSO, 2012d, 2012b; ZSA, 2022b).

Year of Census	Population	Male	Female
1990	1,458,459	739,519	718,940
2000	1,581,221	799,402	781,819
2010	1,972,317	981,887	990,430
2022	2,757,539	1,352,964	1,404,575

3.5 Description of the environment

3.5.1 Location and altitude

The study area is the Copperbelt Province of Zambia located between latitudes 12° 21' 07" and 13°40' 50" South, and longitude 26° 41' 29" and 27° 36' 02" East. The region has an undulating terrain ranging between 900 and 1,500m above sea level, with the elevation occasionally broken by isolated hills (Chadwick, 2013; Phiri et al., 2022).

3.5.2 Topography, geology and soils

Copperbelt area includes the Neoproterozoic Katanga Supergroup, which includes deposits of Cu-Co and many other metals Cu, Pb, Zn, U, Au, Fe, and other metals (Master et al., 2005). Cu ore has a 3 weighted (wt%) average grade, whereas Co ore has a 0.18 wt% average grade (Křibek et al., 2010). The Katanga Supergroup encompasses a considerable chunk of the Copperbelt (Sillitoe et al., 2017). These are meta-sedimentary rocks that were metamorphosed and distorted as part of the Lufilian Arc, which runs northwest to the east (Sracek et al., 2011).

The Katanga Supergroup's copper deposits are concentrated in the Lower Roan Subgroup (Jackson et al., 2003). As a result, mining is mostly done in the Lower Roan Formation, where the ore composition is dominated by pyrite (FeS_2), chalcopyrite (CuFeS_2), bornite (Cu_5FeS_4), chalcocite (Figure 8).

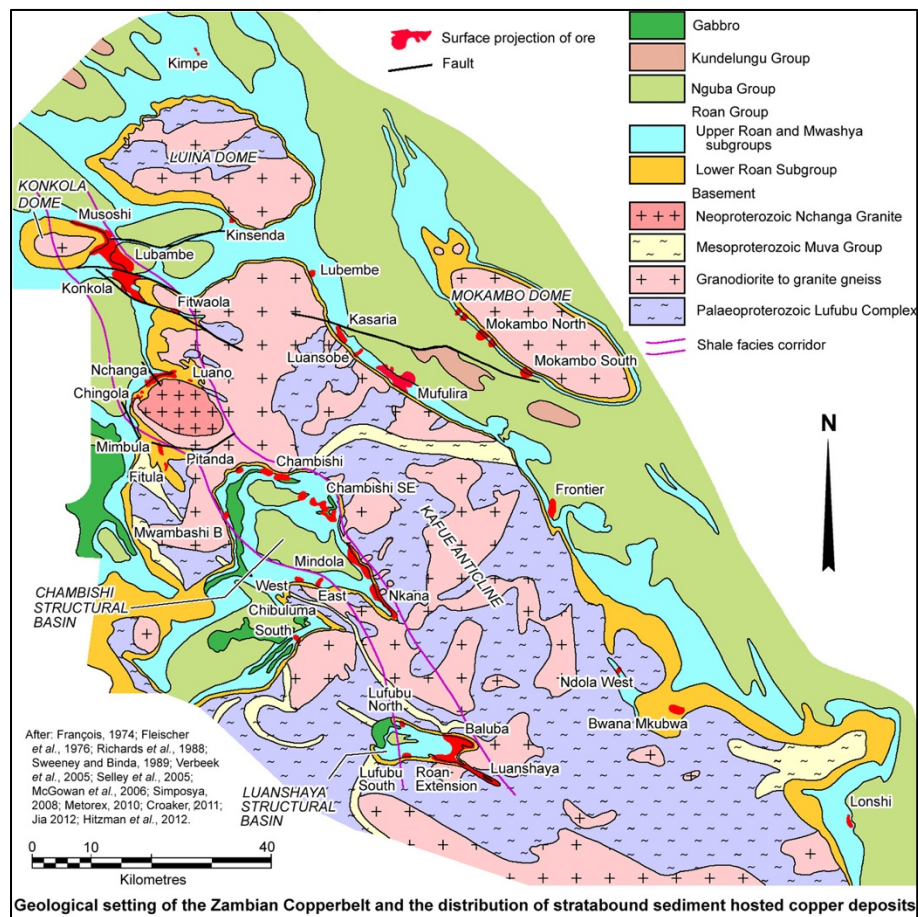


Figure 8. Geological map of the Copperbelt Province. (Source: Porter GeoConsultancy, 2015).

The gently undulating topography of the Zambian Copperbelt has elevations of 1250 to 1400 m. The proposed projects and subprojects are likely to be implemented within the Kafue River drainage basin, which has a well-developed dendritic drainage pattern (Sracek et al., 2011). The headwaters of the Kafue River arise at the northern end of the Copperbelt, close to the DRC border. The area is underlain by crystalline and meta-sedimentary rocks of various lithologies and degrees of metamorphism, deposited during the Proterozoic era (Sracek et al., 2011). The red lateritic soils in the Copperbelt generally have sandy topsoil overlying more loamy clayey subsoil (Brammer, 1976). These soils are susceptible to erosion by water if soil conservation practices are not used. Due to the high rainfall in the Copperbelt, the soils are all strongly leached, have a low reserve of plant nutrients, and have a low base saturation. The soils are acidic with pH ranging from 5.5 - 6.1, with no discernible change in pH down to a depth of +3 m. The majority of the lateritic soils have a low fertility status. They are only suitable for climatically adapted crops under fertilization and good management. The high rainfall in the Copperbelt, rather than the soils, has induced vigorous tree growth which permits the establishment of sparse ground vegetation (Brammer, 1976; Jackson et al., 2003; Křibek et al., 2010; Sillitoe et al., 2017; Sracek et al., 2011).

3.5.3 Climate

The climate of the Copperbelt Province is controlled largely by the north-south migration of the Inter-Tropical Convergence Zone (ITCZ) with seasons. The ITCZ migrates between the equator and the Tropic of Capricorn (23°S) between November and February. In winter, it is located over the northern tropics. The summer rains are brought by the southward migration of the ITCZ and are characterized by thunderstorms, which are occasionally severe, with excessive lightning and sometimes hailstorms (Arslan et al., 2014; The World Bank & Government of Zambia, 2019). The total annual average rainfall is approximately 1,309.1mm, with the majority falling during the summer months of November to April. Annual evaporation exceeds the average annual precipitation in the Copperbelt region with an average evaporation of approximately 2,073mm against the average precipitation of 1,309.1mm (MMMD, 2016). On a month-by-month basis, evaporation exceeds precipitation for three-quarters of the year. The mean annual temperature measured is 19.1 °C, experiencing warm to hot summers, reaching 31.9 °C in October and warm winter days, but cold at night. The predominant wind direction in the Copperbelt is northeast to southwest (MMMD, 2016).

3.5.4 Hydrology

The main river system in the Copperbelt Province is the Kafue River, which traverses the province in the southern direction, and swamps occur along the river and its numerous tributaries. The Copperbelt Province is drained by several streams that ultimately discharging their water into the Kafue River, the principal river in the region (Figure 9) (MMMD, 2016; Sracek et al., 2011).

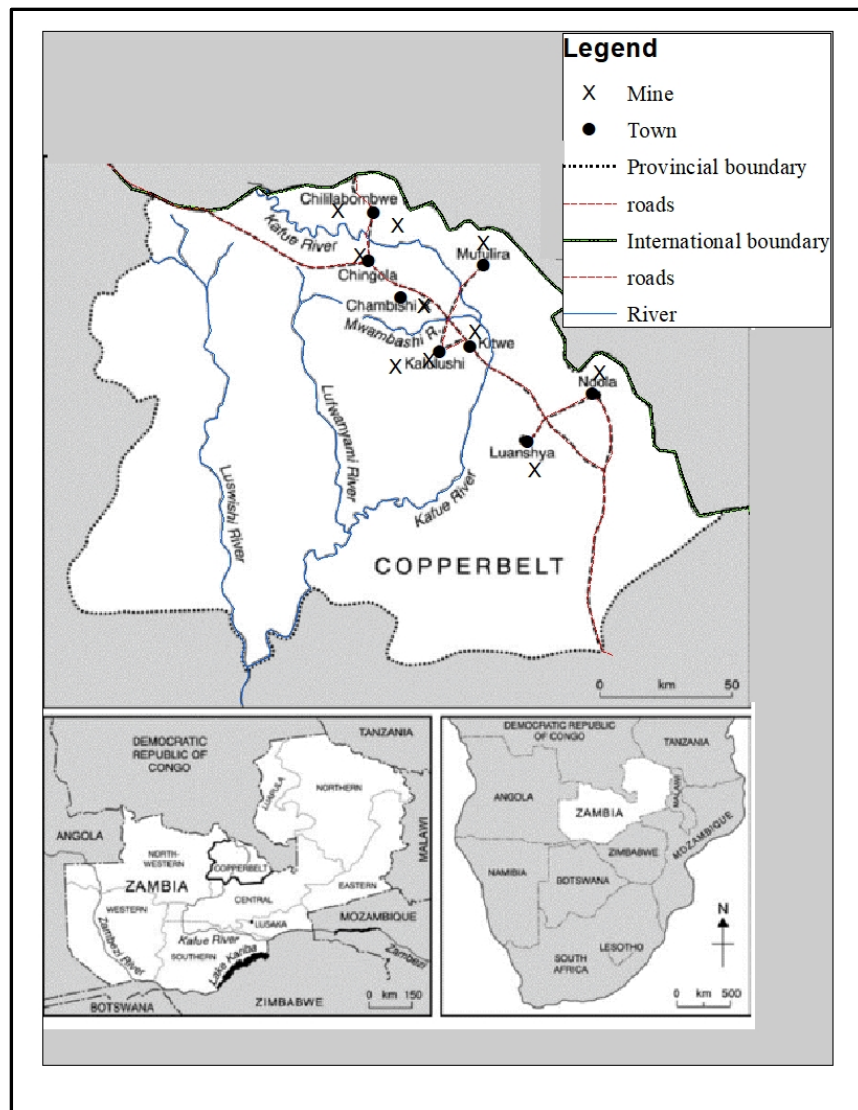


Figure 9. The hydrological map in the Copperbelt Province. (Source: von der Heyden and New, 2003)

The Kafue River originates at the eastern end of the Zambezi – Congo Watershed in the Copperbelt Province, near the country's border with the Democratic Republic of the Congo, and meanders generally southward as it flows close to the Copperbelt mining towns of Chililabombwe, Chingola, and Mufulira, and through the outskirts of Kitwe where its tributaries receive multiple contamination sources from mining discharges that contribute to contamination of surface water and stream sediments (Sracek et al., 2011). It then turns west near the Lukanga Swamp (which it drains).

It then turns southwards or south-westwards and flows into the Itzhi-Tezhi Dam reservoir. Afterward, it turns eastwards and travels across the Kafue Flats and into the Kafue Gorge Dam reservoir. From the hydropower station, it flows through the steep Kafue Gorge before joining the Zambezi Main River near Chirundu. It is one of Zambia's major rivers and its waters are used for irrigation. Located north of Chingola on the Kafue River is the Hippo Pool a protected national monument (MMMD, 2016; Sracek et al., 2011; Vladimir et al., 2011).

3.5.5 Vegetation types

The Copperbelt Province exhibits a distinctive profile of flora and fauna within its geographical boundaries. This region, characterized by its mining-centric landscape, also harbors a diverse array of plant and animal life. The flora of the Copperbelt is marked by the presence of indigenous vegetation, with resilient plant species adapted to the local climatic conditions. The province's vegetation includes a mix of grasslands, woodlands, and shrublands, with plant species such as Acacia, Miombo Woodlands, and various grass species contributing to the ecosystem (Chidumayo, 1997).

In terms of fauna, the Copperbelt Province hosts a variety of wildlife species that have adapted to the dynamic environment. While the intense mining activities have impacted some habitats, the region still supports diverse animal life. Mammals indigenous to the Copperbelt include antelope species, small carnivores, and rodents. Additionally, various bird species, such as raptors and songbirds, contribute to the avian diversity of the region. The aquatic ecosystems within the Copperbelt may also support fish species in rivers and water bodies (Chidumayo, 1997; MMMD, 2016).

3.6 Economy of the Copperbelt Province

The Copperbelt Province stands as a significant economic hub characterized by a robust array of economic activities, primarily centered on the mining industry. The province's economic landscape has been historically shaped by extensive copper mining operations, making it a cornerstone of Zambia's economy (UN-Habitat, 2009a). The extraction and processing of copper ore are pivotal economic activities, with major mining entities, including Mopani Copper Mines, Konkola Copper Mines, and others, contributing substantially to the province's economic output.

Beyond mining, the Copperbelt supports a range of additional economic activities. The mining sector stimulates various service industries, including logistics, transportation, and engineering services, creating a complex web of economic interdependencies. Furthermore, the province is marked by a burgeoning manufacturing sector, driven by the need for equipment and materials for mining operations. This has led to the establishment of metal fabrication plants and other industrial units (Lungu, 2008b; Simpasa et al., 2013; UN-Habitat, 2009b).

The economic significance of the Copperbelt extends to trade and commerce. The province hosts bustling urban centers, such as Ndola, which serve as commercial hubs facilitating the trade of mining-related goods and services. Additionally, the presence of skilled labor in the region has spurred the growth of educational and healthcare services, contributing to the overall Socio-economic development of the area (Lungu, 2008b; Mulder et al., 2024; Simpasa et al., 2013; UN-Habitat, 2009b).

3.7 Employment in Copperbelt Province

Copper and cobalt mining constitute the principal source of employment in Copperbelt Province (UN-Habitat, 2009b). Other economic activities in the region include agriculture, trade, commerce, industry (mainly mining-related), forestry, and fisheries (UN-Habitat, 2009b). The trades and services sector follows closely in terms of the number of workers/employees (Mwitwa & Ng'andwe, 2010). The decline in the mining sector during the 1990s led to a surge in unemployment rates. Mine retrenched thousands of miners most of whom are now self-employed in the informal sector (FAO et al., 2018). Livelihoods are sustained through various income sources, including small-scale entrepreneurship and quarrying for industrial minerals such as laterite, gravel, and sand for construction (FAO et al., 2018). Informal small-scale trading, particularly since the liberalization of the economy, has emerged as a significant contributor to

employment in the province. The rise of informal small-scale trading has offered job opportunities to individuals affected by retrenchment or the closure and restructuring of companies, notably the mines (FAO et al., 2018). Additionally, informal trading is prevalent among women and the youth, involving the exchange of agricultural products, both processed and unprocessed. The decline in metal prices, notably in copper, is anticipated to further boost informal trading due to potential job losses in the mining sector (FAO et al., 2018). The reduction in copper prices, coupled with electricity supply constraints to the mines, has led to substantial retrenchments, with Mopani Copper Mines alone retrenching over 4,000 employees in Kitwe (FAO et al., 2018). This situation is expected to drive more individuals into the informal sector and farming activities in the peri-urban areas of Copperbelt Province. Beyond mining, the population in Copperbelt Province engages in diverse sectors such as fisheries, forestry, hunting, and community, social and personal services. Employment in value addition is encompassed within manufacturing, wholesale and retail, trade, restaurants, and hotels (FAO et al., 2018).

3.8 Methodology

This thesis contains three technical chapters which are presented in chapters 4 to 6. These technical chapters are based on and guided by the specific objectives designed for this thesis. This section critically explores how the methodologies not only support but also advance the research by enabling a thorough investigation into the environmental impacts of mine closure in Zambia.

Objective 1 (Chapter 4) evaluated the Zambian mine closure legislation against environmental principles and indicators of sustainable development aiming at assessing the current status of mine closure in Zambia and mine closure professional's awareness of different mine closure legislations. This evaluation began with a comprehensive literature review to establish a baseline of global best practices and the specific attributes of Zambian mine closure legislation. Finally, the findings informed the creation of a questionnaire survey targeting mining professionals (Mining site, Corporate, Consultancy, Governmental, Academic, and Legal), which further clarified the practical application and effectiveness of these legislative frameworks in promoting sustainable mine closure practices in Zambia.

Objective 2 (Chapter 5) LULC maps for the Copperbelt Province, Kitwe District to be specific were prepared, and multi-temporal LULC changes analysis was done particularly in areas affected by mining activities. The investigation was focused on the changes and drivers of the

LULC changes. It examined the impact of mining on the area's landscape over three decades, using remote sensing data to map and analyze these changes. The methodology involved the Google Earth Engine Random Forest classifier algorithm to process satellite images from 1990 to 2020, assessing changes in various land cover categories such as bare land, forest, and agricultural land. This analysis helped to understand how mining influences the landscape and provided a basis for evaluating the effectiveness of current land reclamation and mine closure practices.

Objective 3 (Chapter 6) focused on the legal framework governing mine closure in Zambia, assessing its adequacy and effectiveness. The chapter used detailed legal analysis and critique to discuss the enforcement challenges and historical environmental liabilities inherited by the government during the privatization of the mining sector, demonstrating the environmental and social burdens on communities. The methodologies used in this investigation include a comprehensive review of Zambian mine closure legislation and, gap analysis comparing practical mine closure practices with legislative requirements. These tools were utilized to provide a detailed critique of Zambia's efforts towards establishing a robust legal framework for mine closure and to suggest improvements for future practices.

Objective 4 (Chapter 7) focused on performing a gap analysis between on-the-ground mining practices based on survey results and the legislative requirements for mine closure. It also aimed to propose a set of environmental sustainability indicators to address the identified gaps, aligning sustainable development principles with Zambian legislation.

The methodologies outlined in this research, primarily through the insights and findings from Chapters 4, 5, and 6, were instrumental in addressing and advancing objective 4, as elaborated in Sections 7.5 and 7.6. The rigorous analysis and synthesis of these chapters not only grounded the study's theoretical frameworks but also enriched the empirical evidence supporting sustainable mining practices. This approach emphasized the interconnections between legislative frameworks, on-the-ground mining practices, and sustainable development principles, revealing both gaps and opportunities within Zambian mine closure processes. Therefore, the methodology adopted has proven critical in navigating the complexities of environmental sustainability in the mining sector, fostering a robust foundation for proposing practical and sustainable closure strategies.

4. Zambian mine closure against environmental principles and indicators of sustainable development

4.1 Introduction

The closure of mines poses complex challenges, requiring a delicate balance between economic objectives and environmental sustainability. In the Zambian context, it is very important to understand the relationship of mine closure legislation with environmental principles and indicators of sustainable development for fostering responsible mining practices. In the past, research in this domain has served to lay further foundation in the understanding of the broader implications of mine closure legislation on sustainable development. Notable contributions include studies that have advanced the understanding of the best practices across the globe regarding environmental principles and indicators within mining (Commonwealth of Australia, 2006). Furthermore, there have been serious investigations of Zambian mine closure legislation in isolation, focusing on its strengths and weaknesses (e.g., Al-Bakri et al., 2023). However, a complete analysis that compares Zambian legislation with both global standards and sustainable development indicators is still a gap in the existing literature.

4.2 Mine closure in Zambia

Mine closure in Zambia presents significant social and environmental challenges. The closure of mines can lead to unemployment, impacting the livelihoods of many Zambians who entirely depend on this industry (Lindahl, 2014a). The sum of this is economic instability brought about by job losses and adds up to social impacts on the affected regions. Further, closure disrupts established infrastructure, including schools, health facilities, and housing provided by the mining company to the detriment of community welfare (Gankhuyag & Gregoire, 2018). Environmentally, mine closures in Zambia cause contentious issues, especially AMD (Lindahl, 2014a). The disagreements, therefore, emanate from the financial liability and responsibility related to historical cumulative environmental damage. Radioactivity and dust from mining wastes, water contamination due to fracking, and heavy metals in AMD decant further contribute to severe environmental problems (Křibek et al., 2023). Besides, most of these problems fall heaviest on communities near and cause degradation to the carrying capacity and the ability of ecosystems to supply essential services. Further compounded with issues ranging from a depleted resource base

and currency instability to uncertain global resource prices, the conventional Zambian mining enterprise is under stress (World Bank, 2015). Compliance with existing legislations, which hold mining companies to the cost of closure, just emphasizes prudent planning, management, and financial provisions. Without saying, it might become criminal litigation, hence the added importance of investigating the indicators of sustainable mine closure in a Zambian context.

4.3 Sustainable development indicators

4.3.1 Indicators of sustainable development

The principles of sustainable development have made it possible to emerge the necessity for indicators that would show the progress or regression of reaching the principles (Holden et al., 2014). Major mining companies acknowledge sustainable development as a central goal and emphasize the significance of information on economic, environmental, and social aspects for informed decision-making in alignment with these goals (Lewis et al., 2016; Worrall et al., 2009; Woźniak et al., 2022). The most commonly used paradigms in effectively monitoring sustainable development include principles, criteria, and indicator frameworks with broad-based applications across the resource sectors (Papageorgiou et al., 2021). Criteria are detailed objectives that reflect human conditions, real-world circumstances sought by society, and tangible standards about quantitative indicators that easily measure or analyze progress or regression (Lewis et al., 2016; MTF, 2010).

Indicators are very crucial in the measure of changes in criteria over time and function as descriptive tools for an assessment. Nonetheless, sometimes the interpretation of indicators may need analysis, as they may not inherently describe why suggested changes have occurred. Van Cauwenbergh et al. (2007) and Bossel (2001) note the challenge of selecting the right number and combination of indicators, balancing the need for meaningful data against the risk of data becoming difficult and unclear. The creation of indicator frameworks is the initial step, serving to structure interpretation, provide a methodology for coverage, and offer a conceptual model for understanding interconnected issues. Generally, there are two types of indicator frameworks: systems-based and content-based (Bossel, 2001; Van Cauwenbergh et al., 2007). The system-based frameworks qualitatively describe overall system behavior with key qualities, but they generally remain qualitative, and often they are applied to the macro-level (Papageorgiou et al.,

2021). The content-based ones describe the specific features of the system and, thus, are clear but often fail to give a holistic view of the system (OECD, 2004). The OECD (2004) tried to propose a solution to this issue, and it was the creation of several classes of indicators. Among these were core environmental indicators, key sets of indicators, sectoral indicators, and environmental accounting indicators, some of them being defined as of highest priority.

The usefulness of the indicators varies across different scales and purposes; being cross-cutting tools, the indicators must be relevant to each scale. Indicators should be used with caution concerning issues of scalability and use, with the understanding that indicators might be effective at one level but not acceptable at the national level. The OECD's methodology for indicator classes tries to cater to different needs and audiences, including core environmental indicators, sectoral indicators, and more detailed sets. However, the challenge of fit-for-purpose and scale remains complex, emphasizing the importance of awareness during indicator development in alignment with specific goals and intended audiences.

4.3.2 Practical considerations and formulating an indicator set

The data's quality and availability present serious problems for the development and monitoring of indicators of sustainable development especially at high levels of monitoring. Additional obstacles include inadequate funding, trouble with aggregation and comparison, gaps in monitoring networks, conceptualizing system measures, low priority, and disparate data aggregation (OECD, 2015). Similarly, when such a challenge is met with a situation of double marginality, Segnestam (2002) advocates reaching the limit of using proxies and maximizing the available data in a case where there is no possibility of developing the indicators for the meantime. On the other hand, involving local stakeholders in data gathering would, however, be a means of supporting sustainability for the project and also serving as a cost-effective strategy (Segnestam, 2002). While credibility, cost-effectiveness, and capacity are additional concerns, these aspects fall beyond the scope of the present research.

Considering the comprehensive scope of sustainable development and the lack of a project-specific case study, a systems approach to indicator creation is proposed, using sustainability principles and closure objectives as the foundation. The resulting environmental sustainability indicators are therefore aimed at helping in the decision-making of the mining industry and further mine closure by publishing sustainability indicators.

4.4 Mine environmental indicators crucial for sustainable mining practices integrated and implemented by other countries

Mine environmental indicators are essential tools for assessing the environmental performance of mining operations. These indicators can be classified into baseline and operational indicators, providing insights into the environmental impact and sustainability of mining activities. Here is an overview of some widely implemented and integrated mine environmental indicators:

- a. Water quality: The parameters monitored for water quality include pH, turbidity, dissolved oxygen, heavy metals (e.g., lead, mercury, arsenic), nitrates, and sulfates. In Australia, baseline water quality monitoring is mandatory before mining activities commence, ensuring that any changes due to mining can be detected and managed.
- b. Air quality: Air quality monitoring focuses on particulate matter (PM10 and PM2.5), sulfur dioxide (SO₂), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). The United States employs the National Ambient Air Quality Standards (NAAQS) to set baseline air quality standards around mining areas to protect human health and the environment.
- c. Soil quality: Parameters for soil quality include heavy metal concentration, pH, organic matter content, and soil texture. In Canada, soil quality assessments are conducted before mining operations to identify potential contamination sources and establish remediation benchmarks.
- d. Biodiversity: Biodiversity monitoring involves assessing species richness, abundance, and diversity indices of flora and fauna. South Africa requires detailed biodiversity assessments to understand the pre-mining ecosystem and ensure the protection of endangered species and habitats.
- e. Hydrogeology: Hydrogeological parameters include groundwater levels, flow rates, aquifer properties, and recharge rates. In Chile, baseline hydrogeological studies are critical in understanding groundwater resources and their vulnerability to mining impacts.
- f. Waste management: The parameters monitored for waste management are the volume and type of waste generated, methods of waste disposal, and tailings composition. Sweden

enforces strict regulations on tailings management, requiring mining companies to report and manage tailings to prevent environmental contamination.

- g. Energy consumption: Monitoring of energy consumption includes total energy usage, the percentage of renewable energy used, and energy efficiency measures. In Canada, mining operations are encouraged to adopt energy-efficient technologies and report their energy consumption to reduce greenhouse gas emissions.
- h. Water usage: Water usage parameters include total water withdrawal, sources of water, and rates of water recycling and reuse. In Australia, water usage is closely monitored and regulated, with incentives for mining companies to adopt water-efficient practices and technologies.
- i. Emissions: Emissions monitoring covers greenhouse gas emissions, dust, and other pollutants. The European Union's Emissions Trading System (ETS) includes mining operations, requiring them to report and manage their carbon emissions.
- j. Land rehabilitation: Parameters for land rehabilitation include the area rehabilitated, soil quality in rehabilitated areas, and the success rate of revegetation. In the United States, the Surface Mining Control and Reclamation Act (SMCRA) mandates the restoration of mined lands to their original or better condition.
- k. Community engagement: Monitoring community engagement involves tracking the number and frequency of community consultations, grievance mechanisms, and social investment projects. In Canada, mining companies engage in regular consultations with Indigenous communities to address their concerns and ensure that mining activities benefit local populations.

Properly implemented and integrated mine environmental indicators are crucial for sustainable mining practices. They help in minimizing environmental impacts, ensuring regulatory compliance, and fostering transparency and accountability. Countries like Australia, Canada, the United States, and Sweden serve as exemplary models in implementing these indicators effectively, thereby contributing to more sustainable mining operations globally.

4.5 Statutes applicable to mining in Zambia

The present debate around mining regulations in Zambia has been a subject of very tight debates in the media and scholarly discussions. The introduction of amendment bills and acts has, however, introduced a level of uncertainty, specifically regarding the misunderstanding of environmental aspects related to mining activities and mine closures (Fraser & Larmer, 2010b). The regulatory landscape governing mining activities is defined by a complex web of statutes. The sophisticated play of these statutes will thus go along with not only defining the regulatory frameworks but, in a sense, how mining operations unfold. The mining operations of Zambia are based on two important frameworks, which are the symbiotic relationship between the legal and the institutional framework. This becomes one of the symbiotic relationships of two frameworks that become fund

4.5.1 Legal framework

The legal framework for mining activities in Zambia is twofold: legislative and regulatory. The different pieces of legislation and regulations (legal framework) with provisions that relate to the mining sector in Zambia include The Mines and Minerals (Environmental) Regulations of 1997, The Mines and Minerals (Environmental Protection Fund) Regulations, 1998, The Mines and Mineral Development Act (MMDA for Mines and Minerals of 2015) with amendments and The Environmental Management Act of 2011 (ICLG, 2023).

The first foundation in Zambia's legal framework for mining is the Mines and Mineral Development Act (MMDA) Act of 2015, serving as the principal legislation regulating mining activities. This act revises laws about mineral exploration, mining, and processing, highlighting safety, health, and environmental protection in mining operations (Government of Zambia, 2015a).

Secondly, the 2011 Environmental Management Act (EMA) is another very important piece that dictates the interactions individuals and entities have with the environment. EMA, 2011 seeks to protect and conserve integrated environmental protection and conservation, mandating the duty of care to the environment from all, including the mining companies (Government of Zambia, 2011a). Notably, the EMA establishes the Environmental Fund, funded through parliamentary allocations, voluntary contributions, and levies, with exemptions for mines due to their coverage under the mining statute. The establishment of the Zambia Environmental

Management Agency (ZEMA) is instrumental in managing various aspects affecting the environment, including the regulation of mining activities (Government of Zambia, 2011a).

The third one, The Mines and Minerals (Environmental Protection Fund) Regulations of 1998, complements the MMDA of 2015 and forms an environmental management framework on mining activities. These laws include a comprehensive set of rules on matters of environmental protection and steps of mitigation to be adopted within the mining industry (Government of Zambia, 1998a). They deal with critical issues such as the preparation of Environmental Impact Assessments (EIAs), regulation of dumping and dump sites, emission standards for air and water discharges, and guidelines for handling, storage, and processing of hazardous materials. Moreover, these regulations incorporate provisions related to the Environmental Protection Fund, contributing to financial mechanisms for mitigating environmental damage caused by mining operations. In this respect, this introduction makes clear the roadmap laid down by the paper for a comprehensive review of the regulatory framework and its implications on mining practices in Zambia vis-à-vis sustainability (Government of Zambia, 1998a).

The other component of the legislative framework comprises the Mines and Minerals (Environmental) Regulations of 1997. In support of the EMA of 2011, this provides more specific guidelines for environmental interactions with the mining operations and emphasizes the mandatory nature of making an Environmental Impact Assessment (EIA) during the mining license application (Government of Zambia, 1997a). Generally, these cover all aspects of the environment, including dumping practices, emission standards, regulations, and hazardous materials, with major attention given to environmental damage that occurs during the active lifespan of mines. The emphasis of these measures is given to remediation within the operational timeframe. It emphasizes that these measures highlight the commitment to regulations that address environmental impacts during the life of a mine (Government of Zambia, 1997a).

4.5.2 Institutional framework

In Zambia, many institutions are closely related to the mining sector. These institutions, through their activities, ensure that the legislative framework should not be some sort of theoretical framework but offer guidance on the implementation of the legal framework (Aguirre Unceta, 2021; Wambwa et al., 2023). These offer through their regulatory function guidance, oversight, and enforcement mechanisms that further the fulfillment of sustainable and responsible mining

practices. The interplay between legislation and institutional frameworks is paramount in shaping the mining sector's impact on the environment, society, and overall sustainable development in Zambia (Wambwa et al., 2023). These institutional frameworks include:

1. Ministry of Mines and Minerals Development (MMMD)
2. Mines Safety Department (MSD)
3. Cadastre Department
4. The Zambia Environmental Management Agency
5. Misenge Environmental-Technical Services-ZCCM-IH.

The Ministry of Mines and Minerals Development plays a central role, in addressing aspects related to prospecting, exploration, and mineral exploitation. Under the Mines and Minerals Development Act of 2015, the Ministry has the authority to issue mining licenses (Government of Zambia, 2015a). The Minister appoints the Committee of the Environmental Protection Fund and can apply regulations such as S.I. No. 29 of 1997 as deemed appropriate (Government of Zambia, 1997a).

The Mines Safety Department, under the Director of Mines Safety, deals with issues related to the health, safety, and environmental concerns of the public regarding its mining processes. It has worked very closely with ZEMA (formally known as Environmental Council of Zambia (ECZ)) in the past on environmental protection and law regulation and forms an important source of professional human resources in the area of protecting the environment in mining activities (Lindahl, 2014a).

The third institution is the Cadastre Department which takes over the administration of mining rights and licenses. This would work with the licensing committee to clear the way for an easy application process (ICLG, 2023; Lindahl, 2014a). The fourth institution, the ZEMA, was established under the EMA of 2011 and plays a key role in the realization of sustainable management of natural resources, environmental protection, prevention, and control of pollution in the country. It supervises inspections and investigations and enforces environmental standards in several sectors, including mining (Government of Zambia, 2011a). ZEMA does ensure compliance with provisions of the EMA and S.I No. 29 of 1997, ensuring the protection of the environment and at the same time facilitating sustainable exploitation of resources (Government

of Zambia, 1997a, and 2011a). Lastly, Misenge Environmental-Technical Services is a subsidiary of ZCCM Investments Holdings (ZCCM-IH) that is committed to offering full-scale environmentally managed services in the Zambian mining industry to enable the enhancement of environmental sustainability in the industry (ZCCM-IH PLC, 2020).

4.6 Conclusion on statutes applicable to mine closure in Zambia

Despite the ongoing legislative challenges surrounding the environmental aspects of mining in Zambia, the principles of sustainable development have fairly made it into the mining legislation on closure in the country. With the constitution in place, the overriding legal framework has at its core sustainable development and environmental protection. This law has contributed to the framework within which specific mining and environmental laws actively advocate some principles such as the precautionary principle in mine closure, polluter pays principle for financial responsibility, sustainable practices in mine closure, environmental identification of threat, and ranking through administration, cooperative governance, and stakeholders' engagement, considerations of aggregate impacts, lifecycle planning which includes closure at all stages, environmental monitoring, sustainable rehabilitation, and cost-effective closure measures. These principles reaffirm a commitment to responsible and environmentally friendly mining practices in Zambia, notwithstanding legislative challenges. While it goes along fairly well with the principles of global sustainable development, remarkable gaps emerge within the legislation of Zambia. Among these are non-inclusion and explicit consideration of the linked system involving mining, environment, public, and financial implications of the 'Subsidiary Principle.' Transparency and public reporting do not seem to necessarily lay great emphasis, but they form the core base of any legislated framework in ensuring sustainability and responsible mining practices. Notwithstanding such gaps, the Zambian legislation exhibits a strong commitment to the principle of responsible mining practice. These challenges, however, remain in the weaknesses of cooperative governance and the technical capacity of the coop members and management. Thus, the issuance of mine closure certificates is delayed, and these become barriers to the sustainable closure of the mine.

4.6.1 Key element of study: The intersection of sustainable development principle, mine closure, and environmental indicators

This study examined the intersection of sustainable development principles and mine closure, specifically emphasizing the identification of environmental indicators to measure progress in achieving the objective of sustainable closure as shown in Figure 10. The aim was mainly to quantify improvements in sustainable closure practice and align these themes in a comprehensible manner through an extensive review of the relevant literature. The literature review highlights an important gap in the practical assessment and quantification of principles of sustainable development during mine closure, despite the attention given to the formulation policy. It hinders the actual impact assessment of the mining practices on sustainable environmental closure. There is, in fact, no discussion of the measurement of real implementation and the actual environmental impact of these principles, particularly concerning mine closure. The author, therefore, supports active measurement of environmental aspects and impacts across the mining life cycle, with focused aims at the sustainable mine closure that has consistently been a necessity for leaving a lasting positive environmental legacy. It outlined continuous assessment as a guide for mining operations with a set of sustainable closure indicators to positively contribute towards sustainable development.

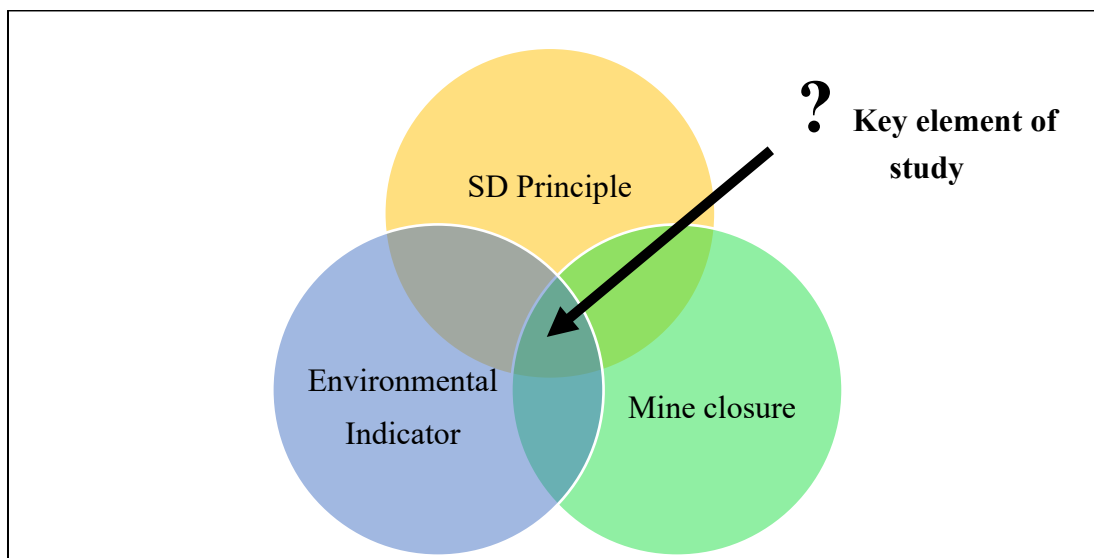


Figure 10. Venn diagram representing the key elements of this study.

4.7 Material and method

This part of the research adopted a non-experimental, in-depth qualitative analysis as a research approach to assess Zambian mine closure legislation against environmental principles and indicators of sustainable development. The following research was hence based on generating a comprehensive and exact understanding of the subject through a case study approach for empirical inquiry into the contemporary phenomenon within its real-life context. This resonated with Stake (1995), who noted that one of the most priceless values of case studies was achieving a comprehensive understanding (Stake, 1995).

The study approach used qualitative methodology, utilizing case studies as the primary technique. This approach was chosen to capture the experiences, views, and opinions of respondents regarding the status of mine closure in Zambia. The study applied three tools: a questionnaire, document analysis of mine closure legislation, and onsite observation of the mining facilities. It was multi-method research, which sought to offer a comprehensive and detailed understanding of the phenomenon. The qualitative exploration of depth within the structured insight from questionnaire responses and direct observation was applied. To accommodate the diverse professional backgrounds of the respondents, the six professional sectors of the participants were organized according to the work experiences that the participants mentioned. This questionnaire, tailored to align with these sectors, adheres to the Tailored Design Method by Dillman et al. (2009).

That means to say, the approach, by its strategic nature, maximizes survey responses by every possible means that can align with the respondents' professional backgrounds in the realization that one is mostly influenced to engaging and giving accurate responses when perceived benefits surpass potential risks (Dillman et al., 2009). The questionnaire's alignment with the specific professional sectors, detailed in Table 3, establishes a foundation of trust between the researcher and respondents.

The design of the questionnaire adherently followed theoretical principles that integrated both open-ended and closed-ended questions (Hansen & Świderska, 2023). The structured questionnaire focused on the different dimensions of mine types, methods, and environment, hence a comprehensive evaluation of mine closure practices in Zambia. The design theory of the questionnaire was navigated to gather insights and experiences from experts in mine closure, aligned with the Labaw framework, and included relevant elements regarding the environment of

the respondent and the understanding and behavior history of the respondents about the subject (Gendall, 1998).

Table 3. Six professional sectors to which the questionnaire was tailored.

Sector	Description
Mining site	Work for a mining company and are involved in mineclosure on the mine site (usually more practical/operational).
Corporate	Work for a mining company and are involved in mineclosure at a divisional or head office level (usually more strategic/management).
Consultancy	Work for a consultancy firm that offers mine closureservices and expertise to mining companies (often on a short-term or project basis).
Governmental	Work for government departments and their remitincludes dealing with mine closure.
Academic	Employed as academics and are involved in oftenlonger-term mine closure research and trials.
Legal	Have a legal background and advise mining companies on legal matters about closure.

The distribution, follow-up, and response procedures were pivotal in shaping the data collection process. Initially, questionnaires were distributed to a targeted group of 300 participants from the 10 districts of the Copperbelt Province, representing a diverse sample. However, despite these efforts, a total of 240 responses were obtained giving the response rate of 80%. Despite a relatively low response rate of 80%, diligent follow-up strategies were implemented, including personalized email cover letters, reminders, and pre-notification about the survey's intent. The tailored questionnaire was categorized based on respondents' professional sectors, ensuring relevance and engagement. The study acknowledged the limitation of the low response rate, attributed to time constraints faced by closure professionals, yet deemed acceptable given the expertise level of the respondents.

The reliability and validity of data were guaranteed through structured questionnaires, participant follow-ups, on-site observations, and document analysis. A mixed-methods approach was employed for data analysis, with quantitative analysis unveiling numerical patterns and

statistical relationships for closed-ended questions, and qualitative analysis exploring the richness of participants' narratives for open-ended questions. This chapter addressed the general concept of research design and methodology before getting down to the results of the study during the respective results sections.

(a)



(b)



(c)



(d)



(e)



(f)



Figure 11. Distribution of questionnaires to mine closure professionals in Zambia ((a) corporate, (b) legal, (c) mine-site, (d) government, (e) consultant and (f) academics).

4.8 Results

In line with the methodology, the administered questionnaire targeted professionals specializing in mine closure in Zambia. The study focused on areas such as the professional experience levels of the practitioners, their working environment, regarding the current state of environmental indicators, and actual aspects of mine closure practices in the mining industry, and recommendations for the best practices. This section sums up very briefly the responses in conceptual categories. The demographic landscape of the study was, therefore, presented quantitatively, giving calculated frequencies and percentages of categorical variables: demographic characteristics of the participants, their academic backgrounds, and mine closure experience.

4.8.1 Demographic characteristics

The demographic breakdown of participants is shown in Table 4. A total of 240 participants were included in the study. The sample was comprised of 188 males (78.3%) and 52 females (21.7%). Most participants (84.2%) reported their age as being between 31 and 50 years of age, and the remaining 15.8% comprised of those below the age of 30 years 10.0%, and above 50 years 5.8 %. In terms of residence, 21.3% of participants were from Kitwe, 17.1% from Chililabombwe, 12.5 % from Luanshya, 11.7 % from Chingola, and the remaining 9.6%, 9.2%, 5.0%, 0.4%, and 0.4 were from Ndola, Mufulira, Lusaka, Choma, and Kasama respectively.

Table 4. Demographic characteristics of participants (N=240).

Characteristic	n	%
Gender		
Male	188	78.3
Female	52	21.7
Age		
25 - 30	24	10.0
31 - 35	54	22.5
36 - 40	62	25.8
41- 45	45	18.8
46 - 50	41	17.1

51 - 55	8	3.3
56 - 60	3	1.3
Residence		
Chililabombwe	41	17.1
Chingola	28	11.7
Choma	1	0.4
Kalulushi	30	12.5
Kasama	1	0.4
Kitwe	51	21.3
Luanshya	31	12.9
Lusaka	12	5.0
Mufulira	22	9.2
Ndola	23	9.6

4.8.2 Academic background

The academic background of participants is included in Table 5. In the sample, 60.4% of participants had a Bachelor's degree, 27.5% had a Master's degree, 10.8% had a PhD, and those with Secondary (S.S.S, Training College, Vocational) comprised 1.3%.

Table 5. Academic Background of Participants (N=240).

Academic qualification	n	%
Secondary (S.S.S, Training College, Vocational)	3	1.3
Bachelor's degree	145	60.4
Master's degree	66	27.5
PhD	26	10.8

4.8.3 Respondents' experience and work environments

The requirement for participants to be eligible for the survey was either working in the Zambian mine industry or receiving a referral from another expert in the field of mine closure.

Consequently, this section aims to provide a concise overview and analyze the extent of mine closure expertise within the surveyed sample group, which primarily consists of professionals experienced in mine closure activities in Zambia.

4.8.3.1 Sectoral analysis

After examining the different stakeholders involved in mine closure (according to the EIA) and considering the input from the questionnaire, a decision was made to classify respondents' mine closure experience into six primary sectors: Academic, Consulting, Corporate, Government, Legal, and On-Site Operations. These sectors were previously defined and elaborated upon in Section 4.7. As an initial representation, Table 6 illustrates the distribution of respondents across these sectors. The sectoral distribution of participants shows that most of the participants worked on a mine site (70.0%), consultants (12.9%), corporate (6.3%), government (4.2%), legal (3.3%) and academic (3.3%).

Table 6. Respondents by sector (N =240).

Sector	n	%
Mine site	168	70.0
Corporate	15	6.3
Consultant	31	12.9
Government	10	4.2
Academic	8	3.3
Legal	8	3.3

4.8.3.2 Academic qualification by sector

To understand the participant's levels of education by sector, the academic background was cross-tabulated with the sector. This also helped in understanding respondents' levels of reasoning, Table 7.

According to Table 7, academicians primarily hold advanced degrees, with 7 out of 8 having a Ph.D. or equivalent qualifications and 1 possessing a master's degree. The corporate sector displays a diverse educational landscape, with 7 out of 15 professionals holding a Ph.D. or equivalent degree, 6 with a master's degree, and 2 with a bachelor's degree, highlighting the significance of advanced education in corporate roles. Government officers exhibit a balanced

distribution across academic qualifications, including a Ph.D. (4 out of 10), a master's degree (4 out of 10), and a bachelor's degree (2 out of 10), reflecting diverse roles that may not uniformly require advanced degrees. Consultants show a prevalence of master's degrees (18 out of 31), bachelor's degrees (8 out of 31), and a Ph.D. (5 out of 31) in this order of majority. In the legal sector, the majority (7 out of 8) hold a bachelor's degree, while one has a master's degree. Mine site workers demonstrate a higher prevalence of a bachelor's degree (128 out of 168), a master's degree (36 out of 168), Ph.D. (3 out of 168), and Secondary (S.S.S, Training College) qualifications (3 out of 168), emphasizing the practical and vocational nature of qualifications in this field.

Table 7. Cross-tabulation of academic background and sector by participants.

Academic	Sector						Total
	Mine site	Corporate	consultant	Government	Academic	Legal	
Secondary (Training College, Vocational)	3	0	0	0	0	0	3
Bachelor's degree	126	2	8	2	0	7	145
Master's degree	36	6	18	4	1	1	66
Ph.D.	3	7	5	4	7	0	26
Total	168	15	31	10	8	8	240

4.8.3.3 Mine closure experience by respondents

The respondents were asked whether they participated in mine closure before or not. As shown in Figure 12, out of 240 participants, 181 (75.4%) had experienced the mine closure and 59 (24.6%) did not have the mine closure experience. All 59 (24.6%) respondents who did not experience mine closure were from the mine site sector.

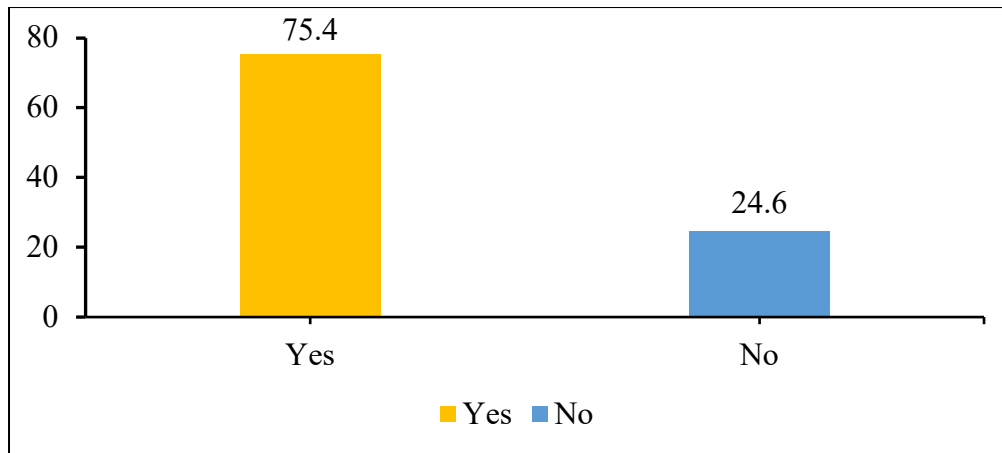


Figure 12. Participation in the mine closure by respondents (Percentage).

In terms of the sectoral distribution among those who have experienced mine closure, Table 8 shows that the majority of respondents who have mine closure experience are from the mine site sector 109 (60.2%), consultants to mine site closure 31 (17.1%), corporate 15 (8.3%), government 10 (5.5%) and legal sectors 8 (4.4%) as well as academic 8 (4.4%).

Table 8. Respondents who have the mine closure experience by sector (N =181).

Sector	n	%
Mine site	109	60.2%
Corporate	15	8.3%
Consultant	31	17.1%
Government	10	5.5%
Academic	8	4.4%
Legal	8	4.4%

4.8.3.4 Mineral type analysis

Respondents were further asked to list the minerals in which their mine closure experience lied. Figure 13 represents the percentage of participants who indicated that they had closure experience in each specific mineral. If a respondent had experience in more than one mineral, each individual mineral was counted as an instance of closure experience in that mineral.

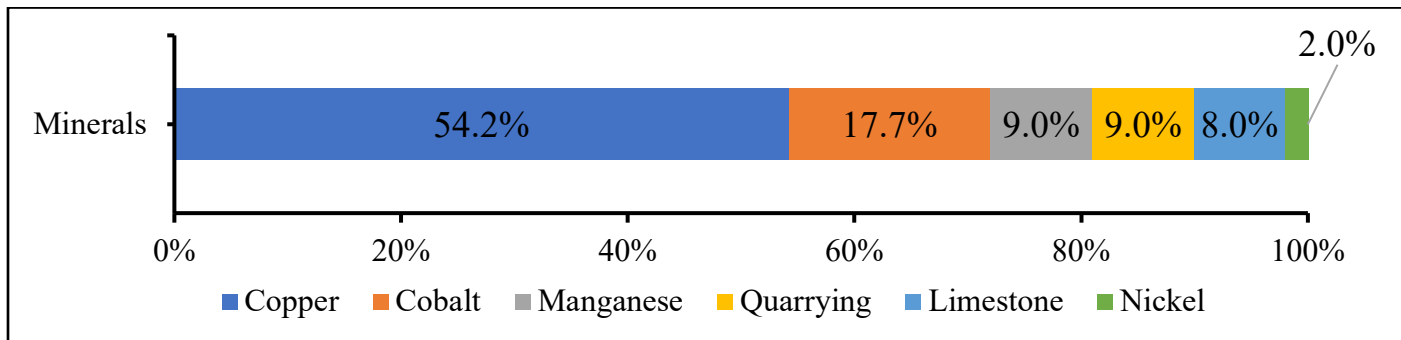


Figure 13. Respondents' closure experience by mineral (Percentage).

According to Figure 13, copper constitutes the majority (54%) of respondents' mine closure experience, followed by cobalt (18%), manganese (9%), and quarrying (9%), covering a total of 90% of respondents' experiences. Other minerals make up the remaining 10%.

Table 9. Closure experience by sector in various mineral types (Multiple response) (N=181).

Academic		Sector						Total
		Mine site	Corporate	consultant	Government	Academic	Legal	
Copper	count	99	13	26	9	8	8	163
	%	60.7%	8.0%	16.0%	5.5%	4.9%	4.9%	
Cobalt	count	22	4	17	7	1	3	54
	%	40.7%	7.4%	31.5%	13.0%	1.9%	5.6%	
Nickel	count	2	0	4	0		0	6
	%	33.3%	0.0%	66.7%	0.0%	0.0%	0.0%	
Manganese	count	6	0	15	6	0	0	27
	%	22.2%	0.0%	55.6%	22.2%	0.0%	0.0%	
Quarrying	count	15	2	4	4	0	3	28
	%	32.1%	7.1%	35.7%	14.3%	0.0%	10.7%	
Limestone	count	11	2	4	4	0	3	24
	%	45.8%	8.3%	16.7%	16.7%	0.0%	12.5%	
Total per sector		109	15	31	10	8	8	181

Further examination of this data by sector reveals that the mine site sector holds the highest percentage of closure experiences in copper (60.7%), cobalt (40.7%), nickel (33.3%), manganese (22.2%), quarrying (32.1%), and limestone (45.8%). The consultant sector also features prominently in various minerals, including copper (16.0%), cobalt (31.5%), nickel (66.7%), manganese (55.6%), quarrying (35.7%), and limestone (16.7%). The corporate, government, academic, and legal sectors also demonstrate varying degrees of involvement in mine closure across different minerals, providing a comprehensive overview of the distribution of closure experiences among specialists in Zambia Table 9.

4.8.3.5 Mine closure cycle experience

In addition to asking about the professional sectors in which the respondents worked and the minerals in which their closure experience lied, the respondents were also questioned about the "stages or phases of" mine closure in which they had taken part. The purpose of this inquiry was to ascertain the depth and scope of experience of mine closure specialists in Zambia. The answers to this open-ended question (asked as such, to gather and populate a mine closing activity list) are summarized in Table 10. Similar to the closure experience in minerals, each occurrence of a respondent's experience in various stages or projects was counted separately. As an aid to categorizing the data, responses were divided into the major stages of the mining cycle, namely: planning, operational, and closure, as well as those independent of stage. Responses which indicated blanket experience in 'all phases' of closure were documented separately. In reviewing the data, common projects and activities were identified and differentiated as per Table 10.

Table 10. The breadth of mine closure experience by Respondents.

EXPERIENCE	Number of Instances of Occurrence						
	Academic	Consultancy	Corporate	Government	Legal	Mine site	TOTAL
All phases: Planning, operational, closure, costing & monitoring	1	4	1	1	1	2	10
PLANNING STAGE							
Baseline assessments	0	4	2	1	0	0	7
Feasibility & conceptual closure planning & design	1	3	1	1	0	1	7
Mine closure framework & planning	1	3	1	1	2	0	8
Emergency response planning	2	3	2	2	2	2	13
OPERATIONAL STAGE							
Operational rehabilitation and performance assessment	2	2	1	1	1	3	10
Operational closure performance assessment	2	2	1	1	1	3	10
Closure studies, trials & assessment of post-closure land-use options	2	1	0	1	1	2	7
Progressive rehabilitation planning & design & implementation	2	2	1	1	0	5	11
CLOSURE PHASE							
Closure implementation & rehabilitation management	2	3	3	3	1	1	13
Post-mining monitoring & performance assessment	1	1	0	3	1	1	7
Application for closure & government consultation	2	2	0	5	0	0	9
Water treatment/reclamation	2	3	0	4	1	1	11
INDEPENDENT OF STAGE							
Drafting, updating & auditing detailed closure plans & programs	2				0	2	4
Closure liability assessment & costing	2	2	1	1	0		6
Water prediction/balances, monitoring & management	0	2	2	1	2	5	12
Mine closure regulation	0	2	0	0	1	2	5
Legal matters	0	0	0	0	7	0	7
Setting closure standards	2	1	1	1	1	4	10
Closure risk assessments	2	1	2	1	0	1	7
Community engagement & planning for closure	0	2	1	1	0	3	7
Totals	28	43	20	30	22	38	181

Table 10 provides a comprehensive overview of the extensive knowledge possessed by consultants across various dimensions of mine closure. Notably, 4 consultants have engaged in mine closure across all phases, indicating a thorough involvement in the entire process, with occurrences in planning, operational, closure, and independent phases being 13, 9, 9, and 13, respectively. The corporate sector exhibits a well-distributed involvement, with the highest count during the independent phase (7 occurrences), followed by the planning, and closure phases, each registering 6 and 3 occurrences. In contrast, the mine site sector shows limited participation, with only 2 participants experiencing mine closure across all phases. The government sector is notably engaged during the closure phase, with 15 instances, and also has a noticeable presence in the planning phase (5 occurrences). The legal sector's involvement is relatively low, concentrated in the independent and planning phases with 11 and 4 occurrences, respectively. Similarly, the academic sector follows a parallel trend, with 4 occurrences in both planning and independent phases.

4.8.4 Status quo of mining environmental indicators in Zambia

Due to the way the Ministry of Mines and Mineral Development (MMMD) manages mining licenses, the monitoring and measurement of certain environmental indicators is required by law. An Environmental Management Plan (EMP) and an Environmental Impact Assessment (EIA) are required for all licenses (Government of Zambia, 1997a, 2015a). To determine the status quo for operational environmental monitoring in Zambia at the moment, respondents were questioned about the operational environmental indicators that are measured at mining projects that they have worked on, both operational and baseline, and which indicators they felt were most deficient.

4.8.4.1 Baseline environmental indicators

An abundance of baseline environmental indicators, particularly for new operations, were produced as a consequence of the EIA process, according to most respondents. Nonetheless, most professional sectors made a key observation stating that the EMPs that resulted from baseline studies were typically poorly executed, leading to insufficient baseline indicators. Consequently, the absence of a trustworthy baseline for comparison and goal-setting makes closure studies more difficult to conduct in the future. Table 11 presents a compiled set of baseline indicators submitted by the participants.

Table 12 offers a comprehensive overview of the distribution of baseline indicators monitored in Zambia, as reported by survey respondents. Surface and subsurface water quality emerges prominently as the dominant baseline indicator, with a substantial majority of participants

(95.0%) consistently acknowledging its significance. This includes parameters such as pH, turbidity and dissolved oxygen.

Table 11. Baseline indicators submitted by respondents.

Water
Water quantity and quality: ground (depth, yields, flow directions, quality) and surface (volumes, quality, drainage patterns)
Geohydrology
Biodiversity
Biodiversity: fauna and flora
Ecological functioning
Protected species (red data species)
Air
Air quality (SOx, NOx, respirable pollutants and fallout dust)
Climatic data (rainfall, temperature, evaporation, wind speeds and direction)
Geology & Soils
Soils (types, depth, structure, quantity, and distribution)
Geology (formations, depth, distribution)
Soil capacity
Vibration
Topography
Land use
Land use
Land capability (potential yield, water retention and infiltration rates, organic composition)
Nature conservation areas / Sensitive landscapes
Agricultural and/or forestry potential
Industrial development potential
Population and planned/unplanned residential densification
Waste
Waste management
Social
Social (demographics, number of households, types of employment)
Heritage sites (archaeological & culturally important/sensitive areas)
Visual/Aesthetic

Biodiversity follows as the second most recognized indicator, with 65.8% of respondents highlighting its importance. For this indicator, parameters such as populations of key species (both fauna and flora), any endangered species in the area and the presence of alien species are monitored. Air quality (PM10 and PM2.5, CO₂, SOx) is also acknowledged by 56.7% of participants, while

land use (settlement, agricultural land, industrial area and forestry) and social (parameters such as demographics, number of households and types of employment) quality follow with 23% and 11%, respectively. Notably, a minimum of 16 respondents identified each environmental indicator, emphasizing their collective recognition and significance within the sampled population. Additionally, soil & geology (parameters such as pH, organic matter content, and presence of contaminants, topography and soil capacity) and waste (domestic) indicators constitute 9.2% and 2.1%, respectively, emphasizing varying degrees of attention and importance attributed to these specific aspects in the environmental monitoring framework.

Table 12. Baseline (pre-mining) environmental indicator that exists according to participants (N=240).

Indicator	n	%
Water quality	228	95.0%
biodiversity	158	65.8%
Air quality	136	56.7%
LULC	54	22.5%
social	27	11.3%
Soil & Geology	22	9.2%
Waste	5	2.1%

4.8.4.2 Current operational environmental indicators

In Zambia, the MMMD is responsible for overseeing mining licenses, and these licenses necessitate the measurement and monitoring of specific environmental indicators. The Environmental Management Program (EMPR) and EIA are obligatory components of this licensing process. As discussed in Section 4.5.1, if the baseline EIAs guiding the permitting process are inadequate, operational mines may possess weak environmental indicators to effectively guide closure planning. This issue persists unless financing organizations and corporate standards, typically applicable to larger, well-funded mining corporations, impose more rigorous environmental monitoring beyond the baseline assessments required for EMPR development. This highlights the importance of comprehensive planning for mine closure at every stage of the mine life cycle, particularly during planning and feasibility stages. Rigorous planning during the operational phase, including focused environmental monitoring, becomes crucial for informed decision-making and actions leading to a well-executed closure. Respondents were questioned

about indicators used in mining projects, their closure, and identified deficiencies, providing insights into the current state of operational environmental monitoring in Zambia.

4.8.4.2.1 Specific operational indicators

Table 13 outlines respondents' specific environmental indicators monitored during the operational phase of mining. Water quality (surface and subsurface) emerged as the most frequently monitored variable, with a significant 92.1% (221 individuals) attesting to its recurrent monitoring. Parameters such as pH, turbidity, dissolved oxygen, and the volume and quality of water discharge are closely monitored. Air quality also featured prominently, with 70.0% of respondents (168 individuals) indicating its frequent monitoring of PM10 and PM2.5, CO₂, SO_x and other dust particles produced during mining activities. Basic biodiversity monitoring including species (both fauna and flora), endangered species and the presence of alien species, was reported by 50.0% of respondents (120 individuals). Meanwhile LULC monitoring, which includes parameters such as settlement, agricultural land, industrial area and forestry was reported monitored by 15.0% (36 respondents). Soil and geology quality (parameters such as soil pH, organic matter content, presence of contaminants, topography and vibration) were reported monitored by 35.4% (85 respondents), respectively. Additionally, waste generation such as domestic, tailings, waste rock and hazardous waste, a crucial environmental impact assessment indicator, was reported by 25.4% of respondents (61 individuals). Social sustainability indicators with parameters such as parameters such as demographics, number of households, types of employment and community complaints, reflecting broader socio-environmental dimensions, were reported monitored by 5.4% of respondents (13 individuals), showcasing the comprehensive range of indicators considered during the operational phase.

Table 13. Specific operational environmental indicators monitored by the mine reported by respondents (N=240).

Indicator	n	%
Water quality	221	92.1
Air quality	168	70.0
biodiversity	120	50.0
Soil & Geology	85	35.4
Waste	61	25.4
LULC	36	15.0
Social	13	5.4

4.8.4.2.2 Environmental indicators beyond the mine site boundary

In Zambia, mine operators are mandated to monitor environmental indicators beyond their designated mining lease area due to the far-reaching environmental impacts. The study investigated whether such monitoring is conducted and which indicators are regularly examined. The findings, presented in Table 14, highlight water quality with basic water parameters such as pH, turbidity, dissolved oxygen as the predominant environmental indicator. A significant 84.2% of respondents (202 individuals) confirmed its recurrent monitoring.

Air quality (PM10 and PM2.5, CO₂ and other dust particles) follows as the second most frequently monitored indicator beyond mine boundaries, reported by 55.0% of respondents (132 individuals). Additionally, the scope of environmental monitoring extends to soil and geology (with parameters such as soil pH and vibration), waste generation (water effluent), and LULC (settlement, agricultural land, industrial area and forestry). Notably, 16.3% of participants (39 individuals) emphasized monitoring soil and geology, while 3.3% (8 individuals) and 2.1% (5 individuals) reported monitoring waste generation and LULC indicators, respectively.

Table 14. Environmental indicators monitored by the mines beyond the mine site boundary reported by the respondents (N=240).

Indicator	n	%
Water quality	202	84.2%
Air quality	132	55.0%
biodiversity	94	39.2%
Soil & Geology	39	16.3%
LULC	5	2.1%
Waste	8	3.3%
Social	0	0.0%

4.8.4.2.3 Do environmental indicators relate to final land use? (M, C, CO, G)

The study investigated participants' perspectives on whether environmental indicators connect to the intended final land use, aiming to ascertain if the "loop is closed" or if the indicators aid in the decision-making process. Figure 14 shows the results, revealing that the majority of government and consultant participants did not perceive an explicit relationship between environmental indicators and final land use.

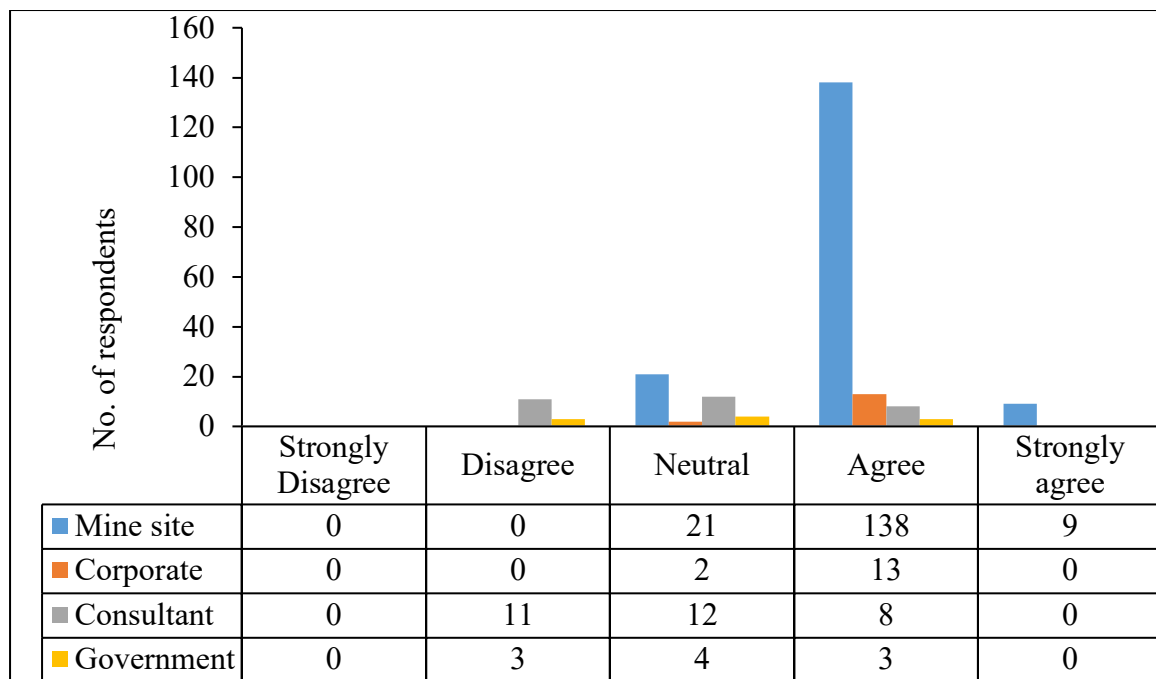


Figure 14. Relationship between the monitored environmental indicators and final land use by respondents (M, C, CO, G) (N=224).

Specifically, 3 government respondents and 11 consultants disagreed, while 4 government respondents and 12 consultants remained neutral on the matter. In contrast, corporate and mine site respondents asserted a connection between environmental indicators and final land use, emphasizing their role in mine closure management as part of a broader risk management process.

Notably, 13 corporate respondents and 138 mine site respondents supported with this perspective, while only 2 corporate respondents and 21 mine site respondents maintained a neutral stance on the interrelation between environmental indicators and ultimate land use.

4.8.4.3 Ideal environmental indicators

Upon evaluating the current state of baseline and operational environmental indicators in Zambia, participants were asked to specify the ideal environmental indicators deemed essential for fostering sustainable mine closure. Table 15 summarizes a thorough analysis of participant preferences, highlighting that a majority, totaling 90.4% of the respondents (217 participants), regarded water quality (water quality: parameters such as pH, turbidity, dissolved oxygen, and presence of contaminants (e.g., heavy metals, sulfates)) and water discharge: volume and quality of water discharged from the site, including treatment effectiveness) as the most ideal environmental indicator. Following this, air quality (dust emissions: levels of particulate matter (PM10 and PM2.5) generated by mining activities and gas emissions: concentrations of greenhouse gases (e.g., CO₂, methane) and other pollutants (e.g., sulfur dioxide, nitrogen oxides)) emerged as the second most

favored indicator, with 51.7% of respondents (124 individuals) emphasizing its importance. LULC secured recognition from 27% of participants (65 respondents) (indicating parameters such as settlement patterns, agricultural land, industrial areas and forestry), placing it in the third position among the selected indicators. Biodiversity (habitat disturbance (area of natural habitats affected by mining activities) and species monitoring (populations of key species and any endangered species in the area)) and soil and geology (land disturbance (area of land disturbed by mining operations) and Soil Quality (Parameters such as pH, organic matter content, and presence of contaminants) were also acknowledged, with 25.4% (61 respondents) and 20.4% (49 respondents) respectively, signifying their order of prominence in the participants' ideal environmental indicators for sustainable mine closure.

Table 15. Ideal environmental indicators by respondents (N=240).

Indicator	n	%
Water quality	217	90.4%
Air quality	124	51.7%
LULC	65	27.1%
biodiversity	61	25.4%
Soil & Geology	49	20.4%
Social	8	3.3%
Waste	1	0.4%

4.8.5 Mine closure and closure planning

Mine closure and planning hold significant roles in the mining industry, emphasizing the crucial necessity for responsible and sustainable resource extraction practices. This is imperative due to the environmental and social implications inherent in mining activities, demanding thoughtful consideration. The proactive and strategic nature of mine closure becomes essential in mitigating potential adverse impacts, ensuring the rehabilitation of mining sites, minimizing environmental damages, and safeguarding the well-being of local communities. Closure planning emerges as a vital component of the mining life cycle, promoting long-term environmental stewardship, social responsibility, and economic resilience. Recognizing the importance of effective mine closure and planning is paramount for fostering a sustainable and ethical mining industry that aligns with global standards and positively contributes to Zambia's overall development. Consequently, respondents were asked about the existence of mine closure plans, closure reporting (mine site and corporate only), and essential environmental research needed to best support sustainable mine closure in Zambia.

4.8.5.1 The presence of mine closure plans and closure reporting

Given the strong emphasis on robust and comprehensive planning for mine closure in existing literature, a sentiment supported by the participants in this study, respondents (Mine site and corporate) were asked about the existence of mine closure plans in Zambia and their effective implementation and reporting. The opinions on this matter were divided, as outlined in Figure 15. A majority of respondents, specifically 135 from mine sites, indicated agreement, with 130 agreeing and an additional 5 strongly agreeing to the notion.

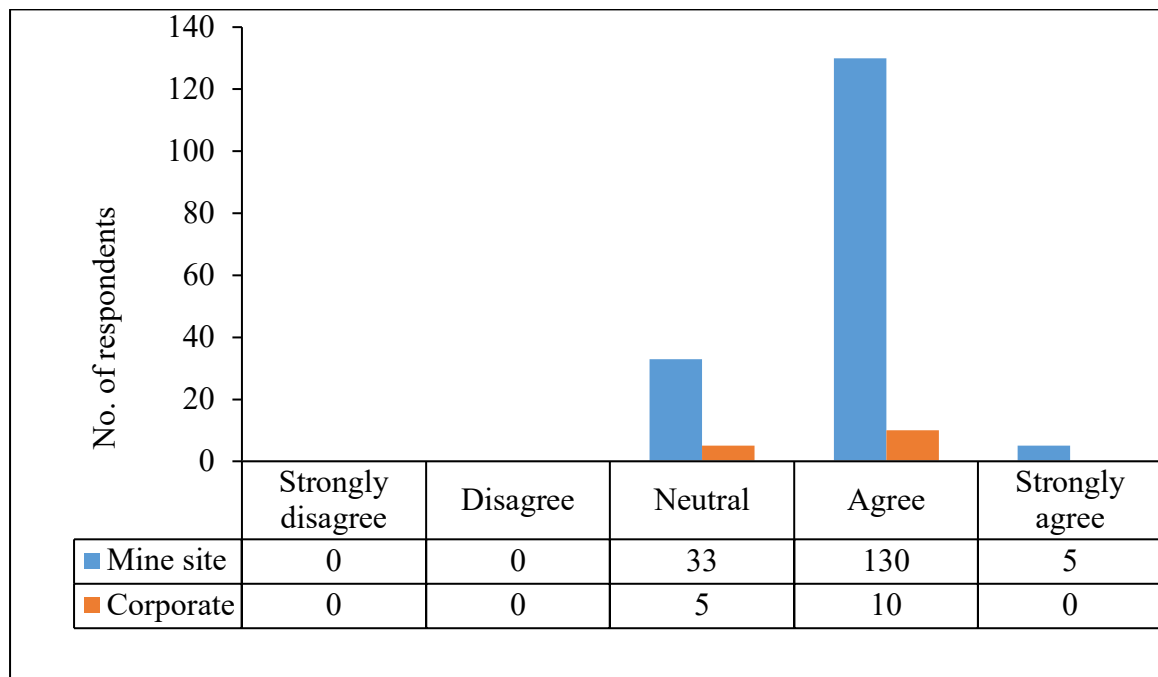


Figure 15. The presence of mine closure plans and closure reporting according to mine site and corporate respondents (N=183).

In addition, 10 respondents from the corporate sector concurred with the effectiveness of mines' comprehensive closure planning, implementation, and reporting. Conversely, some respondents, including 33 from mine sites and 5 from the corporate sector, assumed a neutral stance on the matter. The division of perspectives highlights the complexity and varied perceptions regarding the actual effectiveness of mine closure plans in Zambia (Figure 15).

4.8.5.2 Essential investigations for mine closure

In addition to asking respondents about the existence of mine closure plans and closure reporting, a multiple-response question was posed to gather insights into the essential environmental research necessary for optimal support of sustainable mine closure in Zambia, as detailed in Section 4.7.5.3. The findings, as presented in Table 16, highlight an agreed emphasis on comprehensive

examinations of both surface and groundwater, with 200 respondents (83.3%) asserting the importance of water investigations for sustainable mine closure. This includes water quality (parameters such as pH, turbidity, dissolved oxygen) and presence of contaminants (e.g., heavy metals, sulfates) and water discharge (volume and quality of water discharged from the site, including treatment effectiveness). Similarly, 172 respondents (71.7%) indicated the significance of soil and geology investigations within the broader context of soil capability studies (land disturbance (area of land disturbed by mining operations), soil quality (Parameters such as pH, organic matter content, and presence of contaminants), geology, topography and vibration). Biodiversity investigations were deemed essential by 170 respondents (70.8%) (emphasizing the sustainability of re-vegetation on rehabilitated land and the importance of biodiversity assessments, including the control of invasive alien species). Although social studies were not the primary focus, 160 respondents (66.7%) stressed the importance of aligning community engagement with environmental closure investigations to guide the final determination of land use (LULC), which had 65 respondents representing 27.1%. Other crucial investigations identified include air (dust emissions: levels of particulate matter (PM10 and PM2.5) generated by mining activities and gas emissions: concentrations of greenhouse gases (e.g., CO₂ and methane) and other pollutants (e.g., sulfur dioxide, nitrogen oxides)) and waste, with 120 respondents (50.0%) and 50 respondents (20.8%) respectively, affirming their imperative role in sustainable mine closure, Table 16.

Table 16. Essential environmental investigation needed to best support sustainable mine closure in Zambia by respondents (N=240) (multiple responses).

Indicator	n	%
Water quality	200	83.3%
Soil & Geology	172	71.7%
biodiversity	170	70.8%
social	160	66.7%
Air quality	120	50.0%
LULC	65	27.1%
Waste	50	20.8%

4.8.5.3 Is there a successful mine closure in Zambia?

Participants were also questioned about their awareness of successful mine closures in Zambia, defined by the mitigation of residual risks, the establishment of sustainable land use, and

the issuance of a closure certificate by the state. The predominant response suggested that, according to participants, no mines in Zambia had achieved full legal closure. The responses varied, showcasing diverse opinions on the perceived success of mine closure efforts in the country. Notably, a considerable number of respondents, including 10 from mine sites, 1 from the corporate sector, and 2 from the academic sector, strongly disagreed with the notion. Furthermore, 99 mine site respondents, 10 corporate respondents, and 4 academic respondents expressed disagreement, while an additional 59 mine site respondents, 4 corporate respondents, and 2 academic respondents adopted a neutral stance. Figure 16 illustrates a notable alignment among 2 legal respondents, 8 government respondents, and 20 consultants, all maintaining a neutral position. In contrast, a minimal divergence is observed, with 6 legal respondents, 2 government respondents, and 11 consultants disagreeing with the idea of successful mine closure in Zambia. These varied responses highlight the complex spectrum of viewpoints among different stakeholder groups, emphasizing the intricacy involved in evaluating the success of mine closure efforts in the Zambian context.

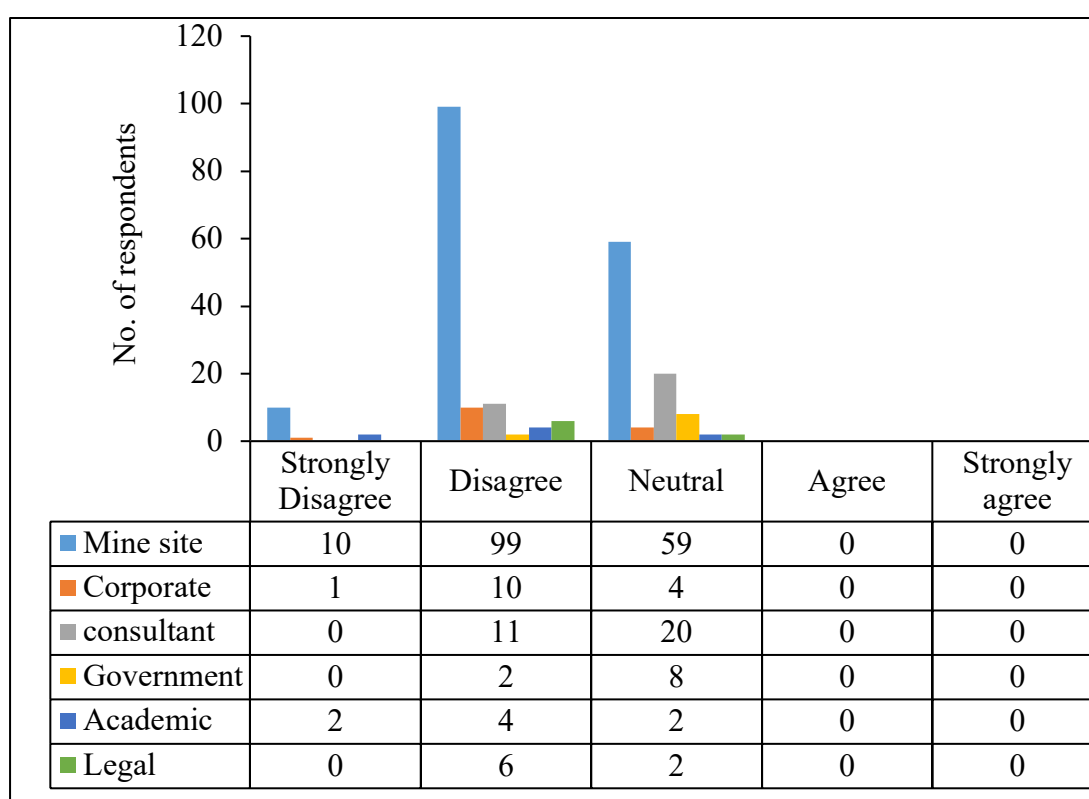


Figure 16. Presence of successful mine closure in Zambia by respondents ((N=240).

4.8.6 Awareness and opinions of Zambian mine closure legislation

The closure of mines is a mandated legal requirement in Zambia, as outlined in the Mine and Mineral (Environmental) Regulation (MMR) 1997 regulations (Section 4.5 and Chapter 6 for details). To comprehensively evaluate the alignment between policy (legislation) and practical

implementation, it was crucial to investigate the participants' awareness of Zambian mine closure regulations. This investigation sought not only to gauge their awareness but also to gather expert opinions on these regulations. The participants' demonstrated knowledge of the related legal framework for mine closure serves as a significant factor in substantiating their expertise within the field. Section 4.8.6 examines the findings related to the participants' awareness of Zambian mine closure legislation, presenting a detailed examination of their responses to a checklist format of the four primary sections of legislation governing mine closure. Respondents were requested to mark the specific pieces of legislation with which they were familiar, which are as follows:

1. Environmental Management Act, 2011,
2. Mines and Minerals Development Act, 2015,
3. Mines and Minerals (Environmental) Regulations, 1997.
4. The Mines and Minerals (Environmental Protection Fund) Regulations, 1998.

However, to successfully uphold the principles of sustainability embedded in the Zambian mine closure legislation, it's crucial to promote substantial knowledge of and alignment with this legislation within the professional field.

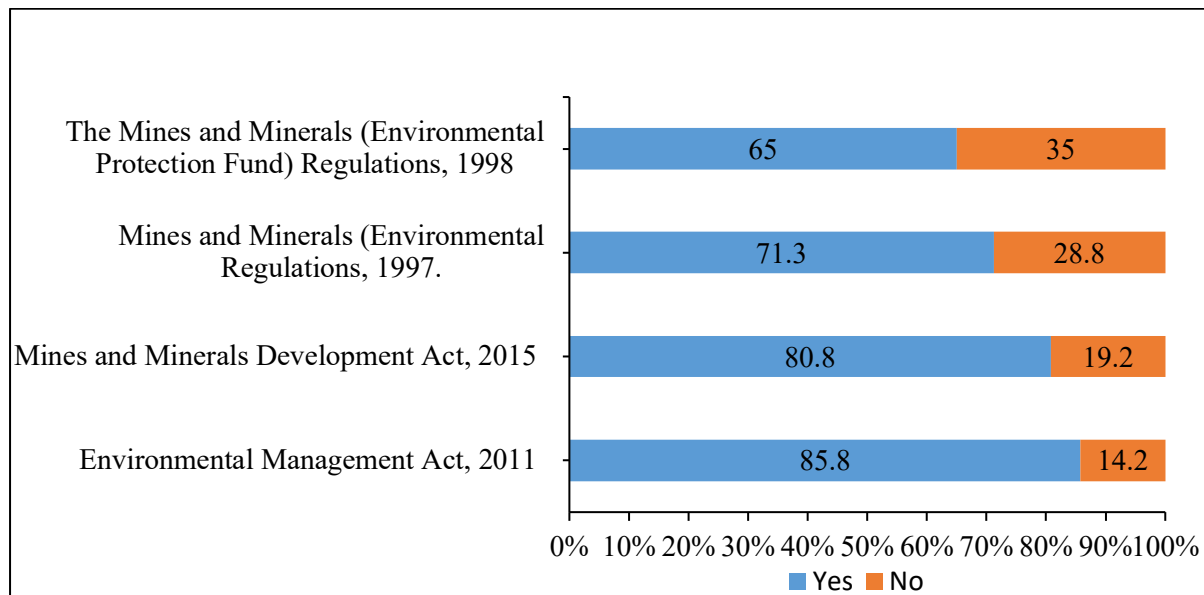


Figure 17. Respondents' awareness of the four extracts of closure legislation (percentage) (N=240) (Multiple responses).

Particularly, there were variations in the overall familiarity with each section of the four main pieces of closure legislation, as indicated in Figure 17.

As illustrated in Figure 17, a significant 85.8% of respondents affirmed their familiarity with the Environmental Management Act, 2011. Following closely, the Mines and Minerals Development Act, 2015 garnered recognition from 80.8% of respondents. However, there was a decline in awareness levels for the Mines and Minerals (Environmental) Regulations, 1997, with 71.3% of respondents claiming acquaintance, and a further decrease to 65% for the Mines and Minerals (Environmental Protection Fund) Regulations, 1998. These findings indicate varying degrees of awareness among professionals regarding specific mine closure legislations, suggesting potential areas for targeted education and awareness campaigns to enhance comprehension and adherence within the industry.

4.8.6.1 Mine closure legislation familiarization by the professional sector

This part of the research showed disparities in familiarity with the mentioned legislation across professional sectors. According to Table 17, academics exhibited the lowest acquaintance with mine closure legislation, with 38% (3), 50% (4), 63% (5), and 75% (6) of academic participants familiar with the Mines and Minerals (Environmental Protection Fund) Regulations, 1998, Mines and Minerals (Environmental) Regulations, 1997, the Environmental Management Act, 2011 and the Mines and Minerals Development Act, 2015 respectively. Mine site participants also demonstrated less familiarity, with 57% (95), 63% (105), 75% (126), and 82% (138) indicating awareness of the Mines and Minerals (Environmental Protection Fund) Regulations, 1998, the Mines and Minerals (Environmental) Regulations, 1997, the Mines and Minerals Development Act, 2015 and the Environmental Management Act, 2011 respectively. In contrast, government employees involved in mine closure exhibited strong knowledge, with 70% (7), 70% (7), 80% (8), and 90% (9) indicating familiarity with the Mines and Minerals (Environmental Protection Fund) Regulations, 1998, Mines and Minerals (Environmental) Regulations, 1997, the Environmental Management Act, 2011 and the Mines and Minerals Development Act, 2015 respectively.

Corporate respondents, while generally well-informed, displayed more knowledge gaps compared to the legal and governmental sectors, with 87% (13), 93% (14), 100% (15), and 100% (15) familiar with the Mines and Minerals (Environmental) Regulations, 1997, the Mines and Minerals Development Act, 2015, the Environmental Management Act, 2011 and the Minerals (Environmental Protection Fund) Regulations, 1998 respectively. Consultants showed a similar trend to corporates as shown in Table 17. Legal professionals demonstrated the most comprehensive understanding, with all legal respondents aware of all four mine closure legislations, aligning with their role and expertise.

Table 17. Mine closure legislation familiarization by professional sector (N=240).

	MMD, 2015	EMA, 2011	MMR (Environ.), 1997	MMR (EPF), 1998	TOTAL
Mine site	75% (126)	82% (138)	63% (105)	57% (95)	168
Corporate	93% (14)	100% (15)	87% (13)	100% (15)	15
Consultancy	94% (29)	100% (31)	81% (24)	81% (25)	31
Government	90% (9)	80% (8)	70% (7)	70% (7)	10
Academic	75% (6)	63% (5)	50% (4)	38% (3)	8
Legal	100% (8)	100% (8)	100% (8)	100% (8)	8

4.9 Discussion

The administered questionnaire in this study sought to capture the insights of mine closure professionals with regard to the various facets of mine closure in Zambia, including the professional experience, work environment, the current state of environmental indicators, and closure practices with recommendations for best practice. Qualitative analysis was employed due to the open-ended nature of survey questions, with quantitative details incorporated where applicable. This collated information on the state of mine closure in Zambia was then critically examined and discussed in relation to existing literature and legislative frameworks, as discussed in Chapter 2 and beginning of chapter 4, providing a comprehensive understanding of the current scenario and aligning it with established knowledge in the field.

The demographic characteristics of the study participants, as outlined in Table 4, provide valuable insights into the composition of the sample. With a total of 240 participants, the majority were male, constituting 78.3%, while females made up the remaining 21.7%. This shows that the mining sector is still a male dominated sector (IGF & IISD, 2023).

Turning to the academic background, Table 5 reveals the educational qualifications of the participants. The majority (60.4%) held Bachelor's degrees, emphasizing a solid foundational education. A significant portion (27.5%) had attained Master's degrees, indicating a higher level of specialization, while 10.8% had achieved PhD status, signifying a notable presence of highly educated individuals in the sample. Those with secondary education (S.S.S, Training College, and

Vocational) comprised a smaller proportion at 1.3%. These demographic and academic characteristics contribute to the diversity and representativeness of the sample, enriching the study with a broad spectrum of perspectives and expertise

4.9.1 Respondents' experience and work environments

The examination of respondents' experience and work environments in mine closure activities reveals critical insights into the expertise within the surveyed sample. As illustrated in Table 6, the majority of participants, totaling 82.9%, were engaged either directly on mine sites or as consultants contributing to mine site closure (70% on mine sites and 12.9% as consultants). This data suggests a clear allocation of funds dedicated to mine closure efforts, incorporating both internal initiatives and external contracts (Gankhuyag & Gregoire, 2018). When incorporating respondents from the corporate (6.3%) and legal (3.3%) sectors, the cumulative figure reveals that 92.4% of professionals involved in mine closure operate within the private sector. This distribution implies a deficiency in mine closure expertise and capability within the government and research domains. This observation aligns with the insights shared by respondents, highlighting the obstacles posed by legislative and bureaucratic hurdles in achieving legitimate mine closure in Zambia (MMSD, 2002).

The sectoral breakdown of academic qualifications emphasizes the prevalence of advanced degrees among academicians, corporate professionals, and consultants, while the mine site sector predominantly holds bachelor's degrees as shown in Table 7. This emphasizes the significance of advanced education, particularly in academia and the corporate sector. Regarding mine closure experience, 75.4% of participants have practical exposure to mine closure (with mine site workers constituting all respondents (24.6%) without closure experience), with the mine site sector leading in experienced respondents (60.2%), followed by consultants (17.1%), corporate (8.3%), government (5.5%), legal (4.4%), and academic (4.4%) (Figure 12, Table 8).

In term of the minerals associated with closure experience, Figure 13 indicates that, copper (54%) and cobalt (18%) make up for over half of the respondents' mine closure experience. With the addition of manganese (9%), quarrying (9%), and nickel (2%), 92% of the respondents' experience was covered. This is in line with the minerals reviewed in the literature (see Section 2.2.3). Limestone constituted the remaining 8%. From this it is clear that Zambia's major economic minerals command 92% of the focus of mine closure specialists (Kolala & Dokowe, 2021; World Bank, 2015).

What is particularly interesting, is that in the further breakdown of this data by sector, respondents who were involved in mine closure on-site or at a corporate level (a combined 68.70%,

48.10%, 33.30%, 22.20%, 39.20% and 54.10% of all respondents who participated in each mineral), had only ever been involved in the limited list of copper, cobalt, nickel, manganese, quarrying and limestone operations respectively, Table 9. This can be compared to the range of minerals that consultants (16.0%, 31.5%, 66.7%, 55.6%, 35.7%, and 16.7% of all respondents) had experience in, which included all major minerals listed in Table 9. From this it is evident that larger mining houses (which mine the major economic minerals) employ mine closure expertise in-house; while minerals of lesser economic importance, likely comprising smaller operations, employ consultants to assess and manage their mine closure aspects (Cole, 2024). This again speaks to a challenge which numerous participants cited as having experienced, in that junior miners are less capable of effectively planning for and implementing successful mine closure due to a lack of capacity and commitment. Due to consultants, by their nature, being employed on a more contractual basis, the long-term management of mine closure cannot be addressed with the same consistency (and thus efficacy) as an in-house professional may be capable of (Starke, 2002a).

Of the few participants who work for the government (5.5%, 13.0%, 22.2%, 14.3%, and 16.7% of all respondents who participated in each mineral), their mine closure experience was only indicated in copper, cobalt, manganese, quarrying and limestones operations respectively (Table 9). This is concerning considering that the government is required to address all types of mine closures from a legislative and compliance standpoint (APEC Mining Task Force, 2016). Further to this, academic research involvement in mine closure was only shown to extend to copper and cobalt. Both these factors and numerous respondents' comments, point toward the lack of institutional capacity in mine closure compliance monitoring and enforcement as well as the support of long-term studies on mine closure impacts and remediation (Mpanza et al., 2021). Legal respondents commented that Zambian mine closure legislation is not differentiated by mineral, however, it was again evident that their experience was limited to copper, cobalt, quarrying, and limestone, abided to only the previously mentioned major economic minerals Table 9. That is to say, lesser economic minerals and smaller mining houses are unlikely to have an in-house legal expert on mine closure; this again speaks to the lack of small and junior miners' capacity to properly address the complex issue of sustainable mine closure which is likely to result in less comprehensive and sustainable mine closure (OECD, 2002).

A comprehensive analysis of the mine closure cycle experience sheds light on the participants' engagement across various phases. While Table 10 reflects the expected involvement in closure planning, auditing, costing, and rehabilitation, a notable aspect is the significant attention given to water treatment and/or reclamation. This highlights the growing emphasis on water management technologies as a crucial solution for addressing long-term water challenges associated

with mine closure. The significant number of responses related to water management highlights its importance in mitigating the impacts of mining activities, especially in water-scarce regions such as Zambia, as corroborated by previous studies (Muller et al., 2009).

The analysis of Table 10 clearly demonstrates that consultants possess the most extensive breadth of experience across various phases of mine closure, encompassing the entirety of closure activities. Specifically, consultants excel in drafting closure plans, conducting baseline assessments, and closure costing, tasks that entail comprehensive consideration of closure aspects. This observation aligns with the finding that consultants also exhibit diverse experience across different minerals, highlighting the common practice of outsourcing closure expertise, which is reinforced by Zambian legislation mandating independent experts for certain studies such as Environmental Impact Assessments (EIA's) (DEA, 2010b). Conversely, participants from mine sites primarily engage in the operational aspects of closure, while government officials predominantly focus on closure standards, regulation, and monitoring. Notably, respondents from mining sites are exclusively involved in direct consultation with and application for closure with the government, revealing a unique relationship between these sectors. Legal professionals predominantly engage in legal activities related to closure, while the academic sector's involvement is limited to preparing mine closure emergency response plans, potentially indicating a gap in emergency planning within closure strategies. Corporate sector involvement primarily centers on strategic functions, aligning with their organizational roles and responsibilities.

Table 10 reveals a concerning trend regarding the limited participation of respondents in crucial mine closure activities, notably baseline assessments, closure studies and trials, post-mining monitoring, and community engagement. This observation aligns with the findings presented in Section 4.7, which highlight deficiencies in baseline indicators, limited long-term trials, simplistic post-mining monitoring, and inadequate community involvement in the closure process. Despite these shortcomings, Table 10 also indicates a broad working practice among mine closure experts in Zambia. While certain areas may lack attention, particularly in the aforementioned activities, there are no significant omissions compared to international mine closure literature (Section 2.3.3). This level of expertise is somewhat expected in a country such as Zambia, characterized by a mature mining and economic sector, with sustainable development principles integrated into national legislation.

4.9.2 Status quo of mining environmental indicators in Zambia

To determine the status quo for operational environmental monitoring in Zambia, the findings from this part of the study shed light on the details of environmental monitoring in Zambia's mining sector, particularly focusing on the baseline and operational phases.

In terms of the baseline indicators, the analysis revealed that while the Environmental Impact Assessment (EIA) process generates an abundance of baseline indicators, the resulting Environmental Management Plans (EMPs) are often poorly executed, leading to insufficient baseline data (Table 11). The responses from most participants highlight a common concern regarding the inadequacies in baseline studies and the resultant Environmental Management Plans (EMPs) conducted as part of the Environmental Impact Assessment (EIA) process in Zambia. While the EIA process typically generates baseline environmental indicators, participants across various professional sectors criticized the quality of these studies, attributing them to be poorly conducted and rushed, often due to insufficient time allocated during the permitting process (ECZ, 2010). Consequently, the data collected is often limited to single-sample assessments, leading to a superficial understanding of local environmental systems and the formulation of weak or ambiguous management plans. This deficiency in baseline data hampers effective closure planning, as the lack of a reliable baseline for comparison and goal-setting makes it challenging to achieve restoration to pre-mining land use, as mandated by the Zambian environmental legislation (Bhatt, 2023; ECZ, 2010). Overall, these findings highlight the need for improvements in the quality and comprehensiveness of baseline studies to facilitate more effective mine closure planning and environmental management practices.

The findings also revealed a common concern among respondents regarding the limited revisitation of baseline studies as mining progresses, leading to outdated methodologies and insufficient content by the time closure becomes imminent. This issue is particularly pronounced for older mining sites, reflecting the less stringent environmental regulations in Zambia (OECD, 2002). While some indication of reviewing baseline studies exists, the lack of detail provided suggests limited implementation. One expert highlighted the absence of comparing original baseline data with the desired end state during closure, attributing it to the integrity issues of baseline data. This sentiment was widely shared across all professional sectors, indicating a common consensus on the challenges posed by poor baseline studies.

The respondent's insight into the limitations of baseline indicators post-mining, particularly regarding hydrogeological changes, challenges the conventional notion of rehabilitating to a pre-mining state, raising questions about the achievability of sustainable mine closure. However, there seems to be flexibility within regulatory frameworks, as indicated by a professional from the

MMMD, suggesting the possibility of negotiating post-mining conditions different from pre-mining states, subject to MMMD approval. This aligns with government notice emphasizing the importance of land rehabilitation to a natural state or a predetermined standard compatible with sustainable development (OECD, 2012). The identification of seven basic categories of baseline indicators, including Land Use, Water, Waste, Air, Geology and Soils, Biodiversity, and Social, reflects conventional environmental indicator classes and provides a framework for assessing mining impacts and guiding closure planning (IFC, 2007, 2017; Miranda et al., 2003).

This deficiency poses challenges for future closure studies, hindering effective comparison and goal-setting. Surface and subsurface water quality emerged as the dominant baseline indicator, emphasizing its paramount importance, followed by biodiversity and air quality (Table 11).

The dominance of water quality as the most cited baseline indicator, followed by biodiversity, and air quality highlights the importance placed on these environmental aspects in baseline studies for mining projects (Table 12) (Purvis & Genovese, 2023). However, the limited representation of social indicators suggests a potential oversight in assessing broader socio-environmental impacts, highlighting a gap that warrants further attention (Partelow, 2018). Additionally, the inclusion of indicators such as, LULC, soil and geology and waste, although less frequently cited, reflects the good considerations needed for comprehensive closure planning and final land use goals (Table 12). Yet, the lack of emphasis on certain indicators for example land capability studies and geochemistry characterization raises concerns about the adequacy of baseline assessments in guiding sustainable mine design and closure. Furthermore, the historical absence of comprehensive environmental requirements for older mines exacerbates the challenge of achieving sustainable closure, as these sites often lack baseline data essential for informed decision-making (Young et al., 2022). This highlights the need for improved integration of baseline studies with a proactive approach to mine design aimed at facilitating sustainable closure from the outset, as well as the importance of addressing knowledge gaps and resource constraints hindering the comprehensive assessment of environmental impacts and land use potentials.

The legal obligation for monitoring and measuring specific environmental indicators, mandated by a mine's approved mining license overseen by the MMMD, highlights the importance of robust environmental assessments throughout a mine's lifecycle. However, if baseline Environmental Impact Assessments (EIAs) informing the permitting process are inadequate, operational mines may have weak environmental indicators, hindering effective closure planning unless supplemented by additional monitoring required by corporate standards or funding bodies (MOREC & ECD, 2018). This highlights the need for diligent mine closure planning integrated into all phases of the mine lifecycle, particularly during feasibility and planning stages (Fourie et al.,

2008). To assess the current state of operational environmental monitoring in Zambia, respondents were questioned about the indicators measured at operating and closing mining projects they have been involved in, highlighting areas of deficiency that deserve attention and improvement. This involved the specific environmental indicators, environmental indicators beyond the mine site boundary, the relationship between environmental indicators relate and final land use, and ideal environmental indicators.

For the specific environmental indicators, water quality (water quality: parameters such as pH, turbidity, dissolved oxygen, and presence of contaminants (e.g., heavy metals, sulfates) and water discharge: volume and quality of water discharged from the site, including treatment effectiveness) and air quality (dust emissions: levels of particulate matter (PM10 and PM2.5) generated by mining activities and gas emissions: concentrations of greenhouse gases (e.g., CO₂, methane) and other pollutants (e.g., sulfur dioxide, nitrogen oxides)) monitoring emerged as the most frequently conducted environmental activity on mine sites, encompassing both surface and underground water monitoring. This emphasis on water monitoring is attributed to the separate regulation and licensing of water uses by the MMMD (Government of Zambia, 2015a). Moreover, water quality monitoring, often conducted according to Global Reporting Initiative (GRI) guidelines, aligns with Zambian water quality guidelines issued by ZEMA, ensuring compliance with national freshwater quality standards (GRI, 2023). Similarly, basic biodiversity monitoring, including species abundance and presence of protected species, is also common. Soil depth, fertility, and land capability are also monitored, reflecting the essential indicators identified in baseline studies. However, more complex indicators such as waste generation (both domestic and mine waste), and LULC receive less attention, highlighting potential gaps in environmental monitoring practices that are crucial for informing sustainable mine closure strategies.

In terms of environmental indicators beyond the mine site boundary, the findings from this research revealed that while mine operators are legally obliged to monitor environmental indicators beyond their lease boundaries, the extent of such monitoring varies significantly. While basic indicators such as water quality (pH, turbidity, dissolved oxygen as the predominant environmental indicator) and air quality (dust emissions such as levels of particulate matter (PM10 and PM2.5) are commonly monitored within a limited radius outside the mine lease area, more comprehensive monitoring beyond these parameters is lacking. This is particularly evident in the limited attention given to biodiversity and cumulative environmental impacts, as highlighted by respondents. The reliance on monitoring primarily within the mine boundary (limited assessment outside the boundaries) poses challenges for understanding and mitigating off-site environmental impacts, especially in the context of mine closure planning (Seki, 2022). Without robust data on extended

environmental impacts, distinguishing between background levels and mine-related effects becomes problematic, hindering effective mitigation strategies. Consequently, there is a pressing need for enhanced monitoring practices to address cumulative impacts and ensure sustainable mine closure in compliance with regulatory standards (IIED, 2002a).

Further, the participants were asked if there is a relationship between the environmental indicator and the final land use. The examination of whether environmental indicators relate with final land use intentions revealed a difference in perspectives among participants (M, C, CO, G). While the majority of consultant and government respondents expressed uncertainty regarding the direct relationship between environmental indicators and final land use, they emphasized the importance of such integration for informed decision-making (Figure 14). This sentiment aligns with international literature emphasizing the significance of linking environmental indicators to land use planning (Rahnema et al., 2023). Conversely, corporate and mine site respondents emphasized a clear connection between environmental indicators and final land use, viewing them as integral components of mine closure management and risk mitigation strategies (Figure 14). However, concerns were raised regarding the lack of comprehensive assessment of various land use options and the tendency for environmental monitoring to focus solely on regulatory compliance rather than a proactive understanding of impacts. Additionally, the absence of well-defined conceptual models and integrated planning exacerbates challenges in achieving sustainable closure and aligning land capability with intended land use. Addressing these issues is essential for ensuring environmentally sustainable final land use and effective closure planning, emphasizing the need for enhanced integration of environmental indicators into decision-making processes.

Lastly, participants were asked to identify ideal environmental indicators. The exploration of ideal environmental indicators essential for supporting sustainable mine closure obtained diverse perspectives from participants, with water quality emerging as a dominant concern. Participants emphasized the necessity of comprehensive water monitoring throughout the mine's lifecycle, citing its critical role in long-term water management post-closure. Air quality and dust monitoring, along with visual impacts and noise assessment, were considered necessary for addressing environmental concerns during both operational and closure phases. Vegetation monitoring, biodiversity assessment, and ecosystem services analysis were identified as essential for gauging the success and sustainability of rehabilitation efforts. Soil and land capability monitoring were also highlighted as fundamental for achieving sustainable rehabilitation and establishing stable topography to mitigate erosion risks. Furthermore, several participants highlighted the importance of incorporating social indicators into monitoring frameworks, recognizing the interconnectedness of social and environmental aspects in achieving sustainable closure. Overall, the agreement among respondents

emphasizes the need for comprehensive, site-specific monitoring programs integrated into legally approved environmental management plans to guide operational practices and inform closure planning effectively. This approach not only ensures environmental sustainability but also facilitates proactive management of financial and social outcomes associated with closure, ultimately contributing to a more holistic and sustainable approach to mine closure (Nehring & Cheng, 2016).

4.9.3 Mine closure and closure planning

Mine closure and planning are integral aspects of responsible and sustainable resource extraction practices within the mining industry, given the environmental and social implications characteristic in mining activities (Chugh et al., 2023). The proactive approach to closure planning is crucial for mitigating potential adverse impacts, rehabilitating mining sites, minimizing environmental damages, and ensuring the well-being of local communities (Ackerman et al., 2018). Recognizing the significance of effective mine closure and planning is essential for fostering a sustainable and ethical mining industry aligned with global standards, thereby positively contributing to Zambia's overall development (Ackerman et al., 2018). Therefore, respondents were asked regarding the presence of mine closure plans (to mine closure and corporate only), closure reporting, and essential environmental research needed to support sustainable mine closure in Zambia in section 4.8.5.

The study recognizing the significance of robust mine closure planning as emphasized in the literature, sought to understand the current status of closure planning in Zambia. Participants were asked about the presence and adequacy of mine closure plans based on their experiences. Responses revealed a mixed perspective as shown in Figure 15. While some participants indicated the existence of closure plans on most mines they worked on (135 respondents from mine sites, stated agreement, with 130 expressing moderate agreement and an additional 5 strongly supporting the notion), others noted that these plans often prioritize short-term goals and may not be sufficiently comprehensive or achievable in practice (33 from mine sites and 5 from the corporate sector, who adopted a neutral stance on the issue), Figure 15. Despite being legislatively mandated and commonly required by corporations, concerns were raised about the feasibility and realism of these plans. Moreover, there was confusion between rehabilitation and closure plans, indicating a need for clarity in terminology and objectives. Although closure plans are updated periodically, their quality and effectiveness remain questionable, with only a minority of participants suggesting comprehensive and detailed planning (Ministry of National Development Planning, 2020). Additionally, differences were noted in reporting practices, with corporate entities more likely to include closure performance in their reports compared to governmental sustainability reporting. This aligns with previous findings

suggesting that sustainability reporting in the mining sector may lack comprehensive coverage, further highlighting the inadequacies in current mine closure practices and the need for improvement to ensure sustainable closure outcomes in Zambia (Wambwa et al., 2023).

Additionally, participants in the study area provided insights into the essential environmental investigations required to support sustainable mine closure effectively. These findings echoed opinions expressed in the previous section on ideal environmental indicators. Notably, detailed studies on both surface and groundwater emerged as essential, emphasizing the importance of long-term water balance and geohydrological modeling for assessing water quantity and quality (Table 16). Additionally, respondents highlighted the necessity of geotechnical and geochemical assessments to predict the physical and chemical evolution of surface waste dumps, referencing the Ministry of Water Development, Sanitation and Environmental Protection's guidelines for water resource protection in the mining industry (Ministry of Water Development and Sanitation, 2022). These investigations were considered crucial for informing integrated mine water management plans and subsequent closure planning efforts. Participants also stressed the importance of sustainable revegetation on rehabilitated land, complemented by biodiversity investigations and ecosystem services valuation to internalize closure costs, as shown in Table 16. Furthermore, soil studies within the broader context of land capability assessments were identified as essential for guiding land use decisions, along with erosion modeling, slope stability analysis, and assessments of soil nutrient function and microbial contribution. While social studies were not the primary focus, respondents emphasized the need for aligning community engagement with environmental investigations to determine final land use. Additionally, participants emphasized the significance of desktop studies such as gap analyses, corporate reputational risk assessments, closure funding liability assessments, and investigations into waste dump reuse, post-closure dust generation, environmental history, climate change risks, post-closure monitoring, sudden and unforeseen closure planning, trade-off assessments, and biodiversity offset opportunities. These findings highlight the complexity of environmental studies and indicators necessary to develop robust and sustainable mine closure plans.

Lastly, participants were asked about their awareness of successful mine closures in Zambia, defined by the mitigation of residual risks, establishment of sustainable land use, and issuance of a closure certificate by the state. The consensus among respondents was that no mines had achieved legal closure in the country (with some strongly disagreeing with this notion, while others expressed disagreement or remained neutral), Figure 16. While some instances of sustainable post-closure land use were acknowledged, closure certification remained largely unattainable due to persistent latent environmental impacts. Primarily, post-closure water issues, particularly AMD, posed

significant challenges, with residual impacts lasting for many years after closure. Kabwe lead mine in the Central province of Zambia was given as an example by many participants with persistent environmental impact 30 years after closure (Burga & Saunders, 2019a; Nakata et al., 2021). The complexity of closure varied across mining types, with sand, limestone, and aggregate mines perceived as easier to close compared to copper, cobalt, and manganese mines due to fewer long-term environmental chemistry changes (Agboola et al., 2020). This deadlock between mining companies and the government highlights the need for a proactive, comprehensive closure plan initiated during the feasibility phase, with ongoing monitoring and maintenance post-closure to quantify and address residual environmental impacts. Financial responsibility, in accordance with the 'polluter pays principle', must be borne by mining companies, as mandated by the MMMD.

4.9.4 Awareness of Zambian mine closure legislation

In Zambia, mine closure is mandated by legislation, as outlined in the Mine and Mineral (Environmental) Regulation (MMR) 1997 regulations. This legal framework highlights the importance of understanding the gap between policy and actual practice in mine closure processes (Government of Zambia, 1997a). To assess this difference carefully, participants were asked about their familiarity with Zambian mine closure laws and asked to provide their expert opinions on the matter. Respondents were asked to indicate their familiarity with specific pieces of legislation, including the Environmental Management Act, 2011, the Mines and Minerals Development Act, 2015, the Mines and Minerals (Environmental) Regulations, 1997, and the Mines and Minerals (Environmental Protection Fund) Regulations, 1998. This approach not only helps measure the participants' legal knowledge regarding mine closure but also serves to validate their expertise in this specialized field.

In terms of familiarization with the above mine closure legislations, the study revealed that most of the respondents were familiar with the Environmental Management Act, 2011, and the Mines and Minerals Development Act, 2015. There was a decrease in familiarity with the Mines and Minerals (Environmental) Regulations, 1997, and Mines and Minerals (Environmental Protection Fund) Regulations, 1998 as indicated in Figure 17. This decline in awareness is worrying for several reasons. Firstly, according to Mines and Minerals Development Act, 2015, the MMMD is required to approve mine closure plans. Therefore, a lack of awareness regarding the involvement of the MMMD in mine closure could lead to neglect of important considerations falling under their jurisdiction. Secondly, the general lack of awareness of the Mines and Minerals (Environmental Protection Fund) Regulations, 1998 among mine closure experts is troubling. The lack of awareness

of these explicitly legislated closure principles among experts in the field may undermine efforts to achieve sustainable mine closure (Fourie & Brent, 2006).

The study revealed that, by sector, academics showed the least familiarity with the listed closure legislation, while individuals in the legal and governmental professions exhibited the highest levels of awareness. While it may be less critical for academics to possess extensive knowledge of closure legislation, their research activities should be mindful of the legal framework. It was expected that legal professionals would be well-versed in all applicable legislation, and it is promising that government employees involved in mine closure displayed similar proficiency. Corporate respondents also demonstrated good awareness of the legislation, although with more gaps compared to the legal and governmental sectors, which aligns with their role in corporate oversight and policy formulation (ECD, 2021). Consultants and mine site employees ranked lower in familiarity. This is concerning as consultants may be proposing closure solutions without a full understanding of closure legislation, and mine site employees may not be aligning plans with applicable laws (Cole, 2024). However, it should be noted that some respondents had previous closure experience in Zambia but were working abroad for some time and may not have kept up with legislative developments. Additionally, a few respondents specialized in certain aspects of closure studies and therefore were less aware of closure legislation. Nonetheless, to effectively implement the principles of sustainability embedded in Zambian mine closure legislation, substantial knowledge of and alignment with the legislation should be promoted within the professional field (Zulu et al., 2022). Across the four primary pieces of closure legislation listed, there were variations in overall familiarity among respondents as indicated in Table 17.

4.10 The intersection of sustainable development principle, mine closure, and environmental indicators

The intersection of sustainable development principles, current operational environmental indicators, mine closure and closure planning, and respondents' experiences and work environments was examined to measure the progress of sustainable closure practices in Zambia. These intersections indicated theoretical sustainability models within the mining sector, applying them to practical cases of environmental and social challenges facing the industries along with progress toward sustainable achievement of mine closure.

The sustainable development principles are emphasized on a broader perspective that would include the precautionary principle, ethical corporate responsibilities, and principles, mine-closure plans with effective community participation. Such principles are crucial to forming the foundation for sustainable closure practices expected to incorporate extensive risk management and iterative

planning regarding continual improvement. However, the reality on the ground reflects a gap between these principles and their actual implementation. Respondents' experiences reveal that while these principles are well understood and accepted, their translation into practical action remains inconsistent, highlighting the need for enhanced commitment and alignment between policy and practice.

Current operational environmental indicators, such as water quality, biodiversity, and air quality, have the critical mission of directing the mine operations towards environmental sustainability or sustainable closure of the mine (OECD, 2020). The indicators are derived from sustainable development principles and are crucial for monitoring the effectiveness of closure activities (Asr et al., 2019). The experiences of the respondents confirmed a wide recognition of the importance of these indicators but also pointed out deficiencies in their comprehensive application during the operational phase and into the closure planning. Such a mismatch pinpoints the critical need for solid environmental monitoring systems. They should not only comply with the law but take part in contributing proactively to the sustainable closure of the mine.

Furthermore, mine closure and closure planning in Zambia are influenced by both corporate and governmental practices. Despite the existence of theoretical frameworks and legal mandates for sustainable mine closure, practical implementation is often disadvantaged by inadequate planning and lack of rigorous execution. This is evident in the mixed responses from professionals about the effectiveness of existing mine closure plans and the actual closure practices, which often prioritize short-term goals over long-term environmental and social sustainability.

Therefore, this part of the research effectively brings together various threads from the dissertation to illustrate the complications and interdependencies involved in achieving sustainable mine closure in Zambia. It calls for a more integrated approach that not only adheres to sustainable development principles but also effectively incorporates these principles into everyday operational and closure practices. Integrating the principles of sustainable development with current operational environmental indicators, mine closure, and closure planning, alongside the respondents' experience and work environments, reveals a multi-dimensional approach to advancing sustainable closure practices in mining (Peck, 2005). As Chapter 4 of this thesis assesses, sustainable development principles urge a balance between meeting today's needs without compromising future generations. This harmonization is particularly significant in the context of mine closure, where the focus shifts toward leaving a positive environmental and socio-economic legacy. Insights from respondents, who often have direct field experience, emphasize the critical need for continuous improvement and adaptation of environmental indicators to reflect ongoing challenges and opportunities in sustainable mining practices.

4.11 Conclusion

In Zambia, professionals responsible for mine closure play an essential role throughout the life of the mining operations, from the first assessment to those under progressive closure, and include continuous post-closure monitoring, as detailed in Table 10. Despite the presence of significant opportunities for achieving successful mine closure, professionals face several challenges. These include inadequate baseline environmental studies, prolonged trials, insufficient monitoring of environmental indicators, poor stakeholder engagement, the creation of closure plans without top management commitment, and notably, an unstable legal framework at the intersection of environmental, and mining concerns. This instability is very critical as it identifies a legal domain that restricts any sustainable mine closure effort.

Chapter 4 brings out the complexities associated with the legislation on mine closure in Zambia in the realm of sustainable development. This part of the research shows a landscape marked by both improvement and shortcomings, where the aspiration for sustainable mine closures is sometimes dissatisfied by legislative and practical challenges. However, it also identifies opportunities for improvement and adaptation, suggesting that a more integrated and innovative approach could significantly enhance the sustainability of mine closures in Zambia. The findings from this chapter highlight the critical need for legislative reform and the adoption of best practices that prioritize environmental sustainability. This entails a more explicit incorporation of sustainability indicators into mining legislation, comprehensive monitoring and enforcement mechanisms, and an openness to learning from global best practices. By addressing these needs, Zambia can better position itself as a leader in sustainable mining practices, ensuring that the mining sector contributes positively to both the economy and the environment without compromising the well-being of future generations.

In a nutshell, though challenges persist, the ability to realize sustainable mine closures is about there in Zambia. It will require efforts from government bodies, the mining industry, and local communities pulling in the same direction towards those common objectives, along with international cooperation and innovation. This chapter lays a solid foundation for further research and action towards sustainable mine closure practices that align with both national ambitions and global sustainability goals.

5. Land Use Land Cover (LULC) change dynamics associated with mining activities in the Copperbelt Province, Zambia: A case study of Kitwe District

5.1 Introduction

The change of Land use and land cover (LULC) became a fundamental component of the current strategies to manage natural resources and monitor environmental changes (Twisa & Buchroithner, 2019). LULC resource uses have resulted in major anthropogenic changes (Rawat et al., 2013; Twisa & Buchroithner, 2019). Increasing human activities have caused large-scale changes in the terrestrial surface, disturbing the productivity of global systems (Lambin et al., 2001). Rapid LULC changes, especially in developing countries, have reduced in essential resources, including vegetation, water, and soil (Twisa & Buchroithner, 2019). Furthermore, factors contributing to LULC change have indigenous causes, one of which is economic activities by the local community.

One such major economic activity responsible for LULC change is mining. The exploitation of mining resources significantly impacts the ecological environment (Xiao, Lv, et al., 2020). The study by (Wang et al., 2020) stated that mining results in urban growth, leading to LULC changes in many areas worldwide, especially in developing countries such as Zambia (Mensah, 2019). Open-pit, ore, and strip mining can lead to LULC change (Xiao, Deng, et al., 2020) which have already contributed to severe environmental landscape degradation in mine-adjacent areas of the USA (Schladweiler, 2018).

Governments in many countries require the recovery of areas degraded by mining (Carvalho, 2017). Both sustainable and eco-friendly mining necessitate continuous LULC change monitoring to identify their long-term environmental impacts (Song et al., 2020). Monitoring these changes provides fundamental security measures and data for planning ecological restoration and land reclamation strategies (Xiao, Deng, et al., 2020). Furthermore, the spatiotemporal change quantification in an area resulting from open-pit mining becomes crucial in understanding the impacts of mining activities and evaluating their socioeconomic, environmental, and ecological impacts (Wu et al., 2019) through related legislation.

Copper mining plays an important role in Zambia's economic development. Commercial copper mines in Zambia have been in operation since 1928, when the first mine opened (Sikamo et al., 2016a). In Zambia, there are five major open-pit and eight underground mines that produce copper and other minerals, such as cobalt (Sikamo et al., 2016a). Copper mining takes place in the Copperbelt Province, located in the northern region of the country, which is the most densely populated and urbanized in the country (Perera, 1981). Consequently, the development of urban

centers around mines have posed spatial problems in reconciling the needs of a rapid population growth with the demands of the mining industry (Perera, 1981).

For over seventy years, mineral resources have been mined near Kitwe, Copperbelt Province (Limpitlaw, 2003b). The long mining history and the existence of other pollution sources complicate the assessment of environmental impacts in Kitwe, thereby necessitating an indicator of environmental change (Limpitlaw, 2003b). Extensive quantities of mine residues, including broken rocks, fine particles, and slag, have been generated and deposited on the land (Limpitlaw, 2003a). These residues indicate the mining extent and indicators of its environmental impact (Limpitlaw, 2003b). However, in Kitwe, the extent and dynamics of the changes have not been comprehensively studied, except for an old-time study before the privatization of mining companies in the 1990s (Limpitlaw & Woldai, 2000). There is limited information about the spatiotemporal extent of the LULC changes in this district, and no evaluation on the information has been done after privatization to enhance land use planning.

This part of the study, therefore, aims to understand the recent land use land cover (LULC) change dynamics resulting from mining activities in the Kitwe District of Copperbelt Province from 1990 to 2020 using Google Earth Engine. This study selected the period from 1990 to 2020 as the privatization of mines in Zambia began in the 1990s. Therefore, I focused on understanding the changes in LULC that occurred immediately before and after the mines were privatized. The above-mentioned aim of this research shall be achieved through completing the following set of sequential objectives;

1. To identify land cover types and their spatial distribution in Kitwe District of Copperbelt Province of Zambia.
2. To monitor the spatio-temporal change in Kitwe District from 1990 to 2020.
3. Analyze the data collected to identify specific patterns and extents of LULC changes associated with mining activities.
5. Using the data and trends observed from past and present analyses, project future changes such as continued mining, expansion of mining, or cessation of mining activities.

5.2 Data and methods

5.2.1 Study area

5.2.1.1 Kitwe District

This study was conducted in the Kitwe District, Copperbelt Province, Zambia (Figure 18), (799.42 km²) located approximately 50 km northwest of Ndola City, the headquarters of the province. It is a mining district within the Neoproterozoic Katangan Supergroup basal succession (Broughton, 1936). Kitwe City (12.8024302°S and 28.2132301°E) lies on the west bank of the Kafue River.

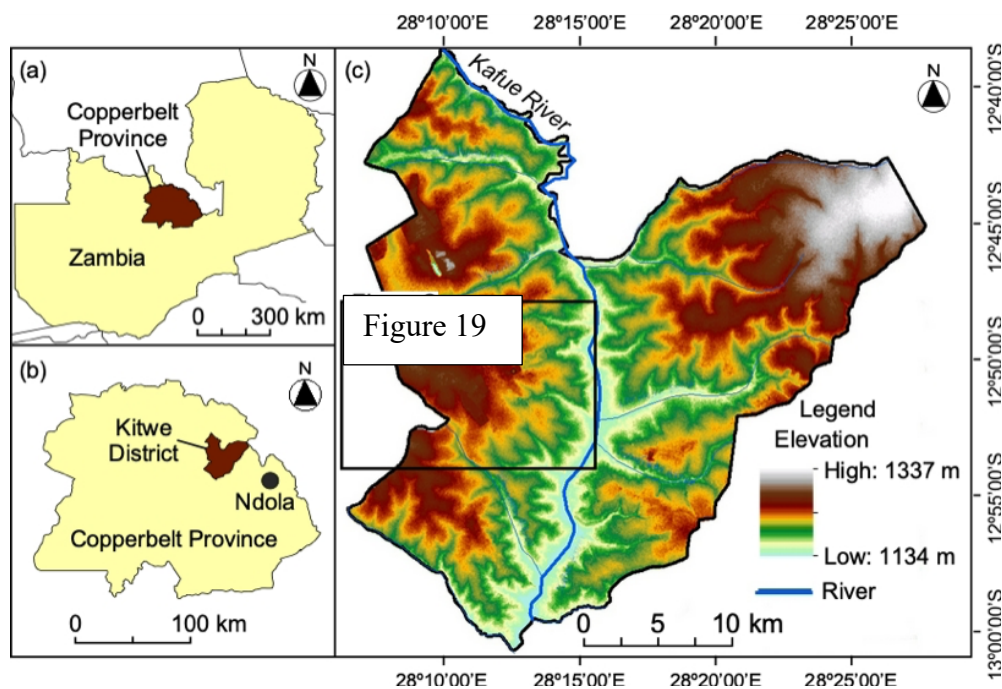


Figure 18. Study area of the Kitwe District, Copperbelt Province, Zambia.

Kitwe, which is the main commercial and industrial center of the province (Britannica, 2015), is the second largest city in Zambia and the largest city in the Copperbelt Province. Kitwe rapidly developed the copper mining industry, especially after 1936 along with the establishment of secondary industries (Britannica, 2015). It is famous for the Black Mountain, a copper slag dump located in the Wusakile Township. Kitwe has four mines, including the Mopani Copper Mine, a joint venture situated in Kitwe, where 95% of its operations take place. The ownership makeup involves Glencore International AG (73.1%), First Quantum Minerals Limited (16.9%), and Zambian Consolidated Copper Mines (ZCCM) Limited (10%), the national mining company (Limpitlaw, 2003b). Prior to privatization, the Nkana Slag Dump (Black Mountain) was owned by Nkana Mine of the ZCCM Limited. This licensed dump received slag from the Nkana Smelter until

the designed limit was reached in the 1990s (Tunatazama., 2011). The Konkola Copper Mine is the second mine in the study area. While the company is headquartered in Chingola, 15% of its operations, including Nkana Refinery, Acid Plants, and Smelter, are situated in Kitwe (Tunatazama., 2011) with the Nkana Smelter being the Zambia's largest main copper production plant. The third mine is Kagem Mining Limited, the largest producer of emeralds and accounts for approximately 25% of the global emerald production. The fourth mine is the Rokana Mine (closed), which owns the Mindola Underground Mine. Extensive tailings are around this mine, and two small tailings dams are located in the city center.

5.2.1.2 Rokana mine

The Rokana mine is one of the oldest copper–cobalt mines owned by ZCCM, located in the central part of Kitwe (12°49'59"S, 28°12'6"E) (Limpitlaw, 2003a). It has been in continuous operation since 1928, and during mine nationalization (1970–1991), underground and open-pit sources were operated (Limpitlaw, 2003a). Mining operations at Rokana were halted in the 1990s owing to unfavorable economic viability, resulting in ZCCM placing the mine under care and maintenance (Munene, 2018).

The Rokana mine generated large amounts of mine waste in the form of tailings (11 tailing dams) and causes serious environmental problems (Limpitlaw, 2003a). All tailings dams in the district and around the abandoned Rokana Mine are currently closed, which means that all mine waste currently produced in Kitwe is transported to TD 15A (located in the Kalulushi district), the only operating tailing dam near Kitwe (Figure 19).

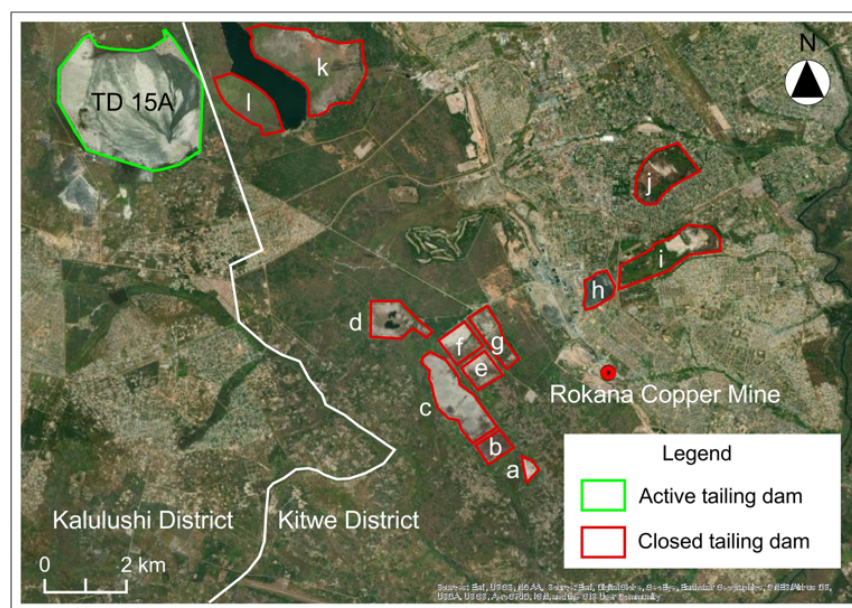


Figure 19. Locations of the Rokana mine and tailing dams in the Kitwe District. See Figure 18c.

5.2.1.3 Kitwe District population

The 2010 population census shows that the Kitwe District population increased from 347,024 in 1990 to 517,543 (27% of the Copperbelt Province's population) in 2010 (Table 18) (CSO, 2012d). The population reached 661,901 in 2022 (ZSA, 2022a), with a population density of 814.7 people per km². Approximately 276,000 people in the Kitwe District are older than 18 years (Mwitwa et al., 2016). The average annual population growth rate of Kitwe is 2.1% (ZSA, 2022a).

Table 18. Population in the Kitwe District, 1990–2020 (source: (Britannica, 2015) and (ZSA, 2022a)).

Year of Census	Population	Male	Female
1990	347,024	175,812	171,212
2000	376,124	189,650	186,474
2010	517,543	256,740	260,803
2022	661,901	321,654	340,247

5.2.2 Dataset

5.2.2.1 Remote sensing analysis (Landsat Imagery and Processing)

Open-access Landsat 5 top of atmosphere (TOA) and Landsat 8 TOA reflectance data available on the Google Earth Engine (GEE) were used to create the satellite images (Table 19). Many Landsat images in this platform are processed with a relatively high level (Liu et al., 2020). The Landsat 8 and 5 TOA reflectance data from Collection 1 Tier 1 are the highest possible quality imagery available (USGS, 2019). In the Tier 1 collection, scenes were georegistered consistently, indicating that all images underwent correction for displacement using ground control points and digital elevation model data. Within this collection, a root-mean-square error ≤ 12 m was used to register all images (USGS, 2019). The geometric registration guarantees that pixel-to-pixel correspondence is essential for the multitemporal image integration (Xiong et al., 2017).

In addition to geometric registration, radiometric normalization is necessary for multitemporal imagery (Du et al., 2002). This normalization ensures consistent spectral-radiometric properties throughout observations from different days or sensors (Chander et al., 2009). During the radiometric calibration, the unprocessed and raw digital numbers for each spectral band in a Landsat scene is converted into at-sensor radiance values that account for the specificities of the sensor acquiring the imagery, including mechanical failures, or deterioration in sensor quality and

measurement changes (Chander et al., 2007, 2009). For consistency with other scenes, the Tier 1 collection was elected in this study due to all images in the collection being radiometrically calibrated with well-established methods (Xiong et al., 2017).

Table 19. Satellite data used for land use land cover (LULC) change analysis in this study.

Data Used	Sensor	Path/Row	Spatial Resolution (m)	Source
Landsat TM	TM	172/69	30	USGS
Landsat TM	TM	172/69	30	USGS
Landsat TM	TM	172/69	30	USGS
Landsat OLI	OLI	172/69	30	USGS
PlanetScope	OrthoTile	2792051_3533219	3	Planet

Following radiometric normalization, the at-sensor reflectance was converted into a planetary reflectance value (Maas & Rajan, 2010). Images can be converted into either surface reflectance or TOA values (Song et al., 2001). The TOA collection was selected instead of the surface reflectance data due to initial tests indicating that a Kauth–Thomas linear transformation significantly enhanced classification accuracy (Yarbrough et al., 2014). Presently, the Kauth–Thomas coefficients for Landsat 8 data are best established for TOA data (Firozjaei et al., 2019; Song et al., 2001). TOA data have consistently been utilized to generate multitemporal image mosaics, resulting in high-accuracy land-cover classifications. This is particularly notable when spectral indices or transformations are applied to enhance spectral signal (Aguilar et al., 2018; Crawford et al., 2013; Dong et al., 2019; Hu & Dong, 2018; Orengo & Petrie, 2017; Wu et al., 2019). Well-established calibration coefficients were used to compute the TOA reflectance values for the Tier 1 collection (Chander et al., 2009).

Between 1990 and 2020, a cloud-screening algorithm was used to eliminate cloud-contaminated pixels from each Landsat image, utilizing quality assessment bands. Six-month composites were then generated by calculating the median value from the images of the target months (July to December) (White et al., 2014). For instance, for 1990, pixel values were calculated by taking the median of all cloud-free pixels from images between July 1, 1990, and December 31, 1990. A six-month window was used to ensure the availability of at least one cloud-free pixel for each composite and seasonality was considered. In this study, the dry season (July to December) was considered to clearly differentiate the spectral signatures of LULC types.

5.2.2.2 LULC classification

Based on existing classifications of land cover (National Remote Sensing Centre) and field observations, the LULC for each year (1990, 2000, 2010, and 2020) was classified into five categories (Table 20): bare land (including mining areas), built-up area, forest, grassland/pasture/agricultural land, and water (Figure 20). The random forest (RF) decision tree classification algorithm in the GEE was used to extract the five LULC classes.

Before selecting the training samples, empirical analyses of satellite imagery, google earth images, and topographic sheets of the district were carefully performed. For most of the classes, a minimum of 50 training samples were collected across the study area.

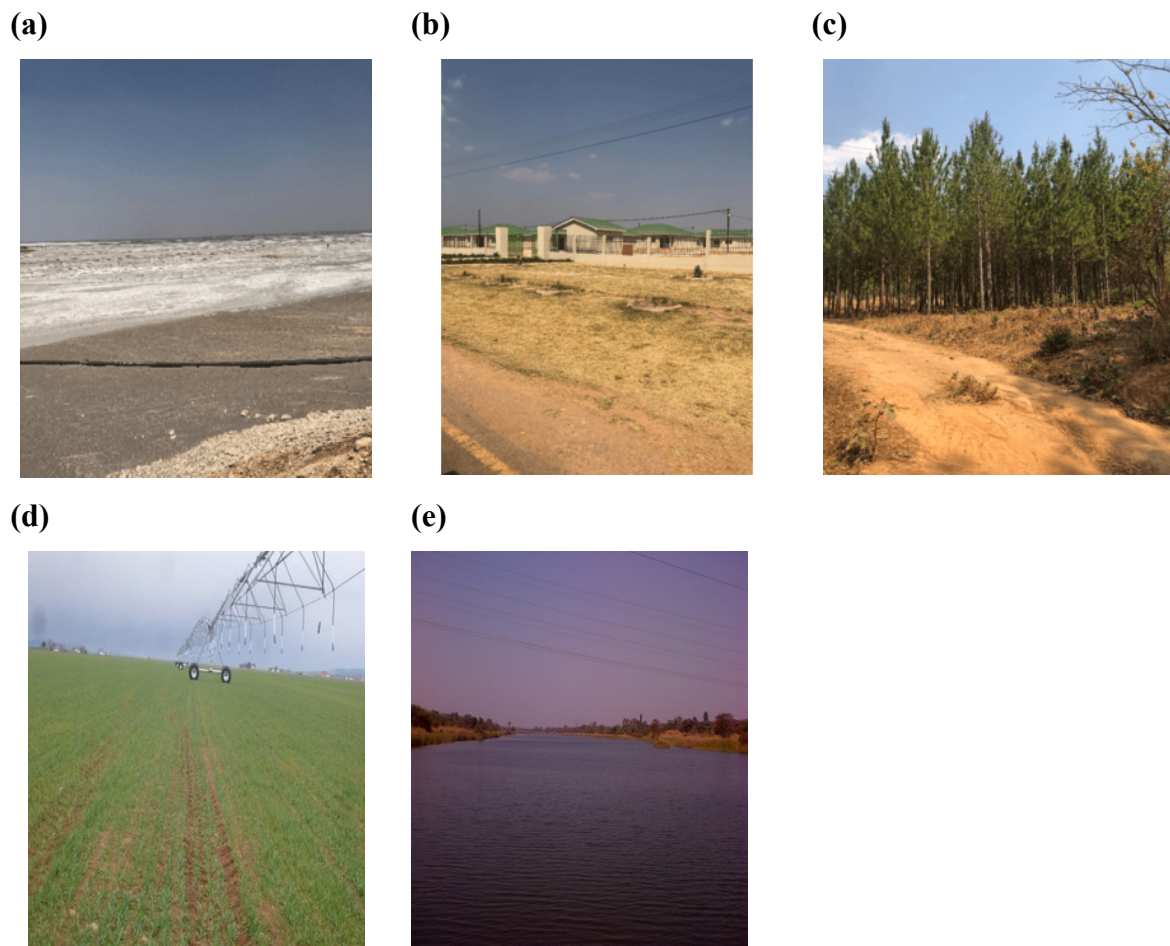


Figure 20. LULC in the study area: (a) Bareland (tailing), (b) Built-up, (c) forest, (d) Grassland/pasture/agricultural land, (e) Water.

Table 20. Description of the five LULC classes used in this study.

LULC Class	Description
Bare land (including mining area) *	Areas devoid of vegetation cover, e.g., mining area, sediments, exposed rocks and unpaved roads
Built-up area	Settlements and tarred roads
Forest	Land with tree canopy density more than 40%
Grassland/pasture/agricultural land	Areas where vegetation is dominated by grasses, pasture, and agricultural use
Water	Water bodies

*Only for the 2020 map produced by PlanetScope, mining area and bare land were distinguished from the class of bare land.

I used RF, a tree-based classifier with K-decision trees, to perform supervised pixel-based classification (Goldblatt et al., 2016; Shelestov et al., 2017). The RF addresses the overfitting problem through building an ensemble of decision trees (Pelletier et al., 2016; Shelestov et al., 2017). To classify the composite Landsat images into five LULC classes (Table 20), I trained the RF classifier on the GEE platform using 250 training samples.

5.2.2.3 Determination of the mining areas

LULC maps prepared by Landsat can identify bare land, including mining areas. However, the mining area must be distinguished from other bare lands; therefore, PlanetScope satellite images were used. The 2020 PlanetScope image was acquired from <https://www.planet.com/products/planet-imagery/>. The satellite image is a 4-band mul-tispectral image (blue, green, red, near-infrared) with a 3-m spatial resolution (image ID planet/item_id: "2792051_3533219_2020-10-29") downloaded on November 19, 2020.

In this study, I did not use a maximum likelihood classifier; instead, a Support Vector Machine was used to analyze the satellite images using ArcGIS Pro software (ESRI, Redland, CA, USA). This is due to statistical methods, such as the maximum likelihood classification method, possessing certain limitations, particularly concerning distributional assumptions and constraints on data input (Deilmai et al., 2014). Many studies claim that machine learning algorithms, including Support Vector Machine, may frequently achieve higher accuracy in classifying a dataset than conventional classifiers (Atik et al., 2023; Kotsiantis, 2007; Vapnik, 1995).

Before classification, training samples were created by the region of interest tool for the five classes (mining areas independently classified). Signature sets involve selecting a set of pixels with similar spectral values, specifically for one class. As a result, for each identified class in the image,

a signature was assigned and a signature set was integrated. Finally, the PlanetScope image was classified, and the classified image of the mining area was merged with the Landsat image.

5.2.2.4 Validation

The composites from different years were separately trained and validated in the classification process. The classifier was trained using approximately 70% of the sample points, with the remaining 30% utilized to assess the accuracy and validate the RF classifier. The error matrix was used to calculate the RF classifier accuracy and kappa statistics. The final maps were compared with the high-resolution imagery on the Google Earth.

5.2.2.5 Class smoothing process

Class smoothing was performed during image processing to remove noisy pixels using ArcGIS Pro. This was done due to the process of classification typically resulting in tiny percentage of unclassified, poorly classified, or solitary pixels, which are frequently seen around the boundaries of two areas that are unambiguously assigned (Janssen & van der Wel, 1994). This can create a "pointillist" or blurry appearance that may pose challenges for map production (Erasu, 2017; Syifa et al., 2020). It is desirable to homogenize the classification by reassigning pixels to one or the other class (Liu & Mason, 2013; Wang et al., 2016). To minimize unnecessary details and improve the classification accuracy, post-classification smoothing using a majority filter is fundamental (Qian et al., 2005). This was performed by eliminating pixels $< 900 \text{ m}^2$ (less than the size of one pixel of the Landsat images). Filtering entails reassigning isolated pixels to the predominant class in which they are located (Jawak et al., 2019). Classified images usually manifest a salt-and-pepper appearance due to the inherent spectral inconsistency faced by a classifier when applied on a pixel-by-pixel basis (Perveen et al., 2008). In the bare land class, for instance, scattered pixels throughout the mining area boundary may be labeled as built-up areas, or vice versa. To address such instances, it is desirable to smooth the classified output, highlighting only the main classification (Dash et al., 2023; Erasu, 2017; Tottrup, 2004).

5.2.2.6 Field survey and accuracy assessment

The classified images from the GEE were exported to ArcGIS Pro for post-classification, where an accuracy assessment was performed (Figure 21).

A widely employed tool for evaluating map accuracy is an error matrix (Anand, 2017), which aligns and compares pixels in classified images with ground data (Morales-Barquero et al., 2019; Thapa & Murayama, 2009). The producer's accuracy assesses errors of omission, measuring

the effectiveness of classifying real-world land cover types (Foody, 2002). The user's accuracy assesses commission errors, representing the likelihood of a classified pixel matching the land cover type of its corresponding real-world location (Janssen & van der Wel, 1994).

The Kappa statistic is a separate multivariate technique to assess accuracy (Janssen & van der Wel, 1994). The reference data for the 2020 map were a combination of data collected during fieldwork and google earth pro image archives. However, clear and updated google earth pro images were lacking for 2010, 2000, and 1990. In this study, stratified random sampling was employed to collect a minimum of 40 reference points. The sampling was based on the sizes of the land use and land cover (LULC) classes for the classified image in 2020. The Kappa coefficient was calculated computed based on the reference of (Janssen & van der Wel, 1994). A value >0.80 shows excellent agreement, and that between 0.4 and 0.80 suggests moderate agreement between classification categories.

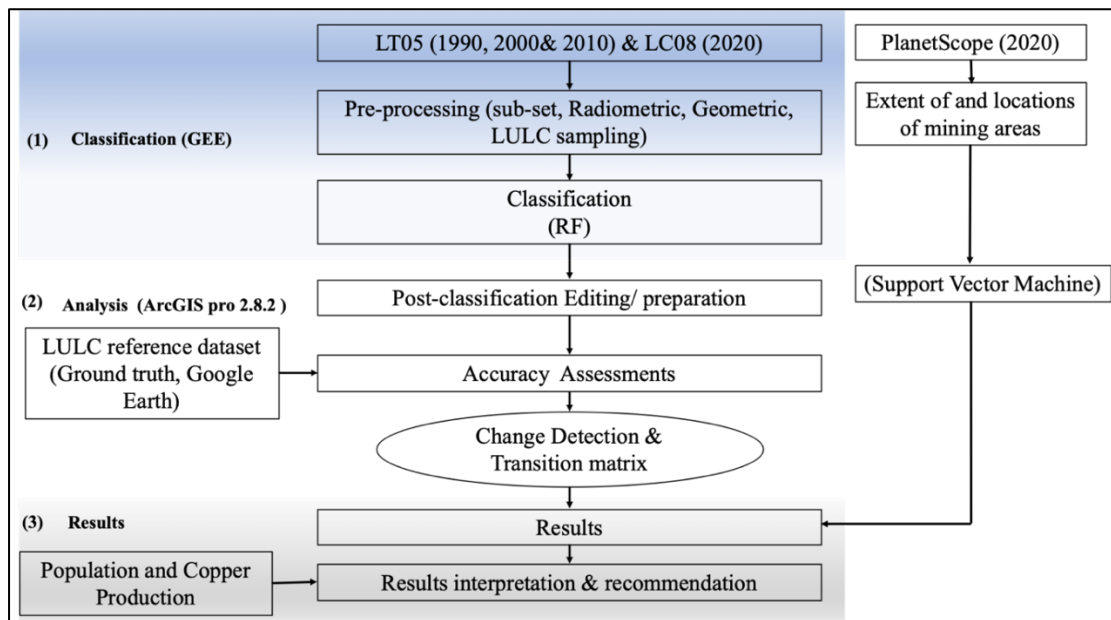


Figure 21. Flow chart showing the methodology of this study

5.3 Results

5.3.1 Major LULC classes of Kitwe District

Figure 22 shows the multitemporal LULC maps with five major classes, bare land (in the 2020 map produced by PlanetScope, mining area and bare ground are distinguished), built-up area, forest, grassland/pasture/agricultural land, and water, from 1990, 2000, 2010, and 2020. Table 21 summarizes the LULC temporal changes from 1990 to 2020. The percentage of each class area in 1990, 2000, 2010, and 2020 showed that grass-land/pasture/agricultural land had the largest proportion in 1990, representing 46.2% (369.43 km²) of the total LULC categories assigned. This class considerably increased by 51.7% (412.96 km²) in 2020 (Table 21). The other class, which showed a large change from 1990 to 2020, was forest. This class decreased during the study period (Table 21). An increase was also observed in the built-up areas and bare land (Table 21). Although there was an increase in the water class during the study period, the change was not significant.

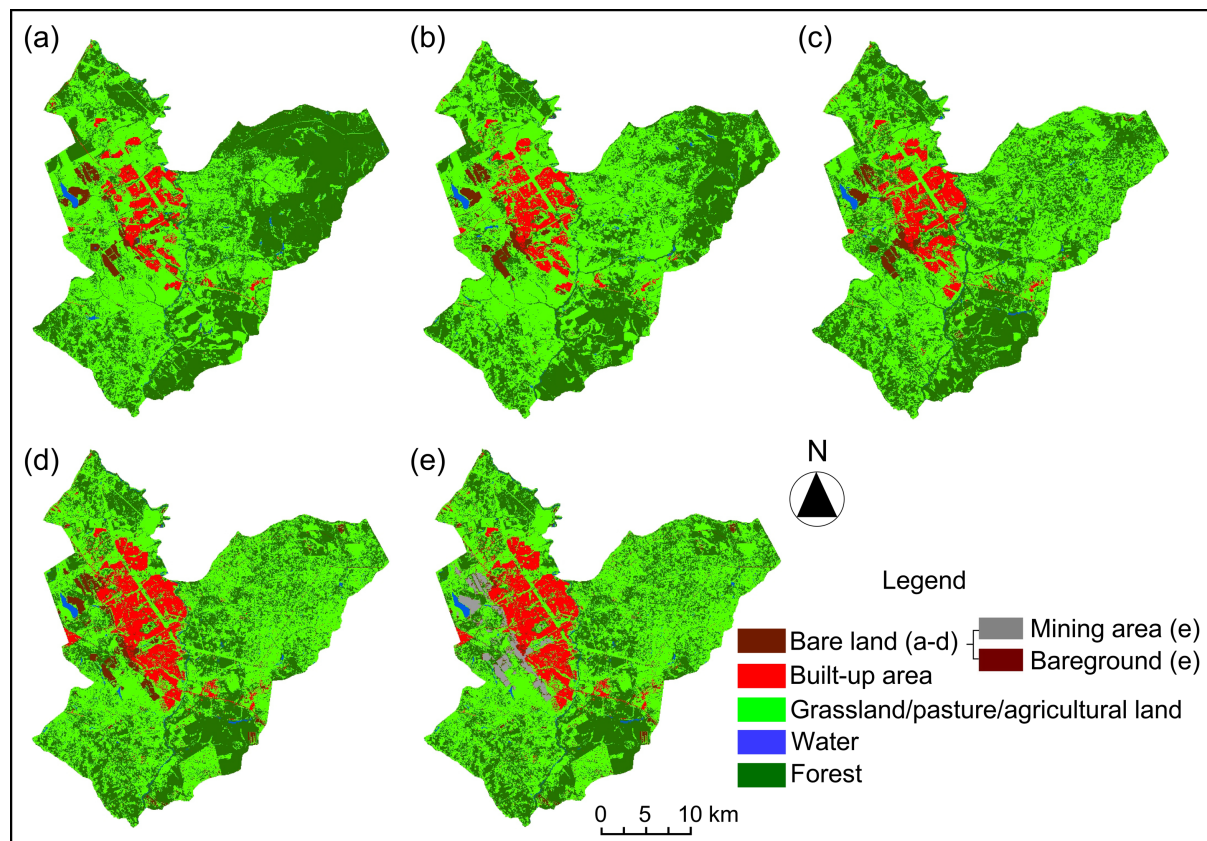


Figure 22. LULC change in the Kitwe District in (a) 1990, (b) 2000, (c) 2010, and (d) 2020 (mining area included in bare land), and (e) LULC map in 2020 (mining area and bare ground distinguished).

The PlanetScope image shows that the mining area was 22.95 km² in 2020 (Table 22). To determine the area of bare land, the mining area was subtracted from the total area under bare land, (35.58 km²) (Landsat 8 image); hence, bare ground occupied 12.63 km² in 2020. Figure 22 shows that the mining area is concentrated in the western part of the study area.

Table 21. LULC distribution in the Kitwe District, Copperbelt, Zambia.

LULC Class	Area in 1990		Area in 2000		Area in 2010		Area in 2020	
	km ²	%	km ²	%	km ²	%	km ²	%
Bare land*	20.90	2.6	21.70	2.7	22.46	2.8	35.58	4.5
Built-up Area	37.06	4.6	49.11	6.1	52.58	6.6	72.90	9.1
Grassland/Pasture/ Agricultural Land	369.43	46.2	398.12	49.8	403.89	50.5	412.96	51.7
Water	5.69	0.7	6.19	0.8	5.59	0.7	6.94	0.9
Forest	366.34	45.8	324.30	40.6	314.90	39.4	271.04	33.9
Total	799.42	100.0	799.42	100.0	799.42	100.0	799.42	100.0

*Bare land includes mining areas.

Table 22. Area and proportion of mining area and bare ground in the Kitwe District in 2020.

Sub-classes	Area (km ²)	Proportion (%)
Mining Area	22.95	64.51
Bare ground	12.63	35.49
Total (Bare land)	35.58	100.00

5.3.2 Field survey and accuracy assessment

The primary focus in selecting accuracy assessment pixels was on areas identifiable in both low- and high-resolution images (Landsat, Google Earth, and Google Maps). A total of 251 points (locations) were generated in the classified image using stratified random sampling based on the sizes of the land use and land cover (LULC) classes in the 2020 classified image (Table 23). The accuracy assessment results for the 2020 LULC map are presented in Table 24, indicating an overall accuracy of 82.47%. Therefore, the classified results are suitable as a data source for post-classification comparisons and further analyses. Producer's accuracy ranged from 64.0% to 96.1%,

while user's accuracy ranged from 68.8% to 96.1% (Table 24). The assessed image showed a Kappa coefficient of 0.78 for 2020, signifying good agreement between the classified map and the reference data (Congalton, 1991).

Table 23. Accuracy assessment error matrix of the classified image in 2020.

LULC Class	Bare land	Built-up Area	Grassland/Pasture/ Agricultural Land	Water	Forest	Ground Truth
Bare land	38	9	5	0	0	52
Built-up Area	4	32	0	0	0	36
Grassland/Pasture/Agricultural Land	5	9	44	5	1	64
Water	3	0	0	44	1	48
Forest	0	0	1	1	49	51
Total	50	50	50	50	51	251

Table 24. Producer's and user's accuracy assessment of the 2020 classified map.

LULC Class	Producer's Accuracy (%)	User's Accuracy (%)
Bare land	76.0	73.1
Built-up Area	64.0	88.9
Grassland/Pasture/Agricultural Land	88.0	68.8
Water	88.0	91.7
Forest	96.1	96.1
Overall Accuracy (%)	82.47	
Kappa	0.78	

5.3.3 LULC Changes

5.3.3.1 LULC changes in Kitwe District

The LULC change matrices in each of the periods 1990–2000, 2000–2010, and 2010–2020 are shown in Table 25, and those in the entire period of 1990–2020 are shown in Table 26.

In 1990–2000, major losses were observed in forest and grassland/pasture/agricultural land (Table 25). A total forest area of 112.66 km² was lost to the other classes, mainly grassland/pasture/agricultural land and built-up area. The area under forest gained approximately 70.62 km², primarily from grassland/pasture/agricultural land, built-up area, and bare land. In terms of total gain and total loss, approximately 118.19 km² of grass-land/pasture/agricultural land was

gained from other classes while about 89.50 km² of forest was lost to other classes. Grassland/pasture/agricultural land and forest was converted to built-up area due to urban expansion, and developmental activities such as mining. About 7.83 km² was converted from other classes to bare land, of which the major gain was from grassland/pasture/agricultural land. Large patches of bare land are concentrated in the western part of the study area (Figure 22). The area devoid of vegetation in the western region most likely represents an area with mining activities.

For the period 2000–2010, bare land, grassland/pasture/agricultural land, and built-up areas showed an increase, in contrast with a decrease in the change rate of the forest class (Table 25). Similar to the changes observed during 1990 and 2000, about 7.76 km² of bare land was converted from other classes. The total gain in built-up area was 13.97 km² from grassland/pasture/agricultural land and bare land. About 100.95 km² of forest was converted to grassland/pasture/agricultural land.

Table 25. LULC change matrices in the Kitwe District from 1990–2000, 2000–2010, and 2010–2020.

LULC Class	BL	BUA	F	GPAL	W	Total	Loss
1990/2000							
BL	13.87	2.25	0.36	4.18	0.24	20.90	7.03
BUA	0.50	31.61	0.37	4.58	0.01	37.06	5.45
F	0.29	2.83	253.68	108.30	1.25	366.34	112.66
GPAL	6.89	12.42	68.38	279.93	1.81	369.43	89.50
W	0.15	0.01	1.51	1.14	2.89	5.69	2.80
Total	21.70	49.11	324.30	398.12	6.19	799.43	217.44
Gain	7.83	17.51	70.62	118.19	3.30	217.44	
2000/2010							
BL	14.70	1.20	0.57	5.16	0.07	21.70	7.00
BUA	0.60	38.61	2.93	6.97	0.01	49.11	10.51
F	0.71	0.66	220.33	100.95	1.65	324.30	103.96
GPAL	6.42	12.12	89.47	289.02	1.10	398.12	109.11
W	0.02	0.00	1.60	1.81	2.76	6.19	3.43
Total	22.46	52.58	314.90	403.89	5.59	799.42	234.01
Gain	7.76	13.97	94.57	114.88	2.83	234.01	
2010/2020							
BL	12.45	1.86	1.20	6.90	0.06	22.46	10.01
BUA	1.35	46.52	0.70	4.01	0.00	52.58	6.06
F	6.11	4.51	177.88	124.14	2.26	314.90	137.02
GPAL	15.52	20.00	90.97	276.47	0.93	403.89	127.42
W	0.15	0.01	0.30	1.44	3.69	5.59	1.90
Total	35.58	72.90	271.04	412.96	6.94	799.42	282.42
Gain	23.13	26.38	93.17	136.49	3.25	282.42	

Note: BL = Bare land, BUA = Built-up area, F = Forest, GPAL = Grassland/pasture/agricultural land, W = Water.

Table 25 presents the change matrix for 2010–2020. During this period, approximately 90.97 km² of land was converted from grassland/pasture/agricultural land to forest. In contrast, approximately 124.14 km² of forest was degraded to grassland/pasture/agricultural land. Grassland/pasture/agricultural land changed into built-up area, bare land and water. Between 2010 and 2020, about 26.38 km² of built-up area and 23.13 km² of bare land was gained from other classes.

The results on the overall change show that 45.2% of the entire study area (360.92 of 799.42 km²) experienced LULC changes (Table 26). Bare land gained 117.5% of the area in 1990 in 2020 due to LULC conversion; of which the conversion from grass-land/pasture/agricultural had the largest share (66.9%), followed by forest (28.7%). The gain from built-up areas was not significant. A total of 53.3% of the forest in 1990 was converted to other LULC types, with grassland/pasture/agricultural land being the highest (93.2%) (Table 26). Built-up areas gained 108.9% of the area in 1990 in 2020, of which grassland/pasture/agricultural land had the highest conversion (81.2%), followed by forest (10.7%). Out of the total area of grassland/pasture/agricultural land in 1990, 40.2% was converted to other LULC types, with the greater proportion of change to forest (65.9%), followed by built-up area (22.1%) and bare land (11.1%). Compared with the other LULC types, water did not show a significant transition.

Table 26. Overall LULC change matrices in the Kitwe District from 1990 to 2020.

LULC Class	BL	BUA	F	GPAL	W	Total	Loss
1990/2020							
BL	11.02	3.28	1.19	5.04	0.37	20.90	9.89
BUA	0.76	32.53	0.49	3.28	0.01	37.06	4.53
F	7.05	4.30	171.03	181.94	2.03	366.34	195.31
GPAL	16.42	32.77	97.89	220.87	1.48	369.43	148.55
W	0.34	0.02	0.45	1.83	3.05	5.69	2.64
Total	35.58	72.90	271.04	412.96	6.94	799.42	360.92
Gain	24.56	40.37	100.02	192.09	3.89	360.92	

Note: BL = Bare land, BUA = Built-up area, F = forest, GPAL = Grassland/pasture/agricultural land, W = Water.

5.4 Discussion

5.4.1 LULC changes related to the mining activities

Table 27 indicates net changes in LULC from 1990–2000, 2000–2010, 2010–2020, and 1990–2020. The overall gain in the grassland/pasture/agricultural class over the last three decades was found to be 43.53 km² (Figure 22 and Table 27). The major reason for this change may be the conversion of forest area into grassland/pasture/agricultural land, mostly due to population increase (increased settlement and farmland) and infrastructure development (access roads, mining facilities, and residential areas).

Table 27. Summary of the net changes in LULC in each period (km²).

LULC Class	Net Change in 1990–2000	Net Change in 2000–2010	Net Change in 2010– 2020	Overall Change in 1990–2020
Bareland	0.79	0.76	13.11	14.67
Built-up Area	12.05	3.47	20.32	35.84
Grassland/Pasture/Agricultural Land	28.70	5.76	9.07	43.53
Water	0.50	-0.60	1.35	1.25
Forest	-42.04	-9.40	-43.86	-95.30

The forest class in the study area has a decreasing trend. During 1990 and 2020, the overall forest loss was 95.30 km² due to mineral exploration activities after the privatization of mines, forest harvesting in some plantations such as ZAFFICO for use in mines, poles for electricity supply, and house construction due to population increase (Figure 23).

Other studies have documented a decrease in vegetation cover due to mining activities (Aboka et al., 2018; Garai & Narayana, 2018; Huang et al., 2015; Obeng et al., 2019). However, the loss in forest was highest in 1990–2000 and 2010–2020 (42.04 and 43.86 km², respectively) (Figure 22 and Table 27). This was partly due to the drought conditions that were experienced in Zambia from 1992 to 1999 (for 1990–2000) (Libanda et al., 2019), settlement expansion due to both natural population growth and rural–urban migration, and timber harvesting for the construction of mining-related facilities, mostly during 2011–2020 (Figure 23).

The second significant change related to mining activities observed during the study period was bare land, which increased in the first period (1990–2000). This indicates that the area under mining increased, although a large portion of the bare land originated from historic mining before

1990 (Table 21). Figure 23a shows that copper production declined from 545,677 metric tons in 1990 to 221,167 metric tons in 2000. The decline in copper production can be attributed to the privatization of mines by the Zambian government. During 2000 and 2010 (second decade), the increase in bare land slowed slightly (Figure 23b). According to BOZ (2020), the copper production in Zambia increased from 221,167 metric tons in 2000 to 852,566 metric tons in 2010 (Figure 23a). After privatization, the copper production increase was due to the revamping of mines by new mine owners. In the third decade (2010–2020), bare land showed an increasing trend but was faster than in previous decades. The newly opened pit mine developed in the south-central part of Kitwe District was supported by an increase in copper production to 882,061 metric tons in 2020 (Figures 22 and 23a). Due to the need to increase copper production in the mines, labor increased, which resulted in migration from both rural areas and other districts, leading to a population increase (Figure 23a). As a result, built-up areas increased (Figures 22 and 23b, Table 21).

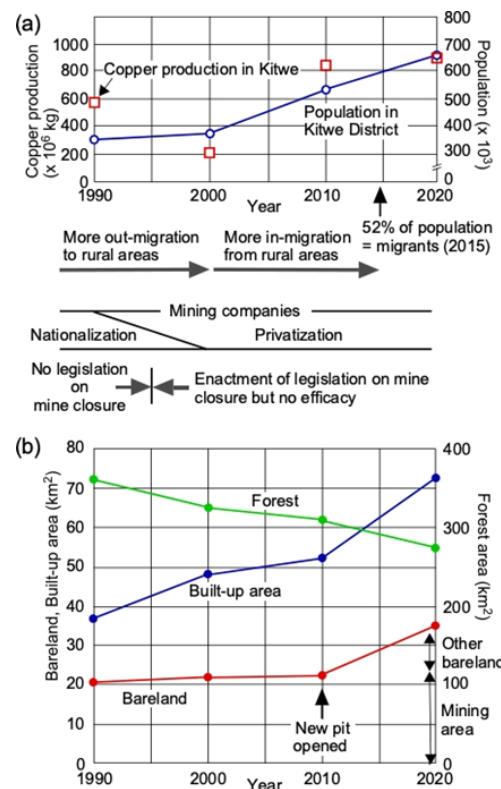


Figure 23. (a) Copper production in the Kitwe District from 1990 to 2020 (source: Bank of Zambia Annual Reports from 1995 to 2021), population in the Kitwe District from 1990 to 2020 (source: (Britannica, 2015) and (ZSA, 2022a)), and some events related to population dynamic and changes of mining-company ownership; and (b) changes of bareland and built-up area in the Kitwe District from 1990 to 2020 (source: this study).

The third class, which has experienced significant changes over the past three decades, was developed, consequently resulting in increased built-up area. During this period, urban expansion may have been linked to industrial development and population growth, as supported by the census data indicating the rapid population growth of the study area (Figure 23a). Concurrently, there was a close relationship among spatial urban expansion, the distance from mines, and the geometric center of a city. This suggests that the primary driving force for the urban expansion was mining.

The rapid population growth in the urban area of Kitwe was mainly derived from both natural growth and migration from other parts of the country in search of better employment (UN-HABITAT, 2009). The population of the study area almost doubled between 2000 and 2010 (Table 18 and Figure 23a), during the time when the mines were privatized. New mine owners invested more money in the mines and needed additional labor to maximize production. The observed land use pattern of built-up area and bare land gain (Table 27) agrees with research conducted elsewhere in the world that mining activities are performed, in which the increase in activities led to settlement expansion.

5.4.2 Future LULC changes

The trends of general decrease in forest coupled with subsequent increments of grassland/pasture/agricultural land, mines/bare land, and built-up areas in the study area are attributed to population expansion, rapid urbanization of the district, influx of small-scale mine operators (usually unemployed youth), and expansion of commercial (private) mining activities. When the changes in LULC shown in Table 27 are extrapolated, some potential threats are expected to arise in the Kitwe District in the near future (Figure 24 a, b, c, d and e). One future concern is the continuation of urban expansion due to the constant increase in population from both natural growth and rural-to-urban migration (Kawashima & Korcelli, 1982).

The United Nations predicts that Kitwe's population will be 1,005,000 in 2030 (Population Stat, 2023). In general, urban expansion negatively impacts the environment as more land and building materials are required for the construction of houses and other buildings (Figure 24) (Enshassi et al., 2014). This means that more forest resources are needed to construct houses and other buildings, which increases pressure on the remaining forests in the district (Contreras-Hermosilla, 2000). Second, as the population increases, the demand for food also increases. This implies that grassland/pasture/agricultural land is likely to increase in the future to meet the demand for food, with further pressure on forests, as land needs to be cleared when preparing for cultivation (Mwitwa et al., 2016). Third, due to the current increase in the mining area and copper production, new bare land (mining area) will be created, which implies that there will be further loss in the area

covered by forest and vegetation among the grassland/pasture/agricultural land classes (Table 27 and Figure 24).

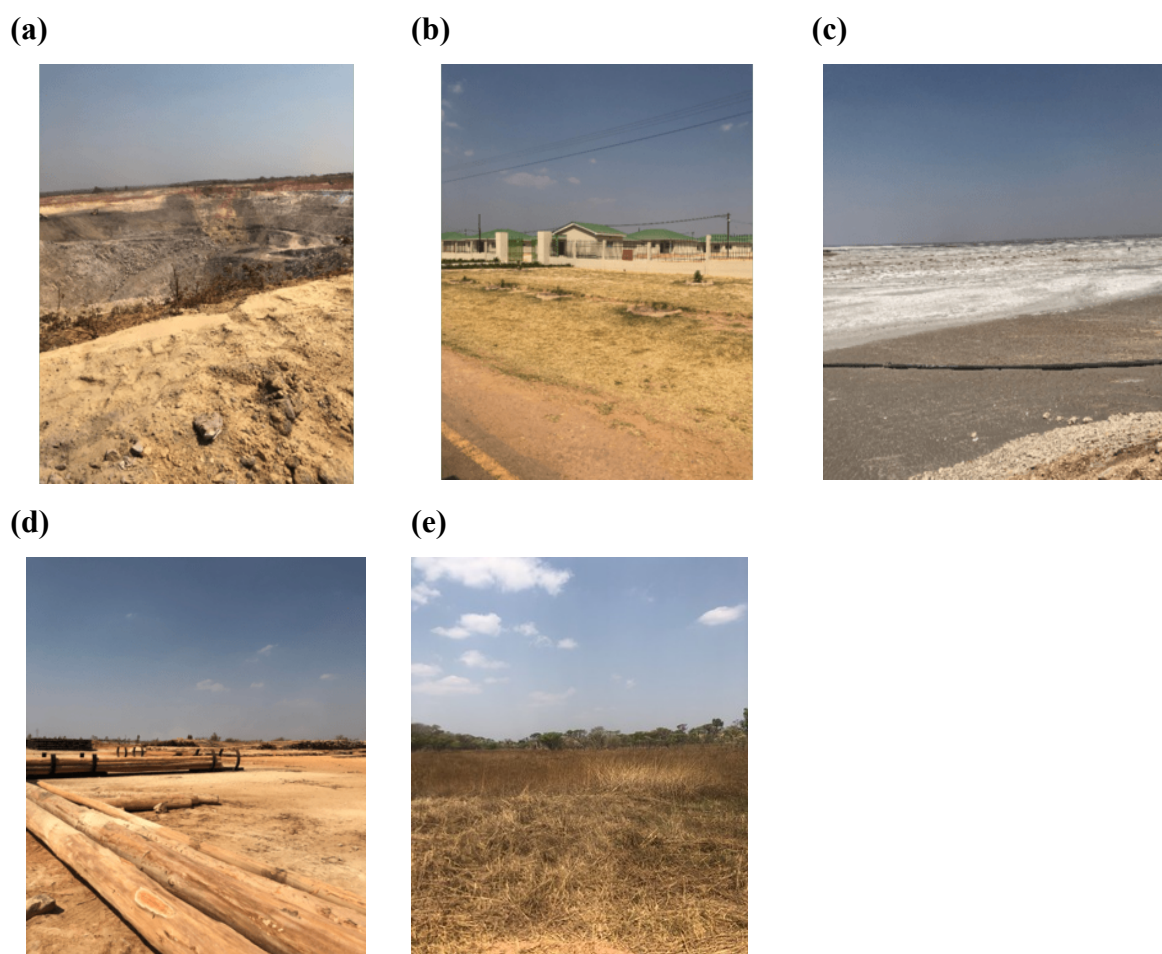


Figure 24. Future projection resulting from (a) increase in mining activities (open pit), leading to an increase (b) built-up, (b) bareland (tailing) (c) forest loss due to timber harvesting, and (d) Grassland/pasture/agricultural land.

When mineral resources are eventually depleted, mines will be closed. This implies that tailings dams and open pits should also be considered for sustainable closure. Proper closure of these sites involves reclaiming and rehabilitating the land to ensure it is safe and stable for future use. This process helps in mitigating the long-term environmental impacts associated with abandoned mines, such as soil erosion, water contamination, and habitat destruction (IIED, 2002). Sustainable closure practices can include re-vegetation, water treatment, and structural stabilization of tailings dams to prevent collapse and leakage (Peck, 2005). By addressing these issues, the overall environmental health of the region can be preserved, contributing to the sustainable development goals and improving the quality of life for local communities.

In trying to prepare for mine closure, the mines in the Kitwe district have undertaken initiatives to revegetate the tailings dams (figure 25 a and b) and turn the old Mindolo open pit mine

into a recreation center (Figure 25 c and d). These efforts not only aim to rehabilitate the land but also to provide new amenities and green spaces for the local community. Such projects help in creating a more sustainable post-mining landscape, offering recreational opportunities and enhancing the overall aesthetic value of the area. This approach demonstrates a commitment to environmental stewardship and community development, setting a positive example for other mining regions.

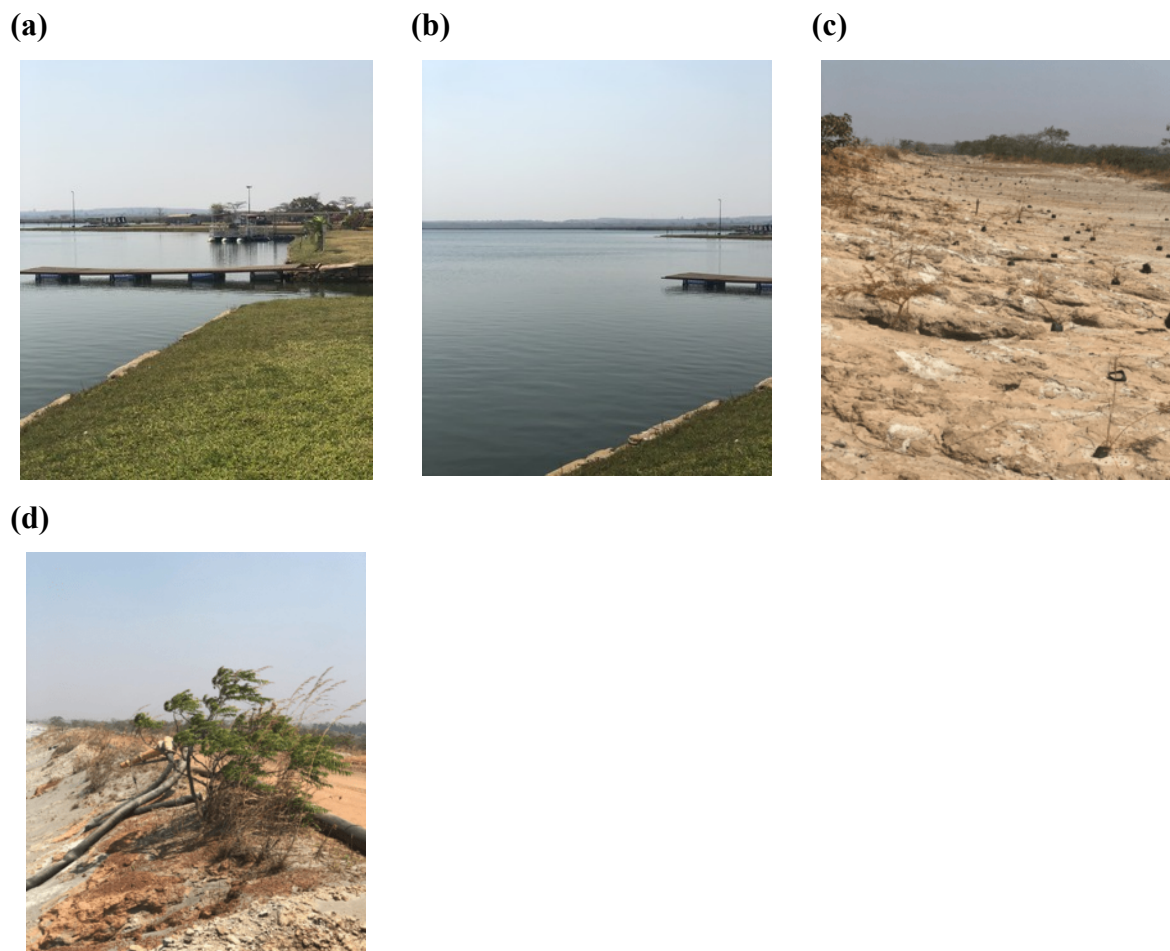


Figure 25. Initiatives by the mine to rehabilitate the mining area through repurposing old open pit mines, (a and b – recreational centre) and revegetation of tailings dams (c and d).

5.5 Conclusion

The remote sensing and GIS tools were adopted to analyze LULC changes in Kitwe District, Zambia for the first time. This study identified LULC change patterns for 1990–2020. Significant changes in bare land (increased from 20.90 km² in 1990 to 35.58 km² in 2020, with 64.5% (22.95 km² in 2020) being mining area), built-up area (increased from 37.06 km² to 72.90 km²), and grassland/pasture/agricultural area (increased from 369.43 km² to 412.96 km²) were observed. Forest decreased from 366.34 km² in 1990 to 271.04 km² in 2020. Population and mining are the

main drivers of the overall increase in built-up areas and bare land in the study area. To mitigate the negative impacts of LULC change and sustain community livelihoods, the interactions between the geoecological and socioeconomic processes leading to LULC change and associated land degradation must be understood. This study suggests that ongoing programs for government-initiated sustainable land management should be strengthened. Effective collaboration and coordination among governmental agencies are essential to address the multifaceted challenges posed by rapid urban expansion and mining activities. By integrating LULC analysis into policymaking, stakeholders can proactively identify and mitigate the environmental risks associated with mining, promote sustainable land-use practices, and safeguard critical ecosystems for future generations.

6. Legal issues related to mine closure in Zambia

6.1 Introduction

Zambia is burdened with abundant unsafe mine waste dumps, mostly from the previous mining operations, without rehabilitation (Simutanyi, 2008b). Mine waste dumps, constituting environmental legacies, are commonly found in Copperbelt Province (>100 km²) and Central Province (2.5 km²). Their presence has resulted in a missed opportunity in forestry, agriculture, livestock grazing, and housing for the local population (Simutanyi, 2008b). During the mid-1990s privatization of mines, the state entered agreements with new mine owners, guaranteeing that none of the historical environmental legacies or their impacts would be the responsibility of the new owners (Sikamo et al., 2016b). Instead, the state, through the ZCCM, would take care of rehabilitation actions and monitor historical sites (Fraser & Larmer, 2010a; Lindahl, 2014b). Unfortunately, this has yet to be achieved (Sikamo et al., 2016b).

A comprehensive legislative framework to govern environmentally sound mine closures had been missing in Zambia before 1995 (World Bank Group, 2016b). However, the privatization of mines in the mid- and late-1990s made the state to realize the need for provision of legal guidance to new mine owners regarding the expected mine closure standards. Consequently, various mine closure provisions were incorporated into different mining-related statutes (IIED, 2002b). Mainly, these provisions focused on environmental rehabilitation, reflecting the fundamental perception on mine closure during that period (Clark & Clark, 2005). Since 1995, when the country enacted legislation that highlighted mine closures, there have been no substantial changes in the legislation. Despite the mine closure framework being developed in response to the closure of mines at that time, it has not been effectively implemented. The state, which accepted most of the environmental liabilities during the privatization process, has particularly struggled with its enforcement (Clark & Clark, 2005). Nowadays, the concept of mine closures extends beyond just environmental considerations. It now includes aspects related to promoting the social and economic well-being of local mining communities after closure (Starke, 2002b). In 2016, a document was prepared to illustrate the correlation between mining activities and the United Nations Sustainable Development Goals established in 2015. The document utilized examples from ongoing industry initiatives, along with knowledge and resources in the field of sustainable development, to map out this relationship (Columbia Center on Sustainable Investment, 2016).

In Zambia, the urgency to address mine closure impacts has intensified due to the recent shutdowns of multiple mining operations as a result of the decline in copper prices and the power shortage experienced (AFRODAD, 2016). Two mines operated by Glencore and China Non-

Ferrous Mining Corporation Limited in Zambia, for instance, were placed under care and maintenance in 2015 (Phiri Darius, 2015). The abrupt mine closures necessitate a comprehensive legal framework to guide the transition of mines toward sustainable closure practices.

Therefore, this study aims to critically assess the existing Zambian legal framework on mine closure, with a particular focus on its adequacy, effectiveness, and alignment with the principles of sustainable development. In light of the evolving economic and environmental landscape, this research seeks to provide valuable insights into refining and strengthening the legal mechanisms governing mine closure in Zambia. The above-mentioned aim of this research shall be achieved through completing the following set of sequential objectives;

1. Document in details all the mine closure legislations within the Zambian Legal framework on mine closure (statutes applicable to mine closure in Zambia): This objective focuses on compiling a comprehensive and detailed inventory of all existing legislations pertaining to mine closure within the Zambian legal system. This will serve as a foundation for evaluating their adequacy and effectiveness in promoting sustainable development.
2. Assess the adequacy of the Zambian legal framework on mine closure: To evaluate whether the current legal standards and regulations in Zambia comprehensively address all necessary aspects of mine closure, including environmental, economic, and social factors.
3. Evaluate the effectiveness of the Zambian legal framework on mine closure: To investigate the practical implementation and enforcement of mine closure laws in Zambia, analyzing how effectively these laws have been applied in past and ongoing mine closure scenarios.

6.2 Data and methods (collecting and analyzing legal documents on mine closure)

Legal documents on mine closures in Zambia were retrieved from Blackhall's Laws of Zambia (<https://zambialaws.com>), which provides free access to Zambian laws containing primary and secondary legislation (Blackhall, 2019). All acts and subsidiary legislations were enacted in terms of principal legislation. The website was chosen due to the presentation of all acts in fully revised and annotated forms, and its online database is updated in accordance with the publication of new and amended legislation (Blackhall, 2019). Blackhall's Laws of Zambia are intended as tools for both the legal community and public. It is arranged such that any enactment can be easily searched for on the Internet in chronological and alphabetical order with annotated amendments.

The laws and policies regulating corporate environmental practices in Zambia, with an emphasis on mining, were examined. The analysis of the legal and regulatory framework involved an examination of the extent to which it met international best practices and standards of corporate

conduct and to which self-regulatory mechanisms were accommodated under the framework. This was accomplished by reviewing mining-related acts, laws, and relevant statutes regarding corporate environmental practices in Zambia.

6.3 Results

6.3.1 Statutes Applicable to Mine Closure in Zambia

6.3.1.1 The Mines Act 2015

Key legislation that governs mining operations in the country is the Mines and Minerals Development Act of 2015 (referred to as 'the Mines Act'). The statute is premised on the foundational principles of the concept of mine closure (Government of Zambia, 2015a). Notably, section 4 of the Mines Act identifies the doctrine of sustainable development. This encourages, more so, the development and utilization of mineral resources in line with current and future generations' aspirations. This meant that by law, it has been provided that this mineral exploitation should take place under strict adherence to safety, health, and environmental protection (Government of Zambia, 2015a).

Specific provisions regarding mine closure are outlined in sections 81, 82, 83, and 86 of the Mines Act. Section 81 outlines the conditions attached to the granting or renewal of a mining right by the Minister of Mines (Government of Zambia, 2015a). Conditions governing such include, among others, rehabilitation, leveling, and re-grassing, as well as re-forestry or contouring of areas affected by exploration, mining, or mineral processing operations. It also includes filling, sealing, or fencing of such excavations, shafts, and tunnels. Applicants or license holders are required to deposit funds to ensure compliance with these conditions (Blackhall, 2019).

Section 82 goes further to provide that a holder of mining or mineral processing right shall remove all associated infrastructure from the land that ceases to be under the jurisdiction of the mining right or mineral processing license. This should be done within six months from the cessation of the right or license or within such a period as may be prescribed by the Director of Mines Safety. Section 83 covers how the state should dispose of any such infrastructure that remains and, in the proceeds from such a sale (Government of Zambia, 2011a).

Section 86 creates the Environmental Protection Fund (hereinafter referred to as "the Fund") and gives a brief of how the funds contributed to it will be allocated (Government of Zambia, 2011a). This will be further discussed in subsequent sections. What is interesting in the new Mines Act is that, for the first time, it specifically provides that a minister may make regulations prescribing or

related to decommissioning or mine closure. No such regulations, however, have been made at the time of this study.

6.3.1.2 The Environmental Management Act 2011

The Environmental Management Act of 2011 is the primary law addressing the protection of the environment from human harm (Government of Zambia, 2011a). While the word 'closure' of the mine is not expressly used in the Environmental Act, there are relevant sections. Section 5, for instance, contains that people have a duty to conserve and develop their environment. Section 6 presents environmental management concepts, which include the polluter pays principle, the need for public participation in the formulation of environmental regulation, long-term planning for the reduction of adverse environmental effects, and sustainable development (Government of Zambia, 2011a).

Of particular interest to mine closure is Section 29 of the Environmental Act. This section prohibits carrying out projects with potential adverse environmental impacts without inscribed authorization from the Zambia Environmental Agency (ZEMA) (Government of Zambia, 2011a). This is an authorization based on assessment results from the Environmental Impact Statement (EIS). In addition, other authorities that would be excluded from the licenses without ZEMA approval include those of the Ministry of Mines and Mineral Development (Government of Zambia, 2011a).

6.3.1.3 The Mines Environmental Regulations 1997

The Mines and Minerals (Environmental) Regulations, 1997, referred to herein as the Mines Environmental Regulations, provide much insight into the mine-closure process in Zambia. Part 3, Regulations 3 to 5, impose a general duty to submit either an Environmental Project Brief (EPB) or an Environmental Impact Statement (EIS) to the Director before carrying out any prospecting, exploration, or mining activities. Particular emphasis is placed on Regulation 5, which specifies what will be contained in the EIS for mine closure (Government of Zambia, 1997a). Regulation 5(1) of the EIS stipulates:

- (a) A concise overview of the project's environmental impact,
- (b) An environmental management plan,
- (c) A rehabilitation and management strategy, and
- (d) The estimated environmental protection cost.

Further elaboration is provided in regulation 5(2) which clarifies that the environmental protection cost, mentioned in (d) above, covers:

- (a) Operational costs for safeguarding the environment over the mine's entire lifespan,
- (b) Expenses for rehabilitating the mine throughout its lifecycle,
- (c) Decommissioning costs, and
- (d) Post-mine closure environmental protection costs.

Regulation 5 should be read together with Regulations 65 and 66. Regulation 65 requires developers to make contributions to the Fund established under section 86 of the Mines Act. Schedule 11 of Regulation 66 classifies the performance of contributing developers, which will be categorized in the main under three groups: Rehabilitation, Environmental Compliance, and Operational Environmental Protection (Government of Zambia, 1997a).

The Environmental Fund primarily consists of payments by developers for mine rehabilitation costs per regulation 5(2). Schedule 3 stipulates estimates of the cost of rehabilitation by a developer of a new project or an acceptable environmental management plan (or approved amendments thereof) for an existing mine will be made over five years from the commencement of the mining operation (Government of Zambia, 1997a). Payments will be annual and set at 20% of the total cost. For mines with a duration of fewer than five years, there would be proportional payment. Further details on the estimation of rehabilitation costs are in Schedule 3.

Payments will be annual and set at 20% of the total cost. For mines with a duration of fewer than five years, there would be proportional payment. Further details on the estimation of rehabilitation costs are in Schedule 3.

The regulations also cover the issues regarding the closure of mine dump (regulations 20, 22, 24) and itself the closure of mine (regulation 6). Regulation 6 allows developers to request partial or complete mine closure, necessitating an independent audit of the surrounding environment. Mines should be closed within 60 days of the application, subject to meeting all regulations' conditions. The Director shall then issue a closure certificate; thereafter, the Minister shall revoke the right or permit to mine (Government of Zambia, 1997a).

These regulations complement the Environmental Management Act's mining regulations by governing environmental interactions. They mandate an Environmental Impact Assessment (EIA) during mining license applications, requiring mitigation measures for environmental damage. They also cover dumping, emission standards, hazardous materials, and the Environmental Protection Fund (Government of Zambia, 1997a).

6.3.1.4 Mines and Minerals (Environmental Protection Fund) Regulations 1998

The Mines and Minerals (Environmental Protection Fund) Regulations of 1998, hereinafter referred to as the "Environmental Protection Fund Regulations," commence with the object clauses of the Fund (Government of Zambia, 1998a). These could be summarized in the form of: First, the assurance that the EIA will be conducted by the developer in line with the Mines Environmental Regulations. Second, ensure standing liability of the government does not stand in case the licensee of a mining permit defaults on the rehabilitation of an area in the future (Government of Zambia, 1998a).

The subsequent sections of the Environmental Protection Fund Regulations describe the creation of the Environmental Protection Fund Committee (referred to as the 'Committee'). This Committee is vested with the authority to oversee and manage the Fund. Its members are appointed by the Minister according to regulation 3(6). The responsibilities of the Committee, detailed in regulation 3(5), encompass various tasks: making determinations regarding the Fund's usage, decisions related to investment matters concerning the Fund, endorsing withdrawals of funds from the Fund, and ensuring overall effective management of the Fund (Government of Zambia, 1998a).

As for the practical scope for application of the Fund, Regulation 7(1) provides that the amount that will be necessary for the purpose of attaining the objectives of the Fund shall be drawn from the Fund itself. Additionally, the Fund is earmarked to license holders upon application, particularly upon the occasion of closing of a mine site (Government of Zambia, 1998a). These refunds are subject to any outstanding amounts due as per the Mines Act.

6.3.2 Assessment of the legal framework on mine closure

A review of the Zambian legal framework described above found that these pieces of legislation have inadequate provisions regarding mine closure planning, as the reference of (World Bank Group, 2016b) pointed out. In Zambia, the mine closure planning process is integrated into the Environmental Impact Assessment (EIA) process. Specifically, according to the Environmental Act outlined in the Mines Environmental Regulations, developers must secure ZEMA's written approval for an Environmental Impact Statement (EIS) or an Environmental Project Brief (EPB) before initiating any operations (Table 28) (Sishekanu & Katati, 2021). The EIS is expected to include specific information related to mine closures.

Requirement of providing a rehabilitation plan should be considered to adhere to best practices. However, the contents of the rehabilitation plan do not have a guideline. In general, rehabilitation plans primarily focus on specific environmental restoration activities (DMP and EPA, 2015). Relying solely on a rehabilitation plan for the entire mine closure process is inadequate if it

addresses only the environmental aspect. Adhering to best practices requires a closure plan to offer comprehensive details, which ensures the sustainable closure of a mine by covering all aspects for effectiveness (DMP & EPA, 2015).

In terms of environmental, health, and safety criteria, the Zambian mine closure regulations generally lack specific technical requirements for comprehensive environmental rehabilitation, typically deferring to regulations (Silwamba et al., 2020). Various applicable statutes contain general provisions on specific aspects. Developers, under the Mines Act, are obligated to clear all plants and equipment from land not covered by mining rights (Government of Zambia, 2015b). Commitments from developers include the sealing or fencing of excavations, shafts, tunnels, and filling in (Government of Zambia, 2011b). Developers were also expected to include a post-mining topography plan for physical stability within the Environmental Impact Statement (EIS) (Government of Zambia, 1998b).

Other mine closure statutes in Zambia include relinquishment and post-closure obligations. However, the legal framework for mine closures seems inadequate in addressing the relinquishment criteria recommended by international best practices (Table 28) (Ndulo, 1987). The legal framework specifically offers broad statements about the criteria for relinquishment and the closure certification process (IIED, 2002b). As previously noted, mine environmental regulations only specify the actual closure of a mine (IIED, 2002b). As mentioned previously, mine environmental regulations only stipulate the actual closure of a mine.

Within its legal framework, Zambia does not address socioeconomic requirements concerning mine closures (Table 28) (Kangwa, 2001). Nevertheless, the Environmental Protection and Pollution Control (Environmental Impact Assessment) Regulations of 1997 ("EIA Regulations") mandate developers to incorporate the project's socioeconomic impacts in the EIS (Government of Zambia, 1997b).

During mine closures, public participation and stakeholder engagement are additional regulations to consider (Pring, 2002). Public participation and stakeholder engagement are integral to the EIA process, which includes mine closure considerations. However, there is no specific requirement for special attention to mine closure in the EIS. Public participation and stakeholder engagement occur at different stages of the EIA process. External stakeholders or the public lack opportunities to participate in alterations to the EIS during its validity. Consequently, this often results in the absence of stakeholder/public involvement in the changes to closure provisions made throughout the mine's lifespan (Government of Zambia, 2011b).

Table 28. Summary of specific provisions of statutes applicable to mine closure in Zambia and their gaps.

Statute	Provision	Focus	Gap
The Mines Environmental Regulations 1997	Regulation 5(2)	Environmental Project Brief (EPB) or an EIS	Limited mine closure planning stipulations required to be included in the EIS
	Regulation 6	Mine closure certificate issuance for any mine closed and the mining right or permit	
	Regulation 22	Checklist on the contents of a decommissioning and closure plan for mine dump	Inadequate provisions directly addressing the review of mine closure provisions
	Regulation 65	Developer's contribution to the Fund established under section 86 of the Mines Act	Relinquishment and post-closure obligations
	Regulation 66	Classifying developers to determine their fund contribution.	Socio-economic requirements
Environmental Protection Fund Regulations 1998	Regulation 3(5)	Approving withdrawals of funds from the Fund and the overall good management of the Fund	Lack of diverse financial assurance forms
	Regulation 7(1)	Developers are to be paid from the Fund money required for the objectives of the Fund and refunds to holders of licenses in accordance with the Mines Act	Ineffectiveness of concession provision for environmental protection fund contributions
The Environmental Management Act 2011	Section 5	Citizen's duty to safeguard and enhance the environment	Inadequate provisions regarding mine closure planning/plans
	Section 29	Environmental Impact Statement (EIS).	Stakeholder engagement and public participation
The Mines and Minerals Development Act, 2015	Section 4	Exploitation of minerals shall ensure safety, health, and environmental protection	
	Section 81	Rehabilitation, leveling, re-grassing, reforestation or contouring	No guidance as to what this rehabilitation plan should contain
	Section 82	Clear away all mining and mineral processing plant	
	Section 83	Backing up section 82 by the government disposing	
	Section 86	Environmental protection fund	

6.4 Discussion

One key legal framework governing mine closure in Zambia is the Mines and Minerals (Environmental) Regulations of 1997, also known as the Mines Environmental Regulations (Government of Zambia, 1997a). This legislation is particularly informative regarding mine closures in the country, mandating developers to submit an environmental project brief (EPB) or an Environmental Impact Statement (EIS) to the director of mine safety prior to engaging in any mining related activity (Government of Zambia, 1997a).

The second statute applicable to mine closures in Zambia is the Environmental Protection Fund Regulations 1998. Environmental Protection Fund regulations has two objectives for the fund.

The first objective is to assure to the director (mine safety) that the EIS shall be executed according to the Mines Environmental Regulations. The second objective is to safeguard the government from the potential obligation to carry out the rehabilitation of a mining site when this responsibility is neglected by mining license holders (Government of Zambia, 1998a).

The Environmental Management Act 2011 (“Environmental Act”) is another statute that looks at mine closure in Zambia. It is the principal legislation addressing comprehensive environmental protection from human activities (Government of Zambia, 2011b). It prohibits individuals from initiating projects that could harm the environment without written consent from the Zambia Environmental Management Agency (ZEMA) (Government of Zambia, 2011b). ZEMA grants this approval after assessing the Environmental Impact Statement (EIS). The Environmental Act's mandate for an environmental impact assessment (EIA) is crucial for mine closures, as closure commitments are specified in the EIS (Government of Zambia, 2011b).

Lastly, the primary legislation governing mining activities in Zambia is the Mines and Minerals Development Act of 2015, commonly referred to as the "Mines Act" (Government of Zambia, 2015b). In relation to mine closures, the Mines Act acknowledges specific principles that form the foundation of the current understanding of such closures. Section 4 emphasizes the principles of sustainable development, urging the utilization and development of mineral resources in a way that takes into account the needs of both present and future generations (Government of Zambia, 2015b). It also examines the conditions under which a mining right is granted or renewed, including requirements for leveling, re-grassing, reforestation affected land from exploration, mining, or mineral processing operations, as well as the filling, sealing, or fencing of excavations, shafts, tunnels, and rehabilitation (Government of Zambia, 2015b).

6.5 Conclusion

In conclusion, Chapter 6 of this research carefully assessed the complex mine closure legal framework in Zambia. The result showed a critical period in the mid-1990s when the Zambian government, recognizing the urgent need for a regulatory basis for mine closure practices, initiated steps to establish environmental rehabilitation standards. Yet these post-1995 legal advances, the actual legal guidelines in place, have seen clear misalignment with their effective enforcement on the ground. The discrepancy clearly indicates a systematic gap between legislative intention and actuality as practiced on the mine ground.

This chapter explained in detail how, despite the mine closure legislations provided in some of the Zambian statutes, the implementation has been disadvantaged due to enforcement challenges and further, how the government has come to inherit historical environmental liabilities during the

privatization of the mining sector. These are the long-term presence of unrehabilitated mine waste dumps across the landscape, demonstrating environmental and social burdens imposed on affected communities that prevent viable land use such as forestry, agriculture, and residential development from taking place. These issues are not only increasing their scale, but they highlight the pressing need for effective mine closure practice.

Drawing to a close, the chapter rendered a reflective critique of Zambia's effort towards having a solid legal framework for mine closure. That goes on to imply that although legislative frameworks have been developed, their effective realization in ensuring sustainability underpinning mine closure remains a mere abstraction. This dissertation is an argument giving an imperative for stronger enforcement mechanisms, enhanced legal compliance, and seamless incorporation of the sustainable development principle in the legal and operational spheres of the mining sector. Therefore, this work of study contributes to that discussion on mine closure, providing the basis for future work to narrow the gap in legislative aspirations versus practical outcomes related to sustainable mine practices

7. General discussion

7.1 Zambian mine closure legislation against environmental principles and indicators of sustainable development

This dissertation provides a comprehensive assessment of mine closure practices in Zambia. It focuses on key aspects such as professionals' experience levels, work environments, the state of environmental indicators, closure planning, and awareness of closure legislation. Therefore, findings from this research presents valuable insights into the current landscape of mine closure in Zambia, shedding more light on challenges, opportunities, and areas for improvement within the mining sector.

The demographic characteristics of the study participants show a majority of male representation in the mining sector, indicating ongoing gender imbalances (IGF & IISD, 2023). However, the diverse range of academic backgrounds, with a major percentage holding Bachelor's degrees, Master's degrees, and PhD qualifications, suggests a highly educated sample, providing a good understanding of closure practices. Despite this, there are concerns about gaps in expertise within government and research sectors, highlighting potential challenges in achieving effective mine closure.

In terms of respondents' experience and work environments, the findings shed light on the distribution of expertise and dynamics within the sector, emphasizing that mining closure in Zambia depends on the private sector with the majority of consultants experiencing mine closure at all mine closure phase and in different minerals particularly in major economic minerals such as copper and cobalt. However, gaps in expertise within government and research sectors pose challenges, highlighting the need for a more diversified approach, especially for smaller mining operations. Collaboration among stakeholders is important to address gaps and improve the effectiveness of closure efforts, emphasizing the need for comprehensive strategies and greater involvement from all sectors (Kozłowska-Woszczycka & Pactwa, 2022).

Furthermore, the examination of environmental indicators in Zambia's mining sector revealed significant challenges and opportunities for enhancing sustainability in closure planning. It has revealed the fact that there are weaknesses in baseline studies, as well as variations in perspective on the relationship of environmental indicators to final land use intentions, hence the incorporation of environmental indicators is not well integrated into the decision-making processes. The lack of robust baseline data hinders effective planning and restoration efforts, confusion between rehabilitation and closure plans highlights the need for clarity and alignment with legislative frameworks (IGF & IISD, 2020). The consensus among respondents on ideal environmental indicators (water quality, air quality, and LULC) highlights the importance of comprehensive monitoring programs integrated into approved environmental management plans to guide operational practices and inform closure planning effectively.

Regarding mine closure and closure planning, the study identified a mixed perspective on the adequacy of closure plans, with concerns raised about the feasibility and realism of these plans. Persistent environmental impacts pose significant challenges, emphasizing the need for ongoing monitoring and maintenance post-closure. Addressing these challenges requires a proactive and comprehensive approach initiated during the feasibility phase, with financial responsibility borne by mining companies in accordance with the 'polluter pays principle', (Government of Zambia, 2011b).

Finally, the awareness of Zambian mine closure legislation among professionals in the mining sector is essential for ensuring compliance and promoting sustainable closure practices. The study revealed a concerning decline in familiarity with specific pieces of legislation (MMR (EPF), 1998 and MMR (EPF), 1997), emphasizing the need for ongoing education and training within the industry to ensure alignment with regulatory requirements. Promoting substantial knowledge of closure legislation within the professional field is crucial for fostering a culture of compliance and responsibility, ultimately contributing to the country's overall development goals and environmental stewardship (Peck, 2005).

This provided a complete understanding of mine closure practices in Zambia, offering insights into challenges and opportunities for improvement. By addressing gaps in expertise, enhancing closure planning practices, and promoting awareness of closure legislation, the mining sector can move towards more sustainable and ethical practices aligned with global standards, ultimately contributing to the country's overall development goals and environmental stewardship. This can also be achieved through understanding the impacts the mines are having on the environment. One way to assess the impact is through the assessment of LULC changes caused by the mines. Therefore, I assessed the LULC dynamics in the Copperbelt Province using the case study of Kitwe District.

7.2 Land Use and Land Cover dynamics in Copperbelt Province, Zambia: A case study of Kitwe District due to mining activities

The study conducted a comprehensive analysis of Land Use and Land Cover (LULC) dynamics in Kitwe District, Copperbelt Province, Zambia, focusing on the impacts of mining activities on environmental changes. Using remote sensing techniques and geographic information systems, the research mapped LULC changes from 1990 to 2020, providing valuable insights into the changing landscape due to mining activities. The findings indicated significant modifications in LULC classes over the study period, with notable changes observed in forest cover, bare land, grassland/pasture/agricultural land, and built-up areas.

One of the key findings of the study is the substantial loss of forest cover (95.30 km²), primarily attributed to mineral exploration activities following the privatization of mines (Table 27). The

conversion of forested areas into other land use types, coupled with factors such as drought conditions, settlement expansion, and timber harvesting, contributed to the decline in forest cover. Similarly, an increase in bare land, particularly in areas under mining activities, reflects the expansion of mining operations over the years (Botezan et al., 2020). The rise in copper production, driven by the revamping of mines and increased labor demand, resulted in urban expansion and the development of built-up areas (Figure 23).

The study also highlighted the implications of these LULC changes for future environmental sustainability and land use planning in Kitwe District. Continued urban expansion, population growth, and agricultural expansion are expected to further pressure forest resources and worsen environmental degradation. The expansion of mining areas is projected to lead to additional loss of forest cover and vegetation, further altering the landscape.

Overall, the research highlighted the urgent need for proactive land use planning and sustainable mining practices to mitigate the adverse environmental impacts of LULC changes in Kitwe District. By providing decision-makers and land use planners with baseline knowledge on LULC changes, the study offers valuable insights for future mining legislation and effective execution of regulatory frameworks to ensure sustainable mine closure. Addressing these challenges requires collaborative efforts from government agencies, mining companies, local communities, and other stakeholders to promote responsible land use practices and environmental stewardship in the mining sector. These challenges can be addressed through the legal framework. Therefore, it was necessary to assess the comprehensiveness and effectiveness of the legal framework on mine closure in Zambia.

7.3 Legal issues related to mine closure in Zambia

The assessment of the legal framework on mine closure in Zambia revealed several inadequacies that may hinder the effective planning and execution of sustainable mine closure practices. While the existing legislation addresses certain aspects of mine closure, such as the submission of Environmental Impact Statements (EIS) or Environmental Project Briefs (EPB) to regulatory authorities such as the Zambia Environmental Management Agency (ZEMA), it lacks comprehensive provisions for rehabilitation planning. The absence of clear guidelines for the contents of rehabilitation plans poses a significant challenge, as rehabilitation plans often focus solely on environmental restoration activities, neglecting other crucial aspects essential for sustainable closure. Thus, there is a pressing need to revise the legal framework to ensure that closure plans encompass all necessary components for effective and sustainable mine closure (Peck, 2005).

Moreover, the Zambian mine closure regulations generally lack specific technical requirements for comprehensive environmental rehabilitation, relying instead on broad statements and provisions

within various statutes (Wambwa et al., 2023). While developers are obligated to undertake certain activities, such as clearing plants and equipment from mining sites and sealing excavations, shafts, and tunnels, there is a lack of detailed guidance on post-closure obligations and relinquishment criteria. This deficiency may lead to ambiguity and inconsistency in closure practices, potentially compromising environmental and safety standards (Gankhuyag & Gregoire, 2018). Therefore, enhancing the legal framework to incorporate specific technical requirements and guidelines for environmental rehabilitation and post-closure obligations is essential to promote responsible mining practices and ensure the long-term sustainability of mining operations (Wambwa et al., 2023).

Furthermore, the current legal framework in Zambia inadequately addresses socioeconomic considerations related to mine closures. While developers are required to assess the socioeconomic impacts of mining projects in EIS, there is no specific requirement for incorporating socioeconomic aspects into closure planning (MMMD, 2016). Additionally, public participation and stakeholder engagement, crucial elements for fostering transparency and accountability in the closure process, lack specific provisions for mine closures within the existing regulations (Kozłowska-Woszczycka & Pactwa, 2022). To address these shortcomings, it is imperative to amend the legal framework to include provisions for socioeconomic impact assessments and stakeholder engagement specific to mine closure activities. By incorporating these elements into the legal framework, Zambia can enhance the effectiveness of mine closure practices, promote sustainable development, and mitigate adverse impacts on local communities and the environment.

7.4 Current situation related to sustainable mine closure practices in the Copperbelt Province, Zambia

The Copperbelt Province of Zambia, which was once rich in copper deposits and minerals, has reached that crossroad where the principles of sustainable mine closure outweigh all other priorities. This has led to the region being subjected to land pollution, deforestation, and changes in the ecosystem due to many years of mining activities. Sustainable mine closure practices focus on land reclamation through reforestation, soil treatment, and development of sustainable land use plans that restore the ecological balance to prevent any long-term damage. The Zambian government has been proactive in developing a regulatory framework under the Mines and Minerals Development Act that makes detailed mine closure plans a mandatory condition with an emphasis on the environment and support for the community. However, the region also has some constraints, such as limited financial resources and technological capabilities; hence, effective coordination of stakeholders is paramount.

The overall socio-economic impacts of mine closures in the Copperbelt are similarly critical. Mining is very vital to the local economy; therefore, its closure would likely lead to great economic

disruptions. Sustainable practices should, therefore, evolve to include economic diversification strategies, such as the retraining of ex-mine workers and other alternative livelihood developments in agriculture or tourism. All these are meant to cultivate new economic opportunities and keep social stability alive. Some challenges remain, with the first being the dearth of environmental impact data and additional needs for technological development, but these also provide some opportunities for innovation and collaboration. Remote sensing and related emerging technologies, in addition to collaborations among governmental bodies, international organizations, and private companies, can significantly monitor, share resources, and promote best practices for a sustainable future of the Copperbelt.

7.5 Gap between sustainability principle, legislation, and closure practice

As outlined in the research objectives (Section 1.3), it was essential to pinpoint the gaps between sustainability principles and Zambian mine closure legislation, as well as the gaps between these legislated principles and their actual implementation on the ground, as assessed through a survey of closure experts. The shortcomings identified in this regard are documented in Table 29 below.

Table 29. The ratification of sustainability principles in Zambian legislation and the shortcomings of the ‘on-the-ground’ implementation thereof (As per in Section 2.3.5 list of principles of sustainable development; Zambian mine closure legislation identified in Sections 4.5 and based on Chapter 4 and 6: results and discussion).

Key sustainable development principle	Ratification in Zambian legislation	Zambian mining industry status quo	Zambian mining industry shortcomings
Precautionary principle	EMA, 2011 Section 2(4)	Due to the licensing of mining rights and closure and the associated environmental reports and plans, a precautionary stance is taken	The precautionary principle is not effected stringently (weak baseline studies and closure plans)
Ethical corporate responsibility, community engagement, and reporting	EMA, 2011 Section 38	Consultation and public participation are legally required in the application for a license and closure certificate	Not engaging communities for final land to attain sustainable closure (operational phase)
Subsidiarity principle and underpinning decision-making	EMA, 2011 Section 4, 5, 9, 27, 39 MMDA, 2015 section 11, 12, 20, 59, 69	Embedded in the legislation	Mine plans and operations are driven by economic goals, guided by top management
Extensive Risk Management	EMA, 2011 Section 2(4), 2(4), MMDA, 2015 section 3, 9, 76, 95, 100, 112, 118	The Environmental Management and ClosurePlans required by the legislation entail a risk management approach	Weak baseline studies, risks are inadequately identified and poorly managed
Internalization of costs	MMR(Environmental) MMDA Sections 59, 89, 101, 119, 120	The principle of ‘polluter pays’ is embedded in the legislation	Proper accounting of such costs is difficult and rarely effected

Iterative planning, monitoring, and continual improvement	MMR (Environmental Protection Fund) MMDA Sections 3, 50, 65, 79, 85	Embedded in the legislation	Mines are disincentivized to implement environmental monitoring toward sustainable closure
Investment in research and development and capacity building	EMA, 2011 Section 35,63, 65 MMDA Sections 61, 67, 100, 113, 114	These legislative weaknesses are seen in the ‘on-the-ground’ status quo. This extends to humanresource (and community/ government) capacity development in this respect	There is a weakness in the legislative mandate for the necessity of long-term research and the trial of closure options
Rehabilitation, appropriate land use, and local sustainability	EMA, 2011 Section 3,19, 30, 32, 33, 40, 41, 47 MMDA Sections 66, 67, 68, 72, 74,	Rehabilitation and land use considerations are included in the legislation	With weak baseline assessments and closure plans, the practical execution is often poor
Systems approach and interconnectedness of principles	EMA, 2011 Section 3,19, 30, 32, 33, 40, 41, 47	The principle is integrated into the legislation	Not seen to be effected beyond being a guiding principle (There is little practical application)
Waste as a resource: Greening a circular economy	EMA 2011, Section 14, 18, 24, 26, 27, 28,29, 30, 31, 47. MMDA part (VI, VII), Sections 60, 61, and 65	Waste reuse is included in the legislation	The principle is not strongly effected by either the legislation or practice

Table 29 presents an analysis of how each sustainability principle aligns with sections of Zambian mining legislation. While the legislation incorporates these principles, there are identified weaknesses, as discussed in Section 7.4. The table compares these legislated aspects with the actual state of mine closure and sustainability based on survey results presented and discussed in Chapters 4 and 6. Despite the principles being embedded in legislation, there is a failure to fully implement them in practice. This failure is attributed to the instability of mining legislation and inadequate implementation, despite the legislation's inclusion of sustainability principles.

7.6 Proposals for bridging the gap between sustainability principle, legislation, and closure practice

This research puts forward two main propositions. First, it introduces a framework of indicators, rooted in the sustainable development principles outlined in Table 29, designed to steer mining operations towards a sustainable closure. Second, it presents a conceptual framework that goes beyond simply monitoring indicators, aiming to guide the entire mine closure process iteratively toward achieving sustainable closure.

7.6.1 An indicator framework developed to address the gaps between mining sustainability policy and current mine closure practice in Zambia

As previously outlined (Section 2.3.5), sustainability principles serve as the foundation for realizing mining's positive contribution to sustainable development, ultimately leading to sustainable mine closure. One of the initial objectives of this research (Section 1.3) was to establish environmental indicators of sustainability, in line with the recommendations of closure. Following the theory on developing indicator frameworks detailed in Section 4.3, these indicators are derived from the compiled list of 'sustainability principles' established in Section 2.3.5, and they are linked to corresponding 'objectives of closure'. The resulting indicator framework is presented in Table 30 below.

Table 30. An environmental sustainability indicator framework to address the gaps between mine closure sustainability policy and current mine closure practice in Zambia (As per in Section 2.3.5 list of principles of sustainable development; section 2.4.4.2 and per international best practice (Section 2.3) and Zambian closure experts (Section 4.8.4)).

Key sustainable development principle	Goals and objectives of closure	Indicators of implementation of sustainability principles and closure objectives to support environmentally sustainable closure
Precautionary principle	Securing the site for any future land use and/or reverting to a pre-mining state, which can tolerate a range of climate change scenarios	• Conduct studies to establish baselines and assess trade-offs. • Define pre-mining conditions to set environmental sustainability goals for rehabilitation. Monitor performance against these goals. • Establish environmental thresholds to guide decision-making. Monitor thresholds and take precautionary measures if approached. Identify and monitor cumulative and regional impacts. • Identify and protect sensitive areas, habitats, and species through proactive management. Establish key indicators to monitor fragility.
Ethical corporate responsibility, community engagement, and reporting	Socio-economic sustainability	• Integrate community engagement into closure planning. Develop and refine a shared closure vision, including environmentally sustainable land use, throughout the life of the mine. • Implement regular and transparent reporting on environmental sustainability and closure. Encourage public feedback.
Subsidiarity principle underpinning decision-making	Socioeconomic sustainability as well as physical, chemical, and biological stability which ensures a sustainable land use	• Environmental baseline studies and Environmental Impact Assessments (EIAs) findings and management actions are incorporated into both mine operations and closure planning. These linkages are well-documented and reported on. • Sustainable closure planning involves inputs from various levels of the business, including rehabilitation operators, environmental and mine planning staff, mine management across departments, corporate management, and local communities. These considerations are documented and acted upon. • Environmentally sustainable closure is considered in all major decision-making processes, with documented considerations and monitored outcomes.

Extensive Risk Management	Physical, chemical and biological stability	• Conduct regular risk assessments and reviews, especially when major changes occur in the mine plan. • Each identified risk is connected to corresponding mitigation management action plans, and their progress is monitored through an Environmental Management System (EMS). • Monitor trends in environmental risk profiles over time and use them to inform future planning and decision-making processes.
Internalization of costs	Financially achievable closure	• Negative impacts (social and environmental) are quantified and included in costing of mine closure. • Such costings are done regularly; trends monitored which in turn inform decision making.
Iterative planning, monitoring, and continual improvement	Physical, chemical and biological stability as well as socioeconomic sustainability at closure	• Continual improvement programs demonstrate the improvement of environmental and social indicators. Such trends are monitored and inform decision-making. Moreover, indicators themselves are refined as studies provide better knowledge regarding risks.
Investment in research and development and capacity building	A sustainable and productive post-closure land use	• Long term scientifically rigorous trials are essential to inform final sustainable land use potential. Such trials are established and monitored. • Similarly, social resources are developed with performance management measures in place to ensure efficacy and value add toward closure objectives.

Rehabilitation, appropriate land use, and local sustainability	Physical, chemical and biological stability as well as socioeconomic sustainability at closure	• Ongoing monitoring of environmental indicators is imperative to inform decision making and maintain alignment with final land use. Cognizance of source/pathway/receptor inform indicator selection. • Environmental indicators classes that require monitoring include: i. Water (e.g. surface and underground, quality and quantity, predictive modeling) ii. Soil (e.g. depth, structure nutrient capacity/fertility, erodibility). iii. Land use (e.g. topography, rehabilitation status, capacity to meet end land use). iv. Biodiversity (e.g. species and ecosystem establishment, basal cover, alien invasive). v. Air (e.g. PM10 and 2.5 dust, NO_x, SO_x).
Systems approach and interconnected-ness of principles	The establishment of sustainable human-natural systems post-closure	• It is necessary to identify the causal relationships between environmental aspects, as well as between social and economic considerations in a systems approach. The state of these relationships is itself an indicator of the balance of the whole system, and thus is to be monitored. • Such systems thinking is also applied from the ground-up in mine design, such that material changes may be monitored for their causal impacts, and consequently managed. • Indicators, and the relationships / dependencies between them, are identified such that meta- indicators are developed which indicate system state change.
Waste as a resource: Greening a circular economy	Future public health and safety are not compromised and socio-economic benefits are maximized	• The volumes and impacts (air, water, land etc.) of mining wastes are measured and monitored. The 'sustainability costs' of these wastes (including avoidance, rehabilitation, land use loss, water pollution, amelioration etc.) are accounted for, against repurposing/reprocessing the wastes to minimize/negate the negative impacts thereof.

Table 30 provides a broad environmental sustainability indicator framework, as each operation is site-specific in its impacts. By analyzing an operation's environmental aspects and impacts and developing site-specific indicators based on the above framework (underpinned by sustainability principles and designed to meet the criteria specified in Section 4.3.1), the mine site will be enabled to guide its decision-making and ultimate trajectory toward an environmentally sustainable closure. These indicators would have to be embedded in a mine's EMS to be effectively implemented; which in itself would require top-management commitment to these sustainability principles and indicators.

This environmental sustainability indicator framework is designed to address the inconsistencies between mine closure sustainability policy and actual closure practices in Zambia. Table 30 categorizes various sustainable development principles, goals and objectives of mine closure, and specific indicators of sustainability and closure objectives to support environmentally sustainable closure. It emphasizes principles such as the precautionary principle, ethical corporate responsibility, and extensive risk management, among others. Each principle is linked to practical objectives, such as securing the site for future land use or achieving socio-economic sustainability, with detailed actions such as conducting environmental baseline studies, integrating community engagement, and monitoring environmental risk profiles over time.

The framework presented in Table 30 aims to ensure that mine closures contribute positively to sustainable development by embedding these principles into everyday operational decisions and long-term planning. It proposes a comprehensive set of actions and indicators that can guide mine operations toward achieving an environmentally sustainable closure. The framework represents a strategic tool to bridge the gap between theoretical sustainability policies and their practical application, ensuring that environmental, social, and economic aspects are considered throughout the mine's lifecycle. This proactive approach to mine closure planning is crucial for mitigating the often-adverse impacts of mining activities, aligning with global sustainability goals, and fostering a responsible mining sector in Zambia (Wambwa et al., 2023).

7.6.2 Idealized conceptual framework for driving sustainable closure decision-making and guiding an iterative closure process

The desired research objective of creating an indicator framework that indicates the trajectory of a mine site toward or away from closure has been presented in Section 7.5.1 above. However, in the course of this research another key recommendation has been arrived at.

Figure 26 illustrates the idealized conceptual framework for driving sustainable closure decision-making and guiding an iterative closure process.

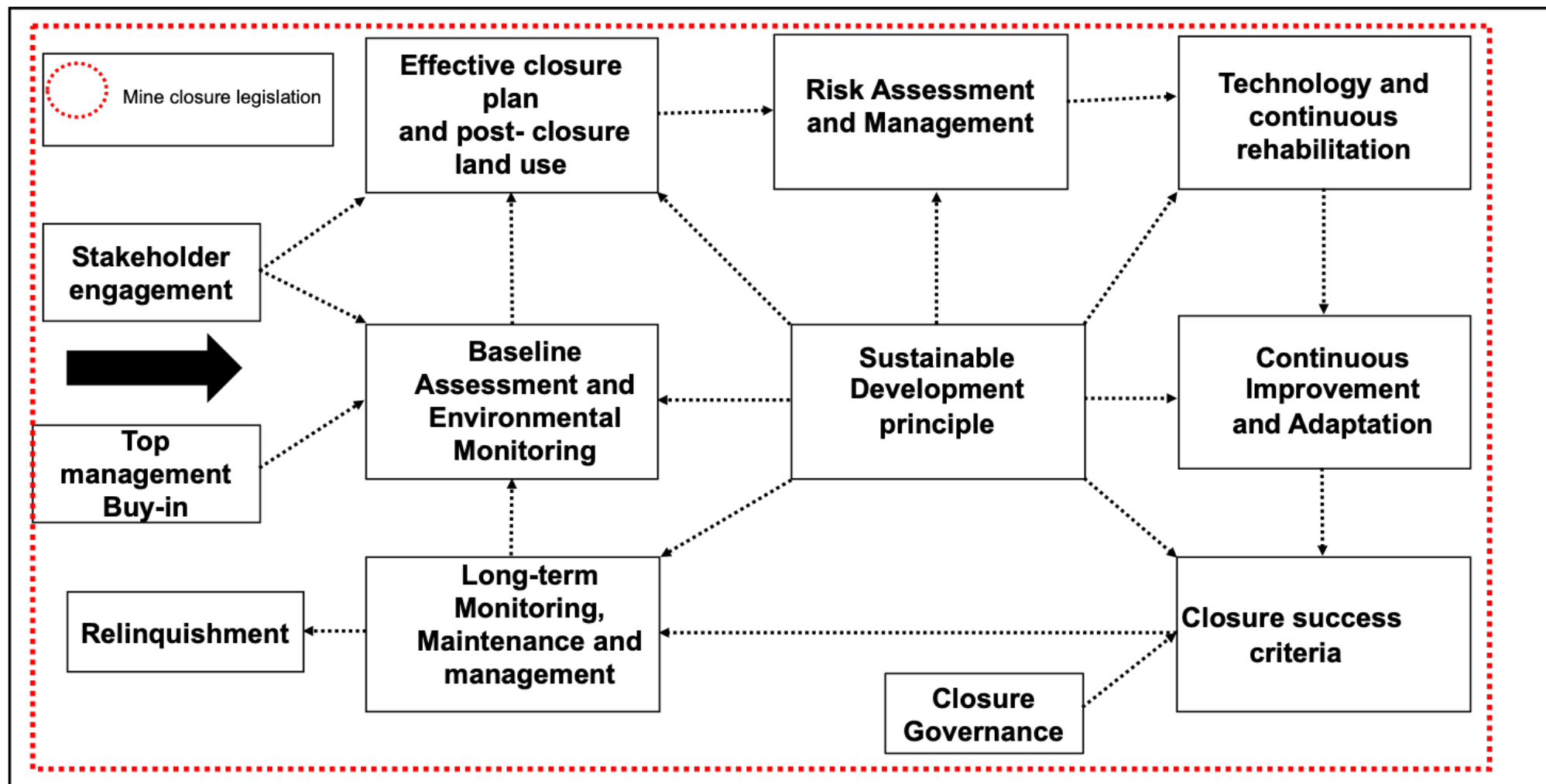


Figure 26. A conceptual framework that iteratively guides sustainable mine closure.

Figure 26, informed by survey responses and closure literature, highlights the Importance of detailed baseline assessments in supporting an effective mine closure plan. It advocates the integration of sustainable development principles in all aspects (stages) of mine closure, ensuring the inclusion of environmental, financial, and technological evaluations to inform closure and post-closure land use planning. The process entails a cycle of continuous improvement through risk management, technological innovation, and adaptive rehabilitation practices, ending in meeting closure success criteria. Baseline assessments are essential for comprehensive operational environmental monitoring and long-term trials that facilitate decision-making toward sustainable land use. The maintenance of this data should be marked by accuracy, reliability, and frequent updates. Alongside, rigorous assessment of closure liabilities and transparent financial provisions are necessary to ensure feasible remediation (PMC, 2012). As mining progresses, continuous and well-informed rehabilitation should occur to prevent unmanageable costs at the point of final restoration. Regular monitoring, guided by the sustainability indicators in Table 30, will identify and address any deviations from the sustainable closure path.

Internal commitment from senior mine management is crucial for a long-term strategy of 'mining for closure', entailing effective communication and cooperation across all stakeholder interactions (Figure 26) (Peck, 2005). Corporate management's vested interest in closure performance supports compliance with high standards (Young et al., 2022). Early dialogues with government and local communities, grounded in environmental studies, will align expectations and outcomes for post-mining land use, with public-private partnerships providing proven solutions to mine closure challenges, as demonstrated in Zambia (Wambwa et al., 2023; Young et al., 2022).

The study calls for sound and stable mining legislation, criticizing the lack of consistency that hinders the attainment of certified mine closure. It points out the unsuitability of the MMMD as the environmental licensing authority, suggesting a conflict of interest, and recommends the ZEMA to assume this role for the mining sector, as it does for other industries and due to the political influence in the MMMD. The study highlights the need for cooperative governance among the MMMD, ZEMA, Ministry of Green Economy and Environment, and other government departments to support sustainable development in Zambia's mineral resources sector. Only with a solid legislative framework and commitment to environmental sustainability can the goal of sustainable and certified closure become an achievable objective for mining companies.

7.6.3 Feasibility of the conceptual framework for mine closure in Zambia

The conceptual framework illustrated in Figure 26 for mine closure is feasible for Zambia and other developing nations; however, it needs major effort, coordination, and commitment from various stakeholders, such as the government, mining companies, local communities, and international partners. From the Zambian perspective, some of the key factors that can influence the feasibility of the framework on mine closure include existing policies and legislation, regulation institutional capacity, financial resources, stakeholder engagement, technological and technical expertise, and governance and transparency.

In order for this framework to be achievable, the Zambian government need to take several steps. Firstly, the government needs to strengthen the legal and regulatory framework. This involves reviewing and updating existing mining laws and regulations to include well-defined requirements for mine closure planning, financial assurances, and environmental rehabilitation, as well as improving enforcement mechanisms for compliance by mining companies. Additionally, building institutional capacity is another important step, which can be achieved through investment in training programs for government officials and local authorities in mine closure management and environmental rehabilitation, along with ensuring regulatory bodies are adequately funded and equipped.

Financial assurance is another essential aspect necessary for the Zambian government to implement the framework. This requires that the government implement a variety of financial mechanisms such as insurance, bonds, or trust funds to secure sufficient resources for mine closure activities and explore international funding and technical assistance. Stakeholders engagement, particularly local communities, in the planning and decision-making process for mine closure plays an important role in addressing their needs and concerns, which can be enabled by the regular public consultations and open communication channels.

Promoting transparency and accountability through robust monitoring and reporting systems will help track progress and ensure transparency in mine closure activities. Additionally, anti-corruption measures should be implemented to ensure that mine closure funds are used appropriately. Leveraging international cooperation by collaborating with international organizations, other countries, and industry experts can provide valuable knowledge sharing and technical assistance to enhance mine closure efforts.

Adopting adaptive management practices, which allow for flexibility in mine closure plans to adapt to new information and changing conditions, and continuously reviewing and improving practices based on lessons learned and stakeholder feedback, is also essential. By taking these steps,

the Zambian government can address governance challenges and ensure the successful implementation of the conceptual framework, leading to sustainable mine closure practices.

7.7 Achievement of mine closure in Zambia

In a survey aimed at understanding best practices and concerns in mine closure within Zambia, the key to success was identified as robust support from senior management. This commitment is important to incorporating "mining for closure" principles throughout the mine's operational lifecycle, highlighting that the demonstration of cost-saving benefits from early closure planning and rehabilitation is crucial to maintaining this support. Moreover, a balanced assessment of various time-bound risks and the implementation of continuous rehabilitation practices are crucial to mitigating future closure challenges.

Corporate adherence to standardized mine closure protocols and careful management of closure liabilities were noted as vital for steering and evaluating operational practices. Quantitative assessments of mining areas and infrastructure facilitate a well-rounded understanding of rehabilitation needs, which should be systematically updated to inform dynamic closure strategies. Success, as indicated by one participant, hinges on the availability of comprehensive baseline data and proactive planning that involves stakeholders' engagement in closure processes.

The extension of closure training and awareness beyond the executive level also plays a significant role in achieving closure goals (Kozłowska-Woszczycka & Pactwa, 2022). The formation of a specialized closure team, inclusive of a steering committee and on-the-ground production staff, is fundamental to the success of closure operations (IIED, 2002a). Participants reported that these collective efforts foster a more robust and informed approach to mine closure.

The application of advanced technology in ecological restoration and water treatment was cited as a critical element of success in mine closure accomplishments. Real-life applications, such as the establishment of the Mulonga Water Treatment facility (using water from the Nchanga underground mine in Chingola), serve as benchmarks for successful collaborative initiatives between the mining sector and governmental bodies (Daka & Kafwembe, 2023). While the permanent alteration of landscapes post-mining presents assessment challenges, restoration of ecosystem functionality, as observed in the Zambian minefield, indicates positive long-term outcomes. An example of these restorations of ecosystem functionality is the revegetation of closed tailings by the mines (Festin, 2020).

Lastly, the potential for innovative mine closure approaches that extend beyond traditional legislative measures was acknowledged. Rethinking mine waste as a resource and recognizing the economic advantages of gradual rehabilitation suggest alternative means to evaluate the efficacy of

mine closure planning. In line with rethinking waste as a resource, the old tailing dams are being re-mined to extract other minerals previously discarded as waste for example cobalt. One example is Black Mountain in the Kitwe district, Copperbelt Province (Kapobe et al., 2021). These innovative strategies, along with top-management commitment, are pivotal for informed closure planning, stakeholder involvement, and achieving sustainable long-term mine closure. The findings stress the necessity for active, inclusive participation in mine closure initiatives to secure sustainability, with further guidance available in Section 7.5 of the dissertation.

7.8 Challenges of mine closure in Zambia

The predominant challenge in sustainable mine closure, as identified by the respondents, is the inadequacy of funds and management of financial resources necessary for long-term remediation activities (Syafunko et al., 2023). This issue intensifies towards a mine's operational end, when revenues reduce and overdue costs mount, a situation documented by the literature (Gankhuyag & Gregoire, 2018). Cost estimations for closure activities were often cited as unrealistic, which hinders the implementation of socially, economically, and environmentally beneficial closure strategies (Wambwa et al., 2023). Moreover, mine closure plans were frequently considered inadequate due to a lack of sustained commitment, and legislative changes and management's commitment issues complicate long-term closure goals (Wambwa et al., 2023). Enforcement failures by the government further undermine the legislative framework, and the challenge of predicting post-closure water quality complicates financial allocation for sustainable water management, along with other poorly understood environmental issues.

Sustainable rehabilitation practices are crucial yet challenging, with poor execution being a common issue. Substandard topsoil management, inadequate sloping, and material placement contribute to the struggle of establishing a sustainable vegetative cover on degraded soil. This was one of the observations at TD15A in Kalulushi District during the fieldwork (Figure 19). Furthermore, stakeholder engagement poses persistent challenges, with communities often lacking unity, having unrealistic expectations, and facing communication barriers. Effective stakeholder consultation throughout a mine's lifecycle is frequently overlooked, with mines also being reluctant to share essential data, and government departments suffering from insufficient resources to handle closure procedures effectively (World Bank, 2015).

Other concerns include the absence of environmental monitoring post-closure, logistical issues in remote mining areas, the impacts of climate factors such as rainfall on rehabilitation efforts, and external issues such as illegal mining activities. One important example the absence of environmental monitoring post-closure in Zambia is the Kabwe lead mine in the Central province

which has continued to affect the environment 20 years after closure (Lombe et al., 2021; Nakata et al., 2021). The Kabwe lead mine in Zambia, closed over two decades ago, stands as a stark example of the environmental devastation that can persist when post-closure monitoring is neglected. Despite the cessation of operations, hazardous lead contamination continues to severely impact the soil and water sources surrounding the area (Nakata et al., 2021). The absence of effective environmental monitoring has left local communities vulnerable to lead poisoning, which is especially detrimental to the health of children (Burga & Saunders, 2019b). This ongoing crisis highlights the critical need for sustained environmental oversight and remediation efforts even after mines are closed. The situation at Kabwe emphasizes the broader implications of inadequate post-closure practices on both ecological and human health for generations (Burga & Saunders, 2019b). The effects of these challenges are far-reaching, rendering key mine closure operations, such as land reshaping and water treatment, ineffective and impeding the achievement of a sustainable closure. The dissertation suggests a transition towards passive water treatment as an active measure faces challenges in mitigating water-related impacts at a mine's end of life.

The process of obtaining closure approval from authorities is burdened with difficulty as residual impacts potentially become the state's burden, resulting in a reluctance to issue closure certificates. Stakeholder participation is also deemed insufficiently collaborative, which further complicates the process. Additionally, discrepancies in skills and governance effectiveness within government bodies and criticism towards junior miners for lack of closure preparedness compound these issues. Larger companies may escape closure liabilities through asset disposal, while the fragmented approach of larger mining houses with substantial assets leads to disjointed and sometimes ineffective closure planning.

These challenges highlight a systemic inadequacy in strategic and technical planning, as well as in cooperative governance, which should be underlined by sustainability principles. The lack of collaborative stakeholder interactions in directing mine closure highlights an area in need of significant improvement to align with sustainable closure objectives.

8. Conclusion

8.1 Conclusion

This study aimed to enhance understanding and practices surrounding mine closure within Zambia's mining sector, focusing on sustainable development principles. For this purpose, the current status of mine closure in Zambia was assessed by assessing the current impacts of mining activities on the environment (in terms of LULC), status quo of mining environmental indicators, mine closure and closure planning and Zambian mine closure legislation and associated issue. This investigation shows the complicated relationship between mining activities and environmental sustainability, highlighting the essential role of legislative frameworks and institutional mechanisms in navigating the challenges from the mine closure processes. Through an interdisciplinary approach, this study bridged the gap between theoretical aspirations and practical outcomes, offering insights that contribute to both academic discourse and industry practice. This research used a mixed-method research approach by combining social surveys with remote sensing analysis. The employment of questionnaires allowed to capture perceptions and experiences of professionals involved in mine closure, while remote sensing using Landsat (30-m resolution) and PlanetScope (3-m spatial resolution) provided objective data on identifying LULC change patterns for 1990–2020 related to mining activities. This dual approach enabled a comprehensive analysis of both subjective and objective elements influencing mine closure practices in Zambia.

In terms of environmental changes associated with the mining activities, the study was conducted in Kitwe District of the Copperbelt Province. The study shows significant changes in the LULC, mainly characterized by the increase in bare land primarily attributed to mining activities, expansion of built-up areas due to population growth and urbanization, and a notable rise in grassland/pasture/agricultural land following the conversion from forests. Simultaneously, a decline in forest cover highlights the environmental impact of mining operations, urban expansion, and agricultural encroachment. These changes highlight the pressing need for comprehensive strategies that address the dual challenge of sustaining community livelihoods while minimizing environmental degradation. The study advocates for enhanced sustainable land management practices, advocating for a concerted effort among governmental bodies to mitigate the adverse effects of LULC changes which can lead to sustainable mine closure when the mines close. By integrating these findings into policy making, there is a potential to promote more sustainable land-use strategies, ensuring the protection of fundamental ecosystems and supporting the well-being of the Zambia's increasing population into the future even after mines closure.

In order to assess the mine closure landscape in Zambia, this study critically examined the insights and experiences of mine closure professionals in Zambia, employing a mixed-method approach to analyze responses from 240 participants regarding their professional background, experience in mine closure practices, environmental indicators, and legislative knowledge. The demographic data reveal a male-dominant sector with a significant portion of respondents holding advanced degrees, emphasizing the high level of expertise within the sample. The gender disparities within the field calls for initiatives aimed at enhancing gender inclusivity is suggested by this research. A majority of professionals are directly engaged in mine site activities or serve as consultants, highlighting a private sector-driven mine closure landscape, with a notable gap in government and academic involvement highlighting the importance of capacity-building efforts that could empower stakeholders across the board to engage more effectively in sustainable mine closure activities. The study explored the respondents' extensive experience across various mineral types, predominantly copper and cobalt, reflecting Zambia's economic focus. However, the diversity of experience among consultants across a wider range of minerals suggests a reliance on external expertise for mine closure activities, especially among smaller operations.

The research's examination of mine closure practices in Zambia, as explained in Chapter 4, navigates through the detailed relationship between legislative frameworks and the on-the-ground realities faced by professionals tasked with overseeing mine closures. The analysis reveals a contradiction where, despite substantial potential for implementing sustainable mine closures, a group of challenges—ranging from insufficient baseline environmental assessments and inadequate stakeholder engagement to the formulation of closure plans and lacking in top management's commitment—overpowers progress. Particularly, the unstable legal landscape governing environmental and mining regulations stands out as a difficult barrier undermining sustainable closure activities. This study not only examines the barriers but also shed light on opportunities for legislative and procedural enhancements, advocating for a more interconnected and innovative methodology to support mine closure sustainability in Zambia. It calls for legislative improvement with a stronger emphasis on sustainability indicators, robust monitoring, enforcement mechanisms, and an openness to international best practices. Such reforms aim to reposition Zambia as a frontrunner in sustainable mining, ensuring the sector's contribution to economic prosperity is balanced with environmental stewardship and intergenerational equity. Thus, the chapter highlights an optimistic perspective, emphasizing that with a collaborative, informed approach, the vision for sustainable mine closures in Zambia is attainable, setting an example for research and practical initiatives aimed at harmonizing mining activities with global and local sustainability targets.

The research also identified significant gaps between sustainability principles, Zambian mine closure legislation, and actual closure practices, highlighting the embedded sustainability principles within the legislation but also pointing out a lack of full implementation due to legislative instability and inadequate execution. To bridge these gaps, the study proposed two main solutions: a framework of indicators based on sustainable development principles to guide mining operations toward sustainable closure, and a conceptual framework aimed at guiding the mine closure process iteratively towards sustainability. The indicator framework is designed to facilitate environmentally sustainable closure decisions, requiring top-management commitment and integration into the mine's Environmental Management System (EMS). Furthermore, the study emphasizes the importance of continuous improvement, detailed baseline assessments, and the integration of sustainable development principles throughout the closure process. It calls for comprehensible and stable legislation, suggesting that ZEMA should oversee environmental licensing for the mining sector to avoid conflicts of interest and ensure a focus on sustainable development. The research advocates for a collaborative governance approach, including early dialogues with government and local communities, to align expectations for post-mining land use, emphasizing the necessity of a legislative and operational commitment to environmental sustainability for achieving certified mine closure.

Lastly, the research presented both the successes and challenges of achieving sustainable mine closure in Zambia, drawing from a comprehensive survey and fieldwork observation. Success centers on robust senior management support, emphasized by the principle of "mining for closure" throughout the operational lifecycle. This includes early planning and rehabilitation to showcase cost-saving benefits, adherence to standardized protocols, continuous risk assessment, and the utilization of advanced technology for ecological restoration. Conversely, the study reveals significant challenges, particularly financial constraints, unrealistic cost estimations for closure activities, and the lack of sustained commitment which undermines mine closure plans. Enforcement failures, inadequate stakeholder engagement, environmental monitoring deficiencies, and logistical barriers further worsen the struggle toward sustainable closure. The contradiction between successes and challenges highlights the complexity of mine closure in Zambia, emphasizing the need for a strategic, collaborative approach that marries innovative closure strategies with rigorous stakeholder engagement, guided by a solid foundation of sustainability principles and closure legislation.

8.2 Significance of the study and recommendations for sustainable mine closure in Zambia

The significance of the study lies in its comprehensive approach to understanding and improving mine closure practices within Zambia. The significance of the research resulting from the findings detailed in the technical chapters is as follows:

1. Advancing Sustainability: The study provides a systematic approach to integrating sustainable development principles into mine closure practices, which is crucial for ensuring environmental and socio-economic benefits post-mining.
2. Legislative Influence: It influences policy by highlighting gaps in current legislation, and urging a revision of the legal frameworks to support sustainable mine closure practices.
3. Improving Practice: By documenting current practices and comparing them to best practices globally, the study aids in improving mine closure strategies in Zambia.
4. Building Knowledge: It contributes to academic and practical knowledge on environmental sustainability, particularly in the context of mining and its impacts on LULC.

The recommendations derived from the detailed findings in the chapters and based on objectives for sustainable mine closure in the study area are as follows:

1. Enhance environmental monitoring and reporting (objective 1).
 - a. Baseline studies: Conduct thorough baseline environmental studies before mining begins to establish benchmarks for post-closure restoration (section 4.8.4.1).
 - b. Continuous monitoring: Implement continuous environmental monitoring throughout the mining process to detect and mitigate adverse impacts in real time within and beyond the mine site boundaries (section 4.8.4.2).
 - c. Transparency: Require mining companies to publish regular environmental impact reports and make them accessible to the public to foster transparency and accountability (section 4.8.5).
2. Integrate sustainable land use planning (objective 2).
 - a. Enhance continuous environmental monitoring: Implement a robust environmental monitoring framework utilizing regular satellite imagery analysis and GIS technologies to track LULC changes. Integrate this monitoring data into a centralized database accessible to all stakeholders to ensure transparency, facilitate better

decision-making processes, and promptly identify and mitigate negative impacts in real-time

- b. Promote reforestation and sustainable land use practices: Develop and implement reforestation programs using native species to restore areas degraded by mining activities, especially in regions that have experienced significant deforestation and soil degradation. Create detailed post-mining land use plans that prioritize ecological restoration and sustainable agriculture, ensuring the land remains productive and supports local communities. Encourage the adoption of sustainable land use practices in post-mining landscapes to provide alternative livelihoods for affected communities.

3. Strengthen legal framework and enforcement (objective 3)

- a. Legal frameworks: Enhance the legal and regulatory frameworks governing mine closure to ensure strict enforcement of environmental standards and rehabilitation requirements. Implement penalties for non-compliance and provide incentives for companies that exceed environmental restoration targets.
- b. Stakeholder engagement: Engage local communities, environmental experts, government agencies, and non-governmental organizations in the planning and implementation of mine closure activities. Regular consultations with these stakeholders are essential for the success of rehabilitation efforts and for addressing the socio-economic impacts of mine closure.

4. Establish a comprehensive sustainability indicator framework (objective 4)

- a. Environmental indicators: Develop and implement specific indicators for soil quality, water quality, air quality, and biodiversity health to track environmental recovery post-closure.
- b. Socio-economic indicators: Measure the socio-economic impacts of mine closure on local communities, including employment rates, income levels, health outcomes, and access to essential services.
- c. Periodic reviews: Conduct periodic reviews of sustainability indicators to assess progress and make necessary adjustments to closure strategies.

8.3 Limitations of the study and recommendation for future research opportunities

This study, while comprehensive in its exploration of sustainable mine closure practices in Zambia, encountered several fundamental limitations that may affect the relevance and applicability of its findings. The study acknowledges limitations as the following:

1. Geographical limitation: The study is region-specific, focusing primarily on Copperbelt province of Zambia, which might limit the applicability of findings to other geographic contexts with different environmental or legislative conditions.
2. Data limitations: Potential limitations in the data quality, especially from baseline environmental assessments, which could affect the validity of the study's conclusions.
3. Stakeholder bias: The study may face biases from stakeholders, particularly those directly involved in the mining industry, which could influence the objectivity of the collected data.
4. Resource constraints: Limited resources might have restricted the extent of field studies and surveys, impacting the depth and breadth of research findings.
5. Lack of high-resolution images from 1990 to 2010: The lack of high-resolution images for the years 1990, 2000, and 2010 to assess the accuracy of the classifications.
6. Unavailability of copper production data at the district level: hindering a precise examination of the relationship between mining activities and environmental impacts.
7. Study's dependence on linear extrapolation: for predicting future threats that may generalize the complex socioeconomic and environmental dynamics, potentially resulting in forecasting inaccuracies.

Therefore, future studies could be improved based on the following recommendations:

1. Wider geographic scope: Future research should consider a broader geographic scope to test the applicability of the findings in different mining contexts and legislative environments.
2. Longitudinal studies: Conduct longitudinal studies to assess the long-term impacts of mine closure practices and the sustainability of land use post-closure.
3. Technology integration: Investigate the integration of advanced technologies in monitoring and managing mine closure to enhance sustainability outcomes.

4. Stakeholder analysis: Further studies should explore the perspectives of a wider range of stakeholders, including community members and environmental groups, to provide a more comprehensive view of the impacts of mine closures.
5. Utilize advanced imaging technologies: To compensate for the lack of high-resolution images from 1990 to 2010, future studies could employ retrospective analysis using newly available satellite technologies or collaborate with space agencies and tech companies that have historical satellite data archives.
6. Detailed local data collection: To address the unavailability of copper production data at the district level, future research should focus on local data collection initiatives. Establishing partnerships with local government bodies and industry players might facilitate access to more data, enhancing the precision of analyses concerning mining activities and environmental impacts.
7. Refine modeling techniques: To improve upon the study's reliance on linear extrapolation, future research should explore more sophisticated modeling approaches such as machine learning algorithms, system dynamics models, or agent-based modeling. These methods can better account for the complex interactions between socioeconomic factors and environmental impacts, leading to more accurate forecasts.
8. Interdisciplinary approaches: Integrating insights from diverse fields such as ecology, sociology, economics, and political science can provide a more holistic understanding of the issues at hand. This interdisciplinary approach can uncover hidden dynamics and interdependencies that a single-discipline study might miss.

By addressing these research limitations and incorporating the recommended future research directions, the scientific community can build upon the findings of this study and contribute to a broader understanding of the potential and challenges of sustainable mine closure practices especially in developing nations.

8.4 Concluding remarks

In conclusion, the comprehensive study presented in this thesis highlights the profound impacts of mining on the environmental sustainability and socio-economic development within the Copperbelt Province of Zambia. It effectively demonstrates the potential of integrating multi-sensor remote sensing techniques to enhance the classification and mapping of LULC changes associated with mining activities. These methodologies provide crucial insights into the spatial dynamics of

environmental degradation and recovery, offering valuable data for the sustainable management and conservation of these affected ecosystems. The findings highlight the importance of refining and applying these remote sensing techniques for broader applications such as estimating decline in forest cover and increase in bare land, built up and grassland as a result of the mining related activities. Furthermore, the research contributes significantly to the development of environmental sustainability indicators that are crucial for guiding the mining industry towards more sustainable practices. These indicators are instrumental in monitoring the effectiveness of mine closure processes and ensuring that mining's legacy is one of environmental stewardship and positive socio-economic impact. The potential for future research to expand these methodologies to other mining regions in Zambia, or even globally, promises to enhance our understanding and management of mining's environmental impacts, thereby supporting the global pursuit of sustainable development goals in resource-rich settings.

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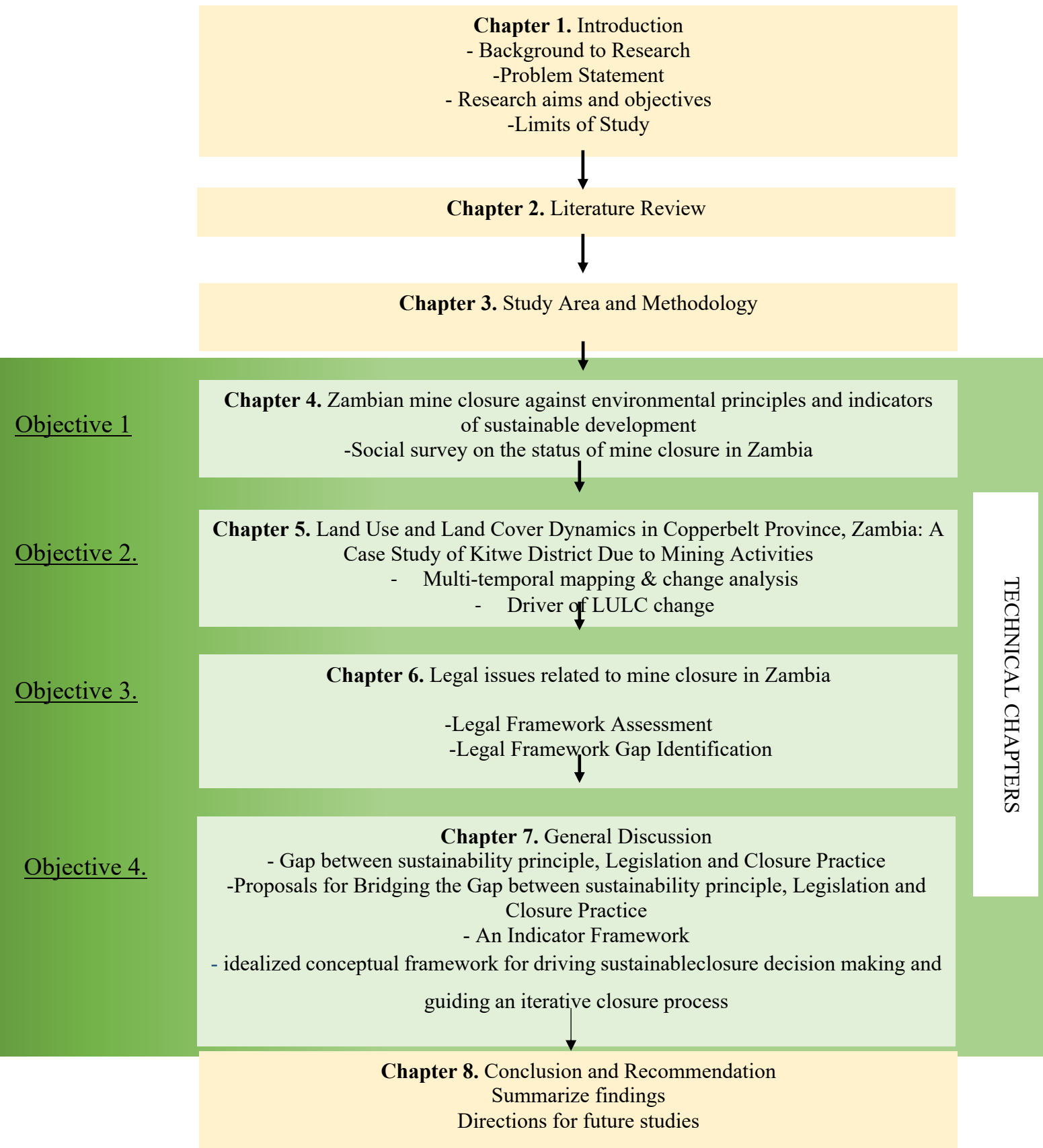
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Appendices

Appendix A. A synoptic view of the Thesis structure including main chapters and their objectives



Appendix B. Sample questionnaires used for the social survey

I am a Zambian male studying at Hokkaido University, in Japan. I am inviting you to participate in a survey to express your views on the mine closure legislation in Zambia. Your completion of this survey indicates your willingness to participate. Please do not write any information that can identify you.

(NOTE: Participants are piped accordingly to tailored questions as designated below by curly brackets)

M – Mining Site C – Corporate Co – Consultant G – Government A – Academic

L – Legal

1. Information on mine closure

1. Have you ever participated in mine closure before? {All}
 - a. Yes
 - b. No
2. In which mineral/s does your closure experience lie if any? {All}
 - a) Copper
 - b) Cobalt
 - c) Nickel
 - d) Manganese
 - e) Quarrying
 - f) Limestone
 - g) Others (.....)
3. In which area does your mine closure experience primarily lie? {All}
 - a) Mine Site
 - b) Corporate
 - c) Consultant
 - d) Government
 - e) Academic
 - f) Legal
4. What mineral type is being mined and with what mining method? {M, C}
 - a) Underground
 - b) open surface (pit)
 - c) Dredging
5. What is the total Tons Moved (TTM) and Run of Mine (ROM) p.a.? {M, C}
 - a. Total Tons Moved (TTM)
 - b. Run of Mine (ROM).....
6. Is ROM processed on-site? {M, C}
 - a) Yes
 - b) No
7. What environmental indicators are monitored beyond the mine boundary? {M, C}

.....
8. What year did mining start? {M, C}

.....

9. What is the expected remaining Life of Mine (LOM)? {M, C}

.....

10. What baseline (pre-mining) environmental indicators exist? {M, C, Co, G}

.....

.....

11. Full list of environmental indicators currently measured (by class: water, land, air, other). {M, C, Co, G}

Water

Land

Air

Biodiversity

Geology & Soils

Waste

Social.....

12. What would be the ideal list of environmental indicators measured to support sustainable closure?
{M, C, Co, G, A, L}

.....

13. Is there an up-to-date closure plan in place and is it reported upon?

13a. {Mine workers, Corporate} – regarding all operations?

a) Yes

b) No

13b. {Consultants only} – Can you estimate from your experience, when consulting on closure, what is the proportion of mines with closure plans in place;

.....

.....

13c. {Government workers only} – Do the mines you are responsible for have closure plans?}

.....

14. Which phase/s of mine closure have you participated in? {M, C, Co, G, A, L}

- a) Planning
 - a. Baseline assessments
 - b. Feasibility & conceptual closure planning & design
 - c. Mine closure framework & planning
 - d. Emergency response planning
- b) Operational
 - a. Operational rehabilitation & performance assessment
 - b. Operational closure performance assessment
 - c. Closure studies, trials & assessment of post-closure land-use options
 - d. Progressive rehabilitation planning & design & implementation
- c) Closure
 - a. Closure implementation & rehabilitation management
 - b. Post-mining monitoring & performance assessment
 - c. Application for closure & government consultation
 - d. Water treatment/reclamation
- d) Independent of stage
 - a. Drafting, updating & auditing detailed closure plans & programs
 - b. Closure liability assessment & costing
 - c. Water prediction/balances, monitoring & management
 - d. Mine closure regulation
 - e. Legal matters
 - f. Setting closure standards
 - g. Closure risk assessments
 - h. Community engagement & planning for closure

15. Please detail specific successes you have encountered in mine closure {M, C, Co, G, A, L}

.....

16. In your opinion, what are the most important ideal environmental indicators concerning mine closure? {M, C, Co, G, A, L}

.....
Which Zambian closure legislation are you aware of? {M, C, Co, G, A, L}

- a. The Mines and Minerals Development Act, 2015
 - i. Yes
 - ii. No
- b. The Environmental Management Act, 2011
 - i. Yes
 - ii. No
- c. The Mines and Minerals (Environmental) Regulations, 1997
 - i. Yes
 - ii. No
- d. The Mines and Minerals (Environmental Protection Fund) Regulations, 1998
 - i. Yes

ii. No

17. What other environmental investigations do you consider imperative for mine closure? {M, C, Co, G, A, L}

.....
.....

18. Do mine closure indicators/plans roll up into divisional corporate reporting on Sustainable Development? {M, C}

a) Yes

b) No

19. Do environmental indicators relate to the planned final land use? {M, C, Co, G}

a) Yes

b) No

20. Do you think a LOM environmental indicator plan would be useful in support of sustainable closure? Why? {M, C, Co, G, A, L}

a) Yes

b) No

Why

.....
.....

2.0 Personal Information

21. Company name (Organisation).....

22. Residence.....

23. Sex.... Male [] Female []

24. Age.....

25. Department.....

a) Mine Site

b) Corporate

c) Consultant

d) Government

e) Academic

f) Legal

26. Highest level of educational attainment

a) Secondary (S.S.S, Training College, Vocational) []

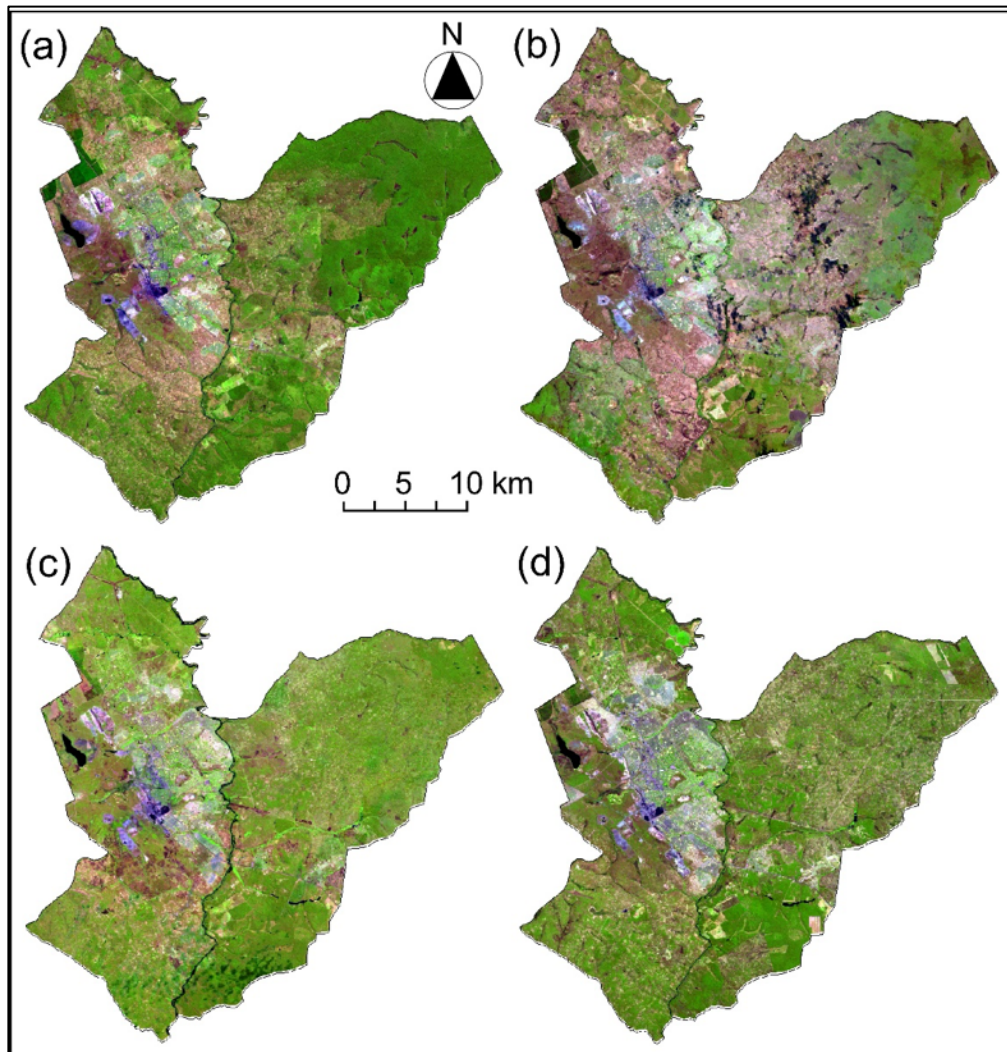
b) Bachelor's degree

c) Master's degree

d) PhD

e) Others, specify.....

Appendix. C False color composite for (a) 1990, (b) 2000, (c) 2010, and (d) 2019 in GEE



Appendix. D. confusion matrix formula for calculating Accuracy Assessment.

$$K = \frac{(\text{probability of correct classification}) - (\text{probability of chance agreement})}{1 - \text{Probability of chance agreement}}$$

As a formula utilizing the element of a confusion matrix, it can also be expressed as

$$K = \frac{(N * d) - q}{N^2 - q}$$

, whereas N is the sum of all elements in the confusion matrix, d is all correctly classified pixels (the diagonal of a confusion matrix), and q is the product of the pixels classified for one class and the pixels that were supposed to be classified as a said class, summed up over all classes.

Appendix. E. Mining area (a) Afforestation program at the tailing dam, (b) Abandoned open pit mine, (c) active open pit mine, (d) Air pollution at the smelter and (e) harvested timber.

(a)



(b)



(c)



(d)



(e)

