AN ASSESSMENT OF THE POTENTIAL POLLUTION RISK OF TAILINGS DUMPS ON THE ENVIRONMENT USING MULTI CRITERIA DECISION ANALYSIS (MCDA)

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A dissertation submitted to the University of Zambia in partial fulfilment of the requirements for the award of the degree of Master of Science in Sustainable Mineral Resource Development.

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DECLARATION

I, Teclah Munanku, declare that this dissertation was written in accordance with the rules and regulations governing the award of Master of Science of the University of Zambia. I further declare that the dissertation has neither in any part nor in whole been presented as a substance for the award of any degree, either to this University or any other University.

Signature: ______________________

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CERTIFICATE OF APPROVAL

This dissertation of Teclah Munanku is approved as partial fulfilment of the requirements for the award of Master of Mineral Science in Sustainable Mineral Resource Development of the University of Zambia.

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DEDICATION

To my son Tangala Siame who has been a major source of my drive and motivation. To the Late Mr. Nchimunya Mwiinga who gave me the first push to start this programme of study.

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ABSTRACT

The mining industry is one of the key economic drivers in Zambia and has tremendously grown since its genesis in the early 1900's. Zambia is one of the largest copper producers in Africa and the world and this translates to thousands of tonnes of mining waste accumulated over the years. Mine tailings have a huge footprint over the environment and can have serious consequences that cannot be reversed during mining and long after mining has ceased. This has resulted into over 2000 dumps lying around the surface on the Copperbelt Province and other provinces. Despite several studies being done around tailing dumps, impact assessments of their risk have been a challenge. This challenge arises mainly from the lack of common criteria for risks to objects of environmental protection as well as the lack of time frames within which these criteria are evaluated and this has made it difficult to conduct impact assessment studies of the mine tailing dumps.

This research assessed the potential pollution risk of tailings dumps using multi-criteria decision analysis, in this case, the analytical hierarchy process (AHP) method was applied to assess which dump has a higher potential pollution risk to the environment. AHP is a widely used assessment method and is based on the premise that decision-making related to complicated problems can be handled using a hierarchical structure that transforms complexity into a simple and comprehensible problem. Appropriate criteria went into the development of a framework for multicriteria decision support analysis and this enabled the determination of the potential pollution risk to the environment from the three tailings dumps selected. The tailings dumps were selected based on the criteria of age, working status of mine and more critically the availability of data needed to carry out the assessment on these dumps. The tailing dumps selected included one from a legacy mine (Kabwe Lead Mine, Kabwe) which is the oldest, one from a relatively older working mine (Mopani Copper Mine, Kitwe) and one from a relatively younger working mine (Lumwana Copper Mine, Mwinilunga).

Criteria with five indicators was developed, the first being physical properties. This indicator considered three factors, size of the tailings dumps in hectares, particle size of dump material and consolidation status of dump. The second indicator was chemical properties that was computed as an index of contamination. The third indicator is properties of the environment

around the dump, this considered four factors; the lithology underlying the dump area, the depth of the water table, the distance to the nearest surface water body, and the distance to the nearest anthropogenic facility. The fourth indicator was climatic factors around the dump area and focuses on the amount of rainfall received in the area. The fifth indicator was protective structures, this considered dust suppression at the site by means of tree cover.

Results of the research revealed that Kabwe mine tailings dump had the highest pollution potential followed by the Lumwana mine tailings dump then Mopani mine tailings dump (TD15A) in Kitwe. The results of the assessment show a successful model for decision making. When compared against a severity of risk scale, the Mopani Mine tailings dump in Kitwe had a low risk while the Kabwe and Lumwana mine tailings had a medium risk. Although this study was conducted using three tailings dumps, the criteria developed can be used to guide assessments of potential pollution risk of any other tailings dump in Zambia. The developed pollution risk criteria were applied to Musina Copper Mine tailings in South Africa where an assessment was previously conducted using a different approach for comparison. The Musina tailings dump had a potential pollution risk score of 0.5 and thus of medium risk which was in agreement with previous studies hence validating the approach. The indicators used thus capture critical aspects related to physical and chemical properties of mine dumps in data scarce environmental settings.

Using the developed tool in assessing the potential pollution risk before mining projects commence will consequently lead to the sustainable management of these dumps even before mining commences by taking deliberate steps to prevent pollution with the guidance of the criteria in the decision-making tool developed.

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LIST OF ABBREVIATION AND ACRONYMS

Abbreviation	Description
AHP	Analytical hierarchy process
AMD	Acid Mine Drainage
CBR	Case Based Reasoning
CEP	Copperbelt Environmental Project
DANIDA	Danish International Development Agency
SIDA	Swedish International Development Cooperation Agency
NORAD	Norwegian Agency for Development Cooperation
DEA	Data Envelopment Analysis
DWA	Department of Water Affairs
ECZ	Environmental Council of Zambia
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
FINIDA	Finish Department for International Development Cooperation
GP	Goal Programming
IAP's	Interested and Affected Person's
ISF	Imperial Smelting Furnace
L/S	Liters per second
MAUT	Multi-Attribute Utility Theory
MCDA	Multiple Criteria Decision Analysis
MGEE	Ministry of Green Economy and Environment
µG/DL	Micro grams per decilitre
MG/KG	Milli Gram per Kilo Gram
MT	Metric tonnes
MWDEP	Ministry of Water Development, Sanitation and Environmental Protection
NGO's	Non-Governmental Organizations
PM 10	Particulate Matter 10 micrometers or less in diameter
SAW	Simple Additive Weighting

SGAB	
SHE	Safety Health and Environment
SI	Statutory Instrument
SMART	Simple Multi-Attribute Rating Technique
SOB	Southern Ore Body
SO_2	Sulphur dioxide
UNZA	University of Zambia
TOPSIS	Technique for Order Preferences by Similarity to Ideal Solutions
TPA	Tonnes per annum
TSF	Tailings Storage Facility
V_2O	Vanadium Pentoxide
ZCCM-IH	Zambia Consolidated Copper Mines Investments Holding
ZEMA	Zambia Environmental Management Agency
ZMERIP	Zambia Mining Environmental Remediation Project

CHAPTER ONE

INTRODUCTION

1.1 Background

Mining and mineral processing produces different types of waste material such as tailings and waste rock (Kim & Jung, 2004). According to Lottermoser, (2010), mineral processing results into two products which are categorised as economic and non-economic. The economic product is a mineral whereas the non-economic product is usually waste and is referred to as tailings. Tailings consists mainly of insignificant quantities of valuable minerals or metals, chemicals, organics and process water which can be categorized as slurry, paste, filtered or cake, based on the availability of water and solids in it. Adiansyah et al, (2015), suggests that the volume of tailings generated by mines can equal that of raw material processed. For mining development projects, tailing deposits are often the most significant environmental liabilities. "Since tailings have no financial value to the mine operator at that particular point in time, they are typically stored in the most cost-effective manner that meets the bare minimum of regulations" (Armenia, 2016).

In the Republic of Armenia (RA) more than 400 of its mines are currently being exploited, and an evaluation indicated that about 40-45 million tonnes of mountain material is mobilized in order to obtain metals. Half of this mass consists of ores and this meant 20-25 million tonnes of waste. An article by Anglo Gold in (2004) on dust fallout from mine tailings in west wits basin in South Africa indicated the generation of 468 million tonnes of mining waste annually between 1997 and 2000. In the same article, Mpanza et al., (2004) reports that more than 270 tailings dams exist in the Witwatersrand Basin of South Africa which covers 400 km^2 of land. In Zambia the Copperbelt Province alone holds 791 million tonnes of tailings which occupy 9,125 hectares (Lindahl, 2014). These large volumes of tailings have huge effects that leave a large footprint on the environment. The environmental footprint caused by tailings is spatial in terms of storage area where these huge volumes of tailings are kept (Figure 1.1). They also pose as a pollution threat to the environment as some of these tailings are not properly managed during mining and not rehabilitated long after mining is done.

Generally, tailings dumps are of major concern throughout the world. This is because they are known for having physical and chemical properties that have serious impact on the environment, as well as human and animal health (Rodríguez et al.,2011). For example, toxic metals found in tailings are mostly in higher concentrations than they are in the ore mined. Furthermore, the tailings undergo physical and chemical change after they have been deposited. These chemical changes are often a result of exposure to atmospheric oxidation and tends to make previously, safely held contaminants mobile and available. This is what makes most tailings dumps potential candidates for discharge of Acid mine drainage (AMD) (Choi et al., 2005).

Figure 1.1: Site Picture of part of Mopani TD15A Tailings Dump site in Kitwe

According to Olobatoke and Mathuthu (2016), the composition of mine tailings differs based on the type of ore mined, the gangue associated with the ore, and the extraction method used. Some of the common toxic metals in tailings are Lead (Pb), Zinc (Zn), Copper (Cu), Nickel (Ni), Manganese (Mn) and Arsenic (As) (Li & Huang, 2015). The impacts that these metals have on people and animals are generally aggravated by their long-term persistence on the environment (Mani & Kumar, 2014). Their accumulation in soils, water and air are direct ways through which the metals enter the human food chain (Kamunda et al., 2016). The transportation of tailings material through different types of erosion (water erosion, air erosion) can result in the pollution of other parts of the environment away from the mining site, and the impacts on the environment are mostly reflected by the changes in land use patterns of the region (Moosavirad & Behnia, 2016). Priority for a reasonable and responsible mining organization must be to proactively isolate the tailings so as to forestall them from polluting groundwater, rivers, lakes and the wind.. In recent years, several small and large development initiatives related to the subject of mining has taken place in Zambia and a lot of studies around mining related issues have already been done. For instance, a study made to discriminate between lithogenic and anthropogenic sources of metals and sulphur in soils of Copperbelt Province of Zambia, (Kříbek et al., 2019) reported very high concentrations of heavy metals in dust samples from areas surrounding mining operations including slag and tailing deposits. Another study by Kříbek et al., (2012) confirmed that soils in the Copperbelt areas surrounding the mines and processing plants are heavily contaminated by fine metal laden tailings deposited from the air, and also particle fall-out from the smelters particularly where smelters are active or where smelting occurred previously. With increased mining ongoing in new sites such in North Western Province, new tailing dams will be available and threaten the environment at varying scale or magnitude. Therefore, there is a need to develop a risk assessment criterion that capture critical information for environmental protection.

Despite having mitigation programmes around environmental impacts of mining in Zambia, the lack of common criteria for risks to objects of environmental protection (people, natural landscapes, and their components) as well as the lack of time frames within which these criteria are evaluated has made it difficult to conduct impact assessment studies of mine dumps (Jaume, 2016). Having appropriate criteria that goes into the development of a framework for multicriteria decision support will enable the determination of immediate potential pollution risks to the environment from the tailings dump. This will consequently lead to the sustainable management of these dumps during mining which reduces potential of these dumps to pollute the environment. This research will seek to use multi criteria decision analysis (MCDA) to assess which tailings dump has a higher pollution risk potential to the environment.

1.2 Problem Statement

Tailings dumps are often the most significant environmental liabilities for mining development projects as they have no financial value to the mine operator at that particular point in time. Some of the common toxic metals in tailings are Lead (Pb), Zinc (Zn), Copper (Cu), Nickel (Ni), Manganese (Mn), and Arsenic (As) (Li & Huang, 2015). The impacts that these metals have on people and animals are generally aggravated by their long-term persistence on the environment (Mani & Kumar, 2014). Their accumulation in soils, water, and air are direct ways through which the metals enter the human food chain (Kamunda et al., 2016), but they can also enter the human anatomy through the inspiration of air and direct drinking of water. Generally, the presence of mine tailing dumps may lead to such negative consequences as changing the properties of rocks underlying dumps, modification of regional hydrological and hydrogeological regimes (Chalov et al., 2015; Pashkevich and Petrova, 2016), and occurrence of geological processes and phenomena that can cause disastrous effects (Aragão and de Oliveira Filho, 2011; Kabas et al., 2012). Studies have thus involved (i) determination of the nature of danger and the nature of technogenic environmental pollution; (ii) study of migration pathways of contaminants; and (iii) definition of objects of environmental protection. However, owing to the negative effects of mine dumps on the environment, there is a need to develop a new, long-term, cost-effective, and environmentally sound management approach to mitigate the impacts of mine tailings to the environment. An early monitoring and assessment approach would be appropriate to support good management techniques. (Lindahl ,2014).

1.3 Main objective

To evaluate the potential pollution risk of tailings dumps on the environment using multi criteria decision analysis (MCDA).

1.3.1 Specific objectives

a. To develop a set of appropriate criteria to use in the MCDA

b. To investigate the risk potential of the dumps based on criteria developed.

c. To evaluate the implications of the selected MCDA on environmental impact assessments.

1.3.2 Research questions

(i) What criteria is the most appropriate for development of a framework for multi criteria decision support?

(ii) Which criteria factor has more influence?

(iii) What are the pollution risks on the environment associated with tailings dumps of interest?

(iv) To what extent do these tailings dumps affect the environment?

(v) What implications does multi criteria decision analysis have on environmental impact assessments?

1.4 Significance of the Study

Zambia is a mining economy and generation of mine tailings dumps is going to be a continuous process for as long as mineral extraction continues. Tailings dumps are among the major sources of pollution and disturbance of various environmental components in the areas where enterprises for extraction and processing of mineral raw materials are located. This produces a need to examine these negative effects. This study aims to develop a risk assessment tool that captures critical information (physical and chemical) about tailing dumps to ensure environmental protection in the long term. We hypothesise that if selected critical indicators of the physical and chemical nature of tailing dumps are captured in a decision support tool, then decision-makers can have a means to evaluate the environmental pollution risk severity, which would serve as a means for early monitoring and assessment to support effective environmental management. Specifically, the study sought to (i) Develop a set of appropriate criteria to use in the multi-criteria decision analysis (MCDA); (ii) Investigate the risk potential of the dumps based on criteria developed; and (iii) Evaluate the implications of the selected MCDA on environmental impact assessments. The end result will be a ranking of the potential pollution risk that a mine dump possesses based on the criteria developed.

1.5 Thesis structure

The research objectives and questions stated above were answered through the following report outline:

(i) **Chapter one** introduces the research topic by describing the background of the study and identifying the problem statement. It further highlights the key research questions and the objectives of the study which are to be achieved through the outlined methodology.

(ii) **Chapter two** gives a description of the study area.

(iii) **Chapter three** provides a review and theoretical background to the research. It gives a brief of the multicriteria decision analysis process and the tool to be used in this study. It gives an account of how similar tools have been used in similar studies. Additionally, the review outlines the environmental management impact assessment process and the legal framework that supports it.

(iv) **Chapter four** gives the overall step by step procedures used to achieve the research objectives. The data collection and analysis instruments and techniques are described in this chapter.

(v) **Chapter five** presents the research findings of the assessment done on the three tailings dumps considered in the study using the multicriteria decision analysis tool described in chapter three. The potential pollution risk of each of the dumps is computed and all are compared against a risk severity scale.

(vi) **Chapter six** provides the conclusions to the study based on the data analysis and findings of chapter four and five. These conclusions were used to deduce relevant recommendations for implementation.

CHAPTER TWO

DESCRIPTION OF STUDY AREA

2.1 Study Area

The study area focused on a case study of three mine tailings dumps in Zambia (Figure 2.1). The selection of these dumps was dependent on the age (a legacy mine, an old working mine, and a relatively younger mine as indicated in (Table 2.1). The final selection was highly dependent on data availability and accessibility of these sites.

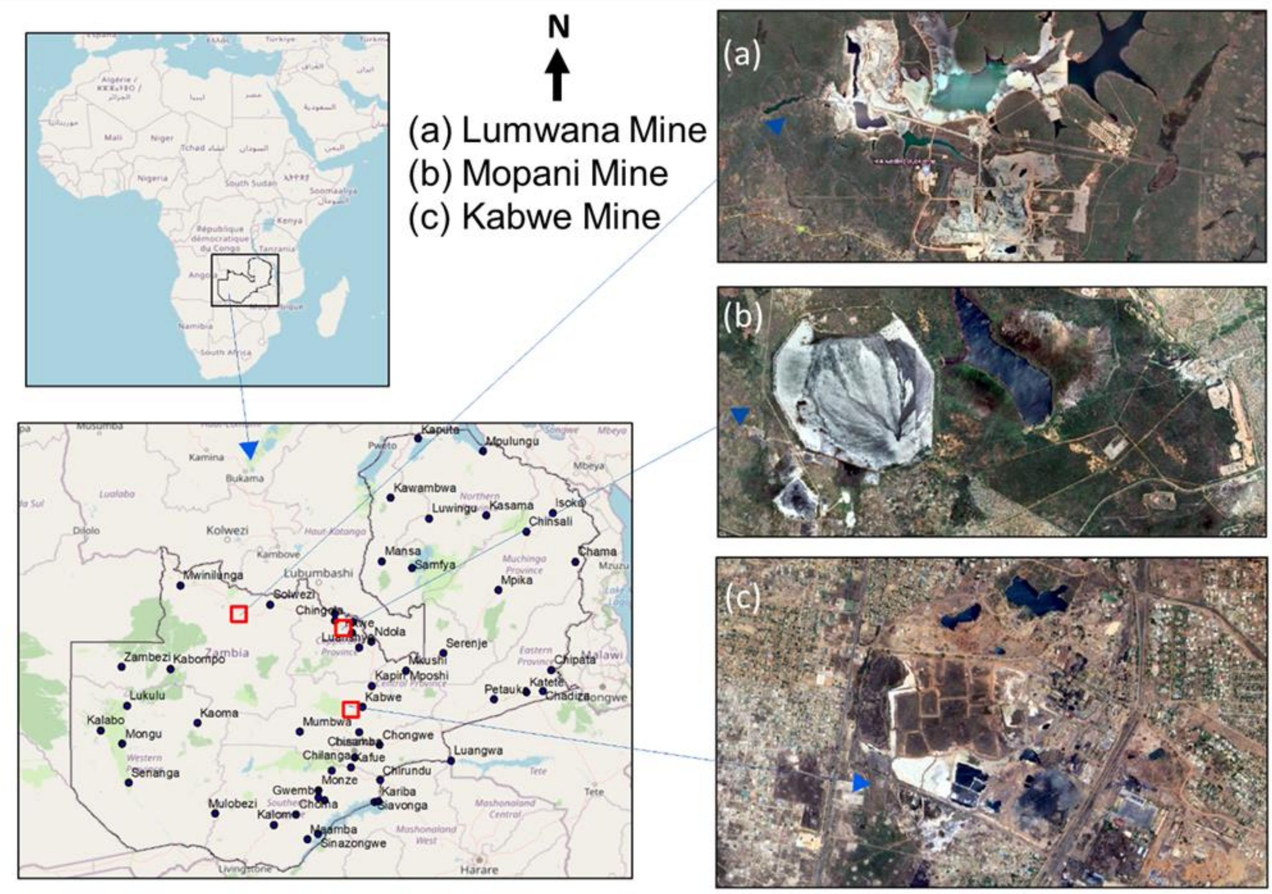


Figure 2.1: Map showing the location of tailings dumps that were investigated.

Table 2.1: Status of mines

Mine	Ore type	Location	Geographical Coordinates	Status
Kabwe Mine	Lead and Zinc	Central province	Latitude: -12.237310 Longitude: 25.83407	Legacy mine
Mopani Mine	Copper and Cobalt	Copperbelt Province	Latitude: -14.462272 Longitude: 28.42886	Working
Lumwana	Copper and Uranium	North Western Province	Latitude: -12.793865 Longitude: 28.10424	Working

2.2 Description of the tailing's dumps and the standing environmental issues

2.2.1 Kabwe Lead/Zinc mine

The Kabwe Lead Mine is located in Kabwe town which is 130 km north of Lusaka. The mine lies south of Kabwe town and occupies approximately 80 hectares. The Kabwe mine was operated continuously from the time it was opened in 1904 by the broken hill company until 1992 when it was put under care and maintenance by its ultimate owner ZCCM. During this time approximately 1.8 Mt of Zn, 800,000 Mt of Pb, 80,000 kg of Ag, 235,000 kg of Cd and 7.8 Mt of V_2O_5 were produced from the Kabwe site. The mine was finally closed in 1994 leaving behind tailings dumps covering a total area of 80 hectares (Figure 2.2). The dump area lies principally south of the Kabwe Mine workings, and west of the main process plant installations. The Kabwe dumps are subdivided into a number of cells, each holding a discrete waste type derived from the various mineral processing and smelting activities historically undertaken. The dump has a discontinuous bund to the north and south, constructed primarily of lateritic soil. To the west, the Waelz Kiln slag forms a continuous north-south positive feature. On the eastern side of the dumps the main feature is formed of ISF sinter slag, with lesser amounts of Waelz Kiln slag. Grey Slags form the lower ground adjacent to the sinter plant and lead smelter. The tailings dump is surrounded by several townships these include the western townships of Kasanda and Makululu, and the eastern townships of Chowa and Katondo (Figure 2.3). Two principal soil types occur in the study area, the distributions of which display a strong bedrock lithological control (Jones, 1972). Sandveld soils, comprising well drained light yellow sandy silts up to 1.5 m thick occur widely over the Basement and schists of the Lower Roan Group. Darker clays, loams and laterites overlie the Kabwe dolomite and related carbonate metasediments, notably close to their contact with the schists. The laterite underlies much of the Kabwe Mine site, and locally reaches thicknesses of up to 30m.

Before mining commenced in the early 20th century, the groundwater level within the Kabwe Mine vicinity was typically 1-6m below ground level (Jones, 1972). Groundwater flow directions were also concordant with the topographic surface, and predominantly trended NW-SE. In addition to the natural drainage network, much of the runoff from the Kabwe mine complex, the western townships of Kasanda and Makululu, and the eastern townships of Chowa and Katondo reports to a canal system. This system discharges to the Muswishi River (and ultimately the Lunsemfwa) via a dambo or natural wetland to the south-east of Katondo. The Main Canal (extending south-eastward from the mine to the Reed Dambo in the Muswishi River headwaters) formerly carried in excess of 100 litres per second of water which was pumped from the underground workings during operations.

The major environmental problem lingering from the historical mining activities is serious contamination of soils as a result of smelting and dust emissions from waste dumps. The content of lead in soils can reach as high as 26000 mg/kg in the most polluted areas and thus a high content is also found in agricultural products (Czech Geological Survey, 2007). Land up to 4km away from Kabwe in all directions, and at least as far away as 14 km to the west is unsuitable for agricultural purposes (Czech Geological Survey, 2007). High concentration of lead in soils, consumption of contaminated vegetables, inhalation of lead rich dust and usage of lead polluted water has led to higher concentrations in the blood of citizens living in Kabwe. Normal blood levels are less than 10 µg/dl, and levels above are considered unhealthy according to the World Health Organization. The current recommended level of lead in children's blood is 5 µg/dL. Levels in excess of 120 µg/dL can potentially be fatal. In some neighbourhoods in Kabwe, blood concentrations of 200 µg/dL or more were recorded in children, and records show average blood levels of children tested ranged between 50 and 100 µg/dL. (www.blacksmithinstitute.org/projects/display/3). Children are particularly vulnerable to toxic effects of lead and can suffer severe and permanent health effects which influence the development of the brain and nervous system (www.who.int/mediacentre/factsheets/fs379/en/). A number of mitigation measures were undertaken in Kabwe between 2003 and 2011. Nonetheless, Green Cross Switzerland and The Blacksmith Institute in 2013 yet again listed Kabwe as one of the 10 worst polluted places in the world (www.worstpolluted.org/).

Figure 2.2: Site pictures from the Kabwe Pb-Zn mine tailing dump.

Figure 2.3: Google earth image of Kabwe mine tailings dump

2.2.2 Mopani Copper/Cobalt Mine

Mopani Copper Mine is situated on the western side of Kitwe approximately 300 km north of Lusaka. The mining area covers an area of about 11200 hectares. On average the area receives 1300mm of rain. The closest surface water body is about 658m and the groundwater table is about 6m below the ground (Figure 2.4). The copper-cobalt operations, comprising four open pit and four underground mines, the North Mindola, Mindola, Nkana Central and Nkana SOB (Southern Ore Body). These mines exploit mineralisation, more or less continuously over a strike length of 14 km on the South West margin of the Kafue Anticline, immediately to the east of the town of Kitwe. Mining operations commenced in 1927 and by 1932 large scale production had commenced which has continued to the present, with a number of major ownership changes (Croaker, M.R 2011). Mining has been on going on for 90 years which has led to the accumulation of 732 hectares of tailings (Figure 2.4).

Generally, most environmental issues resulting from mining on the Copperbelt tend to yield from increased SO_2 emissions because of several copper smelters. High SO_2 concentrations will directly affect the health of both humans and biota. Similar to SO_2, Particulate matter less than 10 µm in size (PM10) originates both from smelters and from dusting of tailings dams and unpaved roads. Children exposed to high concentrations of PM10 are likely to have an increase in lower respiratory symptoms and reduced lung functions (SGAB et al., 2005). Soil contamination; Accumulation of metals in soil results from wind-borne dust particles (from dry tailings dams) and particle fall-out from smelters. The main soil contaminants that occur in concentrations high enough to constitute a significant hazard to human health, are copper and cobalt (SGAB et al., 2005). A broad study on soil contamination has been made in the Copperbelt where large areas within the mining region are contaminated compared to natural ground values and a variety of elements occur in elevated concentrations in addition to copper and cobalt (Czech Geological Survey, 2007).

Figure 2.4: Google earth image showing the distance of Mopani Mine tailings dump (TD15A) to nearest surface water body and footprint of the tailings dump.

Figure 2.5: Site pictures from the Mopani TD15A tailings dump showing fine grained material and tree cover on the slopes of the dump.

2.2.3 Lumwana Copper/Uranium Mine

The Lumwana Copper Mine is an open cut mine project located in Northwest Zambia, about 400 km northwest of Lusaka and 100 kilometres west of Solwezi town. The mine was officially opened in April 2009 by Equinox Minerals which was acquired by Barrick Gold Cooperation in July 2011. At the time of opening Lumwana mine was considered the largest copper mine in Africa. In addition to copper, the Lumwana mine project has rich uranium deposits. Feasibility Studies by initial owners Equinox showed that 2 million pounds a year of uranium oxide could be mined alongside 15,000 tonnes of copper from the discrete uranium reach zones. Lumwana has an expected average of 169,000 tpa of copper ore over the 37 year mine. (Campbell, Graeme and Associates Pty Ltd 2002a). This directly translates to huge accumulation of tailings from the processing of this copper ore.

The topography of the area is gently sloping valleys with side slope gradients typically less than 5% and a maximum of 10%. Existing surface elevations are generally in the range between 1,270 m and 1,410 m above sea level. The total annual rainfall recorded at Lumwana Base Camp in 1999 was 1,310 mm. The Tailings Storage facility is located in the Lumwana East River Valley (Figure 2.6). The embankments of the tailings are constructed across the valley of the Lumwana East River (Figure 2.7). The TSF is designed to operate for the life of the project, 18 years with a total volume of 370 Mt and a surface area of around 2,000 hectares. The copper mineralization in the deposits is hosted almost entirely within high grade metamorphosed, intensely sheared, recrystallised muscovite - phlogopite - quartz - kyanite schists. Groundwater studies have indicated static water levels between 5.7m and 6.5m below ground level. As estimated from Google earth maps, the Lumwana east river is 100m away from the tailing’s storage facility. The closest settlement to the mine site is slightly over 6 kilometres south of the tailing’s facility (SRK Mining consultants limited, 2005)

The North Western province is sometimes also referred to as the new Copperbelt for its abundant and relatively newly found copper resources. Since privatization two large scale open pit copper operations (Kansanshi and Lumwana) have started up nearby the town Solwezi, in addition to copper, the Lumwana mine is also planning on extracting uranium. Unlike the ones in the Copperbelt area, the environmental impacts from mines in the North Western region are not well documented, but a few observations are still made here.

Regarding air pollution, the emissions of both SO_2 and PM_{10} from new smelters are expected to be lower than in the Copperbelt due to new technology. The dust fall-out from dry tailings is likely to be the same as described for the Copperbelt, and the long-term potential for soil contamination is unsecure. Regarding pollution of surface water in the North Western province there are concerns for two reasons. Firstly, the potential for acid mine drainage formation is more likely to occur due to less favourable geological conditions. Secondly, the bedrock naturally contains rather high concentrations of uranium. The run-off from the relatively new mining areas is towards tributaries of both the Upper Kafue and the Upper Zambezi River, where the latter one is less supervised (SRK Mining consultants limited, 2005).

Figure 2.6: Google earth image showing the Chimiwungo pit, Malundwe pit and the tailings facility.

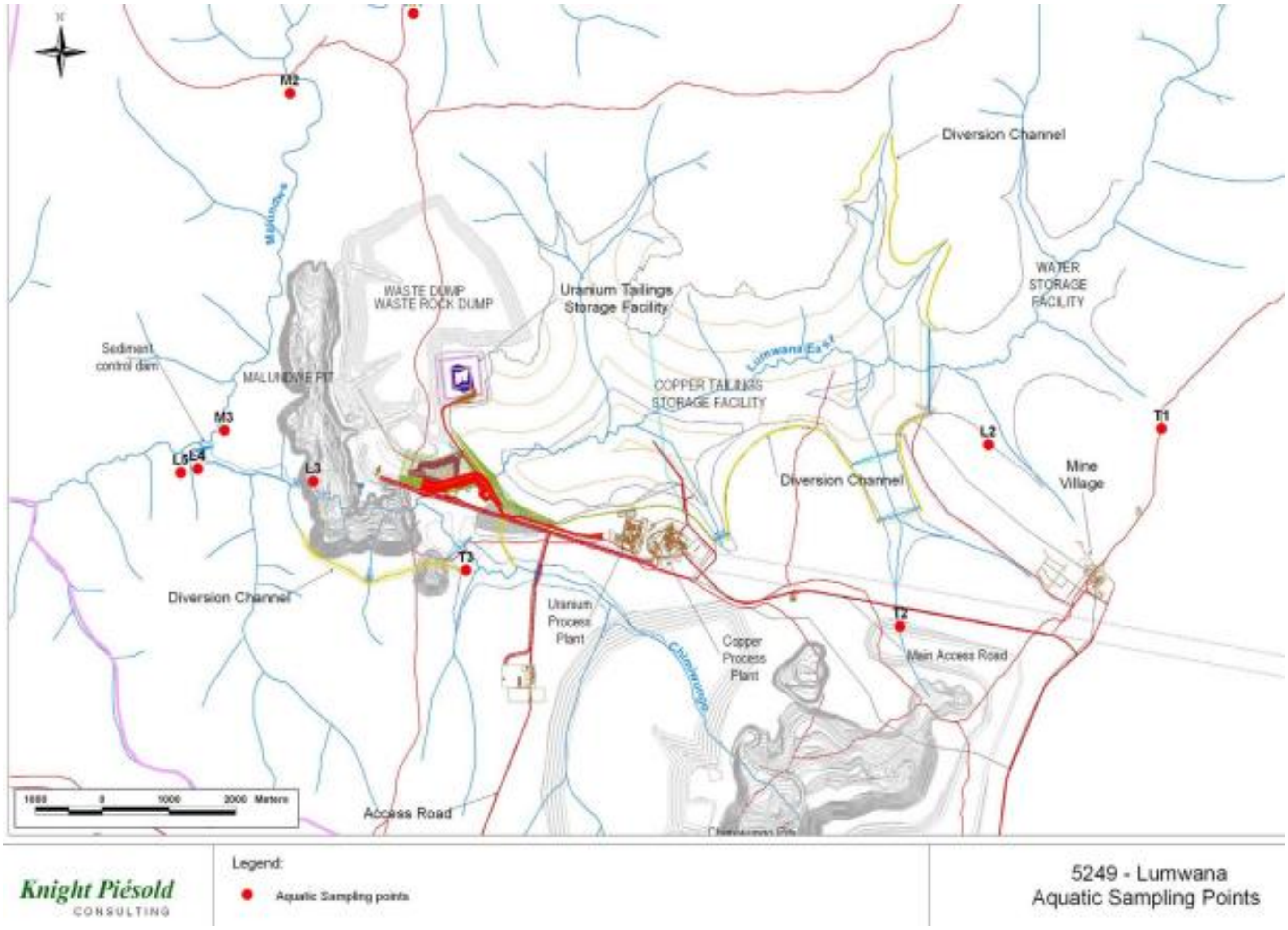


Figure 2.7: Map showing Lumwana mine surface water bodies. (Knights Peisod consulting)

CHAPTER THREE

LITERATURE REVIEW

3.1 Introduction

Mine tailings are made up of the remaining ground up ores that is characterised by fine grained particles. These are left over after minerals of interest have been extracted from mined ore and the related process water containing dissolved metals and reagents for the processing of minerals. When masses of rocks are mined, crushed, pulverized, and processed, mine tailings resulting from this process are usually enormous. Crushed and ground ores could account for 95 to 99 percent of tailings (Edraki., et al 2014). Tailings are generally stored on the surface either within retaining structures (tailing dams), or in form of piles commonly known as dry stacks and structures in underground mine voids by a process known as backfilling (Roca et al., 2019). Tailings can be categorized as slurry, paste, filtered or cake, based on the availability of water and solids in it.

In Zambia there are more than 2000 tailings dumps covering more than 10,000 hectares land (Environmental Council of Zambia, 2008). In the Copperbelt Province alone, 791 million tonnes of tailings occupy 9,125 hectares (Lindahl, 2014). These figures have since increased and will continue to increase because mining in Zambia is a key economic activity. One study by Jones and Boger in (2012) revealed that 14 billion tonnes of tailings were produced by the mining industry in 2010 worldwide. Tailings have the potential to create huge impacts both on the environment and society (Islam, 2021). Therefore, mine tailings management is a critical issue in mining operations as the impacts of these tailings are irreversible. Additional challenges in achieving landscapes that are physically and chemically stable, and do not present risks such as acid mine drainage come in the physico-chemical makeup of tailings. Consequences of failing to manage tailings can be costly and sometimes catastrophic.

3.2 Environmental effects of tailings dumps

Environmental effects resulting from mine tailing dumps can be profound and need significant steps to retain the safe state of the environment. “The tailings deposits are often the most significant environmental liabilities for mining development projects. Because tailings have no financial value to the mine operator at that particular point in time, they are typically stored in the most cost-effective manner that meets the bare minimum of regulations." (Armenia, 2016). Pollution of Water, air and soil is a common result of mine tailings dumps. Water pollution happens when the solids, heavy metals and other chemical compounds coming from tailings overflow. For example, if an embankment is built without putting into consideration the right and appropriate technicalities, there may be a high risk of the dam bursting when the rains come causing inundation in other water bodies and to the adjacent farm lands. The Leachate from the dump percolates to underground aquifers therefore causing contamination to it (Wise-Uranium, 2019).

The air is polluted by Particulate matter less than 10 µm in size (PM10) which originates both from smelters and from dusting of tailing dumps and unpaved roads from the dump (Kossoff, et al., 2014). According to SGAB, et al., (2005) Children exposed to high concentrations of PM10 are likely to have an increase in lower respiratory symptoms and reduced lung function.

According to Norgate and Rankin, (2000) Soil Pollution and disturbances arise from oxidation of the sulphides which come into contact with water, an acid environmentally toxic acid mine drainage results from this interaction. In this process, metal leaching is enhanced in tailings. The areas occupied by dumpsites usually end up losing their fertility therefore, land use and capability is reduced. These spaces also cease to be habitats and cannot be used as grazing land. (Wise-Uranium, 2019).

3.3 Environmental effects of tailing dumps in Zambia

Zambia like most of the mining economies has not been spared of these adverse impacts on its environment resulting from tailing dumps. The copper industry has dominated the mining scene in Zambia for more than eight decades since the first commercial mine was opened in 1928 (Simutanyi, 2008). Environmental problems that are linked directly to mining operations that are historical in the Copperbelt are largely attributed to geotechnical integrity of waste dumps. "There are at least 21 waste rock dumps covering more than 388 hectares, 9 slag dumps covering 279 hectares and finally more than 45 tailing dams covering an area of around 9125 hectares" (ECZ, 2008). There is a total of than 10 000 hectares in the Copperbelt which is covered with mineral waste and this takes away land use opportunities for the local population in terms of agriculture, housing, forestry, ranching etc. (SGAB et al., 2005).

According to Kossoff et al., (2014), naturally occurring metals in ore bodies including Cu, Fe, Mn, Co, Zn etc. are found in mine tailings and contain mainly sulphides. In some cases, oxidation of these Sulphides occurs when tailings come in contact with water and are exposed to air in a process known as Acid Mine Drainage (AMD). Though AMD is uncommon in Zambia, environmentally toxic sulphuric acid is generated during this oxidation process enhances metal leaching in tailings which eventually finds its way into the groundwater (Ngulube R., et al 2016). In the Copperbelt, the geology is underlain by carbonates which act as a buffer against acidification. This makes acid mine drainage a rare feature in the Copperbelt except for 2 hectares of a former ore stockpile in Chibuluma west of Kitwe (SGAB et al., 2005). Water drained from the area has a pH of 2–3 and has a high primary Copper and Cobalt content.

Aside from the Chibuluma acid mine drainage, other environmental impacts including dust fall out and suspended solids that are discharged on surface water will result from historical sites such as the Kabwe Pb-Zn Mine. However, an extensive study by (SGAB et al., 2005) states that old mining legacy sites impact the environment minimally compared to current mining operations. Despite this extensive study, the case of the Kabwe legacy mine disagrees. According to the (Czech Geological Survey, 2007) the major environmental problems lingering from the historical mining activities at the legacy site in Kabwe is serious contamination of soils as a result of smelting and dust emissions from waste dumps. The lead content in soils in the most polluted areas can reach as high as 26000 mg/kg and agricultural products also had a high content found in them. Despite the mine being closed for almost two decades and a number of mitigation measures undertaken in Kabwe between 2003 and 2011, Green Cross Switzerland and The Blacksmith Institute in 2013 listed Kabwe as one of the 10 worst polluted places in the world (www.worstpolluted.org/). This simply shows that mine tailings can still continue to severely impact the environment long after mining ceases. Therefore, a pollution risk assessment is needed to prevent such environmental problems from tailing dumps in the future.

According to the Environmental Council of Zambia (2008) most of the mining operations in the Copperbelt lie within the Kafue River catchment area. Kafue's watershed is the most developed in the country and the river is reportedly coming under increasing threat from pollution as well as competition in water utilization. Domestic water supply for the main cities in the Copperbelt region is from the Upper Kafue and concern for potentially contaminating mining activities is always present. According to Czech Geological Survey (2011), the Kafue River and its branches are used for irrigation and providing fish for the local communities. Several studies have indicated the presence of many dissolved elements in form of ion concentration. These concentrations are elevated in the Kafue River and its tributaries within the Copperbelt. Additionally, washout of fine particles from dumps and ore-processing plants, leakage of water through overflows from tailing facilities, and the drainage of technological water from smelters and acid plants causes siltation, surface water and stream sediments contamination on the Copperbelt. High and extremely high contamination were detected in the sediments of the Mushishima and Changa rivers (Chingola area), high contamination was detected while in the sediments of the Uchi and Wanshimba rivers (Kitwe area) extremely high contamination was detected.

A report by Muloiso and Zulu (1993), indicates how Mwambashi River, which joins the Kafue was heavily contaminated by the Chambishi mine tailings spillage in 1981.Metal discharges can negatively affect biodiversity and alter species composition in streams. Aside from this Chambishi incident, a major tailings accident occurred on the Copperbelt in Mufulira in 1970. Tailings went through a sink hole into underground workings and 89 miners lost their lives. (Seymour, 2005).

According to SGAB et al (2005). Several studies around the impacts of mine tailings especially around the Copperbelt province and Kabwe town in central province have been done. But this information hasn't been used to conduct risk assessments. According to Jaume, 2016 this is attributed to the lack of common criteria for risks to objects of environmental protection such as people, natural landscapes, and their components. Additionally, the lack of time frames within which these criteria are evaluated has made it difficult to conduct impact assessment studies of mine tailing's dumps. One study by Sun et al in 2013 to establish the environmental risks of phosphate tailing dumps using (MCDA) was done. Analytical hierarchical process (AHP) was used and criteria were developed. This study will take a similar approach to develop criteria.

3.4 Multi criteria decision analysis (MCDA)

"MCDA is a general framework for supporting complex decision-making situations with multiple and often conflicting objectives that stakeholder groups and/or decision-makers value differently" (Saarikoski et al., 2016). Belton and Stewart (2002), describe MCDA as "an umbrella term that describes a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter". Furthermore, Mendoza and Martins, (2006) say that support for single decision makers is based on operational research. According to (Fish et al., 2011), recently multi-stakeholder processes to structure decision alternatives coupled with their consequences is where the emphasis has been. This is to pave way for dialogue on the alternative courses of action and their merits thereby enhancing the quality of the procedure in the decision-making process. MCDA methods used for ecosystem service assessments vary and are seen in the following ways: According to Vatn, (2009); Wegner and Pascual, (2011); Chan et al., (2012) it is seen as an "alternative to economic valuation" Or "as a complementary approach to cost benefit analysis". Lastly it is seen "as a decision support system that integrates economic and non-economic values" (Newton et al., 2012). Based on the fact that MCDA can be used as an alternative for economic valuation, the use of MCDA methods has been recommended by several scholars when addressing intangible values such as cultural and heritage values. MCDA also provides a compatible methodological framework for deliberative valuation, which is considered helpful in addressing plural value dimensions related to common goods.

3.4.1 The process of MCDA

"MCDA methods function on the basic idea of evaluating the performance of alternative courses of action (e.g., management or policy options) with respect to criteria that capture the key dimensions of the decision-making problem (e.g., ecological, economic and social sustainability), involving human judgment and preferences. MCDA methods will integrate evaluation methods in the sense that they combine information about the performance of the alternatives with respect to the criteria (scoring) with subjective judgements about the relative importance of the evaluation criteria in the particular decision-making context (weighting)" (Saarikoski et al., 2016).

3.4.2 Advantages and disadvantages of MCDA methods in ecosystem service valuation

Despite MCDA being used in several disciplines and fields just like any other framework it has both advantages and disadvantages.

Advantages of MCDA include:

- It enables the evaluation of ecosystem service by structuring an assessment of a complex problem along both normative and cognitive dimensions which are both essential (Vatn, 2009).

- It allows for ecological, socio-cultural and economic objectives to be compared in a structured and shared framework (Mendoza and Martins, 2006).
- It can facilitate multi-stakeholder processes, transparency and discussion about the subjective elements in policy analysis, including the nature and scope of the decision problem, the selection and definition of options (alternatives), and the characterization and prioritization of evaluation criteria. (Keune and Dendoncker, 2013).
- It can deal with incomplete and uncertain information which is characteristic of most environmental planning situations by allowing use of a mixed set of both quantitative and qualitative information (Chan et al., 2012). In this study there is no set criteria for assessing the risk potential of tailing dumps on the environment, these will have to be developed.

Disadvantages of MCDA include:

- Stirling (2006) points out that environmental policy discourses can either be closed down or opened up by MCDA. In this case, opening up policy discourses means that "all key assumptions in the analysis such as characterization of alternatives, criteria and weightings are made visible and subject to public discussion", while closing down refers to "an opaque process in which experts deliver a single optimal policy recommendation, and the role of general public is only to state their values e.g., through WTP surveys.
- Another problem with MCDA methods is that they are suited for bringing out the preferences of a relatively small group of decision makers and stakeholders, not capturing individual preferences across the whole population. Due to this lack of representativeness, Hanley (2001) has argued that decisions made with the aid of MCDA may well fail on the ground of representativeness and democracy.

- Furthermore, MCDA methods can also be used for legitimizing pre-defined decisions if they are used in a non-transparent way (Stirling, 2006).

3.4.3 Different methods of Multi criteria decision analysis (MCDA)

Multi-Criteria Decision Analysis has seen an incredible amount of use over the last several decades. Its role in different application areas has increased significantly, especially as new methods develop and as old methods improve. Several common MCDM methods have been analysed and their applicability to different situations determined by evaluating their relative advantages and disadvantages. In addition to applying single MCDM methods to real world decisions, the progression of technology over the past couple of decades has allowed for more complex decision analysis methods to be developed. A review study of the different methods of MCDA by (Velasquez & Hester, 2013) gave description of 11 separate methods. Table 3.1 gives a summary of the advantages and disadvantages of these methods identified and their common applications.

Table 3.1: Summary description of MCDA methods

	Method	Advantages	Disadvantages	Areas of Application
1.	Multi-Attribute Utility Theory (MAUT)	Takes uncertainty into account; can incorporate preferences.	Needs a lot of input; preferences need to be precise.	Economics, finance, actuarial, water management, energy management, agriculture
2.	Analytic Hierarchy Process (AHP)	Easy to use; scalable; hierarchy structure can easily adjust to fit many sized problems; not data intensive.	Problems due to interdependence between criteria and alternatives; can lead to inconsistencies between judgment and ranking criteria; rank reversal.	Environmental, transportation and urban planning, agriculture, forestry, waste management, hydrology, geology/geomorphology, natural hazard and risk management Performance-type problems, resource management, corporate policy and strategy, public policy, political strategy, and planning.
3.	Case-Based Reasoning (CBR)	Not data intensive; requires little maintenance; can improve over time; can adapt to changes in environment.	Sensitive to inconsistent data; requires many cases.	Businesses, vehicle insurance, medicine, and engineering design.
4.	Data Envelopment Analysis (DEA)	Capable of handling multiple inputs and outputs; efficiency can be analysed and quantified.	Does not deal with imprecise data; assumes that all input and output are exactly known.	Economics, medicine, utilities, road safety, agriculture, retail, and business problems.

5.	Fuzzy Set Theory	Allows for imprecise input; takes into account insufficient information.	Difficult to develop; can require numerous simulations before use.	Engineering, economics, environmental, social, medical, and management.
6.	Simple Multi-Attribute Rating Technique (SMART)	Simple; allows for any type of weight assignment technique; less effort by decision makers.	Procedure may not be convenient considering the framework.	Environmental, construction, transportation and logistics, military, manufacturing and assembly problems.
7.	Goal Programming (GP)	Capable of handling large-scale problems; can produce infinite alternatives.	It's ability to weight coefficients; typically needs to be used in combination with other MCDM methods to weight coefficients.	Production planning, scheduling, health care, portfolio selection, distribution systems, energy planning, water reservoir management, scheduling, wildlife management.
8.	ELECTRE	Takes uncertainty and vagueness into account.	Its process and outcome can be difficult to explain in layman's terms; outranking causes the strengths and weaknesses of the alternatives to not be directly identified.	Energy, economics, environmental, water management, and transportation problems.

9.	PROMETHEE	Easy to use; does not require assumption that criteria are proportionate.	Does not provide a clear method by which to assign weights.	Environmental, hydrology, water management, business and finance, chemistry, logistics and transportation, manufacturing and assembly, energy, agriculture.
10.	(SAW) Simple Additive Weighting	Ability to compensate among criteria; intuitive to decision makers; calculation is simple does not require complex computer programs.	Estimates revealed do not always reflect the real situation; result obtained may not be logical.	Water management, business, and financial management.
11.	(TOPSIS) Technique for Order Preferences by Similarity to Ideal Solutions	Has a simple process; easy to use and program; the number of steps remains the same regardless of the number of attributes.	Its use of Euclidean Distance does not consider the correlation of attributes; difficult to weight and keep consistency of judgment.	Supply chain management and logistics, engineering, manufacturing systems, business and marketing, environmental, human resources, and water resources management.

As listed above, there are various MCDA methods, but this study will consider only one technique which uses aggregation-The Analytical Hierarchical Process (AHP) developed by Saaty in 1980 because it is commonly used in MCDA and similar studies have been done using it. AHP was chosen mainly because it easy to use, it is scalable, its hierarchy structure can easily adjust to fit many sized problems, it is not data intensive and is the only method from literature reviewed that has been used for waste management. Based on the methodology that was used in this study, AHP was best suited compared to the other methods described. Nowadays, AHP is extensively applied in business, social, industrial, operational, management and research areas and is stimulating growing interest, especially with the integration of GIS, within the research community spanning the fields of environmental, transportation and urban planning, agriculture, forestry, waste management, hydrology, geology/geomorphology, natural hazard and risk management (Bhushan and Rai 2007; Malczewski 2006; Vaidya and Kumar 2006) and evaluating the best alternatives in site selection applications (Erden & Coskun 2010).

3.5 Analytic Hierarchy Process (AHP)

AHP is one of the most widely used assessment methods (Karami,2006) and its major characteristic is its use of pair-wise comparisons which are used both to compare the alternatives with respect to the various criteria and to estimate criteria weights (Loken, 2007) and Saatys scale is used. "The method starts by structuring a decision-making problem as a hierarchy in the form of an upside-down tree where the main goal is placed on top. Partial objectives that meet the main objective are placed at the second level. Each partial objective at the second level can be decomposed into third-level objectives, and each set at each level meets the objective of the level to which they are subordinate". These partial objectives are treated as criteria. The alternatives are listed and then compared in a pairwise matrix (Table 3.3) at a lower level based on their contribution to reaching each objective, or criterion, from the lower level. Pairwise comparisons are performed using the method described by Saaty at the fundamental scale of Saaty (1980) presented (Table 3.2). The scale ranges from one to nine where one implies that the two elements are the same or are equally important. On the other hand, number nine implies that one element is extremely more important than the other one in a pairwise matrix. The pairwise scale and the importance value attributed to each number are illustrated in the Table.

Table 3.2: Fundamental scale of Saaty, 1980.

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance

Table 3.3: Pairwise comparison Matrix

criteria	**Criteria 1**	**Criteria 2**	**Criteria 3**	**Criteria 4**	**Criteria 5**
Criteria 1	1				
Criteria 2		1			
Criteria 3			1		
Criteria 4				1	
Criteria 5					1

The following are the simplified steps for AHP method.

Firstly, the problems and alternatives were defined, followed by the building of surveys (pairwise comparison of alternatives on a qualitative scale). Thereafter, the relative weights were determined. At each hierarchy level, there was a control process for the pairwise comparisons. If the consistency ratio (CR) is less than 0.10, then the ratio indicated an acceptable level of consistency in the pairwise comparisons. If the CR was greater than 0.10, the ratio values are reflective of inconsistent judgements and in such cases. The original values in the pairwise comparison matrix were re-examined and the procedure was repeated. This was done using the formula;

$CR = CI/RI$……………………………………………….Equation 1

$CI = (\gamma_{max} - n)/(n-1)$

Where: γ_{max} is the principal Eigen value of the pairwise comparison matrix

n is number of factors (criteria) or order of the matrix

RI is the Random Consistency Index

The final step was the aggregation of the relative weights of the decision elements by multiplying them successively from down to the beginning of the hierarchy, to ascertain the best alternatives/strategies. (Saaty, 1980). Considering the fact that AHP has some bias the procedure did not use the opinion of the experts throughout. The expert opinion was only used to calculate criteria weights thereafter criteria scores were calculated using a scoring and ranking technique from a detailed desk study and physical site characterization of the tailing's dumps. The following computations were made using the formulae given:

I. The contamination potential (index of contamination)

$$IC = \sum \frac{1}{N} x \sum_{i=1}^{n} \frac{Ci}{PL_C} \text{ ....Equation 2}$$

Where **C*i*** is the concentration of the *i*th metal in the tailing's material.

PL_c is the maximum permissible limit of a toxic metal in soil as reported by DEA (2010) and Kamunda *et al*., (2016)

N is the number of toxic metals ratios considered in the study.

IC is the value of the index of contamination.

Table 4.3: Permissible level of toxic element concentration in South African soils (DEA, 2010; Kamunda *et al*., 2016)

Metals	**Cd**	**As**	**Cr**	**Ni**	**Pb**	**Zn**	**Hg**	**Cu**	**Co**	**U**
Max Permissible limit in soil (mg/kg)	7.5	5.8	6.5	91	20	240	0.93	16	300	3

3.5.1 Examples of AHP case studies

A study by Leung et al (1998) addresses decision making within the Hawaii’s pelagic fisheries using AHP. The AHP method, even with considerable variation among questionnaires used to create its input data, was able to successfully weight criteria important for sustaining fisheries and resulted in alternative rankings similar to successful rankings in the past. Similarly, Bentes et al., (2012) examined a telecommunications company in Brazil and assess its organizational performance using AHP to prioritize performance perspectives and indicators. AHP is used in combination with the Balanced Scorecard (BSC), a framework for performance assessment, to properly rank alternatives. BSC specifically assesses organizational performance from multiple distinct perspectives. This framework revealed the associated necessary criteria and alternatives and AHP was used for comparisons, weighting, and rankings. With four criteria and three alternatives, AHP was able to handle the multiple measures and perspectives. Although limitations, like self-assessment bias affecting internal validity, were certainly present in this application, the paper concluded that the combination of methods led to a ranking of organizational performance that was far superior to previous methods. Lee et al., (2012) evaluated factors and alternatives of Technology Transfer Adoption to approve profitability using AHP to properly weight seven factors and rank three alternatives. Okeola and Sule (2012) used AHP to study urban water supply systems in Nigeria while Ambrasaite et al., (2011) presented a way to utilize a combination of multi-criteria decision analysis and cost-benefit analysis for risk analysis in transport infrastructure appraisals. AHP was utilized in order to assess the various non-monetary criteria. Risk analysis was used to address shortcomings in the multi-criteria decision analysis in weighting the criteria. This was then applied to a railway line in the Baltic countries and Poland. A recent study by Mhlongo (2020) saw AHP being used to weight criteria and an assessment tool called the simple tool being used for further assessment to rank abandoned mine tailings dumps in south Africa’s Giyani and Musina provinces for rehabilitation purposes. The development of AHP and its role in MCDM analysis has seen an increased use in examples from real-world applications as seen in the few applications described.

3.6 Criteria development

Ideas for the criteria proposed to the experts were obtained from similar MCDA studies, for example the Geological Survey of Spain has developed a methodology for the systematic ranking of abandoned facilities of mining wastes, through the assessment of scenarios of potential pollution and physical instability (Alberruche del Campo et al., 2014). The methodology takes into account several issues related to the possible consequences, such as the distance of water bodies, the number of people within a specified distance, the nearby soil-use, etc. Apart from physical stability, and leaving aside pathways and receptors, the potential hazard of pollution caused by the mining wastes depend on the existing mineralogical, chemical, and physical properties. The methodology is focused on the total metal contents and the water-soluble fraction, assuming that chemical pollution of soils and sediments is a consequence of a combination of the dispersion of particles and dissolved elements by wind and water (Gonzalez, 2016). Additionally, studies of pollution on the environment from mining activities and mine tailings by Kosgei et al, (2020) have listed similarly the several issues the methodology for systematic ranking of tailings dumps by the geological survey of Spain takes into account. The study highlights the following effects or impacts; air pollution evident from dry tailing damps which are a major source of wind-borne dust particles. The toxic tailings are blown to the nearest agricultural land where the soils get contaminated by heavy metals that inhibit the enzyme activity in the soil and endanger plant growth. Furthermore, the heavy metals absorbed by these plants poses a potential contamination in the food chain. Water pollution is also eminent when these tailings flow in surficial water bodies, causing undesirable changes to irrigation, industrial and drinking water quality. The dissolved copper content has shown to be considerably higher than standards for protecting aquatic life in more or less all monitoring stations within the Copperbelt region. In other instances, sulphides get oxidized when tailings are exposed to air and when in contact with water, a process known as Acid Mine Drainage (AMD) occurs.

3.6.1 Criteria Scoring

The various indicators in Table 2 include physical properties, chemical properties, properties of the environment around the dump, climate factors, and the protective cover, further broken into factors. Each individual factor was further classified so as to provide thresholds and scores per indicator (Step 3, Figure 2). These scores were then normalized to a sum of one per factor. Table 3 shows the normalization of physical properties scores. The mineralogy/chemical properties were based on the index of contamination (IC). The index of contamination (IC) was calculated by dividing the measured concentration by the maximum permissible (Mhlongo et al., 2019). The IC values were classified as detailed in Table 4. Table 5 has outlined the classification of various environmental factors and normalized scores. For the lithology, a classification is adopted as shown in Figure 4. Limestones are highly vulnerable to pollution compared to alluvial sediments which typically have some clay that attenuates contaminants. For the climatic factors, rainfall was used as a proxy for this. Rainfall classification is shown in Table 6 with the highest vulnerability having rainfall of more than 1500 mm. Table 7 shows the protective cover classification and score normalization.

To allow the integration of the various indicators and factors (Step, 4, Figure 2), a score was calculated using Equation below.

$$Score = \sum \mathrm{WI} \times \sum \mathrm{FS}$$

Where, WI is the Weight of indicator based on AHP, and FS is the factor score based on threshold classification. The score in Equation 1 was further classified into severity as shown

in Table 4.5.

Risk category	**Risk scores**	**Description**
Low	0 – 0.35	Pollution risk is minimal but should be monitored.
Low to medium	0.36– 0.5	Pollution risk is tolerable with increased monitoring.
Medium	0.51 – 0.65	Pollution risk is tolerable with controls. Assess the risk mitigation options and monitor risks.
Medium to high	0.66 – 0.8	Pollution risk undesirable. Risk mitigation should be employed.
High	0.81 – 1.0	Pollution risk intolerable. Risk mitigation required immediately.

3.7 Environmental impact assessments (EIAs)

Environmental compliance in the mining sector is done by the Zambia Environmental Management Agency (ZEMA). The agency is in charge of authorizing mining projects through an environmental impact assessment (EIA) process. The agency issues environmental permits and is responsible for auditing. Environmental issues are also a governmental responsibility of the Mine Safety Department. Despite Zambia having relatively up to date laws and regulations regarding environmental performance, it faces a huge problem when it comes to satisfactory implementation. This is partially attributed to the lack of coordination between stakeholder institutions and to a large extent, the lack of manpower and technical capacity. A major concern exists on the lack of supervision towards the active mining industry and the generally poor quality of EIA reports compiled and used in the license process.

3.7.1 Governmental institutions and Authorities

Environmental issues cut across a number of different sectors in Zambia, and management of these environmental issues similarly involves a number of government institutions. The most important responsibilities regarding environmental impacts of mines are shared between two ministries. The change of government saw the Ministry of Green Economy and Environment (MGEE) unveiled on the 29th of September 2022. Initially the Ministry of water development, sanitation and Environmental protection (MWDSEP was responsible for overall policy formulation on the environment, natural resources and pollution control. This was done by the Department of Environment and Natural Resources Management and it was the focal point for all environmental management issues in the country. Co-ordination, monitoring and evaluation of the operations done by executive agencies (statutory bodies) created for implementation of policies on behalf of the government was also done by the department. One such statutory body is Zambia Environmental Management Agency (ZEMA, www.zema.org.zm). ZEMA was originally established in 1992 under the former name Environmental Council of Zambia (ECZ). It is the major environmental institution in Zambia and the lead agency with a mandate by law to "*do all things necessary to ensure the sustainable management of natural resources and protection of the environment and the prevention and control of pollution*". ZEMA's functions include:

- Advising the government on policy work,
- coordinating the implementation of environmental management in all ministries,
- develop and enforce measures to prevent and control pollution,
- develop guidelines and standards related to environmental quality,

• promoting research and studies,

• controlling the Environmental Impact Assessment process,

• authorize or inhibit industrial projects,

• issuing permits and licenses,

• audit and monitor the compliance of operating industries, and

• publicizing information regarding environmental management and pollution control.

ZEMA is autonomously run by a board comprised of members picked from various ministries, businesses and non-governmental organizations. ZEMA has been continuously strengthened with the continuous improvement in legislation, despite already possessing a lot of power and is continuously being strengthened as the legislation keeps improving. However, the agency is heavily understaffed and can only manage a few of its responsibilities in a satisfactory way. A special concern is raised for the severe lack of supervision towards the industry after projects have been authorized and obtained all its licenses and permits. The principal legislation governing environmental management in Zambia is the Environmental Management Act (No 12 of 2011). The Act is an umbrella law which stands over all other environmental legislation in Zambia. Through the Act, the Environmental Council of Zambia was renamed to ZEMA which now is mandated to ensure the sustainable management of natural resources and protection of the environment. The Act is based on many modern principles:

• The environment is the common heritage of both present and future generations,

• Adverse effects shall be prevented and minimized,

• The people shall be involved in the development of policies, plans and programmes for environmental management,

• Community participation and involvement in natural resource management shall be promoted and facilitated,

• The precautionary principle,

• The polluter pays principles,

• The generation of waste should be minimized wherever practical, and otherwise in order of priority, be reused, recycled, recovered and disposed safely, and

• Non-renewable natural resources shall be used prudently, taking into account the needs of the present and future generations.

The new Act is considerably stronger than its predecessor, the Environmental Protection and Pollution Control Act (No 12 of 1990 and No 12 of 1999), however, part of the old regulations is still enforced in spite of being repealed by the new Act. Relevant regulations which are still in use are:

• The Waste Management Regulations (SI 71 of 1993).

• The Water Pollution Control Regulations (SI 72 of 1993).

• The Pesticides and Toxic Substances Regulations (1994).

• The Air Pollution Control Regulations (SI 142 of 1996).

• The Environmental Impact Assessment Regulations (SI 28 of 1997).

• The Hazardous Waste Management Regulations (SI of 2001).

In Zambia before a developer under takes a project that will have impact on the environment, authorization from the Environmental Management Agency (ZEMA) needs to be obtained. This authorization can be granted only after an Environmental Impact Assessment (EIA) process is undertaken by the developer. In Zambia, mining activities are always considered to have a huge environmental footprint hence developers are required to prepare “full EIA’s” which are called Environmental Impact Statements (EIS). The following steps are to be followed by a developer in the EIS process:

Step 1. Preliminary actions

a. Setting up an environmental team with specialists.

b. Setting up the terms of reference for the study (needs approval from ZEMA).

Step 2. Scoping

a. Review all applicable laws, policies and international obligations.

b. Identify possible alternatives to the project layout.

c. Identify main impacts to determine which specialist studies are needed (should be decided after consultation with ZEMA).

Step 3. Baseline study

a. Detailed description of existing environment.

Step 4. Impact evaluation

a. Evaluation of predicted impacts for various situations.

Step 5. Public Participation

a. Hear the view of the affected community.

Step 6. Identification of mitigation measures

a. Measures for firstly elimination, and secondly reduction of environmental impacts.

b. Include noise control, treatment of effluent waters, air pollution control, waste control and other appropriate measures.

c. The cost of mitigation measures must be calculated and included in an Environmental Management Plan.

Step 7. Assessment of impacts and decision making by the developer

a. Comparison of all alternatives by the team.

b. Ranking and recommendations by the team.

c. Decision by the developer for one alternative and an explanation for the rejection of other alternatives.

Step 8. Submission to ZEMA followed by a review process

a. From the day the EIS is submitted to ZEMA the process by law is not allowed to exceed 65 days.

b. ZEMA sends the application for submission of comment to sector institutions (e.g., Mines Safety Department and Department of Water Affairs (DWA)) who by law are enforced to reply within 30 days.

c. ZEMA shall place notifications in national newspapers and do everything possible to distribute the application to ministries, NGOs and affected parties who are allowed to leave written comments within 20 days after the notification in the newspaper.

d. ZEMA organizes a public consultation in the locality of the proposed project.

e. ZEMA reviews the application and makes a field visit to verify the content of the EIS.

f. ZEMA takes all aspects into consideration and writes a recommendation letter to the decision committee stating if the project should be rejected or approved and if so under which conditions.

Step 9. Decision making

a. A decision committee of five people drawn from the board of ZEMA takes the decision.

b. The committee communicates its decision through a decision letter which shall be distributed to all parties.

c. An approval letter often follows with specific conditions and it also binds the developer to fulfil what is stated under the Environmental Management Plan provided in the EIS."

Despite having this clearly laid down procedure, the quality of EIA reports for mining operations varies a lot, in general they remain low. Characterization of waste and the handling of waste rock and tailings material are often subjects in the EIAs that need to be considerably improved. Mining activities across the country have increased and these poor impact assessment practices have probably contributed to mining impacts such as tailings dumps not being properly managed. The increasing number of tailing dumps is a major environmental concern that needs to be addressed. This study will seek to develop a multi criteria decision-making tool that identifies which tailings dump poses an immediate threat to the environment. This will enable the sustainable management of tailings dumps not only to this case study but for all tailings dumps country wide. Consequently, the study will provide recommendations on the implications of the risk potential prioritization on Environmental impact assessments.

3.7.2 Benefits of the EIA Process

The following are benefits of the implementing an EIA process:

a) "It facilitates informed decision making by providing clear, well-structured analysis of the effect and consequences of proposed projects thereby integrating environmental considerations into project planning.
b) It ensures that potentially negative impacts are foreseen and discussed at an early stage in the project planning process thereby influencing both project selection and design by screening out environmentally unsound projects, as well as modifying feasible projects.
c) It identifies and enhances the positive impacts of the proposed project.
d) It assists in the selection of alternatives, including the selection of the best practicable and most environmentally friendly options.
e) It ensures appropriate participation of the Interested and affected parties (IAPs) in the decision-making process.
f) It guides formal approval, including the establishment of terms and conditions of project implementation and follow-up"

3.8 Gap analysis

Zambia currently experiences environmental pollution from mine tailings resulting from ongoing mining in the Copperbelt, North western provinces as well as from historical mining in central province even after years of the mine being shut down. Although Lindahl, (2014) argues that the main environmental problems are mainly from current mining operations and the contribution from old mining legacy sites have shown to be minor. This isn't the case from Zambia's legacy mine in Kabwe which after almost two decades and a number of mitigation measures being undertaken between 2003 and 2011 still listed as one of the 10 worst polluted places in the world in 2013 by Green Cross Switzerland and The Blacksmith Institute (www.worstpolluted.org/).

In most developing nations like Zambia, this is attributed to the lack of adequate management of the sector. The governmental framework that regulates the mining sectors environmental compliance is centred on Zambia Environmental Management Agency (ZEMA). The agency authorizes mining projects through an environmental impact assessment (EIA) process, issues environmental permits and is responsible for auditing. Existing laws and regulations regarding environmental performance are relatively up to date in Zambia; the main problem for the country is that the implementation is not satisfactory. Partially this is explained by lack of coordination between institutions, also to a large extent on the lack of manpower and technical capacity. A special concern is the lack of supervision towards the active industry and the generally low quality of EIA reports compiled and used in the license process. Multi criteria decision analysis (MCDA) can be used in this study to analyse the potential risk of tailings dumps and give recommendations through governmental frameworks that regulate the mining sector's environmental compliance. Recommendations in this case may be incorporated in the EIA process that allows for proactive and sustainable management of tailings dumps from inception of mining projects. Lindahl, (2014) suggests that taking actions to better implement existing environmental legislation improves the quality of Environmental Impact assessments for future development work focusing on better management of the active mining industry rather than mitigation of old legacy sites.

A review study by kosgei & Mukuwa, (2020) evaluated the impacts/effects of tailings dumps on the environment around the Copperbelt. Furthermore, studies around risk assessment of polluted mining areas to reduce environmental health risks have been conducted by the Copperbelt environment project, a project funded by the world bank from 2003-2011. This study will seek to integrate information from different disciplines and studies through multi criteria decision analysis. Criteria developed by the researcher from literature and opinions from experts were integrated through the AHP process to finally do a potential pollution risk assessment of tailing dumps on the environment.

CHAPTER FOUR

METHODOLOGY

4.1 Nature of Research

To achieve all the stated objectives, the research used the mixed methods approach to collect data alongside desk top studies. Interviews were conducted and the same Interview schedule was used for every expert interviewed to maintain uniformity and to allow for consistency in the collected data. Qualitative data collected in form of numerical values in the pairwise matrices were processed through Microsoft excel and interpretation was done through tables and flow charts. Qualitative data was analysed through close study of literature and logical reasoning.

4.2 Expert profiles

A total of four experts from different fields were interviewed (Table 4.1). These experts were selected based on the premise that they had the experience in fields that could give credible and informed opinions on tailings dumps & how they impact the environment on which they exist, and pollution risk assessments.

Table 4.1: Table showing expert details.

Decision maker	**Expert background**	**Institution**
Expert 1	Geo-Metallurgist	Lulea university of Technology
Expert 2	Environmentalist/metallurgist	University of Zambia, school of mines, department of metallurgy.
Expert 3	Environmental Engineer	University of Zambia, school of mines, department of geology.
Expert 4	Environmental Spatial Risk Expert	University of Zambia, school of engineering, department of geomatic engineering.

4.3 Data collection tools

The data collection instruments included interview schedules with four experts from different professional backgrounds (Table 4.2). An interview schedule was prepared for the key informants to enable them to understand the details of the data that was being collected (Appendix 1- 4). Aerial photographs from the Google earth map application were used for visual representation of the study areas as they gave the needed correlation between visual interpretation reports that were reviewed as well as information gathered through interviews.

4.4 Data collection Techniques

Different data collection techniques were applied for the various objectives as outlined below.

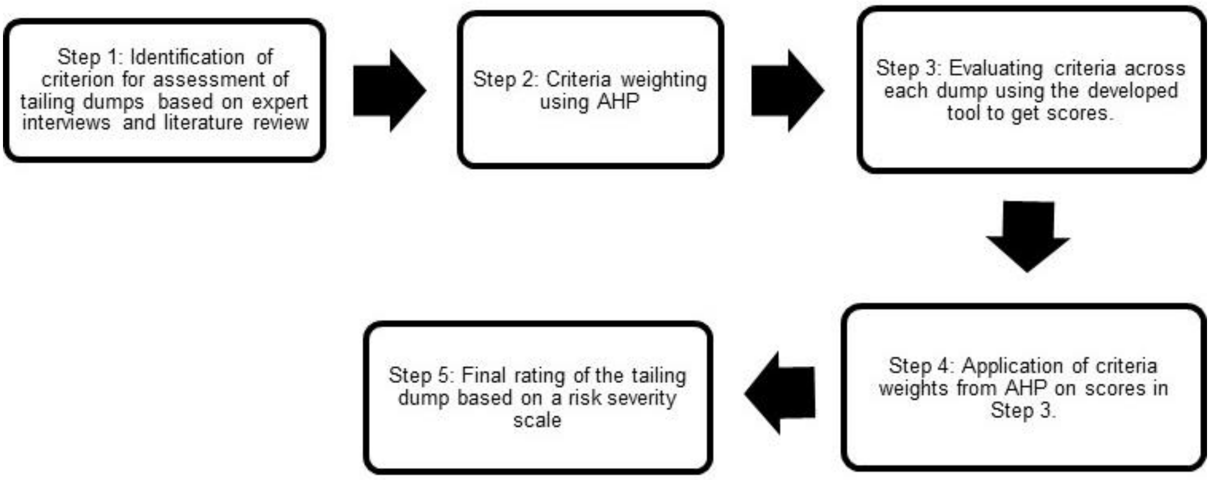


Figure 4.1: Flow chart showing summary of methodology.

4.4.1 Specific objective a: Criteria Development

To develop a set of appropriate criteria to use in the multi criteria decision analysis, each expert was asked if they thought the set of criteria listed and provided was appropriate (Appendix 1-4). Experts were allowed to make adjustments to the list provided by adding or removing indicators and factors they thought were appropriate or inappropriate on the list provided to come up with a final list of indicators (Table 4.2). Responses were taken note of as numerical scales in a pairwise matrix.

Table 4.2: Criteria description

Indicator	Factors	
Physical properties	• Size of dump. • Particle size of dump material. • Consolidation status of dump.	C1
Mineralogical/chemical properties	• Chemistry of material dump is made of.	C2
Properties of environment around the dump	• Lithology underlying the dump. • Depth of water table from surface. • Distance to surface water body. • Distance to nearest anthropogenic facility.	C3
Climatic factors (rainfall)	• Climatic characteristics of mine dump surroundings (intensity of precipitation)	C4
Protective structures (tree and grass cover)	• Dust suppression at mine dump surface.	C5

4.4.2 Specific objective b: Investigate the pollution Risk to the environment

To investigate the risk potential of the dumps based on criteria developed, each expert was interviewed, following the procedures and methodology of AHP for any decision-making problem as described in four general steps (Figure 4.2).

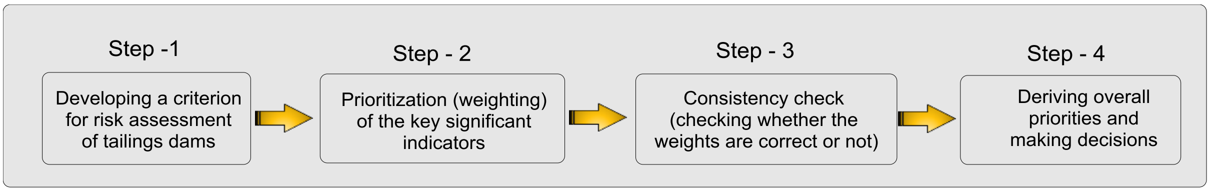


Figure 4.2: Procedures in AHP to derive priority of indicators in pollution risk of tailings dumps.

Criteria scores were calculated and summed up for each tailings dump. The data for each individual tailings dump was sourced from the literature review and physical site verification done. Short interviews were conducted and specific questions were asked to give data needed to compute criteria scores. In some instances, reports by the contact persons were shared. The data was obtained was in different formats and units and the scores were thereby normalised by dividing each score by the column total of the scores. This was to enable results from AHP and this procedure to have the same unit (Table 4.3-4.8).

Table 4.3: Normalisation of physical properties

Indicator 1: Physical Properties			
Size of Dump			
	Size of Dump	**Score**	**Normalized scores**
	>625 ha	1.00	0.333
	25-625	0.80	0.27
	5-25ha	0.60	0.20
	1-5ha	0.40	0.13
	<1ha	0.20	0.067
Sum		**3**	**1**
Grain size distribution (Texture)			
	Texture	**Score**	**Normalized scores**
	Gravel	0.25	0.1
	sand	0.5	0.2
	clay	0.75	0.3
	silt	1.0	0.4
Sum		**2.5**	**1**
Consolidation status			
	Status	**Score**	**Normalized score**
	Consolidated	0.25	0.167
	Mixed	0.5	0.33
	Loose	0.75	0.50
Sum		**1.5**	**1**

Table 4.4: Classification of the index of contamination values and the normalization of scores.

Indicator 2: Chemical Properties		
IC value	**Index**	**Normalized scores**
0.25 – 0.5	0.25	0.1
0.5 – 0.75	0.5	0.2
0.75 – 1.0	0.75	0.3
>1.0	1.0	0.4
	2.5	**1**

Table 4.5: Properties of the environment surrounding dumps and score normalization

Indicator 3: Properties of the environment surrounding the dump			
Distance to the surface water body	**Distance**	**Score**	**Normalized scores**
	<100m	1.0	0.4
	100-300m	0.75	0.3
	300-600m	0.5	0.2
	600-1000m (658m)	0.25	0.1
		2.5	**1**
Depth to the water table	**Depth**	**Score**	**Normalized Scores**
	>100	0.4	0.0816
	50-100m	0.5	0.102
	20-50m	0.6	0.124
	10-20m (15-30)	0.7	0.143
	5-10m	0.8	0.163
	2-5m	0.9	0.184
	<2m	1.0	0.204
		4.9	**1**
Distance to the nearest settlement (Built structure)	**Distance**	**Score**	**Normalized Scores**
	<100m	1.0	0.333

	100-300m (240m)	0.8	0.267
	300-600m	0.6	0.2
	600-1000m	0.4	0.133
	>1000m	0.2	0.067
		3	**1**

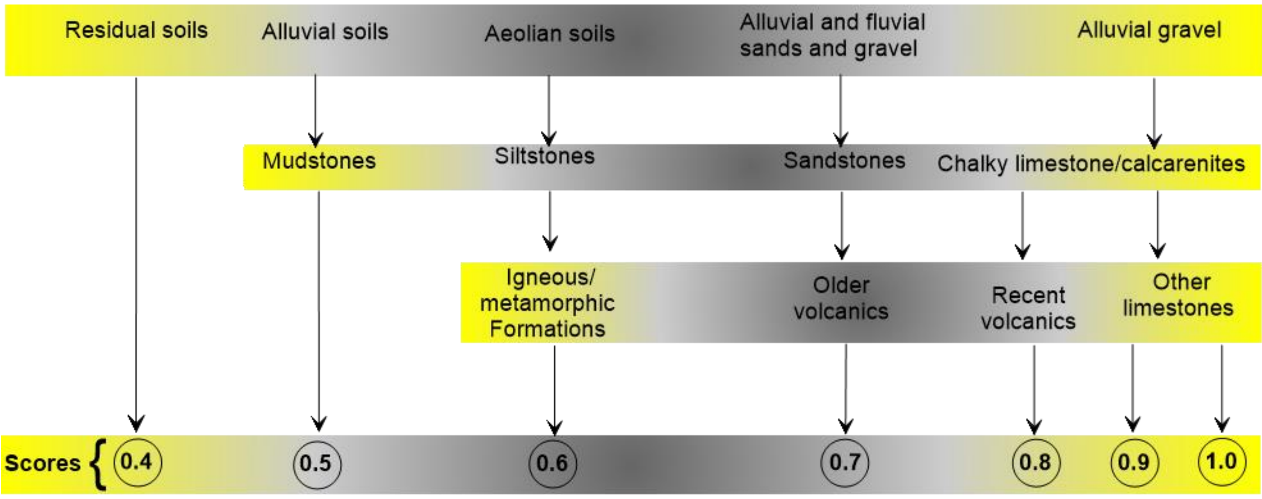


Figure 4.3: Classification of lithology

Table 4.6: Rainfall classification and score normalization

Indicator 4: Climatic Properties			
	Rainfall	**Score**	**Normalized score**
1	>1500 m	1.0	0.4
2	1500-1000	0.75	0.3
3	800-1000	0.5	0.2
4	<800	0.25	0.1
		2.5	**1**

Table 4.7: Protective structures classification and score normalization

Indicator 5: Protective structures			
	Cover	**Score**	**Normalized score**
1	Both slopes and top surface are without any cover	1.0	0.4
2	The top surface is covered by indigenized plants or grass	0.75	0.3
3	Slopes are covered by indigenized plant or grass	0.5	0.2
4	The dump is completely covered by indigenized plants /grass species.	0.25	0.1
		2.5	**1**

The criteria scores (normalized scores for all factors under each indicator as sums) were then multiplied by the AHP criteria weights to get the final criteria weight with respect to each dump. The final criteria weights were summed up to give the final ratings which are the values that gave the potential pollution risk of each dump. The final ratings were compared against a severity of risk scale which ranges from low risk to medium risk to high risk (Table 4.3).

Table 4.3: Risk severity scale classification

Risk category	**Risk scores**	**Description**
Low	0 – 0.35	Pollution risk is minimal but should be monitored.
Low to medium	0.36 – 0.5	Pollution risk is tolerable with increased monitoring.
Medium	0.51 – 0.65	Pollution risk is tolerable with controls. Assess the risk mitigation options and monitor risks.
Medium to high	0.66– 0.8	Pollution risk undesirable. Risk mitigation should be employed.
High	0.81 – 1.0	Pollution risk intolerable. Risk mitigation required immediately.

4.4.3 Specific objective c: Recommendations on environmental impact assessments

To recommend possible implications on environmental impact assessments resulting from MCDA on environmental impact assessments, information from the interviews was analysed qualitatively. A desk study to establish what implications MCDA can have on environmental impact assessment was done based on the findings.

4.5 Data Analysis

The quantitive data collected was analysed using a template developed in Microsoft Excel (Appendix 7). Consistency ratios were calculated at every stage to make sure all the data collected from experts was coherent using equation 1.

CR= CI/ RI……………………………………………….Equation 1

$CI = (\gamma_{max} - n)/(n-1)$

Where: $\boldsymbol{\gamma_{max}}$ is the principal Eigen value of the pairwise comparison matrix

n is number of factors (criteria) or order of the matrix

RI is the Random Consistency Index

Qualitative data was translated and analysed through content analysis.

CHAPTER FIVE

RESULTS AND DISCUSSION

This chapter presents the findings of the research. It focuses on the AHP computations based on the criteria selected by the experts; these include the criteria weights for each individual expert supported by a consistency ratio check for all. A geometric mean for each indicator is then calculated to come up with a single weight using equation 3;

$$\bar{x}_{geom} = \sqrt{\prod_{i=1}^{n} \quad x_i} = \sqrt[n]{x_1 \cdot x_2 \cdots x_n}$$

- $\bar{x}_{geom}$ is the geometric mean
- "n" is the total number of observations
- $\prod_{i=1}^{n}$ is the n^{th} square root of the product of the given numbers.

The final weights are applied to compute the potential pollution risk of the tailing's dumps using the simple tool. The various indicators in Table 4.1 include physical properties, chemical properties, properties of the environment around the dump, climate factors, and the protective cover, further broken into factors. Each individual factor was further classified so as to provide thresholds and scores per indicator (Step 3, Figure 4.2). These scores were then normalized to a sum of one per factor. Table 3 shows the normalization of physical properties scores. The mineralogy/chemical properties were based on the index of contamination (IC). The index of contamination (IC) was calculated by dividing the measured concentration by the maximum permissible (Mhlongo et al, 2019). The IC values were classified as detailed in Table 4.4. Table 4.5 has outlined the classification of various environmental factors and normalized scores. For the lithology, a classification is adopted as shown in Figure 4. Limestones are highly vulnerable to pollution compared to alluvial sediments which typically have some clay that attenuates contaminants. For the climatic factors, rainfall was used as a proxy for this. Rainfall classification is shown in Table 6 with the highest vulnerability having rainfall of more than 1500 mm. Table 7 shows the protective cover classification and score normalization. To allow the integration of the various indicators and factors (Step 4, Figure 2), a score was calculated as follows using Equation 1.

5.1 Criteria weighting using AHP

Four experts were interviewed and the results recorded in a pairwise matrix. A consistency checks as prescribed for the AHP procedure was done for all pairwise matrices giving a consistency ratio (CR) below 1. (Table 5.1, 5.2, 5.3 and 5.4)

Table 5.1: Expert 1

	C1	**C2**	**C3**	**C4**	**C5**
C1	1	1/5	3	3	3
C2	5	1	4	8	7
C3	1/3	¼	1		3
C4	1/3	1/8	1/2	1	1/3
C5	1/3	1/7	1/3	3	1
Σ	**7.00**	**1.72**	**8.83**	**17.00**	**14.33**

CI=0.0957 <1 Acceptable

Table 5.2: Expert

	C1	**C2**	**C3**	**C4**	**C5**
C1	1	1/7	4	3	5
C2	7	1	8	5	7
C3	1/4	1/8	1	2	2
C4	1/3	1/5	1/2	1	2
C5	1/5	1/7	1/2	1/2	1
Σ	**8.78**	**1.61**	**14.00**	**11.50**	**17.00**

	C1	C2	C3	C4	C5
C1	1	1/7	4	2	9
C2	7	1	7	3	2
C3	1/4	1/7	1	1/3	1
C4	1/2	1/3	3	1	5
C5	1/9	1/9	1	1/5	1
Σ	**8.86**	**1.73**	**16.00**	**6.53**	**18.00**

CI=00963 <1 Acceptable

CI= 0.0822<1 Acceptable

Table 5.4: Expert 4

	C1	C2	C3	C4	C5
C1	1	1/7	5	2	3
C2	7	1	6	8	9
C3	1/5	1/6	1	1/4	1/2
C4	1/2	1/8	4	1	3
C5	1/3	1/9	2	1/3	1
Σ	**9.03**	**1.55**	**18.00**	**11.58**	**16.5**

CI=0.0862<1 Acceptable

5.2 Final AHP criteria weights

Criteria weights were calculated for each expert following the AHP procedure stipulated in chapter 4. Final weights computed as geometric means of the four sets (Appendix 5,6,7 and 8) of criteria weights from the four experts as shown in (Table 5.5).

Table 5.5: Individual criteria weights for all experts

	Expert 1	Expert 2	Expert 3	Expert 4	Final criteria weights (geometric means)
C1	0.1671	0.20865	0.2503	0.1969	0.2048
C2	0.5982	0.56716	0.4751	0.5416	0.5383
C3	0.04752	0.09381	0.056	0.1267	0.07674
C4	0.1253	0.08049	0.05036	0.0518	0.0758
C5	0.06183	0.049896	0.21636	0.083	0.1204

Based on the AHP computations done under item 5.5, C2 0.5383 (Chemical properties) ranked the highest followed by C1 0.2048 (Physical properties), C5 0.1204 (Protective structures), C3 0.07674 (Properties of the environment were dump sits) and then C4 0.0758 (Climatic factors) as seen in table 5.5. Despite this ranking from AHP, further analysis when computing the final rating matrix indicated that C1 and C3 seemingly had more influence on the potential of the tailings dump to pollute the environment. This can be seen from the score totals of each indicator for each individual dump in Tables 5.6, Table 5.7 and Table 5.8.

5.2.1 Analysis of the potential pollution risk of the Mopani (TD15A) tailings dump

Generally, the Mopani Mine tailings dump has low scores against all the indicators except for C2. For C1, tailings particles are classed as silty, meaning it can easily be carried by wind giving this factor the highest score of 0.4. Regarding the dump size (footprint) factor, the dump is greater than 625 hectares which gives it the highest score of 0.333 (Table 5.6). Against the consolidation factor, the dump material being loose renders it easily dispersible and it scores the highest score of 0.4. C2 was calculated as an Index of contamination from the combined toxic metals in the tailings using the method described by (Reis et al., 2012) and it gave a very high value of 21.27 showing that the tailings material had a very high contamination potential. For C3, the tailings dump is more than 658m away from the nearest surface water body giving this factor the lowest score of 0.1, the water table lies between 10 to 20m in this area, therefore this factor scores highly at 0.143. The lithology around the area was classified as alluvial soils overlying other Limestones (in this case dolomites) this scored highly at 0.9. The tailings dump lies 240m from the nearest human settlement, giving this factor a high score of 0.267. Kitwe lies in a rainfall zone that receives between 1000 - 1500 mm of rainfall annually giving C4 a high score of 0.3. The tailings dump has protective structures such as tree cover and grass on the slopes that have reduced the amount of material being eroded, C5 had a low score of 0.2 (Table 5.6). The Mopani Tailings dump had a final rating score of **0.53** which entails a low to medium risk potential according to the severity of the risk scale developed.

Table 5.6: Criteria scores for Mopani tailings dump (TD15A)

indicators and factors	**Description**		**Score**
Physical properties C1			
a) Size of dump	732 Ha	>625 Ha	0.33
b) Grain size composition	Silt (grain particle size between 0.002mm to 0.06mm)		0.4
c) Consolidation status	Mixed		0.5
Score total			**1.17**
Chemical properties C2			
a) Index of contamination	21.27	>1	0.4
			0.4
Properties of Environment surrounding dump C3			
a) Distance to surface water	658m	600-1000m	0.1
b) Depth to water Table	m	10-20m	0.143
c) Lithology	Other Limestones (Dolomites).		0.184
d) Distance to nearest settlement	240m	100-300	0.267
Score total			**0.694**
Climatic factors C4			
a) Rainfall		1000-1500mm	0.3
Score total			**0.3**
Protective structures C5			
a) Tree cover	Slopes are covered by indigenize plant or grass		0.2
Score total			**0.2**

5.2.2 Analysis of the potential pollution risk of the Kabwe tailings dump

Generally, the tailings dump scored highly against C1 and C3. For C1, tailings particles are silty meaning it can easily be carried by wind giving this factor the highest score of 0.4. For the dump size (footprint) factor, the dump size falls between 25 and 625 hectares, which gives it a high score rating of 0.27. For the consolidation factor, the dump material being loose renders it easily dispersible and thus scores the highest normalised score of 0.4. C2 was calculated as an Index of contamination from the combined toxic metals in the tailings using the method described by Reis et al., 2012 and it gave a very high value of 495.5 showing that the tailings material had a very high contamination potential. This has been validated by several studies which show that pollution has continued more than 20 years post closure of the mine in Kabwe town, resulting in the city being ranked the most polluted in the world (e.g., Caravanos et al., 2014, Ettler et al., 2020). For C3, the tailings dump is more than 800 m away from the nearest surface water body, giving this factor the lowest score of 0.1. However, the water table lies between 5 to 10 m in this area (Toyoda et al., 2022), therefore this factor scores highly at 0.163. The lithology around the area was classified as alluvial (with clay) soils overlying dolomites and this scored highly at 0.9. The tailings dump lies less than 100 m away from the nearest human settlement, giving this factor the highest score of 0.33. Kabwe lies in a rainfall zone that receives in between 800 - 1000 mm of rainfall annually which is a medium to low rainfall belt, giving criteria 4 a low score of 0.2. The tailings dump has absolutely no form of protective covers such as tree cover around the perimeter of the site. A site visit shows an effort to plant grass (Figure 5), however ,several studies have shown that this environmental anomaly still spreads (Nakamura et al., 2021). Based on the foregoing, criteria 5, had the highest score of 1.0.

The Kabwe Mine tailings dump had a final rating score of **0.60,** which qualifies as a medium risk potential based on the severity scale in Table 8. This means the pollution risk is tolerable with controls and therefore assessments are required for risk mitigation options and monitoring. Several remediation and mitigation activities have been planned for Kabwe that include the use of bio-cementation (Mwandira et al., 2020), the use of raw dolomite (Tangviroon et al., 2020), and the placement of a protective tree cover around the legacy mine boundaries. Table 5.7 shows the individual scores of each criterion across each of three dumps. The findings of this case emphasize the importance of efficient and proactive mine waste management as their impacts can continue to be devastating long after mining has come to an end.

Table 5.7: Criteria scores for Kabwe tailings dump

Indicators and factors	Description		Score
Physical properties C1			
a) Size of dump	85 Ha	25.-625 Ha	0.27
b) Grain size composition	Silt (grain particle size between 0.002mm to 0.06mm).		0.4
c) Consolidation status	Loose.		0.5
Score total			**1.17**
Chemical properties C2			
a) Index of contamination	459.5	>1	0.4
Score total			**0.4**
Properties of Environment surrounding dump C3			
a) Distance to surface water	4086m	600-1000m	0.1
b) Depth to water Table	6m	5-10m	0.163
c) Lithology	Other Limestones (Dolomites).		0.184
d) Distance to nearest settlement	85m	<100	0.33
Score total			**0.78**
Climatic factors C4			
a) Rainfall	913	800-1000mm	0.2
Score total			**0.2**
Protective structures C5			
a) Tree cover	Without cover on both slopes and top.		0.4
Score total			**0.4**

5.2.3 Analysis of the potential pollution risk of the Lumwana tailings dump

Lumwana Mine Tailings dump scored highly against C1 and C3. For C1, tailings particles are silty meaning they can easily be carried by the wind, giving this factor the highest score of 0.4. Considering the dump size (footprint) factor, the dump is greater than 625 hectares which gives it the highest score of 0.333. For the consolidation factor, the dump material being loose renders it easily dispersible and it scores the highest score of 0.4. C2 calculation of the IC gave a very high value of 21.27, showing that the tailings material had a very high contamination potential. For C3, the tailings dump is more than 658 m away from the nearest surface water body, giving this factor the lowest score of 0.1. The water table lies between 10 to 20 m in this area, therefore this factor scores highly at 0.143.

The lithology around the area was classified as alluvial soils overlaying fractured amphibolite schists and gneiss scored highly at 0.9. The tailings dump lies 240 m from the nearest human settlement, giving this factor a high score of 0.267. Solwezi area lies in a rainfall zone that receives between 1000 to 1500 mm of rainfall annually giving C4 a high score of 0.3. For the protective cover (C5) criteria, Lumwana Mine tailings dump had the lowest score of 0.1 due to it being a valley type of dump. The overall score for Lumwana Tailing dump was **0.52**, which entails a low to medium risk potential.

Lumwana is relatively a younger mine, however, waste from this project has a medium potential risk of polluting the environment even in its infancy. Therefore, measures must be put in place to ensure that the risks are reduced during its mine life to avoid major pollution issue even after closure. The findings of this case study only emphasize the importance of efficient and proactive mine waste management as their impacts can continue to be devastating long after mining has come to an end.

Table 5.8: Criteria scores for Lumwana tailings dump

Indicators and factors	**Description**		**Score**
Physical properties C1			
a) Size of dump	1753 Ha	>625 Ha	0.333
b) Grain size composition	Silt (grain particle size between 0.002mm to 0.06mm).		0.4
c) Consolidation status	Mixed.		0.5
Score total			**1.17**
Chemical properties C2			
a) Index of contamination	4.19	>1	0.4
Score total			**0.4**
Properties of Environment surrounding dump C3			
a) Distance to surface water	100m	100-300m	0.3
b) Depth to water Table	10m-20M	20-50m	0.124
c) Lithology	Other Limestones (Dolomites).		0.143
d) Distance to nearest settlement	6224.76m	>1000m	0.067
Score total			**0.5053**
Climatic factors C4			
a) Rainfall	1310mm	1000-1500mm	0.3
Score total			**0.3**
Protective structures C5			
a) Tree cover	Dump is completely covered by indigenize plants /grass species. (Valley dump)		0.1
Score total			**0.1**

5.3 Final rating

The tables below give Criteria indicator score totals which are a summation of the factor scores for each indicator for the three tailings dumps (Table 5.9a). As indicated under chapter four the criteria score totals for each indicator (C1-C5) were multiplied by the AHP criteria weights (CW1-CW5)) for each tailing's dumps (Table 5.9b) to get the final rating matrix (Table 5.9c). The final rating matrix provides the pollution risk potential of the three tailings dumps (Table 5.11) which is compared against a severity of risk scale (Table 5.10).

Table 5.9a: Criteria indicator score totals

	Criteria indicators	**MOPANI**	**KABWE**	**LUMWANA**
C1	Size of dump	0.33	0.27	0.33
	grain size composition	0.4	0.4	0.4
	consolidation status	0.33	0.5	0.33
	criteria score total	**1.06**	**1.17**	**1.06**
C2	Index of contamination	**0.4**	**0.4**	**0.4**
	criteria score total			
C3	Distance to surface water	0.1	0.1	0.3
	Depth to water Table	0.143	0.163	0.163
	Lithology	0.184	0.184	0.184
	Distance to nearest settlement	0.267	0.33	0.067
	criteria score total	**0.694**	**0.777**	**0.714**
C4	Rainfall	0.3	0.2	0.3
	criteria score total	**0.3**	**0.2**	**0.3**
C5	Tree cover	0.2	0.4	0.1
		0.2	**0.4**	**0.1**
	Criteria score total for each dump	**2.654**	**2.947**	**2.574**

Table 5.9b: Criteria scores totals against AHP Criteria weights (CW) for each tailings dump

	D1	D2	D3		(CW) from AHP
	Mopani	Kabwe	Lumwana		
C1	1.06	1.17	1.06	CW1	0.2048
C2	0.4	0.4	0.4	CW2	0.5383
C3	0.694	0.78	0.714	CW3	0.07674
C4	0.3	0.2	0.3	CW4	0.0758
C5	0.2	0.4	0.1	CW5	0.1204
	2.654	**2.947**	**2.574**		

Table 5.9c: Final rating for all dumps.

	D1(Mopani)	D2(Kabwe)	D3(Lumwana)
C1	0.217088	0.239616	0.217088
C2	0.21532	0.21532	0.21532
C3	0.05325756	0.0598572	0.05479236
C4	0.02274	0.01516	0.02274
C5	0.02408	0.04816	0.01204
Final rating (pollution risk potential)	**0.53248556**	**0.5781132**	**0.52198036**
	0.53	**0.6**	**0.52**

Table 5.10: Level of severity scale

Risk category	**Risk scores**	**Description**
Low	0 – 0.35	Pollution risk is minimal but should be monitored.
Low to medium	0.36 – 0.5	Pollution risk is tolerable with increased monitoring.
Medium	0.51 – 0.65	Pollution risk is tolerable with controls. Assess the risk mitigation options and monitor risks.
Medium to high	0.66 – 0.8	Pollution risk undesirable. Risk mitigation should be employed.
High	0.81 – 1.0	Pollution risk intolerable. Risk mitigation required immediately.

Table 5.11: Final rating and severity of risk

Final rating ranked based on severity of risk which ranges from low risk to high risk.

	D1(Mopani)	**D2(Kabwe)**	**D3(Lumwana)**
Final rating	**0.53**	**0.60**	**0.52**
	Low to medium risk	Medium risk	Low to medium risk

5.4 Analysis of implications of MCDA on Environmental impact assessments

Considering Zambia's regulatory framework supporting environmental protection, the environmental management act provides for every mining project at small scale and large scale to carry out environmental impact assessments. Based on this study this decision-making tool can be used to score the proposed mining projects (specifically for tailing dumps) considering the 5 indicators adopted. A properly done environmental impact assessment will have credible baseline data that can be used to do the assessment and a projection of its potential to pollute the environment can be given in form of rating against a scale of severity as has been done for the 3 dumps considered in the study. The idea is to recreate models of proposed mine project tailings dumps that incorporate the lowest pollution potential factors as guided by the decision tool in (Figure 5.1).

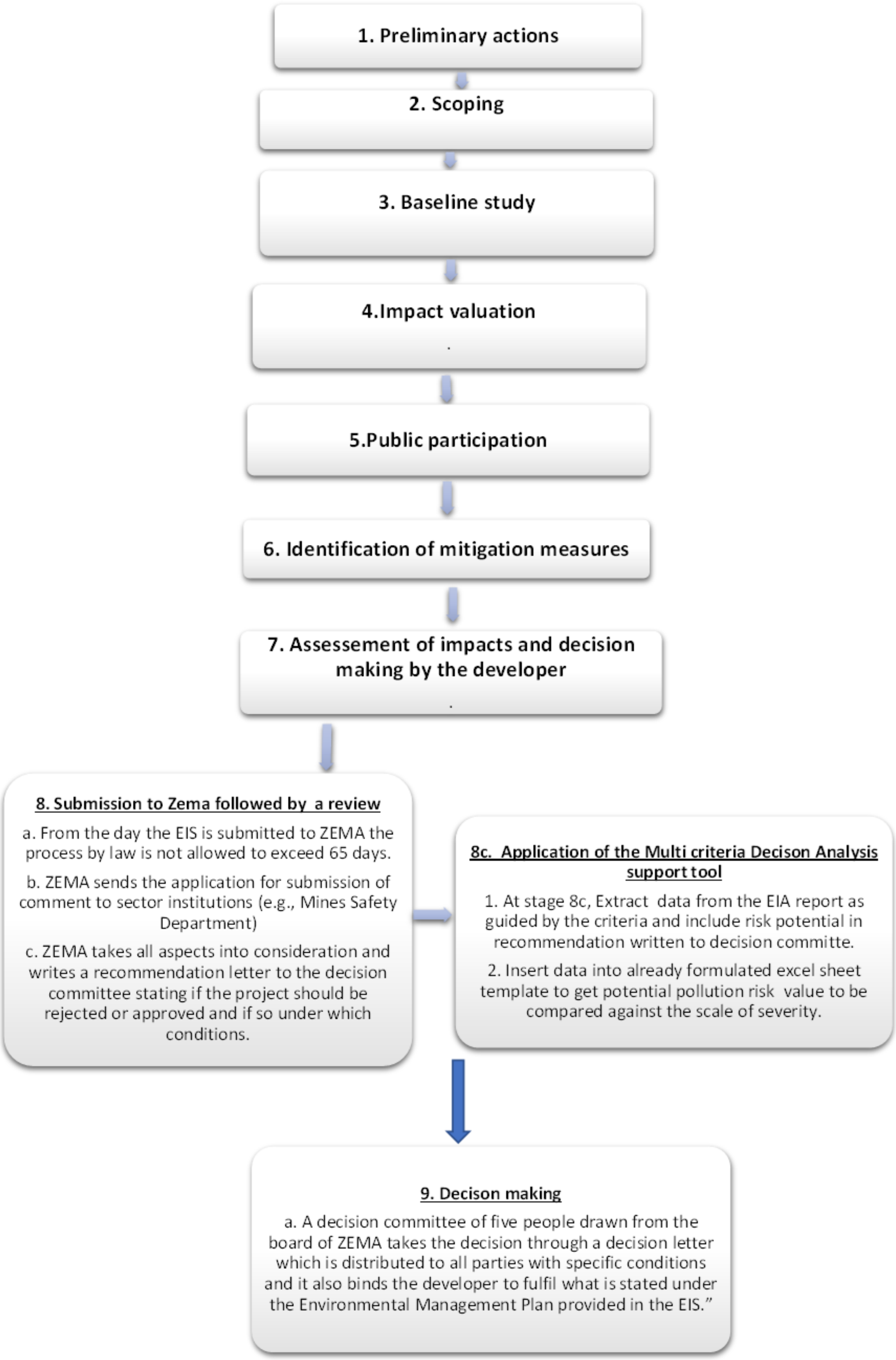


Figure 5.1: Flow chart showing where the decision support tool may fit in the EIA process.

5.5 Analysis of the risk rating results

The Kabwe tailings dump had the highest pollution potential followed by the Lumwana Mine tailings dump and the Mopani Mine tailings dump had the least potential pollution risk. Weighting of the criteria developed using AHP for this assessment indicated that C2 (Chemical properties) had the highest influence on the potential of a tailings dump to pollute the environment followed by C1, C5, C3 and C4. Based on the criteria scores computed from actual data from the dump sites, C3 (properties of the environment were the dump sits) and C1 (physical properties of the tailings dump material) had the highest scores across all dumps and for the medium risk ranking dump, Kabwe dump were higher than the rest of the criteria scores. Of the three dumps assessed the Kabwe dump has major pollution issues documented including soil Lead contamination in the mine townships of Kasanda and Chowa, Lead assimilation in crops, human lead exposure and many others. And these problems were documented years after the mine had closed down (Czech Geological Survey, 2008).

An article by (Mhlongo, 2019) looked at the development and application of a methodological tool for prioritization of rehabilitation of abandoned tailings dumps in the Giyani and Musina areas of South Africa. These dumps were assessed and ranked for rehabilitation. The Musina copper mines tailings was one of the dumps assessed and the developed pollution risk criteria was also applied to it. The Musina tailings dump had a potential pollution risk score of 0.5 and thus of medium risk which was in agreement with Mhlongo's study validating the approach. Additionally, a study by (Singo, 2013) revealed that heavy metal pollution in soil from the abandoned Cu mine in Musina was between medium and low in the contamination index. The indicators used thus capture critical aspects related to physical, chemical and toxicological /hygienic properties of mine dumps in data scare environmental settings. The data used was gathered from a study by (Mhlongo, 2019) in South Africa and some of it gathered off Google earth image analysis of the site location. The dump scored similarly across all criteria (see appendix 6), against C1 the dump scored highly due to its area size falling between 25-625 hectares and fine sized particles. Against C2 the dump also scored highly as it had an index of contamination above 1. This simply means that the tailings material had metal elements with a concentration above the permissible amounts in soil. Against C3 the dump scored highly due to it being approximately 240m away from the nearest human settlement and proximity of the groundwater table to the surface above which the dump sits. The Musina tailings dump like the Kabwe dump has no trees on any of its slopes therefore, it scored highly against C5 as the absence of trees or grass on the slopes means that the tailings dump material is dispersed. The Musina dump which is an abandoned tailings dump ranked similarly with the Kabwe dump (medium risk at 0.535 and 0.60 respectively) which could indicate that dumps from legacy mines pose a great risk to the environment. The Lumwana Mine dump has a lower pollution potential compared to the Kabwe dump attributed to the fact that the tailings dump is of a valley type. This simply means that material is not exposed and is not easily dispersible unlike the Kabwe dump whose material is above ground and highly dispersible. Mopani tailings dump despite being older than Lumwana had a low to medium pollution potential and this can be attributed to progressive rehabilitation measures such as development protective structures that were being erected as mining proceeded. Mopani had factor scores below 0.5 on almost all criteria. Future mining projects may need to target getting such scores or lower even before projects are commissioned by testing their proposed factors of the criteria in the tool.

Although the emphasis on pollution from mining waste in literature has mostly been on legacy mine, (Lindahl, 2014).   This study shows that active mines could relatively have high potential pollution risk to the environment. Grieco et al., (2021), in studying the metal pollution in waters that drain tailings dumps and the change in tailings environmental impact, demonstrates that active similar to legacy mines, are a potential risk to the environment as they could contain higher levels of potentially toxic elements.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The study conducted and presented in this thesis used the Analytical Hierarchy Process (AHP) which is a method of Multi Criteria Decision Analysis (MCDA) to weight criteria proposed for the assessment of the potential pollution risk of the tailings. The following are the conclusions;

A criterion was developed for the assessment of the potential pollution risk which uses the following indicators;

i. Physical properties (C1).
ii. Chemical properties (C2).
iii. Properties of the environment around the dump (C3).
iv. Climatic factors around the dump area (C4).
v. Protective structures (C5).

- Criteria weighting by the experts indicated that (C2) which is the chemical properties of the tailings material computed as an index of contamination had the highest influence on the tailings dump potential to pollute the environment followed by (C1), Physical properties of the tailings material, followed by (C5), Protective structures, followed by (C3), Properties of the environment where dump sits, followed by (C4) Climatic factors.
- The criteria were tested on three tailings dumps and following the method for the assessment of potential pollution risk used, the tailings dumps ranked as follows from the highest to lowest: Kabwe mine tailings dump, followed by Lumwana mine tailings dump, followed by Mopani mine tailings dump. The performance of the tailings dumps across each of the criteria developed showed that although this study was conducted using three tailings dumps, the findings can be compared to the Musina copper mine tailings dump in South Africa showing that the multi criteria decision analysis tool developed in this study is applicable to other tailings dump sites as demonstrated in the test assessment done.

- When compared against a severity of risk scale, the Mopani Mine tailings had low risk while the Lumwana Mine tailings dump had a low to medium risk potential and the Kabwe Mine tailings dump had a medium risk.
- The findings of the study indicated that the Multi criteria decision analysis tool is applicable to other sites and could be used during the environmental impact assessment review process as a decision support tool to determine the potential pollution risk of any other tailings dumps in the country based on data provided by a proposed project's environmental impact assessment report.

6.2 Recommendations

Based on the conclusions of this study the following recommendations are prescribed for consideration by the addressed organisations:

i. ZEMA: Based on the findings of the study, the decision tool can be incorporated by ZEMA as decision support tool for proposed mining projects or other projects as it will allow for assessment of the potential pollution risk of the tailings of the project proposed. The assessment can be done using data from the environmental impact assessment report submitted for the proposed project. This assessment can be used as a decision support tool to be used during the review process. Data can be extracted as guided by the criteria and entered into a formulated excel sheet (Appendix 10) that gives the pollution potential of proposed developments tailings dump as a value between 0 and 1 that can also be compared against a severity scale that runs from low risk to high risk. This can provide a basis for more informed and site-specific conditions of the decision letter issued for an approval.

ii. The Ministry of Mines and Minerals Development: The ministry of Mines and Minerals Development should consider using the decision support tool in the on-going Zambia Mining Environmental Remediation and Improvement Project (ZMERIP) as it will allow for selection of tailings dumps that have a higher pollution risk and need to be prioritised when it comes to remediation

References

Adiansyah, J.S., Rosano, M., Vink, S. and Keir, G., 2015. A framework for a sustainable approach to mine tailings management: disposal strategies. *Journal of cleaner production*, *108,* pp.1050-1062.

Alberruche del Campo ME, Arranz-Gonzalez JC, Rodríguez- Pacheco R, Vadillo-Fernandez L, Rodrı´guez-Go´mez V, Fernandez Naranjo FJ (2014). Manual para la evaluacio´n de riesgos de instalaciones de residuos de industrias extractivas cerradas o abandonadas.

Ambrasaite, I., Barfod, M., and Salling, K (2011). MCDA and risk analysis in transport infrastructure appraisals: The Rail Baltica case. Procedia Social and Behavioural Sciences, 20.

Anil J, R.M. Sona, (2011). Framework for evaluation and selection of the software packages: A hybrid knowledge-based system approach J. Syst.

Aragão, G.A.S., de Oliveira Filho, W.L., (2011). Mine dump classification in the iron ore mining. classificação de pilhas de estéril na mineração de ferro. Rev. Escola Minas 64 (2).

Aulo M, José E L, Antônio M, Tavares T, (2016). A maturity model for demand-driven supply chains in the consumer product goods industry Int. J. Prod. Econ.

Armenia. (2016). Assessment *of the environmental impact of tailings in the Republic of Armenia.*

Bentes, A., Carneiro, J., Silva, J., and Kimura, H. (2012). Multidimensional assessment of organizational performance: Integrating BSC and AHP. Journal of Business Research.

Bini, C. (2011). Environmental Impact of abandoned mine waste: A review. *Nova Science*.

Bhushan N, Rai K. (2007). Strategic decision making: applying the analytic hierarchy process. Springer Science & Business Media;

Byeong S A, (2017.) The analytic hierarchy process with interval preference statements Omega.

Cairney, T. and Kerr, C.D. (1998). Geology of the Kabwe Area. GRZ Ministry of Mines and Minerals Development, Report No. 47.

Campbell, Graeme and Associates Pty Ltd (2002a); Lumwana Copper Project – Geochemical Characterisation of Process Tailings Sample – Implications for Process Tailings Management; Report to Equinox Copper Ventures Limited.

Campbell, Graeme and Associates Pty Ltd (2002b); Lumwana Copper Project – Geochemical Characterisation of Waste Rock Samples from Malundwe Deposit – Implications for Waste Rock Management; Report to Equinox Copper Ventures Limited.

Caravanos, J., Fuller, R., & Robinson, S. (2014). Severe Environmental Contamination and Elevated Blood Lead Levels Among Children—Zambia, 2014. *Morbidity and Mortality Weekly Report*, *63*(44), 1013.

Chalov, S.R., Shkol’nyi, D.I., Promakhova, E.V., Leman, V.N., Romanchenko, A.O., (2015). Formation of the sediment yield in areas of mining of placer deposits. Geogr. Nat. Resour. 36 (2), 124–131.

Chan, K.M.A, Satterfield T and Goldstein J.H. (2012). Rethinking ecosystem services to better address and navigate cultural values. *Ecological Economics.*

Choi, W., Jeong, S., & Chae, Y. (2005). Study on recycling and utilization of abandoned mine waste. Geosystem Engineering, 8(3), 57–62. doi:10.1080/ 12269328.2005.10541237

Chu, J., Young, K. & Phiri, D. (2015). Large scale land acquisitions, displacements and resettlement in Zambia. Policy Brief 41, Zambia Land Alliance. Available online: www.plaas.org.za

Croaker, M.R (2011). The Geology of the Nkana-Mindola sediment-hosted Copper-Cobalt Deposit, Zambian Copperbelt, Zambia

Czech Geological Survey. (2011). Mining and the environment in Africa. *Proceedings of the inaugual workshop igcp/sida No. 594.* Kitwe, Zambia: Bohdan Kříbek.

Ecosystem Services – Global Issues Local Practices, Elsevier, New York, p. 167-180, http://www.sciencedirect.com/ science/article/pii/ B9780124199644000159

Edraki, M., Baumgartl, T., Manlapig, E., Bradshaw, D., Franks, D. M., & Moran, C. J. (2014). Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches. *Journal of cleaner production*.

Environmental Council of Zambia, (2008). Zambia Environment Outlook Report 3. Government of the Republic of Zambia.

Erden T, Coskun MZ. (2010) Natural Hazards and Earth System Sciences Multi-criteria site selection for fire services: the interaction with analytic hierarchy process and geographic information systems. Hazards Earth Syst Sci; 10:2127–34.

Ettler, V., Štěpánek, D., Mihaljevič, M., Drahota, P., Jedlicka, R., Kříbek, B., Vaněk, A., Penížek, V., Sracek, O. and Nyambe, I., (2020). Slag dusts from Kabwe (Zambia): Contaminant mineralogy and oral bioaccessibility. *Chemosphere*, *260*, p.127642.

Fish, R. (2011): Participatory and deliberative techniques to support the monetary and non-monetary valuation of ecosystem services: An introductory guide. Department for Environment, Food and Rural Affairs. Defra Project Code: NR0124

Franck M, Thierry G (2012). A Multi-Criteria Decision-Making Process for Project Risk Management Method Selection. International Journal of Multicriteria Decision Making.

Government of the Republic of Zambia. (2011). Environmental Management Act 2011. Act 12 of 2011. Lusaka: Government Printers.

Grieco G, Sinojmeri A, Bussolesi M, Cocomazzi G, Cavallo A. (2021). Environmental Impact Variability of Copper Tailing Dumps in Fushe Arrez (Northern Albania): The Role of Pyrite Separation during Flotation. *Sustainability*; 13(17):9643. https://doi.org/10.3390/su13179643.

Gupta A, K. Singh, Rajesh V, (2010). A critical study and comparison of manufacturing simulation software's using analytic hierarchy process J. Eng. Sci. Technol.

Hanley, N. (2001): Cost-benefit analysis and environmental policy-making. *Environment and Planning.*

Zambia (Kabwe) - Pilot Lead Remediation Project (Phase 1) - Pure Earth

Islam, K (2021). Environmental-Social footprints of mining sector: Applying Geospatial and operational data.

Jaume, B (2016). "Assessment, Restoration and reclamation of mining influenced soils"

JONES, H. & BOGER, D. V. 2012. Sustainability and Waste Management in the Resource Industries. *Industrial and Engineering Chemistry Research.*

Jones, M.J. (1972). The Groundwater Resources of the Kabwe Area, Report for Department of Water Affairs.

Junyi C, James N.K. Liu, E.W.T. Ngai, (2013). Application of decision-making techniques in supplier selection: a systematic review of literature Expert Syst.

Kabas, S., Faz, A., Acosta, J.A., Zornoza, R., Martínez-Martínez, S., Carmona, D.M., Bech, J., (2012). Effect of marble waste and pig slurry on the growth of native vegetation and heavy metal mobility in a mine tailing pond. J. Geochem. Explor. 123, 69–76.

Kamunda, C., Mathuthu, M., & Madhuku, M. (2016). Health risk assessment of heavy metals in soils from witwatersrand gold mining basin, South Africa. International Journal of Environmental Research and Public Health, 13, 663. doi:10.3390/ijerph13121252

Karami, E, (2006). "Appropriateness of farmers' adoption of irrigation methods: the application of the AHP model," Agricultural Systems, vol. 87.

Keune, H. and N. Dendoncker, (2013). Negotiated complexity in ecosystem services science and policy making - Ecosystem Services. In: Jacobs S., Dendoncker N. and H. Keune (eds.)

Kim, M., & Jung, Y. (2004). Vertical distribution and mobility of arsenic and heavy metals in and around mine tailings of an abandoned mine. Journal of Environmental Science and Health: Part A - Toxic/ Hazardous Substances and Environmental Engineering, A39(1), 203–222. doi:10.1081/ESE120027379

Kříbek, B., Nyambe, I., Majer, V., Knésl, I., Mihaljevič, M., Ettler, V., Vaněk, A., Penížek, V. and Sracek, O., (2019). Soil contamination near the Kabwe Pb-Zn smelter in Zambia: Environmental impacts and remediation measures proposal. *Journal of Geochemical Exploration*, *197*, pp.159-173.

Kříbek, B., Majer, V., Knésl, I., Nyambe, I.A., Mihaljevič, M., Ettler, V. and Sracek, O. 2012. Metals and arsenic in cassava: Indicators of contamination in the Zambian Copperbelt mining district Dendrogeochemical Record of Pollution from Mining and Smelting in Copperbelt, Zambia.

Lee, S., Kim, W., Kim, Y., and Oh, K. (2012). Using AHP to determine intangible priority factors for technology transfer adoption. Expert Systems with Applications, 39(7).

Li, X., & Huang, L. (2015). Towards a view paradigm for tailings phytostabilization-nature of the substrate's amendment option, and anthropogenic pedogenesis. Critical Reviews in Environmental Science and Technology, 45(8), 813–839. doi:10.1080/ 10643389.2014.921977

Lindahl, J. (2014). Environmental impacts of Mining in Zambia; towards better environmental management and sustainable exploitation of mineral resources. Geological Survey of Sweden.

Lottermoser, B. G. (2010). Mine Wastes, A Guide to the Management of Tailings Facilities. Ottawa, Ontario New York, Springer-Verlag Berlin Heidelberg. MAC 2011.: The Mining Association of Canada.

Maggie C.Y. Tam, V.M. Rao T, (2001). An application of the AHP in vendor selection of a telecommunications system Omega.

Malczewski J. (2006).GIS-based multicriteria decision analysis: a survey of the literature. Int J Geogr Inf Sci.

Mani, D., & Kumar, C. (2014). Biotechnological advances in bioremediation of heavy metals contaminated ecosystems: An overview with special reference to phytoremediation. International Journal of Science and Technology, 11(3), 843–872.

Masinja, J., Collins, R. and Westerlund, K. 2005. Determining Responsibilities. Preparation of the Phase 2 of a consolidated Environmental Management Plan. Topical report of the Copperbelt Environment Project (CEP). UNZA, THOMRO, SWECO and Swedish Geological Lab.

McGinley, P. (2012). Decision analysis software survey, http://www.orms-today.org/surveys/das/das.html

Mendoza, G.A. and Martins, H (2006). Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms. *Forest Ecology and Management*.

Mhlongo S. E, Dacosta, A.F., Kadyamatimba (2019). Development and application of a methodological tool for prioritization of rehabilitation of abandoned tailings dumps in the Giyani and Musina areas of South Africa.

Moosavirad, S. M., & Behnia, B. (2016). Suitability evaluation for land reclamation in mining areas: Gol-eGohar Iron Ore Mine of Sirjan, Kerman, Iron. International Journal of Mining, Reclamation and Environment, 1-14. doi:10.1080/ 17480930.2015.1105650

Mpanza M, Adam E, Moolla R (2020). Perceptions of external costs of dust fallout from gold mine tailings: West Wits Basin.

Muloiso, P and Zulu, P. (1993). Waste Management for mine Solid waste. *The International Symposium on Mine Drainage and Environmental Protection from Waste Disposal* (p. 8). Chililabombwe: Environmental Council of Zambia.

Mwandira, W., Nakashima, K., Kawasaki, S., Arabelo, A., Banda, K., Nyambe, I., ... & Ishizuka, M. (2020). Biosorption of Pb (II) and Zn (II) from aqueous solution by Oceanobacillus profundus isolated from an abandoned mine. *Scientific reports*, *10*(1), 1-9.

Nakamura, S., Igarashi, T., Uchida, Y., Ito, M., Hirose, K., Sato, T., Mufalo, W., Chirwa, M., Nyambe, I., Nakata, H. and Nakayama, S., 2021. Evaluation of dispersion of lead-bearing mine wastes in Kabwe District, Zambia. *Minerals*, *11*(8), p.901.

Newton, A. C., Hodder, K., Cantarello, E., Perrella, L., Birch, J.C., Robins, J., Douglas, S., Moody, C., Cordingly, J., et al. (2012). Cost-benefit analysis of ecological networks assessed through spatial analysis of ecosystem services. *Journal of Applied Ecology*

Norgate, T. E., & Rankin, W. J. (2000). Life Cycle Assessment of Copper and Nickel Production. *International* Conference *on Minerals Processing* (p. 8). Melbourne, Vic: MINIPREX.

Ngulube, R., Katundu, L., Nakena, K., Nyirenda, K., & Siakamba, A., (2016). A Review of Nchanga Tailings Dam Operations and Seasonal Assessment of Its Effluent Quality. *American Journal of Environmental Protection.*

Okeola, O., and Sule, B. (2012). Evaluation of management alternatives for urban water supply system using Multi-criteria Decision Analysis. Journal of King Saud University – Engineering Sciences, 24(1).

Olobatoke, R. Y., & Mathuthu, M. (2016). Heavy metal concentration in soil in the tailing dam vicinity of an old gold mine in Johannesburg, South Africa. Canadian Journal of Soil Science, 96, 299–304. doi:10.1139/cjss-2015-0081

Pashkevich, M.A., Petrova, T.A., (2016). Technology of artificial deposit preservation at the Kursk magnetic anomaly. Ecol. Eng. 17 (4), 11–16.

Rajesh, G, Malliga, P, (2013). Supplier selection based on AHP QFD methodology Procedia Eng.

Roca, M., Murphy, A., Walker, L., & Vallesi, S. (2019). *A review of risks posed by failure of tailings dam.* HR Wallingford Ltd.

Rodrıguez, R., Dıaz, M. B., Vigil, H., & Rodrıguez, A. (2011). Development of a user-friendly method to assess the present condition of old abandoned mining waste dumps in Asturias (Spain). International Journal of Mining, Reclamation and Environment, 25(1), 6–31. doi:10.1080/ 17480930.2010.538548

Saarikoski, H.; Barton, D.N.; Mustajoki, J.; Keune. H.; Gomez-Baggethun, E. and J. Langemeyer (2016): multi-criteria decision analysis (MCDA) in ecosystem service valuation. In: Potschin, M. and K. Jax (eds): OpenNESS Ecosystem Services Reference Book. EC FP7 Grant Agreement no. 308428. Available via: www.openness-project.eu/library/reference-book

SGAB, SWECO, THOMRO & UNZA, (2005). Preparation of Phase 2 of a Consolidated Environmental Management Plan – Project Summary Report. ZCCM Investments Holdings, Copperbelt Environment Project.

Sikamo, J., Mwanza, A., & Mweemba, C. (2015). Copper Mining in Zambia – History and Future. *Copper Cobalt Africa*, incorporating *the 8th Southern African Base Metals Conference.* Livingstone: Southern African Institute of Mining and Metallurgy.

Simutanyi, N, (2008). Copper mining in Zambia, The developmental legacy of privatization. *Institute for security studies.*

Singo N, K, (2013). An assessment of heavy metal pollution near an old copper mine dump in musina, South Africa.

SRK Mining consultants limited, (2005). Lumwana Copper Project – Environmental impact Assessment ; Report to Equinox Copper Ventures Limited.

Stirling, A. (2006): Analysis, participation and power. Justification and closure in participatory multi-criteria analysis. *Land Use Policy*.

Tangviroon, P., Noto, K., Igarashi, T., Kawashima, T., Ito, M., Sato, T., Mufalo, W., Chirwa, M., Nyambe, I., Nakata, H. and Nakayama, S., (2020). Immobilization of lead and zinc leached from mining residual materials in Kabwe, Zambia: Possibility of Chemical Immobilization by Dolomite, Calcined Dolomite, and Magnesium Oxide. *Minerals, 10*(9), p.763.

Thomas L. Saaty, (2013) Theory and Applications of the Analytic Network Process: Decision Making with Benefits, Opportunities, Costs and Risks RWS Publications, Pittsburgh, USA

Toyoda, K., Nakano, S., Tanaka, S., Banda, K., Nyambe, I.A., Ishikawa, T., Nakayama, S. and Ishizuka, M., (2022). Geochemical identification of particulate lead pollution in shallow groundwater in inhabited areas in Kabwe, Zambia. *Applied Geochemistry*, *139*, p.105215.

Velasquez and Hester (2013). An Analysis of Multi-Criteria Decision-Making Methods IJOR Vol. 10,

Vaidya OS, Kumar S (2006). Analytic hierarchy process: an overview of applications. Eur J Oper Res 169(1).

Wise-Uranium. (2019, July 19). *Tailing Dams Safety*. Retrieved August 29, 2019, from WISE Uranium Project: http://www.wise-uranium.org/mdaf.html

Weistroffer, H. R., Smith, C. H., and Narula, S. C., Figueira, J., Greco, S., and Ehrgott, M., (2005). Multiple criteria decision support software*: State of the Art Surveys Series*, Springer: New York.

(www.worstpolluted.org/).

Xinyang D, Yong H, Yong D, Sankaran M, (2014), Supplier selection using AHP methodology extended by D numbers Expert Systems with Applications. Expert Syst.

Zccm-Investments holding Plc (2004). Determination of the extent and Magnitude of contamination in the vicinity of the Kabwe mine.

APPENDICES

Appendix 1: Interview Questionnaire for Key Informants 1.

……………………………..

Name of Organisation: University of Zambia

Profession : Metallurgist

Position : Lecturer

Years of experience : 38 years

Date : August 2021

Opening

A. My name is Teclah Munanku, a student from the University of Zambia doing a Masters of Mineral Science in Sustainable Mineral Resource Development.

B. I am currently carrying out my research which is an assessment of the potential pollution risk of tailings dumps to the environment using multi criteria decision analysis (MCDA). I would like to ask you some questions about your background, your experience with the organisation, your observations and expertise on the matter to input into my report.

C. I hope to use this information to recommend possible impacts of MCDA in environmental policy and environmental impact assessment in relation to pollution risks that the environment faces from tailings dumps.

D. The interview should take about 60 minutes. Are you available to respond to some questions at this time?

Interview Questions

1. Looking at the list of criteria proposed, is there any indicator or factor that you feel should be added or removed from the list?

Indicators	Factors	
Physical properties	• Size of dump. • Particle size of dump material. • Consolidation status of dump.	C1
Mineralogical/chemical properties	• Chemistry of material dump is made off.	C2
Properties of environment around the dump	• Lithology underlying the dump. • Depth of water table from surface. • Distance to surface water body. • Distance to nearest anthropogenic facility.	C3
Intensity of air pollutant migration	➢ Climatic characteristics of mine dump surroundings (wind rose, intensity of precipitation).	C4
Design of protective structures	➢ Dust suppression at mine dump surface. ➢ Presence of wind barrier on windward side of dump.	C5

2. Why should the criteria recommended be added or removed?

3. Pairwise matrix completion for the AHP process which evaluates each criterion across each dump.

Indicators	C1	C2	C3	C4	C5
C1	1	1/9	1/5	3	1/5
C2	9	1	7	7	7
C3	5	1/7	1	3	5
C4	1/3	1/7	1/3	1	3
C5	5	1/7	1/5	1/3	1

Table 2: Definition of numerical scales for pairwise comparison (Saaty 1977)

Preference/ordinal scale	Degree of preference	Remarks
1	Equally	Factors inherit equal contribution
3	Moderately	One factor moderately favoured over other
5	Strongly	Judgement strongly favour one over other
7	Very strongly	One factor very strongly favoured over other
9	Extremely	One factor favoured over other in highest
2,4,6,8	Intermediate	Compensation between weights 1,3,5,7 and 9
Reciprocals	Opposite	Refers inverse comparison

4. Pairwise matrix of the tailings dumps against the criteria

Indicators	C1	C2	C3	C4	C5
Dump 1					
Dump 2					
Dump 3					

Request for Documents

Would you have any information either in soft or hard copy that you are able to share with me on the impact assessment of tailings dumps?

Closing

A. I appreciate the time you took for this interview. Is there anything else you think would be helpful for my assessment of the potential pollution risk of tailings dumps to the environment using multi criteria decision analysis (MCDA)?

B. I should have all the information I need. Would it be alright to contact you in future should I need further information?

C. Would you mind sharing your details? (If the answer to B is a yes)

Thank you.

Appendix 2: Interview Schedule for Key Informants 2

Name of Organisation: Lulea University of Technology

Profession : Geo-Metallurgist

Position : Lecturer

Years of experience : 18 years

Date : August 2021

Opening

A. My name is Teclah Munanku, a student from the University of Zambia doing a Masters of Mineral Science in Sustainable Mineral Resource Development.

B. I am currently carrying out my research which is an assessment of the potential pollution risk of tailings dumps to the environment using multi criteria decision analysis (MCDA). I would like to ask you some questions about your background, your experience with the organisation, your observations and expertise on the matter to input into my report.

C. I hope to use this information to recommend possible impacts of MCDA in environmental policy and environmental impact assessment in relation to pollution risks that the environment faces from tailings dumps.

D. The interview should take about 60 minutes. Are you available to respond to some questions at this time?

Interview Questions

1. Looking at the list of criteria proposed, is there any indicator or factors you feel should be added or removed from the list?

Indicators	Factors	
Physical properties	• Size of dump. • Particle size of dump material. • Consolidation status of dump.	C1
Mineralogical/chemical properties	• Chemistry of material dump is made off.	C2
Properties of environment around the dump	• Lithology underlying the dump. • Depth of water table from surface. • Distance to surface water body. • Distance to nearest anthropogenic facility.	C3
Intensity of pollutant migration	➢ Climatic characteristics of mine dump surroundings (wind rose, intensity of precipitation)	C4
Design of protective structures	➢ Dust suppression at mine dump surface. ➢ Presence of wind barrier on windward side of dump.	C5

2. Why should the criteria recommended be added or removed?

3. Pairwise matrix completion for the AHP process which evaluates each criterion across each dump.

indicators	C1	C2	C3	C4	C5
C1	1	1/7	**5**	2	3
C2	7	1	6	8	9
C3	1/5	1/6	1	1/4	1/2
C4	1/2	1/8	4	1	3
C5	1/3	1/9	2	1/3	1

Table 2: Definition of numerical scales for pairwise comparison (Saaty 1977)

Preference/ordinal scale	Degree of preference	Remarks
1	Equally	Factors inherit equal contribution
3	Moderately	One factor moderately favoured over other
5	Strongly	Judgement strongly favour one over other
7	Very strongly	One factor very strongly favoured over other
9	Extremely	One factor favoured over other in highest
2,4,6,8	Intermediate	Compensation between weights 1,3,5,7 and 9
Reciprocals	Opposite	Refers inverse comparison

4. Pairwise matrix completion for the AHP process which evaluates all criteria across all three dumps.

indicators	C1	C2	C3	C4	C5
Dump 1					
Dump 2					
Dump 3					

Request for Documents

Would you have any information either in soft or hard copy that you are able to share with me on the impact assessment of tailings dumps?

Closing

A. I appreciate the time you took for this interview. Is there anything else you think would be helpful for my assessment of the potential pollution risk of tailings dumps to the environment using multi criteria decision analysis (MCDA)?

B. I should have all the information I need. Would it be alright to contact you in future should I need further information?

C. Would you mind sharing your details? (If the answer to B is a yes)

Thank you.

Appendix 3: Interview Questionnaire for Key Informants 3

Name of Organisation: University of Zambia

Profession : Hydrogeologist/Environmental Engineer, Remote sensing expert

Position : Lecturer (Geology Department)

Years of experience : 15 years

Date : August 2021

Opening

A. My name is Teclah Munanku, a student from the University of Zambia doing a Masters of Mineral Science in Sustainable Mineral Resource Development.

B. I am currently carrying out my research which is an assessment of the potential pollution risk of tailings dumps to the environment using multi criteria decision analysis (MCDA). I would like to ask you some questions about your background, your experience with the organisation, your observations and expertise on the matter to input into my report.

C. I hope to use this information to recommend possible impacts of MCDA in environmental policy and environmental impact assessment in relation to pollution risks that the environment faces from tailings dumps.

D. The interview should take about 60 minutes. Are you available to respond to some questions at this time?

Interview Questions

1. Looking at the list of criteria developed, is there any criteria you feel should be added or removed from the list?

indicators	**factors**	
Physical properties	• Size of dump. • Particle size of dump material. • Consolidation status of dump.	C1
Mineralogical/chemical properties	• Chemistry of material dump is made off.	C2
Properties of environment around the dump	• Lithology underlying the dump. • Depth of water table from surface. • Distance to surface water body. • Distance to nearest anthropogenic facility.	C3
Intensity of pollutant migration	➢ Climatic characteristics of mine dump surroundings (wind rose, intensity of precipitation).	C4
Design of protective structures	➢ Dust suppression at mine dump surface ➢ Presence of wind barrier on windward side of dump.	C5

2. Why should the criteria recommended be added or removed?

3. Pairwise matrix completion for the AHP process which evaluates each criterion across each dump.

Indicators	**C1**	**C2**	**C3**	**C4**	**C5**
C1	1	1/7	**4**	1/3	3
C2	7	1	7	5	9
C3	1/4	1/7	1	1/3	1
C4	3	1/5	3	1	2
C5	1/3	1/9	1	1/2	1

Table 2: Definition of numerical scales for pairwise comparison (Saaty 1977)

Preference/ordinal scale	Degree of preference	Remarks
1	Equally	Factors inherit equal contribution
3	Moderately	One factor moderately favoured over other
5	Strongly	Judgement strongly favour one over other
7	Very strongly	One factor very strongly favoured over other
9	Extremely	One factor favoured over other in highest
2,4,6,8	Intermediate	Compensation between weights 1,3,5,7 and 9
Reciprocals	Opposite	Refers inverse comparison

4. Pairwise matrix of tailings dumps against criteria.

Indicators	C1	C2	C3	C4	C5
Dump 1					
Dump 2					
Dump 3					

Request for Documents

Would you have any information either in soft or hard copy that you are able to share with me on the impact assessment of tailings dumps?

Closing

A. I appreciate the time you took for this interview. Is there anything else you think would be helpful for my assessment of the potential pollution risk of tailings dumps to the environment using multi criteria decision analysis (MCDA)?

B. I should have all the information I need. Would it be alright to contact you in future should I need further information?

C. Would you mind sharing your details? (If the answer to B is a yes)

Thank you.

Appendix 4: Interview Questionnaire for Key Informant 4

Name of Organisation : The University of Zambia

Profession : Geomatic Engineering/AHP Expert

Position : Lecturer

Years of experience : 10 years

Date : August 2021

Opening

A. My name is Teclah Munanku, a student from the University of Zambia doing a Masters of Mineral Science in Sustainable Mineral Resource Development.

B. I am currently carrying out my research which is an assessment of the potential pollution risk of tailings dumps to the environment using multi criteria decision analysis (MCDA). I would like to ask you some questions about your background, your experience with the organisation, your observations and expertise on the matter to input into my report.

C. I hope to use this information to recommend possible impacts of MCDA in environmental policy and environmental impact assessment in relation to pollution risks that the environment faces from tailings dumps.

D. The interview should take about 60 minutes. Are you available to respond to some questions at this time?

Interview Questions

1. Looking at the list of criteria proposed, is there any indicator or factor that you feel should be added or removed from the list?

Indicators	**Factors**	
Physical properties	• Size of dump. • Particle size of dump material. • Consolidation status of dump.	C1
Mineralogical/chemical properties	• Chemistry of material dump is made off.	C2
Properties of environment around the dump	• Lithology underlying the dump. • Depth of water table from surface. • Distance to surface water body. • Distance to nearest anthropogenic facility.	C3
Intensity of pollutant migration	➢ Climatic characteristics of mine dump	C4

	surroundings (wind rose, intensity of precipitation).	
Design of protective structures	➢ Dust suppression at mine dump surface. ➢ Presence of wind barrier on windward side of dump.	C5

2. Why should the criteria recommended be added or removed?

3. Pairwise matrix completion for the AHP process which evaluates each criterion across each dump.

Indicators	**C1**	**C2**	**C3**	**C4**	**C5**
C1	1	1/5	**3**	3	1/2
C2	5	1	1	6	4
C3	1/3	1	1	7	5
C4	1/3	1/6	1/7	1	1/3
C5	2	1/4	1/5	3	1

Table 2: Definition of numerical scales for pairwise comparison (Saaty 1977)

Preference/ordinal scale	Degree of preference	Remarks
1	Equally	Factors inherit equal contribution
3	Moderately	One factor moderately favoured over other
5	Strongly	Judgement strongly favour one over other
7	Very strongly	One factor very strongly favoured over other
9	Extremely	One factor favoured over other in highest
2,4,6,8	Intermediate	Compensation between weights 1,3,5,7 and 9
Reciprocals	Opposite	Refers inverse comparison

4. Pairwise matrix for tailings dumps against criteria.

Indicators	**C1**	**C2**	**C3**	**C4**	**C5**
Dump 1					
Dump 2					
Dump 3					

Request for Documents

Would you have any information either in soft or hard copy that you are able to share with me on the impact assessment of tailings dumps?

Closing

A. I appreciate the time you took for this interview. Is there anything else you think would be helpful for my assessment of the potential pollution risk of tailings dumps to the environment using multi criteria decision analysis (MCDA)?

B. I should have all the information I need. Would it be alright to contact you in future should I need further information?

C. Would you mind sharing your details? (If the answer to B is a yes)

Thank you.

Appendix 5: Pairwise comparisons and consistency ratios for all four experts

Consistency ratio CI λ_{max} = Principal Eigen value of the pairwise comparison matrix

CI = (λ_{max} - n)/(n-1)   n = number of factors (criteria) or order of the matrix (formula 1)

Table 5.1: Expert 1

	C1	**C2**	**C3**	**C4**	**C5**
C1	1	1/5	3	3	3
C2	5	1	4	8	7
C3	1/3	¼	1		3
C4	1/3	1/8	1/2	1	1/3
C5	1/3	1/7	1/3	3	1
Σ	**7.00**	**1.72**	**8.83**	**17.00**	**14.33**

CI=0.0957 <1 Acceptable

Table 5.2: Expert

	C1	**C2**	**C3**	**C4**	**C5**
C1	1	1/7	4	3	5
C2	7	1	8	5	7
C3	1/4	1/8	1	2	2
C4	1/3	1/5	1/2	1	2
C5	1/5	1/7	1/2	1/2	1
Σ	**8.78**	**1.61**	**14.00**	**11.50**	**17.00**

	C1	C2	C3	C4	C5
C1	1	1/7	4	2	9
C2	7	1	7	3	2
C3	1/4	1/7	1	1/3	1
C4	1/2	1/3	3	1	5
C5	1/9	1/9	1	1/5	1
Σ	**8.86**	**1.73**	**16.00**	**6.53**	**18.00**

CI=00963 <1 Acceptable

Table 5.3: Expert 3

CI= 0.0822<1 Acceptable

Table 5.4: Expert 4

	C1	C2	C3	C4	C5
C1	1	1/7	5	2	3
C2	7	1	6	8	9
C3	1/5	1/6	1	1/4	1/2
C4	1/2	1/8	4	1	3
C5	1/3	1/9	2	1/3	1
Σ	**9.03**	**1.55**	**18.00**	**11.58**	**16.5**

CI=0.0862<1 Acceptable

Appendix 6: Test potential pollution risk assessment on Musina tailings dump

C1. PHYSICAL PROPERTIERTIES

a) Size of dump

	Size of Dump	**Score**	**Normalized scores**
1	>625 ha	1.00	0.333
2	25-625 ha (95)	0.80	0.27
3	5-25ha	0.60	0.20
4	1-5ha	0.40	0.13
5	<1ha	0.20	0.067
		3	**1**

C_1=a+ b+ c /3

= 0.27 + 0.4+ 0.5/3

C_1=0.39

C_1 X C_{w1} = C_{W1} = 0.2019

0.39 x 0.2019

C_1C_{W1}=0.078741

b) Grain size composition

	Texture	Score	Normalized scores
1	Gravel	0.25	0.1
2	sand	0.5	0.2
3	clay	0.75	0.3
4	silt	1.0	0.4
		2.5	**1**

	D1	D2	D3
C1	C_1C_{W1}	C_1C_{W1}	C_1C_{W1}
C2	C_1C_{W2}	C_1C_{W2}	C_1C_{W2}
C3	C_1C_{W3}	C_1C_{W3}	C_1C_{W3}
C4	C_1C_{W4}	C_1C_{W4}	C_1C_{W4}
C5	C_1C_{W5}	C_1C_{W5}	C_1C_{W5}
SUM	D1	D2	D3

c) Consolidation status

	status	score	Normalized

	RATING
D1	X
D2	Y
D3	Z

			score
1	consolidated	0.25	0.167
2	Mixed	0.5	0.33
3	loose	0.75	0.50
		1.5	**0.997**

2. CHEMICAL PROPERTIES

Chemical composition of dump material (according to WHO standards)

Metals	Ni	Pb	Zn	Cu	Co	Cd	Hg	As	Cr	PH
Maximum permissible limit in soil(mg/kg)	91	20	240	300	7.5	7.5	0.93	5.8	6.5	
Concertation in tailings (%weight)	0.02	0.08	<0.01	0.187	0.025	<0.01	<0.01	<0.01	<0.01	8.57
	200	800	100	1870	250	100	100	100	100	

IC = $1/N \times \Sigma C_i/Plc$

=21.27

IC value	Index	Normalized scores
0.25 – 0.5	0.25	0.1
0.5 – 0.75	0.5	0.2
0.75 – 1.0	0.75	0.3
>1.0	1.0	0.4
	2.5	**1**

3. PROPERTIES OF ENVIRONMENT SURROUNDING DUMP

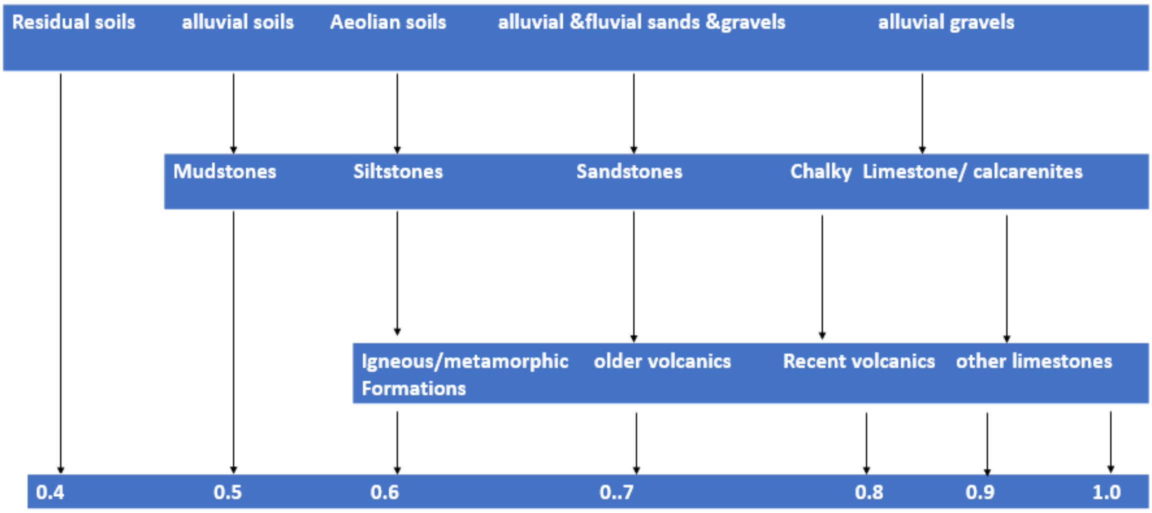
a) Distance to surface water body

	Distance	Score	Normalized scores	
1	<100m	1.0	0.4	
2	100-300m	0.75	0.3	
3	300-600m	0.5	0.2	
4	600-1000m (658m) n	0.25	0.1	
		2.5	**1**	

b) Depth to the water table

	Depth	**Score**	**Normalized Scores**
1	>100	**0.4**	**0.0816**
2	**50-100m**	**0.5**	**0.102**
3	**20-50m**	**0.6**	**0.124**
4	**10-20m (15-30)**	**0.7**	**0.143**
5	**5-10m**	**0.8**	**0.163**
6	**2-5m**	**0.9**	**0.184**
7	**<2m**	**1.0**	**0.204**
		4.9	**1.0016**

c) Lithology



0.082	0.102	0.123	0.0.143	0.163	0.184	0.204
4.9			Gneiss(Namaqua metamorphic rocks			

d) Distance to the nearest settlement

	Distance	Score	Normalized Scores	
1	<100m	1.0	0.333	
2	100-300m (240m)	0.8	0.267	
3	300-600m	0.6	0.2	
4	600-1000m	0.4	0.133	
5	>1000m	0.2	0.067	
		3	**1**	

4. CLIMATIC FACTORS

a) Rainfall

	Rainfall	Score	Normalized score
1	>1500 m	1.0	0.4
2	1500-1000	0.75	0.3
3	800-1000	0.5	0.2
4	<800	0.25	0.1
		2.5	**1**

5. PROTECTIVE STRUCTURES

	Cover	Score	Normalized score
1	Both slopes and top surface are without any cover	1.0	0.4
2	Top surface is covered by indigenized plants or grass	0.75	0.3
3	Slopes are covered by indigenize plant or grass	0.5	0.2
4	Dump is completely covered by indigenized plants /grass species.	0.25	0.1
		2.5	1

	Criteria indicators	**MOPANI**	**KABWE**	**LUMWANA**
C1	Size of dump	0.33	0.27	0.33
	grain size composition	0.4	0.4	0.4

	consolidation status	0.33	0.5	0.33
	criteria score total	**1.06**	**1.17**	**1.06**
C2	Index of contamination	**0.4**	**0.4**	**0.4**
	criteria score total			
C3	Distance to surface water	0.1	0.1	0.3
	Depth to water Table	0.143	0.163	0.163
	Lithology	0.184	0.184	0.184
	Distance to nearest settlement	0.267	0.33	0.067
	criteria score total	**0.694**	**0.777**	**0.714**
C4	Rainfall	0.3	0.2	0.3
	criteria score total	**0.3**	**0.2**	**0.3**
C5	Tree cover	0.2	0.4	0.1
		0.2	**0.4**	**0.1**
	Criteria score total for each dump	**2.654**	**2.947**	**2.574**

	D1	D2	D3		CW from AHP
	Mopani	Kabwe	Lumwana		
C1	1.06	1.17	1.06	CW1	0.2048
C2	0.4	0.4	0.4	CW2	0.5383
C3	0.694	0.78	0.714	CW3	0.07674
C4	0.3	0.2	0.3	CW4	0.0758
C5	0.2	0.4	0.1	CW5	0.1204

	D1(Mopani)	D2(Kabwe)	D3(Lumwana)	D4 (Musina)
C1	1.06	1.17	1.06	0.198656
C2	0.4	0.4	0.4	0.21532
C3	0.694	0.78	0.714	0.05011
C4	0.3	0.2	0.3	0.02274
C5	0.2	0.4	0.1	0.04816
Risk	**0.53248556**	**0.5781132**	**0.52198036**	**0.534986**
	Low risk	**Medium risk**	**Medium risk**	**Medium risk**

Risk category	Risk scores	Description
Low	0 – 0.35	Pollution risk is minimal but should be monitored.
Low to medium	0.36 – 0.5	Pollution risk is tolerable with increased monitoring.
Medium	0.51 – 0.65	Pollution risk is tolerable with controls. Assess the risk mitigation options and monitor risks.
Medium to high	0.66– 0.8	Pollution risk undesirable. Risk mitigation should be employed.
High	0.81 – 1.0	Pollution risk intolerable. Risk mitigation required immediately.

Appendix 7: Expert 1 AHP Criteria weights computations

Pairwise comparison matrix

	C1	C2	C3	C4	C5
C1	1	0.143	5	2	3
C2	7	1	6	8	9
C3	0.2	0.167	1	0.25	0.5
C4	0.5	0.125	4	1	3
C5	0.333	0.111	2	0.333	1
sum	9.033	1.546	18	11.583	16.5

Normalizing (divide each value by sum of column)

	C1	C2	C3	C4	C5
C1	1	0.143	5	2	3
C2	7	1	6	8	9
C3	0.2	0.167	1	0.25	0.5
C4	0.5	0.125	4	1	3
C5	0.333	0.111	2	0.333	1
sum	9.033	1.546	18	11.583	16.5

Normalized pairwise matrix

	C1	C2	C3	C4	C5
C1	0.110705	0.092497	0.277778	0.172667	0.181818
C2	0.774936	0.646831	0.333333	0.690667	0.545455
C3	0.022141	0.108021	0.055556	0.021583	0.030303
C4	0.055353	0.080854	0.222222	0.086333	0.181818
C5	0.036865	0.071798	0.111111	0.028749	0.060606

Criteria weights (by averaging each row)

	C1	C2	C3	C4	C5	Criteria weights
C1	0.110705	0.092497	0.277778	0.172667	0.181818	**0.167092951**
C2	0.774936	0.646831	0.333333	0.690667	0.545455	**0.598244422**
C3	0.022141	0.108021	0.055556	0.021583	0.030303	**0.047520736**
C4	0.055353	0.080854	0.222222	0.086333	0.181818	**0.125316047**
C5	0.036865	0.071798	0.111111	0.028749	0.060606	**0.061825844**
						1

Consistency check (multiply each value in unnormalized pairwise matrix **by criteria weight)**

	C1	C2	C3	C4	C5	weighted sum value	criteria weights	ws/cw
	0.167093	0.598244	0.047521	0.125316	0.061826			
C1	0.167093	0.085549	0.237604	0.250632	0.185478	0.926355207	0.167092951	5.543951
C2	1.169651	0.598244	0.285124	1.002528	0.556433	3.611980466	0.598244422	6.037633
C3	0.033419	0.099907	0.047521	0.031329	0.030913	0.243088078	0.047520736	5.115411
C4	0.083546	0.074781	0.190083	0.125316	0.185478	0.659203549	0.125316047	5.260328
C5	0.055642	0.066405	0.095041	0.04173	0.061826	0.320644642	0.061825844	5.186256

Tmax=	5.428716			
Tmax-n(n=	0.428716		RI=	1.12
CI	**0.107179**			
CR=	0.095696	<0.10	**CONSISTENT**	

Appendix 8: Expert 2 AHP Criteria weights computations

Pairwise Comparison Matrix

	C1	C2	C3	C4	C5
C1	1	1/7	4	3	5
C2	7	1	8	5	7
C3	1/4	1/8	1	2	2
C4	1/3	1/5	1/2	1	2
C5	1/5	1/7	1/2	1/2	1
Σ	**8.78**	**1.61**	**14.00**	**11.50**	**17.00**

Normalization of the pairwise comparison matrix by the formula:

$a_{ij} = a_{ij}/\Sigma a_{ij}$

i.e. to normalize the values, divide the cell value by its column total

****To calculate the priority of attributes or priority vector or weights, determine the mean value of the rows:***

	C1	C2	C3	C4	C5	Weights		Weights	WS Value		λ max (lambda)	CI	CR		
C1	0.11	0.09	0.29	0.26	0.29	20.9%	$= W_{HPD}$	0.2086	1.15586	5.5397	5.431567	0.107891708	**0.096**	< 0.1	*(acceptable)*
C2	0.80	0.62	0.57	0.43	0.41	56.7%	$= W_{PMR}$	0.5672	3.52990	6.2239					
C3	0.03	0.08	0.07	0.17	0.12	9.4%	$= W_{DEF}$	0.0938	0.47763	5.0914					
C4	0.04	0.12	0.04	0.09	0.12	8.0%	$= W_{DHM}$	0.0805	0.41017	5.0960					
C5	0.02	0.09	0.04	0.04	0.06	5.0%	$= W_{WBD}$	0.0499	0.25980	5.2068					
	1.00	1.00	1.00	1.00	1.00	**1.00**									

Calculating the Consistency Ratio (CR)

0.02	0.08	0.04	0.04	0.06
0.80	0.62	0.57	0.43	0.41

CR = CI/RI

Where,

CI = $(\lambda_{max} - n)/(n-1)$

λ_{max} = ***principal Eigen value*** *of the pairwise comparison matrix*

n = *number of factors (criteria) or order of the matrix*

λ_{max} = ***Sum (Σ) of the products*** *between:*

each element of the weights x column (from pairwise comparison matrix)

λ_{max} = **5.431567** **RI = 1.12**

Therefore:

CI = $(\lambda_{max} - n)/(n-1)$ **0.1078917**

Therefore:

CR = **CI/RI**

0.0963 **<** **0.1** (acceptable)

Appendix 9: Expert 3 AHP Criteria weights computations

Pairwise Comparison Matrix

	C1	C2	C3	C4	C5
C1	1	1/7	4	2	9
C2	7	1	7	3	2
C3	1/4	1/7	1	1/3	1
C4	1/2	1/3	3	1	5
C5	1/9	1/9	1	1/5	1
Σ	**8.86**	**1.73**	**16.00**	**6.53**	**18.00**

Normalization of the pairwise comparison matrix by the formula:

$a_{ij} = a_{ij}/\Sigma a_{ij}$

i.e. to normalize the values, divide the cell value by its column total

To calculate the priority of attributes or priority vector or weights, determine the mean value of the rows:

	C1	C2	C3	C4	C5	Weights		Weights	WS Value		? max (lambda)	CI	CR		
C1	0.11	0.08	0.25	0.31	0.50	25.0%	$= W_{HPD}$	0.2503	1.29481	5.1729	5.368032	0.092008005	**0.082**	< 0.1	***(acceptable)***
C2	0.79	0.58	0.44	0.46	0.11	47.5%	$= W_{PMR}$	0.4751	3.22974	6.7973					
C3	0.03	0.08	0.06	0.05	0.06	5.6%	$= W_{DEF}$	0.0560	0.28934	5.1694					
C4	0.06	0.19	0.19	0.15	0.28	17.3%	$= W_{DHM}$	0.1735	0.85036	4.9017					
C5	0.01	0.06	0.06	0.03	0.06	4.5%	$= W_{WBD}$	0.0451	0.21636	4.7989					
	1.00	1.00	1.00	1.00	1.00	**1.00**									

Calculating the Consistency Ratio (CR)

0.01	0.06	0.06	0.03	0.06
0.79	0.58	0.44	0.46	0.50

CR = CI/RI

Where,

CI = ($?_{max}$ - n)/(n-1)

$?_{max}$ = ***principal Eigen value*** *of the pairwise comparison matrix*

n = *number of factors (criteria) or order of the matrix*

$?_{max}$ = ***Sum (Σ) of the products*** *between:*

each element of the weights x column (from pairwise comparison matrix)

$?_{max}$ = **5.368032** **RI = 1.12**

Therefore:

CI = ($?_{max}$ - n)/(n-1) **0.0920080**

Therefore:

CR = CI/RI

0.0822 **<** **0.1** (acceptable)

Appendix 9: Expert 4 AHP Criteria weights computations

Pairwise Comparison Matrix

	C1	C2	C3	C4	C5
C1	1	1/5	3	3	3
C2	5	1	4	8	7
C3	1/3	1/4	1	2	3
C4	1/3	1/8	1/2	1	1/3
C5	1/3	1/7	1/3	3	1
Σ	**7.00**	**1.72**	**8.83**	**17.00**	**14.33**

Normalization of the pairwise comparison matrix by the formula:

$a_{ij} = a_{ij}/\Sigma a_{ij}$

i.e. to normalize the values, divide the cell value by its column total

***To calculate the priority of attributes or priority vector or weights, determine the mean value of the rows:**

	C1	C2	C3	C4	C5	Weights		Weights	WS Value		⍰ max (lambda)	CI	CR		
C1	0.14	0.12	0.34	0.18	0.21	19.7%	$= W_{HPD}$	0.1969	1.08954	5.5325	5.385994	0.096498429	**0.086**	< 0.1	**(acceptable)**
C2	0.71	0.58	0.45	0.47	0.49	54.2%	$= W_{PMR}$	0.5416	3.02812	5.5907					
C3	0.05	0.15	0.11	0.12	0.21	12.7%	$= W_{DEF}$	0.1267	0.68019	5.3702					
C4	0.05	0.07	0.06	0.06	0.02	5.2%	$= W_{DHM}$	0.0518	0.27614	5.3296					
C5	0.05	0.08	0.04	0.18	0.07	8.3%	$= W_{WBD}$	0.0830	0.42363	5.1071					
	1.00	1.00	1.00	1.00	1.00	**1.00**									

	C1	C2	C3	C4	C5
Calculating the Consistency Ratio (CR)	0.05	0.07	0.04	0.06	0.02
	0.71	0.58	0.45	0.47	0.49

CR = CI/RI

Where,

CI = (⍰$_{max}$ - n)/(n-1)

⍰$_{max}$ = **principal Eigen value** of the pairwise comparison matrix

n = number of factors (criteria) or order of the matrix

⍰$_{max}$ = **Sum (Σ) of the products** between:

each element of the weights x column (from pairwise comparison matrix)

⍰$_{max}$ = **5.385994** **RI = 1.12**

Therefore:

CI = (⍰$_{max}$ - n)/(n-1) **0.0964984**

Therefore:

CR = CI/RI

0.0862 < **0.1** (acceptable)

Appendix 10: Microsoft Excel Template for Expert AHP criteria weighting

Pairwise Comparison Matrix

	C1	C2	C3	C4	C5
C1	1	1/7	4	3	5
C2	7	1	8	5	7
C3	1/4	1/8	1	2	2
C4	1/3	1/5	1/2	1	2
C5	1/5	1/7	1/2	1/2	1
Σ	**8.78**	**1.61**	**14.00**	**11.50**	**17.00**

Normalization of the pairwise comparison matrix by the formula:

$\boxed{a_{ij} = a_{ij}/\Sigma a_{ij}}$

i.e. to normalize the values, divide the cell value by its column total

****To calculate the priority of attributes or priority vector or weights, determine the mean value of the rows:***

	C1	C2	C3	C4	C5	Weights		Weights	WS Value		λ max (lambda)	CI	CR		
C1	0.11	0.09	0.29	0.26	0.29	20.9%	= W_{HPD}	0.2086	1.15586	5.5397	5.431567	0.107891708	**0.096**	< 0.1	(*acceptable*)
C2	0.80	0.62	0.57	0.43	0.41	56.7%	= W_{PMR}	0.5672	3.52990	6.2239					
C3	0.03	0.08	0.07	0.17	0.12	9.4%	= W_{DEF}	0.0938	0.47763	5.0914					
C4	0.04	0.12	0.04	0.09	0.12	8.0%	= W_{DHM}	0.0805	0.41017	5.0960					
C5	0.02	0.09	0.04	0.04	0.06	5.0%	= W_{WBD}	0.0499	0.25980	5.2068					
	1.00	1.00	1.00	1.00	1.00	**1.00**									

Calculating the Consistency Ratio (CR)

0.02	0.08	0.04	0.04	0.06
0.80	0.62	0.57	0.43	0.41

$\boxed{CR = CI/RI}$

Where,

$CI = (\lambda_{max} - n)/(n-1)$

λ_{max} = ***principal Eigen value*** *of the pairwise comparison matrix*

n = *number of factors (criteria) or order of the matrix*

λ_{max} = ***Sum (Σ) of the products*** *between:*

each element of the weights x column (from pairwise comparison matrix)

λ_{max} = **5.431567** **RI = 1.12**

Therefore:

$CI = (\lambda_{max} - n)/(n-1)$ **0.1078917**

Therefore:

CR = CI/RI

0.0963 **<** **0.1** (acceptable)

Appendix 11. Formulated excel sheet for the final rating.

	Criteria indicators	**MOPANI**	**KABWE**	**LUMWANA**						
C1	Size of dump	0.33	0.27	0.33						
	grain size composition	0.4	0.4	0.4						
	consolidation status	0.33	0.5	0.33						
		1.06	1.17	1.06						
C2	Index of contamination	0.4	0.4	0.4		D1	D3	D2		CW from AHP
						MOP	KAB	LUM		
					C1	1.06	1.17	1.06	CW1	0.2048
C3	Distance to surface water	0.1	0.1	0.3	C2	0.4	0.4	0.4	CW2	0.5383
	Depth to water Table	0.143	0.163	0.163	C3	0.694	0.78	0.714	CW3	0.07674
	Lithology	0.184	0.184	0.184	C4	0.3	0.2	0.3	CW4	0.0758
	Distance to nearest settlement	0.267	0.33	0.067	C5	0.2	0.4	0.1	CW5	0.1204
		0.694	0.777	0.714						
C4	Rainfall	0.3	0.2	0.3		D1(mopani)	D2(kabwe)	D3(Lumwana)		
					C1	0.217088	0.239616	0.217088		
					C2	0.21532	0.21532	0.21532		
C5	Tree cover	0.2	0.4	0.1	C3	0.05325756	0.0598572	0.05479236		
		2.654	2.947	2.574	C4	0.02274	0.01516	0.02274		
					C5	0.02408	0.04816	0.01204		
					Final rating	**0.53248556**	**0.5781132**	**0.52198036**		
						0.53	0.6	0.52		

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