Development and application of a methodological tool for prioritization of rehabilitation of abandoned tailings dumps in the Giyani and Musina areas of South Africa

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Sphiwe Emmanuel Mhlongo1, Francis Amponsah-Dacosta2 and Armstrong Kadyamatimba2

Abstract: South Africa has numerous voluminous tailings dumps that will certainly require rehabilitation. The aim of this work was to develop a methodological approach for prioritization of rehabilitation of abandoned tailings dumps. To test the applicability of the developed method in different conditions, it was applied on six abandoned tailings dumps denoted as FGMT, LMMT, KLMT, MCMT, NMMT-A and NMMT-B found in the Giyani and Musina areas of South Africa. The method involved integration of quantitative and qualitative techniques in making sound decision on the order of rehabilitation of the tailings dumps in the area. It considered the contamination potential of the dumps, the ease of their dispersion to the surroundings and the impact they have on the appearance of the natural landscape. The use of the tool on abandoned tailings dumps in the study area revealed that gold tailings dumps are to be rehabilitated first than magnesite and copper tailings dumps. The study indicated that the dump with the highest pollution potential was the FGMT and that physical stabilization was considered the most suitable rehabilitation option for abating its high toxic metals from polluting the environment. The combination of methods that improve physical stability of the dump while
enhancing nutrient availability for plant growth were found appropriate for rehabilitation of MCMT. The rehabilitation of the rest of the dumps required the use of chemical methods that promote growth of vegetation. According to the study, the developed tool can be used to guide rehabilitation of abandoned tailings dumps in different settings.

**Subjects:** Mining Engineering; Mining Construction; Sustainable Mining

**Keywords:** Tailings dumps; rehabilitation prioritization; abandoned mines; South Africa

1. Introduction

Mining and processing of solid minerals produce different types of waste material, such as tailings and waste rock (Kim & Jung, 2004). In general, abandoned tailings dumps are of major concern throughout the world. This is because they are known for having physical and chemical properties that have serious impact on the environment, as well as the health of people and animals (Rodríguez, Díaz, Vigil, & Rodríguez, 2011). For example, toxic metals found in tailings are mostly in higher concentrations than they are in the ore mined and most tailings dumps are potential candidates for discharge of Acid Mine Drainage (Choi, Jeong, & Chae, 2005). According to Olobatoke and Mathuthu (2016), the composition of mine tailings depends largely on the type of ore mined, the gangue associated with the ore, and the extraction method used. Some of the common toxic metals in tailings are Lead (Pb), zinc (Zn), Copper (Cu), Nickel (Ni), Manganese (Mn) and Asenic (As) (Li & 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, Mathuthu, & Madhuku, 2016). The transportation of tailings material through different forms of erosion can result to 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).

In many countries or regions, the rehabilitation of abandoned mine sites have taken different forms. In South Africa, the focus of rehabilitation of abandoned mines has for many years been on addressing safety and health risks and then the environmental hazards at these mines (DMR, 2010; Mhlongo & Amponsah-Dacosta, 2016). However, the method used to set such rehabilitation priority of abandoned mines in the country has not been broadly communicated or published. This study used the case of abandoned tailings dumps in Musina and Giyani areas to develop a tool for prioritization of rehabilitation of abandoned mine tailings dumps. The areas of Musina and Giyani have been historically mining areas for copper, magnesite and gold. As the results, these areas have numerous abandoned mine sites that are characterized by large volume unrehabilitated mine tailings dumps. The use of such tailings dumps in this study presented an opportunity for applying the developed tool in tailings dumps of different types and magnitude of problems.

These dumps are found in five abandoned mines which are Mesina, Nyala, Fumani, Louis Moore and Klein Letaba (see Figure 1). Mining and processing of magnesite at Nyala Mine (Zwigodini Village) resulted to two unrehabilitated tailings dumps while copper mining created a huge tailing dump outside Musina Town.

During the preliminary visit to the sites, it was observed that planting of trees on copper tailings was implemented in Mesina Mine but did not show positive results as many of the trees died prematurely thus the lager part of this dump is without cover and its material is continuously being eroded to the surrounding areas. Comparatively, no attempts were made to rehabilitate the gold tailings dumps in the Giyani area and are therefore unprotected and exposed to erosion.
2. Methodology

The method for characterization of tailings dumps and identification of their preferred combination of rehabilitation options was developed and used in this study. The trends in existing abandoned mines rehabilitation prioritization methods show that the problem of pollution is the most common factor used by most methods. The development of the new rehabilitation prioritization tool in this work considered the fact that tailings dumps generally contain high levels of toxic metals and these contribute significantly to contamination of the environment when the tailings are eroded to the surrounding areas. It also considered the fact that in practice the drive for rehabilitation of abandoned tailings dumps is influenced by their potential to pollute the environment and the impact they have on the appearance of the natural landscape.

In view of this, the development of this tool involved using scoring techniques to determine index values that describe the degree of the impact of tailings dumps on the appearance of the landscape and the susceptibility of the tailings to erosion and subsequent disposal to the surrounding areas. The potential of the tailings to pollute the environment was quantified by calculating the index of contamination (IC) of the tailings using the methods described in Section 2.1 of this paper. The method used these indices to calculate the rehabilitation priority score of the abandoned tailings dumps. In addition, based on these indices, a technique for identification of preferred combination of strategies for rehabilitation of the tailings dumps was developed. The step-wise methodology used in developing the rehabilitation prioritization tool in this work is shown in Figure 2.

2.1 Determination of the indices of contamination and material dispersion

The potential of tailings polluting the surrounding environment was quantified by calculating the IC using the method known as mean hazard index (Reis et al., 2012). This method assists with evaluating multiple metal contamination of soils (Chon, Cho, Kim, & Moon, 1996). It involved determining the ratios of the concentration (mg/kg) of the specific metals in tailings to their corresponding maximum allowable limits in soils and dividing them by the member of considered common metals in tailings. The mathematical expression of this process is shown in Equation (1), where \( C_i \) is the concentration of the \( i \)th metal in tailings, \( PL_C \) is the maximum permissible limit of the toxic metal \( C \), and \( N \) is the number of toxic metals ratios considered in the study. The metals considered in this study and their respective maximum permissible limits in soils as reported by...
Department of Environmental Affairs (DEA, 2010) and Kamunda et al. (2016) are shown in Table 1. The fact that remediation of tailings to pollution free level require that the concentration of toxic metals in tailings is reduced to levels close to those recommended in natural soils justified the use of the permissible limits of metals in soils in the method used in this research. These metals were determined in tailings using the Inductively Coupled Plasma Mass Spectroscopy (Agitent 7900 model ICP-MS) instrument.

\[
IC = \frac{1}{N} \sum_{i=1}^{n} \frac{C_i}{P_{LC}} \quad (1)
\]

In order to quantify the possibilities of dispersal of the tailings to the surrounding areas through different forms of erosion, a numerical value called the index of dispersion (ID) of tailings material was determined using Equation (2). This value was determined by scoring of five factors relating to the status of the tailings and their erodibility potential. These factors were: (i) the textural properties of the material \(i_e\), (ii) the nature of waste dump cover \(i_f\), (iii) the efficiency of the design characteristics of the dump in controlling potential pollution of the surrounding environment \(i_d\), (iv) the average distance of the dump from the surface water body \(i_a\), and (v) surface area of land occupied by the tailings dumps \(A\) in hectares. The criteria used to assign weights to these factors is shown in Table 2 was developed based on the situation of abandoned mine tailings dumps in South Africa.

\[
ID = A \times (i_e + i_f + i_d + i_a) \quad (2)
\]

### 2.2 Determination of the index of landscape and visual impact of the dumps

The determination of the index of landscape and visual impact (ILVI) values involved calculation of the factor relating to the exposure of the dumps from the different selected viewpoints (VPs).

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

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Figure 2. A flowchart of the methodology developed and used in this work.
Table 2. Criteria for scoring factors for determination of the index of dispersion of tailings material to the surrounding environs

| Description                                                                 | Weight |
|----------------------------------------------------------------------------|--------|
| **The factor relating to the general configuration and design of the tailing dumps** |        |
| The classification of mine waste dumps                                      | $i_d$  |
| • Heaped fill: waste pile in the form of mound (normally in flat, undulating slopes and slightly inclined) | 1.00   |
| • Side hill fill: waste pile located on the side of a hill.                  | 0.80   |
| • Ridge crest fill: waste pile located on top of a ridge, straddling the crest of the ridge. | 0.60   |
| • Valley fill: waste dump that completely fills the valley (extend upstream to the valley head) | 0.40   |
| • Cross valley fill: waste dumps that crosses the valley but does not fill up the entire upstream portion of the valley (include outlet for controlling floor flows without temporal storage) | 0.20   |
| **The textural properties of the waste material**                           | $i_e$  |
| • Gravel soil (>0.25 mm): 50% or more of course fraction is retained in No.4 sieve | 0.1    |
| • Sandy soil: 50% or more of course fraction passes the No.4 sieve          | 0.5    |
| • Clayey soil: 50% of fine fraction passes 2.0 μm                           | 0.8    |
| • Silt soil: 50% of fine fraction is retained between 0.6 mm and 0.002 mm sieves | 1.0    |
| **The properties of the waste dump cover material**                         | $i_f$  |
| • Both slopes and top surface of the dumps are without any cover            | 1.00   |
| • The top surface is covered by indigenize plant/grass species              | 0.75   |
| • Slopes are covered by indigenize plant/grass species                     | 0.50   |
| • The dump is complete covered by indigenize plant/grass species           | 1.25   |
| **Factor relating to the distance of the dumps from surface water bodies** | $i_a$  |
| • < 100 m                                                                  | 1.0    |
| • 100–300 m                                                                | 0.75   |
| • 300–600 m                                                                | 0.5    |
| • 600–1000 m                                                               | 0.25   |
| **Factor relating to the dump’s area coverage (ha)**                       | $A$    |
| • Dumps occupying a planner area greater than 625 ha                        | 1.00   |
| • Dumps occupying about 25–625 ha planner area                             | 0.80   |
| • Dumps occupying about 5–25 ha planner area                               | 0.60   |
| • Dumps occupying 1–5 ha planner area                                       | 0.40   |
| • Dumps occupying less than 1ha planner area                                | 0.20   |

Georeferenced 5 m resolution orthophotographs covering each abandoned mine site was analyzed in ArcGIS 10.1 Software™ and the VPs were selected in distance zones of 0.5–1.5 km and 1.5–2.5 km away from the tailing dumps. Public areas such as parks, schools, access and main roads in communities around the abandoned mine site were targeted in the selection of VPs. The
area of the dump visible from each VP ($A_{vis}$) and the total area occupied by the dump ($A_{Total}$) were used to calculate the value referred to as an index of exposure (IdE) using Equation (3).

$$\text{IdE} = \frac{A_{vis}}{A_{Total}}$$ (3)

The determined IdE value of the tailing dumps in different VPs was used to calculate the total exposure of the dumps ($\text{IdE}_{Total}$) using Equation (4). In this equation, $\text{IdE}_{av}$ is the average IdE of the dumps in a given viewing distance zone and ($n_i$) is the number of VPs considered in each distance zone.

$$\text{IdE}_{Total} = \sum_{i=1}^{n} \frac{\text{IdE}_{av}}{n_i}$$ (4)

The computed $\text{IdE}_{total}$ was used to multiply the weights of the factor of chromatic contrast ($i_c$), morphology and shape of the dump ($i_r$), and the relationship of the nature of the dump with the surroundings ($i_n$) to determine the ILVI values. This is mathematically demonstrated by Equation (5). This equation was modified from Rodríguez et al. (2011) with the purpose of incorporating the exposure of the dumps in quantifying their impact on the aesthetic appearance of the landscape. The criteria used to assign weights to the factors $i_c$, $i_r$, and $i_n$ was depicted from Rodriguez et al. (2011) and is shown in Table 3.

$$\text{ILVI} = \text{IdE}_{Total} \times (i_c + i_r + i_n)$$ (5)

### 2.3. Determination of rehabilitation priority and rehabilitation requirement

The rehabilitation priority score (RPscore) of abandoned tailings dumps was determined by adding the ILVI to the product of the IC and the ID of tailings. The mathematical representation of this is shown in Equation (6). The sensitivity of the scores of rehabilitation priority to the changing ILVI and IC values was tested by varying these index values. In each case, the ILVI or the IC values were varied, the changes to the RPscore was critically observed. Figure 3(a) shows that when the ILVI was increased by a difference of 4 units, at high material dispersion and contamination potential values, the maximum rehabilitation priority score obtained was $\geq 211$. The maximum rehabilitation priority scores reduced drastically to $\geq 57$ when the IC values were varied by the same 4 units.

On the other hand, when the material dispersion and contamination potential values were kept at lowest possible scores, the variation of ILVI or IC values by 4 units gave rehabilitation priority score that start from the minimum of 1 (i.e. $\geq 1$). When the ILVI values were increased up to 49, the RPscore reached the maximum value of 49. However, when the IC values were increased to 49 (maximum), the RPscore increased to just up to 11 (see Figure 3(b)). The sensitivity analysis demonstrated that high rehabilitation priority scores are mostly influenced by increasing impact of tailings dumps on the appearance of the landscape while low rehabilitation priority scores are influenced by increase in pollution potential scores of tailings dumps. The sensitivity analysis presented an opportunity to understand the range of RPscore attainable in different situations of abandoned tailings and/or tailings dumps.

$$\text{RPscore} = (\text{IC} \times \text{ID}) + \text{ILVI}$$ (6)

Plotting the rehabilitation prioritization score of the tailings dumps on the rehabilitation prioritization curve shown in Figure 4 allowed that a clear sequential view of the priority of rehabilitation of tailings dumps be observed. As a way of quantifying the urgency of rehabilitation of the tailing dumps, the model in Figure 4 allowed the tailings dumps to be classified as requiring (i) low (>10), (ii) moderate (10–100) and (iii) high (>100) rehabilitation attention. This classification of the urgency of rehabilitation requirement was based on the rehabilitation concerns of the dumps as indicated by their respective rehabilitation priority scores. According to this classification, the tailings dumps that do not present any landscape and visual impact or have no potential to
are considered to require low rehabilitation attention. The dumps that have high values for all the three indices are considered to require high rehabilitation attention. The technique developed for identification of the most suitable methods for rehabilitation of tailings dumps is based on potential of the dumps to pollute the environment, their impact on the aesthetic appearance of the landscape, and the potential of tailings material to be dispersed to the surrounding environment. Based on the numerical values determined for quantifying the significance of these factors, a triangle for identifying a suitable combination of strategies for rehabilitation of tailings dumps was developed and this is shown in Figure 5. The main objective of the rehabilitation of abandoned tailings dumps using the approaches indicated in the triangle is to create a safe, stable and pollution-free landform that blends very well with the surrounding natural landscape. An important consideration for ensuring that rehabilitation of the abandoned tailings dumps meets these requirements/criteria was to make use of a combination of physical, biological and/or chemical rehabilitation techniques.

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Figure 5 illustrates the triangle for determining the most appropriate rehabilitation options for tailings dumps. This triangle has been divided into zones that represent different rehabilitation strategies. In order to determine the most suitable rehabilitation strategy or a combination of strategies for a particular tailing dump, IC and ILVI values are used. A line is drawn joining the IC and the ILVI values of the dump. The ID value of the dump is determined on the ID axis and a vertical line is drawn from this point to intersect the line joining IC and ILVI. The point of intersection of these two lines determines the zone of rehabilitation strategies for the tailings dump. This allows that

### Table 3. The criteria for scoring of the factors for landscape and visual impact analysis on the tailings dump (Rodríguez et al., 2011)

| Description | Weight |
|-------------|--------|
| Impact factor by chromatic contrast | |
| Appearance | |
| ● Visual similarity (no significant difference from over 1 km) | 0–1 |
| ● Significant chromatic contrast (yellow-brown, gray-black) | 3–6 |
| ● Clear differences of colour: natural colours | 6–8 |
| ● Clear differences of colour: artificial colours | 8–10 |
| Impact factor on the morphology or shape of the physical environment | |
| Deposit shape | |
| ● Shape of the deposit filling into the natural morphology | 0–1 |
| ● Divergence only in shape, but not in volume | 2–4 |
| ● Divergence in volume and shape | 4–10 |
| Impact factor related to the nature of the deposit and its relationship to the surroundings | |
| ● Nature of the deposit | |
| ● Mining waste like the natural surface materials | 0–1 |
| ● Mining waste different from the natural surface materials | 1–4 |
| Waste dumps located in arid zones | |
| ● With natural colours | 1–2 |
| ● With unnatural (anomalous) colours | 3–5 |
| Waste dumps located in humid zones | |
| ● With natural colours | 0–1 |
| ● With artificial colours | 2–3 |
tailings dumps with IC and ILVI values that are greater than 100 are plotted in Zone-I of the triangle while those with IC and ILVI values that are between 10 and 100 are plotted in Zone-II. The dumps with IC and ILVI values that are less than 10 and the ID values that are greater than 2.2 and less than 2.2 are respectively plotted in Zone-III and IV (see Figure 5). The description of the abandoned tailings dumps rehabilitation approaches in the different Zones of the triangle is provided in Table 4.

3. Results

3.1. Contamination potential of tailings dumps

The concentration of toxic metals in the tailings was determined using the Inductively Coupled Plasma Mass Spectroscopy instrument. Results of the analysis showed that the concentration (mg/kg) of toxic metals such as Cu (22.6–1548.2), Cr (159.5–1088.6) and (22.6–1548.2) in all the tailings dumps were above the maximum permissible limits values. However, the concentration of Co (6.0–87.0) and Hg (0.0–0.4) in all tailings dumps was below the permissible limit in soils. The concentration of arsenic (As) was high in gold tailings dumps and were in the order of FGMT > KLMT > LMMT. However, the concentration of arsenic in the copper and magnesite tailings was below the limit. The concentration...
of Ni and Pb in the tailings material from Fumani and Louis Moore Mines was above the permissible limit while the concentration of Ni was also high in magnesite tailings (see Figure 6(a)). Based on the results of the IC, it can be concluded that the tailings dumps in the study area are contaminated by toxic metals. The lowest IC value of 1.2 was obtained in magnesite tailings while the highest (19.2) was found in gold tailings of Fumani Mine. The tailings from Musina, Louis Moore and Klein Letaba Mines had IC values of 4.1, 2.3 and 2.0, respectively (see Figure 6(b)). According to Chon et al. (1996), the IC value that is greater than 1 indicate that the material is contaminated by multiple toxic metals. Thus, the high IC values for copper and gold tailings indicated that these dumps are highly contaminated by metals from anthropogenic and/or geologic activities (Nimick & Moore, 1991; Reis et al., 2012). The greater the IC value, the higher is the potential of such material to pollute the environment. According to Arranz-Gonzalez et al. (2016), such variation in IC values of tailings material can form the initial basis for ranking of the rehabilitation of the tailing dumps.

3.2 Possibilities of dispersion of tailings to the surroundings

The impacts of tailings on the environment as well as the health of people and animals depends on their erodibility and subsequent dispersion by erosive forces to the surroundings environment which include surface water bodies. In order to determine the erodibility or/and dispersity of the tailings material, the ID was used to rank the significance of this factor for the various tailings dumps.
The results showed that the copper tailings had the highest ID value (3.00) and potential of being dispersed to the surrounding areas. During the field assessment of the dumps, the slopes of the magnesite tailings dumps were found to be extremely eroded compared to gold tailings dumps of the Giyani Greenstone Belt. The effect of erosion on the slopes of copper and magnesite tailings are shown in Figure 7. Although these dumps were found to have been seriously affected by water erosion as evidenced by V-shape erosion gullies developed on their slopes, magnesite tailings had the lowest ID value of 1.2 (see Table 5). This may be explained by the fact that magnesite tailings dumps occupied relatively smaller surface areas and were generally at a distance greater than 1 km away from the nearby surface water bodies. On the other hand, the surfaces of the gold tailings dumps appeared to be relatively stable, they also covered almost equal areas in locations that are at the distance less than 300 m from surface water bodies.

Although the slopes of gold of tailings dumps were without cover, they were less affected by erosion except some areas of the slopes of Klein Letaba and Louis Moore tailings dumps, which were observed to have footprint of piping erosion. It was found that the predominant type of erosion at each of the tailings dumps is influenced by textural or physical properties of the tailings. For example, piping erosion is known to develop in soils of uniform fine sands that are cohesionless; while gullies are developed in soils with particles that are easily detachable. According to the established textural properties of tailings material in the study area, the tailings are dominantly comprised of sand particles with a very small portion of fines. The differences in textural properties of the tailings material was also confirmed by small variations in the alignment of gradational curves of tailings material shown in Figure 8.

According to the Unified Solid Classification System (USCS), the gold tailings from Klein Letaba and Louis Moore Mines as well as copper tailings from Mesina Mine can be classified as poorly graded fine sands (PW); while magnesite and gold tailings from Fumani Mine were classified as....

| Zone | Combination of techniques | Description of the rehabilitation requirement |
|------|---------------------------|-----------------------------------------------|
| I    | P + (*B = C)              | • Require creation of stable landscape with reduced erosion and improved soil physico-chemical quality for easy growth of vegetation. There is a need for removal and mobilization of toxic metals using equal efforts of biological and chemical methods. |
| II   | P + B                     | • Require physical stabilization and removal of toxic metals using biological methods, such as Microbes, Phytoextraction and Phytostabilization. Little chemical methods may be employed. |
| III  | P + C                     | • Require physical stabilization and using chemical methods to enhancement nutrient availability in tailings to promote easy growth of vegetation. Little chemical methods can be used. |
| IV   | C + P                     | • The dumps require chemical improvement of the soil quality to promote vegetation growth followed by minor physical stability of the slopes of the dumps. |

*P, B and C represent the physical, biological and chemical methods of rehabilitation of mine tailings dumps respectively. *B = C: Equal efforts of biological and chemical methods to be applied.
well-graded sands (SW) (see Table 6). This classification supports the development of gully and piping types of erosion on these tailings dumps. According to Masannat (1980), piping erosion is common in poorly graded (well-sorted) silty sands with very low percentage of clay and this matched the characteristics of the copper tailings and the gold tailings from Louis Moore and Klein Letaba Mines.

Figure 6. (a) Comparison of the average concentration of toxic metals in tailings with the maximum permissible limit in soils and (b) the index of contamination of abandoned tailings dumps.
### Table 5. Results of the estimated index of dispersion of the tailing dumps

| Type of tailings | Dump    | Area of the dump (ha) | Scoring of the waste factors | Index of Dispersion (I) |
|------------------|---------|-----------------------|------------------------------|-------------------------|
| Gold             | KLMT    | 6.2                   | \( A \) | \( i_d \) | \( i_f \) | \( i_e \) | \( i_o \) |                         |
|                  |         |                       | 0.60 | 1.00 | 1.00 | 0.50 | 0.75 | 1.95 |
|                  | LMMT    | 5.5                   | \*       | \* | \* | \* | \* | 1.80 |
|                  | FGMT    | 6.8                   | \*       | \* | \* | \* | \* | 1.95 |
| Copper           | MCMT    | 87.8                  | \*       | \* | \* | \* | \* | 3.00 |
| Magnesite        | NMMT(a) | 2.9                   | \*       | \* | \* | \* | \* | 1.10 |
|                  | NMMT(b) | 2.6                   | \*       | \* | \* | \* | \* | 1.10 |
3.3. Landscape and visual impacts of tailings dumps

In general, the tailings dumps in the study area alter the natural landscape by creating artificial hills of contrasting colours with the surroundings. The chromatic contrast of the colour of tailings dumps and the surrounding landscape or soils is often negatively perceived by people who live outside the abandoned mines host town. Based on such unpleasant appearance of the landscape, rehabilitation of the tailings dumps to blend with the surrounding landscape is of absolute necessity. The evaluation of the landscape and visual impacts of tailings dumps in this study considered their exposure to viewers on critical areas in the nearby communities.

Based on this method, Klein Letaba and Louis Moore mine tailings dumps were well-exposed or visible in four VPs while magnesite tailings dumps were visible in three VPs within the Zwigodini Village. Gold tailings dump of Fumani Mine was visible in two points located within the Village Mutititi and the copper tailings dump in one point. The tailings dump of Klein Letaba, Louis Moore and Fumani mines were all clearly visible in VPs KL-VP-02, LM-VP-02 and FM-VP-02, respectively. The copper tailings dump of Mesina Mine could be clearly seen in VP MT-VP-01. On the other hand, magnesite tailings dump A at Nyala Mine was very visible in point NM-VP-03 while dump B was visible in all the three points. The results of the visibility of the dumps in different VPs are shown in Figure 9.

The tailing dumps that appeared as elevated points in the surrounding topography and those that appeared with brighter or different colours compared to the surroundings had higher contrast with the surrounding areas (see Figures 10(b–e)). In view of this, the chromatic contrast of these dumps was assigned relatively high scores ranging from 7 to 9 as depicted in Table 7. However, the grayish colour of copper tailings dump in Mesina Mine and that it had the height and slopes that fits the surrounding topography and that there are few trees growing on this dump made it to contrast relatively less with the surrounding landscape (see Figure 10(f)).

The estimated index of total exposure (\(\text{IdE}_{\text{Total}}\)) of the dumps showed that the tailings dump of Louis Moore Mine was the most exposed dump to the public followed by the tailings dump of Klein Letaba and Nyala Mines (see Table 7). The fact that copper tailings dump was found not visible in most busy sections of Musina Town and its surroundings resulted to it having the least \(\text{IdE}_{\text{Total}}\) score. The visibility of Klein Letaba, Louis Moore and Fumani tailings dumps was boosted by that they are in low laying areas than the VPs which the dumps could be seen. However, larger parts of the slopes of these dumps were somehow obscured by woody trees of the surrounding landscape. As a result, they were mostly visible from the top. The terrain around Nyala Mine is characterized

![Gradational curves of the copper, gold and magnesite tailings](image)
Table 6. Textural characteristics of gold, copper and magnesite tailings

| Type of tailings | Dump  | %Clay (<0.002mm) | %Silt (0.075–0.002mm) | % Sand | % Fine gravel (>2 mm) | C_v | C_z | Classification (USCS) |
|------------------|-------|------------------|-----------------------|--------|-----------------------|-----|-----|----------------------|
| Copper           | MCMT  | –                | –                     |        | 51.0                  | 43.0| 06.0| 2.7                  | 0.7 | PW                   |
| Gold             | FGMT  | –                | –                     |        | 10.1                  | 18.9| 64.0| 07.0                 | 14.3| 1.8                  | SW |
|                  | LMMT  | –                | –                     |        | 13.0                  | 78.0| 09.0| 4.3                  | 1.0 | PW                   |
|                  | KLMT  | –                | –                     |        | 20.0                  | 71.0| 09.0| 3.6                  | 0.7 | PW                   |
| Magnesite        | NMMT  | –                | –                     |        | 03.0                  | 16.0| 51.0| 40.0                 | 11.0| 1.1                  | SW |

PW is the poorly graded soil, SW is well-graded soils.
by flat topography and is dominated by shrubs and few trees and this has been the cause of the slopes of magnesite tailings dumps being so well exposed. However, magnesite tailings dump A had the highest index on landscape and visual impact (ILVI). Consequently, the work of rehabilitation of the tailings dumps should as well aim at improving the aesthetic appearance of the landscape and should be done in the order of NMMT (a) > KLMT > NMMT (b) > FGMT > LMMT > MCMT as shown in Figure 11.

3.4. Prioritization of rehabilitation of tailings dumps

Based on the index values describing the pollution potential of tailings dumps, their potential of getting dispersed to the environment and the impact of the dumps on the appearance of the landscape, the scores that define the priority of rehabilitation of tailings dumps were determined. In general, the results demonstrated that the tailings dumps selected as case studies were classified to be requiring moderate rehabilitation efforts or attention (see Figure 12). However,
Table 7. The total index of exposure of tailings dumps

| Type of tailings | Dump   | $i_c$ | $i_r$ | $i_n$ | $(i_c+i_r+i_n)$ | View distance zone | $i_{D_{Total}}$ |
|------------------|--------|-------|-------|-------|-----------------|-------------------|----------------|----------------|
| Gold             | KLMT   | 8     | 10    | 5     | 23              | A (0.5–1.5 km)     | B (1.5–2.5 km) | 1.1            |
|                  | LMMT   | 7     | 3     | 3     | 13              | 0.4               | 0.7            | 1.2            |
|                  | FGMT   | 8     | 10    | 5     | 23              | 0.1               | 0.7            | 0.7            |
| Copper           | MCMT   | 8     | 7     | 5     | 20              | 0.0               | 0.0            | 0.0            |
| Magnesite        | NMMT(a)| 9     | 10    | 5     | 24              | 0.7               | 0.4            | 1.1            |
|                  | NMMT(b)| 9     | 10    | 5     | 24              | 0.0               | 0.9            | 0.9            |
they also showed that the rehabilitation of tailings dumps should begin with gold tailings of Fumani Mine. This dump had the highest rehabilitation priority score of 53.9 in the study area (see Figure 12). This dump was found with relatively high IC value (19.2) that makes it to have a relatively high potential to pollute the environment in the study area.

Although the tailings dump of Klein Letaba Mine was ranked second for rehabilitation, its potential to be dispersed to the surrounding areas was found to be almost equal to that of Fumani mine tailings but it had a relatively low IC value. This reduced its rehabilitation priority score (RP score) by almost half from that of Fumani Mine tailings. Magnesite tailings dumps had slightly low rehabilitation priority scores and that placed them at the third and fourth place in the priority list. The slight differences in rehabilitation priority scores of magnesite tailings dump A and B was observed to be mainly influenced by their differences in ILVI values which were 25.8 and 2.6, respectively. The copper tailings covered the largest area (=87.8 ha) of all the studied dumps; however, its visibility to the public and the alteration to the landscape it causes led to it having the...
lowest ILVI score of 1.1. This contributed to this tailings dump having lowest rehabilitation priority score that put it at the bottom of the rehabilitation prioritization list (see Figure 12).

3.5. Rehabilitation options of tailings dumps
Plotting the IC, ID and ILVI values on the triangle developed for identifying preferred rehabilitation options for abandoned tailings dumps placed the tailings dumps in the study area in three zones, viz.; Zone-II, III and IV (see Figure 13). The less polluting gold tailings dumps (i.e. KLMT and LMMT) and magnesite tailings dumps (NMMT) were located in Zone-IV. This implies that the rehabilitation of these dumps should be considered relatively less urgent and that slightly less effort should be expended in rehabilitating them. Based on the results of this study, it is recommended that rehabilitation of these dumps should be carried out using chemical methods that promote vegetation growth in combination with minimum application of physical stabilization of the dumps.

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

The gold tailings from Fumani Mine had the highest pollution potential and impact on the appearance of the landscape. In view of this, it was found to be in Zone-II of the triangle (see Figure 13). The rehabilitation of this dump will require use of combination of physical and biological methods. In this case, physical methods are to be employed in stabilizing the dump to prevent them from contaminating the surrounding areas while biological methods are to be used to reduce the level of toxic or heavy metals in the tailings.

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

4. Discussion
Rehabilitation of abandoned tailings dumps is generally costly and requires to be done with utmost precision to ensure that the problems presented by dumps are fully addressed. In view of this, characterization of tailings dumps to determine the nature and severity of their problems and concerns is very important for their effective rehabilitation. In light of this, most countries with many abandoned mines have developed and applied different tools in compiling inventories of abandoned mines and coming up with suitable means of rehabilitating them (Mhlongo et al., 2018). Most of these tools or systems are developed based on existing information about the general characteristics of abandoned mines in those countries or regions. Some of these tools were developed to make them easy to use, inclusive and updatable. The method developed for prioritization of rehabilitation of abandoned mines in Manitoba Province of Canada is a perfect example of these efforts (Priscu, Armitt, & Priscu, 2010). However, the fact that these tools are developed based on site specific understanding of abandoned mines makes their application outside the context they were developed limited. The key factors contributing to the limited application of these tools or methods were identified and discussed by Kubit, Pluhar, and De Graff (2015). Such factors include that these tools lack model calibration and transparency, some important parameters and reclamation methods are not taken into account, and that they are mostly data demanding and time consuming.

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

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

One of the essential and unique features of the rehabilitation prioritization tool developed in this study is the aspect of the technique for identifying the most preferred rehabilitation strategy or a combination of rehabilitation options. This was identified by Kubit et al. (2015) as one of the most important elements of a sound mine site rehabilitation plan but a deficiency in most of the existing ranking systems. The guidance provided by the tool on rehabilitation strategies take into consideration the fact that there is no single panacea for addressing the problems of abandoned mine tailings dumps. In this regard, this important element of the rehabilitation prioritization tool provides guidance that the rehabilitation of tailings dumps combine use of physical or engineering methods with some element or aspect of chemical and/or biological methods. These methods include but not limited to those presented in Table 8. The combination of rehabilitation methods recommended by the developed system is in line with the current trends in remediation of soils contaminated by mining. For example, depending on the level of contamination of soils, the chemical methods have been mostly applied in conjunction with biological methods (Ozkan & Ipekoglu, 2002; Festin et al., 2018; Hamner, Ringe, Pelkki, Graves, & Sweigard, 1999).

5. Conclusion
Musina and Giyani have historically been well recognized for their mineral resources. Most of the mines in these two areas are abandoned or/and inactive. The legacy of this development is tailings dumps that are aesthetically unpleasant and have potential of causing disturbance to the environment and adverse effect on human and animal health. The tailings dumps in the Giyani and Musina areas are generally unrehabilitated and without any cover or protection. As a consequence of these, all the tailings dumps in the study area were found to have experienced different intensities and processes of erosion. Moreover, they were found contaminated by different concentration of toxic metals which include Cd, As, Cr, Ni, Pb, Zn and Cu. The IC of these dumps were determined and the high values obtained show that the dumps have potential to pollute the environment. The order of contamination of these dumps were as follows: Fumani Gold Mine Tailings > Mesina Copper Mine Tailings > Louis Moore Gold Mine Tailings > Klein Letaba Gold Mine Tailings > Nyala Magnesite Mine Tailings.

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

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

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