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Evaluating the post-mining land uses of former mine sites for sustainable purposes in South Africa

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Keywords

mine closure, abandoned mines, terrain modeling, PMLU, AHP, SWOT analysis

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This paper uses a case study of an abandoned magnesite mine in the Limpopo Province of South Africa to find ways of identifying post-mining land used from the current uses of the abandoned mine sites or features. The approach used involved carrying out a field characterization of the mine site and documentation of the current uses of the features of the abandoned mine site. The technique used to identify the internal and external factors of the land uses involved analyzing their Strength, Weakness, Opportunities, and Threats. The Analytic Hierarchy Process (AHP) technique was used for further ranking of the land uses to identify the most post-mining or rehabilitation land uses for the different parts of the mine. Lastly, the earthwork requirement in reshaping the terrain of the mine to support the selected land uses was estimated from the 3D-terrain models generated from height data collected using a Real-Time Kinematic Geographical Positioning System. The results of the study identified land use that needs further surface development as the most appropriate for the abandoned Nyala Mine. These land uses demonstrated the potential of addressing the hazards of the mine with the clear promise of improving the socio-economic status of the host communities.

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1. Introduction

Mining is the process of extracting valuable minerals or other geological materials from the earth's crust. It is by nature a temporal use of land, and it contributes significantly to the economic development of the regions where it is practised. The mining industry of South Africa is one of the oldest and has been, for many years, the major contributor to the gross domestic product (GDP) and creation of employment in the country [1,2]. It has also contributed to the development of infrastructure impotent for the economic growth of the mining regions and the country. However, it should be noted that mining also comes with a fair share of environmental problems, socio-economic concerns, and other hazards. Some of the common environmental problems of mining are alteration of the landscape, pollution of the environment, and destruction of habitats for living organisms. The socio-economic issues associated with the mining sector include the disruption of social values and an increase in drug and alcohol abuse that somehow results in an increase in crime and prostitution that leads to the spread of HIV/AIDS in the mining communities [3]. In different stages of mining projects, companies address these negative impacts of mining by implementing various strategies, plans, and programs [4].

The mines prevent the continuation of these problems beyond the production stage of the operation by implementing closure and rehabilitation. The closure stage is a transition to post-mining uses of the land affected by mining. Its main aim is to ensure that the area disturbed by mining is returned to an acceptable post-mining state and that all the risks of the site are removed. Although the transition stage is known as mine closure and rehabilitation, it is implemented in four different approaches: rehabilitation, reclamation, restoration, repurposing, and co-purposing [5]. Rehabilitation is generally about returning the land affected by mining to a utility or natural state as per the original land development plan, while reclamation involves giving the degraded land a useable value [6]. The term repurposing refers to the process of finding the beneficial reuse of a closed mining operation through value-added changes or by

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reusing the site [5]. The process is known as co-purposing when beneficial activities are developed while mining is ongoing [7]. The process of returning an affected landscape to its pre-mining state, use, and condition is called restoration. It involves creating an original topography and re-establishment of previous land capability, together with groundwater patterns and faunal or floral assemblages [8].

The planning of mine closure and rehabilitation involves making critical decisions about the goals and objectives of the closure process, the selection of appropriate post-mining land uses, and strategies for rehabilitating the site to meet the desired post-mining land uses. Out of all these decisions, many authors, including Fogarty et al. [9] and Rosa et al. [10], stated that deciding on the post-mining land uses is by far the most important decision in the planning of mine closure and rehabilitation. This decision is made after careful consideration of many important factors [11]. It is important to indicate that these important decisions in mine closure and rehabilitation are made differently in operating mines than in abandoned mines. This is because, in some countries, the mining regulations force the mining companies to think about closure and develop a closure plan as early as during the planning stage of the mine [12]. For example, in South Africa, mining companies are expected to develop the Rehabilitation, Decommissioning, and Mine Closure Plan that is submitted as part of the application for the mining license or right. This plan is checked and updated annually to ensure that the planned objectives remain in line with sustainable principles.

In the case of abandoned mines, the rehabilitation process mostly focuses on removing the site's hazards. Other issues, such as ensuring sustainable post-mining land use and enabling alternative livelihoods for the local people, are often ignored. This is partly because abandoned mines are normally rehabilitated by the government, which is obliged to protect the public from the different forms of hazards [12]. Moreover, the government rehabilitates these mines with the taxpayer's money which turn to make the budget not to carry out the rehabilitation not enough. For example, in South Africa, the rehabilitation of abandoned is mainly focused on addressing the health and safety hazards and then their environmental impacts [13]. The work presented in this paper aims to identify appropriate post-mining land uses (PMLUs) for abandoned mine sites based on the present uses of the sites. This approach to finding appropriate uses for abandoned and historic mining sites is an important contribution to the rehabilitation of abandoned mines worldwide. Its adoption will help ensure that the rehabilitation of the abandoned mines takes into consideration the PMLUs that can be implemented to address the socio-economic concerns of these mines.

1.1. The description of the case study

The case study used in this work is an abandoned magnesite mine (Nyala Mine) found in the Village of Zwigodini in the northeastern part of the Vhembe District Municipality, Limpopo Province of South Africa (see Fig. 1). It is at the coordinates of 22°31′48″S and 30°37′40″E. The mine is on the flat topographic relief underlined by the rocks of the Limpopo Mobile Belt (LMB) and along the Tshipise Straightening Zone (TSZ) of the southern periphery of the Central Zone of the LMB. According to Chavagnac et al. [14], the TSZ is characterized by highly deformed orthogneisses, calcsilicates, metapelites, metagreywackes, and pegmatites with some occurrences of quartzites and ultramafic gneisses. The magnesite deposit in the area is amorphous in nature and is hosted by metamorphosed ultrabasic and calcareous rocks [15,16]. It was formed as the result of in-situ weathering of olivine dolerite sills [17]. According to Strydom [16], the magnesite deposit at Nyala Mine occupied an estimated area of 1060 by 200 m and attains a maximum depth of about 23 m. Around 1965, the mining of this deposit at Nyala Mine reached a depth of 21 m. The deposit was estimated to be approximately 270,000 tons and contain 12% magnesite [16,17].

The mining of magnesite at Nyala and other sites in the region used heavy equipment such as tractor-loader-backhoes (TLBs). The exposed magnesite veins are then gathered into piles by collectors [18]. The excavation of magnesite was haphazardly done. The excavation followed the magnesite veins of economic significance. Once such veins can no longer be traced, the pit was then abandoned, and the excavation of the new pit was initiated. This mining approach resulted in the Nyala Mine topography having numerous mining excavations (denoted as Pit-I to Pit-V in Fig. 1) and heaps of mine waste (i.e., spoils and tailings) found in all parts of the mine. The problems of this mine are worsened by the fact that the operations are known to have been abandoned in 1975 without any rehabilitation of the land. In recent years, magnesite tailings have been used by local people for different applications. The water in abandoned excavations is used as drinking water for livestock and washing clothes, casual swimming, and fishing purposes [19].

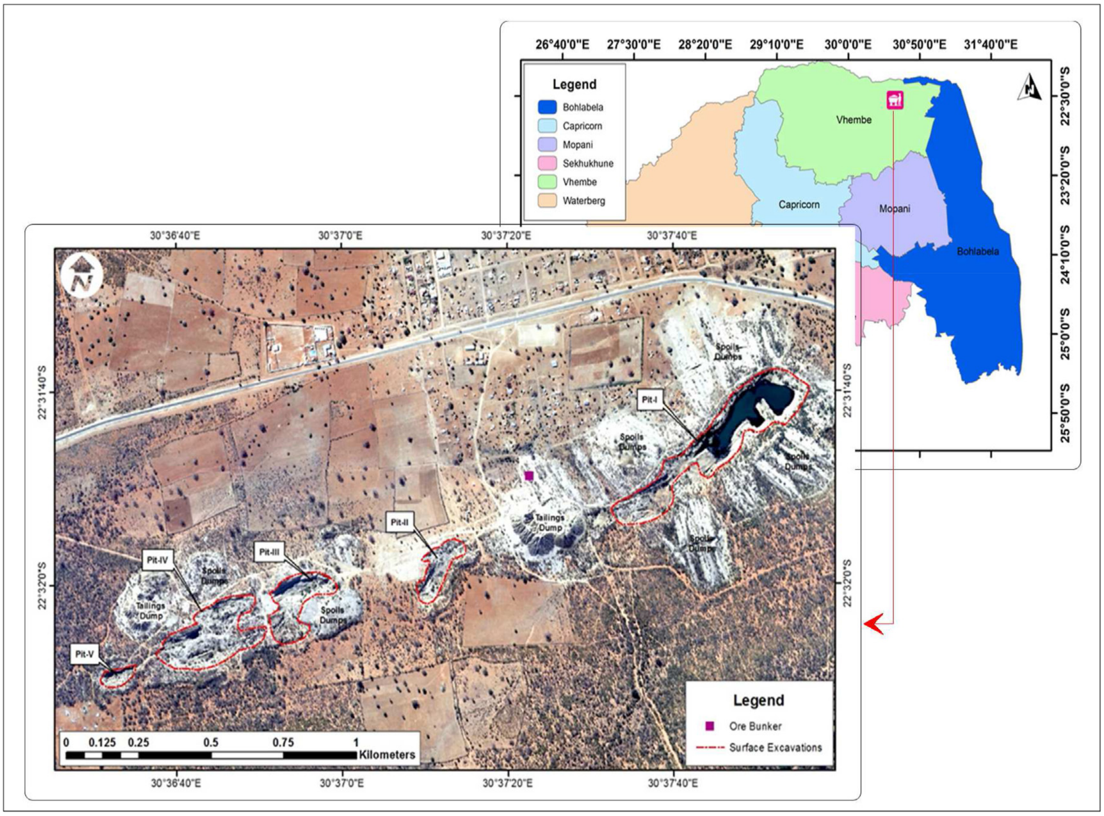


Fig. 1. The location of the abandoned magnesite mine (Nyala Mine) and the distribution of its features in the landscape.

2. Materials and methods

The process of finding the most appropriate post-mining land use (PMLU) for the abandoned magnesite mine began with carrying out the field characterization of the site. The focus of this was to locate the different features of the mine, describe their potential physical and environmental hazards, and, most importantly, document the current uses of the site or its features. The SWOT analysis of the current uses of the mine site or features was performed to find the bases for scores to rank their attractiveness. The documented current uses of the mine site and features, as well as the potential rehabilitation efforts that can be implemented to deal with the problems of the abandoned mine, are described in Table 1. The analyzed PMLU options were then ranked using an Analytic Hierarchy Process (AHP). This was followed by the development of terrain models to quantify the cut and fill areas and volumes in creating an acceptable topography for the identified PMLU options. The summarized procedure of the methodology of this work is shown in Fig. 2.

2.1. The application of SWOT analyses

The SWOT analysis is a powerful technique commonly used for managing strategic processes in different fields. In mining, it has been used extensively for different purposes, including environmental analysis [20]. Its primary application in this work was to examine the strengths (S), weaknesses (W), opportunities (O), and threats (T) of PMLU options applicable in different potions on the abandoned Nyala Mine landscape. The five segments of the mine topography in which the PMLU options were evaluated are in Fig. 3. The main aim behind the use of SWOT and AHP methods in this work was.

- To find the PMLU option that has the potential to address the physical hazards and environmental problems of the abandoned mine site and its features in a way that helps improve the socio-economic status of the host communities.

Given this, the identification of the SWOT statement and the scoring of the PMLU over each other in the AHP method was guided by the above-stated aim of the rehabilitation of the abandoned mine sites.

2.2. Application of the AHP

The Analytic Hierarchy Process is a popular multi-criteria decision-making (MCDM) technique developed by Thomas L. Saaty in 1980. The method

Table 1. The description of the current uses of the abandoned mine site.

No.	Land use	Symbol	Description
1.	Backfilling	BF	• Involves filling up of the surface excavations using spoils and tailings. This is a traditional approach to the rehabilitation of land affected by surface mining.
2.	Crop farming	CF	• Involves using the rehabilitated land for crop farming. This is the option that can better match the surrounding land uses in the area.
3.	Pit lake development	PLD	• It is about converting the abandoned mine pit into a pit lake with end uses that can contribute to the socio-economic development of the communities.
4.	Use of tailings in construction	RPS	• This involves reusing the magnesite tailings as a replacement for sand in the construction industry. The material is currently being used by the local people for some of these purposes.
5.	No action	NA	• Involves doing nothing to improve the safety status of the abandoned mine site.
6.	Development of the site for settlement	RD	• It is about grading the mine topography to make it suitable for the development of residential sites. The local settlement area is already encroaching into the mine lease area.
7.	Development of the site for recreational	RCD	• This is about developing the portion of the mine terrain with haphazardly dumped spoils for appropriate recreational activity such as BMX dirty park.
8.	Using the site for livestock grazing	AG	• Involves using the less disturbing part of the mine site for animal/livestock grazing purposes.
9.	Use of the pit as a landfill site for inert waste	LFS	• It is about repurposing the mine pits for use as a solid waste landfill site. There is no solid waste dumping site in the nearby community, and the practices of uncontrolled waste dumping around the mine sites were witnessed.
10.	Use the tailing material in road construction	RRC	• This involves using the material as a replacement for gravel in road construction.
11.	Management of the tailing dumps	MTD	• It is about managing the tailings to control their effect on the surrounding areas.

is mostly used for complex decisions. In this work, the AHP was used to rank the PMLU options to identify the most attractive options for the different parts of the mine. Based on the results of the SWOT analysis of the PMLU options and the studied conditions of the site, the numerical score (ranging from 1 to 9) described in Table 2 were assigned through the pair-wise comparison matrix (A) to demonstrate the importance of one option over the other (C_i over C_j). In the matrix, the appropriate numerical score was assigned to the preferred option, while the alternative was assigned a reciprocal value ($a_{ji} = 1/a_{ij}$), where i and j correspond to the row and column of the matrix elements, the PMLU.

In general, the matrix was developed to be reciprocal and transitive. The reciprocal matrix represents consistent judgments, while the transitive matrix is developed to certify the rule that if the judgment detects that A is more important than B and B is more important than C, then A is more important than C [21,22]. From the developed matrix, the eigenvectors were calculated in a way that certifies the rule: $AE_{ij} = \lambda_{\max}E_{ij}$ and $\lambda_{\max} \geq n$, where E_{ij} is the eigenvector of the matrix that corresponds to the maximum eigenvector ($\lambda_{\max}$).

The eigenvector was taken as the measure of the significance preferences of the PMLU options. It is calculated by applying the product of the entries of every raw in the matrix to the nth root, which is basically the number of PMLU options considered in each area of the abandoned mine site. The determined eigenvector was normalized by dividing each entry of the matrix by the sum of the eigenvector values in the column of the matrix. This

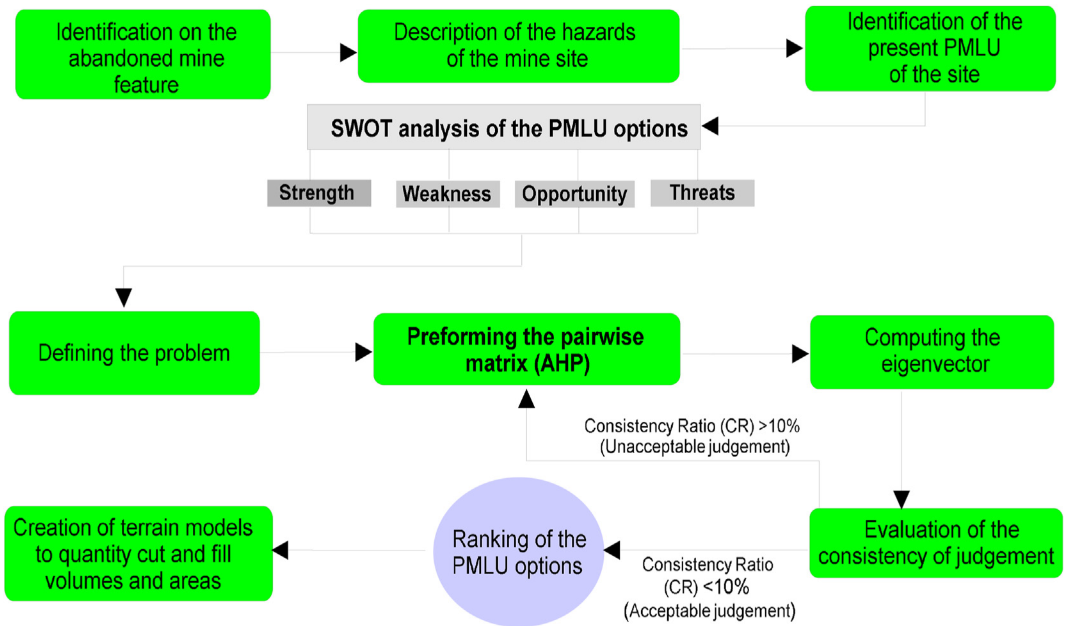


Fig. 2. Flowchart of SWOT and AHP-based post-mining land use evaluation methodology.

brought the sum of the elements of each column vector to 1. The number of the PMLU options considered in each area of the mine was divided by the sum of the normalized eigenvector (EN_{ij}) to determine the normalized principal eigenvector (W_{ij}). The weight used to rank the PMLU options was then based on such a normalized principal eigenvector of the decision matrix.

Since the decision matrix is developed from human judgments, inconsistencies in judgment are likely to occur. The AHP has the advantage of allowing the degree of such inconsistency to be measured by calculating the Consistency Ratio (CR) using *Equation (1)*.

$$CR = \frac{CI(n)}{RI(n)} \quad (1)$$

CI is the measure of the degree of departure from the consistency determined by *Equation (2)*. The RI value is an average index of the randomly generated weights.

$$CI(n) = \frac{\lambda_{\max} - 1}{n - 1} \quad (2)$$

From equation (2), $\lambda_{\max}$ is the largest calculated eigenvector, and n is the number of factors being evaluated. In this method, the results of the comparison of PMLU options against each other will be considered acceptable when the obtained CR values satisfy the rule $CR \leq 0.1$ or $CR \leq 10\%$. The CR values obtained from the comparison of the PMLU options are in Fig. 4. In all the comparisons made, the obtained CR (%) values were within the acceptable level of consistency.

2.3. Development of terrain models and calculation of cut and fill volumes

The determination of the amount of earthwork required in the rehabilitation of the abandoned Nyala Mine terrain was necessary. This was carried out by determining the cut-and-fill areas and volumes in rehabilitating the mine topography. The height data required in treating the 3D terrain modules, on which the areas of cut-and-fill are determined, was collected using the Hi-Target V9 GNSS RTK GPS system shown in Fig. 5a. A total of 15,550 points were marked at every 1–3 m vertical internals along the 15 m spaced traverse lines in the study area. The base of the GPS was set at an elevation musk of 15° while the rover was set at 10°. The system was put at the WGS-84 coordinate system. The collected points ranged from a minimum of 460 to a maximum of 523 m (i.e., above the Main Sea Level, MSL), as shown in Fig. 5b. The original elevation was found to be between 486 and 500 m above MSL.

The collected height data was processed, and the 3D models of the mine topography were produced using the Surfer®11 software. The cut and fill areas were defined by superimposing design terrain models on the models showing the present topography of the mine. The volumes of the excavations and the volumes of areas to be filled were calculated

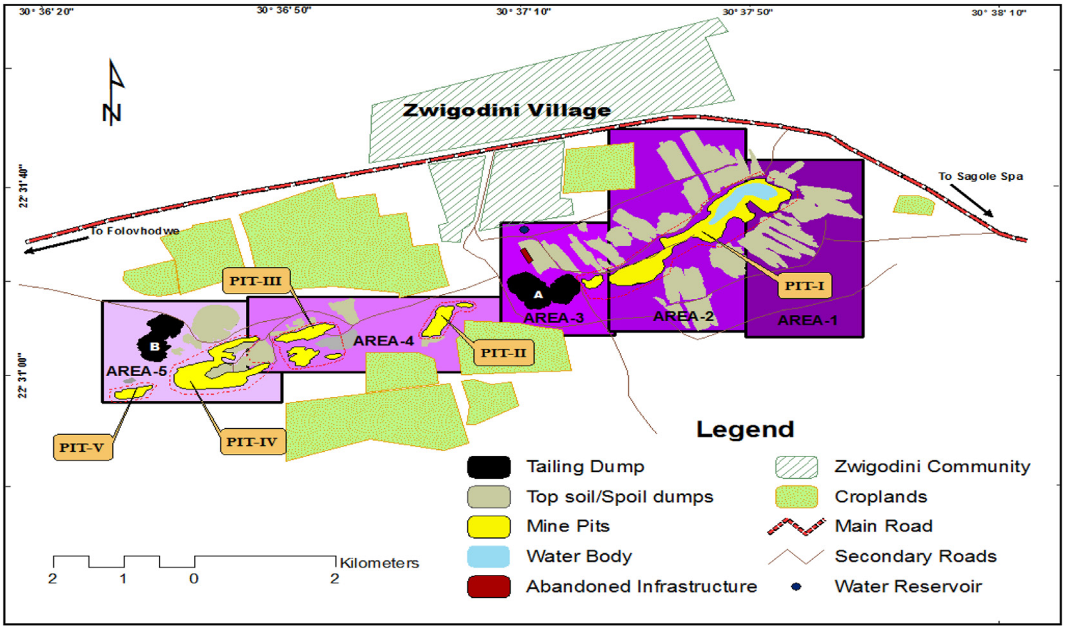


Fig. 3. The areas of the mine that was demarcated for the evaluation of PMLU options and modeling of the mine topography.

in the Surfer Software using three methods, *viz.*, the extended trapezoidal, extended Simpson's, and Simpson's 3/8 [23].

3. Results

The SWOT analysis was used to identify the positive and negative aspects of the potential PMLU options in different parts of the mine lease area. The results of the SWOT analysis shed some light on the important issues of the potential PMLU options that need to be taken into consideration during the rehabilitation process. For example, the weaknesses and threats of the PMLU options helped to understand the amount of work required to close and rehabilitate the mine to support the attractive PMLU option. On the other hand, the strength and opportunities of the PMLU options were the main issues that supported the attractiveness of the evaluated options. Because of this, the comparison of the options in the pairwise matrix of the AHP took into consideration both the positive and negative aspects of the PMLU options evaluated for their attractiveness in the study. The listed SWOT statements for each considered PMLU option in the five demarcated areas of the mine topography are in Appendix-A with the motivation for their consideration.

Table 2. Definition of the scale of relative importance.

Scale	Degree of preference
1	A value is equally important to the other option
3	Moderate important than the other option
5	Strong or essential importance value
7	Very strong
9	Extremely important
2, 4, 6, 8	Intermediate values between the two adjacent judgments

The AHP results shown in Fig. 6 supported the option of developing the largest surface excavation of the mine into a pit lake that can be used by the nearby communities for different purposes. This excavation extends to Area 2 of the mine topography and is estimated to occupy a total area of about 105,685 m^2 (10.6 ha) [23]. However, cleaning up the mine topography for residential and recreational developments was the most attractive post-mining land use option in Area 2 (See Fig. 7). These PMLUs were identified as the second and third most important options in Area 1. These results indicate the importance of ensuring that the pit lake is developed with recreational and residential areas around it. The least preferred option in all areas of the mine topography was the no-action (NA) option (See Figs. 6–10). The use of the large mine excavation in Areas 1 and 2 as landfills was the second least preferred PMLU option in these areas.

Area 4 of the mine topography is characterized by a large volume (279,448 m^3) tailings dump [24] and a very small extension of the largest excavation of the mine dominating Areas 1 and 2. The most preferred PMLU option in this area was the utilization of tailings as a replacement for sand and gravel in the construction sector. The study of the Nyala Mine tailings by Sibanda et al. [24] supported the uses of

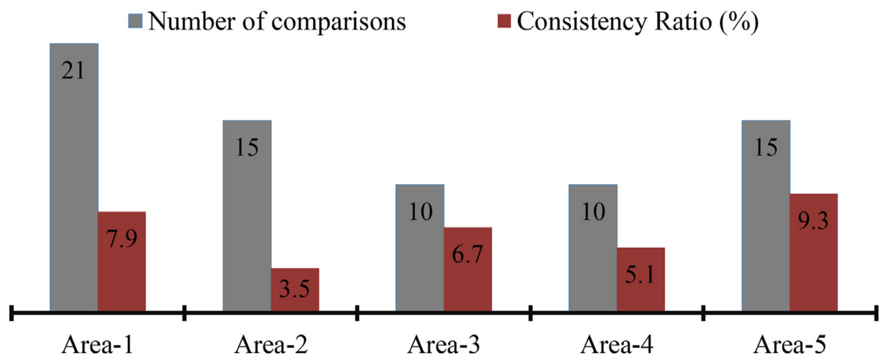


Fig. 4. The CR values and the corresponding number of comparisons performed in the five areas.

this material in different construction works. Moreover, the study that investigated the alternative uses of magnesite tailings by Shanmugasundaram and Shanmugam [25] revealed that magnesite tailings can be easily used to develop construction materials. The third most preferred option was using the mine tailings to backfill some of the abandoned mine excavations, while the management of the tailings dump was the second least attractive option (See Fig. 8).

The parts of the Nyala Mine landscape denoted as Area 4 and 5 are characterized by shallow and relatively less extensive surface excavations with very dangerous highways [26]. This area also has a relatively small amount of haphazardly dumped spoils material and the second tailings dump of the estimated volume of 534,115 m^3 [24]. The use of surface excavation in Area-4 as an inert waste landfill was the most preferred PMLU option in Area-4. This was followed by the option of cleaning up the site for crop farming and animal grazing purposes. Moreover, crop farming and animal grazing were the most preferred options in Area 5. This suggests that preferable the excavation Area 4 be used as an inert waste landfill site, while the surrounding area (including the Area 5 terrain) is levelled for crop farming and animal grazing purposes. The development of the land for residential purposes was among the least preferred PMLU options in both areas, as shown in Figs. 7 and 10.

3.1. Landform design requirements

The rehabilitation of the Nyala Mine to support the different PMLU options identified in different parts of the mine topography require that the existing landscape of the mine be graded to fill some of the mine pits with the mine waste scattered all over the mine's topography. In this case, the volumes of material to be moved and the voids to be filled were estimated from the terrain models shown in Fig. 11. Also determined from the models was the size of the areas occupied by access material and the voids to be filled. The analysis showed that the material that need to be cut in Areas 1 and 2 was slightly more than the size of the void to be filled to create a smooth flat topography around the proposed pit lake while backfilling a small portion of Pit-I in Area 3.

The other three modeled areas (i.e., Areas 3, 4, and 5) covered the portion of the mine occupied by five smaller surface excavations, two tailing dumps, and several heaps of spoil dumps. Tailing-A and -B were estimated to be about 223,906 m^3 and 534,115 m^3, respectively. Both tailing dumps are extensively affected by water erosion. Their material is generally alkaline with an average pH of 9.23 and largely made up of sand-size material [24,26]. This makes the tailings easily eroded to the surrounding areas where they are likely to affect the growth of vegetation. This is because their high pH can affect the availability of plant nutrients such as phosphorus, iron, and zinc in the soil [28]. Because of this, the rehabilitation of the mine topography will need to remove the tailings from the terrain. Given this, the use of some of the tailings to backfill the shallow part of Pit-I in Area 3 was considered. Such backfilling of part of Pit-I will reduce its size by 15.8% and the volume of Tailing-A by 78% (i.e., by 217,613 m^3 of the 279,448 m^3 total volume). The few spoils and Tailing-B material can backfill Pit-III, -IV, and -V characterized by dangerous highwalls, while Pit-II is developed into a landfill site for solid and inert waste. Backfilling these pits will eliminate the safety risks of falling from the highwalls or falling off from the unstable highwalls of people and animals. The safety risks of these pits are currently supported by the fact that the mine site is open to the public and that animals graze on the site and accidently drown in the water in the pit. The volumes of cut and fill material determined in the five areas of the mine site are in Fig. 12, while the area of

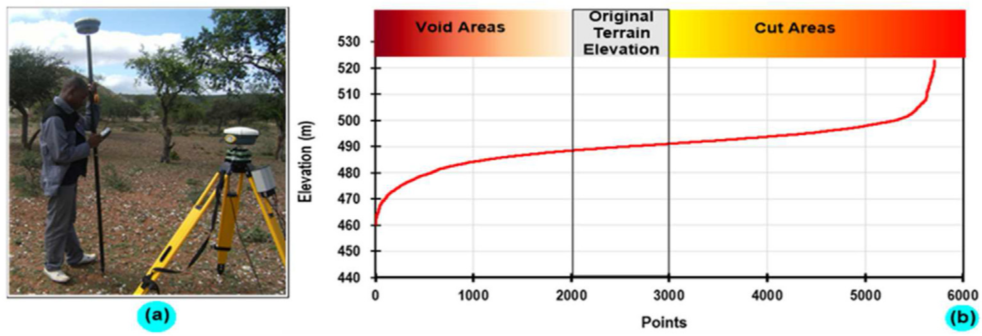


Fig. 5. The height data collection process: (a) The Hi-Target V9 GNSS RTK GPS system that was used, and (b) the distribution of the elevation points collected.

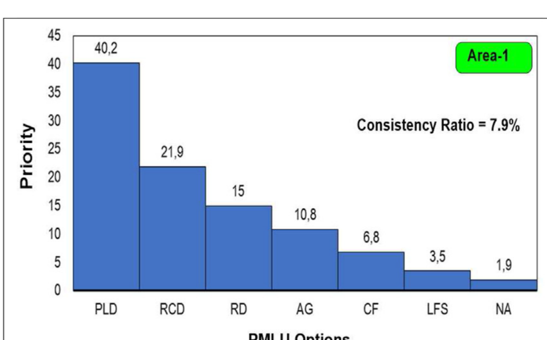
cut material and the voids to be filled are in Fig. 13. According to these results, about 85 ha (47% of the total mine lease area) of the mine topography will have to be graded to fill a void area of 50 ha (28% of the total mine lease area).

4. Discussion

The rehabilitation of mining sites requires a critical decision on suitable post-mining land uses to be made. This becomes even more important when closing and restoration of abandoned mines in poor and rural communities are considered. Depending on different factors, post-mining land uses vary from site to site and are implemented based on the prevailing site conditions. However, according to Skousen and Zipper [29], the decision of which land use to adopt depends also on the interpretation of the legislation. This is because the adoption of any PMLU requires that the regulatory bodies be given appropriate assurance about the attainability and compatibility of the selected land use with the surrounding areas. Some of the traditional and most common PMLUs are agriculture, recreational activities, construction, pit lakes, and forestry [29–31].

The analysis of the PMLU options considered in this work recognized that appropriate land uses for closed and rehabilitated abandoned mines should show some balance in ensuring that the site remains free from environmental and physical hazards and is useable for the social and economic development of the communities. The results of the ranking of the PMLU options showed that a large part of the Nyala Mine topography supported the adoption of land uses that need some degree of surface development. These land uses include the development of the pit lake and residential sites, the convention of one of the shallow abandoned excavations to a landfill site, and the use of the magnesite tailings in the construction sector. These land uses were more attractive because their implementation will need very little further landform design to be undertaken.

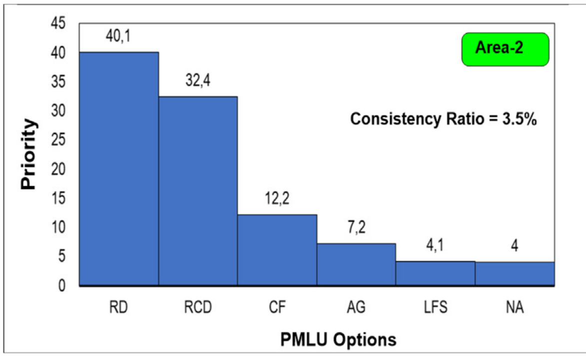
The development of a pit lake from the most extensive and deep abandoned mine excavation will benefit the local community in numerous ways. The communities in the area rely much on groundwater for domestic uses. Consequently, the water in the current (underdeveloped) pit lake has been an important source of water for many uses. The development of the pit lake with improved safety status will unlock the currently ignored socio-economic potential of the lake. Depending on the water balance and quality, pit lakes in many parts of the world have been used for fisheries, recreational



Area - 1

PMLU Options	CF	PLD	AG	NA	LFS	RCD	RD
CF	1	0.2	0.5	8.0	3.0	0.2	0.3
PLD	6.0	1	5.0	9.0	6.0	2.0	6.0
AG	2.0	0.2	1	9.0	4.0	0.5	0.5
NA	0.1	0.1	0.1	1	0.5	0.1	0.1
LFS	0.3	0.2	0.3	2.0	1	0.2	0.2
RCD	6.0	0.5	2.0	8.0	5.0	1	2.0
RD	4.0	0.2	2.0	8.0	5.0	0.5	1

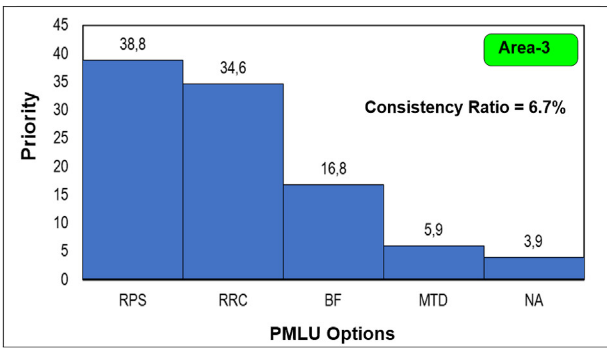
Fig. 6. A comparison of PMLU is Area 1 of the abandoned Nyala Magnesite Mine.



Area- 2

PMLU Options	CF	AG	RD	RCD	NA	LFS
CF	1	3.0	0.2	0.3	3.0	3.0
AG	0.3	1	0.2	0.2	2.0	3.0
RD	6.0	6.0	1	1.0	8.0	7.0
RCD	3.0	5.0	1.0	1	8.0	6.0
NA	0.3	0.5	0.1	0.1	1	1.0
LFS	0.3	0.3	0.1	0.2	1.0	1

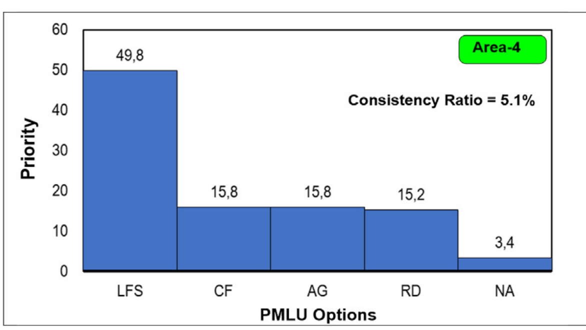
Fig. 7. A comparison of PMLU is Area 2 of the abandoned Nyala Magnesite Mine.



Area - 3

PMLU Options	NA	RPS	BF	MTD	RRC
NA	1	0.1	0.1	0.5	0.2
RPS	9.0	1	3.0	8.0	1.0
BF	7.0	0.3	1	4.0	0.3
MTD	2.0	0.1	0.3	1	0.3
RRC	5.0	1.0	4.0	4.0	1

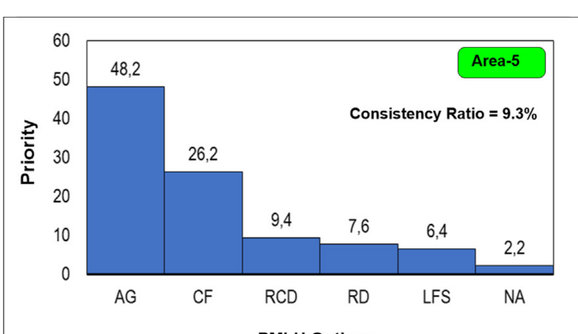
Fig. 8. A comparison of PMLU is Area 3 of the abandoned Nyala Magnesite Mine.



Area - 4

PMLU Options	CF	AG	RD	NA	LFS
CF	1	1.0	1.0	7.0	0.3
AG	1.0	1	1.0	7.0	0.3
RD	1.0	1.0	1	6.0	0.3
NA	0.1	0.1	0.2	1	0.1
LFS	4.0	4.0	4.0	7.0	1

Fig. 9. A comparison of PMLU is Area 4 of the abandoned Nyala Magnesite Mine.



Area – 5

PMLU Options	CF	AG	RD	RCD	NA	LFS
CF	1	0.3	4.0	4.0	8.0	7.0
AG	3.0	1	7.0	7.0	9.0	8.0
RD	0.3	0.1	1	0.5	8.0	1.0
RCD	0.3	0.1	2.0	1	8.0	1.0
NA	0.1	0.1	0.1	0.12	1	0.3
LFS	0.1	0.1	1.0	1.00	4.0	1

Fig. 10. A comparison of PMLU is Area 5 of the abandoned Nyala Magnesite Mine.

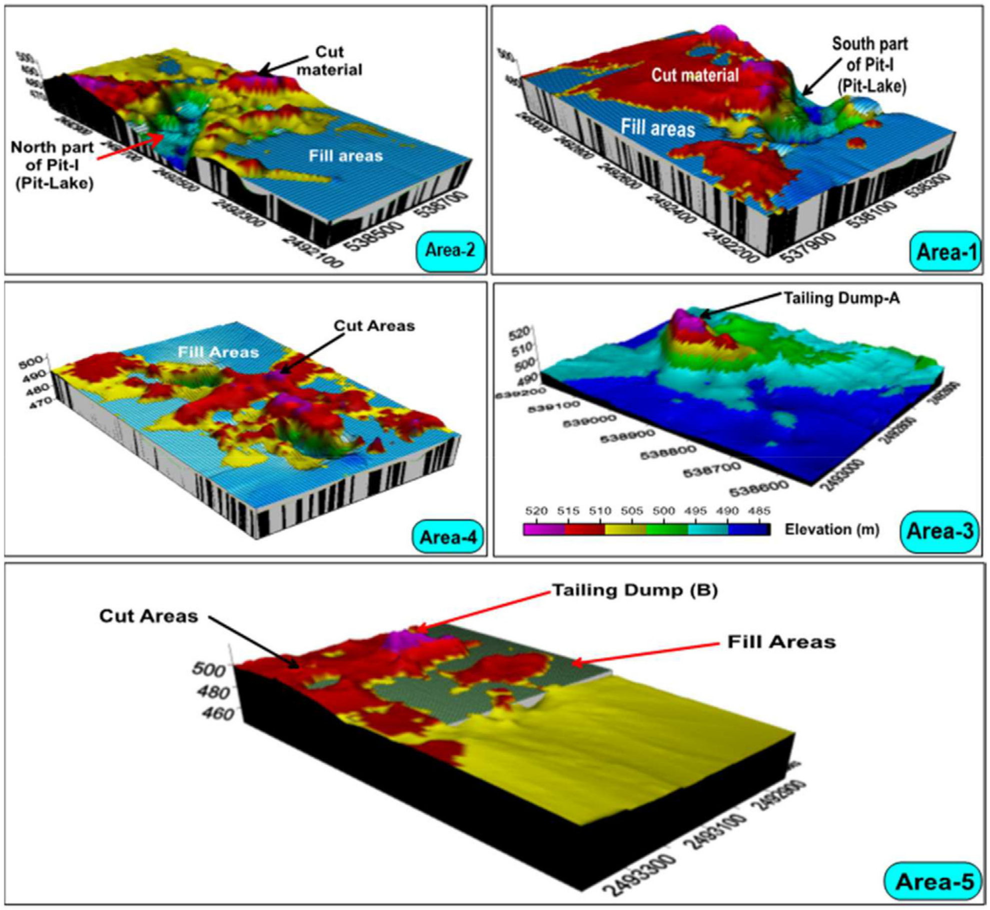


Fig. 11. The 3D terrain models show the areas of the mine to be moved to fill the void areas [27].

(swimming, boating, diving, passive recreation), wildlife conservation, chemical extraction, and livestock and industrial water sources [32–35]. In general, well-planned pit lakes with clearly defined end uses can be the drivers of the local economy after mining. For example, in Germany (Lusatia District), the pit lake developed for recreational end-uses was reported to have the potential to contribute about 10–16 million euros to the local economy per year [36]. Moreover, the lakes help turn the lifeless

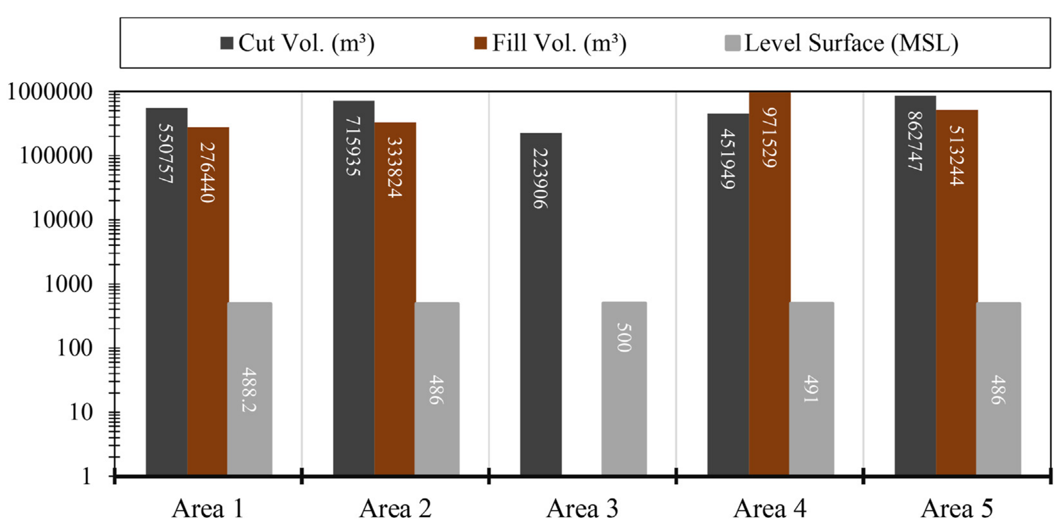


Fig. 12. The estimated volumes of material to be cut and sizes of the voids to be filled.

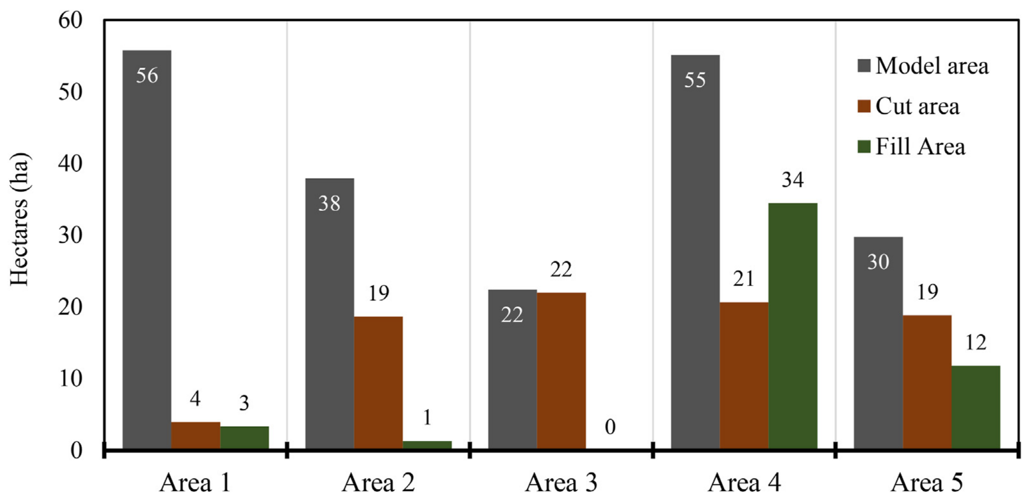


Fig. 13. The areas occupied by material to be cut and voids to be filled.

post-mining landscape into a productive and prosperous landscape with an improved aesthetic appearance.

To ensure that the full potential of the proposed pit lake in the study area is released, land use options that include the development of residential and recreational sites around the lake were found attractive. The lack of access to land by many South Africans is one of the reasons behind the development of informal settlements on abandoned mine sites throughout the country. In this case, the Nyala Mine is not an exception. The case of the development of settlements close to the mine lease area [26] and on the abandoned spoil dumps is evident in some parts of the abandoned Nyala Mine. In view of this, grading the spoils to fill the shallow pits of the mine will be an important step in preparing the mine topography for residential development. Given that the mining and processing of magnesite do not involve the use of chemicals, the reshaping of the mine topography for any possible land use can be done with no worries of possible contamination of the site. This is an important element that also makes magnesite tailings easily considered for use in construction projects or as construction material [24,25,37]. Consequently, the evaluation of the PMLU options in this work identified the reuse of the mine tailings in the construction projects as a replacement for sand and gravel to be one of the most attractive options.

A shallow excavation located relatively far (Area 4 of the mine) from the current and proposed extension of the settlement site showed a potential for use as a landfill site for solid wastes. This land uses option has several benefits [38,39]. It is important in this case because the nearby communities do not have a designated site for the disposal of solid waste. This has led to the problems of open damping and sometimes burning of waste in uncontrolled sites within the community. These practices of dealing with solid waste are associated with numerous environmental problems and the spread of diseases within the communities [40].

A small portion of the mine topography was found suitable for animal or livestock grazing sites. This area was less affected by mining activities and has shown good natural recovery of vegetation. Currently, the livestock from the local community grazes around this area. They are generally attracted to the mine site by that their only source of drinking water is the pit lake in the abandoned mine. Therefore, improving the safety status of the pit lake at Nyala Mine and rehabilitating part of the mine area to support grazing will have excellent direct benefits to the livestock farmers in the community.

5. Conclusions

This study used a case study of an abandoned magnesite mine in South Africa to find a way of identifying post-mining land used from the current uses of the abandoned mine sites and features. It used semi-qualitative (i.e., SWOT and AHP) methods to find the most attractive PMLU options from the present uses. The results of the study showed that post-mining land use options such as the development of the pit lake part surrounded by settlement sites (with recreational sites) and part used as a livestock grazing site. The other land uses found attractive for the abandoned Nyala Mine were the development of one of its show pits for use as a landfill site and the reuse of the tailings as a replacement for gravel and sand in the construction sector. Although some of these land use options require some specific preparation of the mine topography, they have a very high potential of ensuring that the rehabilitated site (free from both environmental and physical hazards) contributes to the socio-economic development of the host communities. The preparation of the topography of the abandoned mine site for these land uses will require that about 2.8 million cubic meters of excess material occupying about 85 ha (47%) of the mine lease area be moved to about 523,759 cubic meters void covering about 50 ha (28%) of the mine lease area.

Ethical statement

The author state that the research was conducted according to ethical standards.

Funding body

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APPENDIX-A
SWOT analysis for selection of appropriate rehabilitation strategies.

Area-1 SWOT analysis

SWOT Parameters	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
No Action	• No disturbance of the recovering sites • No rehabilitation cost is required	• No reduction or elimination of the environmental hazards • No reduction or elimination of physical hazards	• Opportunity for vegetation recovery in some portion of the area	• No beneficial use of the site	• Retain the current state of the site
Development of the residential sites	• Provision of new residential site • Elimination of environmental problems of spoils	• Require reshaping of the spoils materials. • Fencing of Pit-I will be necessary.	• Opportunity for further southward expansion of Zwigodini village.	• Residence close to Pit-I might lid to the use of the pit as a domestic waste dump site.	• Site development to promote future residential, commercial, or industrial development
Agriculture (crop farming)	• Good soil chemistry stability	• Require contouring of spoil materials to provide suitable slopes for this purpose. • Improvement of soil quality will be necessary	• The water contained in Pit-I can be used for irrigation purposes, with little treatment.	• Attempt to use water in Pit-I for irrigation without treatment might influence soil quality	• Strive to create stable cropland
Recreational (dirt park construction)	• Minimum reshaping of spoil materials for bicycle dirt jump • The site is easily accessible by road for this purpose.	• No solution to the environmental and physical stresses associated with the Pit-I portion of the model • The spoil materials comprise mostly boulders, therefore ripping and sieving out of larger soil particles • Removal of the few pieces of vegetation growing on the site	• Introduction of new sporting activity in the area. • The park can attract many bicycles dirt jumping fans as it is also near Pafuri gate to Kruger National Park and Big-Tree tourist destinations.	• The facility may not receive the full support of the community.	• Strive to develop land that supports both inland and water-based recreational activities

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SWOT Parameters	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
Livestock grazing	• No disturbance of the recovering sites. • Reduced rehabilitation cost.	• Not eliminate the physical hazards of the Pit-I portion. • Minimum vegetation growth.	• Development of livestock enterprise	• An increasing number of livestock per hectare may lead to extensive site degradation.	• Develop a site with improved grazing capacity to support livestock production in the area
Pit lake development	• Stabilization of the pit wall and minimizing hazards associated with them and the water in the pit.	• Require revegetation of the site with native species around the pit • The pit walls are too high • The water volume in the pit reduces significantly during winter. • The pit walls are generally of consolidated low-grade magnesite ore.	• The site can also concurrently be used for animal grazing and water base recreational purposes. • Development of picnic facilities around the site.	• Community reluctance to the land use • The pit walls might not support the growth of native spices	• Create a lake and native animal habitat
Development of landfill site for inert waste	• Filling the pit with inert waste has no effect on groundwater	• The pit is extensive and contains water.	• Improve the quality of the backfill soil in the pit • The filled pit can support a range of land uses.	• The backfilling of the pit will lid to the drying up of the water in the pit. • High potential for the use of the site as a domestic waste disposal site.	• Create beneficial use of the abandoned pit while backfilling it.

Area-2 SWOT analysis

SWOT Parameters	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
No Action	• No disturbance of the recovering sites • No rehabilitation cost is required	• No elimination of physical and environmental hazards associated with Pit-I and spoil dumps.	• Opportunity for vegetation recovery in some portion of the area	• No beneficial use of the site	• Retain the current state of the site
Development	• Provision of new residential site • Elimination of environmental problems of spoils dumps	• Require reshaping of spoil materials. • Fencing of Pit-I will be necessary.	• Opportunity for further southward expansion of Zwigodini village.	• Residence close to Pit-I might lid to the use of the pit as a domestic waste dump site.	• Site development to promote future residential, commercial, or industrial development
Agriculture: crop farming	• Site geochemical stability • Growth of crops can minimize dust generation from spoil dumps	• Require contouring of spoil materials • Improvement of soil quality will be necessary	• Opportunity for increased crop production in the area	• No water for irrigation of crops. • The area is covered by large volume spoil dumps which might not support crop growth.	• Strive to create stable cropland

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SWOT Parameters	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
Recreational: Dirt Park construction	• Require minimum reshaping of spoil materials for bicycle dirt jump • The site is easily accessible by road for this purpose.	• No solution to the environmental and physical stresses associated with the Pit-I portion of the model • The spoil materials comprise mostly boulders, therefore ripping and sieving out of larger soil particles • Removal of a few pieces of vegetation growing on the site	• Introduction of new sporting activity in the area. • The park can attract many bicycles dirt jumping fans as it is also near Pafuri gate to Kruger National Park and Big-Tree tourist destinations.	• The facility may not receive the full support of the community.	• Strive to develop land that supports both inland and water-based recreational activities
Livestock grazing	• No disturbance of the recovering sites. • Reduced cost of rehabilitation.	• No elimination of physical and environmental hazards associated with the Pit-I portion. • Minimum growth of vegetation for livestock grazing.	• Development of new livestock enterprises	• An increasing number of livestock per hectare may lead to extensive site degradation.	• Develop a site with improved grazing capacity to support livestock production in the area
Inert landfill	• Filling the pit with inert waste has no effect on groundwater	• The pit is extensive.	• Improve the quality of the backfill soil in the pit as the grass has the potential to improve soil organic matter • The filled pit can support a range of land uses.	• High potential for the use of the site as a domestic waste disposal site.	• Create beneficial use of the abandoned pit while backfilling it.

Area-3 SWOT analysis

SWOT Parameters	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
No Action	• No disturbance of the recovering sites • No rehabilitation cost is required	• No reduction or elimination the environmental hazards • No reduction or elimination of physical hazards	• Use of the dump as a study site for university students.	• No beneficial use of the site	• Retain the current state of the site
Use of tailing for block making	• Significantly reduce the amount of in the tailing dump. • The material has good engineering properties for this purpose.	• Very little material can be used for such a purpose • Minimum construction being carried out in the study area	• Development of new brick/blocks making enterprises.	• River sand abundance in the area can reduce the attractiveness of the strategy	• Reduce the volume of tailing and spoil dumps material through the use of the material for brick making.

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SWOT Parameters	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
Use of tailing as fill material in road construction	• Reduce the amount of in the tailing dump. • Loading of the material won't require the use of an excavator.	• Not less than 5 km distance from the potential site for road construction	• Reduce risks of further damage to the environment due to excavation material for road construction.	• Alternative site closer to the road construction site can be identified	• Reduce the volume of tailing and spoil dumps material through the use of the material in road construction.
Backfilling of part Pit-I portion in Area-2	• Extremely reduce the amount of in the tailing dump. • Will eliminate physical and environmental hazards associated with the tailing dump as well as those associated with Pit-I portion in Area-2	• The material is characterized by poor soil structure.	• The backfilled area can support a wide range of land uses	• Increase salinity of water Pit-I due to magnesite leaching from tailing material	• Reduce the volume of tailing and spoil dumps material by backfilling Pit-I portion in Area-2.
Tailing management alternative	• The environmental and physical hazards can be contained.	• The tailing does not support vegetation growth used mostly to prevent excessive erosion of tailings • Budget for continuous tailing management will be required.	• Non was found	• No easy and cost-effective strategy for water and wind erosion control of tailings can be found.	• To contain the environmental and physical hazards associated with the mine.

Area-4 SWOT analysis

SWOT Parameters	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
No Action	• No disturbance of the recovering sites • No rehabilitation cost is required	• No elimination of physical and environmental hazards associated with Pit-III, Pit-IV, and spoil dumps.	• Opportunity for vegetation recovery in some portion of the area	• No beneficial use of the site	• Retain the current state of the site
Development	• Provision of new residential site • Elimination of environmental problems of spoils dumps	• Require reshaping of spoil materials. • Fencing of the pits will be necessary.	• Opportunity for further southward expansion of Zwigodini village.	• Residencesce close to Pit-III and Pit-IV might lid to the use of the pit as a domestic waste dump site.	• Site development to promote future residential, commercial, or industrial development
Agriculture: crop farming	• Site geochemical stability in filled areas • Growth of crops can minimize dust generation from spoil dumps • Very small portion of the area was disturbed by mining	• Require filling of Pit-III and Pit-III by a few spoil dumps found around the area	• Opportunity for increased crop production in the area • Opportunity to connect the southern crop field with the northern one	• No water for irrigation of crops. • Agricultural activities might disturb extensive area that was not disturbed by mining.	• Strive to create stable cropland

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SWOT Parameters	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
Livestock grazing	• No disturbance of the recovering sites. • Reduced cost of rehabilitation.	• No elimination of physical and environmental hazards associated with Pit-III and Pit-IV portions. • Minimum growth of vegetation for livestock grazing.	• Development of new livestock enterprises.	• An increasing number of livestock per hectare may lead to extensive site degradation.	• Develop a site with improved grazing capacity to support livestock production in the area
Use of pits as Inert landfill	• Filling the pit with inert waste has no effect on groundwater • Both pits (Pit-III and IV) are shallow above the water table. • Pit-I is at less than 100 m distance from the current expunction of Zwigodini village • The pit of reason able size for this purpose	• Fencing of Pit-I to provide controllable access to the pit is necessary.	• Improve the quality of the backfill soil in the pit as the grass has potential to improve soil organic matter • The filled pit can support a wide range of land uses.	• High potentials of use of the site as domestic waste disposal site.	• Create beneficial use of the abandoned pit while backfilling them.

Area-5 SWOT analysis

SWOT Parameters	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
No Action	• No disturbance of the recovering sites. • No rehabilitation cost is required.	• No elimination of physical and environmental hazards associated with Pit-IV, Pit-V, and tailing dumps.	• Opportunity for vegetation recovery in some portion of the area	• No beneficial use of the site	• Retain the current state of the site
Development	• Provision of new residential site • Elimination of environmental problems of spoils dumps	• Require reshaping of tailings and spoil materials.	• Opportunity for further southward expansion of Zwigodini village.	• The area is far from the existing residential area; thus, the strategy might receive little support.	• Site development to promote future residential, commercial, or industrial development
Agriculture: crop farming	• Site geochemical stability in filled areas • Growth of crops can minimize dust generation from spoil dump	• Require filling of Pit-IV and Pit-V by tailing material from Tailing Dump-B	• Opportunity for increased crop production in the area	• No water for irrigation of crops.	• Strive to create stable crop land

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SWOT Parameters	Strengths	Weaknesses	Opportunities	Threats	Driver for end land use
Livestock grazing	• No disturbance of the recovering sites. • Reduced cost of rehabilitation.	• No elimination of physical and environmental hazards associated with tailing, Pit-IV portion, and Pit-V. • Minimum to medium growth of vegetation for livestock grazing.	• Development of new livestock enterprises.	• An increasing number of livestock per hectare may lead to extensive site degradation.	• Develop a site with improved grazing capacity to support livestock production in the area
Use of pits as Inert landfill	• Filling the pit with inert waste has no effect on groundwater • Both pits (Pit-IV and V) are shallow above the water table.	• Pit-IV is extensive and shallow. • Pit-V is far from the community.	• Improve the quality of the backfill soil in the pit as the grass has the potential to improve soil organic matter • The filled pit can support a wide range of land uses.	• High potential of the use of the site as a domestic waste disposal site.	• Create beneficial use of the abandoned pit while backfilling them.
Recreational: Dirt Park construction	• Require minimum reshaping of spoil materials for bicycle dirt jump • The site is easily accessible by road for this purpose.	• No solution to the environmental and physical stresses associated with the pits and tailing dumps a portion of the model • The spoil materials comprise mostly boulders, therefore ripping and sieving out of larger soil particles • Removal of few vegetation growing on the site	• Introduction of new sporting activity in the area. • The park can attract many bicycles dirt jumping fans as it also at proximity to Pafuri gate to Kruger National Park and Big-Tree tourist destinations.	• The facility my not receive full support of the community.	• Strive to develop a land that support both inland and water-based recreational activities

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