



IN SEARCH OF APPROPRIATE REHABILITATION STRATEGIES FOR ABANDONED NYALA MAGNESITE MINE, LIMPOPO PROVINCE OF SOUTH AFRICA

S.E. Mhlongo^{1*}; F.A.Dacosta¹ and N.F. Mphephu²

¹University of Venda, School of Environmental Sciences, Department of Mining and Environmental Geology, Private Bag x 5050, Thohoyandou 0950 South Africa

²Environmental Specialist, Xstrata Alloys, P. O. Box 1050, Rustenburg 0300 South Africa

*Email: emmanuel.mhlongo@univen.ac.za; emapiwana@gmail.com

ABSTRACT

Mining operations have a disruptive effect on the environment and abandoned surface mines exacerbate the problem. Some of these historic mine sites are in a deplorable state and continue to cause damage to the environment and potential risks to human and animal health in the surrounding areas. The main aim of this research was to identify and evaluate practical rehabilitation strategies for addressing physical and environmental problems at an abandoned Nyala Magnesite Mine. The approach used involved characterization of tailings and spoil materials as well as water within the excavations, development of current and post-rehabilitation terrain models using RTK-GPS data, and selection and evaluation of alternative land uses for the mine used SWOT and QSPM analysis respectively. The mine waste characterization showed that the tailings are suitable for engineering purposes based on their physical properties and high silica content. The laboratory analysis of the water samples from the pit-lake showed that the water is highly alkaline with unacceptable levels of Cl^- , Mg^{+2} , F^- and K^+ thus making the water to be unsuitable for domestic uses. Characterization of mine waste and water, together with terrain modeling provided are more robust scientific techniques for making sound decision on selection of appropriate rehabilitation strategies and on determination of Cut and Fill volume. Based on SWOT and QSPM analysis results; three post-mining land use scenario plans for rehabilitation of the mine site were developed. Cost estimation of these practical rehabilitation strategies was recommended in order to ensure that low-cost strategies are implemented at the mine site.

Keywords: Terrain Modeling, Mine Rehabilitation Strategies, Abandoned Mines, Land-use Selection, Nyala Mine

1. INTRODUCTION

Mining is a temporary land use that adversely degrades the natural environment. Surface mining in particular can severely erode the soil and reduce its fertility, pollute water and other components of the environment, drain underground water reserves, disrupt all visually aesthetic elements of the landscape, and destroy wildlife.^[1] These problems continue even after mining has ceased if the mine was not properly closed or abandoned. Mine rehabilitation, therefore, is a significant and essential element of mining that is carried out to improve the disturbed part of the environment to a degree that it

integrates well with the surrounding environs thus effectively supporting other land uses.

Backfilling of disrupted areas and re-contouring of slopes are significant measures to be taken in restoration of land mined by open pit to original or accepted alternative uses.^[2] Landform design for mine rehabilitation purposes is about planning for the immediate and long term future in tandem, optimizing post-mining land capacity while minimizing the cost of achieving optimal land use, and sustainable development.^[3] The operations of re-contouring and backfilling of

voids areas require extensive grading of mine waste in order to create stable and acceptable topography with improved land use capacity. In view of this, it is important that characterization of mine waste is conducted so as to reduce the risks of contamination of water regimes. This is due to the fact that mine waste can contain a range of properties that are likely to impact negatively on the environment if allowed to enter the environment. Characterization of mine waste can also assist in determining their suitability for alternative uses.

Mining of magnesite by open pit at Nyala Mine has resulted to extensive degradation of the natural environment around the study area. It has created a landscape with extremely reduced capacity to support other land uses.^[4] This is due to the fact that the mining operations in the area were not subjected to the current environmental laws, thus the mines were abandoned without any attempt of rehabilitation of the land for other uses. The main aim of this research was to identify and evaluate practical and appropriate rehabilitation strategies for addressing physical and environmental problems at the historic Nyala Mine.

1.1. Location of the Study Area

Nyala Magnesite Mine is found in the vicinity of Zwigodini Village. It is situated approximately 50 km North East of Thohoyandou and at about 60 km from the Pafuri gate of the Kruger National Park as shown in Fig.1. The region is dominated by agricultural, residential and recreational activities, and small-scale magnesite mining operations.



Figure 1: Locality map of the study area

1.1.2. Geologic setting

The Nyala Magnesite Mine falls within the Tshipise Straightening Zone along the southern periphery of the Central Zone of the Limpopo Belt. Generally, the Central Zone comprise dominantly of high grade metasediments which are interlayered with quartzofeldspathic gneisses and mafic rocks (collectively known as Beit Bridge Complex). These rocks are lithologically subdivided into three groups; namely, Mount Dowe, Malala Drift and Gumbu Groups in their order of younging. The Mount Dowe Group mainly consists dominantly of quartzite, magnetite quartzite and metapelitic gneiss, with intercalations of quartzofeldspathic gneiss. Comparatively, the Malala Drift is dominated by quartzofeldspathic gneisses with minor quartzite, magnesite quartzite and metapelite, while the Gumbu Group is characterized predominantly of marbles and calc-silicate rocks with minor fine-grained metapelite and metapsammite.^[5]

The magnesite deposits at Nyala Mine are hosted by metamorphosed ultrabasic and calcareous rocks of the Limpopo Belt. These deposits are known to be extending for about 50 km east-north of Tshipise.^[6] Magnesite deposits in the study area are amorphous in nature and they occurs as veins and irregular masses that were derived by weathering from olivine-rich rocks, namely; basalt and limburgite rocks of the Drakensburg Stage of the Stormberg Group.^{[6][7]} Other similar deposits of little economic importance occurring



around the region include the deposits occurring within pyroxinite and veins of crystalline, around the Musina and Mopane districts. However, most of the magnesite deposits of the country are of amorphous in nature.^[7]

2. METHODS AND MATERIALS

2.1. Physical Characterization of Tailings and Spoil Materials

The particle size distribution technique was used in determination of physical characteristics of tailings and spoil dumps materials at Nyala Mine. It included measuring the grain size distribution of the wastes by passing them through a series of sieves ranging from 4, 3.15, 2, 1 mm; 500, 250, 125, 63, 32 μm in sizes. A pan was placed at the bottom of the stack.

The procedure included passing the dried sample of known weight through the set of sieves of known individual empty weight. The sieve stack was placed on the motorized mechanical shaker and shaken for 1 hour. Material retained in each sieve was weighed and expressed as a percentage of the whole sample. The results of sieve analysis expressed as percentage passing were plotted on the logarithmic graph using Dplot[®] Software. The plotted gradational curve was used in the calculation of uniformity (C_u) and curvature (C_c) coefficient.

2.2. Chemical Analysis of Tailings Material

Magnesite tailings are generally inert rock particles with little direct environmental impact associated with their chemical nature. This is due to that no chemical reagents are used in the processing of magnesite. The chemical analysis of tailings material involved determination of percentage of major oxides in order to establish their potential alternative use.

The procedure for samples preparation for direct analysis with PANalytical Axios X-ray fluorescence spectrometer instrument involved milling of tailings materials to the fraction less than 75 μ using the Retsch RS 200 vibratory disk milling machine. The milled specimen was then roasted at 1000 °C for at least 3 hours to oxidize iron (Fe^{2+}) and Sulfur (S), and to determine the Loss on Ignition (L.O.I) percentage of the samples. The analysis of major oxides required

that the glass disks are prepared through fusing 1 g roasted sample, 8 g (12-22) flux consisting of 35% alkali borate (LiBO_2) and 64.71% lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$) at 1050 °C. The glass disks were then analyzed by XRF machine equipped with a 4 kW Rhodium (Rh) tube.

2.3. Chemical Analysis of Water

The water samples were analyzed for anions and cations concentrations using the 850 Professional Ion Chromatograph (IC) and the Flame Atomic Absorption Spectrometry (FAAS) (Perkin Elmer AAnalyst 400) respectively. For the analysis of anions, the mobile phase of the IC instrument was equipped with two litres solution of 168 g sodium carbonate (NaHCO_3) and 678 g disodium carbonate (Na_2CO_3) in the analysis of anions. The water samples were then passed through the pressurized Metrosep A Supp 5 anions column at 0.8 ml/minute flow rate. The standards used for instrument calibration were 1 ppm, 5 ppm, 10 ppm and 20 ppm.

Alkali metals (cations) in water were analyzed using the FAAS. Sodium, calcium, magnesium, potassium and iron were detected in water samples by plotting non-linear calibration curve using well prepared standard solutions for each metal under investigation. Prior to the instrument calibration, optimization was done to obtain the best response of the instrument. The analysis involved introducing a water sample to the instrument aspirator where it was then aspirated to flame in the form of aerosol. The beam of ultraviolet light at a specific wavelength was focused to the flame prior to sample aspiration. The machine detected the metal existence in water by measuring the change in intensity of each metal under investigation. The computer system then converted the measured change in intensity into an absorbance that was subsequently converted to parts per million (ppm).

2.3.1. Mine water and waste pH determination

Mine water and solid waste (both tailings and spoil materials) were analyzed for their pH and electrical conductivity (EC) levels. The slurry was prepared by adding 20 ml of deionized water to the homogenized 20 g scoop of clay and silt particles of solid waste. The samples were vigorously stirred for 15 minutes with a glass stirring rod and let to stand for 30 minutes. The



pH meter was then calibrated over the appropriate alkaline range of 7.00 to 9.00 using the buffer standard solution and thereafter pH and EC rods were respectively immersed in to the beaker with slurred soil samples. The pH and EC readings of the soil were recorded from the instrument. In the case of water samples, the pH and its corresponding EC were measured by immersing the pH and EC rods in 40 ml of water for a minute after the sample have been vigorously stirred and let to stand for at least 60 minutes.

2.4. GPS Setting and Data Collection

The height data required as input for digital terrain modeling was collected through the use of Hi-Target V9 GNSS RTK Surveying system. The procedure for data acquisition using RTK-GPS involved setting of the GPS base at a known point at 50 m radius away from high voltage power lines and at clear view of the sky. The base point was localized to the nearest Lwandze trig station (-22.55431S; 30.6949E and the height of 633.6 above MSL). The GPS base receiver was placed on the fixed height tripod and set at the elevation musk of 15° under WGS-84 coordinate system. The rover’s receiver was mounted on the fixed height rod (2 m) and set at elevation musk of 10° to enhance the accuracy of the points. Both base and rover heights were kept at an ellipsoids set-up. The points were collected at every 1 m vertical interval as the rover moves from point to point along the designed 15 m spaced traverse lines. The measured points were stored in the mobile PC and downloaded for processing purposes.

2.4.1. Data processing for terrain modeling

The surfer® 8 software using linear interpolation methods was used in creation of Nyala Mine terrain models. Prior to the creation of the actual surfaces; the height data was processed to make it compatible for the software. Kriging interpolation method was used to produce visual maps from irregularly spaced height data. Adjustments on the relief data were made for the creation of an engineering surface design. The designed engineering surface models were superimposed on the models representing the current terrain to define cut and fill areas.

2.4.2. Cut and fill volume calculation

The volumes of material to be cut and voids to be filled in order to create level mine surfaces were calculated and considered as an average of the extended trapezoidal, extended Simpson’s, and Simpson’s 3/8 rules as expressed mathematically in equation (i), (ii) and (iii) respectively.^[8] In these equations, Δx represents the grid column spacing, Δy represents the grid row spacing, and G_{i,j} represents the grid node value in row i and column j.

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

$$Volume \approx \frac{\Delta y}{2} [A_1 + 2A_2 + 2A_3 + \dots + 2A_{ncol-1} + A_{ncol}] \dots \dots \dots (i)$$

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

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

$$Volume \approx \frac{\Delta y}{3} [A_1 + 4A_2 + 2A_3 + 4A_3 \dots + 2A_{ncol-1} + A_{ncol}] \dots \dots \dots (ii)$$

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

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

$$Volume \approx \frac{3\Delta y}{8} [A_1 + 3A_2 + 3A_3 + 3A_3 + \dots + 2A_{ncol-1} + A_{ncol}] \dots \dots \dots (iii)$$

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

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

2.5. Development of Appropriate Rehabilitation Strategies

Based on the interpretation of the mine topography from the developed terrain models, mineral composition and geotechnical characteristics of tailing materials; several rehabilitation alternatives for each modeled section of the mine were suggested. SWOT analysis was used to select the appropriate rehabilitation options. Quantitative Strategic Planning Matrix (QSPM) for the selected strategies was developed to evaluate the options in terms of their relative attractiveness. The three

most favorable rehabilitation options indicated by the QSPM analysis were considered in the design of the rehabilitation scenarios for the mine. Thus three rehabilitation scenarios were developed from the rehabilitation alternatives evaluated to be most attractive in the five modeled mine segments. ArcGIS® 9.3 software was used in the representation of the designed rehabilitation plans in the form of the maps.

3. RESULTS AND DISCUSSION

3.1. Physical Characteristic of Mine Waste

The grain size analysis for both tailings and spoil showed that the materials comprised of grains spanning from fine gravel, sand and silt to clay particles, thus both materials were classified as uniformly graded sands. The interpretation of the steep slope gradient of the plotted gradational curves for both tailings and spoil materials shown in Fig.3 qualified the classification of these materials as poorly graded or uniformly graded sands. The calculated C_u of greater than 6 (10.97 for tailings and 9.97 for spoils) and the C_c ranging between 1 and 3 (that is 1.09 for tailings and 1.14 for spoils) justified the classification of the mine waste materials as well-graded sands. This was also supported by the fact that both materials comprise of less than 5% silt to clay particle sizes (<63µm). The similarity of grains comprising both tailings and spoil materials at Nyala Mine can be interpreted from the similarity of the plotted grain size distribution curves (see Fig.2).

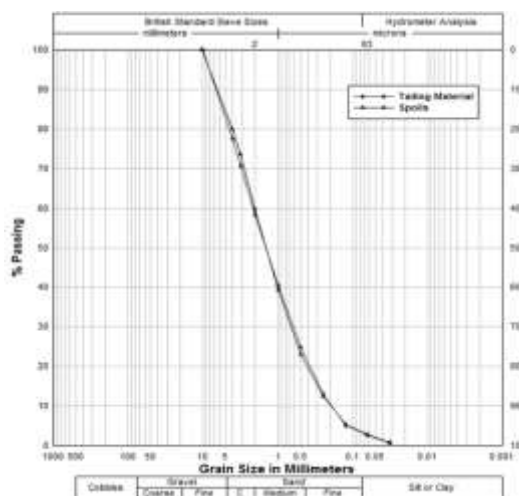


Figure 2: Grain size distribution curves tailings and spoil materials

It was observed in the field that the tailings were characterized by absence of coarse gravels and cobbles. Comparatively, the spoil material showed to differ from tailings in one respect; it appeared to comprise of high level of coarse gravel, cobbles and even large boulders. These large boulders and cobbles were observed along the toe of the spoil dumps. It was also observed during field inspection that spoils are characterized by dark brown colour which suggests the presence of organic matter in these soils, while magnesite tailings possess white colour that can be attributed to deficiency of organic matter (see Fig 3).



Figure 3: Visual appearance of magnesite tailings and spoil materials

These slight differences on physical properties of the waste materials together with the fact that spoil were found to be supporting the growth of *aristida-congesta-subsp* grasses required that strategic backfilling be adopted. These should involve systematic backfill of deeper voids with tailing materials then overlaying them with spoil materials.

3.2. Chemical Characteristics of Tailings and Mine Water

3.2.1. Chemical composition of tailings

Analysis of major oxides showed that magnesite tailing are rich in silica (SiO_2) with relatively high MgO and $Fe_2O_3(t)$. Oxides such as Na_2O , K_2O , P_2O_5 and Cr_2O_3 were each found to be contributing less than a percent of the



composition. The concentrations of major oxides in tailings are presented in Table.1.

Table 1: Chemical characteristics of tailing materials

Composition	Concentration (%)
SiO ₂	43.32
TiO ₂	2.22
Al ₂ O ₃	3.99
Fe ₂ O ₃ (t)	11.43
MnO	0.15
MgO	20.56
CaO	3.74
Na ₂ O	0.12
K ₂ O	0.42
P ₂ O ₅	0.15
Cr ₂ O ₃	0.20
L.O.I.	13.70
Total	100

3.2.2. Chemical composition of mine water

The pH analysis of water revealed that the water in Pit-I is strongly alkaline in nature; with the average pH and the electrical conductivity values of 9.20 and 2.30 mS/cm. The measured pH value of water was found to be above Department of Water Affairs (DWA) recommended range for domestic (6.0 - 9.0), recreational (6.5 - 8.5) and agricultural (6.5 - 9.0) uses of water. The results of analysis of anions and cations concentrations in water are presented in Table 2. The water was generally found to comprise of Cl⁻, Mg²⁺, F⁻ and K⁺ concentrations that are above the recommended range for domestic use of water (see Table 2).

Table 2: Chemical characteristics of mine water

Composition	Concentrations (ppm)	
	Mine Water	STD (ppm)
F ⁻	1.09	0-1.0
Cl ⁻	169.6	0-100
NO ₃ ⁻	0.76	0-30
PO ₄ ³⁻	-0.04	0-50
SO ₄ ²⁻	0.71	0-0.1
Na ⁺	8.22	0-100
Ca ²⁺	15.70	0-100
Mg ²⁺	67.85	0-6
K ⁺	87.6	-
Fe ³⁺	-0.27	0-200

ⁱDWA Standards for domestic use of water

The determined Cl⁻ and F⁻ levels increase the corrosive rate of the water and the potential to cause slight mottling of dental enamel in sensitive persons respectively. The detected concentration of K (87.6 ppm) is undesirable for infants or persons with renal diseases, while Mg (67.85 ppm) level has potential of introducing bitter taste and scaling problems is the water is used as drinking water by people.^[9]

3.4. Modeling of the Historic Nyala Mine Terrain

Terrain models of the Nyala Mine were developed in five meaningful segments (denoted as Area-1 to Area-5) covering the mine lease area as shown in Fig.4.

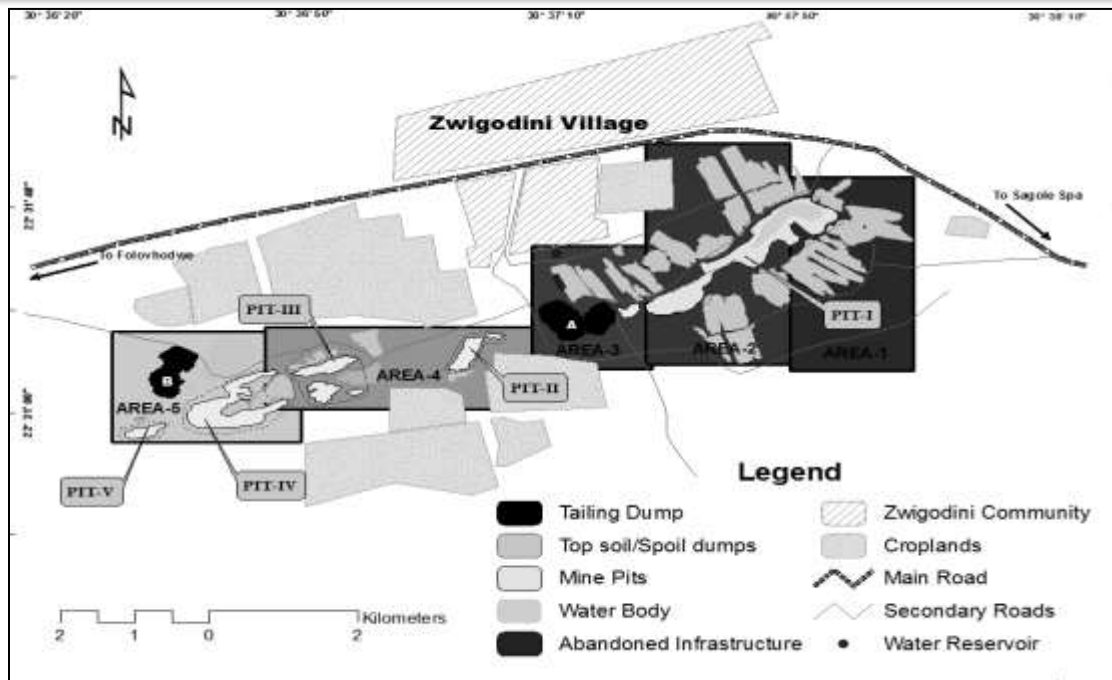


Figure 4: Areas delineated for landform modeling

3.4.1. Models description

Area-1 surface model covered an area of about 558103 m² along the southern part of Pit-I. The walls of Pit-I covered in the model were found to be approximately 29 m high and attaining the slope angles ranging from 14° to 44°. The spoil dumps directly above the south east facing pit walls added an extra height of about 14 m, making the pit walls to be about 43 m high. The surface model for Area-1 is presented in Fig.5A. The determined volume of Pit-I void shown in the model was estimated to be approximately 1323241 m³ over an area of 189903 m².

The 3D surface model of Area-2 covered the south western portion of Pit-I and its surrounding terrain. The model in Fig.5B shows extremely rugged terrain around Pit-I portion and this can be attributed to be due to relatively small excavations as well as the carelessly dumped spoils material found in the area. The walls of Pit-I portion covered in the model attained the slope angle ranging from 8° to 50° at the measured height of 20 to 36 m.

The central part of the mine (Area-3) is overlain by a large volume of magnesite tailings denoted as Tailing-A and few spoil materials (see Fig.5C). The tailings and spoil materials were found to be

about 23 m high and covering an area of 56152 m² above the estimated level surface defined by an elevation of 499 m above MSL. Slope angles maintained by the tailings material were estimated to be between 8° to 38°. The terrain along the north eastern part of Tailing-A appears rugged due to scattered spoil materials while the south western part is dominated by shallow excavations.

Area-4 portion of the mine is relatively flat with minimum excavations and spoils dumps (see Fig.5D). The modeled area of this part of the mine extent over an area of approximately 551292 m² and the major features covered by the model include Pit-II, Pit-III and the portion of Pit-IV. Areas of high grounds were only identified along the central part of the model that is; between Pit-II and Pit-III. Pit-II and Pit-III measured maximum depths were found to be 20 m and 29 m respectively. The spoil materials dumped directly above the northern part of Pit-III highwalls extended this wall to the maximum high of 27 m.

The last modeled portion of the mine (Area-5) covered an area of about 297997 m². The prominent features in this area include Tailing-B, Pit-V and half portion of Pit-IV (see Fig 5E). The height of the dump was measured to be about 26 m above a level surface of 495 m above the MSL.

Pit-V was identified to be the deepest pit followed by the small portion of Pit-IV measured to be about 25 m deep in this section of the mine.

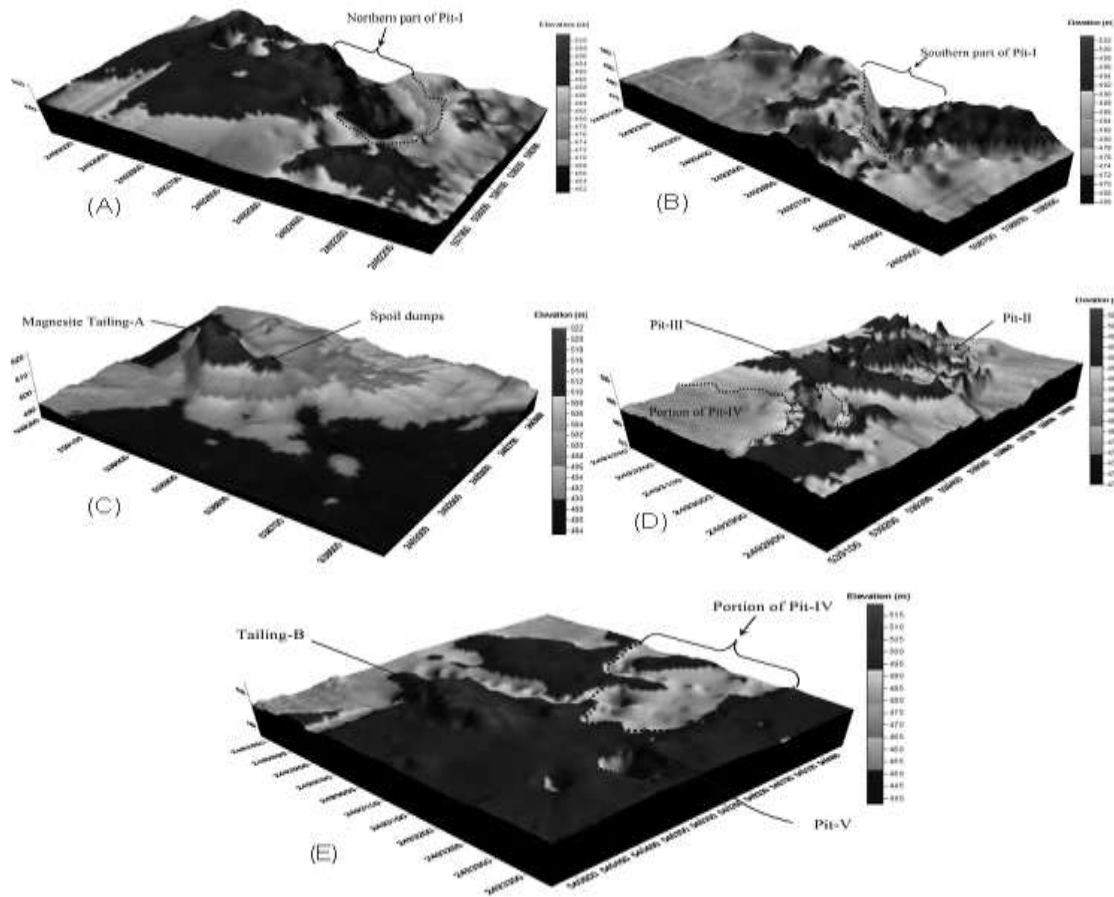


Figure 5: 3D surface models of the five terrain segments of the Nyala Mine, (A) Area-1; (B) Area-2; (C) Area-3; (D) Area-4 and (E) Area-5

3.4.2. Description of the proposed terrain

The development of level surface around Pit-I in Area-1 involved defining the volume of material required to fill the void areas below the adopted level surface of 488.2 m above MSL. According to the surface rehabilitation simulation model in Fig.6A, the development of the relatively level surface around Pit-I in Area-1 required that about 550757 m³ of high grounds materials is graded over the plane area of 39413 m² to fill the void of about 276440 m³ extending over an area of 32878 m².

The level terrain of this portion of the mine can be developed by cutting a reasonable amount of the waste material forming the high grounds to fill relatively low sections around Pit-I. As a result,

the horizontal plane at 486 m above MSL was critically selected to ensure effective leveling of the spoil dumps high grounds. The designed rehabilitation terrain model for Area-2 as shown in Fig.6B required cutting of about 715935 m³ waste material over an area of 186311 m², whilst the estimated fill volume was found to be approximately 333824 m³ at a plane area of 13104 m².

Despite the use of tailing material as fill material in road construction as well as bricks and/or blocks making purposes that were found attractive, the back filling of part of Pit-I portion in Area-2 with this material was found to be more favorable. The calculated volume of Pit-I portion that require backfilling was found to be 217613 m³ over the plane area of 219905 m². This volume of material if used as backfill will reduce the

tailing and spoil dump volume from the estimated 223906 m³ (above the level surface of 500 m above the MSL) to 6293 m³ that is sufficient for the material use for road construction and blocks making purposes. The filling of the portion of Pit-I with Tailing-A material is expected to reduce Pit-I volume by 15.8%.

Although Area-4 portion of the study area is characterized by relatively flat landscape the need for leveling spoil dumps around Pit-II and Pit-III to fill and level the rugged portion of Pit-IV and Pit-III was identified. Fig.6C illustrates the portion of the ground to be cut above the designed level surface around Pit-II to completely fill both Pit-III and part of Pit-IV covered in the surface model. The level surface that defines the Cut and Fill volumes was developed at 491 m above MSL. It was computed from the model that approximately 451949 m³ (over the level surface

of 491.5 m above MSL) of material will have to be moved to fill the relatively low grounds around Pit-II. The total estimated fill volume was found to be 971529 m³. The surface area occupied by the cut volume was estimated to be approximately 206637 m² while the fill volume area was estimated to be 344655 m².

The rehabilitation of Area-5 (see Fig.6D) terrain was developed such that a cut volume of 862747 m³ is to be graded to fill a void of about 513244 m³. Without material compaction operation, about 349503.42 m³ of this material was determined as an extra cut volume material. The rehabilitation of the terrain in Area-5 involved complete filling of Pit-IV and Pit-V with Tailing-B material and its surrounding spoils. The material to be graded or cut occupied an area of 188183 m². On the other hand, the area occupied by the fill volume material was estimated to be 117813 m².

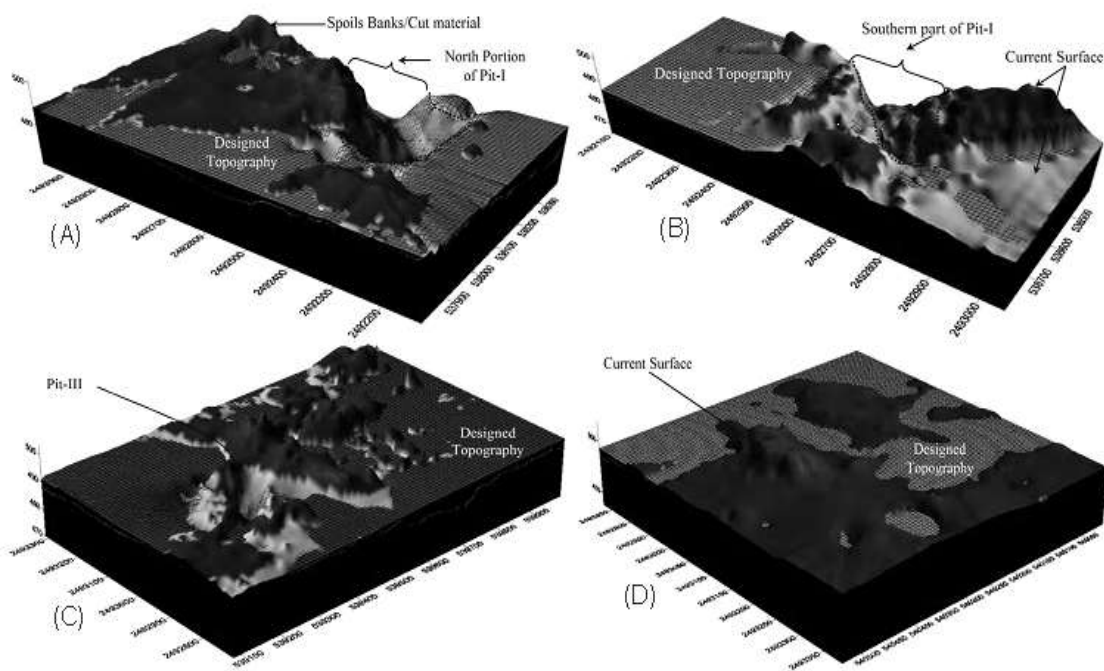


Figure 6: 3D representation of the developed level terrain surfaces for rehabilitation of the mine site, (A) Area-1; (B) Area-2; (C) Area-4 and (D) Area-5

3.5. Rehabilitation Options

The calculated sum total attractiveness score of the selected rehabilitation alternatives in Area-1 showed that crop farming alternative is the most attractive strategy, followed by the use of Pit-I as pit-lake, and development of the site for

settlement purposes. It was observed that Area-2 portion of Pit-I covered in the model rarely contain water and as a result, the construction of pit-lake alternative was not selected for evaluation in this area. Crop farming, site development for settlement purposes and construction of Dirt Park for BMX cycling purpose were found to be the



most attractive alternatives for the rehabilitation of Area-2 (see Table 3).

Rehabilitation options selected for Area-3 focused on addressing issues of environmental problems and physical hazards associated with large volume tailings and spoil materials covering the larger part of the area. These options ranged from doing nothing (no-action alternative), removal of the dump by means of evaluating alternative use of the tailings, and management of the dumps as an alternative strategy for containing the hazards. The results of the evaluation enabled identification of three most attractive land uses for Area-3, namely; (1) removal of the tailings material and its subsequent use to backfill part of Pit-I portion covered in Area-2, (2) utilization of the tailings material as fill material in road construction and (3) use of the material as replacement of river sand in making of blocks or bricks.

The use of Area-4 mine site for agricultural and development purposes as well as the use of Pit-II as landfill site for inert waste were found to be the most favorable rehabilitation alternatives. The rating of alternative rehabilitation strategies for Area-5 showed the use of the site for livestock grazing, agricultural purposes (crop land) and development of the site for residential purposes are the most attractive rehabilitation options.

3.5.1. Nyala Mine rehabilitation scenarios

The first scenario designed for rehabilitation of the Nyala Mine was developed from the land use alternatives with the highest attractiveness scores. These alternatives include the development of the site for crop farming purposes, pit-lake and inert landfill construction. The second most attractive rehabilitation options for individual mine terrain segments were used to design the second rehabilitation scenario. The rehabilitation strategies suggested in Scenario-II included cleaning up of the land for settlement and industrial development purposes, livestock grazing and construction of inert-landfill site, pit-lake associated with picnic site.

Finally, the third rehabilitation scenario was mainly developed using rehabilitation alternatives selected as less attractive operations. The most prominent options in Scenario-III were the rehabilitation of the site to support development

and the construction of earth ramp dirt pack along the north eastern part of the mine area. The rehabilitation plans for the three designed scenarios are presented in Fig. 7a, Fig.7b and Fig.7c.

4. Conclusions

The characterization of mine waste and water, together with terrain modeling proved to be robust scientific techniques for making sound decision on selection of appropriate rehabilitation strategies for the historic Nyala Mine.

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

Based on the outcome of interpretation of the developed terrain models, several rehabilitation alternative strategies for each modeled portion of the mine were selected. The results of the SWOT and QSPM analysis indicated that about 97% of the total rehabilitation area in the first rehabilitation scenario was favorable for cropland development. It also emerged that about 62% and 78% of the total area will be more appropriate for development of residential areas in the second and third scenarios respectively. The alternative use of Pit-I as pit-lake (in conjunction with picnic site in scenario II) and Pit-II as a landfill site for inert waste were proposed in all the rehabilitation scenarios.

Cost estimation of these practical rehabilitation strategies was recommended in order to ensure that low-cost strategies are implemented at the mine site.

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6. References

[1] Squillace, M. (1990.). *The Strip Mining Handbook*, Environmental Policy Institute. p150.

[2] Spitz, K. and Trudinger, J. (2009). *Mining and Environment from Ore to Metal*. Taylor and Francis Group, London, UK, pp 816-841.

[3] Australian Government (2006), *Mine Rehabilitation, Leading Practice Sustainable development Program for the Mining Industry*. Department of Industry Tourism and resources, pp 77.

[4] Mhlongo, S.E. (2012). *Development of a Modeling Framework for Design of Low-Cost and Appropriate Rehabilitation Strategies for Nyala Abandoned Mine*. Unpublished MSc. Dissertation, University of Venda, p 175.

[5] Kramers J.D., McCourt S. and van Reenen, D.D. (2006). *The Limpopo Belt*. In: M.R. Johnson, C.R. Anhaeusser, and R.J. Thomas, (Ed.), *The Geology of South Africa*. Geological Society of South Africa, Johannesburg and the Council of Geosciences, Pretoria, pp 209-239.

[6] Strydom J.H. (1998). *Magnesite*. In: M.G.C. Wilson and C.R. Anhaeusser, *The Mineral Resource of South Africa*, 6th Edition, Handbook 16. Council for Geosciences. pp 444-449.

[7] Herzberg W. (1976). *Magnesite*. In: C.B. Coetzee, *Mineral Resources of Republic of South Africa*, 4th Edition. Government Print, Pretoria, pp. 385-388.

[8] Surfer[®]8 User’s Guide (2002). *Surfer[®]8 Contouring and 3D Surface Mapping for Scientists and Engineers*. Golden Software, Inc. Colorado, p 640.

[9] DWA: Department of Water Affairs (1996). *South African Water Quality Guidelines (2nd edition)*. Vol.1, Domestic Use. pp 17, 47, 129.

Table 3: Selected appropriate rehabilitation options and the designed rehabilitation scenarios

Mine Area	Selected rehabilitation alternatives		Designed rehabilitation Scenarios		
	Most attractive rehabilitation option	Attractiveness scores	Rehabilitation Alternatives	Surface Area of Total (ha)	%Total
Area-1	▪ Agriculture: crop farming	5.70	▪ Proposed Crop land	1593	97
	▪ Pit lake	4.95	▪ Pit-lake	41	2.5
	▪ Development of residential sites	4.75	▪ Inert landfill site	10	0.5
			<i>Total area</i>	<i>1644</i>	<i>100</i>
Area-2	▪ Agriculture: crop farming	5.60	Scenario II		
	▪ Development of residential sites	4.95	▪ Pit-lake	41	1.9
	▪ Recreational: dirt park construction	4.85	▪ Inert landfill site	10	0.5
Area-3	▪ Back filling of part Pit-I portion in Area-2	5.50	▪ Proposed residential site	1329	61.9
	▪ Use of tailings in road construction	4.80	▪ Picnic park	339	15.8
	▪ Use of tailing for block making	4.10	▪ Livestock grazing site	425	19.8
Area-4	▪ Agriculture	5.00	<i>Total Area</i>	<i>2144</i>	<i>100</i>
	▪ Development of residential sites	4.95	Scenario III		
Area-5	▪ Use of pits as Inert landfill	4.10	▪ Proposed residential site	1541	77.8
	▪ Agriculture (crop farming)	5.10	▪ BMX Dirt Park construction site	390	19.6
	▪ Livestock Grazing	4.30	▪ Pit Lake	41	2.0
	▪ Development	3.90	▪ Inert landfill site	10	0.5
			<i>Total Area</i>	<i>1982</i>	<i>100</i>

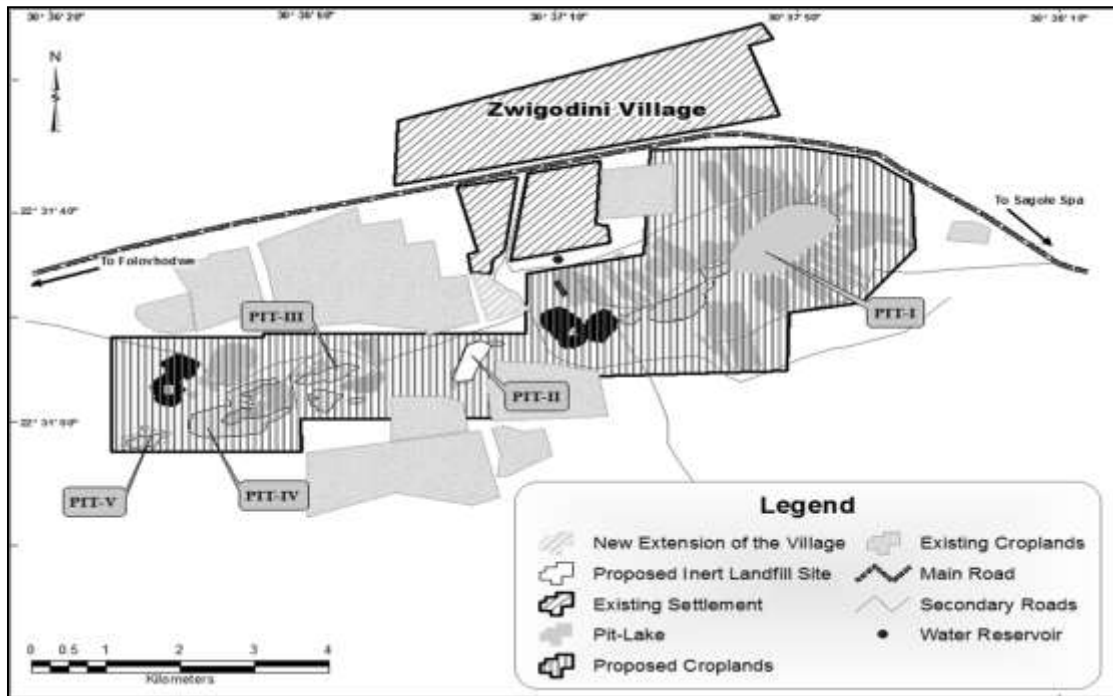


Figure 7a: Proposed mine site rehabilitation Plan I.

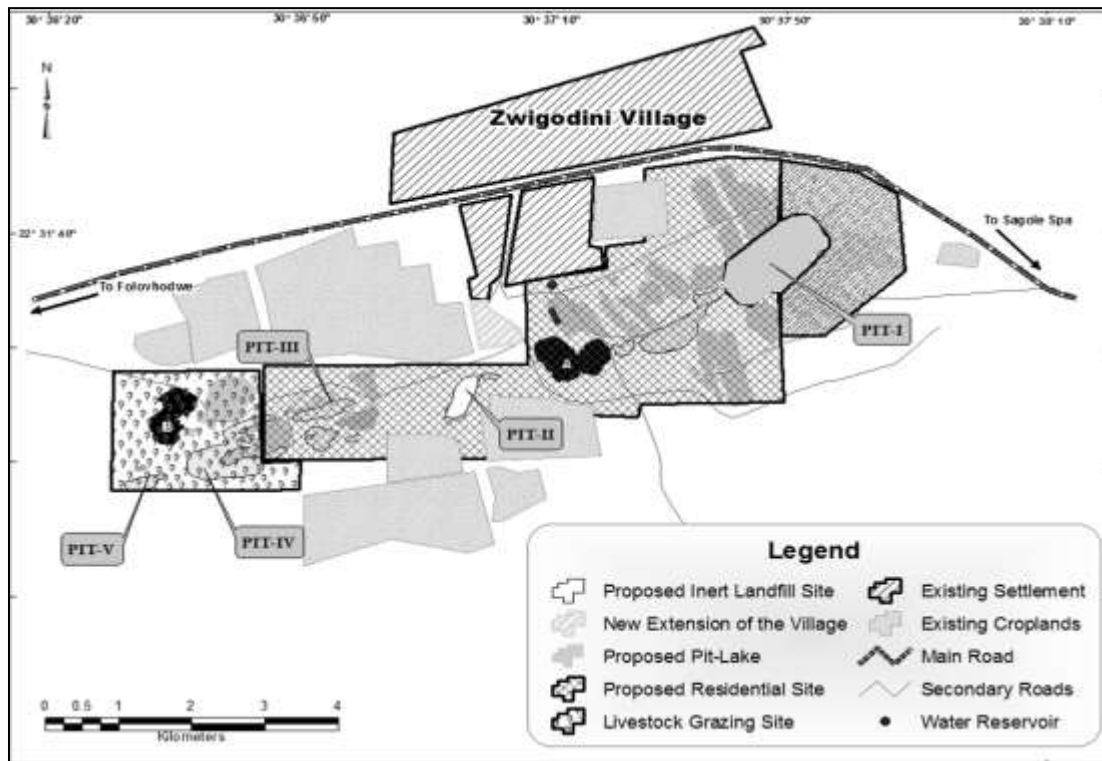


Figure 7b: Proposed mine site rehabilitation Plan II.

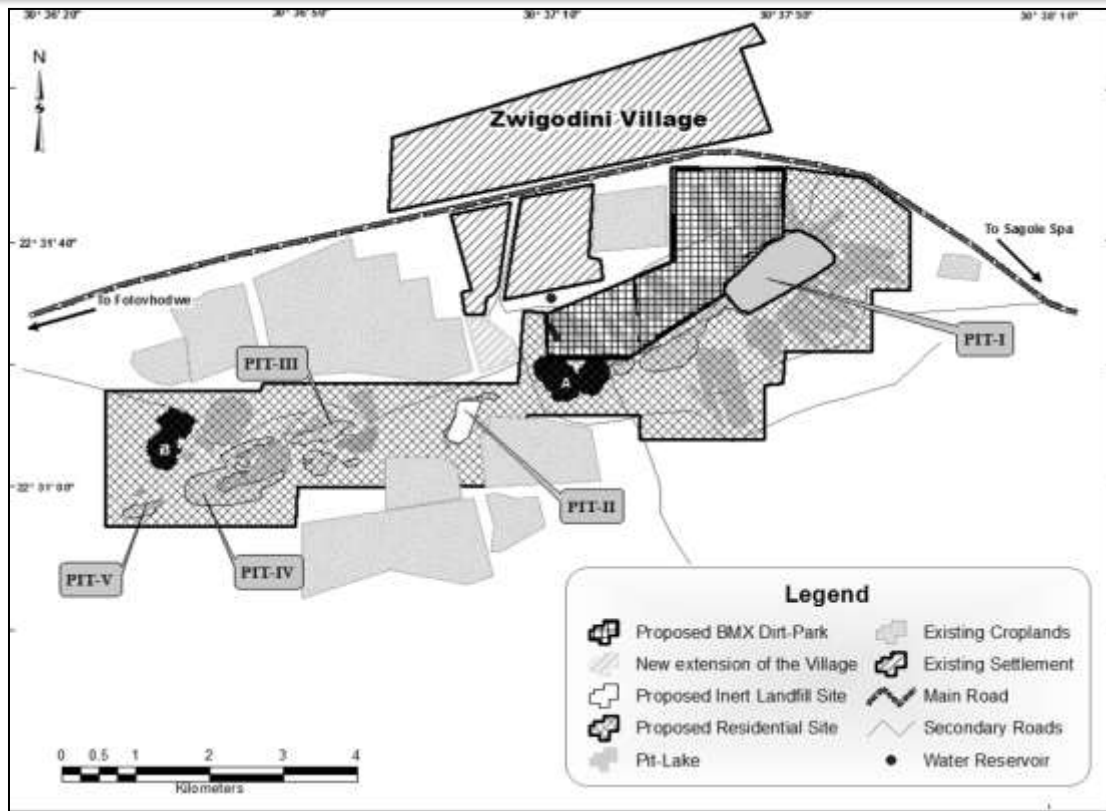


Figure 7c: Proposed mine site rehabilitation Plan III.