THARISA MINE WASTE ROCK GEOCHEMISTRY STUDY AND WASTE ASSESSEMENT

Tharisa PGM & Chrome mine

Tharisa Platinum Group Metal and Chrome Mine

Prepared for: Tharisa Minerals (Pty) Ltd

tharisa

SLR

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EXECUTIVE SUMMARY

Tharisa Minerals (Pty) Ltd runs an opencast mining operation that targets Platinum Group metals (PGM) and Chrome ore mineralisation situated in the North West Province of South Africa. The mine has been in operation since November 2008 and operates with an approved Environmental Management Programme (EMPr), which was amended in 2014. Waste rock (WR) from the open pit areas is stockpiled on waste rock dumps (WRDs). Key existing mine infrastructure includes haul roads, run-of-mine, a concentrator complex, various product stockpiles, topsoil stockpiles, WRDs, Tailings storage facilities (TSFs) and supporting infrastructure such as offices, workshops, change house and access control facilities.

As part of its on-going mine planning, Tharisa has identified the need for additional waste rock storage on site. In this regard, Tharisa is making an application to the Department of Mineral Resources and Energy (DMRE) for an integrated EA and update of the mine's current EMPr. The following activities are now proposed:

- the expansion of the existing and approved Far West WRD 1 by a footprint of 109 ha. The expanded area will be referred to as the West Above Ground (OG) WRD. Portions of the West OG WRD will be located on backfilled areas of the West Pit; and
- the establishment of a waste rock dump (referred to as the East OG WRD) on backfilled portions of the East Pit. The proposed East OG WRD will cover an area of approximately 72 ha.

Three (3) WR composite samples from the Tharisa PGM and Chromite mine were collected by a SLR agent and subjected to comprehensive geochemical investigation and waste assessment to predict the leachate quality from the waste storage facilities on site and if they pose any risk to surface or groundwater resources.

The laboratory results (LCT and SPLP) are based on first flush static tests that often give conservative (elevated) concentrations whereas the modelled source terms are calibrated to long term water quality monitoring data that is subject to field scale conditions and are regarded as more accurate indicators of site leachate quality.

The X-Ray Diffraction (XRD) analysis confirmed the dominant minerals for all waste materials at Tharisa mine to be Enstatite and Plagioclase, with minor Muscovite, Augite and Quartz present. The Synthetic Precipitation Leaching Procedure (SPLP) results for Tharisa waste materials returned only SANS 241: Operational and Aesthetic exceedances for Al and Fe, respectively.

According to NEMWA GN R. 635 and 636 guidelines, all the waste rock samples can be classified as equivalent to **Type 4** waste using a risk-based approach and will be required to be incorporated into a storage facility with a **Class D** barrier.

The geochemical source terms modelled for the Tharisa WR materials predicted the following CoCs for possible risk to water resources due to:

- Exceedance of DWAF livestock TWQG nitrate levels for all the waste streams.

However, nitrate is not sourced from the mined geochemistry but originates from operational blasting and decays with time. Based on the kinetics of the bacteria-controlled nitrate reduction, the half-life of nitrate is estimated to be between 500 – 1350 days (Eppinger and Walraevens, 1998) and proven to be between 108-162 days based on long-term site monitoring data.

The increase in the modelled pH levels relative to the SPLP input values is due to the dominant mineral Enstatite, which tends to uptake 2 H^+ ions in exchange for Mg^{2+} on the mineral surface, which ultimately results in an increase in modelled leachate pH (Oelkers & Schott, 2001).

RECOMMENDATIONS

Although the predicted leachate quality from the Tharisa waste storage facilities is expected for mine effluent, SLR would like to make the following recommendations:

- Results of the source term assessment should not be evaluated in isolation but together with numerical or reactive groundwater modelling risk assessment. The complete source, pathway and receptor should be considered in evaluating the overall potential risks to groundwater.

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ACRONYMS AND ABBREVIATIONS

Acronym / Abbreviation	Definition
BIC	Bushveld Igneous Complex
CBE	Charge Balance Equilibrium
CoC	Constituents of Concern
DWAF TWQG	Department of Water Affairs and Forestry (now DWS) target water quality guidelines
DWS	Department of Water and Sanitation
EMPr	Environmental Management Programme
IFC	International Finance Corporation
IWUL	Integrated Water Use Licence
LC	Leachable Concentrations
LCT	Leachable Concentration Threshold
MAR	Mean Annual Rainfall
MG	Middle Group
MQF	Magaliesberg Quartzite Formation
NEMWA	National Environmental Management: Waste Act
PET	Potential Evapotranspiration
PGM	Platinum Group Metals
PHREEQC	PH, Redox, Equilibrium Code
RLS	Rustenburg Layered Suite
SANS	South African National Standard
SPLP	Synthetic Precipitation Leaching Procedure
TC	Total Concentration
TCT	Total Concentration Threshold
TSF	Tailings Storage Facility
TWQGR	Target Water Quality Guideline Rangers
WCMR	Waste classification and management regulations
WMA3	Marico Water Management Area
WR	Waste Rock
WRDs	Waste Rock Dumps
XRD	X-ray Diffraction

Tharisa Mine Waste Rock Geochemistry Study and Waste Assessment

1. INTRODUCTION

Tharisa Minerals (Pty) Ltd runs an opencast mining operation that targets Platinum Group metals (PGM) and Chrome ore mineralisation situated in the North West Province of South Africa. The mine has been in operation since November 2008 and operates with an approved Environmental Management Programme (EMPr), which was amended in 2014. Mining is undertaken in two sections, namely the East Mine and West Mine, using conventional open pit truck and shovel methods. The two mining sections are separated by the perennial Sterkstroom River and the D1325 (Marikana Road). Waste rock (WR) from the open pit areas is stockpiled on waste rock dumps (WRDs). Some in-pit dumping of WR has taken place at the East mine. Key existing mine infrastructure includes haul roads, run-of-mine, a concentrator complex, various product stockpiles, topsoil stockpiles, WRDs, Tailings storage facilities (TSFs) and supporting infrastructure such as offices, workshops, change house and access control facilities.

As part of its on-going mine planning, Tharisa has identified the need for additional waste rock storage on site. In this regard, Tharisa is making an application to the Department of Mineral Resources and Energy (DMRE) for an integrated EA and update of the mine's current EMPr. The following activities are now proposed (Figure 1-1):

- the expansion of the existing and approved Far West WRD 1 by a footprint of 109 ha. The expanded area will be referred to as the West Above Ground (OG) WRD. Portions of the West OG WRD will be located on backfilled areas of the West Pit; and
- the establishment of a waste rock dump (referred to as the East OG WRD) on backfilled portions of the East Pit. The proposed East OG WRD will cover an area of approximately 72 ha.

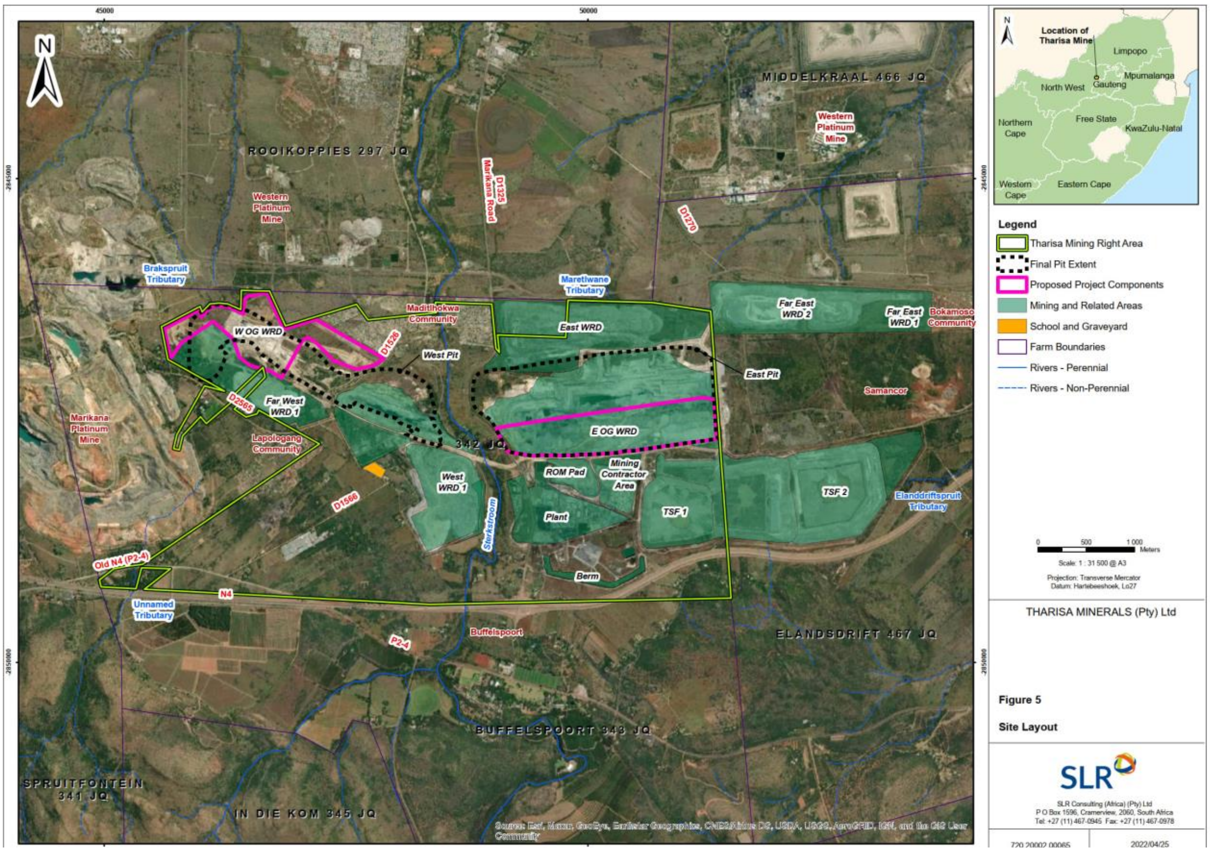

Figure 1-1: Location of proposed extended Waste Rock storage areas

The changes in operating and processing procedures had prompted for an updated geochemical characterisation, waste assessment and modelled source term of the different extractive waste rock (WR) that may have an impact on the local ground water at Tharisa Mine.

The objective of this updated Geochemistry investigation is to produce the following:

- confirm the geochemical characterisation of all WR lithologies,
- undertake a waste assessment and determine the barrier requirements for WR materials,
- produce geochemical source term of the different extractive waste materials which can be used to update the sites groundwater numerical model to predict the risk to groundwater of the mining operation.

2. BACKGROUND

2.1 SITE CHARACTERISATION

2.1.1 LOCATION AND TOPOGRAPHY

The Tharisa mine is located on farms 342 JQ and Elandsdrift 467 JQ near the town of Marikana, approximately 35 km to the east of Rustenburg, North West province, South Africa (Figure 2-1). In general, the area surrounding the Tharisa Mine comprises flat plains with a gentle slope (1%) towards the north. The Magaliesberg Mountain range lies approximately 2 km to the south of the mine. Peaks in this part of the Magaliesberg Mountain range rise to approximately 1 400 mamsl.

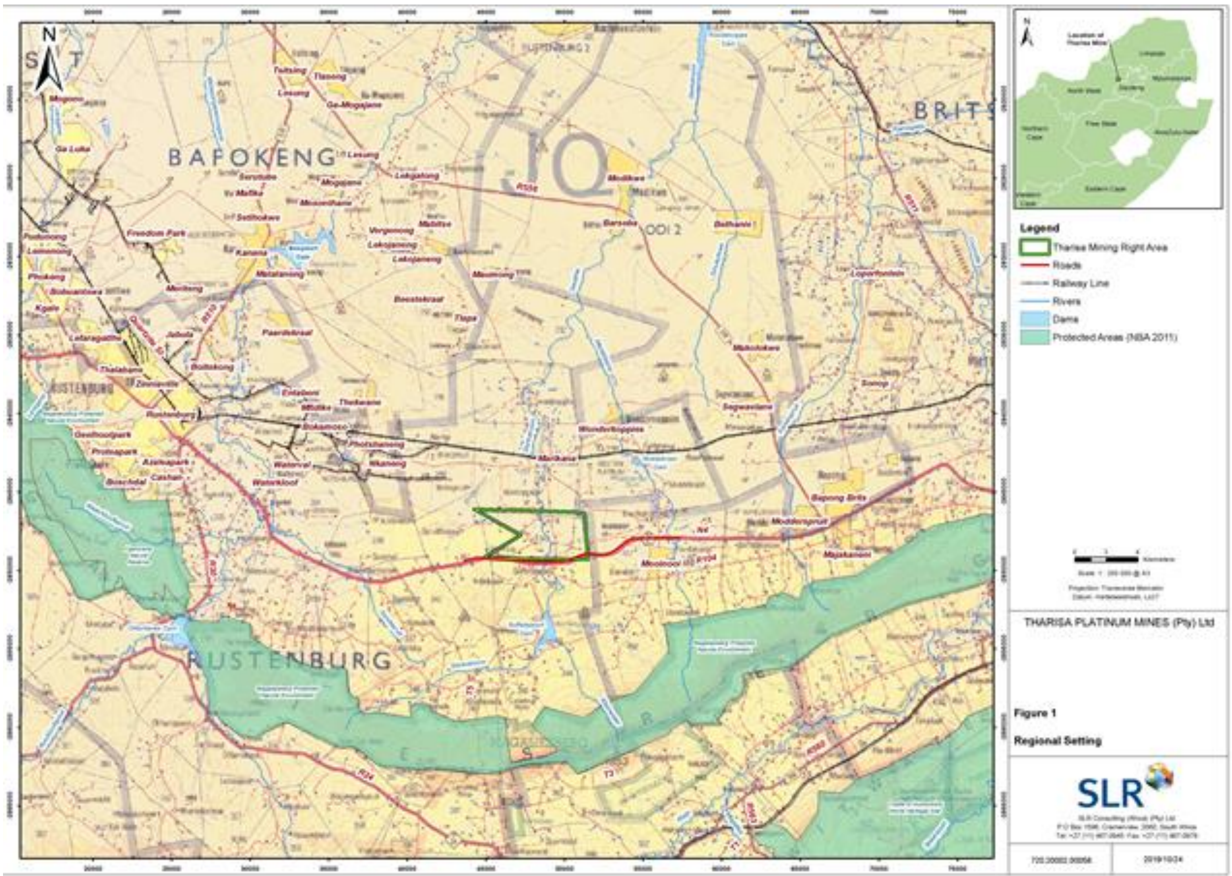

Figure 2-1: Regional Site Setting

2.1.2 GEOLOGY

In general, Tharisa Mine and the surrounding area are underlain by igneous rocks of the Rustenburg Layered Suite (RLS), which forms part of the Bushveld Igneous Complex (BIC) and deposited approximately 2 050 million years ago. The RLS layered sequence is generally planar in nature and gently folds around a thickened part of floor rocks known as the Magaliesberg Quartzite Formation (MQF). The general stratification of the RLS, BIC is illustrated in Figure 2-2. The Magaliesberg Mountain Range is formed by quartzites (Transvaal Sequence), which are common as floor or basement rocks to the BIC. All the chromitite and platinum mineralisation is in the RLS. These layered rocks have a maximum thickness of up to about 8 km consisting of pyroxenite, norite, gabbro and other mafic to ultramafic lithologies.

The RLS comprises five stratigraphic zones representing the sequential fractional crystallisation that accompanied the cooling of this magmatic body:

- The Marginal Zone, which comprises pyroxenites and norites with no economic potential;
- The Lower Zone which comprises ultramafic rocks, such as pyroxenites and harzburgites, containing thin, high-grade chromitite seams;
- The Critical Zone pyroxenites, norites and anorthosites that host all the significant platinum group metals chromite deposits;
- The Main Zone, which consists mainly of homogeneous norites and gabbros that are locally exploited as dimension stone; and
- The Upper Zone norites, gabbros and diorites, which host over 20 massive magnetite seams, some of which are exploited for vanadium and iron ore.

Tharisa Mine is located on the southwestern limb of the BIC in the Marikana section. The Marikana section is separated from the Brits section to the east by the Wolhulterskop fault and the Rustenburg section to the west by the Spruitfontein upfold (Figure 2-3). The target ore body is the Middle Group (MG) Chromitite Layers (MG1 –MG4). The MG Chromitite Layers outcrop on the farm 342 JQ striking roughly east - west and dipping at 12-15° to the north. Towards the western extent of the outcrop, the stratigraphy typically narrows, and the dip is steeper, with a gentle change in strike to northwest- south-east. The entire MG package is developed over a true thickness of 47 m on the eastern portion of 342 JQ and thins to 25 m to the west near the Spruitfontein upfold. The Wolhulterskop fault and the Spruitfontein upfold occur to the east and west of the Tharisa Mine, respectively. Within the Mining Right area, minor faults and some dykes occur, but there are no major displacements.

The MG package has four main groups of chromitite layers hosted in anorthosite, norite and feldspathic pyroxenite. These chromitite layers are important as they contain significant concentrations of chromite and PGMs.

The waste rock associated with the PGM at the Tharisa Mine generally comprises lithologies of the RLS as follows (SLR, 2019):

- Pyroxenite
  - Ultramafic rock with less than 45 % total silica;
  - Composed almost entirely of one or more pyroxenes (inosilicate mineral); and
  - Other minerals may include biotite, hornblende, olivine and iron oxides.

- Anorthosite
  - Basic rock with less than 55 % total silica;

- Quartz virtually absent;
- Composed at least 90 % plagioclase feldspar; and
- Other minerals may include olivine, pyroxene and iron oxides.

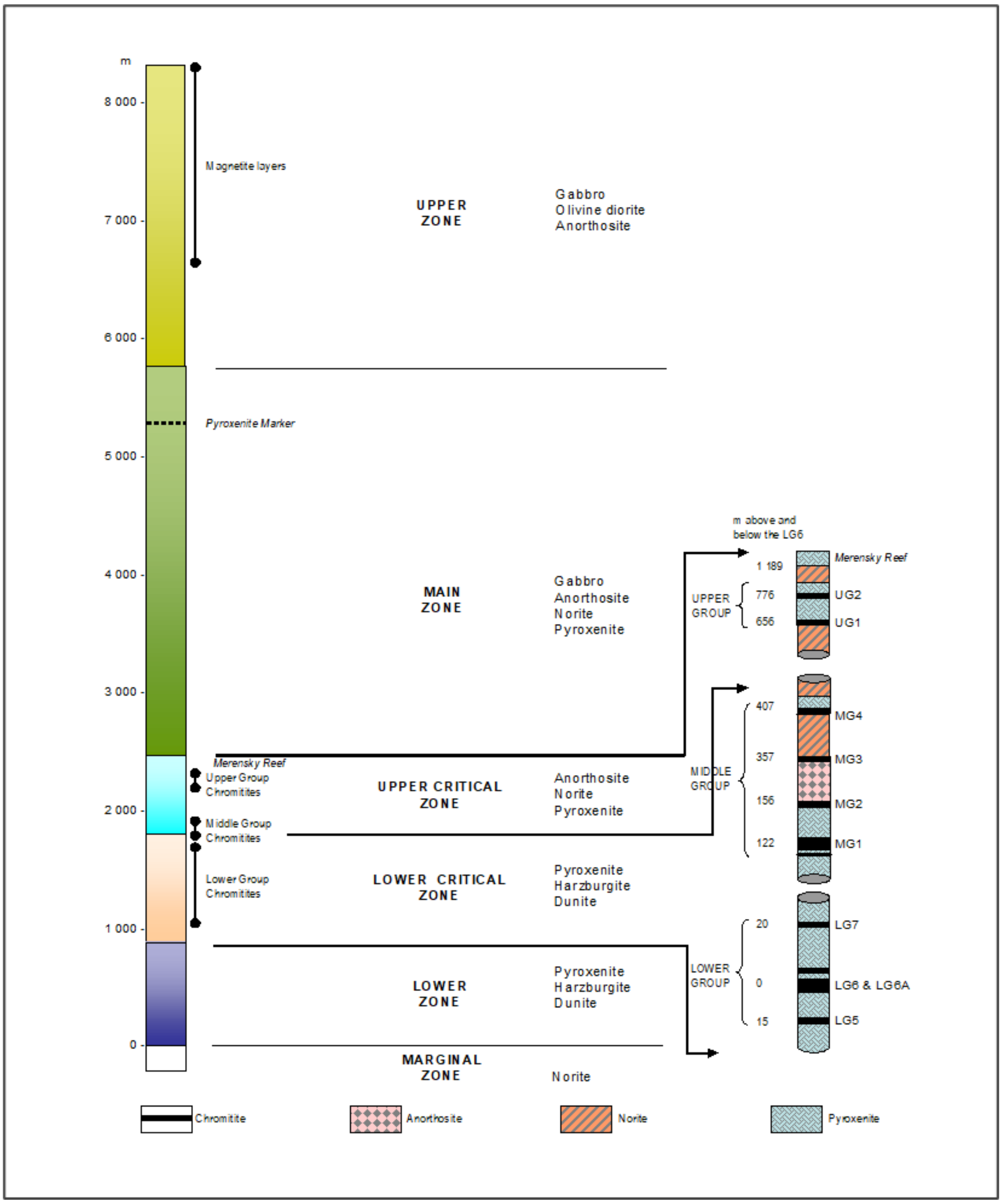

Figure 2-2: Stratigraphic column of the MG chromite Layer at Tharisa mine

- Norite
    - Basic rock with less than 55 % total silica;
    - Composed of plagioclase feldspar and pyroxene;
    - Orthopyroxene is dominant over clinopyroxene; and
    - Other minerals may include olivine, biotite, hornblende and cordierite.

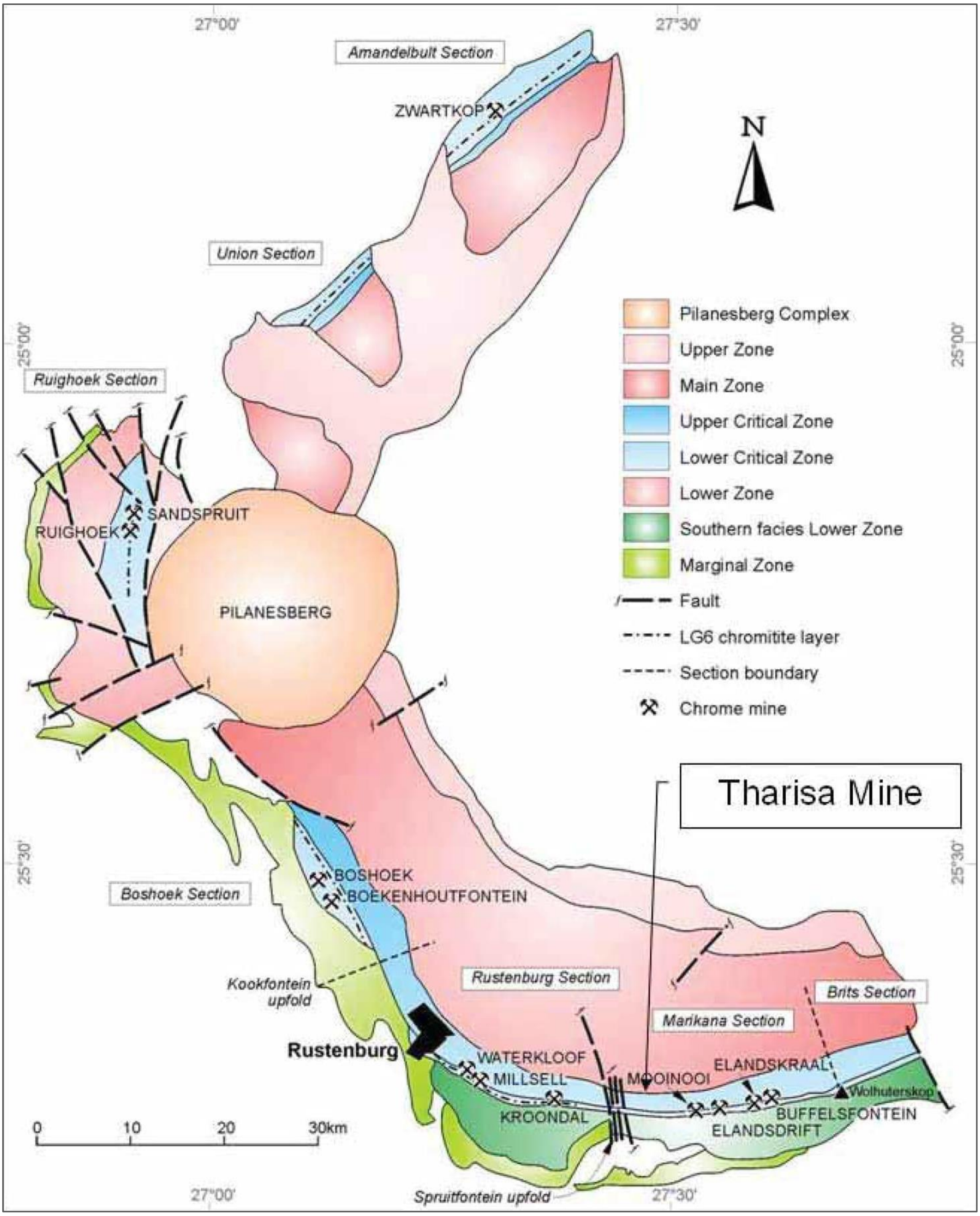

Figure 2-3. Map of the western limb of the Bushveld Igneous Complex (BIC) showing the location of Tharisa Mine.

2.1.3 HYDROLOGY

The mine is located within the upper reaches of the A21K quaternary catchment, which falls within the Lower Crocodile Secondary catchment and the Crocodile West and Marico Water Management Area (WMA3).

The perennial Sterkstroom and its tributaries rise in the Magaliesberg Mountain Range, south of the N4, from where it flows through numerous agricultural and industrial areas into the Bufflespoort Dam[1]. The Sterkstroom then flows from the Buffelspoort Dam through agricultural areas and the Tharisa mining operations, between the western and eastern mining areas. Downstream of the mine, the Sterkstroom flows into the Roodekopjes Dam, and ultimately flows into the Crocodile River.

The normal dry weather flow of the Sterkstroom is dependent on the rate of release from the Buffelspoort Dam situated about 3.25 km upstream of Tharisa Mine. Water from the Sterkstroom is used for domestic purposes such as washing and bathing, livestock watering and for agricultural purposes.

Tharisa monitors surface water quality monthly as part of its water monitoring programme. The surface water quality is compared against the amended Integrated Water Use Licence (IWUL) surface water quality guideline limits. In addition to this, given that surface water in the area is mainly used for domestic and irrigation purposes, surface water quality data is also compared against the Target Water Quality Guideline Ranges (TWQGR) for domestic use and irrigation.

2.1.4 HYDROGEOLOLOGY

The Tharisa Mine is underlain by a shallow upper weathered aquifer and a deeper fractured aquifer. The weathered overburden is highly variable in thickness from 3 m to more than 30 m based on existing borehole logs and evidence of borehole depths. The deeper fractured bedrock aquifer is characterized by very low matrix permeability, poorly connected joints/fractures and dolerite/diabase dykes (that may act as barriers to groundwater flow). Near the water courses, alluvium either fully or partially replaces the weathered overburden and the water courses do lose and gain water to the alluvium aquifer. Recharge of the alluvial aquifers is also through lateral groundwater flow from the shallow weathered aquifer and by rainfall events. The thickness of the alluvial sediments has been estimated at 3 to 5 m with its lateral distribution restricted to the immediate banks of the current active channel.

The interface between the overlying weathered or alluvial aquifer and the deeper fractured aquifer features is relatively impermeable. Its effective permeability is determined by interconnected and open fracture systems. These fracture systems can potentially allow for rapid vertical groundwater flow from the weathered overburden as well as surface water bodies to greater depths. Whilst in general the weathered aquifer and lower fractured aquifer are poorly connected; this is not always the case. The aquifer system is defined as a minor aquifer region with potential for higher yielding zones (defined by the groundwater specialist in accordance with Parsons (1995)). Pump tests of a range of boreholes indicated that the average upper aquifer yield is between 1 and 2.5 litres /second (SLR, 2014).

Quaternary catchment A21K receives an estimated average annual groundwater recharge of 24.4 million m^3 (Mm^3), of which 3.4 Mm^3 per annum or 13.8% is required for the Reserve, consisting of both basic human needs (estimated at 0.5Mm^3/a) and an ecological component (estimated at 2.9Mm^3/a). This equates to an approximate recharge across the catchment of about 28 mm/a (SLR, 2014). Tharisa also monitors groundwater quality monthly as part of its water monitoring programme and compared with the amended IWUL quality guideline limits and TWQGR for domestic use and irrigation.

[1] Aquatico Scientific (Pty) Ltd. 2018. Quarterly Groundwater Quality Assessment Report; July 2018 to September 2018 prepared for Tharisa Minerals. Ref: TM/GWQR3/2018/IF

2.1.5 CLIMATE

The Tharisa Mine falls within the Highveld Climatic Zone. This is a warm temperate climate. Rain generally occurs in the spring and summer months between October and March and is generally characterised by high intensity rainfall often in the form of thunderstorms (on average 75 storms per annum) with lightning. The area also receives strong, gusty winds and the frequency of hail in the area is high (on average four to seven times per season). The site experiences a mean annual rainfall (MAR) and potential evapotranspiration (PET) of 625 mm and 2148 mm respectively[2].

Average monthly rainfall and evaporation data for the Buffelspoort weather station is provided in Figure 2-4. The average monthly rainfall at the Buffelspoort weather station is 55 mm. Given that the Buffelspoort weather station is only 5 km from the Tharisa Mine, similar rainfall levels can be expected at the mine. The average monthly evaporation rates are 141 mm. Consequently, monthly average evaporation rates recorded at the Buffelspoort weather station exceed the monthly average rainfall for all months.

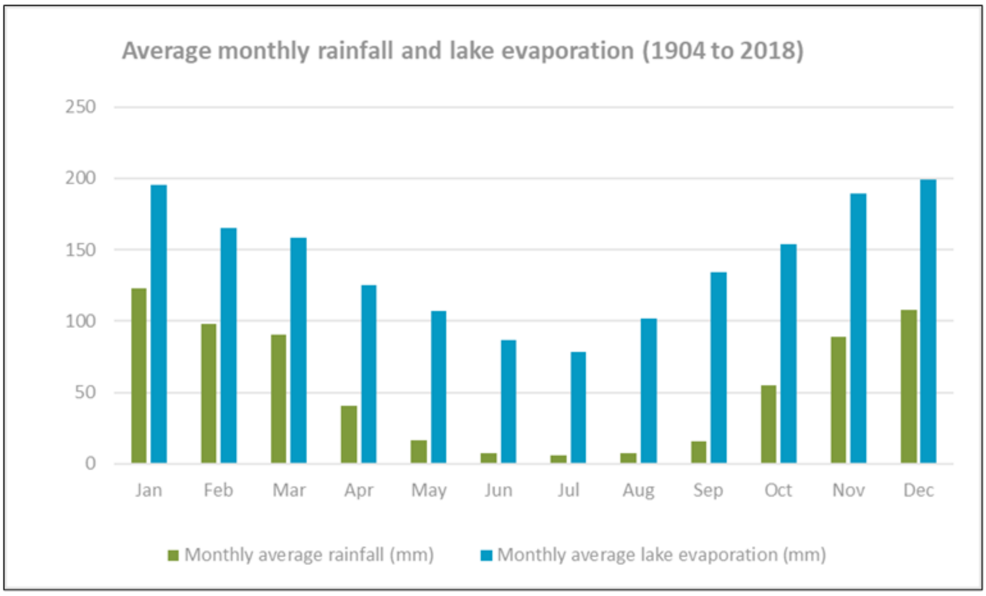

Figure 2-4: Average monthly rainfall measured at the Buffelspoort Weather Station

The average monthly maximum and minimum temperature values for the Buffelspoort Weather station has been recorded as 26.2°C and 11.1°C, respectively (Table 2-1).

Table 2-1: Minimum, average and Maximum temperatures measured at Buffelspoort weather station

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Year
Min	17.1	16.8	15.1	11.4	6.8	3.3	3	5.5	9.9	13	14.9	16.1	11.1
Ave	23.6	23.1	21.6	18.3	14.9	11.7	11.9	14.5	18.6	20.8	21.9	22.9	18.6
Max	30.1	29.4	28.1	25.3	22.9	20	20.6	23.6	27.4	28.5	29	29.8	26.2

[2] www.samsamwater.com/climate/

3. METHODOLOGY

3.1 SAMPLING

A SLR field agent visited the site on 26 January 2022 to collect WR samples for geochemical analysis (Figure 3-1). Three rock samples were collected from the East Dump, four from the West Dump and Far West Dump encompassing all the main WR lithologies. All the samples were then transported to Waterlab geochemistry laboratory, accompanied by chain of custody documentation for comprehensive analysis. Before joining the analysis que, the hand WR samples were crushed, milled, partitioned, and constituted into three composite samples representing the overall WR lithology for the main waste rock dumps as per Table 3-1 below.

Table 3-1: Tharisa Mine WR composite lithological proportions

Composite #	Location	Lithology	%	Sample #	Total %
Comp 1	East Dump	Pyroxenite	19	THED-03	**100**
		Norite	74	THED-01	
		Anorthosite	5	THED-02	
		Dolerite Dyke	1	THWD-01	
		Fe rich ultramafic pegmatoid (IRNP)	1	THFWD-04	
Comp 2	West Dump	Pyroxenite	19	THWD-03	**100**
		Norite	74	THWD-04	
		Anorthosite	5	THWD-02	
		Dolerite Dyke	1	THWD-01	
		Fe rich ultramafic pegmatoid (IRNP)	1	THFWD-04	
Comp 3	Far West Dump	Weathered Pyroxenite	19	THFWD-01	**100**
		Weathered Norite	74	THFWD-02	
		Anorthosite	5	THFWD-03	
		Dolerite Dyke	1	THWD-01	
		Fe rich ultramafic pegmatoid (IRNP)	1	THFWD-04	

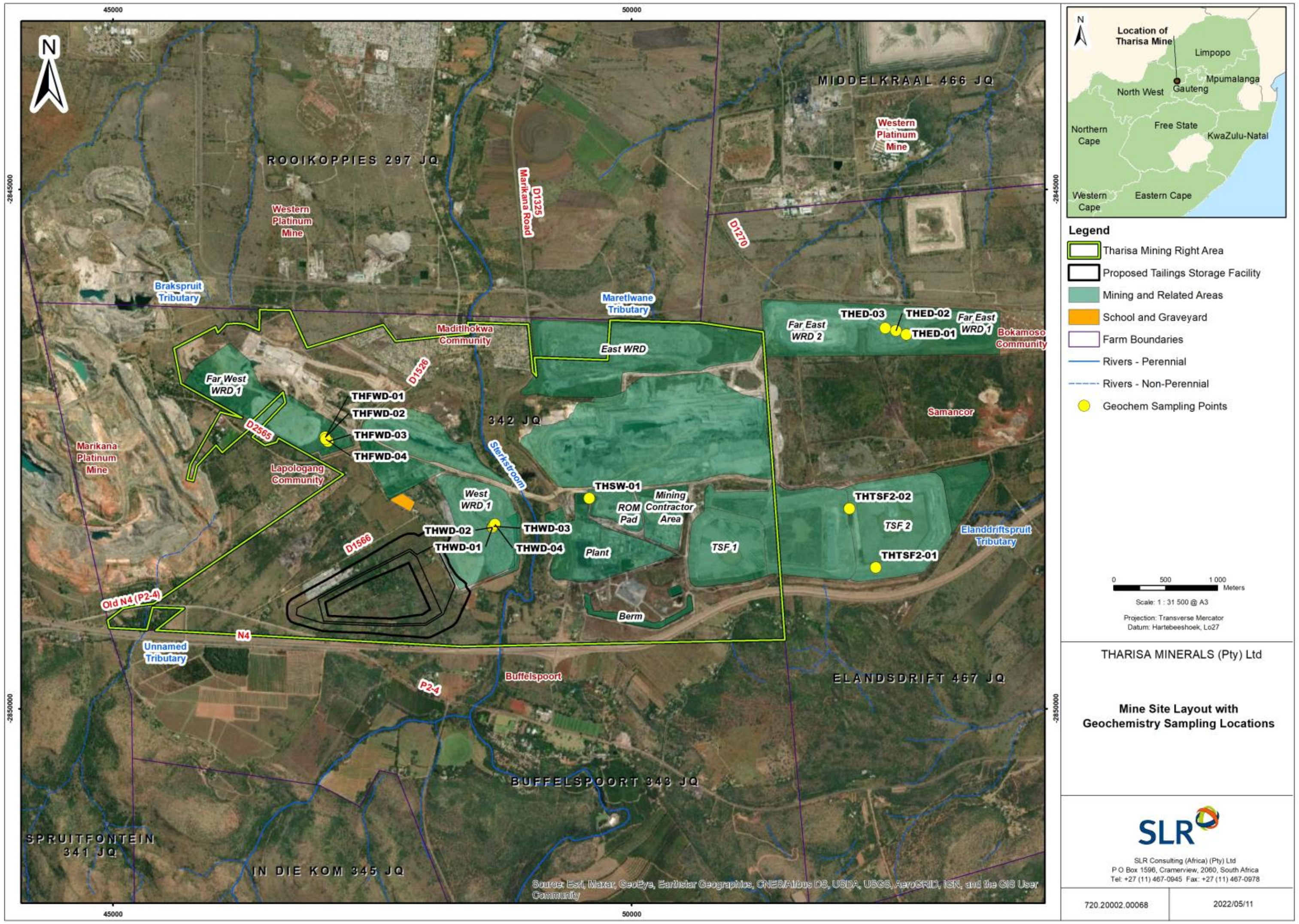

Figure 3-1: Geochemical sampling locations at Tharisa Mine

3.2 MINEROLOGY: X-RAY DIFFRACTION (XRD)

Minerals are the building blocks of rocks. Mine drainage quality is generally a function of mineral dissolution (or precipitation) during interaction of rocks with water. X-ray Diffraction (XRD) analysis identifies the main crystalline mineral phases in each sample. XRD is conducted on whole rock samples that have been crushed and ground to a powder. The powdered sample is placed on a flat holder, which faces the X-ray beam. The X-rays are diffracted by the crystal planes in the minerals, with diffraction peaks at characteristic angles. The phases are identified by comparing the locations and intensities of the diffraction peak with the peaks of mineral reference standards (Price, 2009). Limitations of XRD are that it is not easy to identify non-crystalline minerals, and minerals present in low concentrations may not be detected.

3.3 SYNTHETIC PRECIPITATION LEACHING PROCEDURE (SPLP)

The Synthetic Precipitation Leaching Procedure is a quick and inexpensive method to determine:

- The mobility/leachability of low volatility organic and inorganic analytes in liquids, soils, and wastes.
- The measure of desorption of contaminants from soil (rather than adsorption).
- The possibility of leaching metals into ground and surface waters.
- A site-specific impact to groundwater soil remediation standard.

Since the test uses custom pH levels to simulate rainfall in a particular geographic region, this test is often recommended over other methods when predicting leachate quality and risk to ground water.

Many factors can affect the leaching potential of organic constituents: pH, redox conditions, liquid-to-solid ratio, solubility, partitioning, presence of organic carbon, and non-aqueous phase extraction. Therefore, SPLP concentrations are used as input concentrations to Geochemical models to simulate realistic field conditions and produce more accurate source terms.

As part of this assessment, the SPLP and modelled source terms were subject to preliminary screening to identify potential CoCs by comparing the results to the following relevant water quality and effluent standards:

- South African National Standards (SANS) 241 Drinking Water (SANS 241:2015)
- Department of Water and Forestry (now department of Water and Sanitation; DWS) livestock target water quality guidelines (DWAF TWQG).

Use of drinking water guidelines does not suggest that leachates and drainage from mine activities will be used for drinking purposes. Use of these guidelines is purely intended as a preliminary indicator of potential environmental risk.

3.4 WASTE ASSESSMENT

The objective of the waste assessment is underpinned by the legal provisions of the National Environmental Management: Waste Act (NEMWA) 59 of 2008 which prescribes the following in terms of waste streams:

- Undertake a waste type assessment in terms of GN R. 635 (23 August 2013); and
- Determine the barrier requirements as per GN R. 636. (23 August 2013).

The South African waste classification regulations provide norms and standards for assessing/classifying (GN Regulation 635) waste material. Although the Norms and Standards refer to landfills, the definition of waste in South Africa includes mine residues such as tailings and waste rock and therefore the norms and standards apply to mine residue classification.

In terms of the regulations, the total concentration (TC) of chemical substances specified in Section 6 of GN R. 635 that are known to occur, likely to occur or can reasonably be expected to occur are determined. The TC of the chemical substances is compared to the total concentration threshold (TCT) limits specified in Section 6 of GN R. 635. The leachable concentrations (LC) of the chemical substances must be determined and compared to the leachable concentration threshold (LCT) limits specified in Section 6 of GN R. 635. The TC and LC limits of elements and chemical substances in the waste material exceeding the corresponding TCT and LCT limits determine the specific waste type according to Section 7 of GN R. 635.

The waste type and related risk-based assessment approach is used to inform the potential barrier requirements. Figure 3-2 illustrates the flow diagram of the general processes to be followed to determine the waste type and then associated barrier requirements.

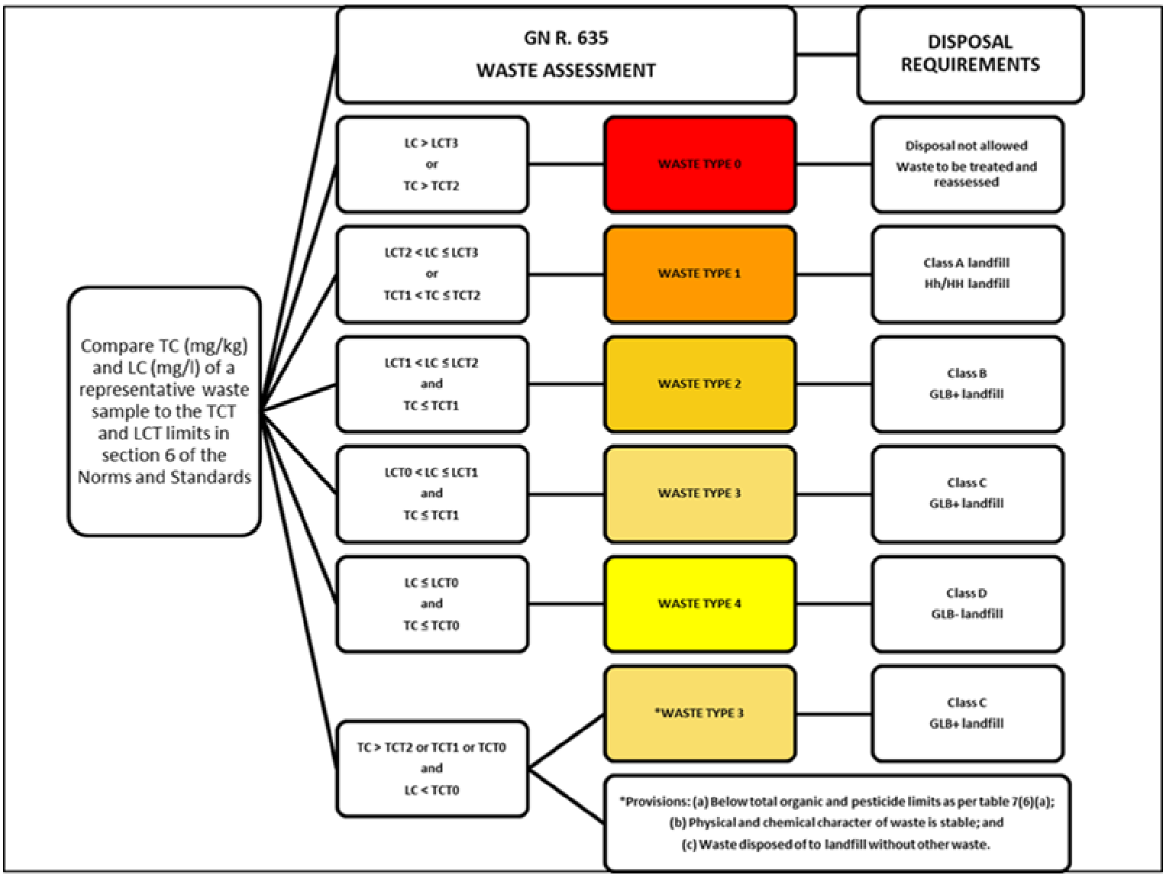

Figure 3-2: Flow Diagram for Assessing Waste in Terms of South African Waste Assessment Regulations (GN R. 635 of 2013)

3.5 GEOCHEMICAL SOURCE TERMS

The SPLP results, calibrated to long term water quality monitoring data, will be used as input concentrations to generate leachate source terms for the site. As laboratory leachate results are only an indicator of site drainage water quality, due to the test conditions not fully representing field conditions, most especially the liquid to solid ratio and varying redox setting, PHREEQC geochemical modelling software is used to perform geochemical calculations to predict field mineral speciation, surface complexation, ion exchange equilibria and kinetic reactions. PHREEQC includes thermodynamic databases for a wide range of inorganic parameters relevant to industrial water quality and the field conditions they are subject to. The generated geochemical source terms (predicted analyte concentrations) can then be input into a groundwater model to predict the significance and extent of any contamination. A comprehensive geochemical and geohydrological assessment will assist SLR in gaining a better understanding of potential risks to better advise the client on how to minimise those risks in the context of the site.

3.5.1 Model Code

This assessment applies the pH, Redox, Equilibrium Code (PHREEQC) for hydrogeochemical modelling (Parkhurst and Appelo, 2013).

PHREEQC is a versatile geochemical model initially developed in 1995 by the United States Geological Survey. It has undergone extensive use, testing and validation by third parties with version 3 released in January 2015. This assessment used version 3.4.0.12927 (released 9th November 2017). PHREEQC can perform low-temperature aqueous geochemical calculations, including speciation, saturation indices, batch reaction and 1-dimensional transport calculations. PHREEQC can account for aqueous, mineral, gas, solid solution, surface complexation and ion exchange equilibria, as well as kinetic reactions.

PHREEQC is widely used for environmental geochemical modelling because it is freely available, open source, and flexible. It includes thermodynamic databases for a wide range of inorganic parameters relevant to mine water quality.

3.5.2 Model inputs

The key model inputs are the contact water quality determined from laboratory leach tests calibrated to long term water quality monitoring data (Appendix A). The input data concentrations were adjusted to achieve a charge balance equilibrium (CBE) < 10%. Concentrations indicated as below detection limit were entered as one-half of the detection limit or omitted were practical.

It is assumed that the sediment materials have a field moisture capacity of about 20%. The column of waste material can only generate seepage if the water content exceeds this value. No analysis was conducted to confirm this.

3.5.3 Boundary Conditions

The model boundary conditions are summarised in Table 3-2.

Table 3-2: Model boundary conditions

Boundary Conditions	Description
Gas phase	It is assumed that there is little biological activity in the material and the CO_2(g) pressure was set to $10^{-3.5}$ atm.
Minerals	Based on the mineralogical analysis the pure phase that can react reversibly with the aqueous phase is Enstatite. Although Enstatite is an endmember of relatively recalcitrant pyroxene silicates, it has been included in the modelled reactions due to the tendency to release Mg in exchange for two aqueous H^+ ions followed by relatively slow detachment of silica from partially liberated tetrahedral chains (Oelkers & Schott, 2001). Mineral phases to simulate only precipitation reactions were added for each sample modelled if they were over saturated in the solution.
Adsorption surface	Metal cations can sorb to charged surfaces. In this simulation no such sorption was simulated.

3.5.4 Model Algorithm

The algorithm comprised the following:

1. For simulations were mixing of different solutions were required the solutions were proportioned according to the determined ratios.
2. Determine pore water quality by adjusting solid-liquid ratio of leach test to expected ratio at field capacity. This was done by modelling the removal of water from the solution.
3. Establish equilibrium composition of pore water in sediments, allowing relevant minerals to dissolve/precipitate.

3.5.4.1 Model Limitations

Predicting water qualities from an evaporation and settling setting, requires some assumptions and has limitations. The statistician George Box said: all models are wrong, but some models are useful (Box, 1976). This statement captures the essential truth that all model's approximate reality in that they reduce complex systems to a limited number of significant processes. How "useful" a model is depending on how closely the selected processes approximate reality. Predicting the water qualities of complex systems demands assumptions. Even a rigorous sampling and analysis programme cannot precisely determine the physical and geochemical characteristics of the system. Nor can they precisely indicate how these characteristics may change over time. Table 3-3 summarises the key limitations of the input data and the hydrogeochemical model used for this assessment.

Table 3-3: Model Limitations

No	Limitations	Description
1	Predicting field scale water quality from lab scale test results is an approximation	Leaching of salts and metals at the field scale is variable in time and controlled by factors not fully applied at the lab scale. Amongst others, these factors include temperature, evaporation, nature of the leaching solution, the solution to solid ratio, solution-solid contact time and particle size of the solid. The modelled quality of water due to interaction with tailings or waste is an informed estimate.
2	The geochemical database is relevant to the system being modelled	Hydrogeochemical modelling uses the inherently uncertain laboratory results and water qualities as inputs. These are processed using thermodynamic data determined in the laboratory on ideal materials and solutions. The laboratory determined constants may not be directly applicable to the materials, solutions, and chemical context of the waste material. The llnl.dat database was used for the model.
3	The modelling assumes thermodynamic equilibrium in the model system	In the field, all chemical components are subject to kinetic variation and the system might, at best be in a state of quasi equilibrium. This may suggest that attempts to simulate or predict the state of these complex systems have questionable value. However, geochemical evaluations of natural and mine waters over the last few decades have shown that the equilibrium assumption is a powerful tool that in many circumstances produces results that accurately describe the general chemistry of such waters.
4	Adsorption surface	Metal cations can sorb to charged surfaces. There is no data to quantify either these surfaces, or their effect on water quality. Cation sorption linked to the amount of ferrihydrite precipitating was not modelled.

Considering the uncertainties outlined above, the available information is sufficient to provide the preliminary estimated sediments seepage quality presented in this report. However, even though this report presents deterministic concentration values, these should be viewed as first-order approximations[3]. As such, the predicted concentrations in this report indicate the likely order of magnitude concentrations.

4. RESULTS AND INTERPRETATION

4.1 MINEROLOGY: X-RAY DIFFRACTION (XRD)

The mineralogy of Tharisa mine waste materials is listed in Table 4-1 below.

Table 4-1: Tharisa composite waste rock minerology

Mineral Name	Formulas	Composition (%)		
		East Dump	West Dump	Far West Dump
Quartz	SiO_2	1.3	1.9	0.2
Plagioclase	$(Na,Ca)(Si,Al)_4O_8$	61.4	74.3	58.3
Augite	$Ca(Fe,Mg)Si_2O_6$	3.4	5.3	5.4
Enstatite	$MgSiO_3$	29.9	17.7	35.0
Talc	$Mg_3(Si_2O_5)_2(OH)_2$	1.5	0	0
Muscovite	$KAl_2((OH)_2 Al Si_3 O_{10})$	2.46	0	0
Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)$	0.1	0.5	0
Rutile	TiO_2	0	0.2	0
Chlorite	$(Mg,Fe)_5Al(AlSi_3O_{10})(OH)_8$	0	0	1.1

All the Tharisa mine WR materials are dominated by Plagioclase and Enstatite. Minor minerals include Muscovite, Augite and Quartz with Talc, Actinolite, Rutile and Chlorite present in trace amounts.

4.2 SYNTHETIC PRECIPITATION LEACHING PROCEDURE (SPLP)

The SPLP concentrations for the Tharisa WR samples returned no constituents of concern (CoCs) except for a marginal exceedance of SANS 241: Operational for Al (East Dump and West Dump) and SANS 241: Aesthetic for Fe (Far West Dump; Table 4-2).

4.3 THARISA MINE WASTE MATERIALS WASTE ASSESSMENT

4.3.1 Total and Leachate Concentrations

The waste assessment according to total and leachable concentrations for the Tharisa waste samples is presented Table 4-3 and Table 4-4. A summary of the waste type classification and barrier requirements is presented in Table 4-5. In accordance with GN R. 635 of 2013, for a waste to be **Type 3**, results must meet the following criteria:

- Leachable concentrations of all elements are below the LCT0, irrespective of the total concentrations of elements or chemical substances in the waste, provided that:
  - Concentration limits for organics and pesticides are low;
  - The inherent physical and chemical character of the waste is stable and will not change over time; and
  - The waste is deposed to landfill without any other waste.

[3] A first-order approximation is an estimated value of a quantity, often preliminary to more precise determination. Mathematically, it is a linear approximation of a polynomial function.

Table 4-2: Tharisa Mine composite waste rock SPLP results

Analytes	Ag	Al*	As	Au	B	Ba	Be	Bi	Ca*	Cd	Ce	Co	Cr (total)	Cs	Cu	Dy	Er	Eu	Fe*	Ga
Unit	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*
1. DWAF TWQG		**5**	**1**		**5**				**1000**	**10**		**1**			**5**				**10**	
2. IFC: Mining effluent			**0.1**							**0.05**					**0.3**				**2.0**	
3. SANS 241: Operational		**0.3**																		
4. SANS 241: Aesthetic																			**0.3**	
5. SANS 241: Acute Health																				
6. SANS 241: Chronic Health			**0.01**		**2.4**	**0.7**				**0.003**		**0.5**	**0.05**		**2.0**				**2.0**	
Comp 1 East Dump	<0.010	0.553	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	5	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	0.185	<0.010
Comp 2 West Dump	<0.010	0.673	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	4	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	0.153	<0.010
Far West Dump	<0.010	0.257	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<1	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	0.323	<0.010

Analytes	Gd	Ge	Hf	Hg	Ho	In	Ir	K*	La	Li	Lu	Mg*	Mn*	Mo	Na*	Nb	Nd	Ni	Os	P
Unit	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*
1. DWAF TWQG				**1.0**								**500**	**10**	**0.01**	**2000**			**1**		
2. IFC: Mining effluent				**0.002**														**0.5**		
3. SANS 241: Operational																				
4. SANS 241: Aesthetic													**0.1**		**200**					
5. SANS 241: Acute Health																				
6. SANS 241: Chronic Health				**0.006**									**0.4**					**0.07**		
Comp 1 East Dump	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	1.439	<0.010	<0.010	<0.010	1	0.025	<0.010	<1	<0.010	<0.010	<0.010	<0.010	0.016
Comp 2 West Dump	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	1.842	<0.010	<0.010	<0.010	<1	0.025	<0.010	<1	<0.010	<0.010	<0.010	<0.010	0.037
Far West Dump	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	0.138	<0.010	<0.010	<0.010	<1	0.025	<0.010	<1	<0.010	<0.010	<0.010	<0.010	0.012

Analytes	Pb	Pd	Pr	Pt	Rb	Rh	Ru	Sb	Sc	Se	Si*	Sm	Sn	Sr	Ta	Tb	Te	Th	Ti	Tl
Unit	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*
1. DWAF TWQG	**0.5**									**50**										
2. IFC: Mining effluent	**0.2**																			
3. SANS 241: Operational																				
4. SANS 241: Aesthetic																				
5. SANS 241: Acute Health																				
6. SANS 241: Chronic Health	**0.01**							**0.02**		**0.04**										
Comp 1 East Dump	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	2.41	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Comp 2 West Dump	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	2.241	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Far West Dump	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	4.161	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010

Analytes	Tm	U	V	W	Y	Yb	Zn	Zr	pH	EC	TDS	Tot Alk	Cl	SO4	NO3	NO2	F	Free NH3	Ortho-P
Unit	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*		*mS/m*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*
1. DWAF TWQG			**1**				**20**				**3000**		**3000**	**1000**	**100**	**10**	**6**		
2. IFC: Mining effluent							**0.5**		**6 - 9**										
3. SANS 241: Operational									**5 -9.7**										
4. SANS 241: Aesthetic							**5**			**170**	**1200**		**300**	**250**				**1.5**	
5. SANS 241: Acute Health														**500**	**11**	**0.9**			
6. SANS 241: Chronic Health		**0.03**	**0.2**														**1.5**		
Comp 1 East Dump	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	8.1	4.2	50	20	<2	<2	0.1	<0.05	0.2	<0.1	<0.1
Comp 2 West Dump	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	0.21265	<0.010	8.1	4.3	64	16	<2	<2	0.3	<0.05	0.2	0.1	<0.1
Far West Dump	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	6.7	1.8	38	8	<2	<2	<0.1	<0.05	0.2	<0.1	<0.1

Table 4-3: Tharisa Mine Waste Rock Total Concentration and Screening

Analyses	Units	TCT0	TCT1	TCT2	East Dump	West Dump	Far West Dump
As, Arsenic	mg/kg	5,8	500	2000	1,2	1,2	<0,400
B, Boron	mg/kg	150	15000	6000	<10	<10	<10
Ba, Barium	mg/kg	62,5	6250	25000	56,3	49,3	55,0
Cd, Cadmium	mg/kg	7,5	260	1040	<0,400	<0,400	<0,400
Co, Cobalt	mg/kg	50	5000	20000	40,9	24,5	52,5
CrTotal, Chromium Total	mg/kg	46000	800000	N/A	1518,7	798,7	1284,2
Cu, Copper	mg/kg	16	19500	78000	14,2	17,9	17,0
Hg, Mercury	mg/kg	0,93	160	640	<0,400	<0,400	<0,400
Mn, Manganese	mg/kg	1000	25000	100000	721,3	435,8	898,5
Mo, Molybdenum	mg/kg	40	1000	4000	<10	<10	<10
Ni, Nickel	mg/kg	91	10600	42400	245,4	157,8	339,6
Pb, Lead	mg/kg	20	1900	7600	1,4	1,5	1,0
Sb, Antimony	mg/kg	10	75	300	<0,400	<0,400	<0,400
Se, Selenium	mg/kg	10	50	200	<0,400	<0,400	<0,400
V, Vanadium	mg/kg	150	2680	10720	79,2	61,7	67,8
Zn, Zinc	mg/kg	240	160000	640000	48,1	32,4	52,8
Cr(VI), Chromium (VI)	mg/kg	6,5	500	2000	<2	<2	8,9[4]
Total Fluoride [o]	mg/kg	100	10000	40000	10,9	13,7	<0,5
Total Cyanide as CN [o]	mg/kg	14	10500	42000	<1,55	<1,55	<1,55

[4] The total Cr(VI) concentration reported for the Far West WRD sample is anomalous due to the fact that Cr(VI) is mobile in groundwater but there is no detectable concentration of the parameter in the total leachate results for the same sample and long term site water quality monitoring data. Therefore, we suspect that this result could be due to an analytical error. This is reinforced by the lack of any detectable Cr(VI) in the extensive water quality monitoring data from the site.

Table 4-4: Tharisa Mine Waste Rock leachable concentrations and screening

Analyses	Units	LCT0	LCT1	LCT2	LCT3	East Dump	West Dump	Far West Dump
As, Arsenic	mg/l	0,01	0,5	1	4	<0,001	<0,001	<0,001
B, Boron	mg/l	0,5	25	50	200	<0,025	<0,025	<0,025
Ba, Barium	mg/l	0,7	35	70	280	<0,025	<0,025	<0,025
Cd, Cadmium	mg/l	0,003	0,15	0,3	1,2	<0,001	<0,001	<0,001
Co, Cobalt	mg/l	0,5	25	50	200	<0,025	<0,025	<0,025
CrTotal, Chromium Total	mg/l	0,1	5	10	40	<0,025	<0,025	<0,025
Cr(VI), Chromium (VI)	mg/l	0,05	2,5	5	20	<0,010	<0,010	<0,010
Cu, Copper	mg/l	2	100	200	800	<0,010	<0,010	<0,010
Hg, Mercury	mg/l	0,006	0,3	0,6	2,4	<0,001	<0,001	<0,001
Mn, Manganese	mg/l	0,5	25	50	200	<0,025	<0,025	<0,025
Mo, Molybdenum	mg/l	0,07	3,5	7	28	<0,025	<0,025	<0,025
Ni, Nickel	mg/l	0,07	3,5	7	28	<0,025	<0,025	<0,025
Pb, Lead	mg/l	0,01	0,5	1	4	<0,001	<0,001	<0,001
Sb, Antimony	mg/l	0,02	1	2	8	<0,001	<0,001	<0,001
Se, Selenium	mg/l	0,01	0,5	1	4	0,002	0,001	<0,001
V, Vanadium	mg/l	0,2	10	20	80	<0,025	<0,025	<0,025
Zn, Zinc	mg/l	5	250	500	2000	<0,025	<0,025	<0,025
Total Dissolved Solids*	mg/l	1000	12 500	25 000	100 000	20	30	18
Chloride as Cl	mg/l	300	15 000	30 000	120 000	<2	<2	<2
Sulphate as SO4	mg/l	250	12 500	25 000	100 000	<2	<2	<2
Nitrate as N	mg/l	11	550	1100	4400	<0,1	0,2	<0,1
Fluoride as F	mg/l	1,5	75	150	600	0,2	0,2	0,2
Total Cyanide as CN [o]	mg/l	0,07	3,5	7	28	<0,07	<0,07	<0,07
pH	mg/l					8,1	8	7,5
Paste pH	mg/l					9,5	9,5	9,3
Moisture %	mg/l					---	---	---

Based on the results, the WR composite samples are classified as a **Type 3** criteria in terms of total and leachable concentrations.

Table 4-5: Waste type determination for Tharisa waste samples

Sample Name	Waste Type	Reason for Classification	Landfill Class
East Dump composite	Type 3	All LC < LCT0; Ni > TCT0	Class C
West Dump Composite	Type 3	All LC < LCT0 Cu & Ni >TCT0	Class C
Far West Dump Composite	Type 3	All LC < LCT0 Co, Cu, Ni, Cr(VI) > TCT0	Class C

The DWS accepted a proposal by the Chamber of Mines of South Africa to follow a risk-based approach on a case-by-case basis to allow for representations on alternative barrier systems for Mine Residue Deposits and Stockpiles based on a risk assessment (29 June 2016). The risk assessment will enable an evaluation of the efficacy of the alternative barrier system to prevent pollution as required in terms of Section 19 (1) and (2) of the NEMA:WA (Singh, 2016). Since the purpose of the Norms and Standards is to protect water resources it may be appropriate to consider the potential water quality risk associated with existing facilities, rather than retroactively applying the legislated barrier requirements.

SLR recommends a risk-based approach for protection of water resources from the Tharisa WR materials rather than a formulaic application of the Norms and Standards. Therefore, it follows that the Tharisa WR can be classified as a **Type 4** waste, requiring a **Type D** liner which is similar to the existing receiving storage facilities' base layer, due to the following reasons:

- All the leachable concentrations for the WR materials are below the LCT0 limit which indicates a low seepage risk;
- The acidic SPLP leach concentrations for the WR materials recorded only SANS 241: Operational and Aesthetic COCs for Al and Fe, respectively (see section 4.2);
- A high failure probability of class C barriers exists for receiving WR materials.

4.3.2 Determining Landfill Class (Barrier requirements)

The Tharisa mine WR materials has been classified using a risk-based approach as equivalent to a **Type 4** waste and therefore disposal or incorporation into a storage facility will require a **Class D** barrier lining. Figure 4-1 depicts the prescribed barrier requirements for the waste type.

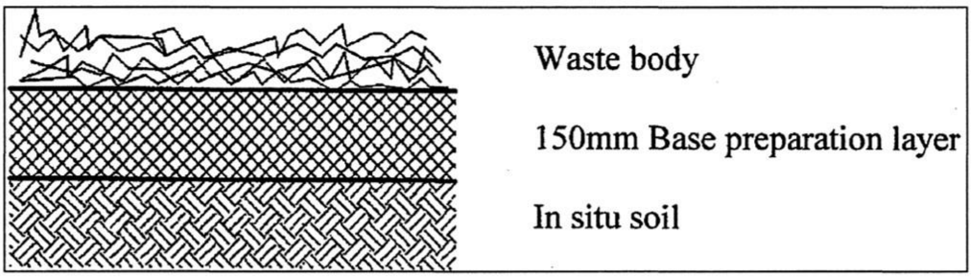

Figure 4-1: Class D landfill prescribed barrier

4.4 GEOCHEMICAL SOURCE TERMS

The geochemical source terms modelled for the Tharisa waste samples are listed in Table 4-6 below. The input data was calibrated to the long-term water monitoring data equivalent to 457 samples over 7-8 years monitoring that increases the confidence of the modelled outputs.

Table 4-6: Tharisa Mine waste material geochemical source terms

Element	Units	SANS 241 / DWAF*	East Dump WR comp	West Dump WR comp	Far West Dump WR comp
Al	mg/L	5*	0,007	0,007	0,367
As	mg/L	1*	0,007	0,001	0,001
B	mg/L	2,4	0,007	0,001	0,007
Ba	mg/L	0,7	0,007	0,001	0,007
Alkalinity as HCO_3^-	mg/L		375,3	375,9	265,9
Ca	mg/L	1000*	72,0	71,9	21,4
Cd	mg/L	10*	0,007	0,001	0,001
Cl (-1)	mg/L	300	52,7	52,7	52,7
Co	mg/L	0,5	0,007	0,001	0,007
Cr	mg/L	0,05	0,003	0,003	0,003
Cu	mg/L	2	0,013	0,013	0,013
F	mg/L	1,5	0,300	0,300	0,300
Fe	mg/L	10*	0,264	0,219	0,007
Hg	mg/L	0,006	0,001	0,001	0,001
K	mg/L		2,056	2,632	0,197
Li	mg/L		0,007	0,007	0,007
Mg	mg/L	500*	108,1	107,7	118,6
Mn	mg/L	10*	0,036	0,001	0,036
Mo	mg/L	0,07*	0,001	0,007	0,007
N as NO_3^-	mg/L	22*	126,6	126,2	127,1
Na	mg/L	200	21,6	21,6	21,6
Ni	mg/L	0,07	0,007	0,063	0,006
P	mg/L		0,023	0,053	0,017
Pb	mg/L	0,1*	0,007	0,003	0,003
S as SO_4^{2-}	mg/L	500	111,2	111,2	111,1
Sb	mg/L	0,02	0,007	0,007	0,007
Se	mg/L	0,04	0,007	0,001	0,001
Si	mg/L		10,9	10,9	24,8

Element	Units	SANS 241 / DWAF*	East Dump WR comp	West Dump WR comp	Far West Dump WR comp
Sn	mg/L		0,007	0,007	0,007
Sr	mg/L		0,007	0,007	0,007
Ti	mg/L		0,007	0,007	0,007
U	mg/L	0,03	0,007	0,007	0,007
V	mg/L	1*	0,007	0,007	0,007
W	mg/L		0,007	0,007	0,007
Zn	mg/L	5	0,007	0,304	0,010
pH		5 - 9,7	8,7	8,8	8,5

The only CoC predicted for the Tharisa waste materials is the exceedance of DWAF livestock TWQG nitrate levels for all the waste streams. The increase in the modelled pH levels relative to the SPLP input concentrations is due to the dominant and intermediate reactive mineral Enstatite, which tends to uptake 2 H^+ ions in exchange for Mg^{2+} on the mineral surface, which ultimately results in an increase in leachate pH (Oelkers & Schott, 2001).

The nitrate mass build-up in the site leachate is as a direct result of the use of ammonium nitrate explosives in the mining process. The nitrate load will systematically decrease in the ground water via heterotrophic chemo-organotrophic denitrification which is a thermodynamically favoured reduction process:

$$\mathbf{5C_{org} + 4NO_3^- + 2H_2O \longrightarrow 2N_2 + 4HCO_3^- + CO_2} \quad \mathbf{(1)}$$

Nitrate is not sourced from the mined geochemistry but originates from operational blasting and decays with time. Based on the kinetics of the bacteria-controlled nitrate reduction, the half-life of nitrate is estimated to be between 500 – 1350 days (Eppinger and Walraevens, 1998) and proven to be between 108-162 days based on long-term site monitoring data.

5. CONCLUSION

Three (3) WR composite samples from the Tharisa PGM and Chromite mine were subjected to comprehensive geochemical investigation and waste assessment to predict the leachate quality from the waste storage facilities on site and if they pose any risk to surface or groundwater resources. The laboratory results (LCT and SPLP) are based on first flush static tests that often give conservative (elevated) concentrations whereas the modelled source terms are calibrated to long term water quality monitoring data that is subject to field scale conditions and are regarded as more accurate indicators of site leachate quality.

The XRD analysis confirmed the dominant minerals for all waste materials at Tharisa mine to be Enstatite and Plagioclase, with minor Muscovite, Augite and Quartz present. The SPLP results for Tharisa waste materials returned only SANS 241: Operational and Aesthetic exceedances for Al and Fe, respectively.

According to NEMWA GN R. 635 and 636 guidelines, all the waste rock samples can be classified as equivalent to a **Type 4** waste using a risk-based approach and will be required to be incorporated into a storage facility with a **Class D** barrier.

The geochemical source terms modelled for the Tharisa WR materials predicted the following CoCs for possible risk to water resources due to:

- Exceedance of DWAF livestock TWQG nitrate levels for all the waste streams

However, nitrate is not sourced from the mined geochemistry but originates from operational blasting and decays with time. Based on the kinetics of the bacteria-controlled nitrate reduction, the half-life of nitrate is estimated to be between 500 – 1350 days (Eppinger and Walraevens, 1998) and proven to be between 108-162 days based on long-term site monitoring data.

The increase in the modelled pH levels relative to the SPLP input values is due to the dominant mineral Enstatite, which tends to uptake 2 H^{+} ions in exchange for Mg^{2+} on the mineral surface, which ultimately results in an increase in modelled leachate pH (Oelkers & Schott, 2001).

5.1 RECOMMENDATIONS

Although the predicted leachate quality from the Tharisa waste storage facilities is expected for mine effluent, SLR would like to make the following recommendations:

- Results of the source term assessment should not be evaluated in isolation but together with numerical or reactive groundwater modelling risk assessment. The complete source, pathway and receptor should be considered in evaluating the overall potential risks to groundwater.

6. REFERENCES

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APPENDIX A: LABORATORY CERTIFICATES

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