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HYDROGEOLOGICAL ASSESSMENTS AND INVESTIGATION OF INFLOW SOURCES AT LUMWANA COPPER MINE, ZAMBIA

MSc Research Report

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DECLARATION

I hereby declare that this Research Report submitted to the Faculty of Science at the University of the Witwatersrand, Johannesburg, is my own original independent work. To the best of my knowledge, I have duly acknowledged all the sources of information used in this Research Report.



Mike Mbilima
22nd August 2023

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ABSTRACT

This Research Report presents results of integrated field and desktop-based hydrogeological investigations at the Lumwana Mine, Zambia. Groundwater occurrence in the mine poses challenges with effective mining operations and slope stability. The primary aim of this study was to establish the sources of groundwater inflows and to establish the nature of surface water and groundwater interaction within the Lumwana Mine hydro-geotechnical units. The Lumwana hydrogeological investigation has been achieved through the integration of multi-disciplinary data types, which include geology, structures, hydrochemistry, meteorological data (rainfall, temperature, humidity and evapotranspiration), environmental isotopes, dewatering pumping records, groundwater level monitoring, water temperature, general hydrogeological data and surface hydrology. The investigation has confirmed the presence of hydraulic connections between different surface water bodies such as dams, diversion channels, streams and open pit excavation, and has proven to be a useful approach in tracing the source of mine inflows. Rainfall, groundwater and surface water samples have similar $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotopic signatures thus lamenting the existence of a hydraulic link between groundwater and surface water. Recharge estimation through Water Table Fluctuation method (WTF) determined 8% of mean annual precipitation (MAP). The dominant hydrochemical facies are Ca-Mg-HCO_3 and Ca-Mg-SO_4 . The local geology and geochemistry of the tailings are the main controllers of groundwater chemistry through rock-water interaction. The geology of the study area consists of older metamorphosed gneisses, schists, migmatites, amphibolites and granitoids. Integrated assessment of the Lumwana hydrogeological environment has enabled the development of the Lumwana Mine hydrogeological conceptual model. In the shallow, highly to moderately weathered zones, groundwater flows from south towards low topographic regions in the northwest mimicking the general topography. The hydraulic test conducted at Lumwana Mine has revealed the saprock units have higher hydraulic conductivity by several orders compared to the saprolites and the fresh bedrock, where groundwater flow is mainly controlled by the occurrence and distribution of the fracture network.

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ABBREVIATIONS

AAS-ICP: Atomic Absorption Spectrometer Inductively Coupled Plasma

AET: Actual Evapotranspiration

BDO: Biological Dissolved Oxygen

CW: Chimiwungo West

DEM: Digital Elevation Model

DO: Dissolved Oxygen

DRC: Democratic Republic of the Congo

D-excess: Deuterium Excess

EC: Electrical Conductivity

FC program: Flow characteristic program

GMWL: Global Meteoric Water Line

GNG: Grey Gneiss

GNP: Pink Gneiss

GDP: Gross Domestic Product

ITCZ: Intertropical Convergence Zone

JICA: Japanese International Corporation Agency

KD: Katangan Décollement

LMC: Lumwana Mining Company

LMWL: Local Meteoric Water Line

LOM: Life of Mine

MAP: Mean Annual Precipitation

Mbgl: Meters below ground level

MD: Mwombezhi Decollement

NNE: North to Northeast

PET: Potential Evapotranspiration

pH: Potential of Hydrogen

Sy: Specific yield

TDS: Total Dissolved Solids

TSF: Tailings Storage Facility

UAV: Unmanned aerial vehicle

UPVC: Unplasticised Polyvinyl Chloride

USGS- United States Geological Survey

VW2100: Vibrating Wire 2100 model.

VWP: Vibrating Wire Piezometer

VSMOW: Vienna Standard Mean Ocean Water

WSF: Water Storage Facility

WTF: Water Table Fluctuation

1. INTRODUCTION AND LITERATURE REVIEW

1.1 General Introduction

The Lumwana Copper Mine is in the North-Western Province of Zambia, south of the border between Zambia and the Democratic Republic of the Congo (DRC). The mine is 100% owned and operated by Lumwana Mining Company Limited, a subsidiary of Barrick Gold Corporation, (Barrick Gold Corporation, 2014). The Lumwana Mine consists of two known major orebodies, the Malundwe and the Chimiwungo orebodies, with great potential for major on-mine brownfields discoveries (Equinox Minerals Limited, 2011). The Lumwana deposits together with its exploration prospects sit on six large-scale mining licenses managed by the Ministry of Mines and Minerals Development on behalf of the government of the Republic of Zambia (Barrick Gold Corporation, 2014). The Lumwana deposit is hosted within the Central African Copperbelt structural corridor called the Lufilian Arc, which is a major fault and shear zone covering the northwestern and northern parts of Zambia, as well as the southern part of the DRC and extends into southwestern part of Angola (Golder Associates, 2011).

Copper mineralisation, mainly chalcopyrite and bornite, is hosted within the muscovite-biotite-kyanite schist locally known as the Ore Schist. In addition to the sulphide mineralisation, the Lumwana Deposits consist of a minor quantity of surficial oxides, mainly malachite in areas where the orebody outcrops to the surface (Golder Associates, 2005). The Lumwana Mine deposits are characterised by disseminated sulphide mineralisation within the strata-bound geology (Golder Associates, 2005). Mining operations at Lumwana Mine commenced in 2008 at the Malundwe Deposit, however, the focus on mining operations shifted to the Chimiwungo Deposit since 2014. Mining activities at Lumwana Mine are being carried out through multi-open pits through a sequence of activities. These include grade control drilling, blast hole drilling, charging and blasting, loading and hauling using hydraulic shovels and conventional heavy-duty trucks, respectively, to the stockpiles and crushers. However, topsoil and overburden stripping is being carried out by contractors with specialised and suitable light articulated dump trucks and shovels (Barrick Gold Corporation, 2014). The crushed ore is transported through the conveyor belt to the processing plant for the milling and floatation process until the final product of copper concentrate is produced. The waste products of sulphide ore processing are transported to the

tailings storage facility through various pipe networks (Equinox Minerals, 2011). Tailings produced from copper ore processing with elevated uranium content are separated within the tailings storage facility to prevent the environmental dispersion of contaminants (Equinox Minerals, 2011). Over the life of the mine, mineral processing has created enormous amounts of waste and posed other mining-related environmental risks. Generally, the following are the common environmental risks (Table 1.1) in mining environments.

Table 1.1 Mine environmental risks classification (Czech Geological Survey, 2008).

Category	Environmental risk
Geological	Ground falls, damage to water balance, soil erosion
Environmental damage	Water resources, solid waste, land resources destruction, soil stripping, vegetation clearing
Environmental pollution	Water, Air, Soil pollution

Mining is the backbone of Zambia's economy, and the industry creates thousands of direct and indirect jobs. Lumwana Mine, being one of the largest copper mines in the region, has great potential to contribute to foreign exchange generation. The mining industry contributes to over 12% of Zambia's GDP and contributes immensely to government revenue through mineral royalties, employee pay-as-you earn, corporate income tax and value added tax (Deloitte and Touché, 2005).

The life of Mine at Lumwana's Chimiwungo Pits extends up to the year 2039. Open pit excavations at the new Chimiwungo East pits are expected to reach over 360 m below ground level with a strike length of over 2.5 km. On the other hand, the open pit floor elevations at the current Chimiwungo Main pits are expected to extend over 150 m below the current floor elevations with a total strike length of over 6 km. An effective hydrogeological assessment is key to inform strategy for effective water management at the Lumwana open pit for safe and profitable mining operations. Direct precipitation within the footprint of the open pits and surface runoff are the primary source of water for the open pits that requires dewatering. Direct precipitation and runoff is channelled into the sumps for collection and pumping. Groundwater occurrence on

drilling and blast patterns poses challenges with effective drilling and blasting while groundwater occurrence near the open pit faces causes elevated pore pressure and subsequent instability challenges. As the open pit deepens and extends in areal extent, effective water management and slope depressurisation is critical for successful mining operations.

1.2. Research problem

Sustainable management of groundwater in mining environment is one of the most critical aspects of mining economics (Lines, 1985; Rubio and Loca, 1993; Wolkersdorfer, 2008; Woldeyohannes *et al.*, 2015). Failure to have a thorough understanding of groundwater flow dynamics affects the profitability of the overall mining business due to excessive operational, material and human costs (Rubio and Loca, 1993; Balasubramaniam and Panda, 2004). Sustainable development requires a thorough understanding of the flow dynamics of an aquifer system (Taylor *et al.*, 2017), where the understanding of the hydrogeological system requires a vast amount of data about the various aspects of groundwater occurrence, storage, circulation and quality (Mohuba, 2020). Sustainable groundwater and surface water management in the mining environment may be difficult if there is a lack of required data such as geology, geostructural data, hydrochemistry, environmental isotope, meteorological and hydrogeological data (Ahmed, 2009). Groundwater management in the mining environment has another layer of difficulty because of the substantial infrastructure development within and in the proximity of the mine area coupled with considerable changes of the groundwater flow regime in relation to the natural conditions (Hodgson *et al.*, 2001). It is undisputable that a reliable numerical model cannot be developed without a fact-based conceptual model (Zhou and Li, 2011; Singhal and Goyal, 2011).

At Lumwana Mine, geotechnical slope instabilities of varying scales ranging from single to multi-benches are dominant in the saprolites and transition weathering zones (Figures 1.1 and Figure 1.2) (SLR, 2019). Back analysis of saprolite slopes at failure has shown that the strength of the saprolites at Lumwana Mine is sensitive to pore pressure and respective pressure head at any location (Beale and Read, 2013). Life of Mine (LOM) geotechnical slope stability modelling at Lumwana Mine has revealed that the frequency and magnitude of these failures are expected to worsen with the expansion of the mine. The current geotechnical slope design parameters

assume that the slopes are fully depressurised at least 50 m into the back of the slopes (Knight Piesold Pty, 2005). Groundwater monitoring from a network of piezometers near pit crests and seepage mapping in these geotechnically challenging units shows that these hydrogeological conditions are not present at Lumwana.

To mitigate the anticipated effects of groundwater pore pressure slopes on slope performance and mine safety, the slopes have been overdesigned (flattened) (SLR, 2019), and this has an adverse impact on the mining economics as it requires disposal of more waste to extract the same amount of ore. This translates into a higher stripping ratio as huge volumes of the material require to be mined out. In slope engineering, groundwater pore pressure is the only geotechnical parameter that can readily be modified (Beale *et al.*, 2013). Therefore, a thorough understanding of groundwater flow dynamics and formulation of an efficient and effective long lasting slope depressurisation strategy presents an opportunity to improve mining economics and slope performance and, therefore, enhance mining operations safety and profitability (Beale and Read, 2013).

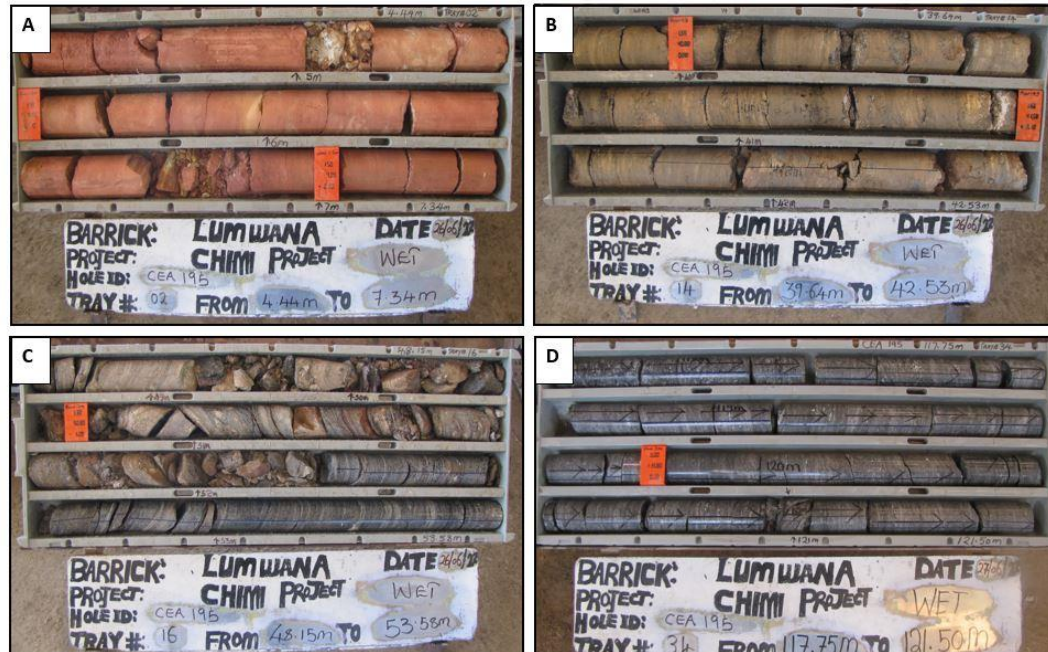


Figure 1.1 Geotechnical domains for Lumwana Mine. (A) Highly weathered, iron-rich oxide, clayey saprolites of granitic gneiss protolith. (B) Moderately weathered, medium-grained Augen Gneiss saprock with preserved fabric. (C) Heavily fractured Augen Gneiss and (D) Fresh competent Augen Gneiss.



Figure 1.2 Example of pit wall failure in the weak saprolite zone along a fault plane at Lumwana Mine. Note the saturated ground floor below the failure. (Source: Lumwana Geotechnical Engineering Department).

1.3. Literature review

Conceptual models have extensively been employed in the characterisation of aquifers as a realistic, albeit simplified representation of hydrogeological systems (Beale and Read, 2013). For any conceptual model, it is important to gain much information on the detailed geological conditions and the main hydrostratigraphic units, in addition to the response of the hydrogeological systems within the domain area to changes in hydraulic stresses (recharge and discharge) (Beale and Read, 2013). At Diavik Diamond Mine in Northwest Territories of Canada, a sector-scale conceptual model was developed for the A154 pit to understand how depressurisation occurs in a fractured rock slope (Beale and Read, 2013). This was done through a detailed analysis of the site's structural and hydrogeological data from a well-instrumented rock

slope at the open pit mine. Hydrogeological investigation of the site was undertaken in the form of a packer testing program, borehole flow measurements and well temperature logging. The site represents an open pit with fractured low permeability slopes (Beale and Read, 2013). Due to the sensitivity of the slope stability to groundwater pressures (particularly for shallow bench scale), it was found prudent to model groundwater conditions at the site. As the A154 pit was progressively deepened, it was noted that pore pressures in parts of the north-west wall were decreasing at a lesser rate than the mine sinking rate. As a result, a program of groundwater monitoring borehole drilling and installation was carried out in mid-to-late 2006 with active slope depressurisation drilling (Golder, 2010).

Maps of selected water chemistry parameters can be used to support the conceptual hydrogeological model by showing the variation in water quality across the site. It may be possible to correlate water chemistry values with different geological units or across different structural zones (Beale and Read, 2013). Typically, several substances categorised as 'major ions' define the chemical composition of water, along with low concentrations of minor ions (Candela and Morell, 2009). The major ion chemistry of groundwater is a robust tool in the determination of the origin of solutes and for describing water evolution due to rock-water-soil interactions leading to the dissolution of minerals, weathering and ion-exchange reactions (Elliot *et al.*, 1999; Edmunds and Smedley, 2000). Environmental isotopes are routinely employed worldwide in the study of groundwater and surface water as they provide unique information on the transport and interconnectivity of water resources (Abiye, 2013). The molecules making up water molecules are subjected to thermodynamic processes including condensation and evaporation, which result in the molecules changing their isotopic signature accordingly and their flow path can be traced in groundwater system (Abiye, 2013). Integrated application of hydrochemistry and environmental isotopes has also been useful to solve complex hydrogeological challenges of excess groundwater inflows in Zambian Mines. At Lubambe Mine in Zambia, there were excessive groundwater inflows at the East Limb ramp at a depth of 250m, causing problems as the ramps were advancing in the footwall formation (SRK, 2015). A high-level investigation was carried out to understand the source of inflows and recharge so as to cut off the source of mine inflows. Detailed major ions hydrochemistry and environmental isotope analysis demonstrated that the

source of excessive mine inflows was the flooded Musoshi Mine in the neighbouring country of the D.R.C and not the leakage from process water sources from the tailings dam and plant storm dam (SRK, 2015). Water level measurements at both Lubambe and Musoshi Mine provided further evidence for a hydraulic connection. Dewatering at Musoshi Mine commenced in 1972 at the rate of 20,000 m³/day at a level of 150 m below ground. In 1977 water level in the footwall aquifer at Lubambe Mine was 300 m and the pumping rate was 40,000 m³/day. Water level in the Hanging Wall Aquifer (HWA) at Musoshi Mine dropped from 50 m below the surface to between 120 m and 150 m without active dewatering of the HWA. To validate the conceptual model findings, a numerical flow model was developed, and a groundwater flow simulation was conducted that confirmed the induced hydraulic gradient along strike from the flooded Musoshi Mine towards the Lubambe shafts, with the East Limb ramps between the two mines (SRK, 2015).

In the characterisation of hydraulic parameters of different material properties, different hydraulic tests are employed including pumping, packer testing, slug tests, shut in, etc. Among these, the variable head test also known as rising head or falling head test or slug test offers lowest cost method for in-situ measurement of hydraulic conductivity (Kruseman and De Ridder, 1990). Various methods for analysing slug tests have been described by various authors and the simplest and most robust method is that devised by Hvorslev (1951) and described in great detail by Freeze and Cherry (1979). The method was primarily devised for hydraulic testing in boreholes that are relatively short compared with the thickness of the formation. This method assumes the formation in question is homogeneous and that both the formation under investigation and water are incompressible. The concept applied for both falling head and rising head tests is similar except the signs for drawdown and flow directions are reversed (Stacy and Read, 2009). The Hvorslev method (1951) and the Bouwer and Rice (1976) method of slug test data analysis for unconfined conditions use a simple graphical technique that is based on the concept of shape factor, which considers the radius and length of the test interval in relation to the bed boundaries. Hvorslev argued that the inflow at any time will depend on the hydraulic conductivity of the formation, the head difference between the water in the formation and that in the well or piezometer, and the geometry of the piezometer intake section, which he summarised as the 'shape factor', F (Stacy and Read, 2009).

The presence of water in the mining environment poses a lot of operational and mine instability problems and requires a deliberate mine water management strategy to improve the safety of operations (Rubio and Lorca, 1993). According to Brawner (2006), the management of groundwater flow in mines is improving with advanced investigation techniques and better understanding of hydrogeology. Several mine-dewatering methods have been implemented across the globe, including:

- Horizontal (or sub-horizontal) drainage boreholes technique: Mine dewatering strategy where nearly horizontal drain holes are drilled at the toe of the slope or excavation to drain the water and stabilise the pit wall (Brawner, 2006). These are commonly used worldwide to relieve groundwater pressure behind the slopes in rock units not amenable to pumping via vertical wells (Beale *et al.*, 2013).
- Pit perimeter wells for both general mine dewatering and pit slope depressurisation: This method has been applied in most mines and involves drilling and installation of dewatering boreholes within and around the pit. The method was applied at Loy Yang Coal Open pit, Victoria, Australia, and Orapa Diamond Open pit Mine in Botswana (Bowell *et al.*, 2002).
- Some of the larger open pit operators, both for mine dewatering and to achieve pit slope depressurisation, are increasingly considering drainage tunnels installed behind the pit slope or underneath the pit (Beale *et al.*, 2013). This option involves drilling and blasting adit through the orebody and the adit as a drainage gallery from which water is pumped to surface.
- Passive groundwater cut-off systems applied to open pits include slurry walls, grouting programs and ground freezing. Slurry walls or low permeability barriers are mainly used in the construction industry (Beale *et al.*, 2013).

1.4. Aims and Objectives

The primary aim of this research was to establish the origin of groundwater and understand the nature of surface water and groundwater interaction within the Lumwana Mine hydrostratigraphic units. The hydrostratigraphic units coincide with site geotechnical

domains. This will be useful to generate a site-specific hydrogeological system conceptual model that should work as a framework for future groundwater numerical modelling.

The following are the specific objectives drawn for this research work:

- To characterise the hydrochemistry of groundwater and surface water in order to establish their geochemical signature.
- To investigate the isotopic character of mine surface water and groundwater.
- To determine the hydraulic nature of different hydrostratigraphic units at Lumwana Mine.
- To develop the conceptual hydrogeological model of the Lumwana Mine area that should work as a framework for future numerical groundwater modelling.

2. STUDY AREA DESCRIPTION

2.1. Location

Lumwana Copper Mine is located in the North-Western Province of Zambia, south of the border between Zambia and the Democratic Republic of the Congo (DRC) and approximately 465 km north of the capital city of Zambia (Figure 2.1). Lumwana Copper Mine is on the western extension of the Lufilian Arc, which is a fold and thrust belt. The study area covers a surface area of approximately 200 km². It consists of two deposits; (Figure 2.1) the Malundwe and Chimiwungo deposits, which are on the southern extension of the Lumwana concession. Malundwe deposit is currently not being mined due to flooding and therefore, all the mining activities are concentrated around the Chimiwungo area. Plans to resume mining at Malundwe are dependent on the rate of mine dewatering.

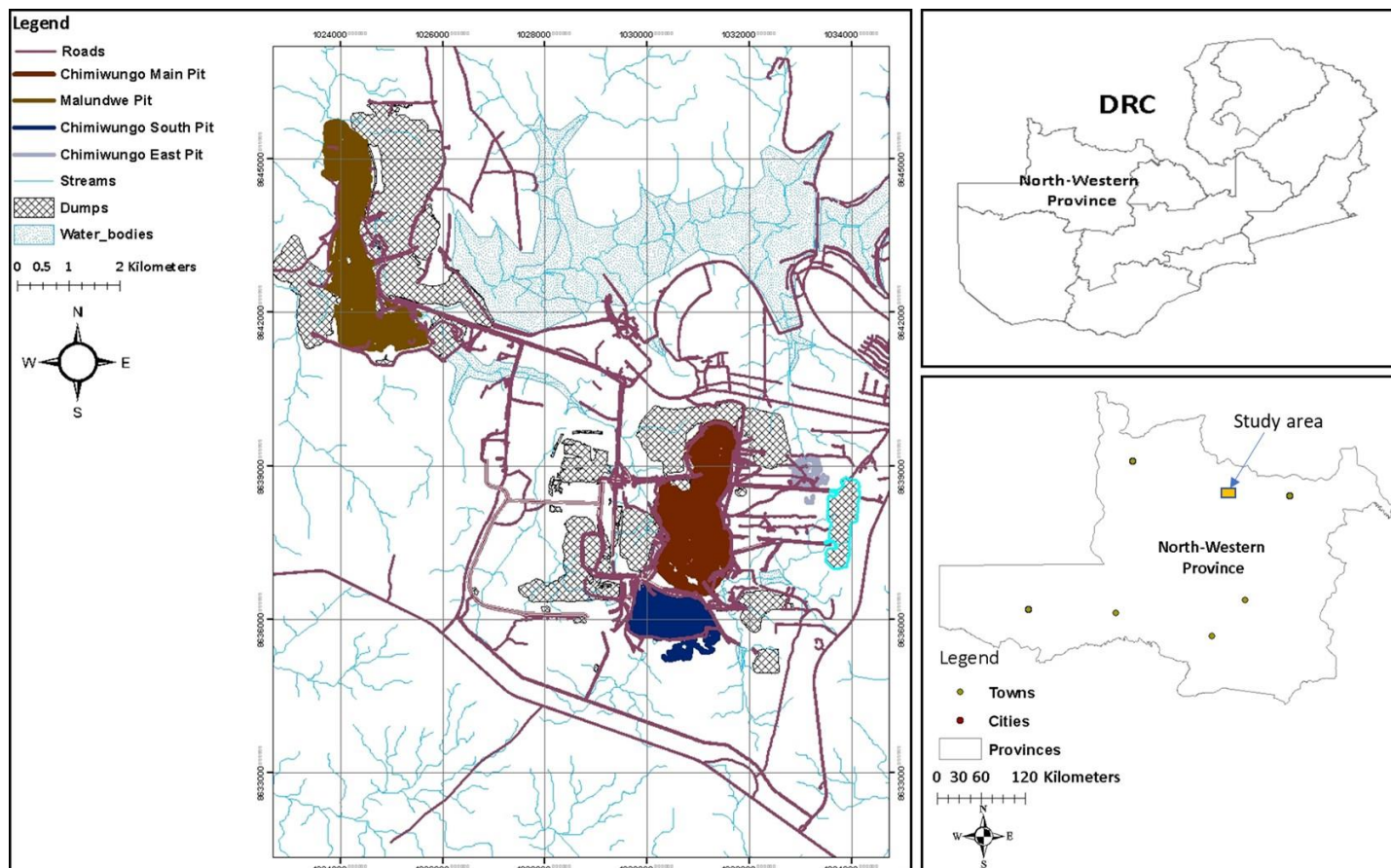


Figure 2.1 Locality map of the study area

2.2. Topography

The Lumwana mine area is situated on a generally elevated relatively flat land as shown on the digital elevation model (DEM) in Figure 2.2. The highest point in the study area is located in the northeastern part around 1410 meters above sea level, while the lowest point is located about 1280 above mean sea level in the western part of the mine site.

2.3. Hydrology

The Lumwana Mine area is drained by the Lumwana East River and its tributaries as shown in Figure 2.2. The Lumwana East River flows from the northeast towards the southwest while the seasonal streams flow nearly to the north and seldomly to the south. The Lumwana East River and its tributaries flow along the fault system and across different lithological units consisting of the feldspathic gneisses and occasionally across the quartzites (Golder Associates, 2005).

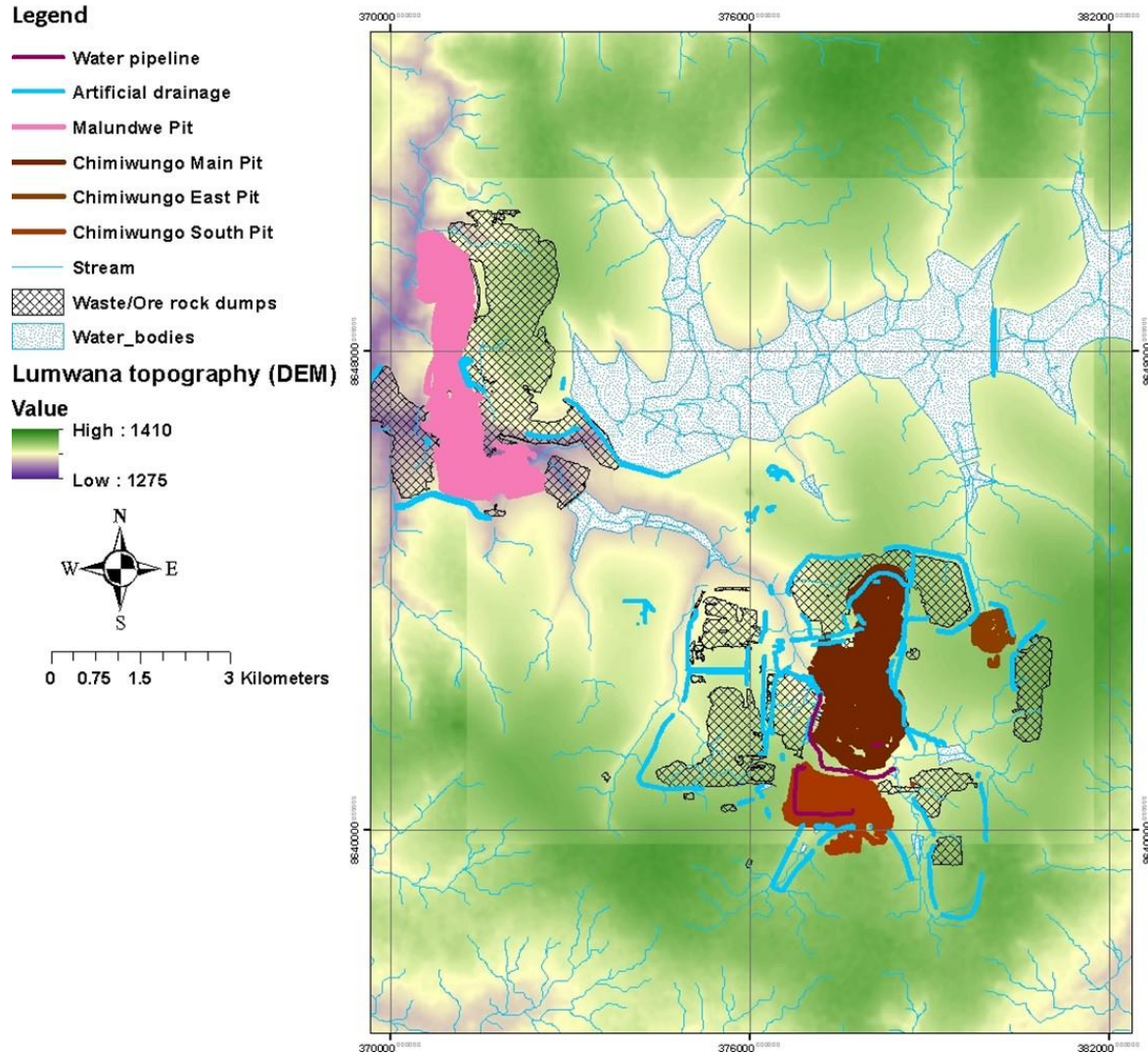


Figure 2.2 Digital elevation model (DEM) and hydrological map of the study area.

2.4. Climate

Lumwana Mine area is located in the sub-tropical region and is characterised by distinct wet and dry seasons covering the period October to May and June to September, respectively (JICA, 1995). The region generally experiences heavy rainfall averaging around 1200 mm/year during the summer period, with unimodal month-to-month rainfall distribution pattern as depicted in Figure 2.3. The highest amount of rainfall during a 10-year monitoring period was recorded during the 2021/22 wet season, amounting to 1500 mm. Regional monthly mean temperature ranges from a minimum of 5.6 °C to a maximum of about 30.5 °C and the mean annual temperature is 19.8 °C at an altitude of about 1350 m (Karen *et al.*, 2015). The average pan

evaporation is 2080 mm per year and the average potential evapotranspiration (PET) is 1485 mm per year (JICA, 1995). The rainfall in the area is linked to southward shift of the Inter-Tropical Convergence Zone (ITCZ). The southward shift of the ITCZ creates a convergence of the trade winds into a low-pressure zone and pronounced convective activity that is associated with heavy tropical rainfall (Karen *et al.*, 2015).

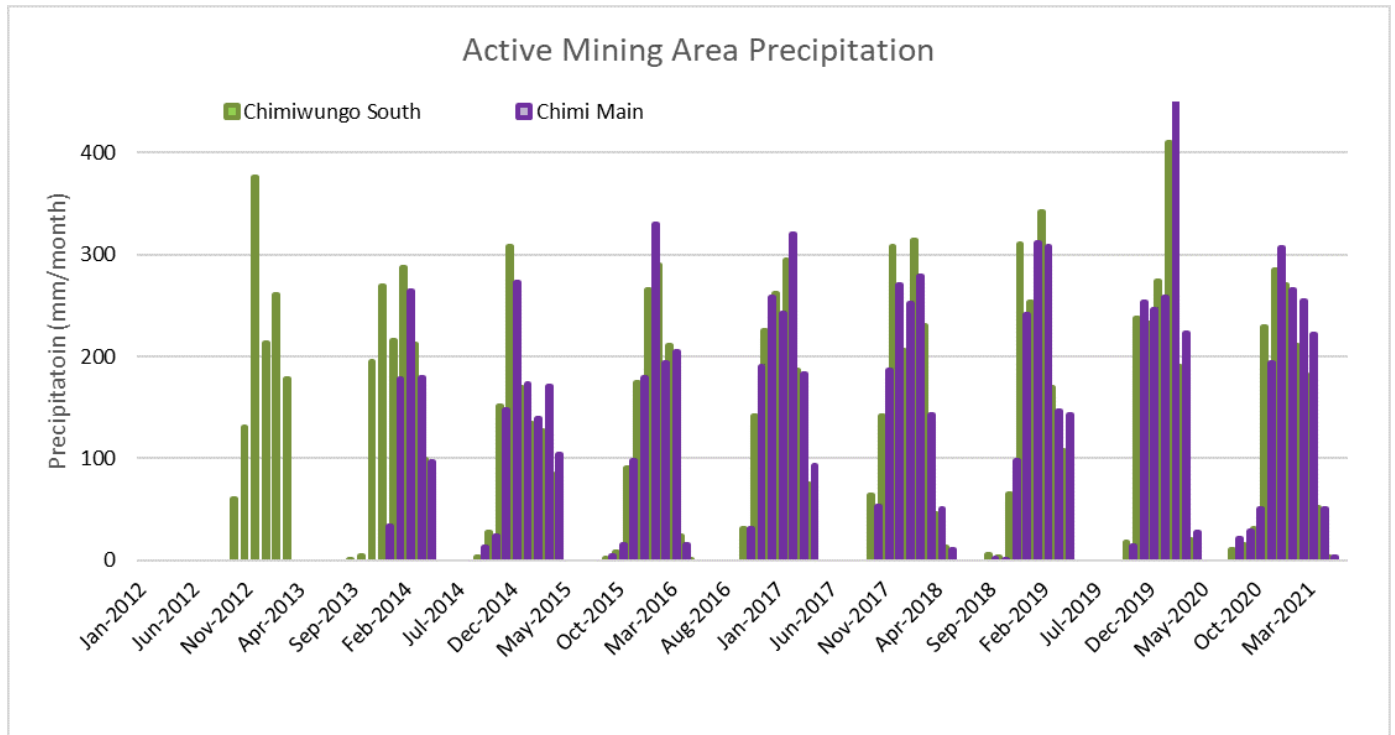


Figure 2.3 Chimiwungo active mining area's measured monthly rainfall between 2012 and 2021. (Source: Lumwana Copper Mine, Environmental Department).

Analysis of the existing weather data collected from the site meteorological station in Figure 2.4 shows an inverse relationship between humidity and evaporation. Singh *et al.* (1992) investigated the relationship between evaporation from US Class A open pan evaporimeter and meteorological parameters at Hisar. Wind velocity, sunshine hours, mean air temperature and solar radiations were positively correlated with evaporation and relative humidity was negatively correlated with evaporation. At the Lumwana Mine area, humidity is at its peak during the wet season due to reduced vapour pressure deficit and therefore, reduced capacity for the air to accommodate moisture while daily evaporation rate reduces owing to the low capacity of the air to accommodate moisture. Jhajharia *et al.* (2009) reported a significant influence of wind speed

and mean temperature on evapotranspiration, which agrees with the observations in Figure 2.4. The rate of evaporation also shows positive relationship with daily mean temperature and wind speed.

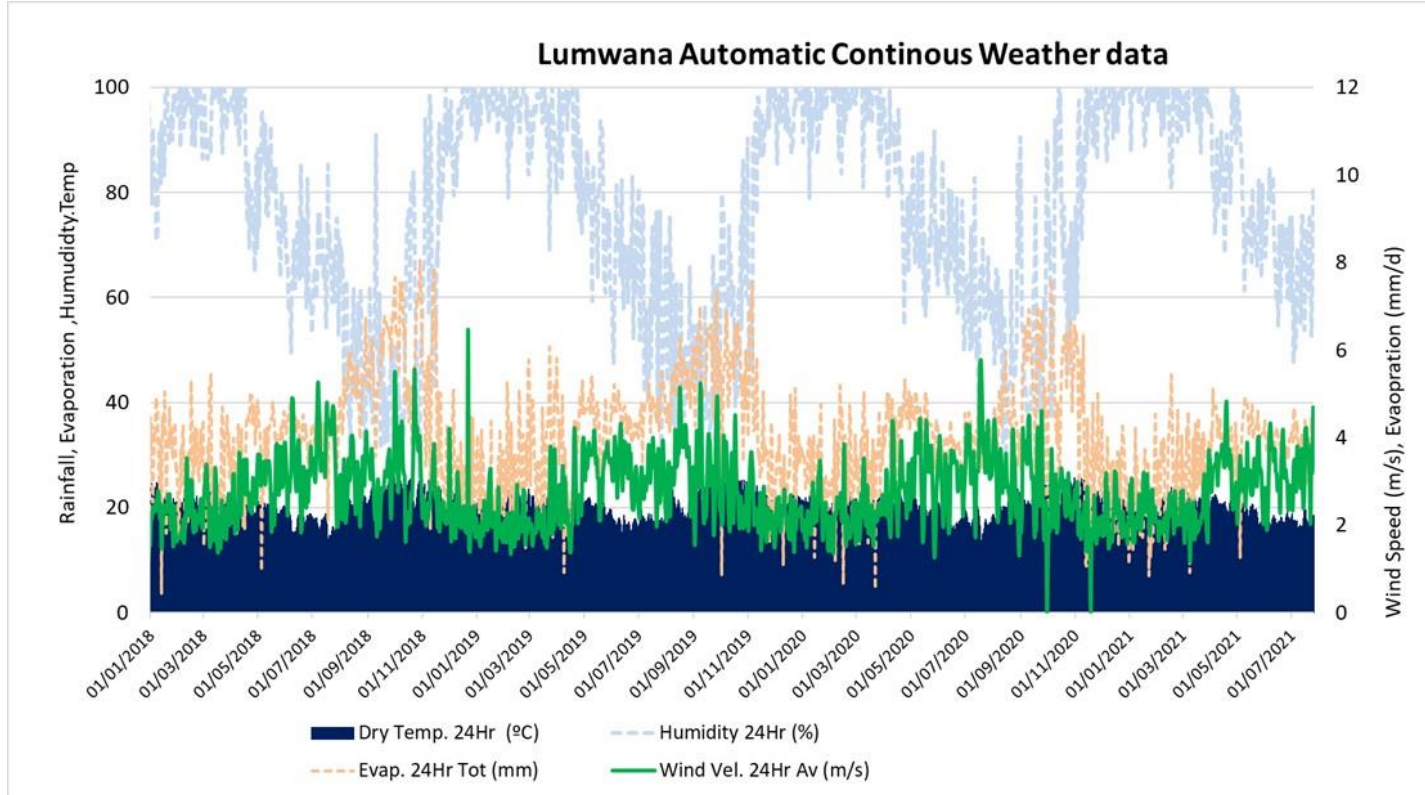


Figure 2.4 Monthly site rainfall, evaporation, humidity, temperature, wind speed and evaporation at Lumwana mine for the period between 2018 and 2021. (Source: Lumwana Copper Mine, Environmental Department).

Further analysis of the automatic weather station rainfall data versus wind direction has revealed nearly distinct moisture sources during the wet and dry seasons attributed to atmospheric kinetics driven by changes in solar radiation from season to season (Zhou *et al.*, 2021). In-situ climate observations indicate that the southeastern near-surface wind dominates within Zambia (Libanda and Paeth, 2021). While there are variations from season to season, results show that southeasterlies remain dominant throughout the year with minor variations observed from December to February when the southwesterlies prevail (Libanda and Paeth, 2021). During the period from March to May and June to August, the winds turn back to southeasterlies before veering again from September to November (Libanda and Paeth, 2021). The different moisture

sources from site continuous weather data are responsible for the changes in site weather patterns and weather characteristics. The climatological-observed southeasterly wind system is responsible for moisture advection from the Indian Ocean and the tropical South Atlantic Ocean, thereby contributing significantly to the rainfall patterns in Zambia and across the region (Hachigonta and Reason, 2006). The observed mean wind speed of 2.4 m/s within the study area is consistent with the wind speed reported at the national and regional levels, including neighbouring Malawi (Ngongondo *et al.*, 2012).

2.5. Regional Geology

The Lumwana Mine deposits, which include the Malundwe and the Chimiwungo deposits are hosted within the Lufilian Arc (Figure 2.5) Domes region in the north-western part of Zambia called the Mwombezhi Domes (MD) (Figure 2.6). The Mwombezhi Dome in the Domes region of the Lufilian Arc trends SW-NE and forms the 70 km long and about 20 km wide structural window into the pre-Katangan basement core complex (Rainaud *et al.*, 2005; Eglinger *et al.*, 2016). The core of the MD consists predominantly of the Paleoproterozoic ortho- and paragneisses that may be correlated with the Paleoproterozoic Lufubu Metamorphic Complex of the Kafue Anticline to the east (Rainaud *et al.*, 2005; Eglinger *et al.*, 2016). The sporadic copper mineralised schist in the basement records younger Irumide ages (ca. 1084 – 1059 Ma), denoting relict Mesoproterozoic protoliths or reworking of Paleoproterozoic basement gneiss during the Irumide Orogeny (Eglinger *et al.*, 2013; Silitoe *et al.*, 2015). The Mwombezhi Dome is unconformably overlain by several amphibolite facies belonging to the Lower Roan Group supracrustals, consisting of the muscovite-quartz-talc (hematite) schist (white schist) and micaceous quartzite (rimming quartzite), which are assigned to the base of the Katangan Supergroup in terms of their protoliths (Eglinger *et al.*, 2013; Silitoe *et al.*, 2015). The base of the Roan Group is a representation of a major tectonic unconformity, viz. a regional Décollement/detachment zone, known as the Katangan Décollement (KD), which was responsible for decoupling of the overlying Katangan Supergroup from the basement (Porada and Berthorst, 2000; Selley *et al.*, 2005).

In terms of order or sequence on the stratigraphy or tectonostratigraphy, the rimming quartzites are overlain by meta-carbonates and metapelites of the Upper Roan and Kundelungu Group, respectively. The Lower and Upper Roan sequences are broadly consistent throughout the

Domes Region, although facies in their original protoliths varied according to the basin or sub-basin geometry or context (Selley *et al.*, 2005).

In general, the structural geometry of the MD remains enigmatic, mostly due to the poor exposure and limited structural and geophysical data (e.g. Porada, 1989, Cosi *et al.*, 1992; Selley *et al.*, 2005, Eglinger *et al.*, 2016, Turlin *et al.*, 2016). An initial model of deformation was proposed by Cosi *et al.* (1992), who ascribed the formation of the MD to low angle stacking and antiformal doming/folding of “alpine-like” nappes that were cored by transposed, allochthonous basement slivers. This model stems from overturned/inverted Roan tectonostratigraphically (i.e. the Malundwe deposit’s footwall), which underlies basement gneiss within the MD. These units are inferred to be continuous with upright, structurally or tectonostratigraphically-higher Roan stratigraphy mantling the MD (viz. Rimming quartzite, White schist) (Rainaud *et al.*, 2005; Eglinger *et al.*, 2016). In other words, the inverted Roan sequences are assigned to the lower limb of a recumbent, dome-scale nappe. However, this rationale does not account for the general absence of thick Katangan Supergroup stratigraphy at lower structural levels, i.e below the MD and other domes (Eglinger *et al.*, 2016; Williams and Nibset, 2017). Different recent researchers have a proposition that the domes are “autochthonous” basement inliers (Williams and Nibset, 2017), although the mechanism of dome uplift or development remains unclear. Models of blind, deep-crustal, imbricate thrust stacking of basement wedges or slivers, subsequently underthrusting the Katangan SG, have also been proposed (e.g. Porada and Berthorst, 2000).

The MD core complex (i.e. lower structural levels) records peak high-temperature metamorphism at 9-11 kbar and 640-660°C at 540-530 Ma, indicated by amphibolite boudins enveloped by magmatic gneisses, or by foliated metatexites (Eglinger *et al.*, 2016). This is reinforced by even higher peak P/T estimates of 13 kbar and 750°C for mantling Rimming quartzites and White schists at ca.550-530 Ma (John *et al.*, 2004). These conditions indicate the initial burial of basement and mantling rocks at significant depths of ca. 40-50 km, with geothermal gradients of ca. 15-20°C (John *et al.*, 2004). This suggests that the MD likely formed part of the partially molten root of the overthrust Congo Craton and Lufilian Belt, during continental collision. After peak metamorphism, shearing and transposition of the MD margins along the KD were characterised by wide, intensely strained, schistose mylonitic zones that locally record retrogression to 6-8 kbar

and 600-640°C towards ca. 5000 Ma, and eventual exhumation and structural collapse of the Lufilian Belt (Eglinger *et al.*, 2016). Locally, the KD is complex and many may include low-angle thrust duplication of basement, partially or locally tectonically interleaved with recumbent and isoclinally-folded Katangan Supergroup (Cosi *et al.*, 1992; Key *et al.*, 2001).

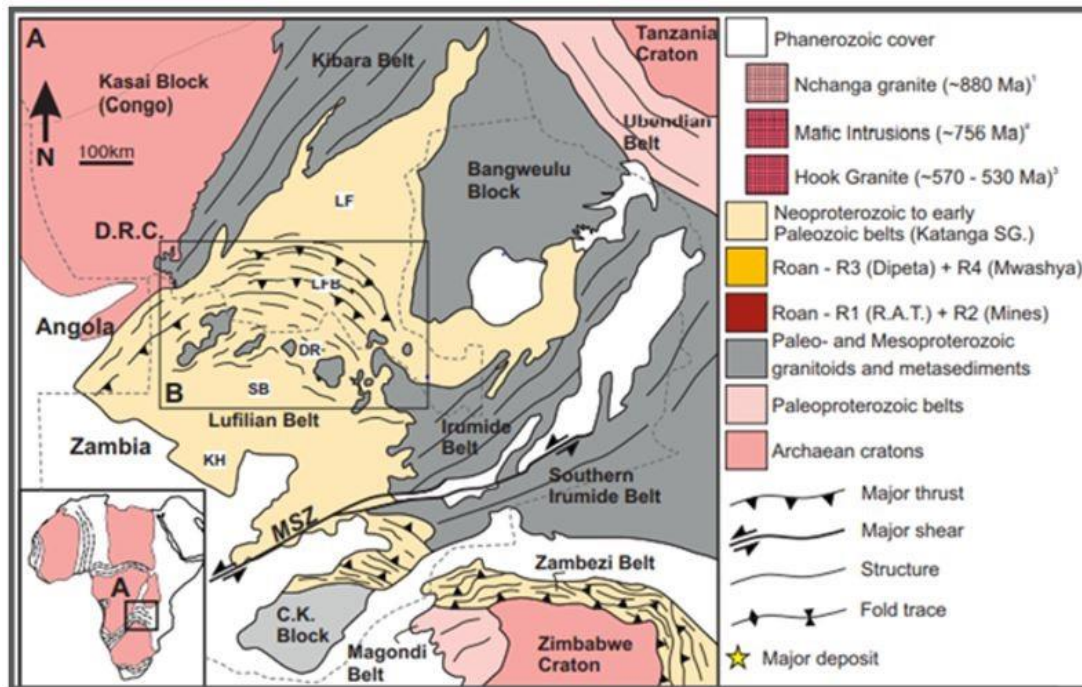


Figure 2.5 Geology of the Central African Copperbelt Lufilian Arc, the associated blocks and major geosubstructural belts (Rainaud *et al.*, 2005).

Legend

- Section line
- LOM Chimiwungo East Pit
- LOM Chimiwungo South Pit
- LOM Chimiwungo Main Pit
- Mwombezhi Faults

Mwombezhi Dome Geology

Lithology

- Syenite
- Neoproterozoic Mafic Intrusives
- Neoproterozoic Granite
- Upper Roan - Carbonaceous Shale
- Upper Roan - Limestone
- Upper Roan - Undifferentiated Siliciclastics
- Lower Roan - Siliciclastics
- Schist
- Palaeoproterozoic Basement - Gneiss
- Paleoproterozoic Basement - Gneiss & Schist

0 1.75 3.5 7 Kilometers

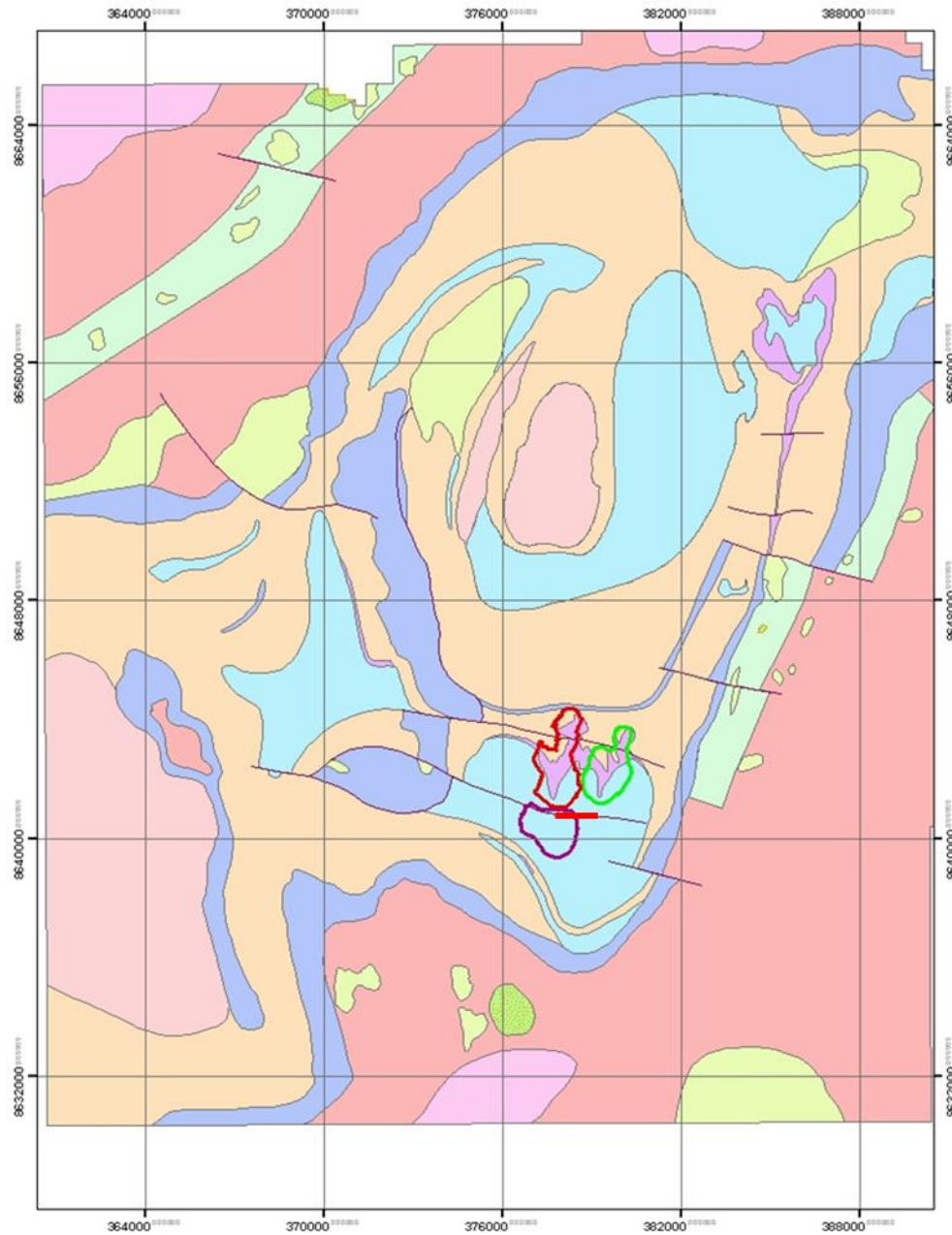


Figure 2.6 Mwombezhi Dome geology with the life of mine pit footprint.

3. RESEARCH METHODOLOGY

Different hydrogeological investigative approaches have been employed in the assessments of the Lumwana hydrogeological conditions. These include both fieldwork and desktop studies. Field work includes but is not limited to borehole drilling, grouted in vibrating wire piezometer installations, hydraulic testing for aquifer hydraulic characterisation, geological and seepage mapping employing unmanned aerial vehicles (drone surveys) during the peak of the dry season, environmental isotopes, hydrochemical sampling, and general hydrogeological investigation. In-situ permeability testing conducted within diamond drill holes during this investigation includes falling head tests, shut-in and discharge tests. Other investigative fieldwork includes water sampling for major ion hydrochemistry, physicochemical parameters and environmental isotope laboratory analysis. Desktop computer studies include analysis of meteorological data, analysis of existing packer testing results, hydrochemical data analysis, environmental isotopes analysis, processing of geological and structural leapfrog data and hydrogeological system conceptual model development.

3.1. Desktop studies

Desktop studies carried out include analysis of meteorological data, analysis of existing hydraulic data for packer tests, hydrochemistry data analysis, environmental isotope data analysis, stereographic projections, processing of geological and structural leapfrog data and conceptual model development. Evapotranspiration is an important component of the hydrological cycle (Trajkovic *et al.*, 2019). The Penman-Monteith method (PM) is recommended as the sole standard method for estimating reference evapotranspiration. However, the usage of the PM is limited in many regions due to lack of required weather data. In such instances, Thornwaite-Mather equation is often used to estimate evapotranspiration (Trajkovic *et al.*, 2019). Potential evapotranspiration and actual evapotranspiration were estimated using meteorological data from the site weather monitoring station. Potential evapotranspiration is defined as maximum amount of water that would be evapotranspired under unlimited moisture supply while actual evapotranspiration is the actual amount of water evapotranspired (Trajkovic *et al.*, 2019).

Potential evapotranspiration estimate for the Lumwana Mine catchment was determined using the Thornwaite-Mather method (equation 1), while the actual evapotranspiration was determined using the Turc empirical formula (equation 2) based on the site climatic data.

$$PET_m = 16N_m \left(\frac{10 \bar{T}_m}{J} \right)^a \quad (\text{Equation 1})$$

Where:

PET_m is monthly potential evapotranspiration

$$a = 6.75 \times 10^{-7} J^3 - 7.71 \times 10^{-5} J^2 + 1.792 \times 10^{-2} J + 0.49239$$

$$J = \sum j_m = \sum (\bar{T}_m / 5)^{1.514}$$

N_m is the monthly adjustment factor depending on the season and latitude

m = months in a year 1, 2, ---12

$\bar{T}_m$ = monthly mean temperature (°C)

J = the heat index for the year

AET was determined from Turc method

$$AET = P / [0.9 + (P/L)^2]^{1/2} \text{ mm per annum} \quad (\text{Equation 2})$$

P is the mean annual precipitation in mm

$$L = 300 + 25T + 0.05T^3$$

T is the mean annual temperature in degrees Celcius

3.2. Field Work

3.2.1 Diamond Drilling and Core Logging

Diamond drilling is a reliable method useful for geological data collection that forms the basis for determining the main hydrostratigraphic units (Beale *et al.*, 2013). Diamond drilling of pit perimeter piezometers was carried out before and during this research work. The diamond drilled core logging was also conducted on-site drill holes presented in Table 3.1 to establish the

lithological and structural characterisation prior to vibrating wire piezometers installations to ascertain the specific zones for sensor installations. The geological data collected in the field provided confirmation of the geology and improved confidence for the geological and structural leapfrog model.

Table 3.1 Completed diamond drilling and Piezometer installation holes.

NO.	HOLE ID	COLLAR			SURVEY		DEPTH (m)
		X Coordinate	Y Coordinate	Elevation (m)	Azimuth (°)	Dip (°)	
1	CPD001	378298.5	8642779.6	1367.8	255.0	60.0	126.5
2	CPD002	378400.0	8642363.2	1365.0	270.0	50.0	150.5
3	CPD003	378537.0	8641871.0	1360.7	290.0	45.0	175.5
4	CPD004	377307.2	8642215.6	1343.4	70.0	55.0	125.0
5	CPD005	378284.9	8641318.6	1341.6	315.0	55.0	175.0
6	CWHP001	378327.0	8641990.0	1246.3	100.0	45.0	125.0
7	CPD006	377172.7	8641478.9	1371.2	55.0	55.0	275.0
8	CPD007	378212.0	8641185.0	1345.7	5.0	55.0	275.0

3.2.2 Geological and seepage mapping

Geological mapping was part of the fieldwork conducted at Lumwana Mine within the active pits with fully exposed and properly scaled walls to confirm the geology of the study area. The geological mapping involved the use of a digital-based method, which was regularly calibrated with a regular manual compass as per the standard geological mapping procedure at Lumwana Mine (Koegelenberg and Basson, 2018). The method employed uses a preprogrammed geological application called Rocklogger, which was installed on mobile phones linked to a bluetooth mobile device. The technique offered the quickest and most robust approach for geological field mapping of lithologies and discontinuities. The data collected was downloaded, imported and processed in Leapfrog Geo software. The data collected from the mapping provided valuable data for updating the 3D Leapfrog Geological Model for the mine. The confirmatory geological

mapping involved collecting lithological and structural data, especially in the new pit stages exposed.

3.2.3 Piezometer installations

Following the completion of diamond drilling, piezometer installations were carried out at predefined depth based on the geological and structural logging data.

Vibrating wire sensors were installed in critical geotechnical zones or hydrostratigraphic units, including the saprolites, transition and fresh bedrock, and where possible, within the fractured zone for continuous monitoring of the pore pressures and phreatic surfaces. The guide-tremie pipe method is the most frequently applied method for the installation of multi-level, grouted-in Vibrating Wire Piezometers, particularly where there is a large number of installations programmed and ground conditions are competent such that there is limited risk of borehole collapse during installation (Beale *et al.*, 2013). For Vibrating Wire Piezometer installations, a grout mix with in-situ hydraulic conductivity of less than 10^{-8} m/s should be achieved. It is common that mix of relative proportions by weight of cement: water: bentonite is 1:2.5:0.3 is used (Mikkelsen, 2002).

Figure 3.1 and Table 3.2 provide the plan for installed Vibrating Wire Piezometer monitoring network to improve pit wall pore pressure and water level monitoring coverage. RST Instruments, VW2100 model and HGA Geotechnical vibrating wires were installed according to the tremie-guide method shown in Figure 3.2 by means of strapping the sensors to the PVC guide pipe and injecting the cement-bentonite grout through the PVC until the grout settles. Before the installations, sensors were fully submerged in water in a bucket to normalise sensor readings with the environment. Static water levels and sensor zero reading recording were done immediately before installation using a dip meter and RST Instruments portable readout units, respectively. The Vibrating Wire Piezometer installations completed during this phase provided data to fill in the gaps identified and improved piezometric pore pressure monitoring resolution.

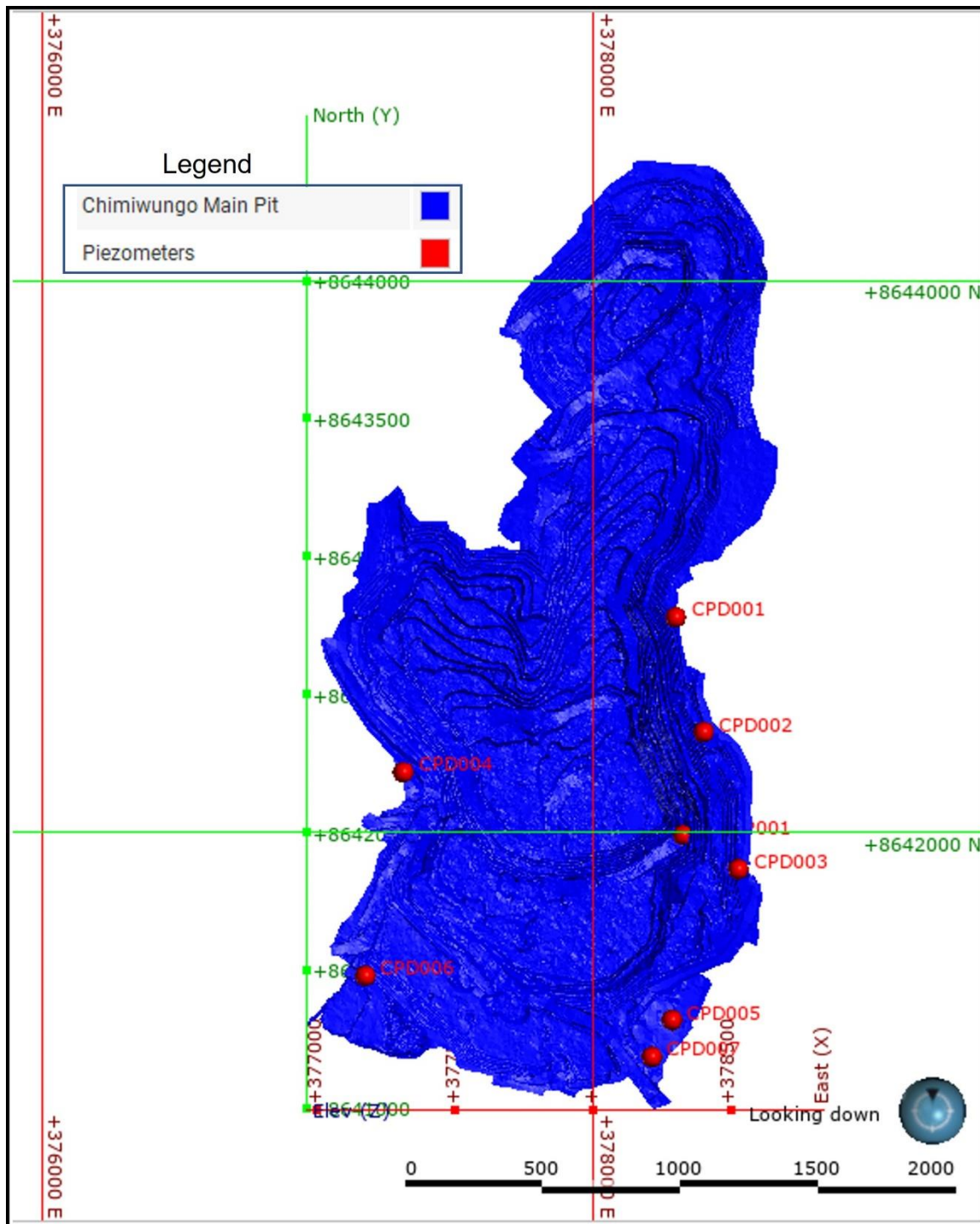


Figure 3.1 Diamond Drill holes and Vibrating Wire Piezometers monitoring network coverage at Lumwana Mine.

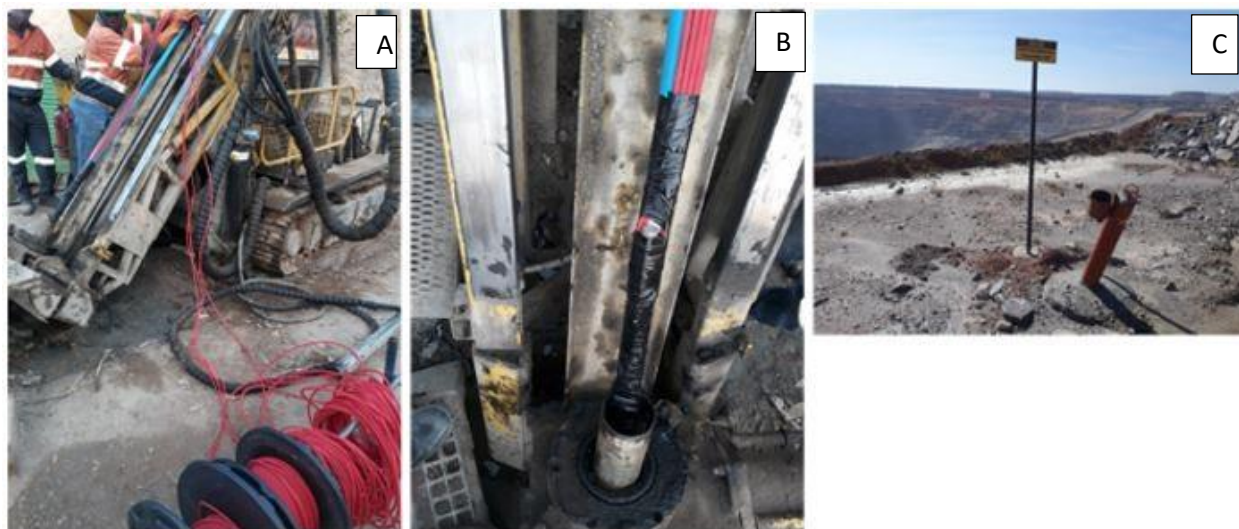


Figure 3.2 (A) Vibrating Wire Piezometer on reels during installations (B) after installation by guide-tremie (C) after commissioning and monitoring.

Table 3.2 Vibrating Wire Piezometers installation specifications at Lumwana Mine.

Hole ID	Depth(m)	Angle (°)	VIBRATING WIRE PIEZOMETER SPECIFICATIONS				SWL(mbgl)	Geotechnical Unit
			Sensor Serial Number	VWP Model	Sensor Depth along hole path(m)	Vertical Depth(m)		
CPD001	126	60	17342	HMA Geotechnical Systems	120.00	104	48	Fresh
			17354	HMA Geotechnical Systems	49.00	42		Transitional
			7355	HMA Geotechnical Systems	34.00	29		Saprolite
CPD002	150	50	17497	HMA Geotechnical Systems	145.00	111	23.6	Fresh
			17494	HMA Geotechnical Systems	53.00	41		Transitional
			17493	HMA Geotechnical Systems	30.00	23		Saprolite
CPD003	175	45	17497	HMA Geotechnical Systems	169.20	119.6	30.8	Fresh
			17494	HMA Geotechnical Systems	59.25	41.8		Transitional
			17493	HMA Geotechnical Systems	47.25	33.4		Saprolite
CPD004	125.5	55	17348	HMA Geotechnical Systems	91.00	71	11	Fresh
			17348	HMA Geotechnical Systems	19.29	15		Transitional
			17351	HMA Geotechnical Systems	13.29	10		Saprolite
CPD005	175	55	17618	RST Instruments, VW2100	170.00	139	4.9	Fresh
			17496	RST Instruments, VW2100	97.00	79		Fresh
			17492	RST Instruments, VW2100	36.00	29		Trans
			17429	RST Instruments, VW2100	22.50	18		Saprolite
CPD006	275	50	VW52564	RST Instruments, VW2100	7.66	10	7	Fresh
			VW57965	RST Instruments, VW2100	15.70	21		Fresh
			VW57966	RST Instruments, VW2100	93.46	122		Transitional
			VW57973	RST Instruments, VW2100	206.83	270		Saprolite
CPD007	275	50	VW52533	RST Instruments, VW2100	17.62	23	6	Fresh
			VW52536	RST Instruments, VW2100	36.77	48		Fresh
			VW57969	RST Instruments, VW2100	87.33	114		Transitional
			VW57974	RST Instruments, VW2100	206.83	270		Saprolite
BH01	30	90	VW52535	RST Instruments, VW2100	25	25	5.7	Transitional
BH02	24.5	90	VW57965	RST Instruments, VW2100	16.5	16.5	7.2	Transitional
BH03	24.5	90	VW52537	RST Instruments, VW2100	16.5	16.5	5.5	Transitional
CWP001	125	45	VW57964	RST Instruments, VW2101	41.5	31.8	0	Fault
			VW57968	RST Instruments, VW2102	74	56.7	0	Fresh
			VW57970	RST Instruments, VW2103	109.1	84.1	0	Fresh

3.2.4 Hydraulic testing

Aquifer parameter testing can be carried out using different techniques such as packer tests, slug tests, single drawdown or multiple drawdown-recovery tests. According to Theis (1935), the recovery method is the most reliable method for estimating representative values for hydraulic parameters.

In-situ permeability tests were successfully done in both subvertical and horizontal diamond drill boreholes as part of the fieldwork hydraulic testing program for the research and these were done for hydraulic characterisation of the different geotechnical and geostructural zones. The hydraulic testing campaign supplemented the historical hydraulic tests conducted before Chimiwungo pit development. The earlier hydraulic tests include packer tests in geotechnical investigation drill holes at the Chimiwungo Main starter pit and Chimiwungo East starter pit. Figure 3.3 provides a plan view of the diamond drill holes hydraulic testing completed at Lumwana Mine.

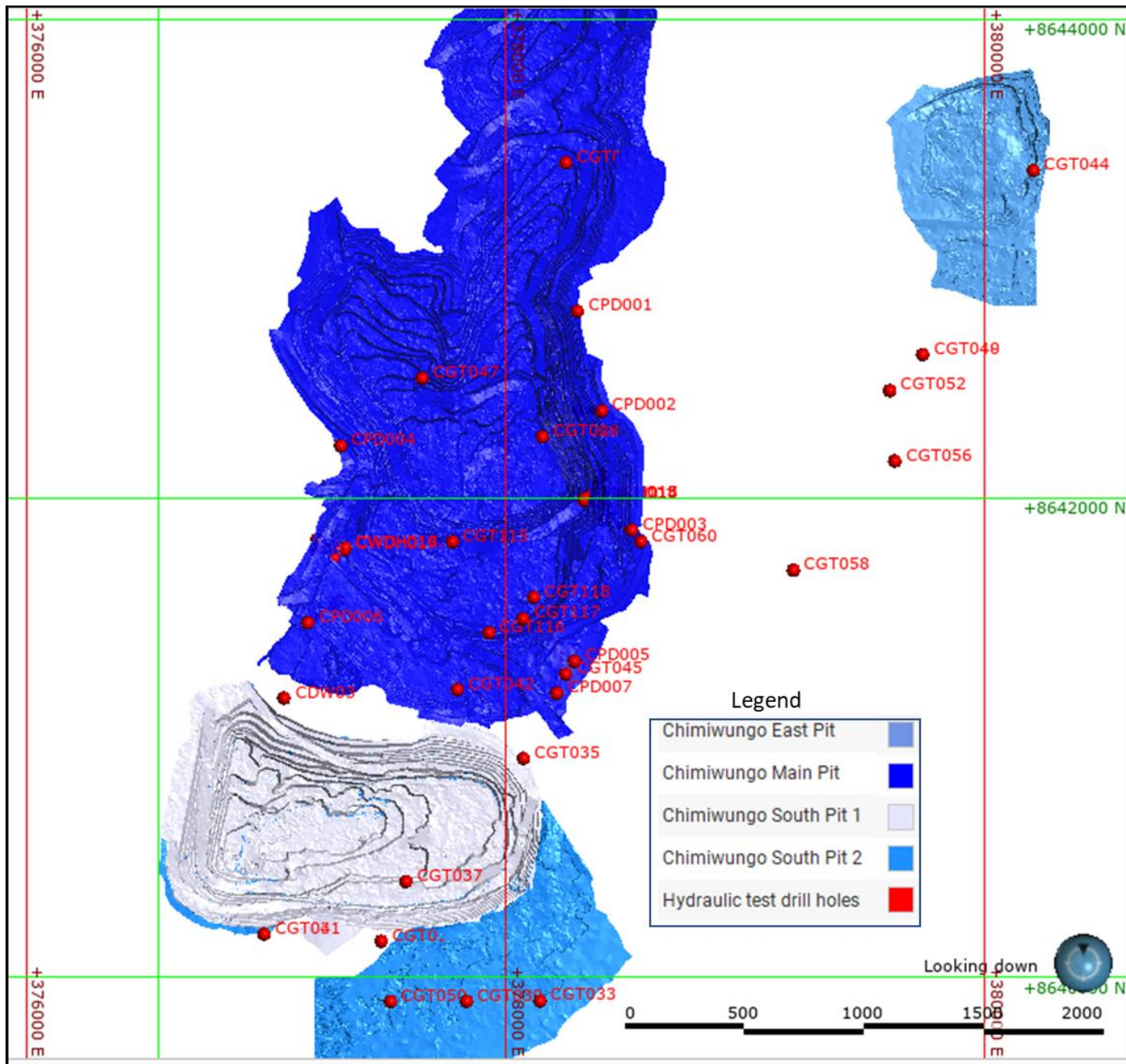


Figure 3.3 Locations of diamond drill holes hydraulic testing sites at Lumwana Mine.

3.2.5 Falling Head Tests

Variable-head test also known as falling or rising head test or slug test offer the lowest cost and simplest method of in-situ hydraulic conductivity tests either in existing boreholes or boreholes

that are actively being drilled (Beale *et al.*, 2013). Freeze and Cherry (1979), Kruseman and De Ridder (1990) and Brassington (1998) provided detailed procedure for carrying out rising or falling head tests with reference to the detailed procedure provided by the British Standard Institution and testing method ASTM D 4044-91 (1991). Slug testing through falling head test (Figure 3.4) was carried out on eleven boreholes during the drilling stage according to the plan in Figure 3.5. The falling head test was conducted on different representative zones, manually using dip meter and digitally using preprogrammed level logger by introducing a slug in a sub-vertical diamond drill hole and monitoring the change in hydraulic head over a period of an hour. Falling head test works on the assumption that the change in hydraulic head is related to the hydraulic conductivity of the geotechnical unit under investigation (Hvorslev, 1951). Prior to the testing procedures, the length of the test section, the diameter of the borehole, the length of the borehole section cased and the geology of the interval under investigation were noted. Various authors have described standard techniques for analysing slug tests results (Beale *et al.*, 2013). The simplest and most robust method of slug test results analysis is the method devised by Hvorslev (1951) as described by Freeze and Cherry (1979), which is devised for testing sections of the drill hole that are relatively short compared with the thickness of the formation under investigation. It assumes geological formation homogeneity and that both geological formation and water are incompressible and therefore, cannot be used to estimate storage properties. Slug test analysis suitable for full thickness of the aquifer have been presented by other authors including Cooper *et al.* (1967), taking into consideration the compressibility of the aquifer formation and water using a curve fitting method that theoretically provides value for storage.

Slug test results in unconfined condition can be carried out using Hvorslev (1951) and Bouwer and Rice (1976). The Hvorslev (1951) method of analysis uses a simple graphical technique based on the concept of 'shape factors', which considers the radius and length of the interval under investigation in relation to the bed boundaries. Hvorslev (1951) argued that the inflow at any time depends on the hydraulic conductivity of the formation, the head difference between water in the formation and that in the well or piezometer, and the geometry of the piezometer intake section summarised as the 'shape factor'. The rate of inflow at any time, t , must be equal to the

rate of change of volume in the cased or standpipe portion of the piezometer. Hydraulic conductivity, K is calculated as (equation 3).

$$K = r^2 \ln\left(\frac{l}{r_w}\right) / 2lt \quad (\text{Equation 3})$$

Where:

r is the radius of the cased section or standpipe in which the changes are being observed, l is the length of the test interval, the ratio l/r_w is greater than 8 and t is the time required for the head in the piezometer to return to its original level.

The raw data collected in addition to the borehole specifications, was analysed through the Flow Characteristic (FC) computer programme based on the Bouwer and Rice (1976) method.



Figure 3.4 Falling Head test on an open diamond drill hole at Lumwana Mine.

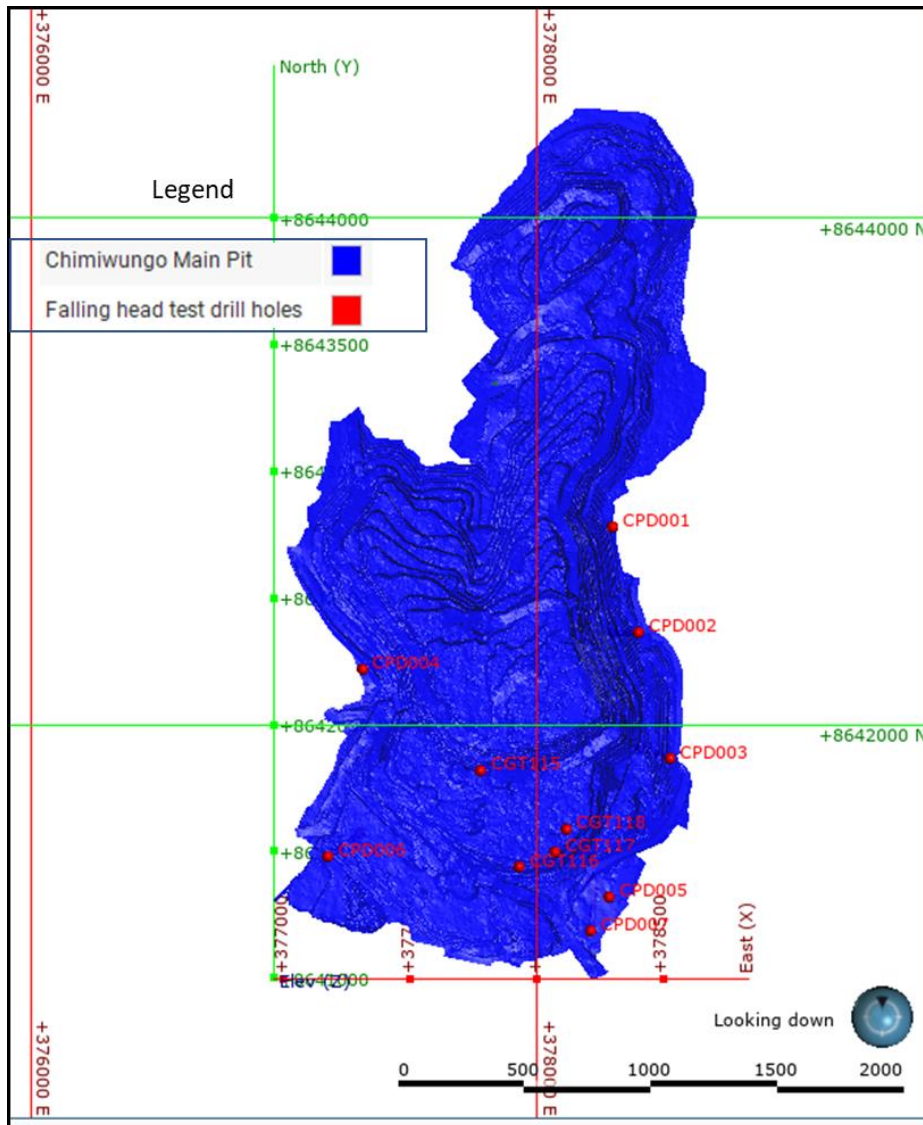


Figure 3.5 Location for the falling head test diamond drill holes at Lumwana Mine.

3.2.6 Shut-in test

A single-well test is a test in which piezometers are not used. Water-level changes during pumping or recovery are measured only in the well itself (Kruseman, 1999). In the hydraulics of well flow, the well is generally regarded as a line source or line sink and the well is assumed to have an infinitesimal radius so that the well-bore storage can be neglected (Papadopoulos and Cooper, 1967). Shut-in tests were conducted on all newly drilled horizontal drainage boreholes according to the plan in Figure 3.6 and Table 3.3 immediately after drilling and construction of the boreholes. At Lumwana Mine, horizontal drainage holes were drilled in sets of three holes,

about a meter apart at 30 degrees apart and inclined upwards at 5 degrees to allow water to drain freely through the collar assemblage under the influence of gravity. Shut-in tests were conducted by inserting the preprogrammed level loggers into the collar assemblage and shutting the valve until the hydraulic head built up to the maximum stabilised pressure head over time. The level loggers were left inside the horizontal drain holes for a duration of four to seven days for the pressure head to build to its maximum. To ascertain the hydraulic response of the geotechnical unit under investigation, shut-in tests were conducted at high resolution, with a discharge test towards the end of the shut-in test. Different hydraulic responses, as seen in Figure 3.7 and Figure 3.8, were observed in various locations within the Chimiwungo pits and thus indicating high variability of hydraulic conductivities within different geotechnical units, hence providing evidence for fracture flow (Beale *et al.*, 2013).

Jacob's (1946) straight-line method can be applied to single-well constant-discharge tests to estimate the aquifer transmissivity. However, not all the assumptions underlying the Jacob method are met if data from single-well tests are used. In applying the Cooper and Jacob straight line method, it is assumed that radial and horizontal flow existed (Tonder and Dzanga, 2002). The Cooper-Jacobs equation for calculating the aquifer transmissivity is given by equation 4:

$$T = \frac{2.3Q}{4\pi\Delta s} \quad (\text{Equation 4})$$

Where:

T is the aquifer transmissivity (m^2/d)

Δs is the drawdown difference per log cycle

Q is the well discharge (m^3/d)

The data collected from the shut in and discharge test was analysed using the Jacob-Cooper recovery method.

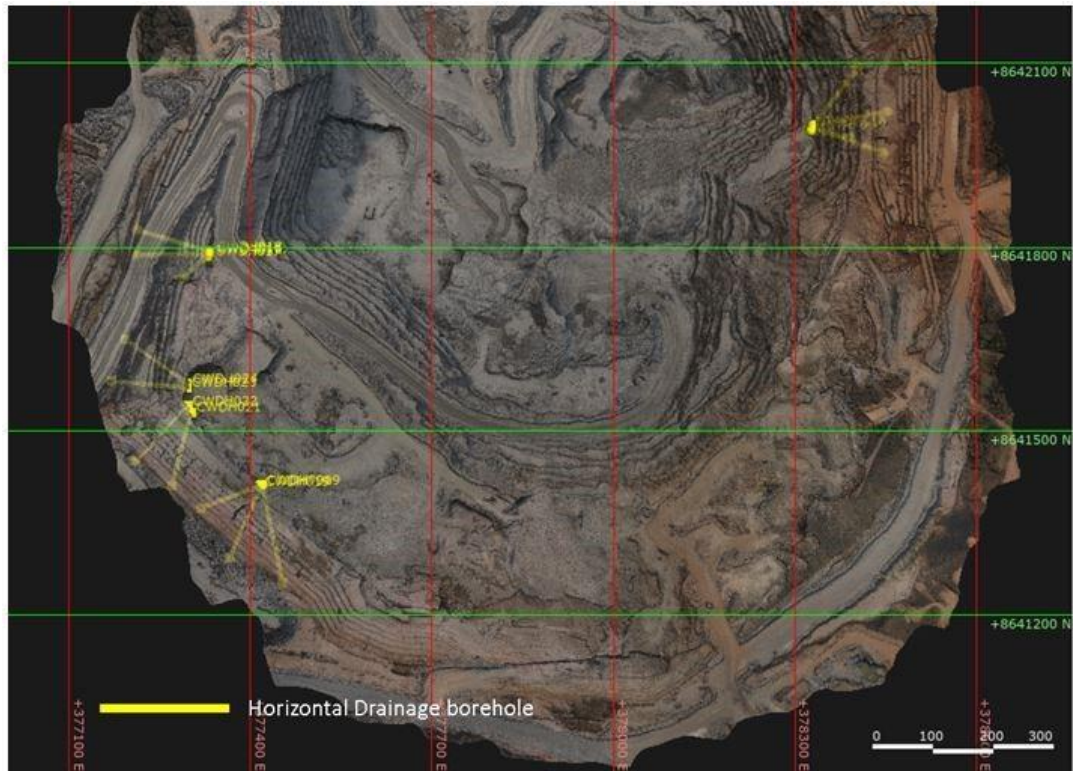


Figure 3.6 Plan view of drone image insert for the pit with horizontal drainage holes drilled in slopes at Lumwana Mine (Courtesy; Lumwana Mining Survey department).

Table 3.3 Horizontal drainage diamond drill holes data from Lumwana Mine.

Drillhole Name	Easting	Northing	Elevation (m)	Azimuth (°)	Dip (°)	Depth (m)	Pit Stage
CWDH013	378329.3	8641997	1246.1	78.9	-5	125	CW4
CWDH015	378329.2	8641998	1246.1	38.4	-5	122	CW4
CWDH014	378329.0	8641994	1247.7	109.2	-5	125	CW4
CWDH016	377329.3	8641789	1311.8	269.2	-5	120.3	CW5
CWDH017	377327.7	8641785	1310.5	230.5	-5	55	CW5
CWDH018	377329.7	8641793	1311.7	286.7	-5	123	CW5
CWDH0019	377418.0	8641413	1317.0	204.0	-5	130	CW6
CWDH020	377419.2	8641412	1317.0	168.0	-5	162	CW6
CWDH019	377415.6	8641412	1325.4	250.0	-5	104.3	CW6
CWDH021	377301.5	8641532	1321.5	195.0	-5	125	CW6
CWDH022	377295.9	8641543	1320.3	223.0	-5	125	CW6
CWDH023	377294.1	8641571	1318.5	275.0	-5	125	CW6
CWDH024	377295.5	8641578	1317.5	305.0	-5	125	CW6

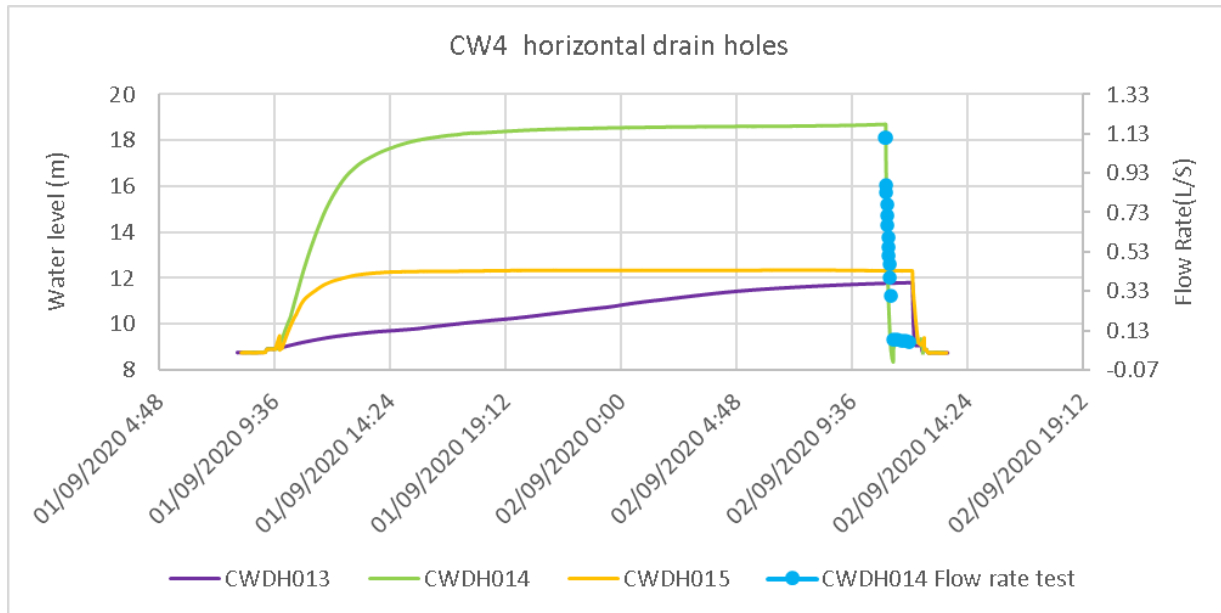


Figure 3.7 Horizontal drainage hole response at stage 4 from Lumwana Mine's Chimiwungo West Pit's eastern wall.

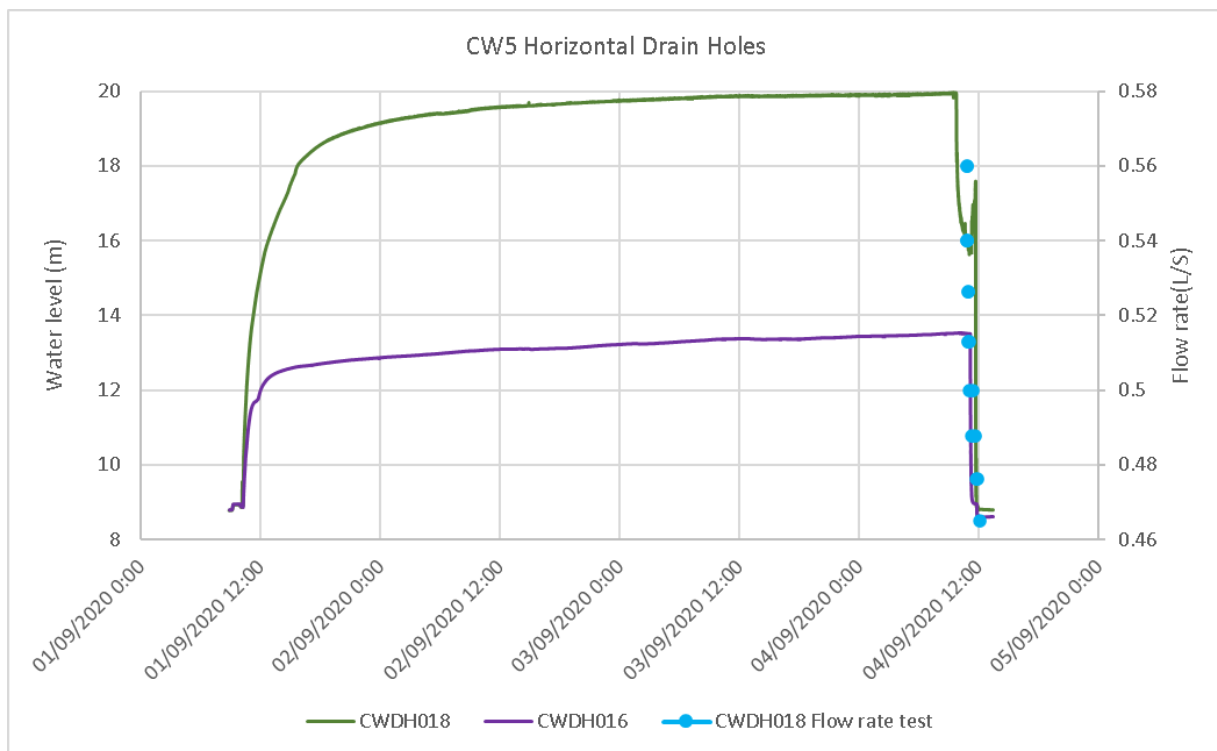


Figure 3.8 Horizontal drainage hole response at stage 5 from Lumwana Mine's Chimiwungo West Pit's western wall.

3.2.7 Hydrogeological investigation

Groundwater level monitoring was conducted from a network of Vibrating Wire Piezometers and open Standpipe Piezometers around the study area. The boreholes monitored for water level measurements include geotechnical groundwater monitoring boreholes within the active mining (see Figure 3.9) area and regional environmental groundwater monitoring boreholes. Drilling reports and geological logs for all the existing piezometers and groundwater monitoring boreholes were reviewed to assess the nature of aquifers intersected during drilling. Both Vibrating Wire Piezometers and standpipe piezometer data were reviewed to ensure calculations for water level and pore pressure were correctly done. Water level measurements from environmental groundwater monitoring boreholes were carried out manually using Solinst TLC dip meter during a once-off campaign in November 2021 while data from a network of Vibrating Wire Piezometers was digitally downloaded from the system on field computer and processed at the office.

The network of vibrating wire piezometers has a varying number of sensors in each set-up, ranging from two to four sensors depending on the geotechnical monitoring requirements. All the sensors in each piezometric drill holes were installed according to the fully grouted in guide-tremie method and connected to the data loggers, which collect and record data on a predefined frequency. Long-term hydrograph analysis from piezometric data collected from the monitoring network provides means for the assessment of the effect of mining on the natural groundwater condition (Stacy and Read, 2009). The data collected from this research phase will be useful for the calibration of the numerical groundwater model.

Borehole CGT085 was selected for recharge estimation using Water Level Fluctuation method due to the availability of continuous groundwater level records for the 2014/15 wet season and aquifer storage data. The water table fluctuation method was applied based on the groundwater level fluctuations from the site geotechnical monitoring boreholes. The water table fluctuation (WTF) method (equation 5) works on the assumption that changes in groundwater level in unconfined aquifer are due to groundwater recharge (Xu and Beekham, 2003). Recharge estimate using WTF method is based on the empirical relationship below:

$$R = Sy \frac{\Delta h}{\Delta T} \quad (\text{Equation 5})$$

Where:

R is the recharge, Sy is the specific yield estimated from the pumping test, Δh is the water table fluctuation for the period, and ΔT is time based on a full wet season hydrography analysis.

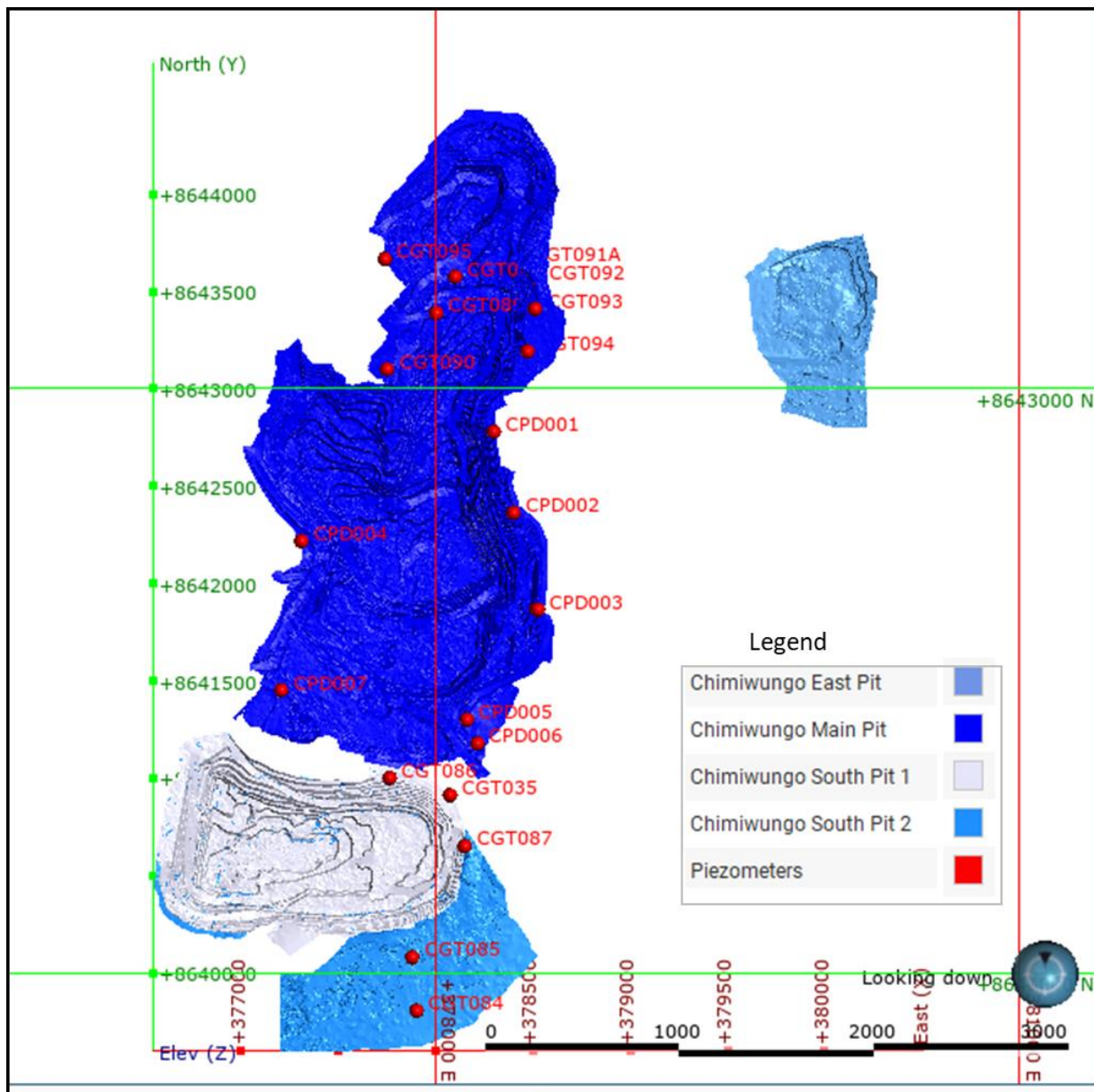


Figure 3.9 Groundwater monitoring network of Vibrating Wire Piezometers and open standpipe piezometers which includes active and decommissioned piezometers at Lumwana Mine active mining areas.

3.3 Field sampling

A field sampling programme was carried out within the study area to collect samples for different investigative purposes from environmental groundwater monitoring boreholes, streams, dams, Tailing Storage Facility (TSF), Water Storage Facility (WSF) and in-pit horizontal drainage boreholes, including rainfall from 1st September 2021 to 31st January 2022. Forty water samples were collected from the study area in one litre PVC plastic water bottles for physicochemical and

hydrochemical analysis. Before sample collection, the water was purged for five minutes and subsequently collected in plastic water containers that were tightly sealed off and placed in a cooler box for storage. The water quality sampling programme was conducted according to the layout below in Figure 3.10. Physicochemical parameters such as pH, temperature, dissolved oxygen (DO), Electrical Conductivity (EC) and Total Dissolved Solids (TDS) were measured in the field during sampling activities using a portable water quality meter. Water samples were submitted within 24 hours after sampling to Alfred H Knight Laboratory in Kitwe, Zambia, for analysis. No chemical preservatives were used on the water samples as the samples were delivered to the laboratory within 24 hours after sampling.

To ensure quality results, QAQC was conducted on the samples through the use of blanks, standards and ionic balance. Ionic balance for samples laboratory results was within the internationally acceptable limit.

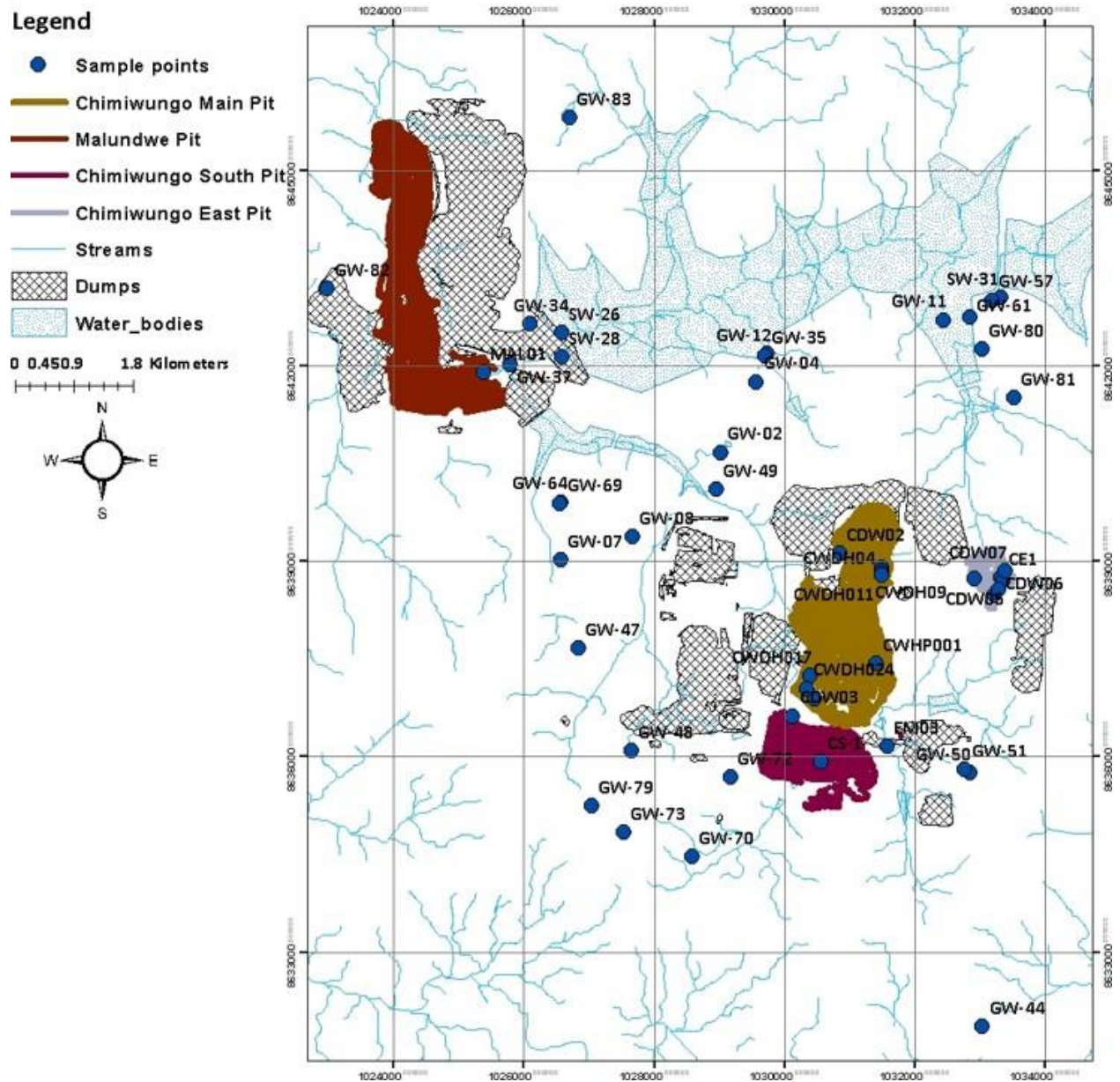


Figure 3.10 Groundwater and surface water field sampling points around the open pits, dumps, streams, TSF and the area around the Lumwana Mine.

3.4 Laboratory Analysis

3.4.1 Hydrochemistry

Thirty-one water samples collected from the field were submitted within 24 hours after sampling to Alfred H Knight Laboratory in Kitwe, Zambia, for analysis of major ions, minor ions, metals and selected physical parameters such as pH, EC and TDS. Chemical parameters were analysed using the atomic absorption spectrometer inductively coupled plasma (AAS-ICP).

3.4.2 Stable environmental isotopes

Analysis of the naturally occurring stable isotopes of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in water has been used as a tool to examine the hydrological cycle (Karen *et al.*, 2015). They are considered as ideal tracers for analysing the movement of water (Mazor, 1997). Surface water-groundwater interaction through recharge and discharge processes within the aquifer are identified through the analysis of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (Karen *et al.*, 2015). Environmental isotopes are routinely employed worldwide in the study of groundwater and surface water, as they provide unique information on the transport and interconnectivity of water resources and reservoirs (Abiye *et al.*, 2013). Different water types are expressed according to an international reference standard known as the Vienna Standard Mean Ocean Water (VSMOW) and deviation of a water sample's isotopic relationship is noted in ‰ (Clark and Fritz, 1997). The deviation of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ are calculated according to equations 6 and 7, respectively.

$$\delta^2\text{H}(\text{‰}) = \frac{(^2\text{H}/^1\text{H})_{\text{sample}} - (^2\text{H}/^1\text{H})_{\text{VSMOW}}}{(^2\text{H}/^1\text{H})_{\text{VSMOW}}} \times 1000 \quad (\text{Equation 6})$$

$$\delta^{18}\text{O}(\text{‰}) = \frac{(^{18}\text{O}/^{16}\text{O})_{\text{sample}} - (^{18}\text{O}/^{16}\text{O})_{\text{VSMOW}}}{(^{18}\text{O}/^{16}\text{O})_{\text{VSMOW}}} \times 1000 \quad (\text{Equation 7})$$

Where,

δ is the relative deviation in ‰

$(\text{Ratio})_{\text{sample}}$ is the isotope content of the sample

$(\text{Ratio})_{\text{VSMOW}}$ is the isotope content of the Standard Mean Ocean Water.

Consistent proportionality of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in meteoric water through Craig (1961) defined by the best fit line (Equation 8) determined the Global Meteoric Water Line (GMWL), which forms the basis for both climatological and hydrological applications.

$$\delta^2\text{H} = 8\delta^{18}\text{O} + 10\text{‰} \quad (\text{Equation 8})$$

Deviations from the slope of 8 is caused by various fractionation processes (humidity change) that may influence the isotope values in rainwater and consequently in groundwater. The isotope values of rainwater may be influenced by temperature (cloud forming), elevation (orographic) and amount (dilution) due to the effect on local isotopic composition (Dansgaard, 1964; Kendall *et al.*, 1998). Therefore, water in specific environments obtains isotopic labels that are transported and can be traced along the flow path (Abiye *et al.*, 2013)

Sixty-one water samples were collected from the study area for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ analysis. The samples collected consisted of water samples from environmental groundwater monitoring boreholes, horizontal drainage boreholes, streams, dams, TSF, WSF and rainfall. Groundwater and surface water for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ analysis were collected in 120ml containers. Before sampling, boreholes were purged for over 5 minutes to remove stagnant water and to enable the collection of aquifer representative samples. To ensure quality control for the samples, precautions were taken during sampling process for stable isotope analysis. Water sample evaporation through sample open exposure to the atmosphere was avoided by tightly capping the PVC sample bottles. Water samples were properly labelled and stored in a cooler box before shipping to the laboratory at Wits University, School of Geoscience. Sample duplicates were also simultaneously collected and dispatched for precision checks during $\delta^{18}\text{O}$ and $\delta^2\text{H}$ laboratory analysis.

3.4.3 Radioactive isotopes analysis (Tritium)

Tritium is an isotope of hydrogen, which is radioactive in nature. It is effective in the determination of residence time of water as pre and post 1952, the time when hydrogen bomb tests began (Mulenga, 1991). In nature, tritium is produced by cosmic ray interaction with the upper atmosphere, and readily oxidised to water in which it is preserved as a conservative tracer as part of the water molecule (Verhagen *et al.*, 1991). It has a half-life of 12.3 years (Mazor, 1991) and decays through low energy beta ray emission (Verhagen *et al.*, 1991). According to Verhagen

et al. (1991), environmental tritium is a useful tracer of water and is globally used in hydrological studies. Tritium can be used to establish the recharge and dynamics of monitoring boreholes (Levin and Verhagen, 2013). Low or zero tritium level in groundwater would indicate slow or no recharge while rain level of tritium would indicate ongoing recharge (Levin and Verhagen, 2013). To determine groundwater mean residence time (MRT) and further confirm the potential for a hydraulic link between surface water storage infrastructures and the mine, groundwater and surface water samples were collected and analysed for tritium.

Eighteen water samples were collected for tritium analysis including rainwater, groundwater boreholes, stream, dams, pit seepage, TSF and WSF. Water samples for tritium analysis were collected in clean 1 L PVC bottles which were properly labelled and immediately placed in cooler boxes for proper storage and transportation to the laboratory. Samples were later analysed at NRF iThemba Labs in South Africa. Groundwater residence time using tritium was determined using equation 9 (Clark and Fritz, 1997) below.

$$T = -17.93 \ln\left(\frac{A_t {}^3H}{A_o {}^3H}\right) \quad (\text{Equation 9})$$

Where,

T is the mean residence time of groundwater in years

$A_t {}^3H$ is the residual activity remaining after decay over time (t)

$A_o {}^3H$ is the initial tritium activity

For this analysis, the concentration of tritium in rainfall was used as the initial activity of tritium. Isotope studies for tritium carried out in Kabwe and Lusaka in Zambia by Tembo and Nkhuwa (1997) indicated mean groundwater residence time of 5 to 14 years.

3.5 DATA ANALYSIS AND CONCEPTUAL MODEL DEVELOPMENT

3.5.1 Hydraulic Data Analysis

Different industry standard numerical and analytical data analysis techniques have been employed in this study for hydraulic parameterisation. Analysis of the hydraulic test results data enabled the characterisation of hydraulic and storage parameters for different hydro-geotechnical units. The hydraulic parameters are important to define both the vertical and lateral (directional) permeability of different stratigraphic units (Beale *et al.*, 2013).

3.5.2 Falling Head Test

Manual falling head test results from all new sub-vertical diamond drill holes were analysed using the Flow Characteristic (FC) program using the Bouwer and Rice (1976) analysis method. Example results for the analysis are presented in Figure 3.11, Figure 3.12, Figure 3.13, Table 3.4, Table 3.5 and Table 3.6.

Table 3.4 Borehole CGT115 Falling Head test data analysis.

Test No.	Geotechnical Unit	Lithology	Diameter	Test Interval	K (m/s)
1	Saprolite	Amphibolite	PQ	24.1 to 30.1 m	6.60E-07
2	Transition	Granitic Gneiss	PQ	36.1 to 42.1 m	3.09E-07
3	Fresh	Fractured Schist	HQ	194 to 200 m	7.09E-07

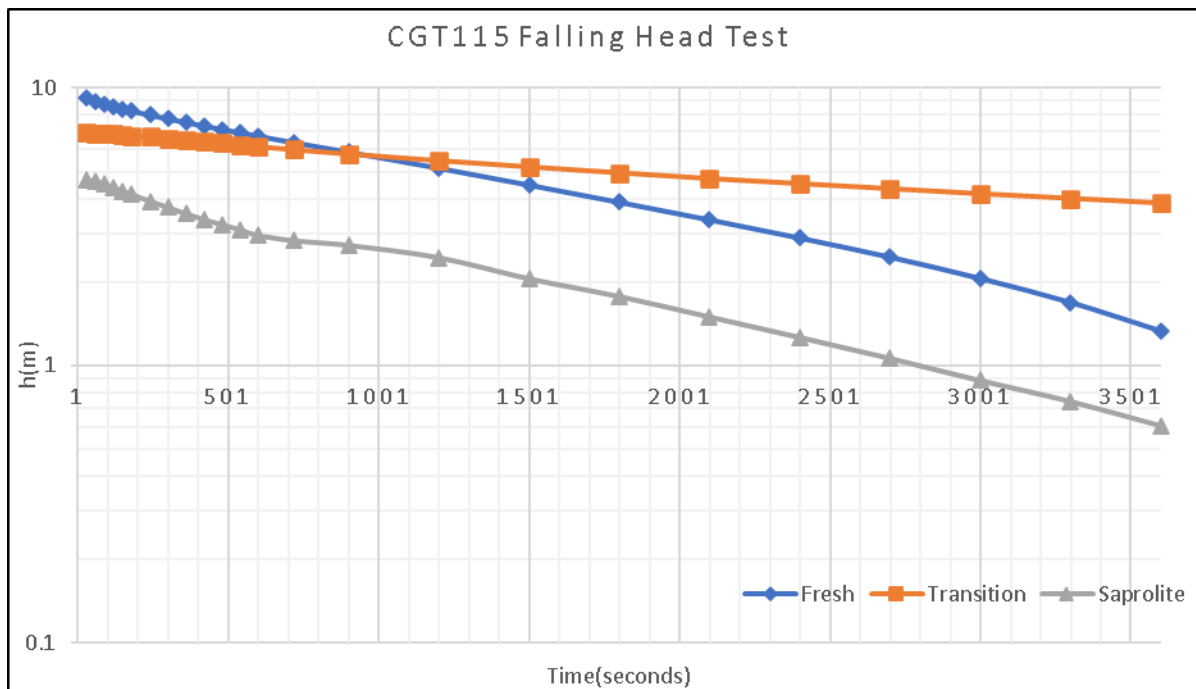


Figure 3.11 Borehole CGT115 Falling Head test results.

Table 3.5 Borehole CGT116 Falling Head Test analysis results.

Test No.	Geotechnical Unit	Lithology	Diameter	Test Interval	K (m/s)
1	Saprolite	Granitic Gneiss	PQ	16.6 to 21.1 m	4.34E-07

2	Transition	Granitic Gneiss	PQ	33.5 to 39.5 m	1.62E-07
3	Fresh	Granitic Gneiss	HQ	68 to 74 m	8.95E-07
4	Fresh	Granitic Gneiss	HQ	275 to 281 m	9.02E-08

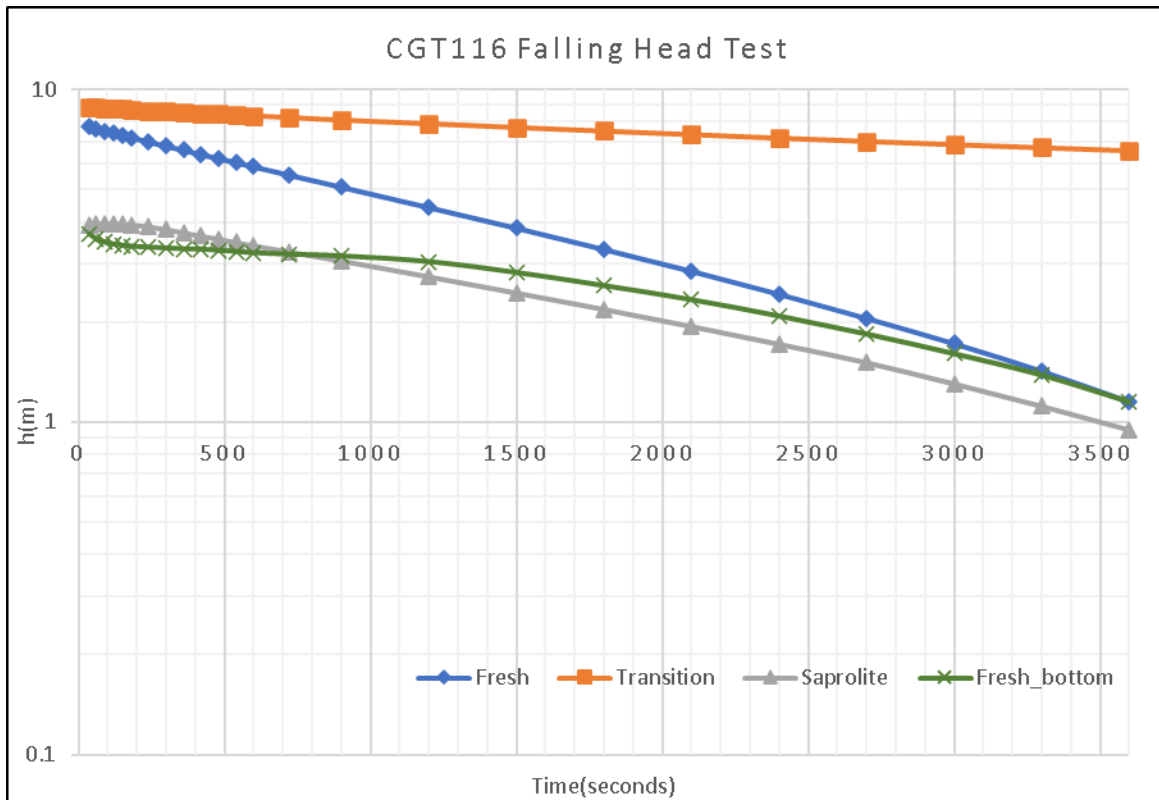


Figure 3.12 Borehole CGT116 Falling Head test results.

Table 3.6 Borehole CGT117 Falling Head Test analysis results.

Test No.	Geotechnical Unit	Lithology	Diameter	Test Interval	K (m/s)
1	Saprolite	Granitic Gneiss	PQ	10.6 to 15.1 m	2.28E-09
2	Transition	Granitic Gneiss	PQ	25.6 to 31.6 m	5.39E-07
3	Fractured Fresh	Ore schist	HQ	67.5 to 73.5 m	7.74E-07

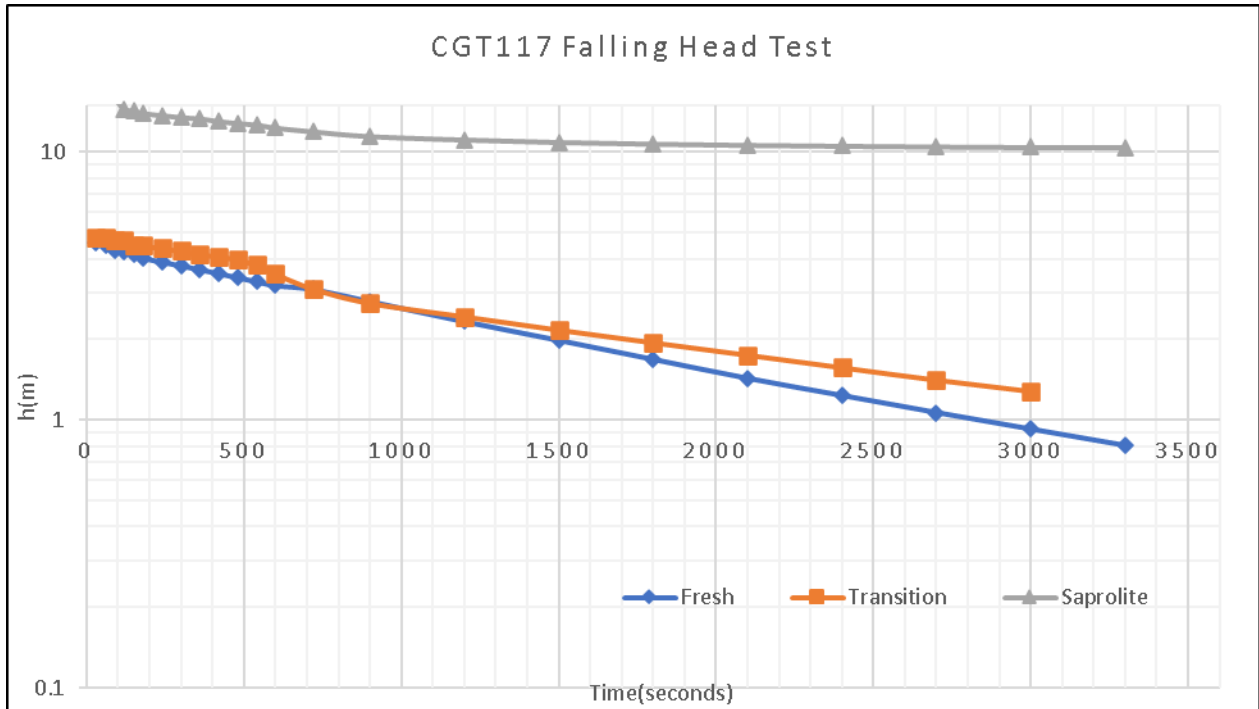


Figure 3.13 Borehole CGT117 Falling Head test results.

3.5.3 Shut-in tests

Analyses of the Shut-in test results were also carried out on horizontal drainage holes drilled into the slope faces within the pit targeting specific geotechnical units. The boreholes were shut for a period of approximately 72 hours until the water levels were built to the maximum static water level. A discharge test was concurrently run on the borehole towards completing the shut-in test, and the test results were analysed using the Cooper-Jacob recovery Method. Figure 3.14 and Table 3.7 provide a summary of the horizontal drainage borehole shut-in test results.

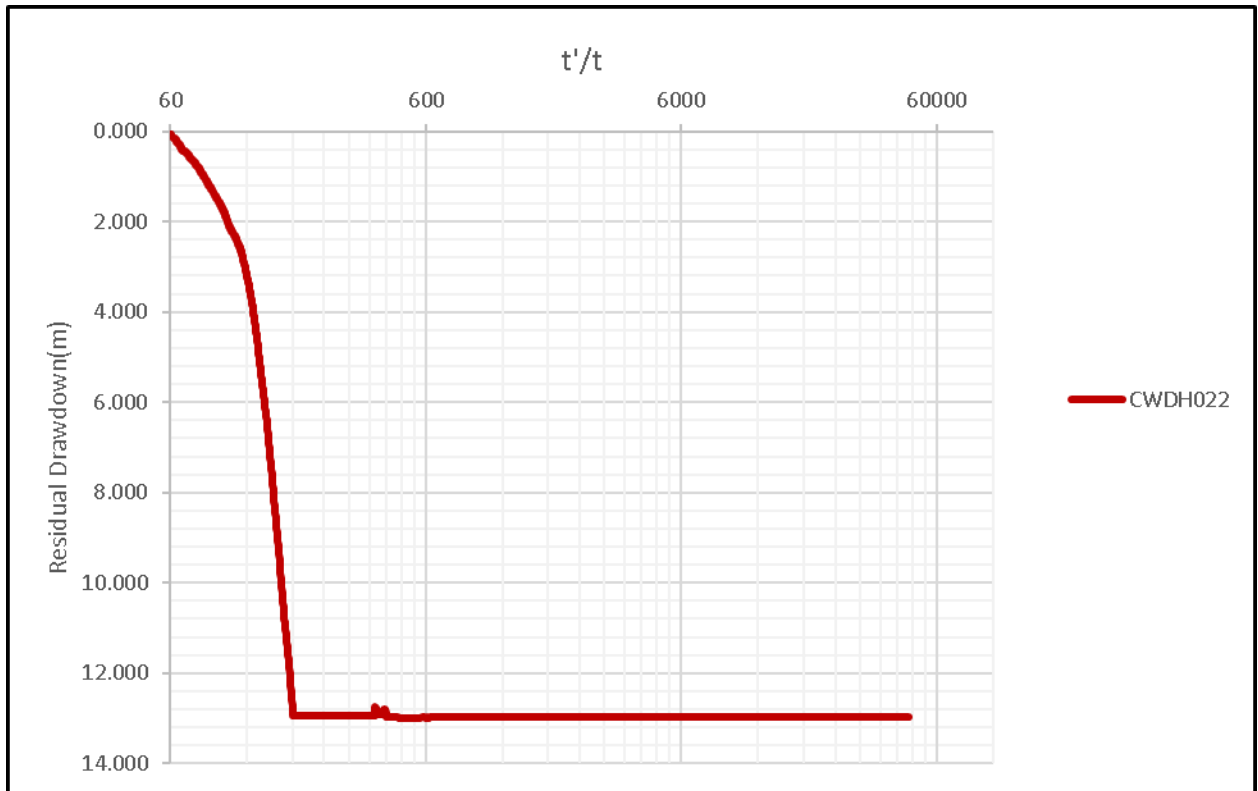


Figure 3.14 Borehole CWDH022 Shut in test analysis results showing plots of residual drawdown versus time in saprock geotechnical domain.

Table 3.7 Horizontal drainage holes shut in test analysis results.

HOLE ID	Geotechnical Unit	Saturated thickness(m)	Mean Q (L/s)	Average T (m ² /s)	Average K (m/s)	Specific capacity, S _c (m ³ /d/m)
CWDH022	Saprock	12.95	1.20	1.24E-04	9.55E-06	8.01
CWDH025	Saprock	15.1	0.78	8.87E-05	5.87E-06	4.46
CWDH018	Saprock	11.2	0.51	1.16E-04	1.04E-05	3.93
CWDH014	Fresh	9.9	0.51	1.01E-04	1.02E-05	4.45
CWDH019	Saprock	11.9	1.45	2.07E-04	1.74E-05	10.54
CWDH021	Saprock	7.89	0.51	7.85E-05	9.95E-06	5.54

3.5.4 Conceptual Model Development

A conceptual model is described as a realistic, defensible albeit simplified representation of the hydrogeological system (Read and Stacey, 2009). For any scale of hydrogeological system conceptual modeling, it is important to gain as much information as possible on the detailed geological conditions and the main hydrogeological system within the model domain to changes in hydraulic stresses (essentially recharge and discharge) (Beale *et al.*, 2013). Over the life of the mine, substantial amount of information was collected and made available for the development of a reasonably detailed Lumwana hydrogeological system conceptual model. It is strongly recommended that at both regional and mine scale, the hydrogeological conceptual model must consider three regimes including geology, hydraulics and hydrology (Lorig *et al.*, 2009).

- **Geology:** This regime focuses on stratigraphic units, weathering profile and large-scale variations within the stratigraphic units, location and nature of regional geological structures (Beale *et al.*, 2013). For the Lumwana hydrogeological conceptual model, the basis for the conceptual model was the geological model that was generated from different data sets compiled and updated over the life of mine. These include exploration drill hole data, resource drill hole data, geotechnical investigation drill hole data and hydrogeological investigation drill hole data, including field mapping structural data collected through the period of mining operations.

Geological data formed the basis for determining the main hydrogeological units (Beale *et al.*, 2013).

- **Hydrology:** There are four important regimes to consider under hydrology requirements for hydrogeological systems conceptual modelling (Beale *et al.*, 2013). These include artificial recharge to the groundwater system, natural recharge to the groundwater system, discharge from groundwater system and groundwater-surface water interactions (Beale *et al.*, 2013). Natural recharge to the groundwater system may be derived from net infiltration or areal rainfall but is more commonly derived from concentrated water in the form of runoff channels, temporary ponding of water, losses from ephemeral or perennial streams, rivers and lakes (losing reaches) (Beale *et al.*, 2013). In addition, the other regime that should be considered under hydrology is the artificial recharge to the groundwater

system, which is often an important factor to consider in mining environment and may include leakage from artificial water storage facilities nearby (Beale *et al.*, 2013). It is possible to alter the pattern of artificial recharge to a greater extent than the natural recharge can be altered.

The third regime for hydrology component is the discharge from the groundwater system, which usually consists of passive hydrological outflows that may occur due to evaporative losses where the perched or main water table occurs at a shallow depth; groundwater flow into the streams, rivers or lakes (gaining reaches) or active hydrological outflows that may be added in the form of pumping wells or other forms of groundwater abstraction (Beale *et al.*, 2013). The fourth important regime is the groundwater-surface water interactions that may occur within the overall domain of the conceptual model, for example gaining and losing stream segments (Beale *et al.*, 2013).

- **Hydraulics:** Hydraulic properties of geological units help to determine when the geological units can be lumped together or when they must be separated (Beale *et al.*, 2013). At a gross scale, it is important to define both the vertical and lateral permeability of the geological units (Beale *et al.*, 2013). For example, hydraulic layering of an alluvial sequence is common because of the nature of their geological deposition, and many regional geological structures exhibit enhanced flow in a direction parallel to the strike and reduced flow in a direction perpendicular to the strike (Beale *et al.*, 2013).

Hydraulic characterisation for the Lumwana hydrogeological conceptual model considered all the hydraulic tests conducted prior to and during the research. Hydraulic tests conducted during hydraulic properties investigation include packer tests in geotechnical investigation drill holes prior to open pit development at the Chimiwungo area, falling head tests which were conducted prior to and during this study within hydrogeological investigation drill holes before installation of vibrating wire piezometers and shut-in tests that were conducted in horizontal drainage boreholes. Hydraulic tests were conducted on specific hydrostratigraphic units identified during core logging.

Read and Stacey (2009) provide guidance on the development of conceptual and numerical pore pressure models for pit slope evaluation purposes, including discussions

of the influence of fracturing on groundwater flow in a fractured rock slope based on the “A-B-C-D” concept of fracture flow, which is linked to the principle of a size-order relationship within the fracture network. A typical fracture network might comprise a few highly transmissive and pervasive ‘first-order’ fractures (A), many more less transmissive second-order fractures (B) and so-on for third – (C) and fourth- (D) order fractures (Beale and Read, 2013). In a more porous rock setting or rock types containing a pervasive network of micro-fractures, ‘D’ may also be considered as rock matrix (Beale and Read, 2013).

The more permeable ‘A’ fractures respond first to depressurisation by drainage. An interconnected ‘plumbing’ system of these first-order fractures allows rapid propagation of pressure changes through the system. The higher the fracture frequency of interconnected first order fractures, the easier the rock will drain. According to Read and Stacey (2009), as pore pressure within the first-order fractures begins to decrease, flow along the second-order, less permeable fracture sets begins to occur towards the first-order fractures. This dual-porosity response similarly occurs from third-order fractures, and so on through the entire interconnected network of fractures (Read and Stacey, 2009). Although the ‘A-B-C-D’ concept is simple and theoretically robust, further review of pore pressure responses in fractured-rock mining environments was required to verify its suitability at the scale of measurement required in pit slope design studies, and particularly with regard to the time dependency of the pressure responses in the lower order fracture sets and/or the matrix porosity.

It is worth noting that the ‘A-B-C-D’ concept of fracture flow is based on hydraulic conductivity, as such it must be supplemented with factors that consider also the regimes of the geology and the general hydrology (Beale *et al.*, 2013).

4. RESULTS AND DISCUSSION

4.1 Lumwana Mine Geology

The Lumwana deposits, central to this research, are situated on the southeast limb of the major dome structural feature referred to as the Mwombezhi Dome. Base metal mineralisation (mainly copper) is hosted within the intensely strained, relatively thick ore schist horizon, structurally representing the major D3 (third deformation phase) shear zone (Koegelenberg and Basson, 2016). Waste rock inclusions of different protolith (mainly gneiss, amphibolite and schist representing D2 strained wall rock) are common within the ore schist package in varying sizes and shapes ranging from cm-scale to multi-bench lenticular shapes. The mineralised ore schist horizon is gently folded with a NNE axis and plunges to the south (Golder Associates, 2003). Late kinematic, north steeply dipping, D4 normal faults cut across the ore shoots and translate the ore zone, thereby making ore accessibility challenging.

The local geology at the mine site, which includes the Malundwe and the Chimiwungo, has been classified into packages in relation to the ore schist horizon. The tectonostratigraphic categories assigned are the hanging wall package above the ore schist and the footwall package overlain by the ore schist package (Koegelenberg and Basson, 2016).

- Hanging wall package: The hanging wall tectonostratigraphic package overly the Ore package and predominantly consist of interlayered undifferentiated greyish quartz-feldspar-biotite gneisses and pink albite-biotite gneiss (Koegelenberg and Basson, 2016). The gneissose foliation S1, in Table 4.1 shallowly dips SSE and its contact with the underlying ore schist package is very gradational. The hanging wall gneiss dominated by the pink granitic gneiss (GNP), provides the most dominant protolith for the dambo sands and stream bed, saprolites and saprock weathering units by virtue of their continuity from the surface. Generally, the weathering front terminates within the GNP and deepens southwards.
- Ore package: Ore unit in Figure 4.1 is confined to the zone between the top and bottom intersection of the Ore schist (OS), generally consisting of intensely strained quartz-muscovite schist with copper sulphide dissemination. The Ore package is generally characterised by continuous sub-parallel S3 schistose foliation and associated shears

parallel to the D3 shear geometry (Koegelenberg and Basson, 2016). The Ore schist varies in thickness between 5 m and 60 m. Internal barren inclusions in the ore schist are derived from either the amphibolite, gneiss or barren schist and vary in thickness up to 40 m and therefore, are exposed on multiple benches. Within the ore package, internal waste lenses of gneisses and schists are transposed sub-parallel to the S3 schistose foliation.

- Footwall package: The footwall lithostratigraphic package at Lumwana is overlain by the ore schist package and comprises sub-parallel undifferentiated quartzofeldspathic grey gneiss with augen texture along strike length and down dip (Koegelenberg and Basson, 2016). The package also comprises overprinted lenses of biotite schists and mottled schist. The footwall package is predominantly characterised by gently dipping sporadic amphibolitic bodies distributed throughout the footwall package, as shown in Figure 4.1 from the geological block model. The vertical continuity of this horizon is poorly defined as the drilling terminates mainly below the ore schist.

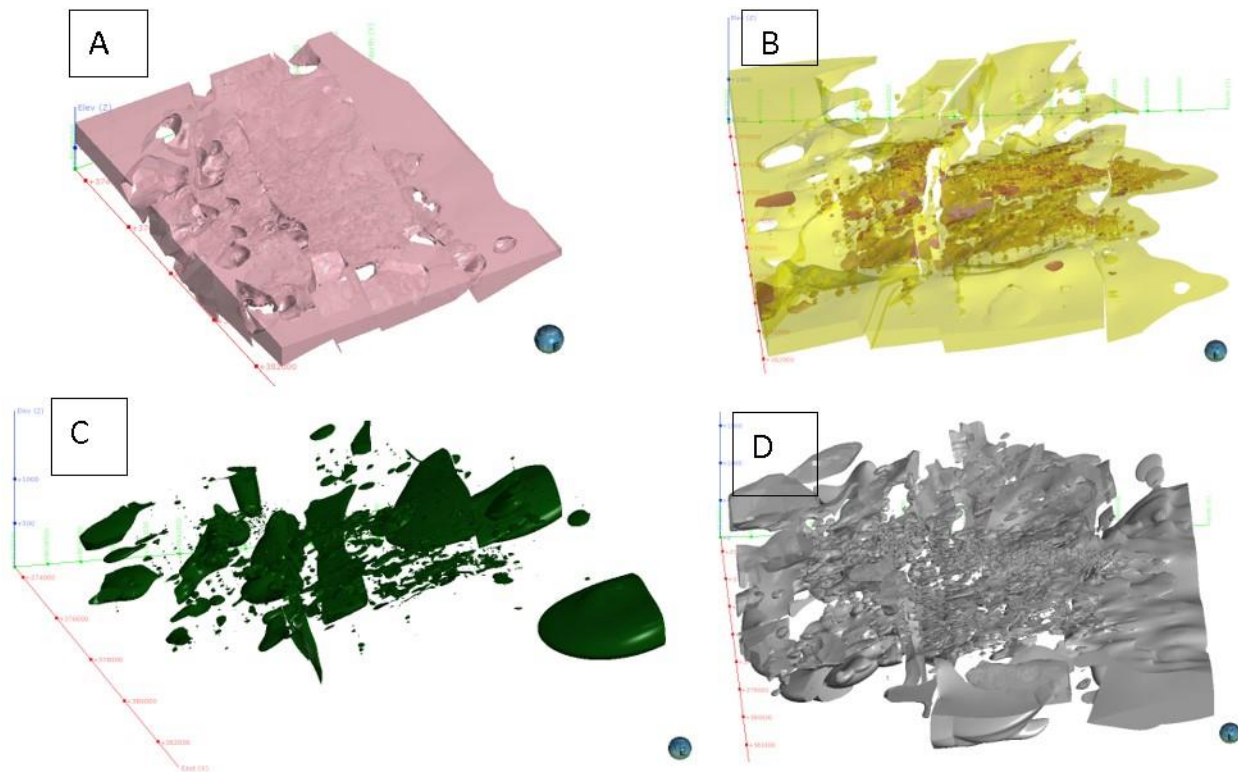


Figure 4.1 Dissected Lumwana modelled tectonostratigraphic packages; (A) Hanging wall package (B) Ore package, (C) Amphibolite bodies and (D) Footwall package.

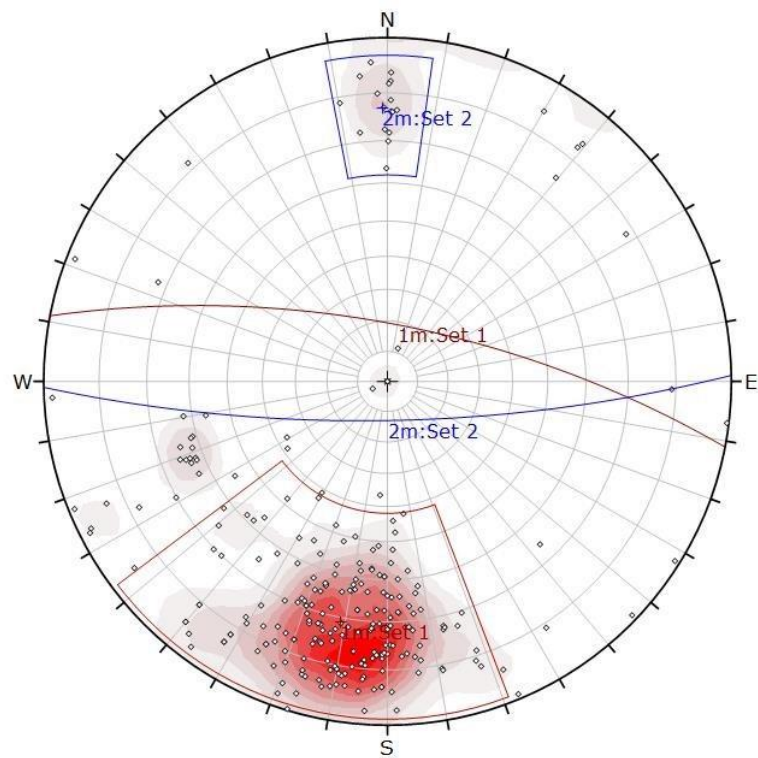
Table 4.1 Tectostratigraphic packages orientations at Lumwana Mine.

Tectonostratigraphic package	Rock Code	Strike (Degrees)	Dip (Degrees)	Vector Count
Hanging wall (Granitic Gneiss)	GNP	109	11	97
Ore schist	TSx	202	9	37
Footwall (Augen Gneiss)	GNG	227	14	95

At the Lumwana Mine region, regional tectonic flattening is accommodated by intense strain and shearing of country rocks and formation of shear-type foliation boudins comprising pink granitoid gneiss and grey gneiss, at all scales (Koegelenberg and Basson, 2018). The dominant fabric within the gneiss boudins and hanging wall gneiss is the gneissosity, which is at an acute angle to the ore schist (Koegelenberg and Basson, 2018). Within the active mining region, several faults crossing the mine area have been delineated based on geological drilling and mapping. Stereographic projection in Figure 4.2A shows that the faults within Chimiwungo area are steeply dipping, mainly north-northeast direction at 71° while the minor faults strike at nearly E-W with a dip of 77° towards the South. Two major faults at both the north and south downthrows the schist orebody by 10s to 100s of meters. On the northern end of the Chimiwungo orebody, the Chimiwungo North fault downthrows the orebody up to 50m displacement while on the south, the Chimiwungo South fault downthrows the orebody to the northern side over 400 m. The Chimiwungo South fault is among the significant regional faults and separates the Chimiwungo Main pit and the Chimiwungo South pit.

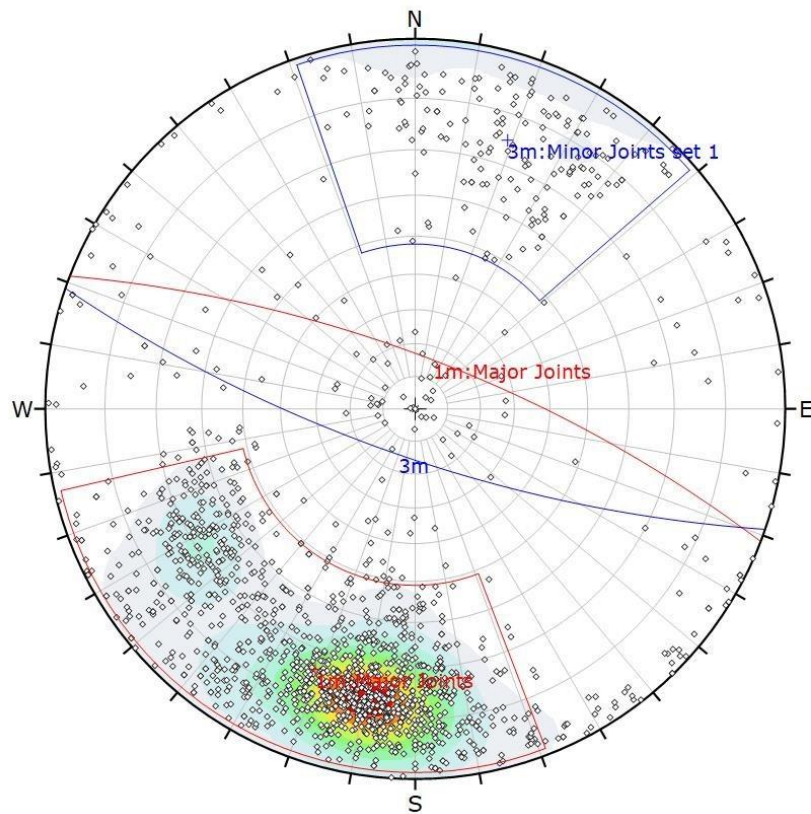
The fault system in Lumwana regional area extends the weathering zones vertically to a depth of over 100 m and is characterised by angular brecciation of the country rock and significant jointing of the region adjacent to the fault system. Several water storage structures such as dams for surface water control are built along the fault system footprint. This presents a potential for surface water direct recharge into the ground and the open pit, especially when the structures interact with the mine. Stereographic data analysis in Figure 4.2B show that two joint sets are predominant in the Lumwana area, striking W-NW and E-SE dipping at an average of 74°-75° towards the north and south, respectively.

A



Symbol	Feature		
◊	Pole Vectors		
Color	Density Concentrations		
	0.00 - 1.40		
	1.40 - 2.80		
	2.80 - 4.20		
	4.20 - 5.60		
	5.60 - 7.00		
	7.00 - 8.40		
	8.40 - 9.80		
	9.80 - 11.20		
	11.20 - 12.60		
	12.60 - 14.00		
Contour Data			
	Pole Vectors		
Maximum Density	13.94%		
Contour Distribution	Fisher		
Counting Circle Size	0.8%		
Color	Strike (Left)	Dip	Label
Mean Set Planes			
1m		101	71 Set 1
2m		269	77 Set 2
Plot Mode		Pole Vectors	
Vector Count		261 (261 Entries)	
Hemisphere		Lower	
Projection		Equal Angle	

B



Symbol	Feature
○	Pole Vectors

Color	Density Concentrations
	0.00 - 1.80
	1.80 - 3.60
	3.60 - 5.40
	5.40 - 7.20
	7.20 - 9.00
	9.00 - 10.80
	10.80 - 12.60
	12.60 - 14.40
	14.40 - 16.20
	16.20 - 18.00

Contour Data	Pole Vectors
Maximum Density	17.64%
Contour Distribution	Fisher
Counting Circle Size	1.0%

Color	Strike (Left)	Dip	Label
Mean Set Planes			
1m	111	74	Major Joints
3m	289	75	Minor Joints set

Plot Mode	Pole Vectors
Vector Count	1598 (1598 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure 4.2 Lumwana Mine structural trends (A) fault network Joints and (B) joint sets.

4.2 Hydraulic Characterisation

Figure 4.3A presents a profile of the various hydraulic test results conducted at Lumwana Mine in different geotechnical domains. These tests (Figure 4.3B) include packer tests, falling head tests, constant pumping tests and shut-in tests carried out in sub-vertical drill holes and sub-horizontal drainage holes. The hydraulic test results were useful for the analysis of hydraulic properties of different hydrostratigraphic units (Beale *et al.*, 2013). Regional and local hydraulic test results in different lithological, geotechnical units and structures (Figure 4.3A) show a general decrease in hydraulic conductivities with an increase in depth, despite a wide range of hydraulic conductivities.

Hydraulic conductivity distribution in Figure 4.3A varied based on different hydrostratigraphic units with depth. Hydraulic conductivity in saprolite varies between 1.50×10^{-7} m/s and 1.80×10^{-6} m/s, with a geometric mean of 5.86×10^{-7} m/s. Hydraulic conductivity for the moderately,

relatively fractured saprock unit ranges between 3.10×10^{-7} m/s and 1.8×10^{-5} m/s, with a geometric mean of 4.3×10^{-6} m/s. Fresh intact bedrock hydraulic conductivity ranges from 7.1×10^{-11} m/s to 9.6×10^{-7} m/s, with a geometric mean of 2.1×10^{-7} m/s. Lastly, the fractured bedrock hydraulic conductivity ranges between 6.8×10^{-7} m/s and 1.2×10^{-6} m/s with a geometric mean of 9.4×10^{-7} m/s. Saprolite unit has smaller range of hydraulic conductivity laterally and vertically with high storage capacity, which is dependent on clay and silt content due to high porosity (Showmaker, 2013). The low hydraulic conductivity and high storage properties observed in the saprolite are responsible for consistently elevated pore pressure observed in most vibrating wire piezometers shown in Figure 4.7, including CGT091A, CGT092, CPD001, CPD002, CPD003 and CPD004 installed in the saprolite hydrostratigraphic unit. Conversely, the saprock and fractured fresh bedrock have relatively wide range of hydraulic conductivity values and are responsive to passive drainage due to open pit excavation as can be seen in Figure 4.7. This observed phenomenon is attributed to the increase in fracture frequency and aperture within the saprock due to physical weathering and tectonic activities (Kruseman and De Ridder, 2000). Fractures can increase the hydraulic conductivity of solid rocks by several orders (Kruseman and De Ridder, 2000). Most of the Vibrating Wire Piezometers including CGT086, CGT093 and CGT094 installed in the saprock hydrostratigraphic unit have relatively better response to passive drainage as evidenced by increased seepage faces within the saprock unit. The saprock provides indicative potential for vertical and lateral groundwater flow (Beale *et al.*, 2013).

The wide range of hydraulic conductivities from the in-situ conductivity tests provides evidence for fracture flow as the dominant flow type, especially in the saprock and fractured fresh bedrock (Beale *et al.*, 2013). In an environment where nearly all the groundwater flow is due to fractures, the general downward decrease in hydraulic conductivity and transmissivity is attributed to the reduction in both fracture frequency and aperture magnitude (Beale *et al.*, 2013). It is also worth noting that the controls on groundwater flow are essentially dependent on the regional interconnectivity of the fracture network rather than the hydraulic conductivity of a single fracture (Beale *et al.*, 2013). Hydraulic conductivity values distribution for Lumwana lithologies and discontinuities generally exhibit a skewed distribution of parameters to the lower side as shown in Figure 4.4A and relatively higher in saprock (Figure 4.4B).

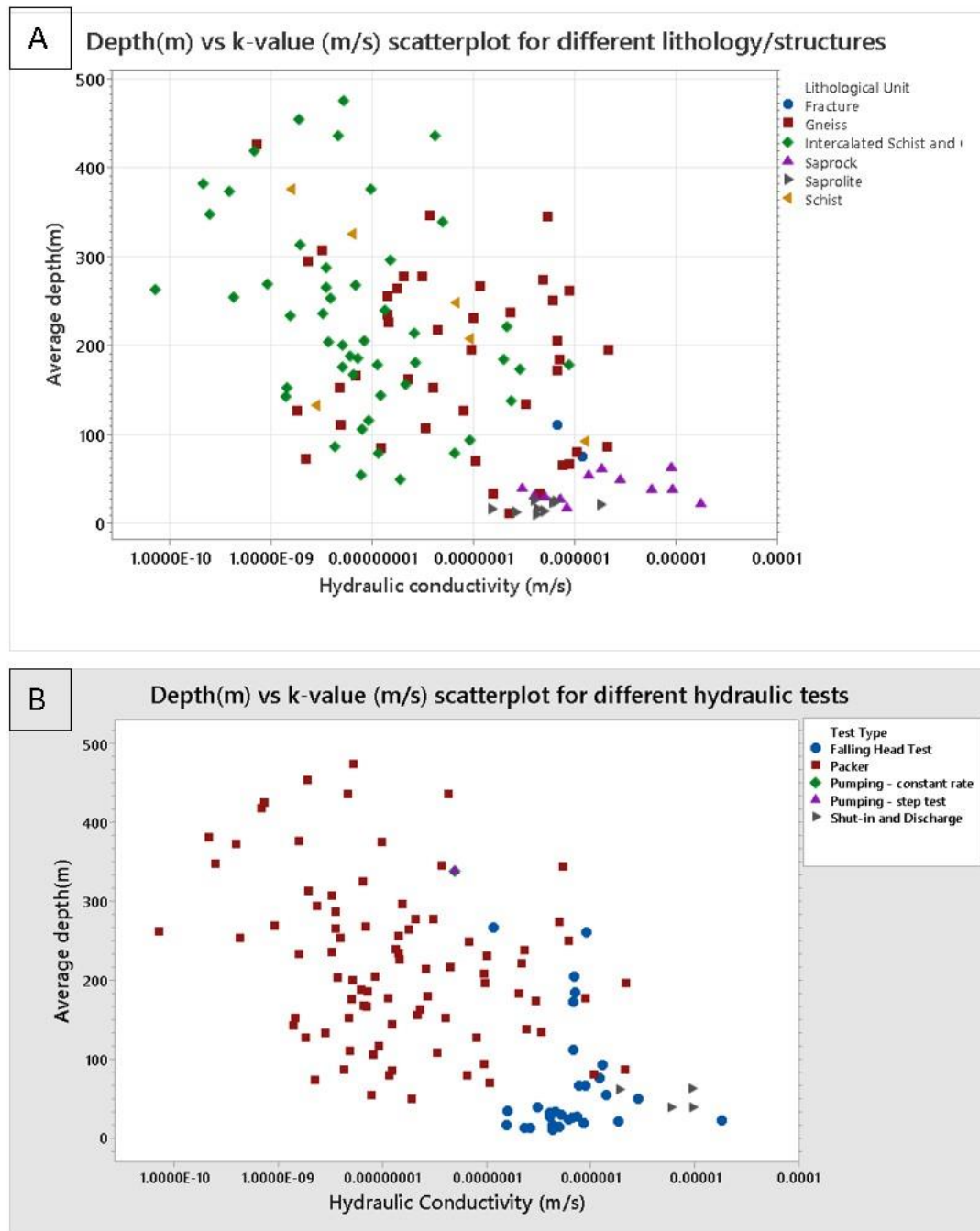


Figure 4.3 Scatter plots of hydraulic tests conducted at Lumwana (A) based on lithology/ geological structures (B) based on test type.

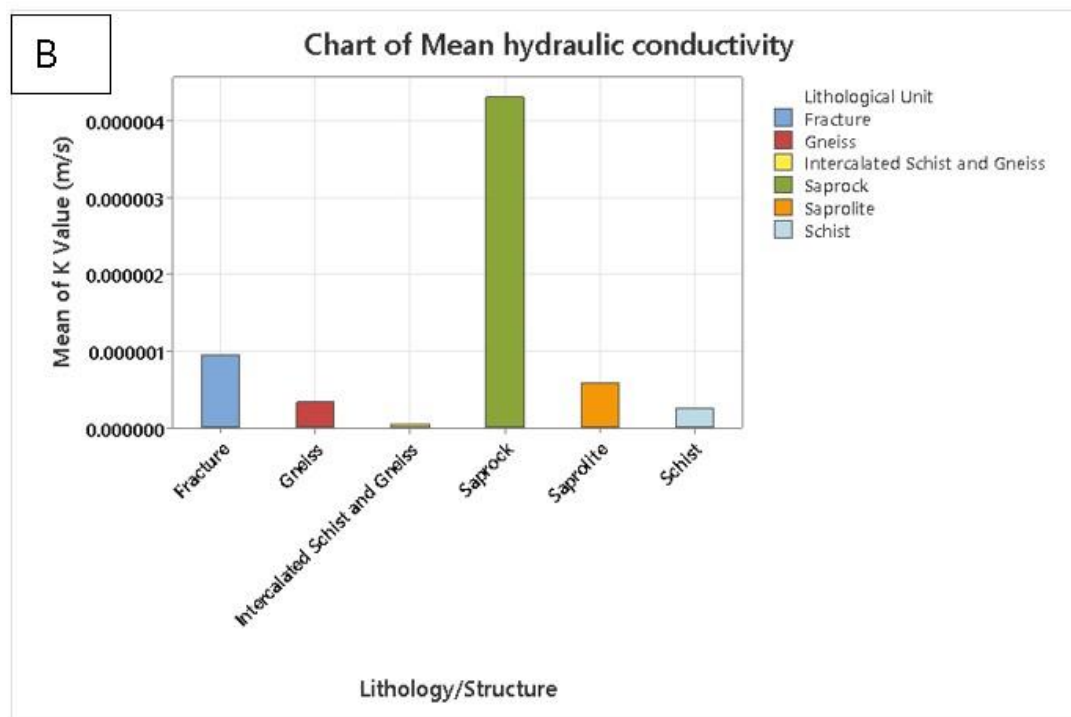
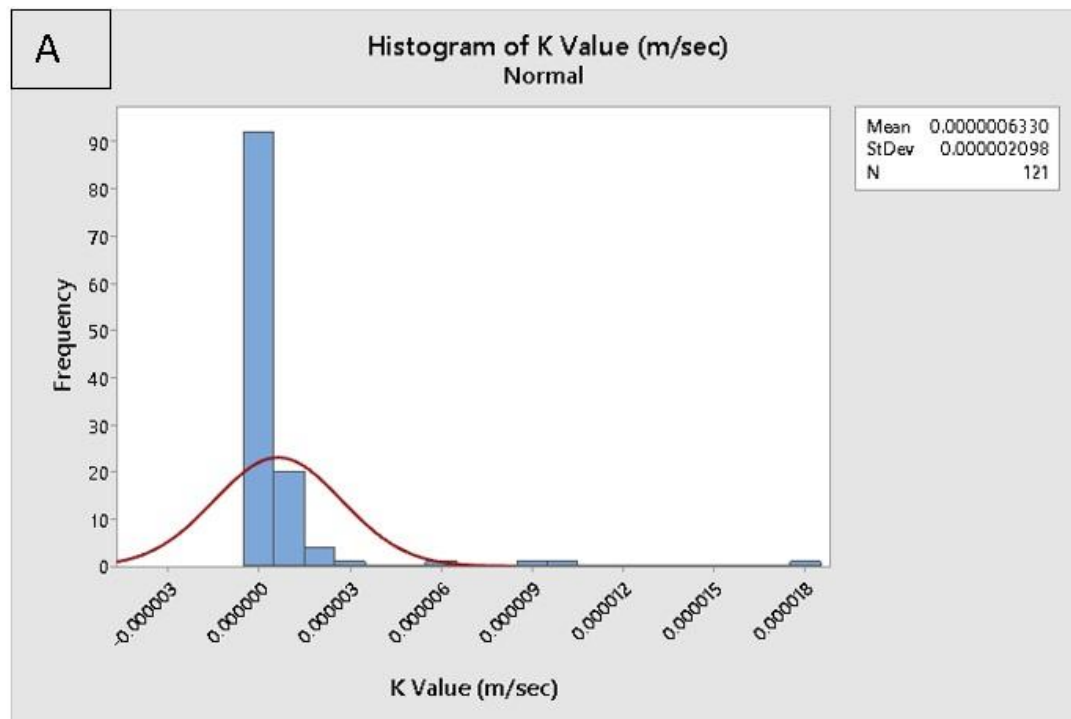


Figure 4.4 Histograms of hydraulic conductivities (A) for all the different tests conducted and (B) based on lithological units.

4.3 Hydrogeology

The groundwater system in the Lumwana area is limited and there is no identified regional aquifer, regional groundwater flow systems or extensive sedimentary deposits (Showmaker, 2013). The Lumwana Mine area is characterised by only one type of aquifer, and these are unconfined aquifers. According to Kruseman and De Ridder (2000), an unconfined aquifer also known as watertable aquifer, is bounded below by an aquiclude, but is not restricted by any confining layer above it. Water in a well penetrating an unconfined aquifer is at atmospheric pressure and does not rise above the water table (Kruseman and de Ridder, 2000).

Physical weathering and tectonic activities control the hydrostratigraphy of Lumwana Mine. Aquifers are classified based on the degree of weathering into saprolite, transition/saprock, fresh rock and fractured network, and coincide with local geotechnical domains classification. The aquifer within the weathered zone behaves as a primary porosity and permeability aquifer (Freeze and Cherry, 1979). The permeability varies based on clay content of the weathered zone developed over the feldspathic gneiss and biotite schist and reduce the specific yield. The fractured network at Lumwana results from secondary deformation and consists of the fault network, joints and shearing. Generally, the area is characterised by relatively low primary permeability and relatively higher secondary permeability in zones intersected by conductive secondary structures. The following are the key hydrogeological units as adopted by the mine shown in Table 4.2;

- Surface sand: Near-surface thin layer of clayey-sand generally observed in the dambo area with varying hydraulic conductivity. The stream banks in the Lumwana mine area are characterised by extensive dambos with depositional clayey sands.
- Laterite: Consist of highly weathered bedrock, hematitic-clayey material of varying thickness from place to place and provides greater storage potential than bedrock. Theoretically, the laterite zone is moderately consolidated and relatively more permeable compared to other hydrostratigraphic units.
- Saprolite: Represents highly weathered residual country rock with relatively high clay content. With the Lumwana mine area characteristic high rainfall (>1200 mm/year), the

water table appears high, typically 5 to 10 m below ground level. In some localities, the clayey saprolite supports the occurrence of perched aquifers.

- **Saprock:** The unit represents fractured transition between the highly weathered and fresh bedrock. Generally, the unit has comparatively high hydraulic conductivity and varies between 10 to 15 m thickness depending on the bedrock characteristics, topography and rainfall intensity.
- **Basement:** The basement consists of fresh intact bedrock, including the gneiss and schist with low primary permeability.
- **Fractured network:** The fracture network consists of secondary permeable structures that are spatially extensive and other poorly developed secondary structures. The fracture network is attributed to physical weathering and tectonic activities and tend to decrease with depth on a regional scale. The fractured network acts as a conduit for groundwater flow and deepens the weathering profile in certain locations. Figure 4.5 provides a schematic depiction of the regional hydrostratigraphy of Lumwana Mine area.

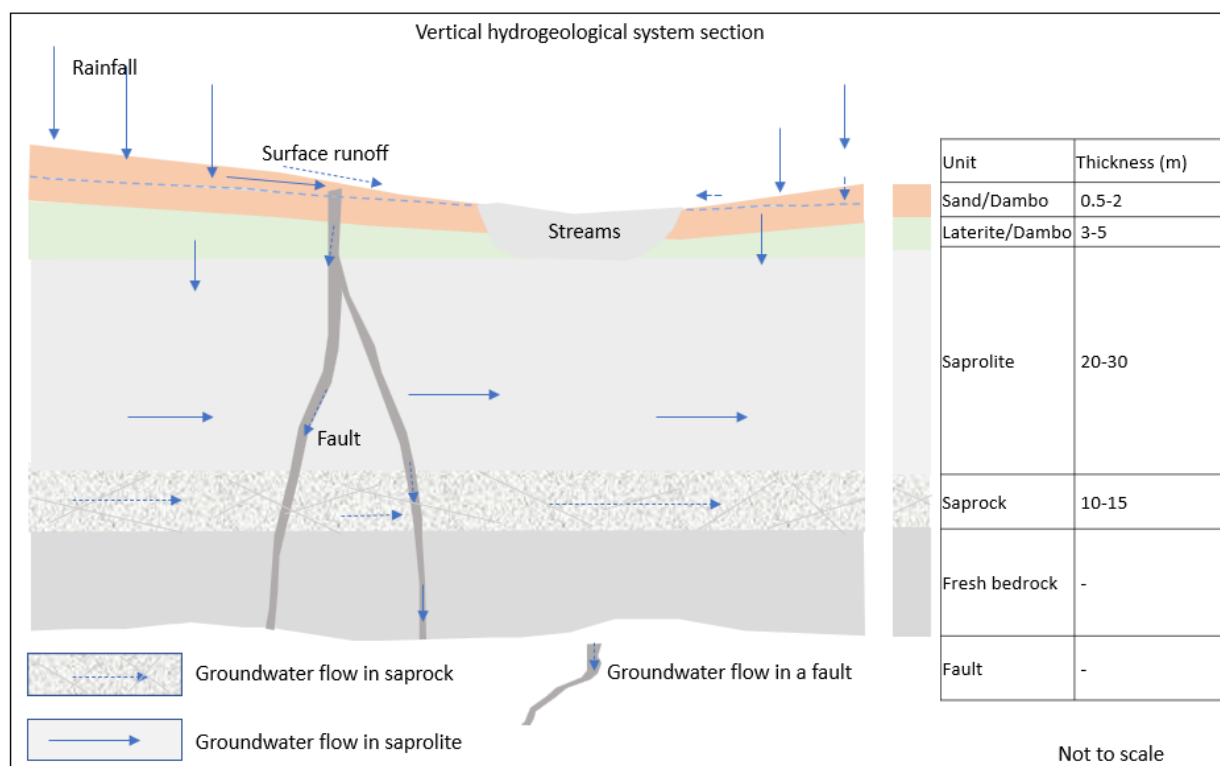


Figure 4.5 Schematic sketch depicting the study area's hydrogeological system (Modified after Showmaker, 2013).

Table 4.2 Hydrostratigraphy of Lumwana mine area (Showmaker, 2013).

UNIT	Description
Surface sand	Surficial layer, about 2 m thick, permeability influences rainfall recharge
Laterite	Highly weathered, iron-rich clayey materials, 3-5 m thick
Saprolite	Highly weathered, residual country rock, average 20-30 m thick, high clay content
Saprock	Fractured transition zone between saprolite and underlying solid rock, varies from 10 to 15 m thick, weakly weathered permeable zone
Basement	Consist of schists and gneisses with low primary permeability
Fractured network	Secondary permeability, laterally extensive, poorly developed secondary anisotropic aquifer

4.4 Pre-mining/Pristine groundwater conditions

Regional groundwater conditions before the start of mining activities around the Chimiwungo area and the Malundwe deposits were determined from a network of standpipe piezometers and vibrating wire piezometers consisting of geotechnical groundwater monitoring and environmental monitoring boreholes. Pre-mining groundwater contours from the groundwater monitoring network show groundwater elevations ranging between 1408 m relative to the mean sea level in the southern part of the study area and 1290 m above mean sea level in the northwestern part of the study area as shown in Figure 4.6. Therefore, groundwater flow was from south to northwest towards the Lumwana East River. Pre-mining groundwater elevations in this environment mirror the general topography and show approximately 5 to 10 m depth to the top of the groundwater table thus providing evidence for shallow groundwater flow.

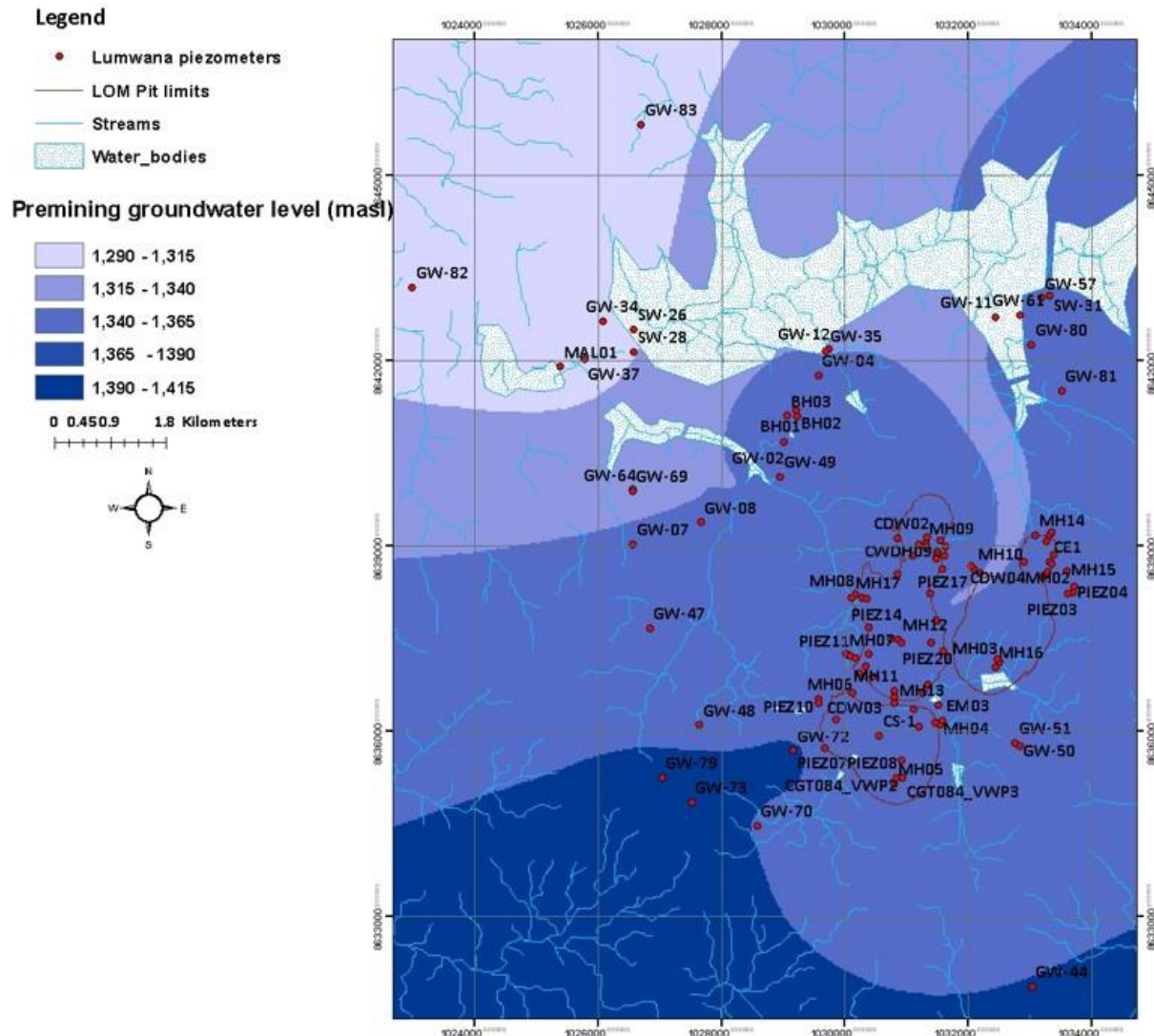


Figure 4.6 Pre-mining groundwater contour map of the Lumwana Mine area.

4.5 Transient groundwater levels.

Since the start of mining activities within the study area, several groundwater monitoring boreholes have been drilled and equipped for routine monitoring of the groundwater levels as shown in Figure 4.7. The data range is from 2012 to 2021 with a number of old groundwater monitoring boreholes destroyed or replaced in the process of setting up mining and mineral processing infrastructure in different locations. The following provides a summary of the groundwater monitoring network in Figure 4.7;

- The monitoring network has fairly good spatial coverage around the active mining area.

- The monitoring network consists of both vibrating wire piezometers (CGT and CPD borehole IDs) with sensors installed in saprolite, saprock, fractured zones and fresh bedrock and standpipe piezometers (PZ, GW and MH hole IDs).
- Geotechnical monitoring boreholes with IDs CGT and PZ have a relatively longer-term record compared to CPD, which were recently installed in 2018.
- Environmental monitoring boreholes with IDs GW and MH have a regional spatial spread and show shallow regional groundwater level, although the measurements were taken on a once-off monitoring campaign in November 2021.

From the groundwater monitoring network, in Figure 4.7, the following observations were made:

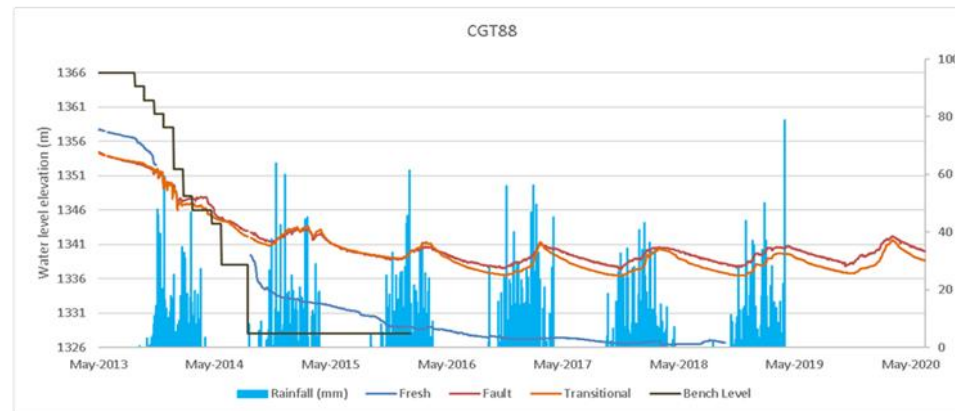
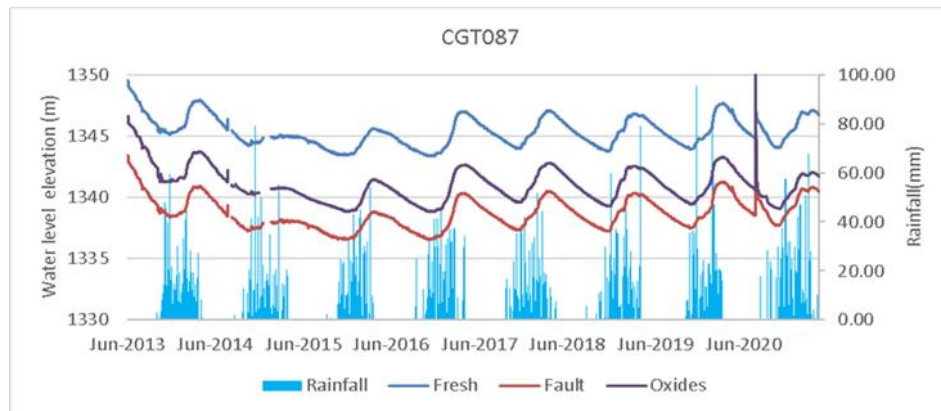
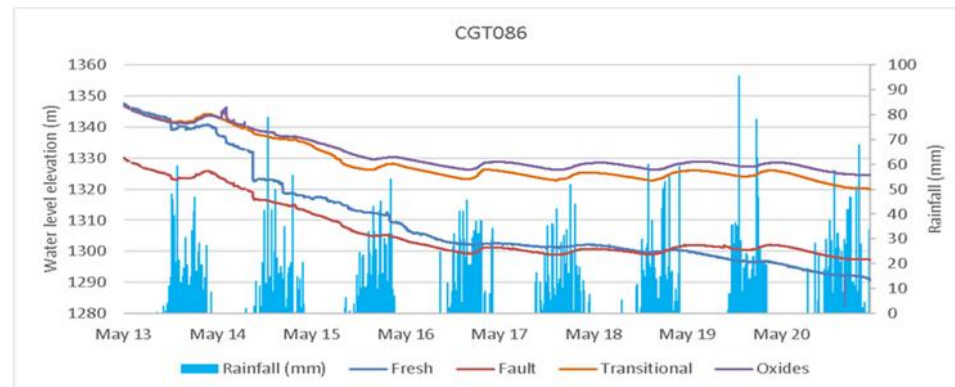
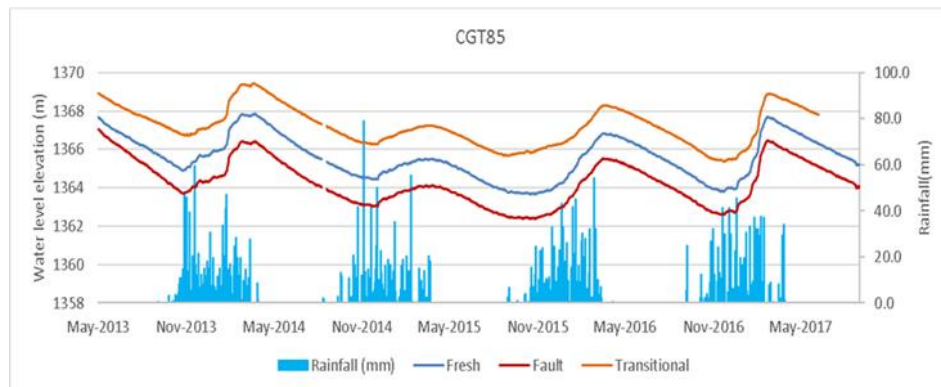
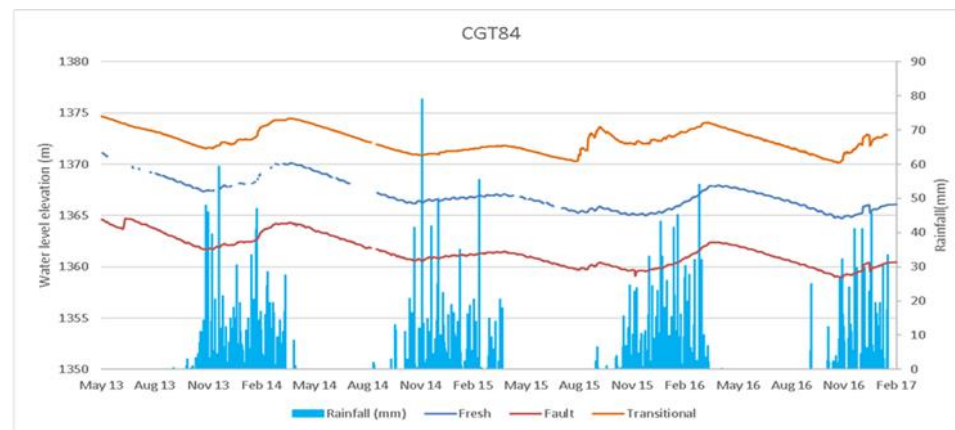
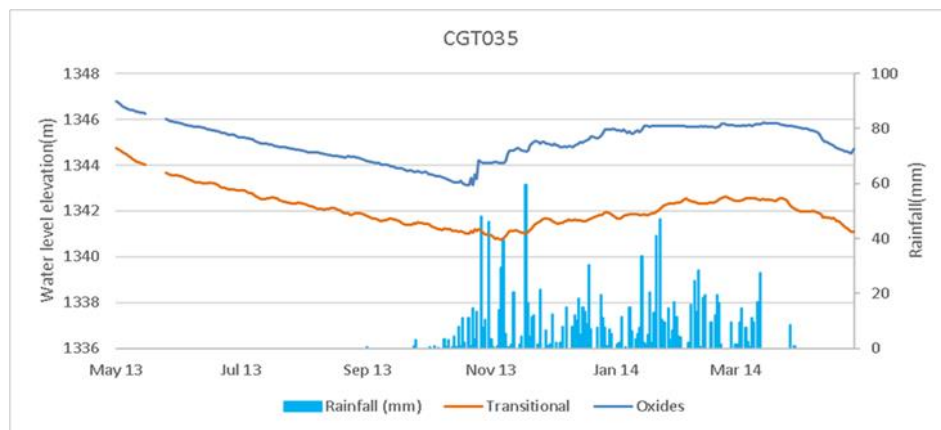
- Most piezometers, including CGT35, CGT84, CGT85, CGT86, CGT87, CGT88, CGT89, CGT90, CGT91, CGT92, CGT93, CGT95, CPD01, CPD02, CPD03, CPD04 and CPD05, show seasonal variation in groundwater levels, with nearly two to three months lag in groundwater response following the onset of each wet season.
- Piezometers CGT86, CGT88, CGT091, CGT94, CPD01, CPD02, CPD03, CPD04 and CPD05 located around or within the open pit that are in direct hydraulic connection with the mine show little or no response and sometimes decreasing response to groundwater level during wet season, due to passive drainage effect of the pit excavations.
- Most of the piezometers including CGT35, CGT86, CGT88, CGT90, CGT91A and CGT94 that were drilled and installed prior to or during starter pit development show rapid response to passive drainage due to pit development in the period 2014 to 2016 and nearly stabilised thereafter.

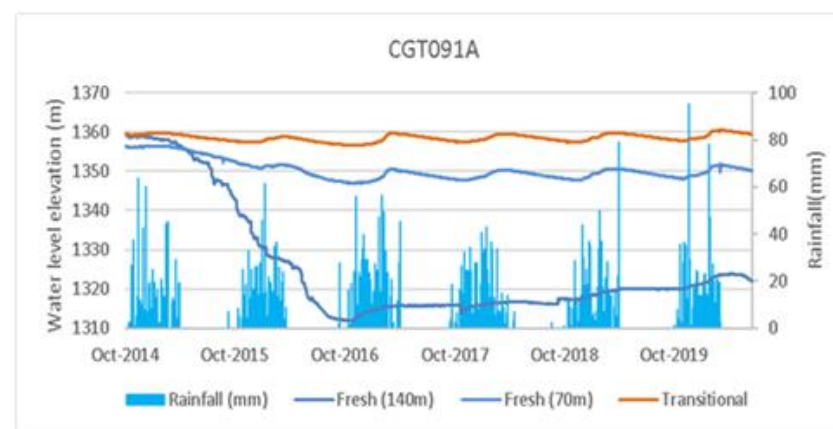
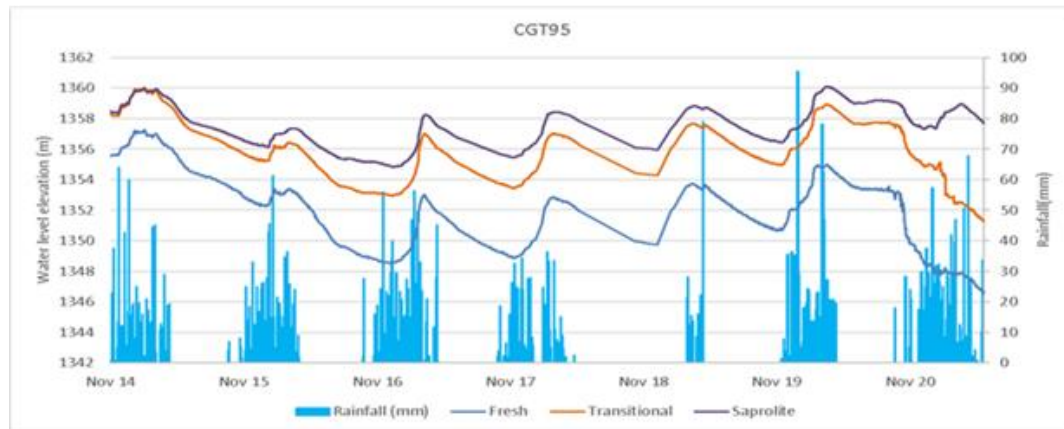
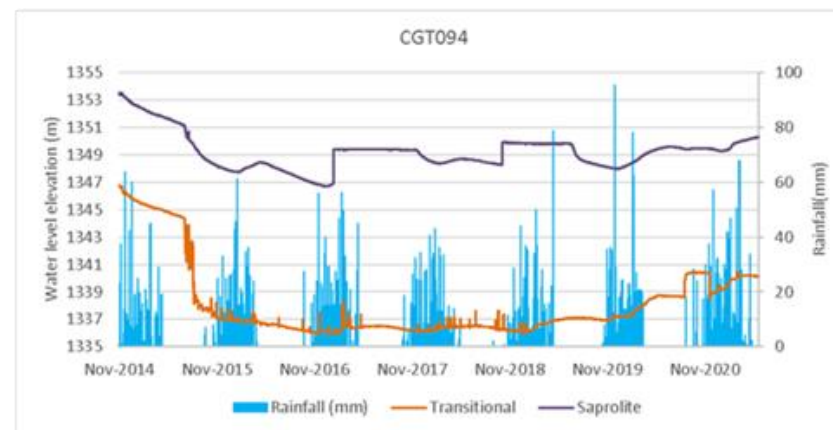
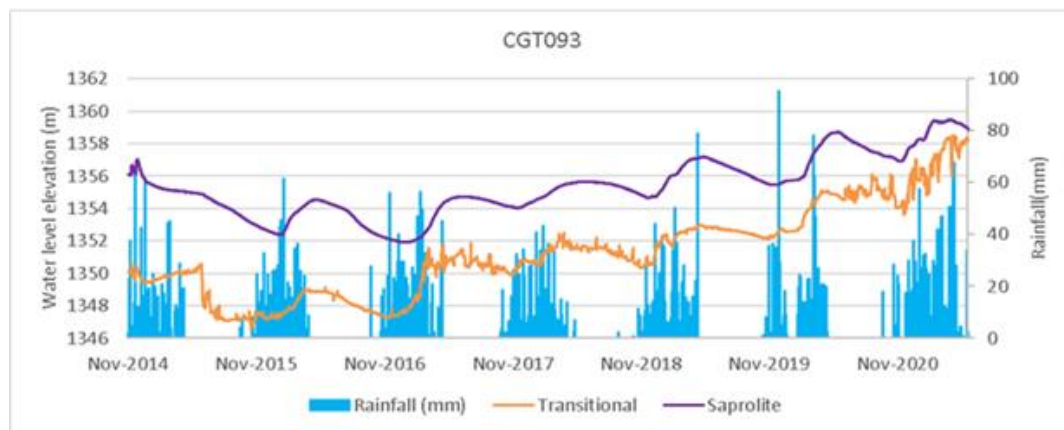
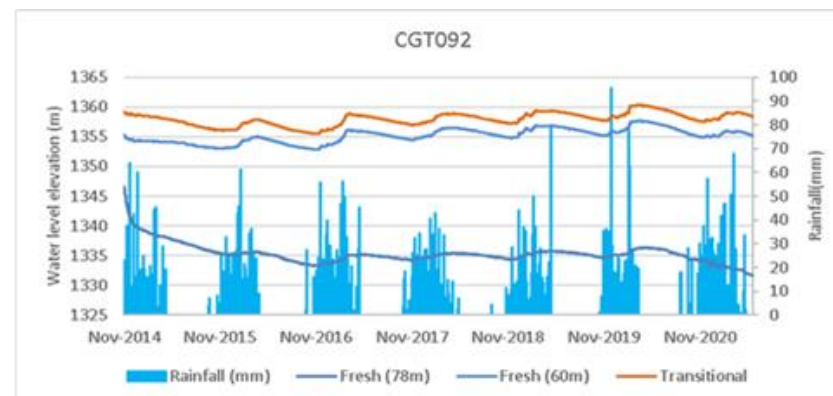
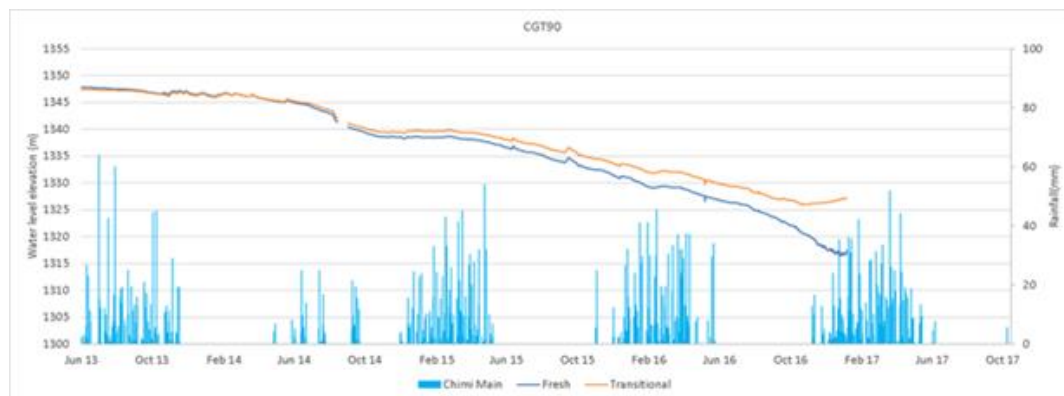
Groundwater investigation around the mine area has demonstrated the following:

- A steep cone of depression around the mine excavations has developed due to passive drainage as a result of mining developments. Each pit stage, Chimiwungo South, North, and East, has an isolated zone of depression except for the Chimiwungo Main pit and Chimiwungo South pit, which have been passively drained due to an intense interconnected fracture network adjacent to the Chimiwungo south main fault.

- Vibrating wire piezometers drilled and installed in the saprolite around 10 to 15 m from the pit crest show elevated persistent pore pressure throughout the year and very little response to passive drainage with a cyclical piezometric annual change. The phenomenon observed is explained by the observed relatively low hydraulic conductivities, high porosity, and low specific yield in the saprolites around the Chimiwungo pits.
- A relatively high drawdown effect is observed in the saprock and fractured rock (fresh) in response to passive drainage and active drainage from the horizontal drainage holes.
- Construction of critical mine infrastructures such as tailings storage facility (TSF), water storage facility (WSF), dams and dumps have distorted the initial observed pre-mining groundwater contours. Topsoil, saprolite and waste rock dumps act as a sponge that retains water after a rainfall event and slowly drain the water from storage, as can be seen in the latest groundwater contour map in Figure 4.8.

The hydrographs in Figure 4.7 provide the life of mine groundwater level trends. Figure 4.8 provides a pictorial summary of the above discussions and the latest observations relative to the pre-mining groundwater conditions. Figure 4.7 also shows seasonal and rainfall-induced pore pressure trends around the piezometer monitoring network on site. A lag of two to three months has been observed in the monitoring data after the onset of each rainy season. This observed rebound in pore pressure due to the onset of the rainy season is mainly linked to numerous ground falls in the open pit.





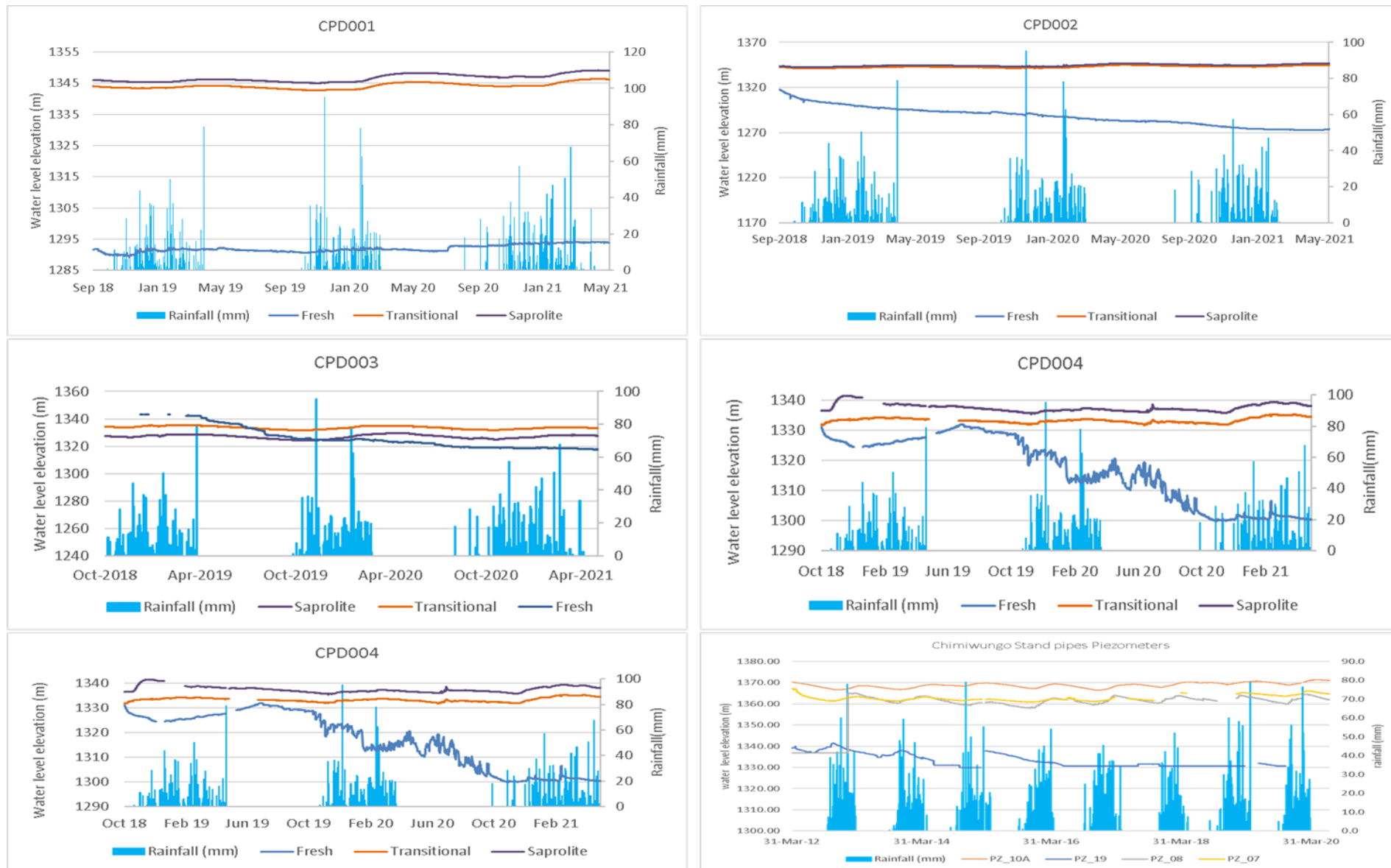


Figure 4.7 Lumwana Mine piezometer groundwater level monitoring results.

Groundwater elevations from monitoring boreholes in Figure 4.7 revealed that a steep zone of influence due to mining has developed around the mine workings in each pit stage. In these regions, the groundwater contours changed with respect to the pre-mining groundwater elevations. Table 4.3 summarises the life of mine monitoring boreholes drawdown effect from the start of monitoring to date. Monitoring borehole CGT086 fresh geotechnical unit in Figure 4.7 and in Table 4.3 revealed a drawdown of 45.8 m over a period of nearly five years in response to mining progression (average 9.16 m/year). Other monitoring piezometers that were drilled away from the pit crests did not show any drawdown response to mining, and the groundwater levels appear cyclical in response to rainfall-induced pore pressure change.

There has been no active dewatering activities from vertical dewatering wells at Lumwana Mine in the past due to the lack of information to suggest a mine dewatering strategy. Therefore, the steep confined zone of influence was attributed to mine developments only. The extension of the zone of influence depends on local geology and geostructural features (Beale *et al.*, 2013). As observed in the groundwater monitoring data, a fault system with regional interconnectivity tends to pull and distort the surface for the zone of influence, while in certain localities, the fault system acts as a hydraulic barrier, constraining the propagation of the zone of influence away from the pit limits. Figure 4.8 provides an updated groundwater contour map. Shallow groundwater tables are observed on the southern side of the study area. Groundwater flows from the south towards the northwestern side of the study area with relatively shallow groundwater levels around the dumps, indicating the possibility of focused recharge.

Table 4.3 Observed drawdowns in the Life of mine monitoring boreholes.

Hole ID	From	To	Time (days)	Time (years)	VW1(Δr) m	VW2(Δr) m	VW3(Δr) m	VW4(Δr) m
CGT035	29/05/2013	12/06/2013	14.00	0.04	0.74	0.54		
CGT084	28/05/2013	27/01/2017	1339.91	3.67	6.37	5.73	4.50	
CGT085	28/05/2013	28/09/2017	1583.50	4.34	4.18	4.66	4.05	
CGT086	23/05/2013	26/03/2018	1767.50	4.84	45.89	30.86	23.76	20.57
CGT087	23/06/2013	27/03/2018	1737.76	4.76	6.19	6.91	7.81	
CGT088	24/05/2013	27/03/2018	1767.90	4.84	30.63	16.92	17.86	
CGT089	23/06/2013	21/10/2013	120.00	0.33	2.87	4.26		

CGT090	22/06/2013	27/01/2017	1314.94	3.60	31.39	21.48		
CGT091	22/10/2014	26/03/2018	1251.50	3.43	47.72	9.59	3.23	
CGT092	12/11/2014	12/11/2014	0.00	0.00	13.42	3.34	3.83	
CGT093	12/11/2014	07/03/2018	1210.50	3.32	5.35	5.11		
CGT094	12/11/2014	24/01/2017	803.50	2.20	10.82	6.82		
CGT095	11/11/2014	27/03/2018	1232.00	3.38	8.75	7.11	5.15	
PZ_07	31/03/2012	01/11/2017	2041.00	5.59	6.55			
PZ_08	08/02/2013	28/03/2018	1874.00	5.13	7.13			
PZ_10A	31/03/2012	28/03/2018	2188.00	5.99	3.73			
PZ_19	31/03/2012	28/03/2018	2188.00	5.99	11.96			

Where, VW1(Δr), VW2(Δr), VW3(Δr) and VW4(Δr) are groundwater level changes in Vibrating Wire sensors 1, 2, 3 and 4, respectively.

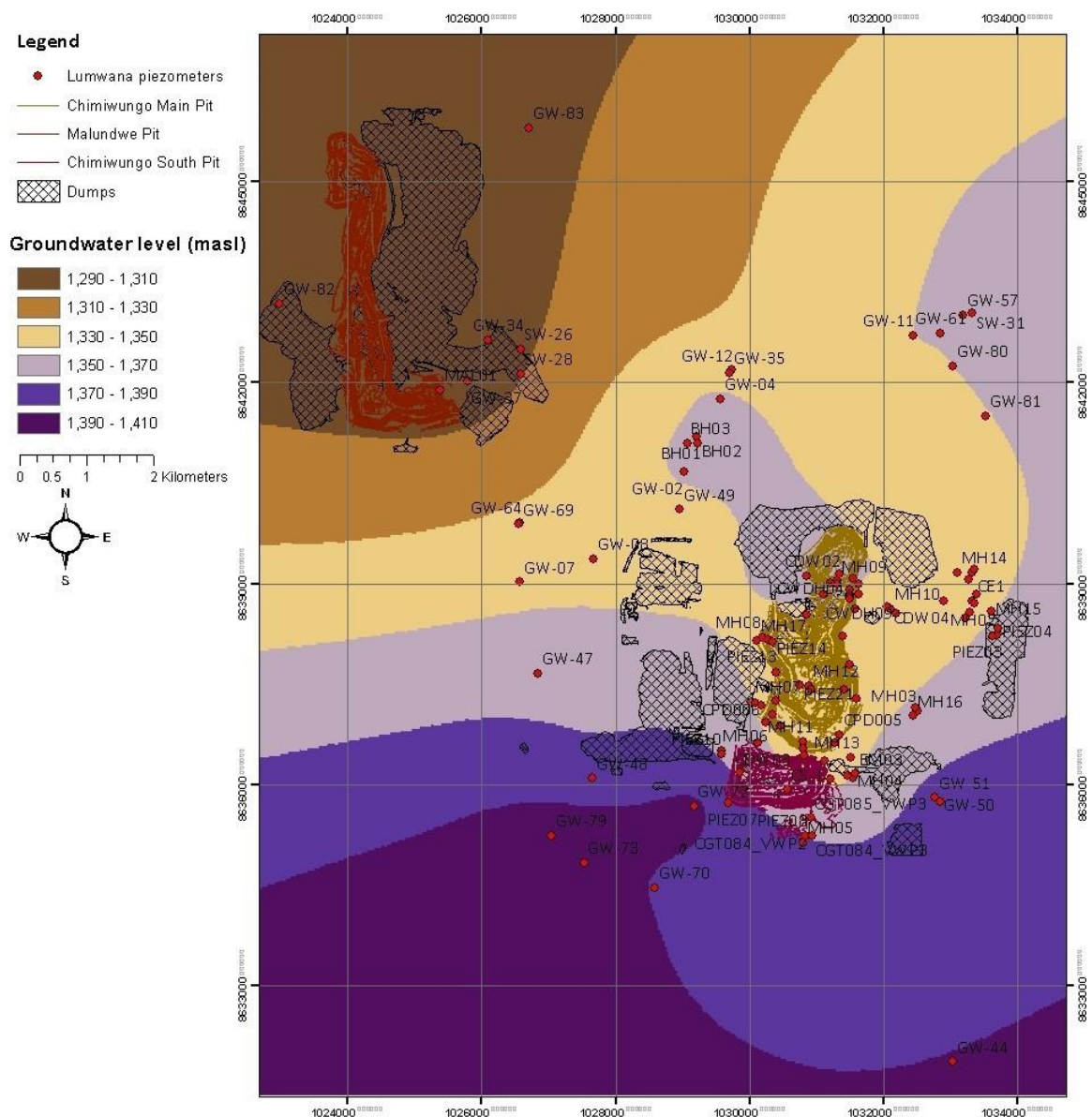


Figure 4.8 The 2021 groundwater contour map of the Lumwana Mine area.

4.6 Groundwater flow and discharge mechanisms

Regional baseline pre-mining groundwater conditions show a relatively shallow groundwater table with nearly uniform south to north-west groundwater flow direction towards the Lumwana East river (Showmaker, 2013). The Lumwana East river and numerous streams in the region, including the main Chimwungo stream, in essence, act as regional drains that release groundwater from storage in geological units. Numerous streams flow along the lowest points of topographic depression with preferential groundwater discharge and are incised by dambos.

During the peak of the dry season, streamflow is sustained by groundwater discharge from shallow geological units and transported regolith. Due to the contrast in hydraulic conductivities of geological units and different weathered zones, groundwater flow is concentrated in the weathered top profile, mainly saprolites and transported regolith.

A significant amount of water discharged from storage requires continuous pumping due to extensive and persistent coverage of topographic depressions and dambos around Lumwana Mine area. Therefore, as a water management strategy, diversion channels and embankment system have been built to impound and contain the water and subsequently pump and discharge the water at a downstream point away from the pits. Due to the proximity of these water storage facilities in relation to the pits, it is envisaged that these water storage facilities leak and are therefore, in direct hydraulic connection with the pits, thereby contributing to wet pit floor conditions and prevalent slope failures due to elevated pore pressures.

4.7 Catchment water balance

The regional catchment water balance at Lumwana provides relationships among different hydrologic parameters. These hydrologic processes and rock mass properties dictate groundwater generation and distribution across the catchment in accordance with the law of mass conservation, whereby the catchment sum of inflows equals the sum of outflows.

4.7.1 Groundwater recharge estimates

Recharge estimates in any hydrogeological environment are conducted using different approaches depending on the climatic region or on the basis of hydrologic sources or zones obtained, namely surface water, unsaturated zone and saturated zone (Scanlon *et al.*, 2002). Within each zone, recharge estimating techniques are subdivided into physical, tracers or numerical modelling approaches. Another attribute that is considered in recharge estimation is the applicable space and time scales of recharge (Luckey *et al.*, 1986). Water levels within the study area are a function of the precipitation amount, soil and rock properties of the aquifer. Water levels enable the behaviour of the aquifer to be understood including recharge, which provides information on whether the aquifer is being over-exploited (Karen *et al.*, 2015). Groundwater recharge estimate studies conducted by Beekman (1997) in Southern Africa

indicate typical recharge in the range of 2 -15% of the mean annual precipitation recorded. Other studies conducted by the Japan International Cooperation Agency (JICA, 1995) revealed recharge estimates of 8% of mean annual precipitation. Showmaker (2013), tried to estimate groundwater recharge for the region under investigation on a catchment area of 600 km². It was understood that water stored in low topographic regions contributed to groundwater recharge during wet season. The water balance method applied estimated total groundwater recharge of 8.3% (100 mm) of mean annual precipitation. The recharge estimation technique employed for this research is the Water Table Fluctuation.

The Water Table Fluctuation (WTF) method was applied based on the groundwater level.

Recharge estimation was conducted on a continuous dataset where groundwater level and time attributes were captured on a daily basis using pre-programmed sensors. The estimates were based on the 2014/15 wet season piezometric hydrographs from selected borehole (CGT085) without hydraulic connections with the pits or water storage infrastructure. Table 4.4 provides a summary of the site borehole selected for recharge estimation using the Water Table Fluctuation method. The recharge estimates at the Lumwana Mine area using the Water Table Fluctuation method is 8.8% of mean annual precipitation, translating into an annual recharge value of 105 mm.

From the onset of each wet season in Table 4.4, a time lag of two to three months was observed in groundwater monitoring boreholes and groundwater level fluctuations of about 1.1 m in response to the rainfall recharge. It was also observed that the higher rainfall intensity was not followed by a higher groundwater level change, which can be explained by the intensity of rainfall exceeding the infiltration capacity of the soil, which usually results in excess rainfall amount flowing overland into the local drainage systems and later lost to the groundwater system in the environment (Karen *et al.*, 2015).

Table 4.4 Recharge estimates using WTF method.

Hole ID	Period from	Period to	ΔT (Months)	Δr (m)	Sy	Recharge
CGT085	01/01/2015	01/04/2015	3.0	1.1	0.02	8.8%

where, ΔT is time in months, Δr is change in groundwater level in metres and S_y is the specific yield from pumping tests.

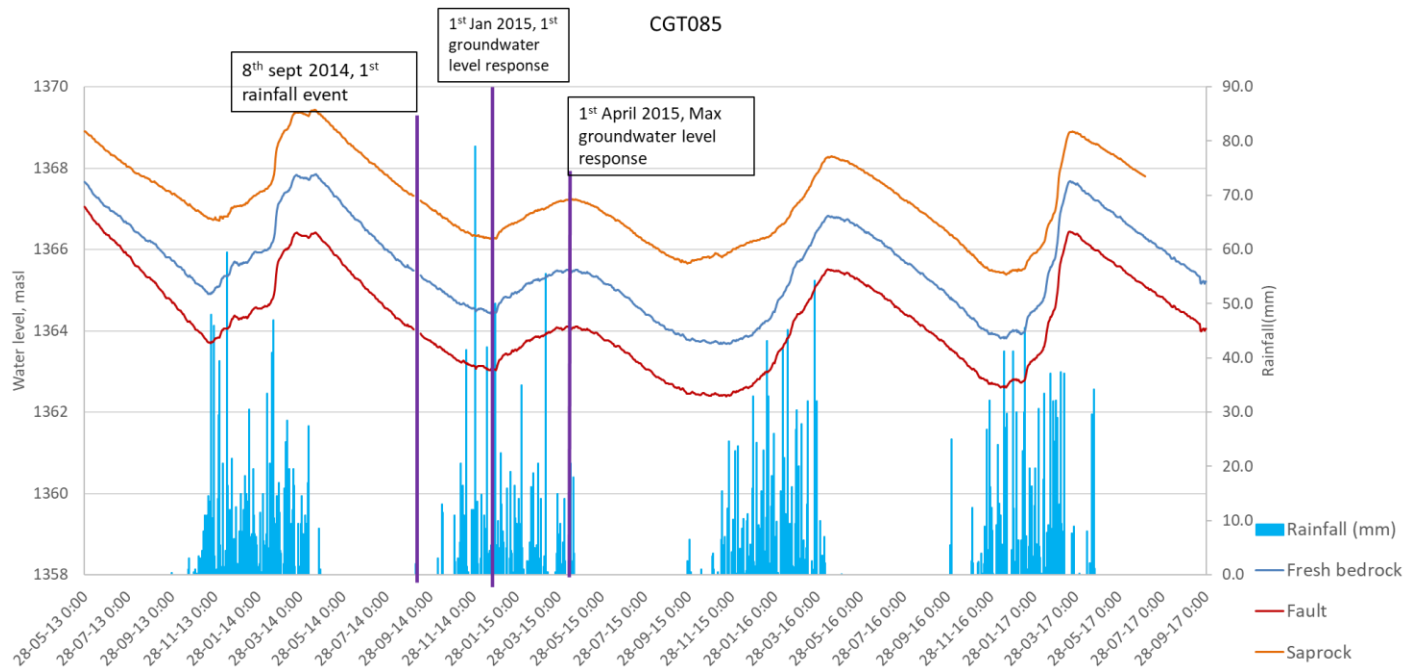


Figure 4.9 Water level and rainfall data (Data source: Lumwana Mining Company weather data records).

4.7.2 Evapotranspiration

Potential evapotranspiration and actual evapotranspiration for the study area were calculated using the Thornwaite-Mather and Turcs method, respectively based on the 2019/20 and 2020/21 full season. There is a minor reduction in potential evapotranspiration between 2019/20 and 2020/21 wet season owing to a slight change in monthly average temperatures. Table 4.5 and Table 4.6 present a summary of the theoretical annual PET and AET. From the summary table, the Lumwana mine area has shown that AET is lower than PET, possibly due to limited water availability.

Based on site climatic data, monthly potential evapotranspiration ranges between 107.5 mm and 142.9 mm, with an average annual potential evapotranspiration of 1498 mm. This calculated annual PET magnitude has a strong correlation with the site-measured annual evaporation rate of 1561.4 mm for the same period under discussion. Although Table 4.5 and Table 4.6 show high

month-to-month potential evaporation for the seasons under consideration, Figure 4.10 provides evidence for excess rainfall that potentially generates runoff and recharge starting from November, December, January, February and March.

Hennings (2012) calculated potential evapotranspiration for the year 1989/90 and 1983/84 hydrological years from the five daily meteorological input parameters (minimum temperature, maximum temperature, mean humidity, mean wind speed and duration of sunshine) for Lusaka International Airport, Zambia. Annual sums of evapotranspiration in 1989/90 and 1983/84 were estimated at 1908 mm and 1815 mm, respectively. Monthly potential evapotranspiration calculated for the 2019/20 and 2020/21 hydrological year from the Lumwana area is slightly lower than the potential evapotranspiration values reported for the 1989/90 and 1983/84 years. This provides indications of long-term reduced potential evaporation processes. The highest daily potential evaporation during 1989/90 hydrological year never exceeded 6 mm/day while at the end of the dry season in September and October, the maximum values calculated exceeded 10 mm/d (Hennings, 2012). According to the Zambian National Water Resources master plan (YEC, 1995), potential evapotranspiration calculated using a revised version of the Penman equation ranges from 1530 mm to 1590 mm for the Lusaka area and a range of 1394 mm to 1892 mm within Zambia.

Hennings (2012) calculated actual evapotranspiration using the MABIA software, which was incorporated into the “Water Evaluation and Planning ” decision support system developed by the Stockholm Environment Institute (2005). According to Allen *et al.* (1998), the software applies FAO 56 dual crop coefficient method for estimating crop evapotranspiration from the soil, considering crop-specific water demand and transpiration as well as soil water availability depending on net precipitation and soil physical properties such as soil water capacity. Actual evapotranspiration calculations were carried out on the 1989/90 daily meteorological data from the Lusaka International Airport. Actual evapotranspiration reported from this exercise ranges between 400 mm and 700 mm during dry and wet seasons, respectively. The values reported are in agreement with the actual evapotranspiration values reported for this research using the Turc equation.

Table 4.5 2019/20 season potential and actual evapotranspiration.

Season		Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20	Feb-20	Mar-20	Apr-20	May-20
2019/20	Monthly PET (mm)	134.8	130.3	126.8	122.9	116.3	107.5	107.8	114.9	123.8	132.4	142.7	142.9
	Annual PET (mm)	1503.1											
	Monthly AET (mm)	63.1	63.2	63.5	63.7	63.7	63.6	63.6	63.5	63.5	63.5	63.6	63.5
	Annual AET (mm)	762.2											

Table 4.6 2020/21 season potential and actual evapotranspiration.

Season		Jun-20	Jul-20	Aug-20	Sep-20	Oct-20	Nov-20	Dec-20	Jan-21	Feb-21	Mar-21	Apr-21	May-21
2020/21	Monthly PET (mm)	137.1	129.9	126.4	122.4	115.9	107.1	106.3	112.5	123.0	131.4	140.9	140.1
	Annual PET (mm)	1493.0											
	Monthly AET (mm)	63.3	63.2	63.5	63.7	63.7	63.6	63.5	63.4	63.5	63.5	63.5	63.4
	Annual AET (mm)	761.8											

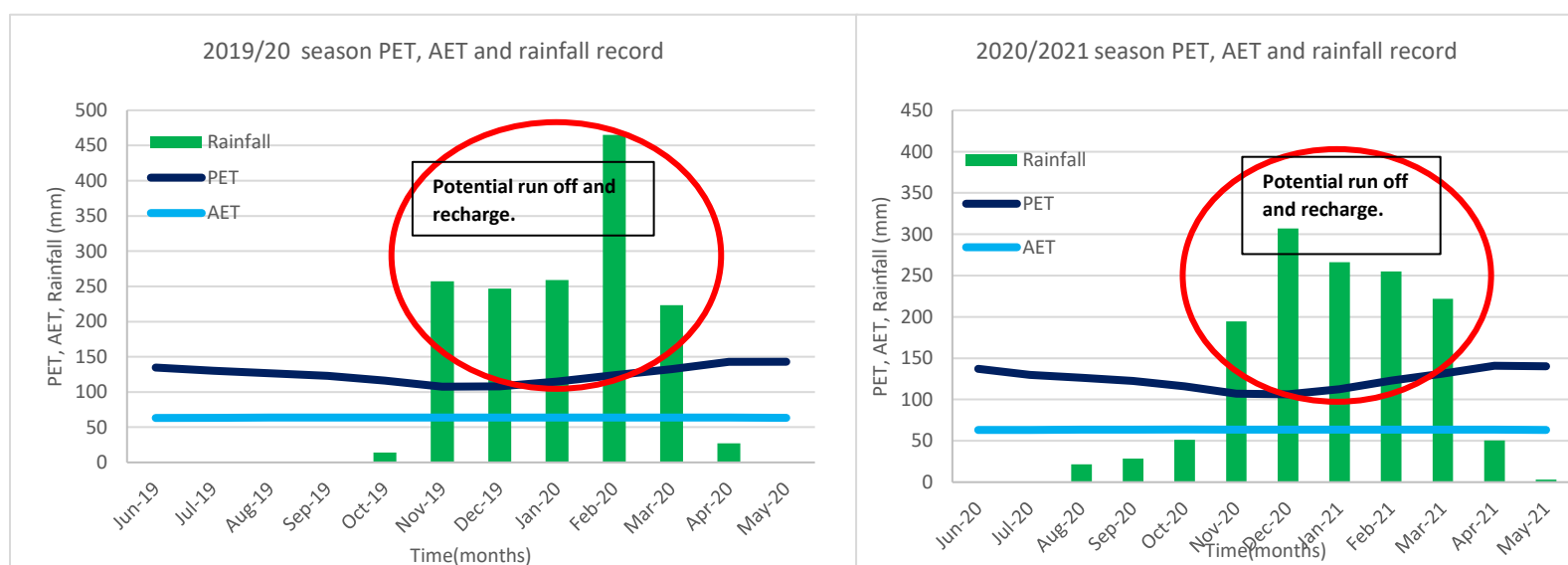


Figure 4.10 Potential evapotranspiration, actual evapotranspiration and rainfall estimates for the Chimiwungo catchment.

4.7.3 Pit dewatering volumes

Monthly pit dewatering figures have been captured and recorded from the start of mining in Chimiwungo pit in 2012, although the records are inconsistent, and this is mainly due to poor data capture and records update. For the sake of hydrograph analysis, the 2016/17 wet season data have been selected due to consistency and reliability, as shown in Table 4.7 and Figure 4.11. Monthly pit dewatering volumes for the Chimiwungo pits range from 3914 m³/month (1.5 L/s) to over 200,000 m³/month (80 L/s) for Chimiwungo South pits and 14,463 m³/month (5.5 L/s) to over 153,041 m³/month (59 L/s) for the Chimiwungo main pits during the dry and wet season, respectively. Hydrograph analysis for the period in discussion has shown that dry season dewatering volumes represent roughly 5% or 1/10th of the total volume discharged during the wet season. The volume reported represents the total inflow collected on the catchment within the pit footprint.

Table 4.7 Chimiwungo rainfall hydrograph analysis.

Month	Chimiwungo South (m ³)	Chimiwungo Main (m ³)	Rainfall (mm)
Aug-15	66029	40370	0
Sep-15	20323	35317	2.5
Oct-15	25225	40909	8
Nov-15	37939	63400	91
Dec-15	108870	97533	174.2
Jan-16	156979	146049	265.3
Feb-16	144453	153041	289.6
Mar-16	206609	147148	210.4
Apr-16	78786	81337	24.4
May-16	32352	37245	0.1
Jun-16	3914	14463	0
Jul-16	6956	15573	0
Aug-16	23894	28416	0
Sep-16	14030	26333	0
Oct-16	7943	21999	31.5
Nov-16	25451	42117	142
Dec-16	72319	144307	225.2
Jan-17	103766	125987	262

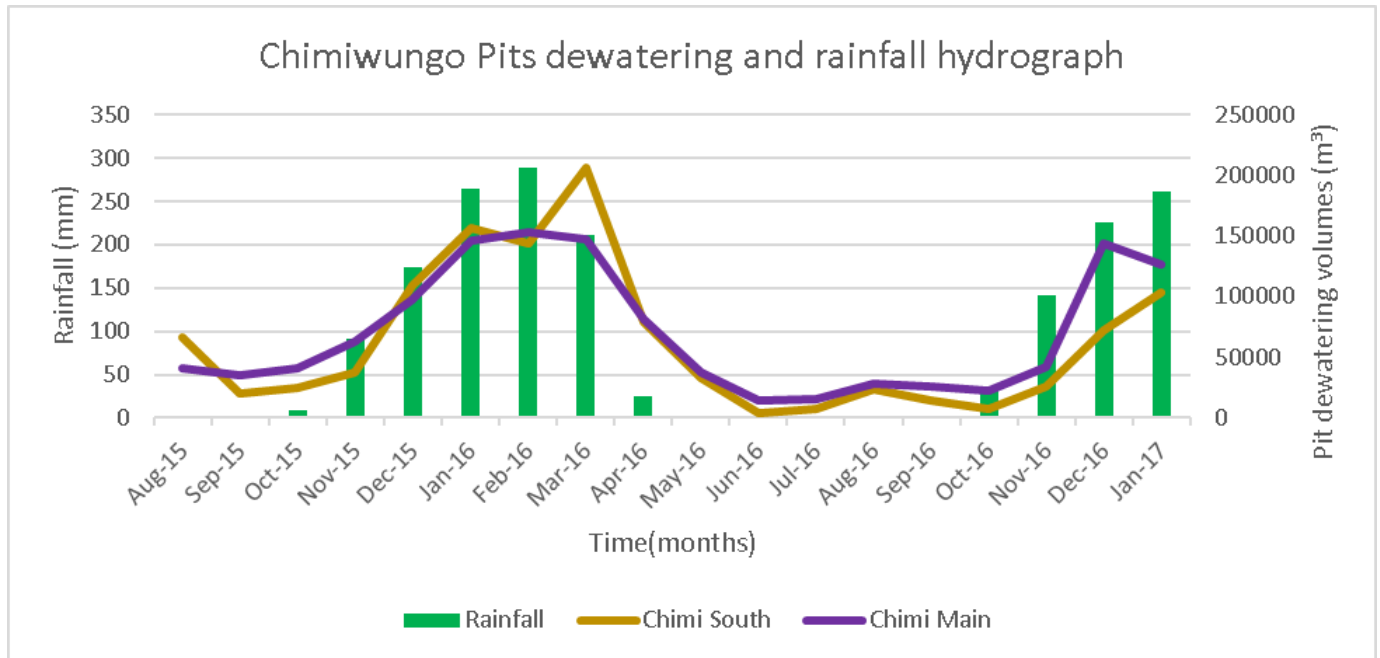


Figure 4.11 Chimiwungo main and Chimiwungo South pit dewatering and rainfall hydrograph.

4 7.4 Runoff estimation

Runoff forms an important component of the hydrological cycle (Karen *et al.*, 2015). Total runoff from a stream or river can be divided into direct runoff (overland flow and interflow) and baseflow (groundwater runoff) (Krekeler and Siwale, 2012). Inflow runoff estimation has been carried out using the empirical formula based on different runoff coefficients for different catchment types (Knight Piesold, 2011), as highlighted in Figure 4.12 and Table 4.8. Three catchment types have been identified within the study area; mined, dumped and vegetated. Runoff coefficients for different catchments were adopted from long term site measured waste dumps, undisturbed and disturbed catchment runoff (Knight Piesold, 2011) while the inflows are based on rainfall amount measured from site rain gauge. The mined-out area contributes significantly to the pit dewatering during wet season. Inflow estimations based on historical data inform pit dewatering requirements and strategy. To improve the efficiency of pit dewatering, emphasis is put on improved surface water management by ensuring surface seepage entry into the pit is minimised through improved drainage to channel water away from the pits and consistent pit dewatering operations.

Legend

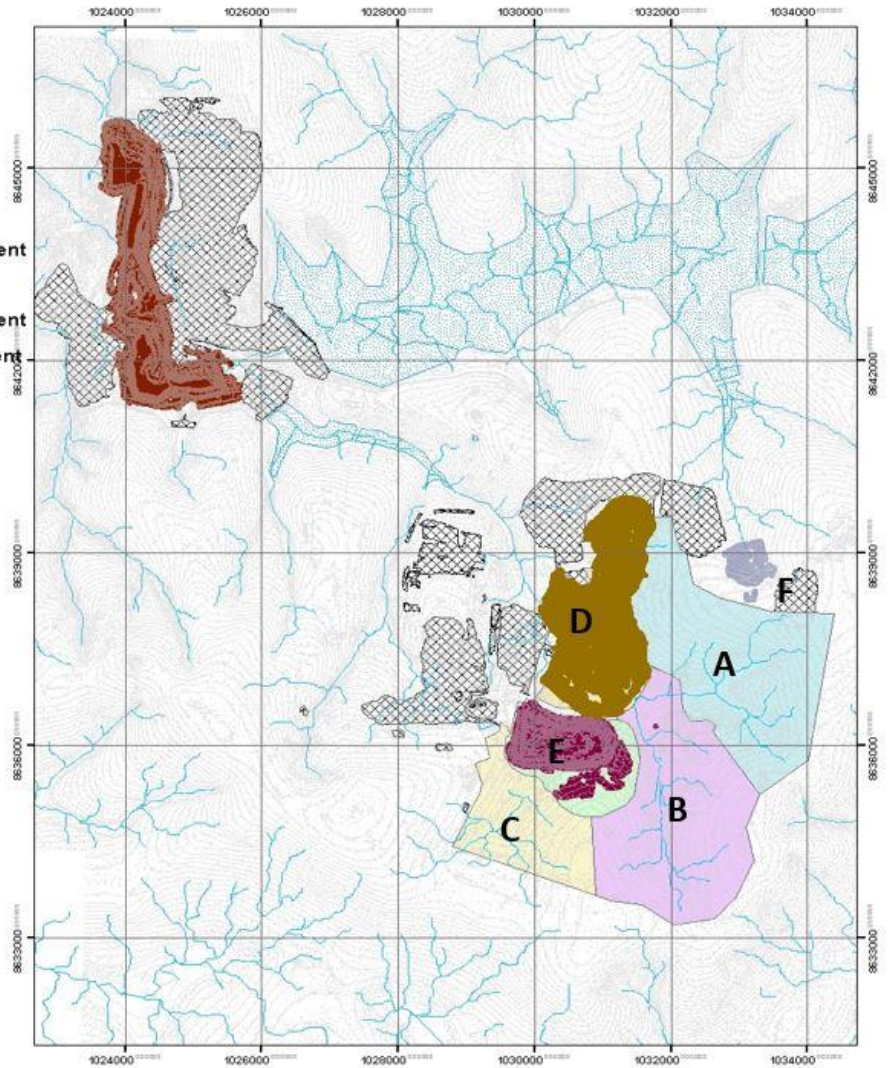
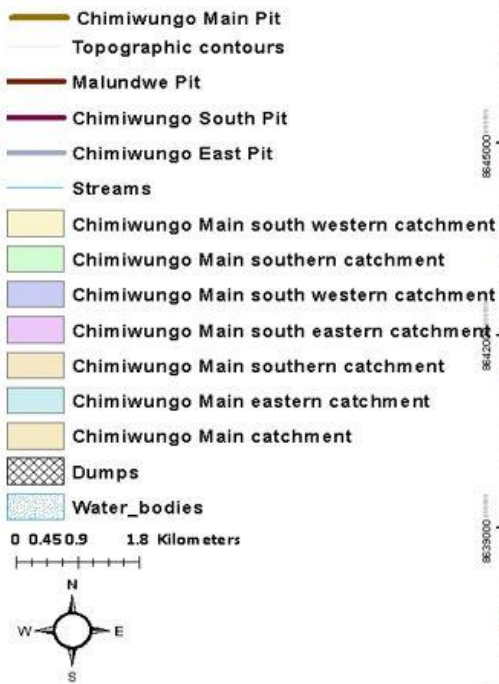


Figure 4.12 Lumwana open pits hydrological effective catchments.

For the purpose of inflow quantification for each catchment type highlighted above, runoff has been calculated according to the empirical formula (equation 10) (Hooydonck, 2016),

$$Q = (C \times I \times A) / 3.6 \quad (\text{Equation 10})$$

Where, Q is the maximum runoff (m^3/d)

C is the runoff coefficient based on each catchment type

I is the inflow (mm) at a particular time (d) and place

A is the area (m^2)

Lumwana catchment rainfall analysis has shown that 28.5% of the total rainfall received in the Lumwana catchment area is reported as average catchment runoff. For the Chimiwungo main pit eastern catchment, the volume of inflow from precipitation should be diverted through excavated pit perimeter drainage and pumped around the pit to avoid flooding the mine. Improved site-wide surface water management requires improved water management actions, including dam construction and physical barriers along the pit perimeter to shed water away from the pit into the drainages. In addition, drainage design parameters should be adequate to convey maximum instantaneous inflows across the catchment without flooding. Recommended design parameters are therefore, based on the catchment expected inflows highlighted in Table 4.8 and the existing topographic gradient around the site channelling water into the diversion embankment pumping systems. Without proper surface water management, surface inflows can potentially contribute about 4600 L/s into the Chimiwungo main pit, which has the potential to flood the pit and paralyse operations.

Table 4.8 Rainfall runoff estimates.

Catchment type	Catchment ID	Area (m ²)	Runoff coefficient	Runoff (L/s)	Runoff (m ³ /s)
Chimiwungo Main North Vegetated	A	5,394,484	0.4	4,620.28	4.62
Chimiwungo Main South vegetated	B	5,074,000	0.4	4,345.79	4.35
Chimiwungo South vegetated	C	2,803,000	0.4	2,400.72	2.40
Chimiwungo Main pit	D	3,544,000	1	7,588.43	7.59
Chimiwungo South pit	E	1,941,000	1	4,156.08	4.16
Chimiwungo NE dump	F	943,516	0.6	1,212.16	1.21

4.8 Hydrochemistry and physical parameters

Potential for surface water and groundwater interaction can be assessed through application of major ions hydrochemistry (Williams *et al.*, 1986). The mineral composition of the rock is usually reflected in the chemistry of the water, and therefore, origin of water and its flow path can be

traced using water chemistry (Mulenga, 1991). Different physicochemical parameters were analysed during the field sampling programme in November 2021. These include pH, temperature, dissolved oxygen, electrical conductivity and total dissolved solids.

4.8.1 Temperature and geothermal gradient

With respect to groundwater flow pattern tracing, temperature measurement is of great importance (Chapman and Pollack, 1977). For the purpose of assessing the source of recharge and the preferred flow paths, groundwater temperatures were measured and compared to the atmospheric temperature. It is envisaged that if the source of recharge is old meteoric water from a deep-seated aquifer, groundwater temperature increases towards the source of recharge (Mulenga, 1992). Plots of piezometric groundwater temperature versus depth have been generated for each drill hole. Inclined and horizontal piezometers were drilled and equipped with pressure transducers for temperature and pore pressure readings in each geotechnical unit. A varying number of vibrating wire sensors were installed in each borehole ranging from 1 to 4 at different depths depending on the monitoring requirements to provide temperature data at a discrete point. Analysis of groundwater piezometric temperature in Figure 4.13 has revealed that groundwater temperature measured in shallow geotechnical units resembles temperature in the lower atmosphere. Moreover, the measured groundwater temperature generally increases progressively downwards hence providing evidence for surficial recharge (Mulenga, 1992).

Data plotted from this investigation in Figure 4.14 has revealed a geothermal gradient of 1°C for every 35 m, which is in very close agreement with the global trend. On average, the global geothermal gradient is about 1°C for every 33 m (Mulenga, 1991). The slightly lower geothermal gradient calculated is attributed to the cooling effect of surface water recharging the ground.

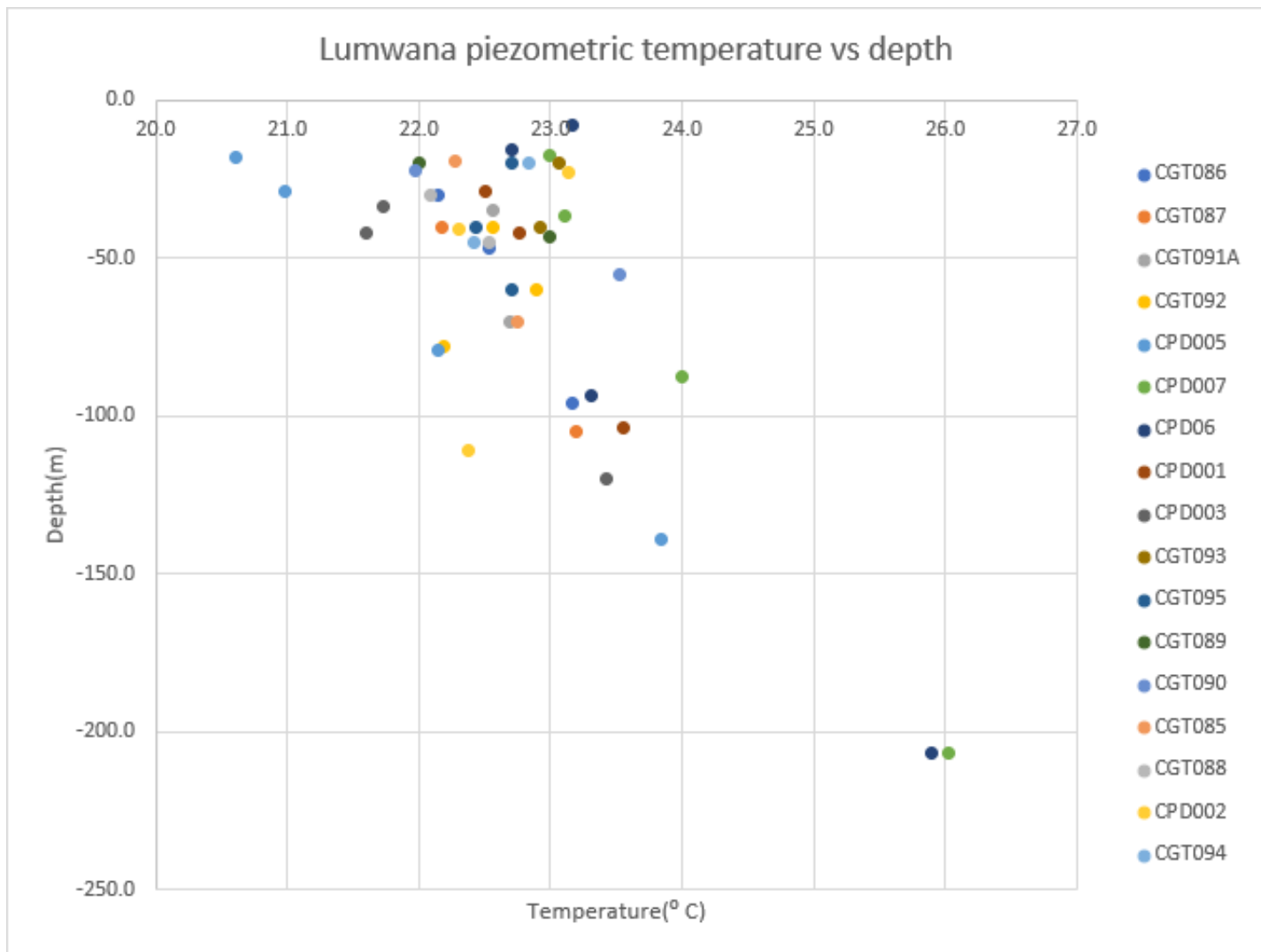


Figure 4.13 Piezometric-measured groundwater temperatures at Lumwana Mine.

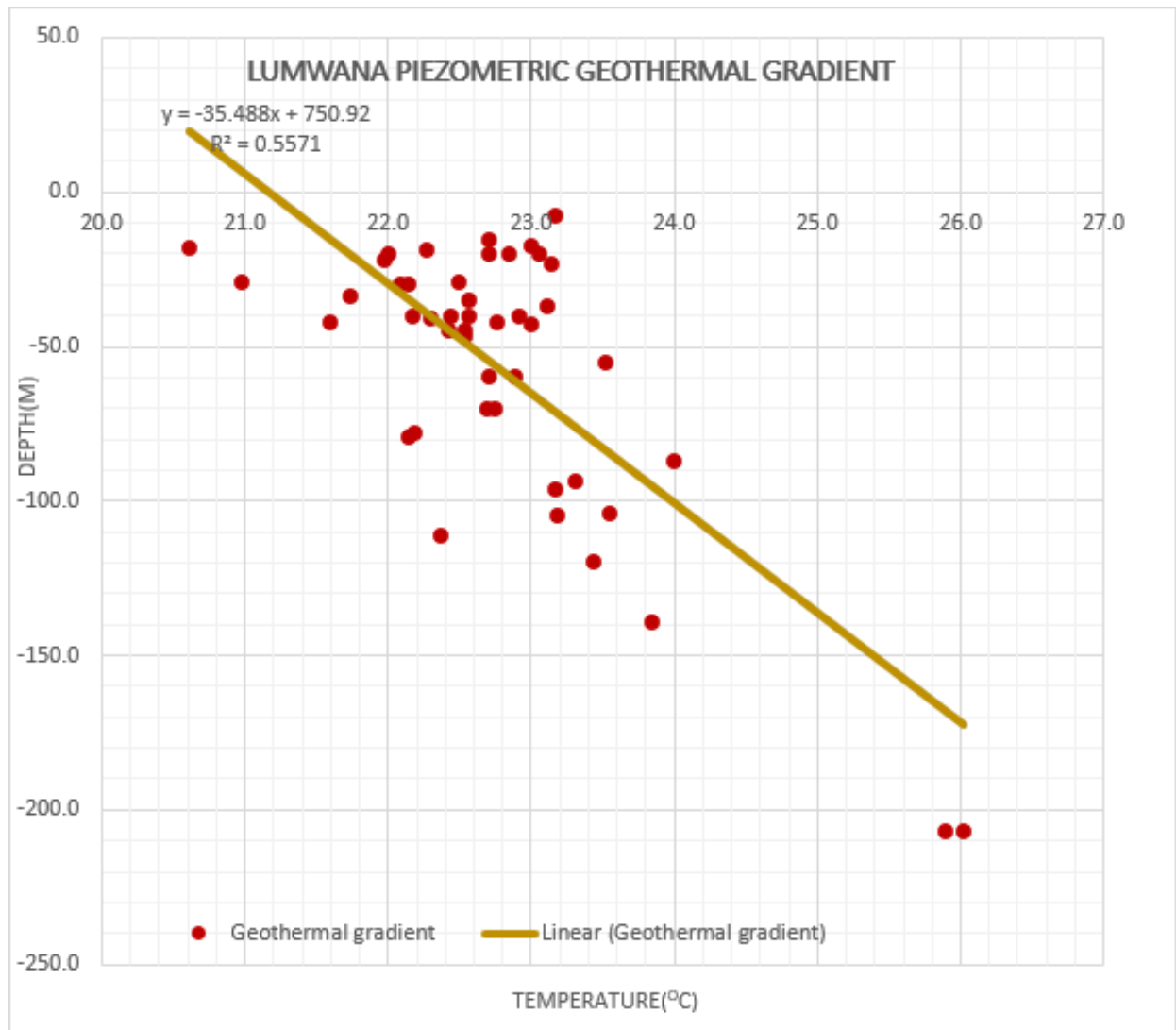


Figure 4.14 Piezometric geothermal gradient at Lumwana Mine.

4.8.2 Potential of Hydrogen (pH)

Groundwater and surface water pH range between 4.7 and 8.24 (Figure 4.15). Surface water pH from the tailings storage facility and Malundwe pit lake ranges from 5.32 to 7.89, which are classified as weakly acidic to neutral. The weak acidity of the TSF surface water is due to the oxidation of metal sulphide-rich mineral processing effluents (Yuan *et al.*, 2022). Acid Mine Drainage is primarily generated by the oxidation of sulphide minerals in the presence of air, water and microbial activity and is common in active or abandoned polymetallic mines (Yuan *et al.*, 2022). The iron-rich water, high dissolved metal ion content and low pH evidence the sulphide

mineral oxidation processes in this environment, especially at the TSF underdrain stream, which discharges excess TSF overflow into the Malundwe pit.

Groundwater boreholes GW34 and GW37, which are located downstream of the TSF and upstream of the Malundwe pit, are equally characterised by a similar pH range, indicating slightly weak acidic water from the surface water and groundwater active interaction with TSF effluents. Conversely, borehole (GW83) at the upstream side of the TSF have neutral pH ranges. Groundwater samples from boreholes GW48 and GW49 (see Figure 4.16) that are located in the vicinity of ore rock dumps have relatively lower pH values attributed to sulphide ore oxidation. On the contrary, boreholes GW80, GW81 and GW57, which are all located between TSF and the community sewage treatment plant, have relatively higher pH (weakly acidic to neutral) and elevated electrical conductance and associated total dissolved solids. Owing to the different pH values from the nearest potential source of contamination, the most probable source of dissolved solids in these boreholes is sewage recharge from the nearby community sewerage treatment plant. Generally, surface water in streams, WSF, dams and groundwater have a neutral to basic pH range.

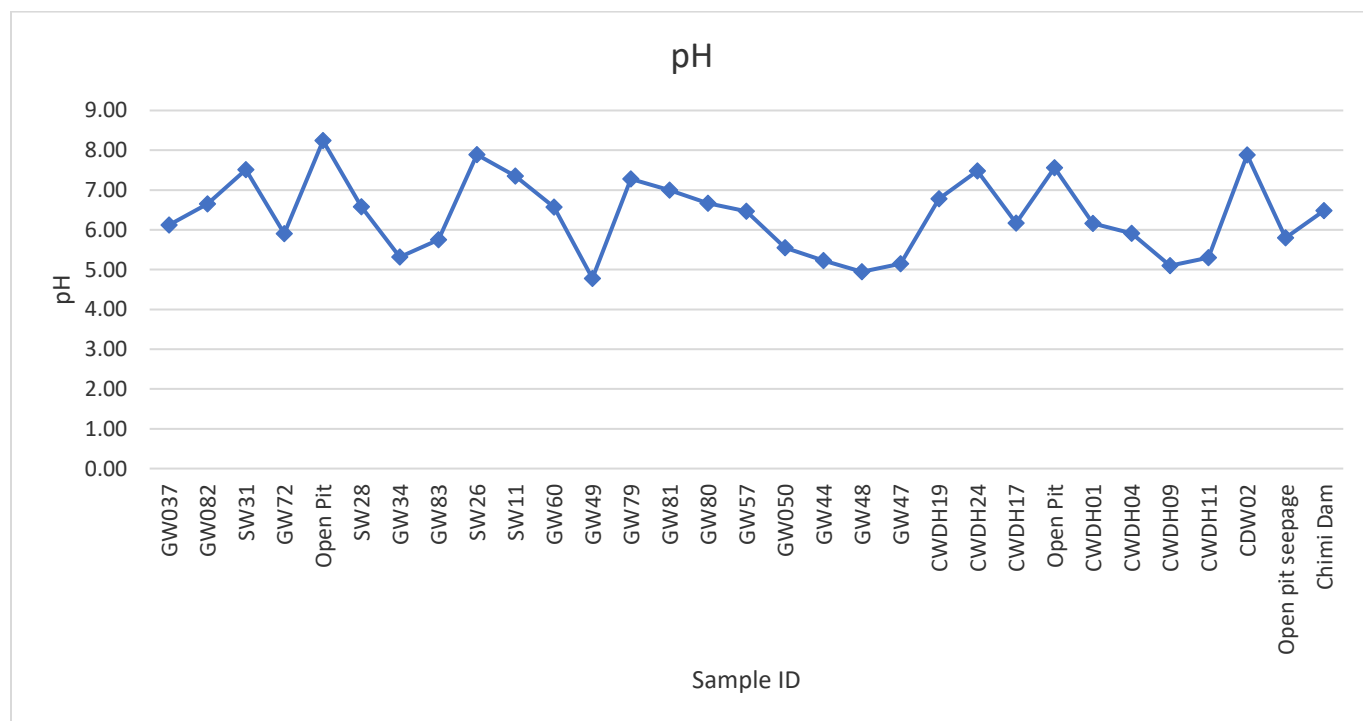


Figure 4.15 pH values of water samples from the Lumwana Mine.

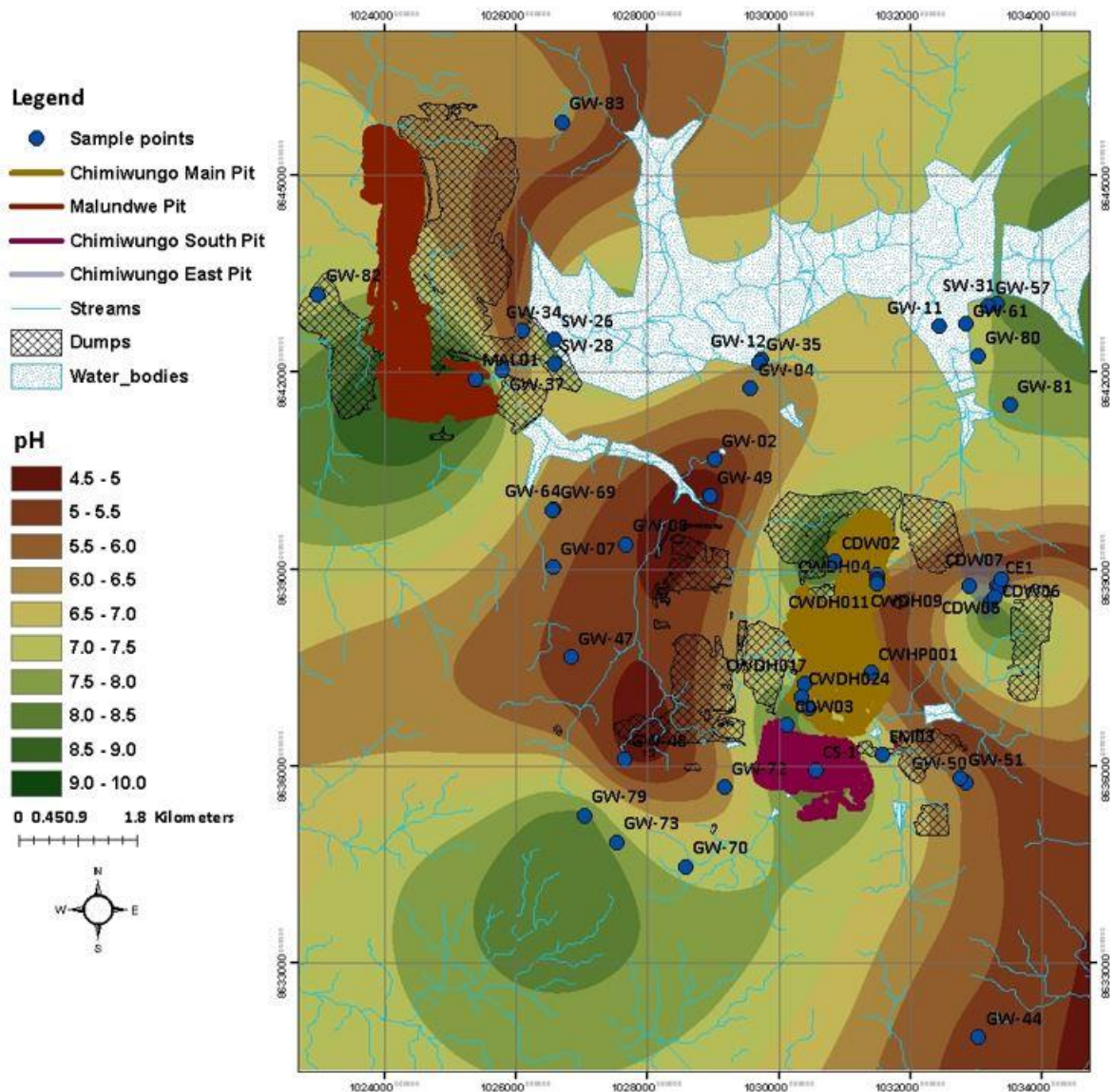


Figure 4.16 Spatial distribution of water pH in the Lumwana Mine area.

4.8.3 Dissolved Oxygen (DO)

Dissolved oxygen is an important component of natural water bodies because the presence of dissolved oxygen is critical to maintaining the aquatic life and aesthetic quality of streams and lakes (www.usgs.gov/special-topics/water-science-school/science/biological-oxygen-demand-bod-and-water#overview).

Oxygen demand is the measure of oxidisable substances in a water sample that can lower DO concentrations. Different regions of the study area have different concentrations of dissolved

oxygen in the water bodies as depicted in Figure 4.17. Dissolved oxygen is low in samples SW26, SW28, GW37 and GW 82, ranging between 0.2 and 0.25 mg/l, and these samples were collected downstream of the process plant area and within the flow path of process plant discharge. This is mainly due to mineral processing effluents. Dissolved Oxygen concentration in the tailings storage facility is generally low due to dissolved oxygen consumption during sulphide oxidation processes (Pabst *et al.*, 2014). Dissolved oxygen (DO) in Lumwana Mine can, therefore, be used as an index degree for industrial pollution. The upstream area of the tailings storage facility and the water storage facility have relatively higher dissolved oxygen concentrations because the water has not been disturbed by industrial activities. The area around the active mining area at the Chimiwungo Pits has moderate dissolved oxygen ranging between 0.3 mg/l and 0.4 mg/l. Mining activities have not impacted groundwater and surface water in the area, and the water quality has been nearly maintained in its pristine condition.

Legend

- Sample points
- Chimwungo Main Pit
- Malundwe Pit
- Chimwungo South Pit
- Chimwungo East Pit
- Streams
- Dumps
- Water_bodies

DO (Mg/L)

- 0.2 - 0.25
- 0.25 - 0.3
- 0.3 - 0.35
- 0.35 - 0.4
- 0.4 - 0.45

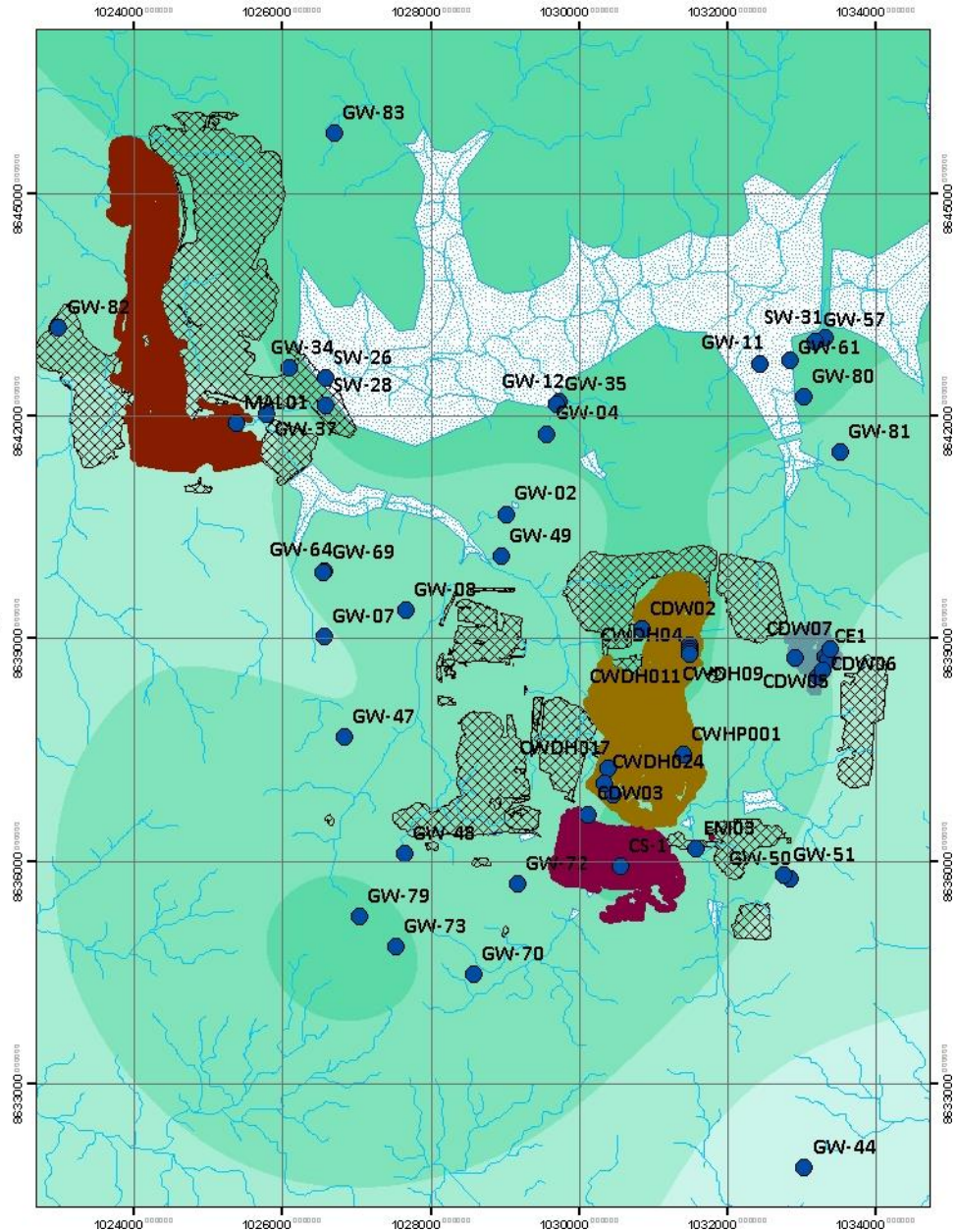
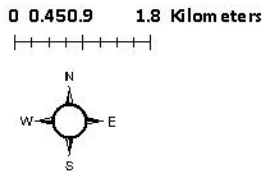


Figure 4.17 Dissolved oxygen spatial distribution map in the Lumwana Mine Area.

4.8.4 Total Dissolved Solids (TDS)

Total dissolved solids refer to the total inorganic compounds dissolved in water, including cations, anions, salts and heavy metals (WHO, 2011). Inorganic salts that constitute TDS include magnesium, calcium, sodium, potassium, bicarbonates, chlorides, sulphates and small amounts of organic matter that are dissolved in water (WHO, 2011). At Lumwana Mine, total dissolved solids are linked to different sources of dissolved ions, which are categorised as artificial and

natural sources. Surface water samples SW26, SW28 and MAL01 from the tailing storage facility area and the tailings overflow path, including samples from the Malundwe pit (MAL01) region, reported higher total dissolved solids than the average background concentration of 90 mg/l. The higher total dissolved solids in these surface water samples were linked to the elevated concentration of dissolved inorganic compounds including sodium, magnesium, carbonate, potassium, sulphate (Figure 4.18), calcium and bicarbonate from mineral processing effluents. In the same manner, groundwater samples from borehole GW37 in the vicinity and on the downstream side of the tailings storage area show relatively higher concentration of dissolved ions, which include sulphate, bicarbonate, magnesium and sodium. These ions reported in the groundwater within the TSF area are an indication of potential for active surface and groundwater interaction within the TSF area.

Groundwater samples from boreholes GW79, GW82 and CDW02 within the vicinity of the ore rock dump reported high TDS values than the average background mainly due to dissolved ions including sodium, carbonate, bicarbonate (Figure 4.19), magnesium and calcium. The elevated TDS was linked to the dissolution of the ore rock and subsequent infiltration of water with higher concentration of inorganic compounds or subsurface rock-water interaction. Water samples from both the Chimiwungo and Malundwe open pit have higher TDS (>414 mg/l) (Figure 4.20), mainly due to sulphate leaching from the sulphide copper ore. The open pit samples are also characterised by elevated concentration of metals such as copper and cobalt. Groundwater samples from boreholes GW80, GW81 and GW57 on the upstream side of the TSF and in the vicinity of the community sewage treatment plant reported higher TDS values (>422 mg/l) (Figure 4.19). The higher TDS values are linked to elevated concentration of bicarbonate, carbonate and calcium. The higher TDS is potentially from the community sewage treatment plant. Other sources of elevated dissolved solids are the dissolution of carbonate-bearing minerals within the study area due to the interaction with acidic water. The nature of the rock, in this case, has an impact on total dissolved solids concentration. The quartz and feldspathic granite on the southern part of the concession are resistant to weathering and, therefore, low TDS as reported in GW44 and GW70. According to World Health Organisation (WHO, 2011), there is no reliable

data and no health guidelines on the health effects associated with the ingestion of TDS in drinking water.

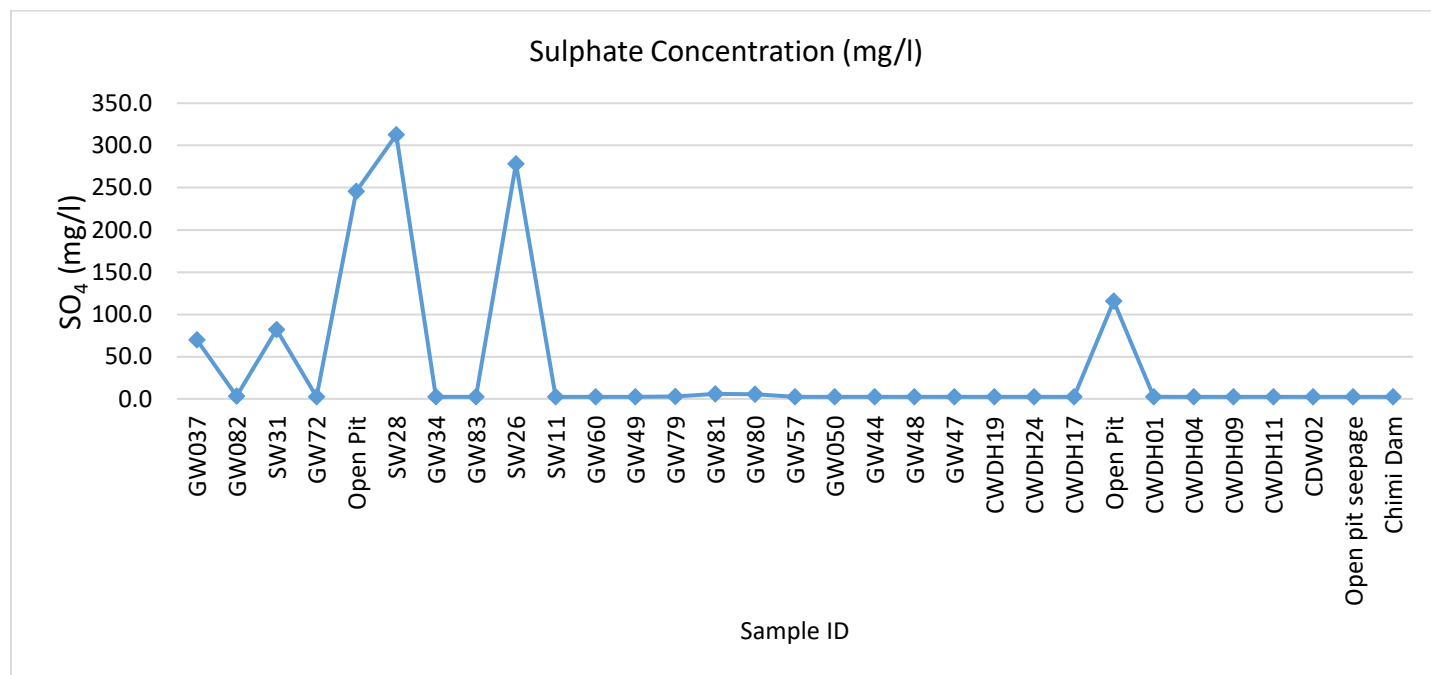


Figure 4.18 Groundwater and surface water sulphate concentrations (mg/l) in water from the Lumwana Mine area.

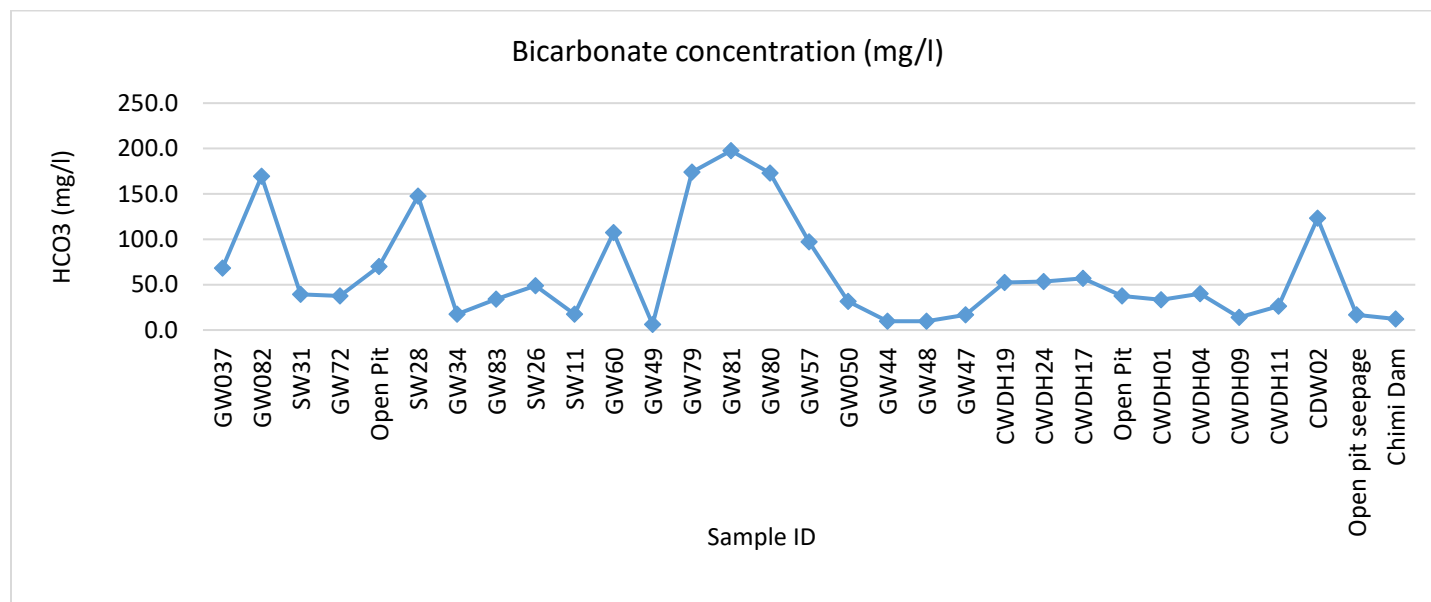


Figure 4.19 Groundwater and surface water samples bicarbonate concentration in mg/l.

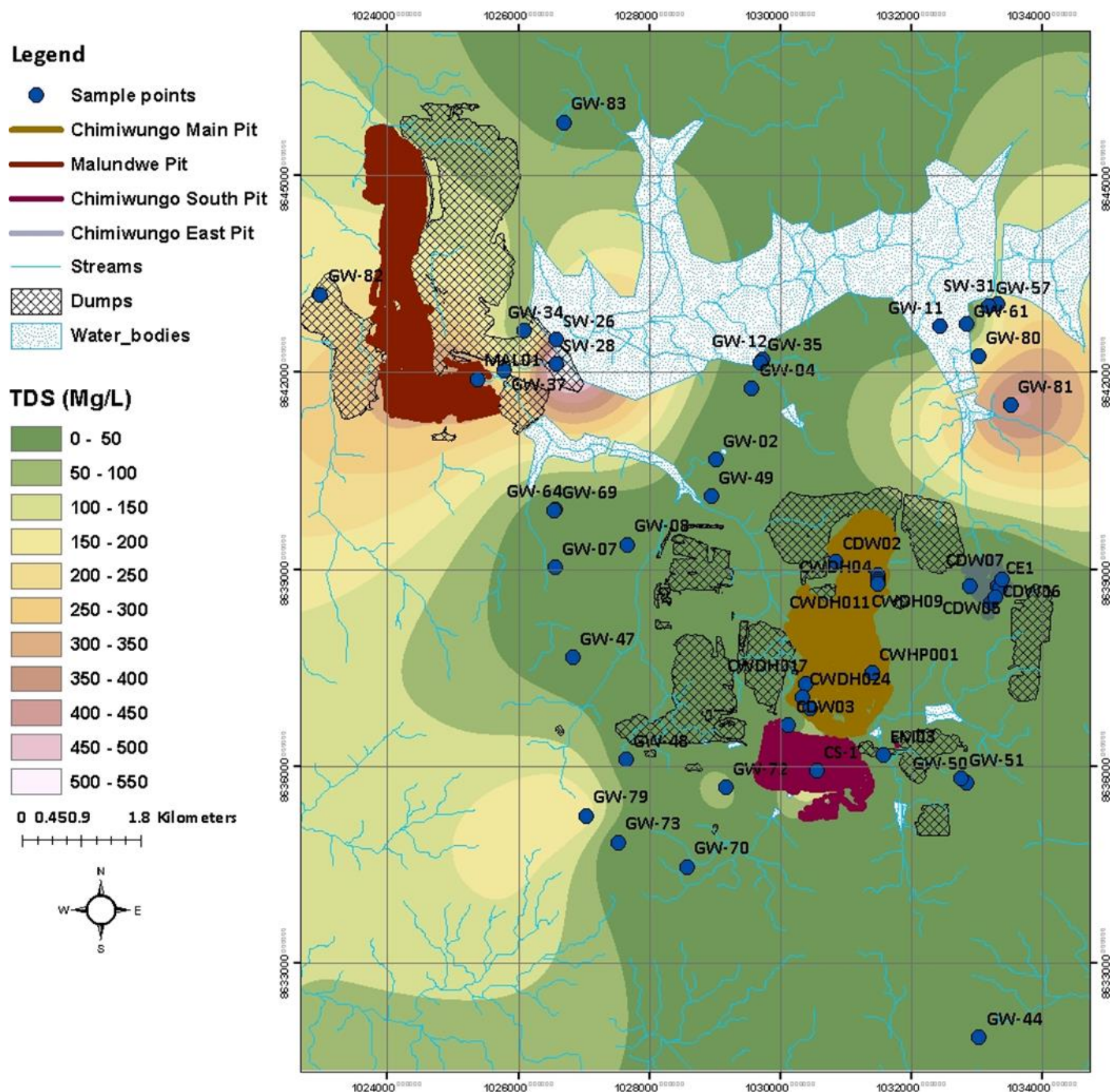


Figure 4.20 Spatial distribution map of total dissolved solids in surface water and groundwater from the Lumwana Mine.

4.8.5 Electrical Conductivity (EC)

Electrical conductivity is a water quality parameter that is used to describe salinity level (Rusydi, 2018). It is defined as the measure of liquid capacity to conduct an electrical charge. According to Velmurugan *et al.* (2020), water samples can be classified into three categories based on EC.

Water samples with EC between 0 to 700 $\mu\text{S}/\text{cm}$ are classified as freshwater; water samples with EC ranging from 700 to 45000 $\mu\text{S}/\text{cm}$ are classified as slightly to very highly saline, while water samples with EC greater than 45000 $\mu\text{S}/\text{cm}$ are classified as brine. Relatively high electrical conductance has been observed in surface water samples SW26 and SW28 from the TSF decant and the underdrain discharge due to higher concentration of ions such as sulphate (Figure 4.18), sodium, carbonate, calcium and magnesium from mineral processing activities. Water sample from Malundwe pit, MAL01, has also reported high EC values due to interaction with excess overflow from the tailings storage dam into the pit. The tailings within the study area are characterised by high sulphide concentration and metal content such as uranium, copper and cobalt. Groundwater sample from borehole GW 37, located adjacent to Malundwe pit, has also reported relatively high EC values with similar chemical signature as the tailings overflow. This is probably due to seepage of the excess TSF overflow. Groundwater samples from boreholes GW79, GW82 and CDW02 (Figure 4.21), on the toe of waste rock dumps reported higher EC values linked to elevated concentration of, mainly bicarbonate, sodium, and calcium due to mineral dissolution associated with rock-water interaction. The surface runoff potentially seep through the waste rock and recharge the groundwater.

Relatively high EC values (210-496 $\mu\text{S}/\text{cm}$) have also been reported in boreholes GW81, GW80 and GW57 on the upstream side of the TSF but close to the community sewage treatment plant. These groundwater samples have higher concentration of bicarbonate, calcium, carbonate, and sodium. These borehole water samples are also associated with higher nitrate concentration. The most probable source of elevated dissolved ions reported in these groundwater samples is the community sewage treatment plant and not the TSF. It is likely the community sewage treatment plant overflow interacts with groundwater within the area hence similar water chemistry. Chimiwungo South pit water sample has equally relatively high EC compared to the general site reported values due to copper sulphide orebody leaching, thereby contributing to elevated dissolved ions in the pit lake. The water samples are also associated with relatively low pH values of 5.8. Based on Velmurugan *et al.* (2020) EC classification scheme, generally, water samples in the study area belong to the freshwater while water around the TSF area and community sewage treatment plant belong to slightly saline category as can be seen in Figure 4.21.

Legend

- Sample points
- Chimiwungo Main Pit
- Malundwe Pit
- Chimiwungo South Pit
- Chimiwungo East Pit
- Streams
- ▨ Dumps
- ▨ Water_bodies

EC ($\mu\text{S}/\text{cm}$)

- 0 - 100
- 100 - 200
- 200 - 300
- 300 - 400
- 400 - 500
- 500 - 600
- 600 - 700
- 700 - 800
- 800 - 900
- 900 - 999

0 0.450.9 1.8 Kilometers

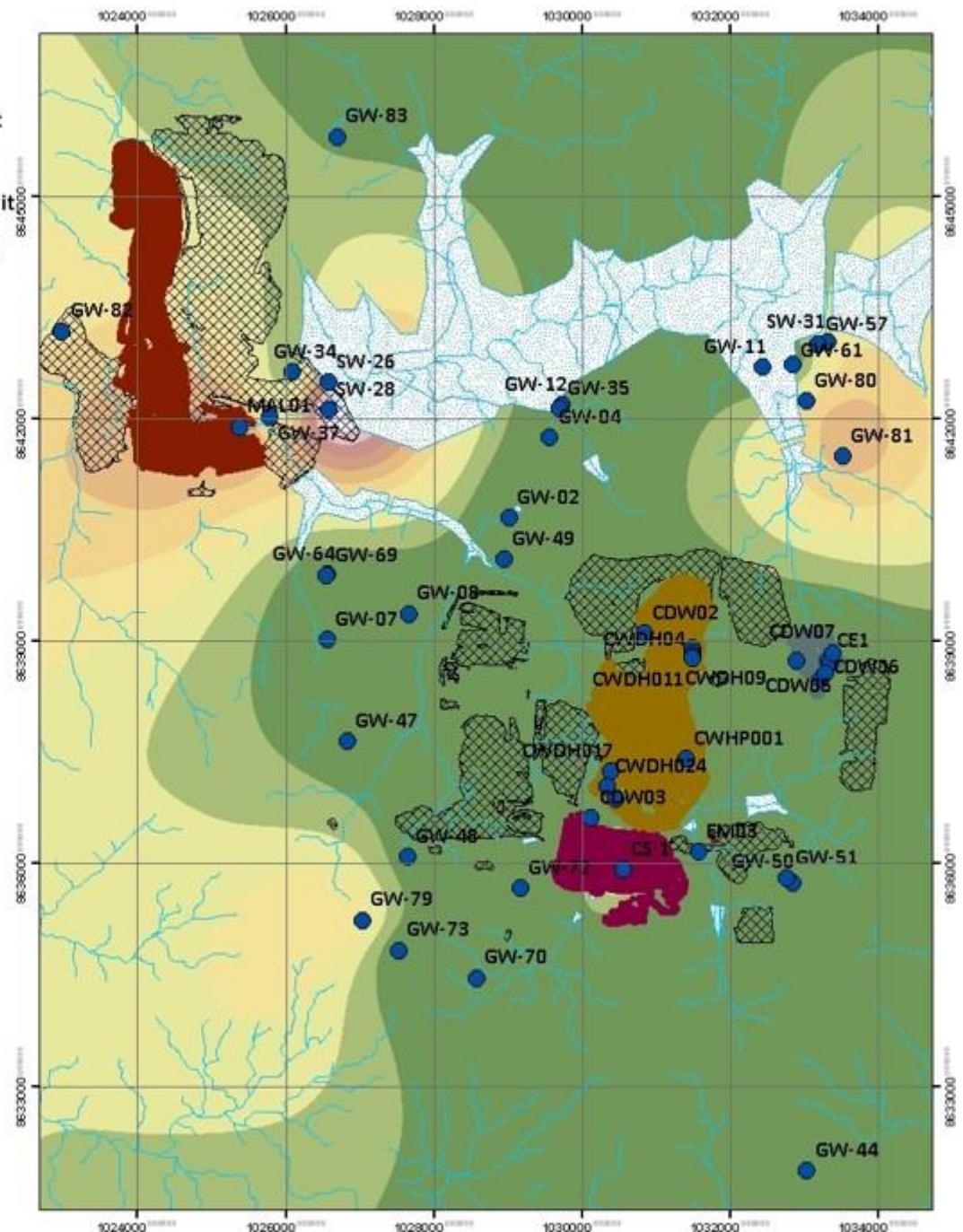


Figure 4.21 Spatial distribution of electrical conductance in surface water and groundwater at Lumwana Mine area.

4.8.6 Hydrochemical analyses

Various hydrochemical facies have been identified for a range of groundwater and surface water samples from the streams, dams, pits, boreholes, TSF and WSF from the Lumwana Mine catchment. The trilinear Piper diagram (Piper, 1944) in Figure 4.22 was used for the

hydrochemical classification of surface water and groundwater samples and to decipher the various interaction of water from different sources, surface and underground. Different hydrochemical facies have been identified in the study area, including Ca-Mg-SO₄ type, Ca-Mg-HCO₃, SO₄ type, bicarbonate and the mixed type. Surface water samples SW26 and SW28 from the tailings storage facility area are dominated by sulphate, calcium, potassium and magnesium ions and, therefore, belong to the Ca-Mg-SO₄ hydrochemical facies. Their hydrochemical signatures is controlled mainly by the geochemistry of the tailings from sulphide ore mineral processing activities. Surface water samples from the Malundwe open pit located downstream of the tailings storage facility reported similar concentration of major ions. Excess overflow from the tailings storage facility is channelled into the Malundwe Open pit, hence similar major ions concentrations.

Groundwater sample from borehole GW37 located on the southern side of Malundwe pit reported high concentration of sulphate and magnesium. Hydrochemical classification of water using the Piper (1944) diagram shows that GW37 water sample plot within the mixing region on the Piper diagram between Ca-Mg-SO₄ and Ca-Mg-HCO₃ hydrochemical facies implying possible interaction between surface water from the tailings storage facility and fresh groundwater around the boreholes within the vicinity of the TSF. Chimiwungo South pit water sample reported high concentration of major ions of sulphate, calcium, bicarbonate and magnesium and therefore, belongs to Ca-Mg-SO₄ hydrochemical facies. The hydrochemical signature of Chimiwungo South Pit water is impacted by leaching of the copper sulphide orebody, which is exposed within the pit faces. Relatively higher concentration of metals such as cobalt and copper have been reported in Chimiwungo South open pit water samples. Groundwater samples from boreholes GW57, GW80 and GW81, which are situated upstream of the TSF and downstream side of the community sewage treatment plant, are characterised by high concentration of bicarbonate, carbonate, calcium and magnesium ions and therefore, belong to the Ca-Mg-HCO₃ hydrochemical facies. The source of elevated calcium and bicarbonate ions could be anthropogenic due to the sewage treatment plant leachate, which is located within proximity of the boreholes.

Groundwater samples from boreholes GW79, GW82 and CDW02 located within the vicinity of waste rock dumps and intersecting the hanging wall units, have elevated dissolved ions such as HCO_3 , Mg, Ca, Na, CO_3 . The groundwater from these boreholes belong to the Ca-Mg- HCO_3 facies mainly due to accelerated rock-water interaction (Gibbs, 1970) of the percolating water with the waste rock dumps as well as in-situ rocks (Mazor, 1991) due to physical weathering and exposure of the waste rock dumps to the atmospheric condition. The majority of surface water in the streams and groundwater from the boreholes (CDW07, CWDH17, GW07, GW08, GW44, GW50, GW51, GW49 and GW70) belong to the Ca-Mg- HCO_3 type. Heavy vegetation cover within the study area is the potential source of bicarbonate (Mohuba, 2020). In Addition, the source of bicarbonate ions in the study area is also potentially from weak carbonic acid dissociation and geological sources from the dissolution of calcite limestones on the rims of the Chimiwungo orebody. The similarity in hydrochemical facies provides evidence for active interaction between surface water in the streams and groundwater, hence displaying similar hydrochemical signature.

EXPLANATION

- GW37
- GW82
- SW31
- GW72
- ▲ Malundwe pit
- SW28_TSF under drain
- △ SW34
- ▼ GW83
- ▲ SW26_Tailings decant
- SW11_WSF
- GW60
- GW49
- GW79
- ▼ GW81
- ▲ GW80
- GW57
- ☆ GW50
- GW44
- GW48
- GW47
- △ CWDH19
- CWDH24
- ✚ CWDH17
- ☆ Chimiwungo South pit lake
- ★ CWDH01
- ▽ CWDH04
- ▼ CWDH09
- △ CWDH11
- CDW02
- ▼ CE1
- ▼ EM3

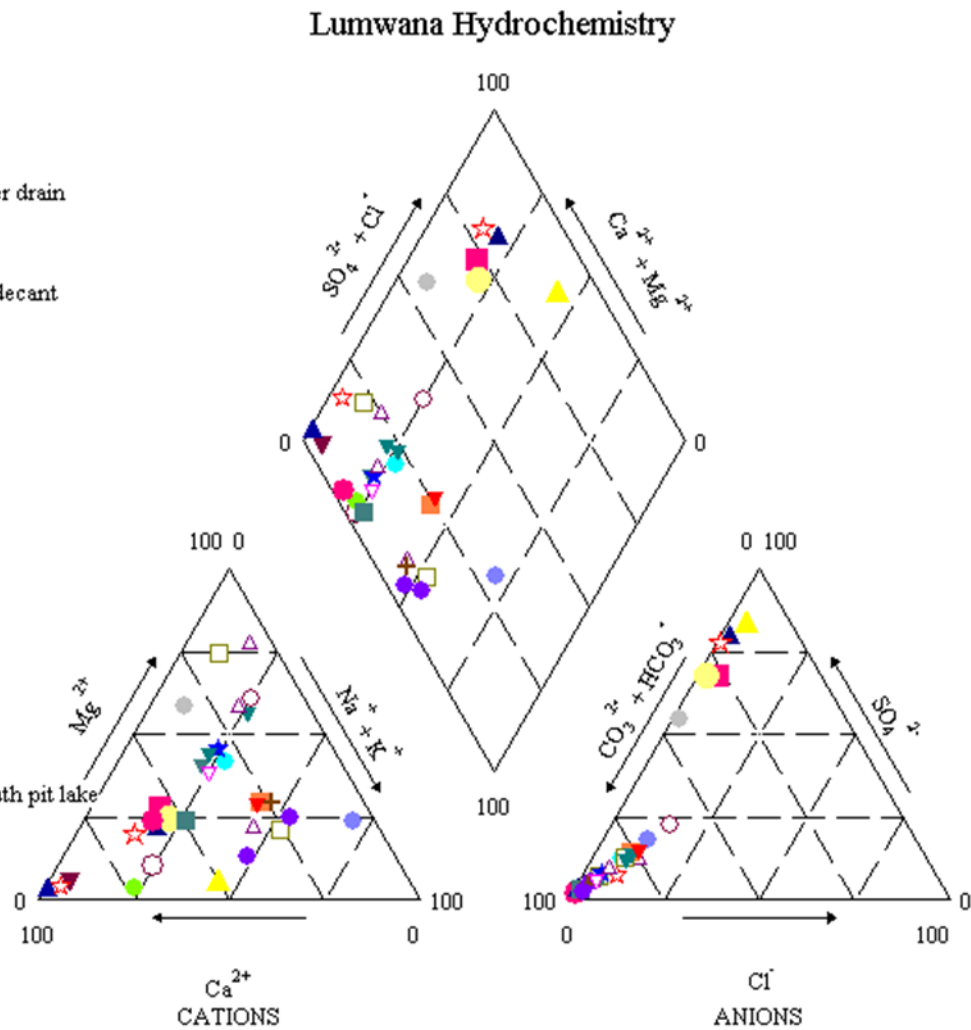


Figure 4.22 Piper diagram classifications of groundwater and surface water sampled from the Lumwana Mine.

Variation diagrams have been generated to interpret correlations between ions and understand the source of hydrochemical variations in surface water and groundwater. The ratio between sodium and chloride is useful for establishing the source of ions in the surface water and groundwater (Rajmohan and Elango, 2004). A ratio of 1 for Na/Cl in milliequivalent per litre indicates halite dissolution as the source of ions. A strong positive correlation ($R^2=0.6956$) in Figure 4.23 between sodium and chloride has been established in these samples, which infers a common source of ions. Considering the nature of the environment and the distribution of sodium and chloride ions in samples, the probable source of ions could be geological as well as

rainfall deposition and subsequent infiltration of chloride-rich water. Several samples have Na/Cl ratio less than 1 as shown in Figure 4.23. This is indicative of elevated chloride concentration in soil, which is probably dissolved in water possibly following sodium uptake by plants during transpiration, which is characteristic of the study area. The preferential uptake of sodium by plants during transpiration leaves chloride ions in the soil, which results in an increase in chloride concentration in the soil and water (Alcala and Custodio, 2008). However, from the Piper plot, the absence of Na-Cl type implies the Na-Cl type is of less relevance.

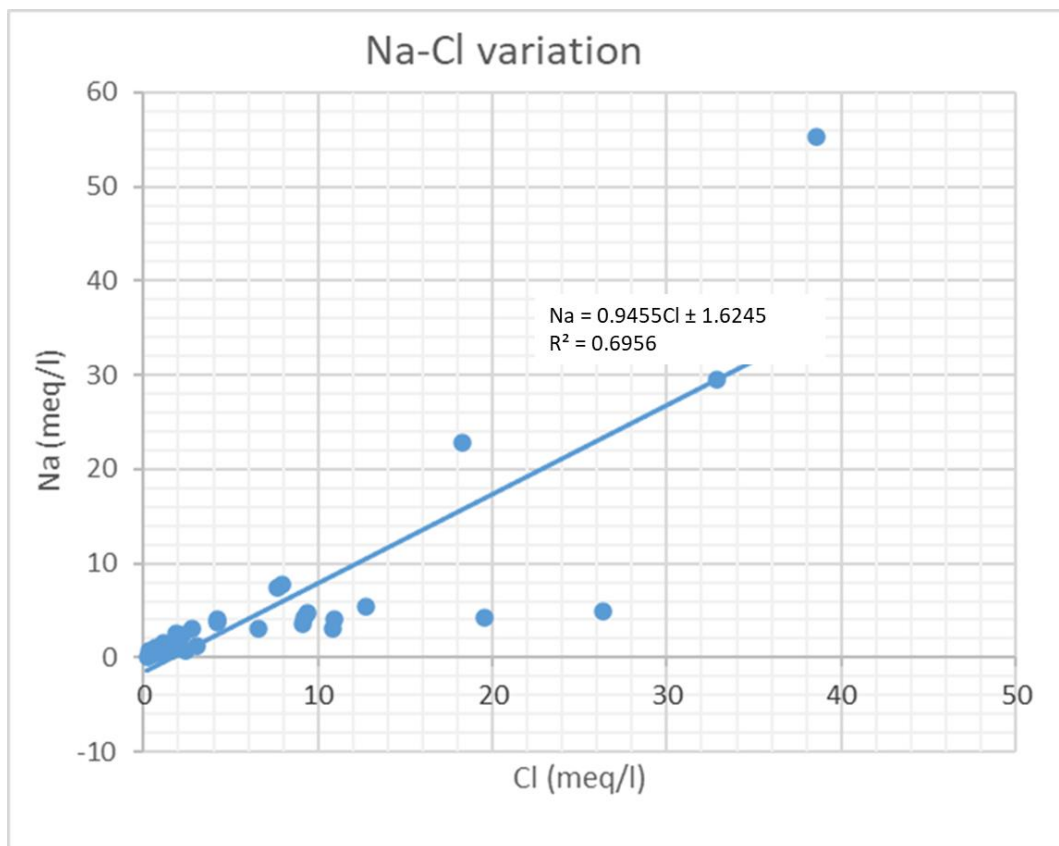


Figure 4.23 Sodium - Chlorine variation diagram for water samples at Lumwana Mine.

Weak correlation ($R^2=0.0132$) has also been established between bicarbonate and chloride in most of the water samples analysed. The weak correlation in Figure 4.24 indicates that the bicarbonate and chloride ions do not have a common source.

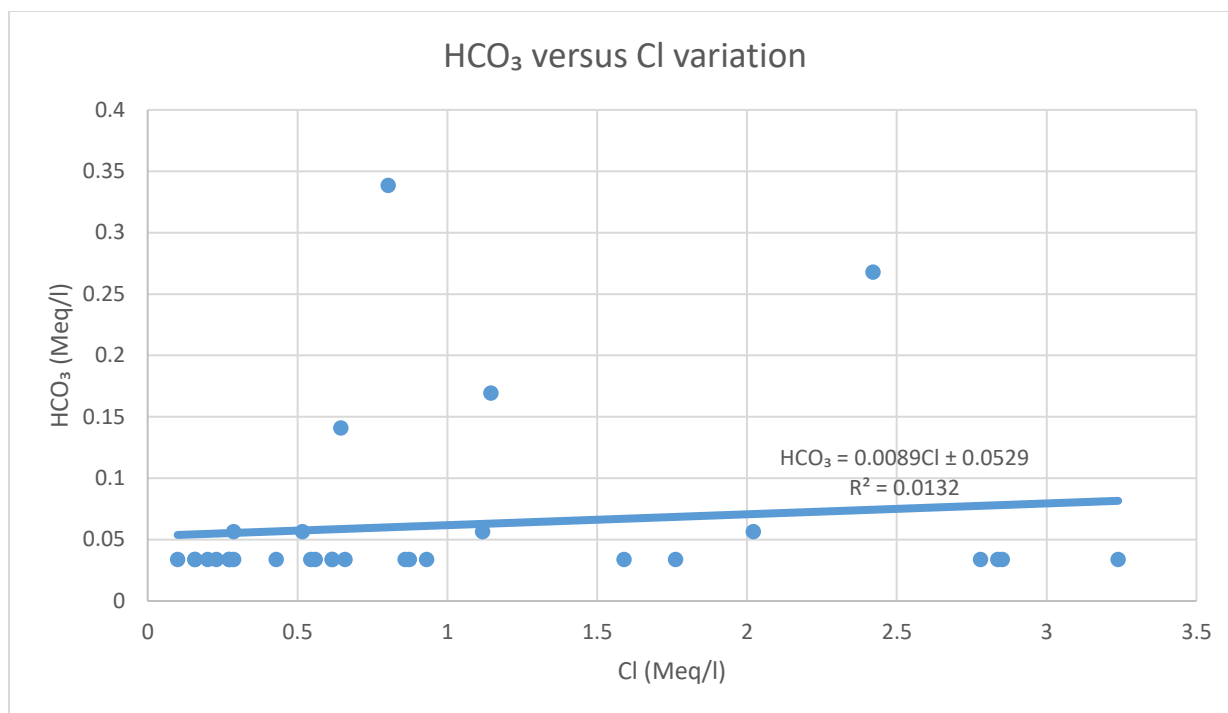


Figure 4.24 Bicarbonate - Chloride variation diagram of water samples from the Lumwana Mine area.

The Gibbs diagram in Figure 4.25 and Figure 4.26 was used to establish the relationship between groundwater and surface water composition and the aquifer lithological properties (Gibbs, 1970). The Gibbs diagram consists of three zones: rock-water interaction, evaporation dominance and precipitation dominance. Majority of water samples plot within the rock-water dominance zone, and a few samples plotting within the precipitation dominance region of the Gibbs diagram in Figure 4.25. This indicates that dissolution of minerals from rocks by groundwater and surface water through rock-water interaction is the dominant process relative to other processes such as precipitation and evaporation dominance (Gibbs, 1970). The rock-water process dominance is due to the interaction between the chemistry of aquifer lithological material and the chemistry of water, giving rise to the chemical signature observed in water samples (Gibbs, 1970). The huge waste rock and ore rock dumps also potentially interact with surface runoff and seep into the ground hence the similar chemical signature.

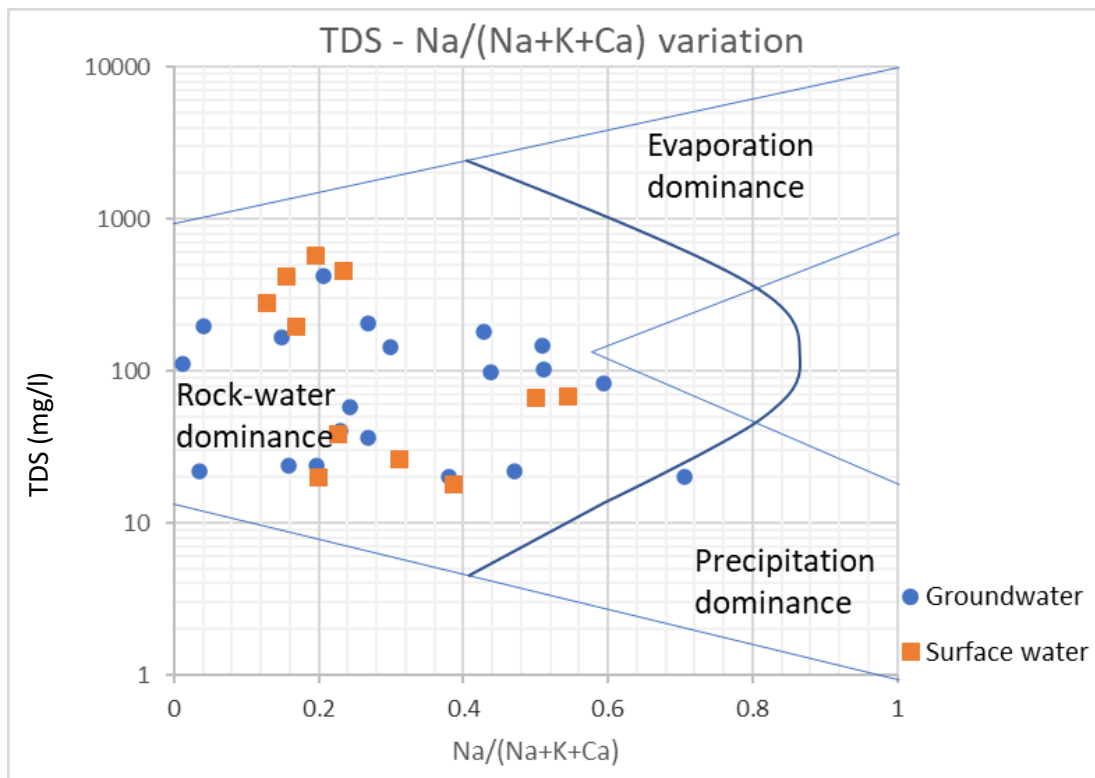


Figure 4.25 TDS - $Na/(Na+ K+ Ca)$ Gibbs diagram of surface water and groundwater from the Lumwana Mine area.

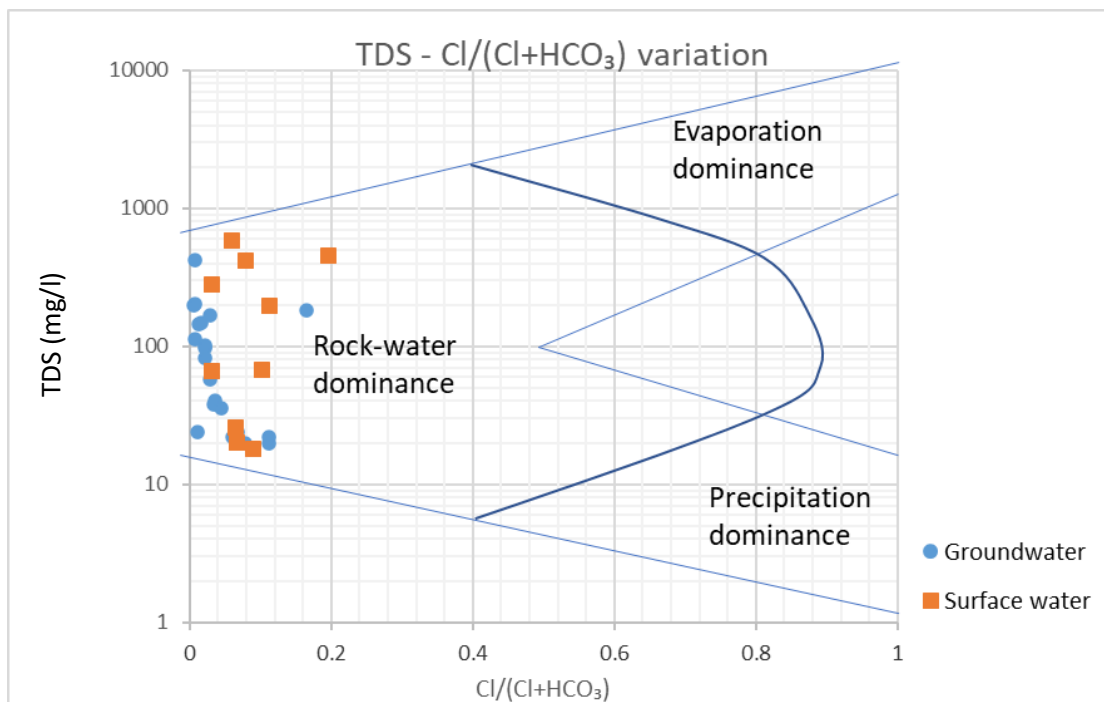
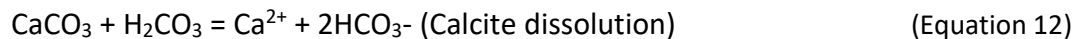
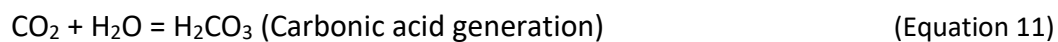
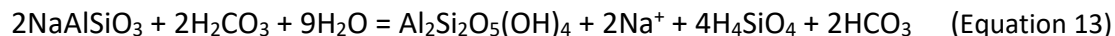


Figure 4.26 TDS - $Cl/(Cl + HCO_3)$ Gibbs diagram of surface water and groundwater from the Lumwana Mine area.

Hydrogeochemical results have shown that calcium and magnesium are the most abundant ions found in all water samples at Lumwana Mine. They are potentially generated from limestone and other mafic minerals (amphibolite) dissolution during rock-water interaction. Datta and Tyagi (1998) stated that Ca + Mg and HCO₃ + SO₄ scatter plots in Figure 4.27, ionic concentrations plotting above aquiline are generated from carbonate weathering while those plotting below the aquiline result from both carbonate and silicate weathering. Figure 4.27 has shown that the majority of water samples plot above the aquiline, implying that the main source of calcium in most groundwater samples is carbonate weathering. In this process, carbonic acid from carbon dioxide dissolution (equation 11) in groundwater and soil reacts with limestone within the study area in the soil during recharge to form bicarbonate (equation 12) and liberate calcium ions (Lakeshmana, 2016).



A few samples plotting below the equiline indicate that silicate weathering (equation 13) is the minor physical process in this environment responsible for generation of both calcium and magnesium ions. Gypsum dissolution (equation 14) is another potential source of calcium ions.



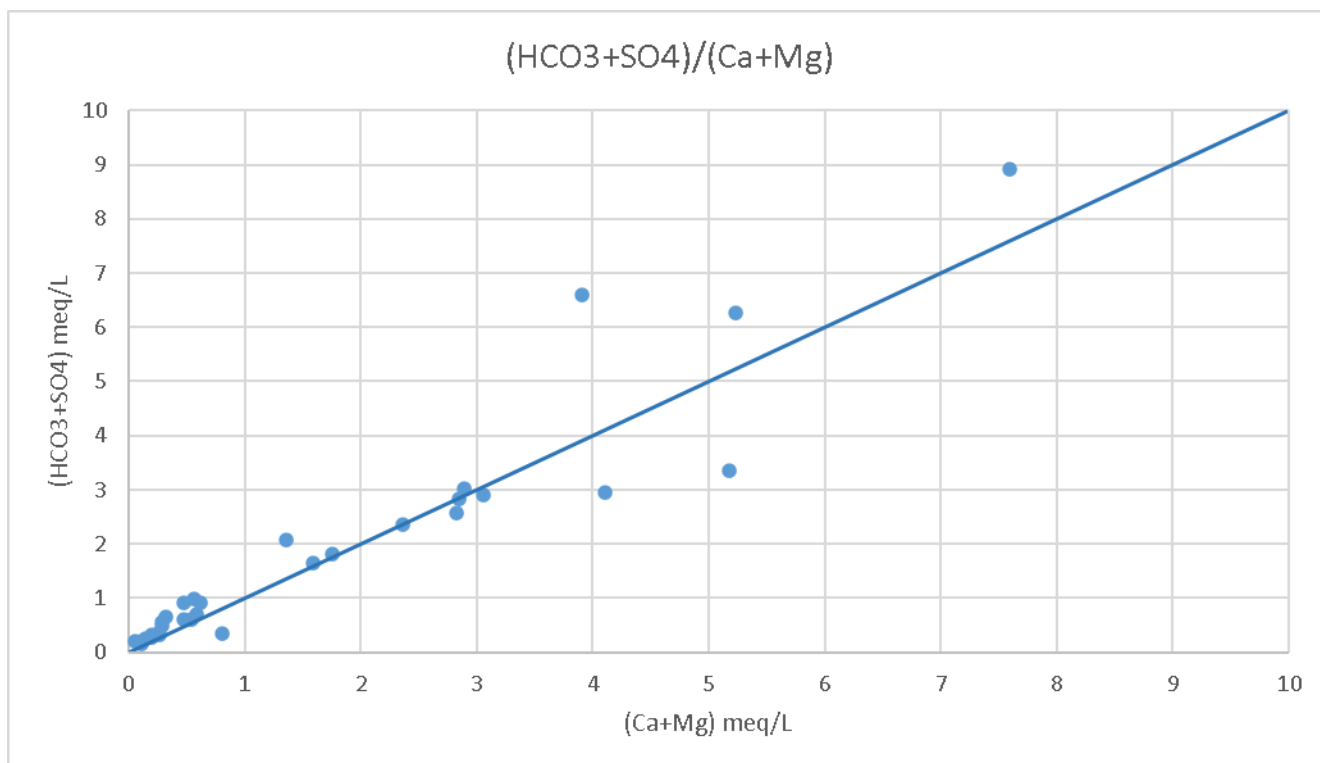


Figure 4.27 (Ca + Mg) versus (HCO₃ + SO₄) scatter diagram illustrating carbonate dissolution and silicate weathering.

Carbonate weathering through dissolution by carbonic acid is an intense process, which can dissolve carbonate minerals along the flow path and increase soluble ion content in water, including chloride, sodium, potassium, magnesium and bicarbonate ions in groundwater (Lakeshmana, 2016). To further refine geochemical interpretation of the processes, the hydrochemical evolution of groundwater and surface water at Lumwana Mine was further investigated by plotting the percentages of the milliequivalent concentrations of major and minor ions on the Durov diagram (Durov, 1948). The Durov diagram in Figure 4.28 was used to decipher the hydrochemical processes controlling groundwater systems at Lumwana Mine. As can be seen in Figure 4.28, most groundwater samples from boreholes that belong to the carbonate facies have undergone reverse ion exchange mechanism, potentially within the clay-rich saprolite zones. Figure 4.28 also shows that some groundwater borehole samples have undergone simple dissolution or mixing process, potentially due to rock-water interaction.

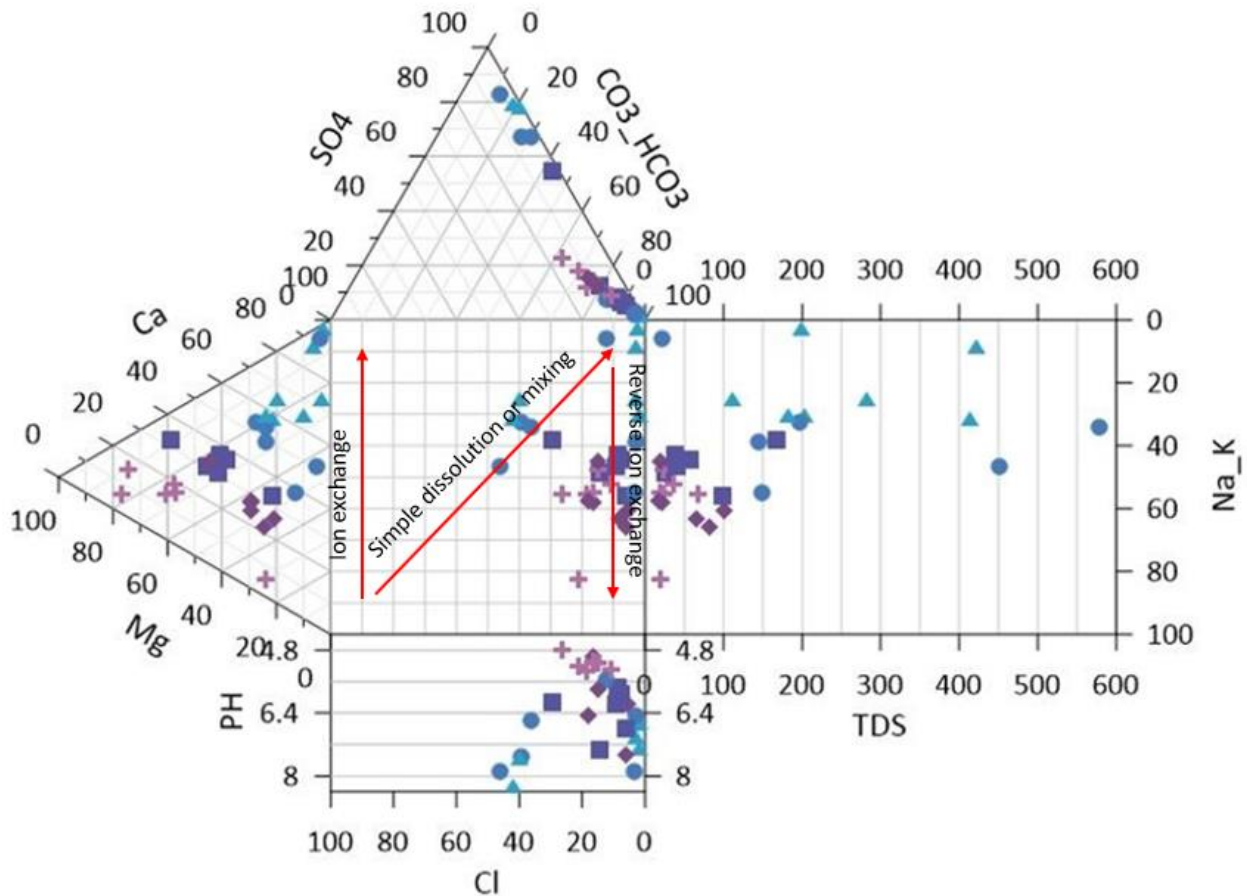


Figure 4.28 Extended Durov diagram for Lumwana groundwater and surface water samples (Adapted from Durov, 1948).

4.9 Environmental isotopes

4.9.1 Stable environmental isotopes

Stable isotopes of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ were analysed to decipher the origin and possibility of interaction between different water sources at Lumwana Mine. The different water sources have different $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotopic characters/signatures. Different water types expressed according to an acceptable global standard known as the Vienna Standard Mean Ocean Water (VSMOW) were plotted relative to the Global Meteoric Water Line (GMWL) in Figure 4.29 (Clark and Fritz, 1997). Altitude and physical processes such as fractionation result in local meteoric water plotting parallel or crossing the GMWL, also referred to as the Local Meteoric Water Line (LMWL) (Clark and Fritz, 1997).

The isotopic values for rainfall range from -20.24 to 1.63‰ for $\delta^{18}\text{O}$ and -131 to 17.62‰ for $\delta^2\text{H}$, respectively. The isotopic values for groundwater from boreholes varied between -9.24 and -7.27‰ for $\delta^{18}\text{O}$ and -48.03 and -37.68‰ for $\delta^2\text{H}$, respectively (Figure 4.29). The clustering of all the groundwater borehole samples around rainfall indicates that the meteoric water is the main source of groundwater recharge in the study area (Wassenaar *et al.*, 2011). Groundwater from boreholes around and within the active mining areas have strong, unique and highly depleted $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotope fingerprints, therefore, suggesting that moisture that resulted in recharged precipitation was sourced from high latitude regions or recharged during the colder season. Rainfall, borehole groundwater and water from the dams around the active pits have similar $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotopic compositions thus indicating interaction between surface water and groundwater. This also further suggests that the primary source of groundwater is rainfall, which is recharged into the surrounding aquifers and reports into the pit in the form of seepage. The active hydraulic connection between groundwater and surface water bodies, including streams, dams and diversion channels is also supported by physicochemical properties and hydrochemistry. During the peak of the dry season, stream flow is sustained by baseflow discharge from the aquifer.

Borehole CDW06 drilled adjacent to the stream, has shown a very strong environmental stable isotopic similarity with stream flow. This also provides further evidence of the influence of surface water bodies on groundwater and their hydraulic interconnectivity. Water bodies around Lumwana mine area including the tailings storage facility (TSF), water storage facility (WSF), dams and the pit lakes in Malundwe and Chimiwungo South pit, have nearly similar isotopic composition and plot within the evaporation region. These water bodies (in dark red circle in Figure 4.29) show slight shift from the global meteoric water line as a result of heavy $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotope enrichment due to evaporation processes (Wassenaar *et al.*, 2011). Heavily isotope-depleted precipitation (-20.24‰ for $\delta^{18}\text{O}$ and -131‰ for $\delta^2\text{H}$) was recorded on 15th January 2022 following heavy downpours (sample ENV049) at Lumwana Mine area. The moisture has been envisaged to originate from a distant source in the south polar regions towards lower latitudes due to cyclonic activities (Zambia Meteorological Department, 2022).

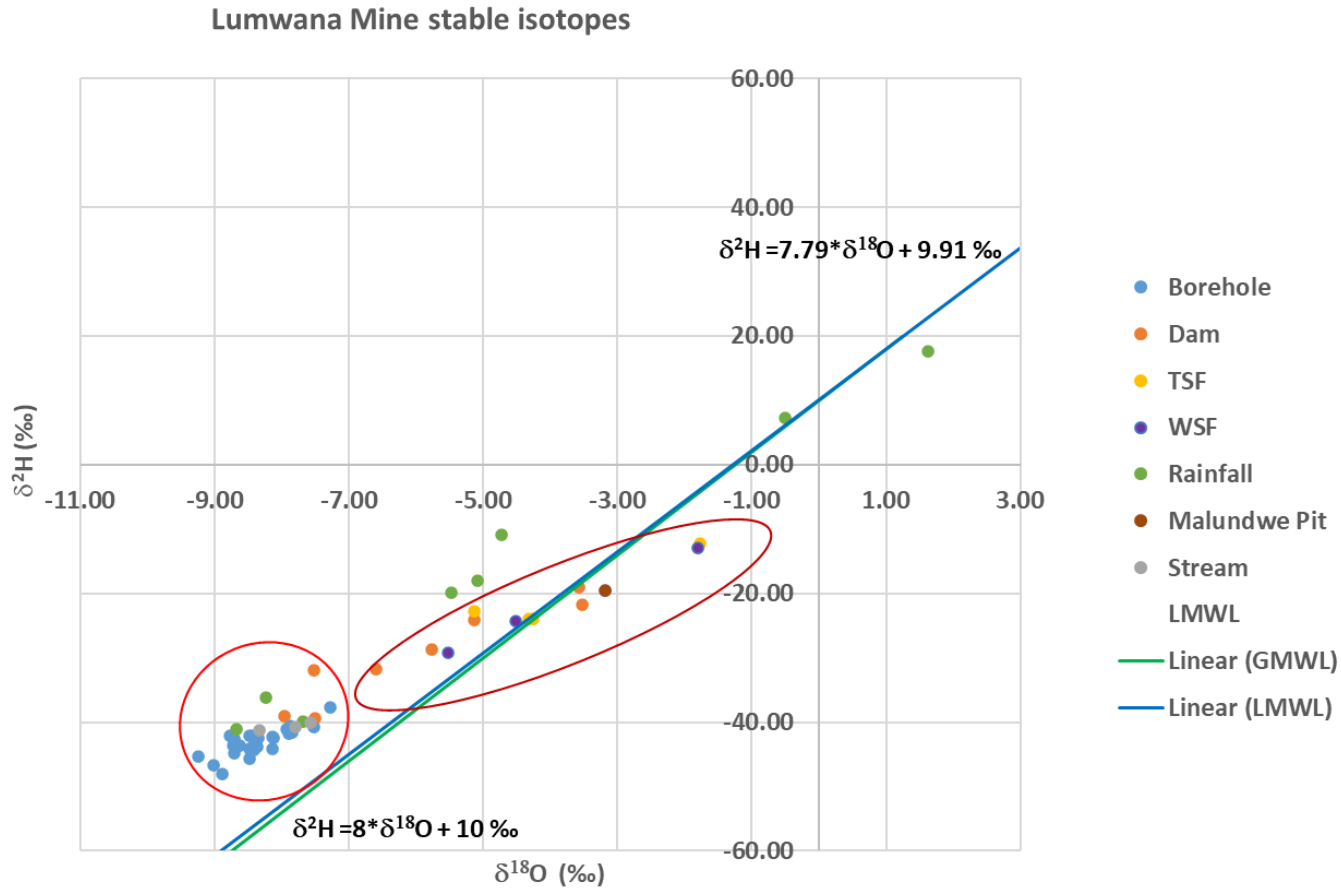


Figure 4.29 Stable isotopes for Lumwana water samples and the associated LMWL.

Deuterium excess (d- excess) for the study area was calculated using the local meteoric water line (Karen *et al.*, 2015) using equation 15.

$$d = \delta^2\text{H} - 7.79 \cdot \delta^{18}\text{O} \quad (\text{Equation 15})$$

where d is the d-excess (‰), $\delta^2\text{H}$ is the amount of deuterium enrichment, 7.79 is the gradient, and $\delta^{18}\text{O}$ is the oxygen-18 enrichment.

Deuterium excess depends on prevailing conditions during evaporation including wind speed, humidity, surface temperature and therefore, gives information on the sources of vapour (Clark and Fritz, 1997). It is understood that equilibrium processes do not affect the deuterium excess for any of the phases, non-equilibrium evaporation causes a decrease in the d-excess which indicates an increase in the vapour phase (Clark and Fritz, 1997). Deuterium excess was established with the objective of characterising the source of rainfall generation moisture.

Deuterium excess is the measure of the relative proportion of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ contained in water and can be visually depicted as an index of deviation from the global meteoric water line in $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ (Dansgaard, 1964).

D-excess for groundwater samples from boreholes, as depicted in Table 4.9, ranges between 18 and 28 ‰, with a mean of 23 ‰, indicating that the source of moisture is local. Streams and borehole samples in Figure 4.30 have a similar range and mean distribution of the d-excess values thus indicating a similar source of moisture that generated rainfall, which recharged the aquifers (Dansgaard, 1964). This provides an indication that streams and boreholes are hydraulically linked. Rainfall samples have d- excess ranging between 5 and 27 ‰. The broad range of d-excess indicates that the source of moisture causing precipitation is both local possibly from the Congo moist air and regional from high latitudes. Figure 4.31 provides a summary of the statistical distribution of the calculated sample d- excess. Rainfall samples have a wide range of d-excess compared to other water sources in the study area. One rainfall sample (ENV049) has heavily depleted $\delta^{18}\text{O}$ and $\delta^2\text{H}$ signatures with high d-excess values (Figure 4.30) due to regional moisture circulation from the cold polar regions into the tropical regions due to cyclonic activities (Zambia Meteorological Department, 2022). The box and whisker plot in Figure 4.31 and Table 4.9 provide details on the range and mean d- excess distribution for different water samples. Rainfall at Lumwana Mine has a broad range of d-excess values. All the water samples from Lumwana catchment area have mean d-excess value ranging between 10 and 25‰.

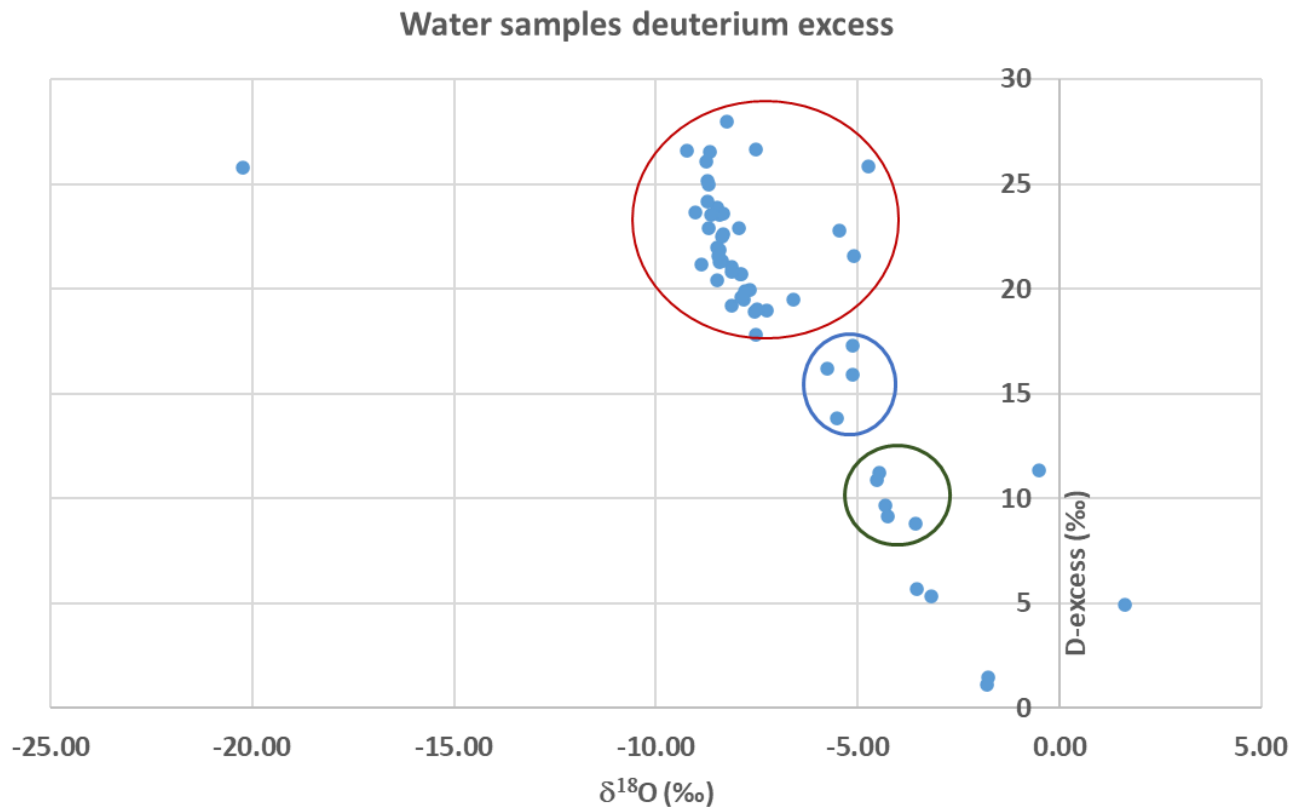


Figure 4.30 Deuterium excess estimates for water samples from the Lumwana Mine area.

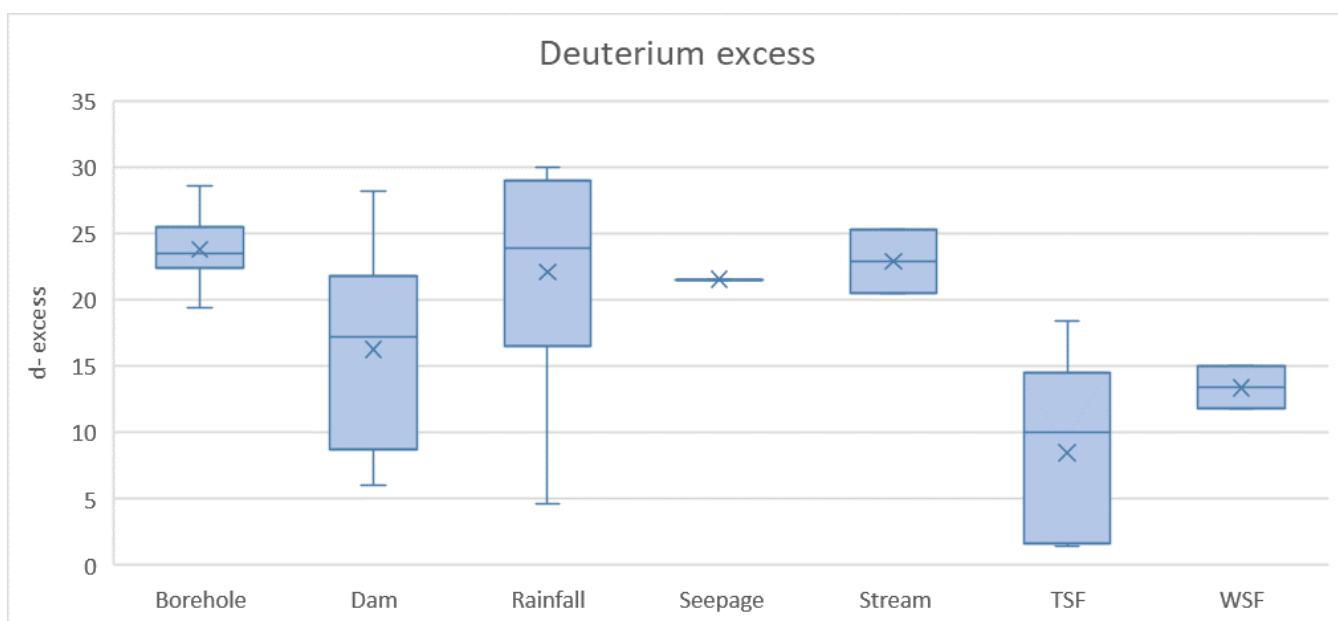


Figure 4.31 Statistical analysis of d-excess distribution for different water samples at Lumwana Mine.

Table 4.9 Stable isotopes of rainwater, surface water and groundwater and associated deuterium excess results from the Lumwana Mine area.

Date	Sample ID	Type	Location	$\delta^2\text{H}$ (‰)	$\delta^{18}\text{O}$ (‰)	d-excess
15 Jan 2022	ENV038	Borehole	CDW02	-46.62	-9.02	24
15 Jan 2022	ENV045	Borehole	CDW03	-45.32	-9.24	27
14 Jan 2022	ENV036	Borehole	CDW07	-43.70	-8.71	24
15 Jan 2022	ENV044	Borehole	CW017	-44.27	-8.42	21
15 Jan 2022	ENV039	Borehole	CWDH01	-42.87	-8.71	25
15 Jan 2022	ENV041	Borehole	CWDH010	-40.65	-7.88	21
15 Jan 2022	ENV043	Borehole	CWDH024	-42.31	-8.13	21
15 Jan 2022	ENV042	Borehole	CWDH04	-41.60	-7.84	19
15 Jan 2022	ENV040	Borehole	CWDH08	-42.19	-8.44	24
15 Jan 2022	ENV048	Borehole	GW034	-42.70	-8.71	25
13 Jan 2022	ENV027	Borehole	GW037	-42.12	-8.47	24
13 Jan 2022	ENV017	Borehole	GW047	-42.18	-8.76	26
13 Jan 2022	ENV018	Borehole	GW048	-43.70	-8.42	22
13 Jan 2022	ENV015	Borehole	GW049	-43.79	-8.36	21
13 Jan 2022	ENV035	Borehole	GW050	-44.87	-8.70	23
13 Jan 2022	ENV034	Borehole	GW052	-41.05	-7.92	21
13 Jan 2022	ENV020	Borehole	GW053	-48.03	-8.88	21
13 Jan 2022	ENV033	Borehole	GW057	-44.08	-8.48	22
15 Jan 2022	ENV046	Borehole	GW060	-43.69	-8.63	24

13 Jan 2022	ENV021	Borehole	GW064	-42.41	-8.12	21
13 Jan 2022	ENV019	Borehole	GW07	-41.84	-7.89	20
13 Jan 2022	ENV023	Borehole	GW072	-42.41	-8.35	23
13 Jan 2022	ENV030	Borehole	GW079	-45.60	-8.47	20
13 Jan 2022	ENV016	Borehole	GW08	-40.80	-7.52	18
13 Jan 2022	ENV032	Borehole	GW080	-44.29	-8.46	22
13 Jan 2022	ENV031	Borehole	GW081	-37.68	-7.27	19
13 Jan 2022	ENV024	Borehole	GW082	-44.11	-8.13	19
15 Jan 2022	ENV047	Borehole	GW083	-42.74	-8.37	22
13 Jan 2022	ENV026	Dam	Stage 10	-19.52	-3.19	5
16 Jan 2022	ENV054	Dam	Chimi Dam	-28.70	-5.76	16
16 Jan 2022	ENV052	Dam	EM1	-31.79	-6.58	20
16 Jan 2022	ENV053	Dam	EM2	-31.96	-7.52	27
16 Jan 2022	ENV051	Dam	EM3	-24.06	-5.13	16
16 Jan 2022	ENV050	Dam	EM4	-39.00	-7.95	23
22 Oct 2021	ENV007	Dam	Embankment 2	-19.08	-3.58	9
22 Oct 2021	ENV008	Dam	Embankment 3	-21.79	-3.52	6
22 Oct 2021	ENV009	Dam	Embankment 4	-39.44	-7.50	19
13 Jan 2022	ENV022	Dam	SW05	-23.58	-4.47	11
31 Oct 2021	ENV010	Rainfall	CRE	7.35	-0.51	11
1 Nov 2021	ENV011	Rainfall	IPS	-10.96	-4.72	26
17 Nov 2021	ENV012	Rainfall	IPS	17.62	1.63	5
21 Dec 2021	ENV013	Rainfall	IPS	-39.92	-7.68	20
9 Jan 2022	ENV014A	Rainfall	IPS	-18.01	-5.08	22
22 Dec 2021	ENV014B	Rainfall	IPS	-41.02	-8.67	27
7 Jan 2022	ENV014C	Rainfall	IPS	-36.14	-8.23	28
17 Jan 2022	ENV056	Rainfall	IPS	-19.83	-5.47	23
15 Jan 2022	ENV049	Rainfall	IPS	-131.88	-20.24	26
22 Oct 2021	ENV006	Seepage	CE1	-40.77	-7.79	20
22 Oct 2021	ENV005	Stream	CE1	-40.01	-7.57	19
16 Jan 2022	ENV055	Stream	CE1	-41.28	-8.33	24
22 Oct 2021	ENV004	TSF	SW26	-23.97	-4.25	9
15 Jan 2022	ENV037	TSF	SW28	-23.98	-4.32	10
22 Oct 2021	ENV003	TSF	SW28	-22.68	-5.13	17
13 Jan 2022	ENV028	TSF	SW28	-12.28	-1.77	1
22 Oct 2021	ENV002	TSF	SW28	-12.87	-1.79	1
13 Jan 2022	ENV025	WSF	SW031	-29.20	-5.52	14
22 Oct 2021	ENV001	WSF	SW11	-24.36	-4.52	11

Sample elevation versus stable isotope of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for all the water samples from the groundwater boreholes, TSF, WSF, dams and streams have been plotted. The data from different samples have been plotted in order to obtain trends in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ vertical variability. The data plots presented in Figure 4.32 and Figure 4.33 show the following:

- Depleted $\delta^{18}\text{O}$ and enriched $\delta^2\text{H}$ isotopes in all the groundwater borehole samples relative to other sample types in the study area are due to selective recharge. $\delta^{18}\text{O}$ in groundwater samples fall within a narrow range between -9.24 and -7.27‰ while other surface water samples range between -7.95‰ to -1.77‰.
- Surface water samples from the TSF, dams, WSF and streams are enriched in $\delta^{18}\text{O}$ and depleted $\delta^2\text{H}$ isotopes compared to the groundwater samples from the boreholes. This corresponds with increased evaporative processes on surface water bodies hence the enrichment $\delta^{18}\text{O}$ (Wassenaar *et al.*, 2011).
- Generally, $\delta^{18}\text{O}$ enrichment decreases with an increase in depth as can be seen in Figure 4.32.

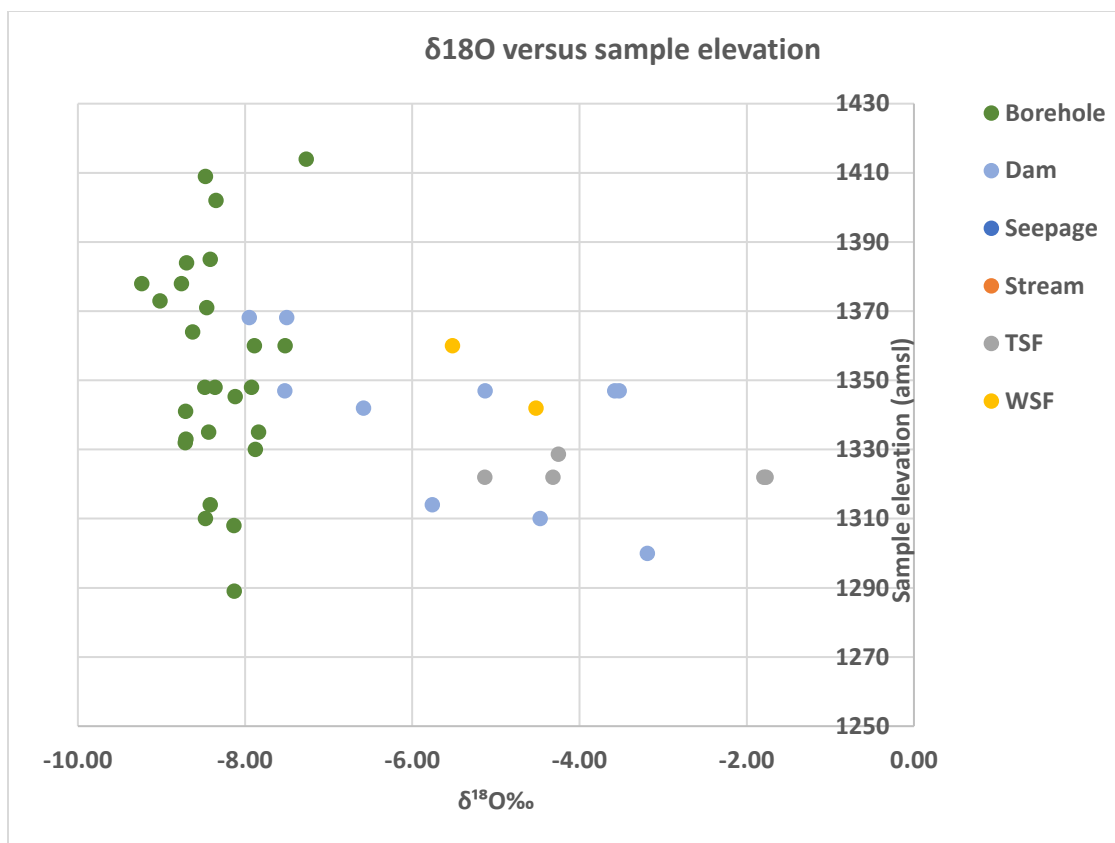


Figure 4.32 $\delta^{18}\text{O}$ versus elevation of water samples from the Lumwana Mine area.

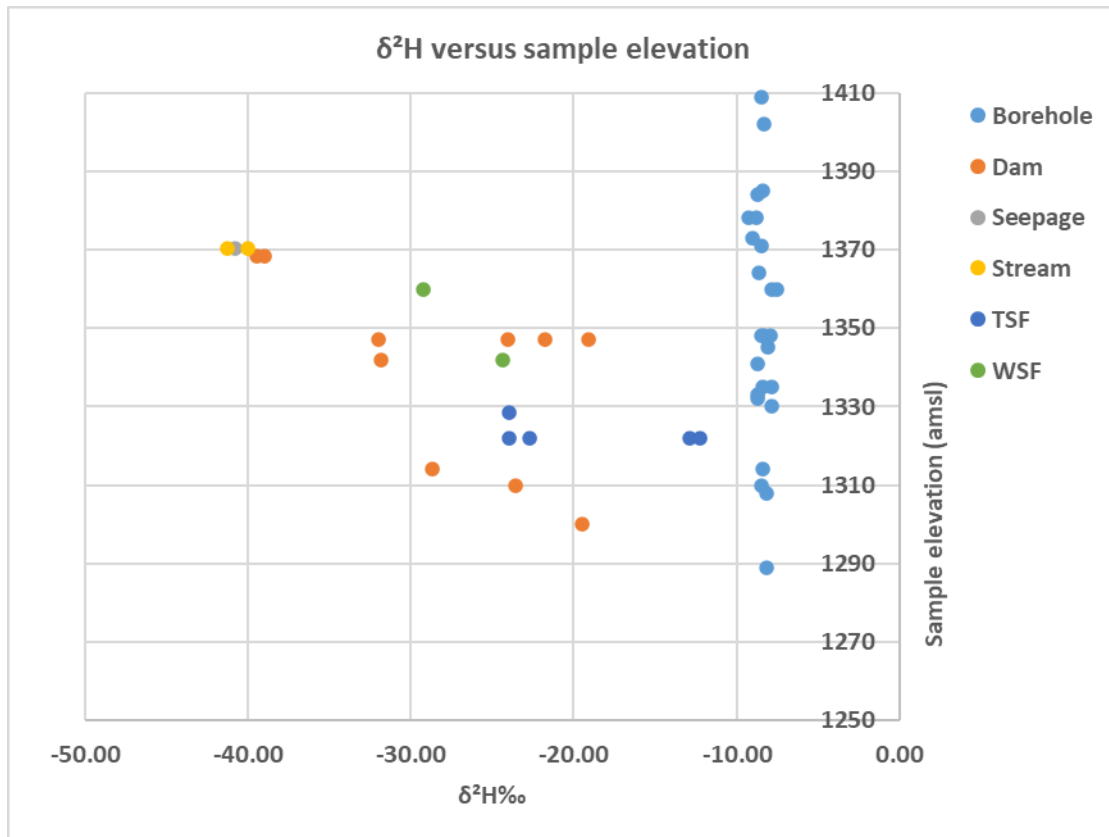


Figure 4.33 Deuterium versus elevation of water samples from the Lumwana Mine area.

4.9.3 Tritium

Determination of the mean groundwater residence time and further confirmation of the potential for hydraulic link between surface water bodies such as streams, dams and the open pit excavations were carried out using radioactive environmental isotopes (Tritium). Isotopic characterisation of mine water provides support for the understanding of sources of mine inflows affecting mining operations and destabilising the slopes (Mulenga, 1991). The average concentration of tritium in borehole groundwater samples ranges from 0.1 ± 0.3 T.U to 2.1 ± 0.3 T.U, both vertically and laterally, with an average concentration of 1.3 ± 0.3 T.U, while the mean tritium concentration of rainfall within the study area is 1.9 ± 0.3 T.U. Tritium concentration in borehole groundwater samples shows a decline with an increase in depth, however, the groundwater samples collected at shallow depth show a wide range of concentration from 0.1 ± 0.3 T.U to 2.1 ± 0.3 T.U, compared to samples collected at greater depth. The low concentration of tritium in groundwater at depth compared to shallow groundwater indicates a relatively longer

travel time in the groundwater flow system, leading to the loss of tritium through radioactive decay (Clark and Fritz, 1979).

Table 4.10 presents a summary of the surface water, groundwater and rainfall samples collected for tritium analysis and the corresponding residence time. The concentration of tritium in rainfall was used as the initial activity of tritium for mean groundwater residence time estimation. From fifteen samples that were analysed, the groundwater residence time ranges from ≤ 1 year to over 52 years (MM15), with a mean groundwater residence time of 6.6 years. Low groundwater residence time was established in samples MM01, MM05, MM06 and MM10 thus indicating active hydraulic interaction between surface water and groundwater, which confirms the stable isotopes and hydrochemical findings. Sample MM01 from groundwater borehole CDW06 located adjacent to and on the downstream side of an active stream, indicates active recharge from the stream that is rain-fed, into the subsurface and further into pit excavation as seepage. The presence of tritium in groundwater in amounts similar to that in present-day rainfall of the area would be an indication of rapid and active percolation (Levin and Verhagen, 2013). Groundwater samples from boreholes CDW06, GW08, GW048 and GW080 reported similar concentration of tritium with rainwater (average 1.9 ± 0.3 TU), suggesting very rapid and active percolation of rainfall, which is the primary source of recharge (Levin and Verhagen, 2013). The wide range of residence time established provides an indication of active mixing between young water and old groundwater. Due to low hydraulic conductivities of the fresh bedrock in Lumwana Mine, high groundwater residence time indicates slow and active deep circulation of old groundwater despite strong hydraulic stresses induced by open pit excavations within the active mining environment.

Table 4.10 Lumwana Mine area's surface water and groundwater tritium concentration and associated mean residence times.

Sample Identification	Water type	Sample source ID	Tritium		Residence time (Years)
			(T.U.)	$\pm$	
MM01	Groundwater	CDW06	2.0	0.3	0.91
MM04B	Groundwater	GW049	1.3	0.3	6.8
MM05	Groundwater	GW08	2.1	0.3	1.79
MM06	Groundwater	GW048	2.0	0.3	0.92

MM07	Groundwater	GW07	1.6	0.3	3.08
MM09	Groundwater	GW081	0.9	0.3	13.39
MM10	Groundwater	GW080	2.1	0.3	1.79
MM11	Groundwater	GW050	1.5	0.3	4.23
MM12	Surface	SW28	1.1	0.3	9.79
MM14	Groundwater	CWDH01	0.7	0.3	17.9
MM15	Groundwater	CWDH017	0.1	0.2	52.7
MM16	Groundwater	CDW03	0.6	0.3	20.67
MM17	Groundwater	GW034	1.4	0.3	5.48

Spatially, lower tritium concentrations have been reported on the study area's southwestern side, which also corresponds with high topographic regions and from relatively deep boreholes flowing towards lower topographic regions in the north. Low but measurable tritium concentration in groundwater indicates long residence time, due to the delay in the unsaturated zone (Levin and Verhagen, 2013) or the possibility of low hydraulic conductivity of the aquifer lithology. Transmissivity values reported from the borehole (CDW03) on the southwestern side of the Chimiwungo Pit area are low, ranging between 0.9 and 3.3 m²/d. This is equivalent to a low hydraulic conductivity value in the order 10⁻⁸ m/s, hence, long groundwater residence time.

5. TRACING THE SOURCE OF MINE INFLOWS AND CONCEPTUAL MODEL DEVELOPMENT

5.1 Tracing the source of mine inflows

Following long-term transient pore pressure analysis on the existing pit wall slopes, it is envisaged that slope pore pressure and the associated phreatic surface will remain elevated over the life of mine. From the preliminary geotechnical stability assessments, the increased seepage faces exposed in the pit faces, with the lateral and vertical expansion of the pit will result in increased frequency and magnitude of ground falls. Saprolite and transition slope performance at Lumwana has shown a common trend of failures along the seepage faces within the weak saprolites and transition geotechnical domains which coincides with different hydrostratigraphic units. Occasionally, multi-bench slope failures have been recorded in the fresh bedrock with strong linkages to unfavourable geological structures such as shears, faults and other fractures depending on its interaction with the pit excavations. A multi-disciplinary approach has been employed in the assessment of Lumwana hydrogeological conditions. Integrating different data sets ranging from hydraulic and rock storage properties, site meteorological data, environmental isotope data, local geothermal gradient investigation, hydrochemistry and pit dewatering data provided an opportunity for a multi-faceted assessment of the hydrogeology of Lumwana Mine. The conceptual model developed from this investigation will work as framework for future numerical modelling work to quantify future expected mine inflows and pore pressure trends for the life of mine as the mine continues to develop (Beale and Read, 2013).

Potential for surface water and groundwater interaction was assessed through application of major ions hydrochemistry (Williams *et al.*, 1986). The lithology mineralogical composition is usually reflected by the hydrochemistry of water (Mulenga, 1991). Based on the chemistry of the representative water samples, aquifers within the study area are grouped into two hydrochemical facies (see Figure 4.22) and are mainly controlled by rock-water interaction processes. The Piper trilinear diagrams essentially reflect the relative content of the major ions in groundwater and the general water hydrochemistry. The water-rock interactions were found to be the controller of groundwater chemistry, and therefore, Lumwana groundwater hydrochemistry was broadly discussed on the basis of rock types due to rock-water interaction (Gibbs, 1970). As water seeps through the rock, it dissolves part of the rock and from the

dissolved constituents, one can determine the groundwater geological history, the rock type through which water percolated and the mode of origin within hydrological cycle (Mazor, 1991; Singh, 1989, Mazor *et al*, 1989; and Davis and De Wiest, 1966). The rock types include a sequence of quartz-feldspar-biotite gneiss (granitic gneiss) locally known as Pink Gneiss which is overlain by the Lower Roan quartzites and carbonates on the flank of the Mwombezhi Dome (Equinox Copper Ventures Limited, 2005). The ore schist, an intensely mylonitic biotite-muscovite-kyanite-quartz schist, underlies the hanging wall gneiss. Mineralisation within the Ore Schist is mainly disseminated copper and iron sulphide (mainly chalcopyrite and bornite at Malundwe and assemblages of chalcopyrite-pyrite and chalcopyrite-pyrrhotite-cubanite at Chimiwungo) (Equinox Copper Ventures Limited, 2005). Other trace metals such as cobalt occur in pyritic zones while uranium occurs along discrete zones within the hanging wall and footwall contacts (Equinox Copper Ventures Limited, 2005).

The footwall lithological unit at Chimiwungo area differs from the Malundwe Open Pit area. The footwall at Chimiwungo area consists of quartz-feldspar-biotite gneiss with kyanite-mica-quartz interbands while at Malundwe area the footwall consists of kyanite-mica-quartz schist and footwall quartzite (micaceous quartzite/muscovite-quartz schist) (Equinox Copper Ventures Limited, 2005). The bulk of waste rock is mainly the feldspathic gneiss from the hanging wall with sporadic mafic intrusives.

Groundwater samples from boreholes GW79, GW82, and CDW02 within the vicinity of waste rock dumps and intersecting the hanging wall units, have relatively high TDS values (Figure 5.1) ranging from 148 to 204 mg/l and high EC values ranging from 110 to 351 $\mu\text{S}/\text{cm}$. These are attributed to elevated dissolved ions such as HCO_3 , Mg, Ca, Na, CO_3 , with a pH range of 6.17 to 7.88. The groundwater from these boreholes belongs to the Ca-Mg- HCO_3 hydrochemical facies mainly due to accelerated rock-water interaction (Gibbs, 1970) of the percolating water with the waste rock dumps as well as in-situ rocks (Mazor, 1991) due to physical weathering and exposure of the waste rock dumps to the atmospheric condition. Further interpretation of correlation diagrams to determine hydrochemical characteristics has shown the source of hydrochemical variations. Ca and HCO_3 variation helped to understand the relationship between the two major ions. A strong positive correlation coefficient between the two ions indicates a common source.

A strong positive correlation ($R^2=0.9567$ and $R^2=0.7877$) (Figure 5.2) exists between Ca and HCO_3 concentration and TDS, respectively, thus suggesting that TDS concentration is strongly influenced by Ca and HCO_3 concentration in water. The mineral composition of the rock (mainly limestone and mafic intrusive) is reflected in the chemistry of the water samples constituents (Mulenga, 1991). As water flows through the waste rock dumps and the hanging wall formation, the dissolution of dolomite and mafic intrusives through rock-water interaction results in elevated concentration of Ca, Mg, Na, HCO_3 , CO_3 ions (Mulenga, 1991). Groundwater samples from community boreholes (Figure 5.1) GW80, GW81 and GW57 situated between upstream side of the TSF and the downstream of the community sewage treatment plant have relatively higher TDS values ranging from 144 to 422 mg/l, and EC values ranging from 210 to 496 $\mu\text{S}/\text{cm}$. These values are associated with high ion concentrations, specifically HCO_3 , CO_3 and Ca with pH range of 6.4 to 7-7. A strong positive correlation ($R^2= 0.6389$ and 0.6555) exists between Ca, HCO_3 and TDS respectively, suggesting that TDS is dependent on Ca and HCO_3 ion concentration. On the basis of hydrochemical characterisation, the most probable source of elevated ion concentration is anthropogenic, from the community sewage plant leachate infiltrating into the groundwater.

Surface water samples (SW26, SW28, Malundwe open pit) and groundwater sample GW37 from a borehole within the vicinity of the TSF area, have relatively higher TDS (282 – 578 mg/l) and EC values (360 - 930 $\mu\text{S}/\text{cm}$). These are attributed to elevated concentrations of dissolved ions, mainly SO_4 , HCO_3 , Ca, Na, CO_3 and Mg with pH ranging from 4.95 to 8.24. Surface water samples belong to Ca-Mg- SO_4 facies while groundwater samples within the TSF area plot in the mixing region of the piper diagram. The mixing of Ca-Mg- SO_4 and freshwater (Ca-Mg- HCO_3) water types provide an indication of the great possibility for surface water-groundwater interaction. Overall, the hydrochemical data presented in Figure 4.22 and geochemical water classification from the Piper diagram clearly show two distinct water types within the study area. The local geology and geochemistry of the tailings are the main controllers of groundwater chemistry. Groundwater samples from boreholes within the vicinity of waste rock dumps are characterised by high TDS and EC values attributed to elevated concentration of HCO_3 and Ca, mainly due to rock-water interaction (Figure 4.25). The water belongs to Ca-Mg- HCO_3 hydrochemical facies. Moreover, the open pit seepage water sample and Chimiwungo Dam located within the vicinity of the mine area

have similar EC and TDS, including associated concentrations of HCO_3 , Ca, CO_3 , Mg and Na, and pH. Correlation diagrams between ions and physicochemical parameters (TDS) confirm the existence of different water types within the study area. Plots of Ca and TDS in Figure 5.3 show two clusters of distinct water types, which according to Mazor *et al.*, 1985 and Mazor (1991), is evidence for active mixing. The similarity in physical and hydrochemical properties of surface water and groundwater within the study area, especially at the TSF area and the mine area strongly indicate active interaction between surface water and groundwater and interconnectivity between the mine and water storage facilities.

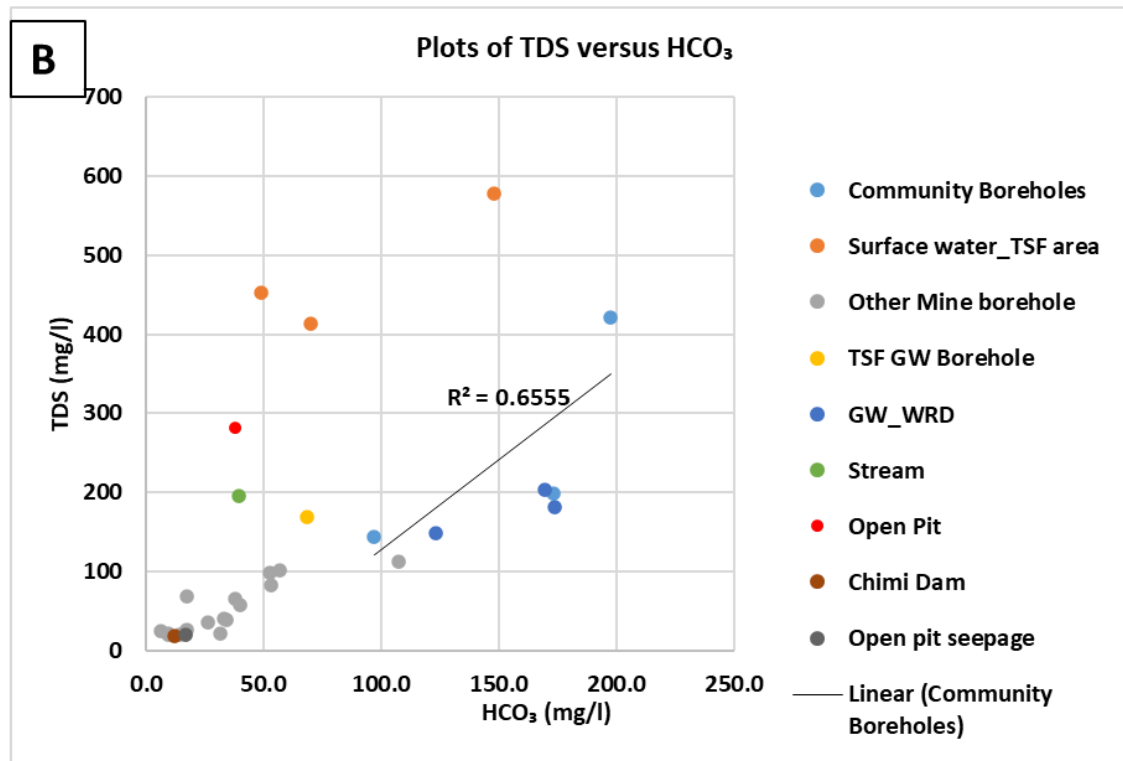
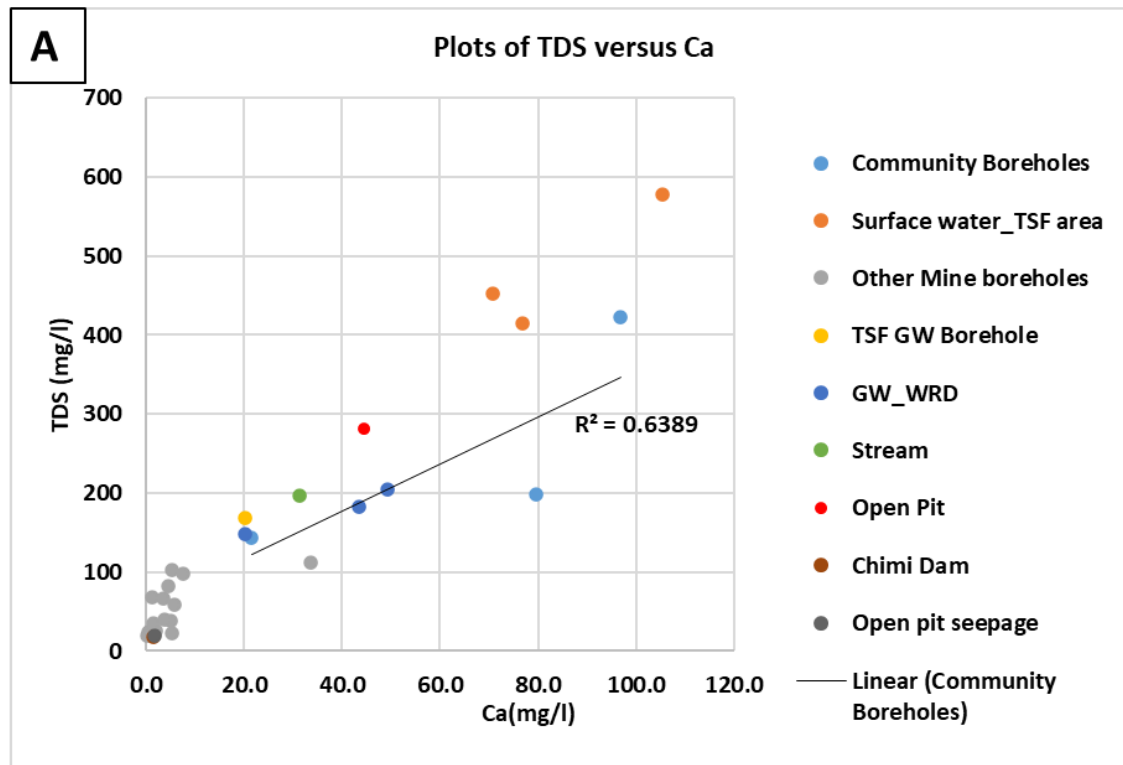


Figure 5.1 Variation diagrams of (A) TDS and calcium (Ca) (B) TDS and HCO_3 including respective correlation plots.

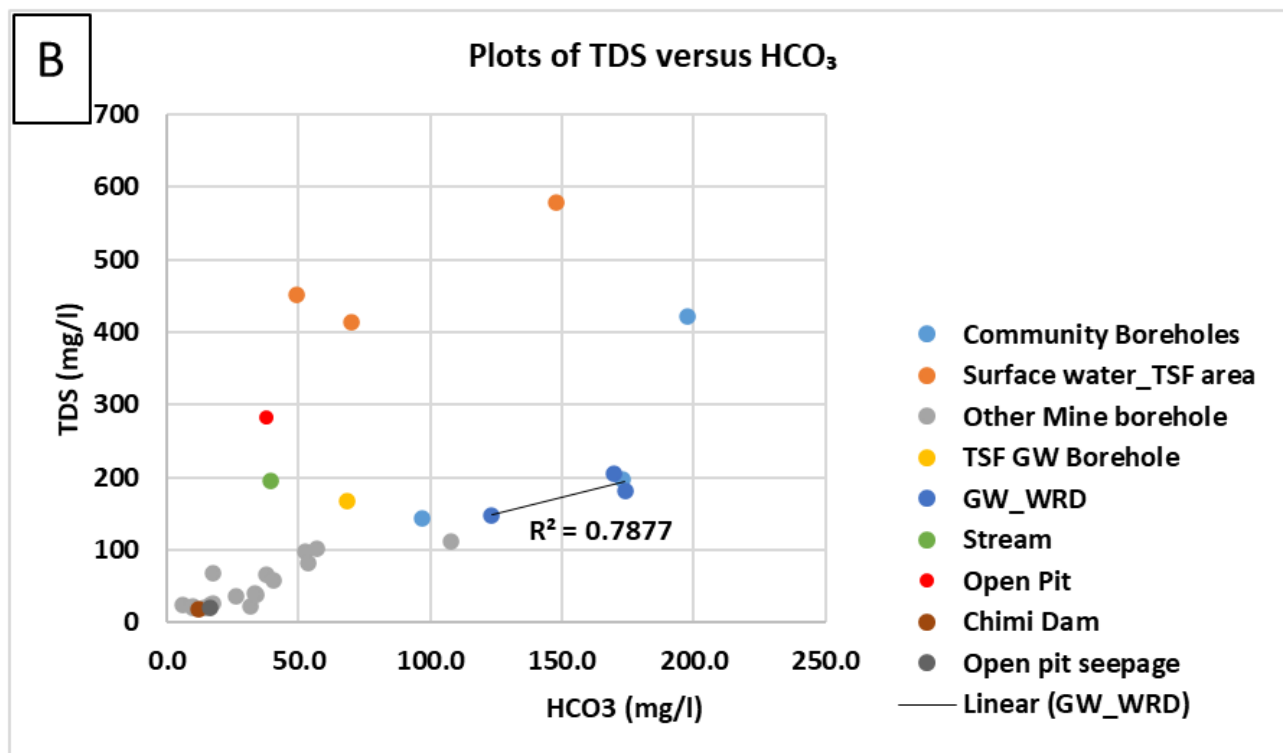
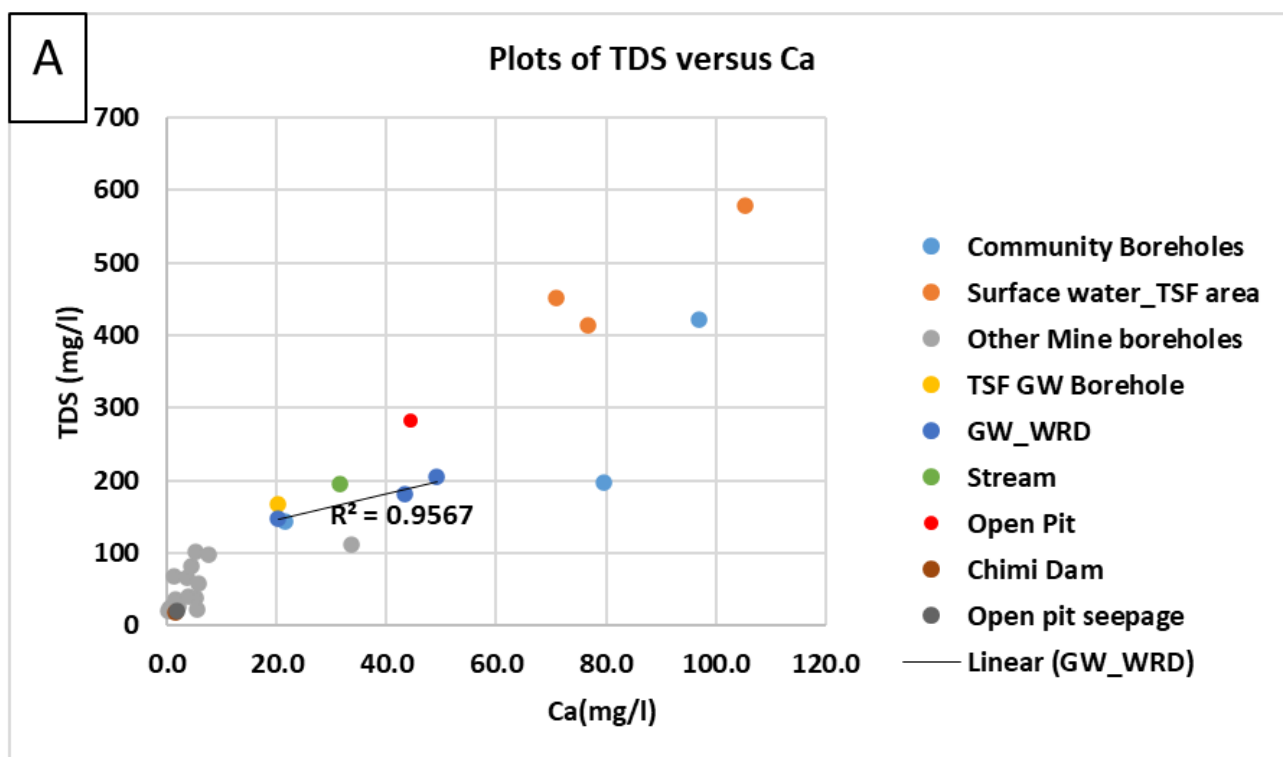


Figure 5.2 (A) Ca and HCO₃ correlation diagrams and (B) TDS and HCO₃ correlation diagram and respective correlation coefficient for boreholes from waste rock dumps at Lumwana Mine.

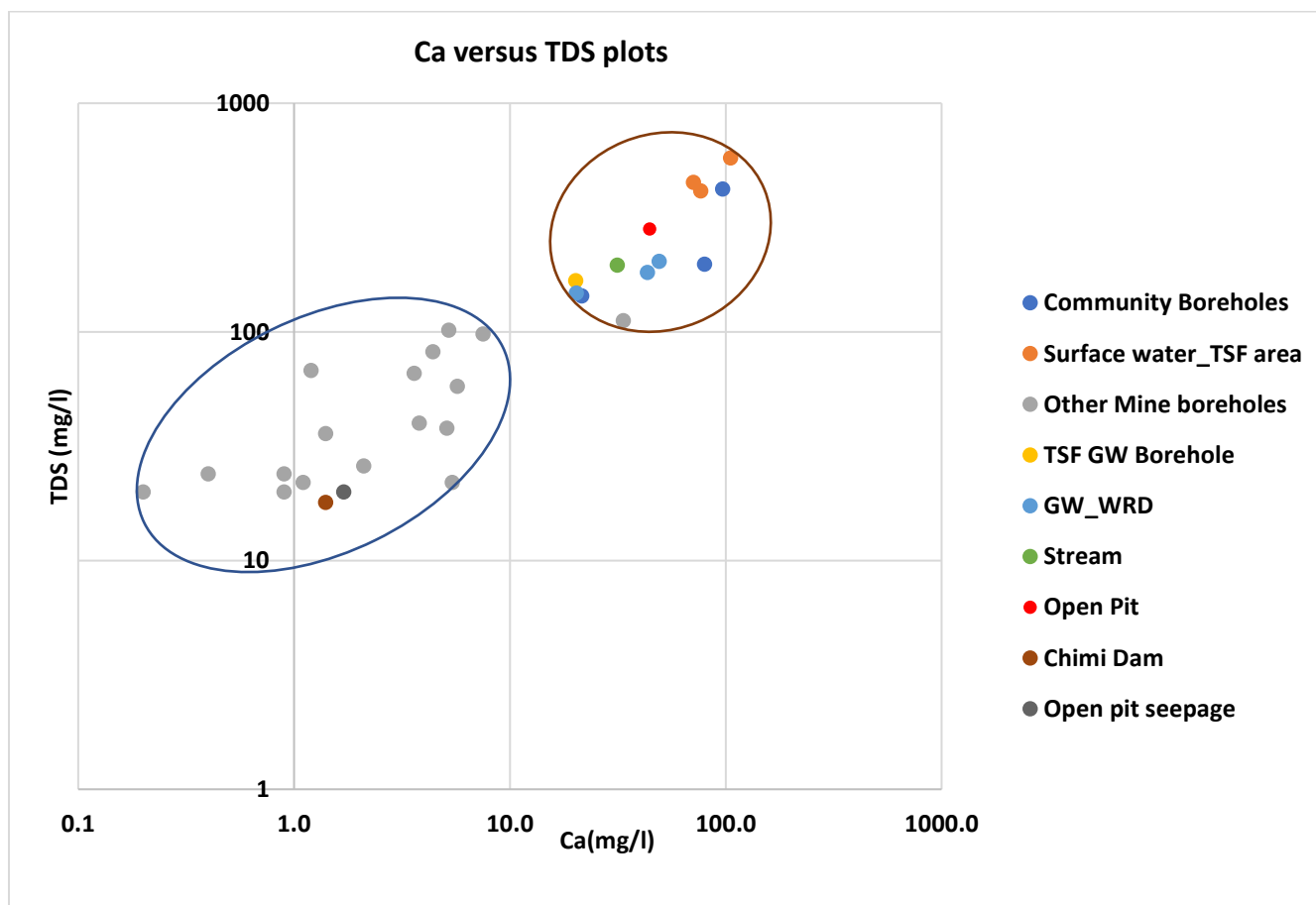


Figure 5.3 TDS and calcium (Ca) correlation diagram of Groundwater and surface water from the Lumwana Mine area.

Major ion hydrochemistry using the Piper diagram has confirmed two major types of groundwater hydrochemical facies. However, Ca-Mg-HCO₃ type is recharging the mine from the water storage facilities in the vicinity of the Chimiwungo open pit, in addition to rainfall that feeds the streams. To further confirm hydraulic link between surface water storage infrastructure and groundwater, analysis of tritium content of water was carried out. Streams and boreholes adjacent to the streams reported similar concentration of tritium (1.9±0.3 TU to 2.1±0.3 TU), suggesting similar source of recharge (precipitation). According to Levin and Verhagen (2013), rain level of tritium provides an indication of an ongoing recharge. This is also confirmed by the short groundwater mean residence time (≤1-2 years) indicating a very recent recharge. The broad range of tritium concentration at shallow depth and progressive reduction with increased depth

has been observed. Low tritium concentration at depth is attributed to long travel time and subsequent natural decay of tritium along the travel path.

In addition to major ion hydrochemistry, temperature, structural geology and tritium analysis, environmental stable isotopes were applied to identify zones for direct groundwater infiltration (Van Wyk, 2013). Meteoric water isotope results are in fact represented by differentiated rainwater samples from the so-called 'early' season input from October to December and peak seasonal rainfall from January to April (Van Wyk, 2013). The study area is characterised by meteoric water with d-excess range of 4.6 - 30.1 ‰. However, these values indicate a slight shift from the global meteoric water line and local meteoric water line mainly due to the rainfall samples collected at the peak of dry season. The shift from the GMWL is mainly caused by temperature (cloud forming), elevation (orographic), amount (dilution) due to the effect on local isotopic composition (Dansgaard, 1964 and Kendall *et al.*, 1998). It has been observed from rainfall sampling programme that heavy rainout events introduce lighter environmental stable isotopes of $\delta^{18}\text{O}$ and $\delta^2\text{H}$, thus lighter $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ that plot away from the GMWL (Dansgaard, 1964).

The sampling programme for environmental stable isotopes during this research was focussed on the hydrological investigation of potential for groundwater-surface water interactions. Surface water samples from the TSF, WSF, dams and streams in Figure 4.29 appear heavily subjected to atmospheric evaporative processes, hence enriched with respect to $\delta^{18}\text{O}$ and $\delta^2\text{H}$ and plot along the evaporation line, with a slight shift away from GMWL (Mazor, 1997).

Groundwater samples from boreholes and dams in Figure 4.29 plot within the same cluster. Local groundwater samples' isotopic composition ranges from -3.19 to -9.24‰ for $\delta^{18}\text{O}$ and -19.52‰ to 48.03‰ for $\delta^2\text{H}$ thus suggesting that the recharged precipitation responsible for this plot originated from a series of depleted rainfall events (Van Wyk, 2010) while isotopic composition for surface water from the dams range from -3.58 to 7.5‰ for $\delta^{18}\text{O}$ and -19.08 to 39.00‰ for $\delta^2\text{H}$.

Vadose zone physical infiltration is complex. Nkotagu (1997) made the following observations in the crystalline rock environment in Tanzania:

- (i) $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values in shallow groundwater correlate with surface and rainwater isotopic composition, indicating that local rainwater recharges the shallow groundwater with little evaporation, possibly during flash floods.
- (ii) Isotopic values of groundwater are more depleted than the local rainwater and surface runoff thus indicating the local aquifers are recharged by rainwater originating from a higher altitude (the Altitude Effect), or that 'specific, local, heavy (depleted) rainfall events are responsible (the Amount Effect).

The clustering of meteoric water, groundwater and surface water from the dams validates active surface water and groundwater interaction identified from hydrochemistry, temperature studies, tritium analysis, geostructural analysis and hydraulic characterisation. Moreover, the groundwater within the study area is recharged by specific, isotopically depleted heavy rainfall in shallow geological units and at depth through interconnected regional fractures that act as conduits for groundwater flow.

5.2 Conceptual hydrogeological Model

The conceptual hydrogeological model is a simplified representation of the wide complex groundwater and surface water flow systems (Beale *et al.*, 2013). Conceptual models that focus on the characterisation of aquifer properties are widely useful to enhance the understanding of different hydrogeological systems and groundwater flow dynamics (Zen *et al.*, 2015). Integrated application of various methods such as environmental stable isotopes, hydrochemistry, hydraulic characterisation, groundwater level data, geothermal gradient, hydrology, geology and structural data as well as other desktop investigations have been widely applied to gain insights into the understanding of sources of mine inflows and for the construction of hydrogeological conceptual models (Mulenga, 1991). This approach was applied to the Lumwana Mine area for the purpose of hydrogeological conceptual modelling. In the conceptual hydrogeological model, the regional climatic data including precipitation, surface runoff, infiltration rates and evapotranspiration is reconciled with the observed physical flow property of the hydrogeological units. The conceptual model forms the basis for any numerical groundwater model, providing primary input solved through a series of differential equations. The following components of the conceptual model were considered.

5.2.1 Site water balance

Inherent physical rock mass property and prevailing catchment climatic conditions determine the magnitude of different hydrological components. Important hydrological parameters for estimating the water balance and groundwater generation include precipitation, runoff, evapotranspiration and recharge. The site water balance for the Lumwana area conceptual model developed in Figure 5.4 shows that evapotranspiration constitutes the most considerable proportion of the amount of rainfall received, approximately 63.5% of the mean annual precipitation recorded. Mean annual precipitation of 1200 mm has been reported for the 10-year rainfall record within the study area. Actual evapotranspiration for the study area was determined using the Thornwaite-Mather method using the 2019/20 and 2020/21 seasons data while potential evapotranspiration was determined using the Turcs method for the same period. Conversely, surface runoff contributes 28.5% of the mean annual precipitation, and therefore, recharge is estimated at 8% of the annual precipitation recorded, reflecting as groundwater contribution of MAP. The annual recharge for the study area was determined using the Water Table Fluctuation method for the 2014/15 season hydrograph. Considering the shallow groundwater table and low hydraulic conductivities, most groundwater contribution is discharged in topographic low regions such as dambos, streams and rivers as baseflow and seepage. For the Lumwana study area catchment, Table 5.1 presents a summary of the site water balance.

Table 5.1. Lumwana catchment area water balance.

Component	Amount (mm/year)	% MAP	Analysis Method
Inflow			
Rainfall	1200	100	Site measured (rain gauge)
Outflow			
Evapotranspiration	762	63.5	Thornwaite-Mather
Runoff	342	28.5	Water balance
Groundwater Recharge	96	8	Water table fluctuation

5.2.2 Geology, hydrostratigraphy and aquifer parameters

The study area contains two copper deposits, which are structurally controlled shear zone deposits hosted within the Mwombezhi Dome, a northeast trending basement dome in the western arm of the Lufilian Arc thrust fold belt. The basement dome consists of order metamorphosed gneisses, schists, migmatites, amphibolites and granitoids. The study area geology has been subdivided into domains. The footwall domain consists of predominantly augen textured quartzofeldspathic gneisses while the ore schist domain is an intensely mylonitic biotite-muscovite-kyanite-quartz schist characterised by disseminated coarse-grained copper sulphides (mainly chalcopyrite and bornite at Malundwe and Chalcopyrite-pyrrhotite-cubanite at Chimiwungo, with nickel mineralisation along pyritic zones and uranium along hanging wall and footwall contacts discrete zones). The hanging wall domain is mainly dominated by a sequence of undifferentiated quartz-feldspar-biotite gneiss (grey gneiss) and albite-biotite gneiss (pink gneiss). The Lumwana region hydrostratigraphy is mainly controlled by the degree of physical weathering and tectonism. The hydrostratigraphic units as shown in the site conceptual model in Figure 5.4 are differentiated on the basis of the degree of weathering into saprolite, saprock and fresh bedrock. The saprolite mainly generated from hanging wall gneiss is highly weathered, residual country rock, with thickness ranging between 20-30 m below ground level, characterised by relatively low hydraulic conductivity, geometric mean of 5.86×10^{-7} m/s with a depth to groundwater level between 5 m to 10 m. The bottom limit for the saprolite unit is marked by the bottom of complete oxidation in Figure 5.4. The saprock unit is a fractured zone between saprolite and underlying solid bedrock with relatively high hydraulic conductivity with geometric mean of 4.3×10^{-6} m/s and thickness varying between 10 m to 15 m. Fresh bedrock constitutes solid lithological units. The fresh bedrock has low primary hydraulic conductivity with a geometric mean of 2.1×10^{-7} m/s (Figure 4.4).

The general groundwater table mirrors the geometry of the topography, with recharge concentrated in high topographic regions during wet season. Conversely, groundwater is mainly discharged in the topographically-low regions, including pits, dambos, streams and rivers as baseflow. Open pits at Lumwana Mine provide hydraulic stresses, thereby acting as drains. However, within the saprolite and saprock domains, the groundwater table is elevated and

persistent and shows very little response to passive drainage. The fractured network represents secondary permeability and form laterally extensive, poorly developed secondary anisotropic aquifer. These are mainly preferred groundwater flow paths within the Lumwana hydrogeological system. In some cases, the fault system is characterised by very deep weathering profile in the order of 100s of meters as shown in Figure 5.4. There are several regional faults crossing the active mining area, which are steeply dipping toward the north-northeast. At the north and south end of the Chimiwungo deposit, the north fault downthrows the orebody by over 50 m to the north while the south fault downthrows the orebody by over 400 m. The region adjacent to most of the faults within the study area is characterised by a damage zone that exhibits high intensity of jointing, which predates the formation of the E-W fault system.

The local geothermal gradient, environmental stable isotopes and tritium analysis have confirmed the potential for hydraulic linkage between the surface water storage infrastructure and the open pit mine. Analysis of groundwater vibrating wires piezometric temperature showed that temperature measured in shallow hydrostratigraphic units resembles temperature in the lower atmosphere and progressively increases downwards away from the source of recharge. The presence of tritium in groundwater in amounts similar to that of present-day rainfall of the area indicates rapid and active percolation of precipitation. Spatially, lower tritium concentrations have been reported on the study area's southwestern side, which also corresponds with high topographic regions and from relatively deep boreholes flowing towards lower topographic regions in the north. Low but measurable tritium concentration in groundwater indicates long residence time. Stable isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) of groundwater samples from boreholes and dams plot within the same cluster, suggesting hydraulic interconnectivity. Major ions hydrochemistry analysis using Piper diagram confirmed two major types of groundwater hydrochemical facies (Ca-Mg-SO_4 and Ca-Mg-HCO_3). However, Ca-Mg-HCO_3 type is recharging the mine from the water storage facilities within the vicinity of the Chimiwungo open pit, in addition to rainfall that feeds the streams.

5.2.3 Groundwater flow

Lumwana Mine area consists of East-West striking, structural discontinuities that steeply dip to the north, within the southeastern, gently-dipping metamorphic rock units. In an environment

with low primary porosity, fractures provide conduits for groundwater flow and, therefore, target for dewatering drilling. Geological sections cut along the west-east section line in Figure 5.4 provide details of the hydrogeological units for the conceptual hydrogeological model. The following concepts apply to the Lumwana hydrogeology environment:

- In the upper layers, typically 50 m within highly and moderately weathered zones consisting of the saprolite and saprock domains, groundwater flows from the south to the north under unconfined and semi-confined condition.
- Beneath the moderate to highly weathered saprolite zones, groundwater flow is controlled by fracture occurrence and distribution, mainly the E-W striking fracture network toward the drains (mainly pit excavation).

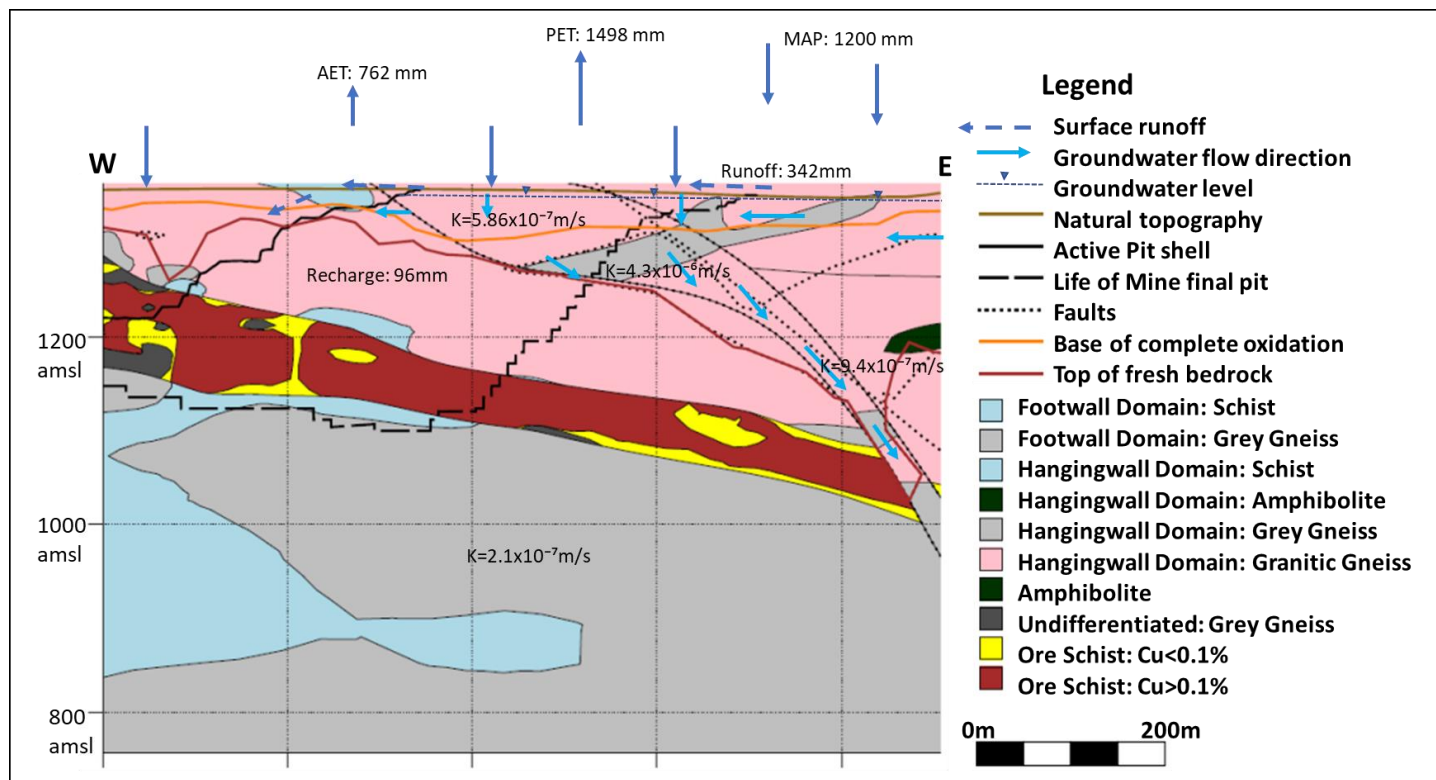


Figure 5.4 Conceptual hydrogeological model of the Lumwana Mine area (modified after Showmaker, 2013).

6. CONCLUSION

A multi-disciplinary approach has been employed in the assessment of Lumwana hydrogeological conditions. Integrating different data sets ranging from geology, structural geology, hydraulic and rock storage properties, site meteorological data, environmental isotopes, hydrochemistry and pit dewatering data provided an opportunity for a multi-faceted assessment of the hydrogeology of Lumwana Mine and subsequent development of data-based, site-specific hydrogeological conceptual model. Analyses of major ion hydrochemistry of thirty-one surface water and groundwater samples including boreholes, streams, dams, WSF and TSF from the study area has shown enrichment of most samples with either HCO_3 or SO_4 . Water samples' major ion classification using the Piper diagram demonstrated that water samples around the TSF area belong to Ca-Mg-SO_4 hydrochemical facies while surface and groundwater water samples around the active mining area belong to the Ca-Mg-HCO_3 hydrochemical facies. However, the Ca-Mg-HCO_3 water type is recharging the mine. Interpretation of the Gibbs diagram shows that water-rock interactions are the dominant processes controlling the hydrochemistry of groundwater within the active mine area through a dissolution of carbonate, siliceous and mafic waste rock dumps exposed to atmospheric conditions by percolating water as well as in-situ rock units. The similarity in physical and hydrochemical properties of surface water and groundwater within the study area, especially at the TSF and the mine areas strongly indicates active interaction between surface water and groundwater, and interconnectivity between the mine and water storage facilities.

Hydrochemical classification has established that the primary source of mine inflows is recharge from rainfall and active interaction from the diversion channels around the active mine area. This observation has been confirmed through environmental isotopic characterisation and piezometric temperature distribution patterns. Shallow piezometric temperatures were generally low and approximate mean lower atmospheric temperatures thus indicating active interaction with recharging surface water while at deeper levels, piezometric temperature steadily increased away from the source of recharge. A relatively lower geothermal gradient of $1^\circ\text{C}/30\text{ m}$ has been established at Lumwana compared to the global geothermal gradient of $1^\circ\text{C}/33\text{ m}$, mainly due to the cooling effect of the recharging groundwater.

To further investigate hydrological processes and confirm hydraulic linkages between surface water and groundwater, environmental stable isotopes analyses were carried out. Groundwater samples from boreholes and dams plot within the same cluster, suggesting that the recharged precipitation originated from a series of depleted rainfall events, mainly linked to heavy rainout events. The study area's meteoric water d-excess ranges from 4.6 to 30.1 ‰, which indicates a slight shift away from the global meteoric water line and local meteoric waterline. The shift from the GMWL is attributed to the effects of temperature (cloud forming), elevation (orographic), and amount (dilution) of rainfall. Interpretation of tritium concentration confirms the potential for active mixing between different water types. Streams and borehole water samples adjacent to the streams indicated similar tritium concentration, suggesting a similar source of recharge (precipitation). The occurrence of rain level tritium in groundwater provides evidence for surface water and groundwater interaction and the presence of active recharge. The groundwater is responsible for destabilising mining operations and affecting pit wall slope stability; therefore, managing mine inflows from these sources is key to sustainable, safe and profitable mining operations.

Hydraulic testing programmes have shown that the saprock hydrostratigraphic units have a relatively higher and broader range of hydraulic conductivities than the saprolites and fresh bedrock. Generally, groundwater flow within the upper hydrogeological units is from higher topographic regions in the south towards low topographic regions in the north-west. On the other hand, hydraulic characterisation has revealed that relatively lower hydraulic conductivities characterise the fresh bedrock and therefore, groundwater flow is dependent on the occurrence and distribution of fracture networks. As such, groundwater flow direction in the deeper sections of the bedrock is east-west, towards the pit excavations. Several regional faults have been defined based on geological drilling and mapping data. Generally, fault networks within the study area are steeply dipping at 71 and 77° in the N-NE and E-W direction, respectively. It has recently been realised that most of the water storage facilities within the vicinity of the mine area are located within the footprint of the fault network, hence providing a source of focused recharge for the mine as confirmed by major ions hydrochemistry and environmental isotope studies. An integrated study of the site hydrology, meteorology, geology, structural geology, environmental

isotopes and hydrogeology has resulted in the development of the Lumwana Mine conceptual hydrogeological model. The site-specific conceptual model developed will work as a framework for future groundwater flow and pore pressure numerical modelling work.

7. RECOMMENDATIONS

The following key points provide a summary of the additional work required in assessing the Lumwana hydrogeological environment and developing strategic long-lasting slope depressurisation and dewatering solution to support mining operations and improve slope stability.

- Plan and implement a robust hydraulic testing program using the following techniques:
 - i. Pumping tests
 - ii. Packer tests
 - iii. Slug tests

The testing programme should be carried out in strategically selected boreholes for improved hydraulic characterisation, groundwater flow and pore pressure numerical model development. In addition, the testing program should have good lateral coverage of the representative hydrostratigraphic units across future mining areas.

- Robust pore pressure and groundwater monitoring program through drilling and installation of vibrating wire piezometers targeting key geotechnical domains.
- Develop and implement a robust groundwater and surface water monitoring programme that includes:
 - i. Drilling and installation of vibrating wire piezometers and standpipe piezometers along the future pit limits for continuous piezometric pore pressures and groundwater level monitoring.
 - ii. Introduction and implementation of consistent quarterly groundwater and surface water sampling and laboratory analysis for water quality assessments and environmental isotope studies to better understand the dynamics of groundwater flow and fully understand the potential for hydraulic linkages between different water sources.
 - iii. Identify locations and implement weekly stream flow gauging along strategic points using pre-programmed pressure transducers where data collected can be downloaded on a computer on weekly basis.
- Carry out detailed groundwater flow and pore pressure numerical modelling, engineering slope stability assessment and cost to benefit analysis for key dewatering strategies.

- i. Assess the potential for drilling of sub-vertical dewatering boreholes, horizontal depressurisation boreholes or a combination of both.

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