# Towards a Conceptual Hydrogeological Model of the Chimiwungo Ore Body, Lumwana Mine. Northwestern Zambia

**by**

**Benedict Mabenge**

**2008102556**

Thesis submitted in the fulfillment of the requirements for the degree of

**MASTER OF SCIENCE**

**In the Faculty of Natural and Agricultural Sciences,**

**Institute for Groundwater Studies**

**University of the Free State**

**Bloemfontein, South Africa**

**November 2011**

**Study Leader: Dr F. Fourie**

**ACKNOWLEDGEMENTS**

This thesis was made possible by the co-operation of many individuals and institutions. I wish to record my sincere thanks to the following:

- The Lumwana Mining Company for allowing me the use of their data.
- Dr Francois Fourie for his mentorship and continuous assistance
- Prof G. Van Tonder for his help and technical advice.
- Dr Vermeulen for his help and technical advice.
- Mr E. Lukas for his help and technical advice.
- The personnel and fellow students at the Institute for Groundwater Studies.
- Special thanks to my wife, Yvonne and my two boys (Tinotenda and Tinashe) for their love, motivation and prayers and support during the preparation of my thesis.

And to the Almighty Lord and Saviour Jesus Christ for giving me comfort through the most difficult of times

# Table of Contents

# List of Tables



# List of Figures

# List of Appendices

***APPENDIX A***

*Borehole Logs*

***APPENDIX B***

*Water Quality Data*

**APPENDIX C**

*Photographs*

# 1 INTRODUCTION

## 1.1 General

The Lumwana Mining licence (LML-49) in the North-western Province of Zambia covers a surface area of 1,355km$^2$ and consists of two ore bodies, Malundwe and Chimiwungo. The two ore bodies are structurally controlled deposits of the Central African Copperbelt type. The Malundwe deposit is smaller but with higher grade copper and contains discrete zones of uranium and gold. Chimiwungo is much larger and lower in copper grade, but has higher overall cobalt grades. The proposed Chimiwungo mine pit is expected to go to depths beyond 300m by the year 2040. Mining is currently taking place at Malundwe where copper ore is hauled to the mine plant and processed whilst uranium ore is stockpiled for later processing. Copper is the main ore that will be mined at Chimiwungo and cobalt will be processed as a by-product.

A series of interconnected fractures are suspected to be the main conduits for groundwater movement. In order to achieve pit slope stability, pore water depressurization will need to be carried out alongside the dewatering of the main fractures and faults.

A thorough understanding of the hydrogeology of an area is paramount in any dewatering project. The development of a detailed conceptual hydrogeological model goes a long way in creating an appreciation of the prevailing groundwater situation in active and proposed mining areas. The influx of water during mining and the collapse of pit walls present perennial problems and dangers to those involved. Over recent years, dewatering has evolved into a highly specialized field of hydrogeology.

## 1.2 Structure of the thesis

This thesis comprises 10 chapters.

- Chapter 1 is an introduction, focussing on the objectives of the project and a summary of the methodology of investigations;
- Chapter 2 presents a discussion and background information on the occurrence and the importance of copper in Zambia and the world;
- Chapter 3 is a description of the study area;

- Chapter 4 is an overview of the geology of the Zambian Copperbelt and Lumwana Mining area. A brief outline of the hydrogeology is included;
- Chapter 5 is an outline on the methods used;
- Chapter 6 is a discussion of the results obtained through the investigation
- Chapter 7 brings together the information collected throughout the study and presents the conceptual hydrogeological model;
- Chapter 8 presents conclusions;
- Chapter 9 provides recommendations for future work and monitoring; and
- Chapter 10 contains a list of cited references.

A list of appendices follows Chapter 10.

## 1.3 Objectives

The study focused on:

- The collection and collation of available information; and
- Providing a framework for numerical modelling;

The information collected required to be synthesized and interpreted by standard methods, and presented in a logical manner. Information collected during the study included:

- Regional Geology;
- Local Geology;
- Topography and soils;
- Climatological data, precipitation, temperatures, wind speed, evapotranspiration;
- Hydraulic properties of all the significant hydrogeological units;
- Surface water, runoff, storage facilities, river and stream flows;
- Groundwater level monitoring data; and
- Mine plans.

The ultimate objective of the hydrogeological study is to assess the feasibility of achieving the desired water level drawdowns and pore water pressure distributions by implementing a suitable dewatering strategy. Recommendations on the most effective methodology to optimize the rate of dewatering and depressurisation of the geological strata in the Chimiwungo area may be inferred from the gathered data. This will, in turn, allow recommendations to be made on appropriate slope angles and potential mechanical means of stabilising the pit slopes.

## 1.4 Data Sources and Reports

Lumwana Mine has a vast collection of reports of geotechnical and hydrogeological investigations carried out prior to the current investigations. The reports listed in Table 1 below were the main sources of information used to gain an understanding to the history and current status of the groundwater regime at the mine. Other documents cited are listed under References (Chapter 10).

**Table 1. Data sources**

| Title | Author | Date |
|---|---|---|
| Lumwana Bankable Feasibility Study Volume 8 – Water and Waste Management, Chapter 6 Hydrological Characterisation and Surface Water Plan | Golder Associates Pty Ltd | August 2003 |
| Lumwana Bankable Feasibility Study Volume 4 – Appendix D Geotechnical Study | Golder Associates Pty Ltd | August 2003 |
| Lumwana Bankable Feasibility Study Volume 4 – Appendix H Hydrogeology Study | Golder Associates Pty Ltd | August 2003 |
| River Diversion scheme. Lumwana Copper Project, Zambia | Golder Associates Pty Ltd | March 2005 |
| Draft Report on Hydrogeological Study of Malundwe Pit, Lumwana Zambia. | Groundwater Resource Management | September 2007 |
| Lumwana Mining Company, Lumwana Uranium Project, Tailings and Water Management Feasibility Study | Knight Piésold Pty Ltd | May 2008 |
| Lumwana Mining Company, Lumwana Uranium Project UTSF Hydrogeology Update | Knight Piésold Pty Limited, Australia | June 2008 |
| Lumwana Mining Company Limited Lumwana Uranium Project Environmental Impact Assessment | Knight Piésold Pty Ltd | July 2008 |
| Lumwana Copper Mine Visit Guide | Equinox Minerals Ltd | October 2008 |
| Lumwana Mine Water Quality Database | LMC Environmental Department | May 2011 |
| Lumwana Mine Geological Model | Geology Department | May 2011 |

In addition to these reports several other sources of data were used to prepare the conceptual hydrogeological model. These sources include electronic copies of database information, including water levels, on-site rainfall, hydrochemistry, geological borehole logs and borehole/piezometer construction data.

Spatial data were also obtained. These included:

- Geological country rock model;
- Regional geology;
- Structural information;
- Mine infrastructure; and
- Water quality monitoring point positions.

## 1.5 Some results from previous investigations

Golder Associates (Golder) carried out a Bankable Feasibility Study (BFS) in 2003 (Garnham and Wright, 2003). As part of the BFS, they made an assessment of the dewatering requirements for the Malundwe and Chimiwungo proposed pits. Their studies included a preliminary desktop study, field investigations (drilling and pumping tests) and the development of conceptual and numerical groundwater models.

Golder concluded that groundwater levels within the area generally mirror the ground surface, such that groundwater flow is from areas of high to low topography. Their report defined groundwater recharge as being primarily from rainfall, while groundwater discharge is to the drainage system, via the dambos in the major drainages (i.e. the Lumwana East River and lower reaches of the Chimiwungo Stream).

The Golder report noted that main drainages, which are perennial, receive groundwater inflows year round. The drainages in the upper reaches of the catchments are ephemeral and only flow during the wet season. Groundwater flows across the Malundwe Deposit are regionally controlled by pervasive slight to moderate fracturing of the rock mass. Locally, however, groundwater regimes are dominated by highly permeable zones of more intense fracturing, which act as conduits for groundwater flow and are in turn fed by the surrounding lower permeability rock mass. These zones are generally concentrated along the Lumwana East River valley and are exposed in the southern part of the Malundwe Main Pit and the SE Malundwe Pit. No high permeability fracture zones were identified at Chimiwungo. Therefore, it is inferred that groundwater flows are via the slight to moderately fractured rock mass, which is considered to be less well developed than the pervasive fracturing at Malundwe.

To predict groundwater inflows a detailed numerical model was developed for Malundwe and a simpler scoping model for Chimiwungo (Garnham and Wright, 2003).

Groundwater Resource Management (GRM) later converted the Golder numerical model from a MODFLOW code to FeFlow (Wilkes and Garnham, 2007).

Knight Piésold carried out an Environmental Impact Assessment (EIA) of Lumwana Mine in July 2008. They adopted the Golder 2003 report for defining aquifer characteristics. The Knight Piésold investigations focused mainly on establishing the baseline groundwater quality within and around Lumwana Mine. The study also dealt with establishing groundwater and surface water monitoring sites throughout the mining concession (Knight Piésold, 2008).

## 1.6 Overview of Investigations

The investigation commenced with a thorough desktop study of available information on the Chimiwungo area. A large portion of the data came from reports prepared by other consultants during the exploration phase of the mine. Most of the data relates to the adjacent ore body that is currently being mined, namely the Malundwe ore body. A host of highly valuable data has been harvested from the current mining at Malundwe. The geology of the two areas is essentially the same except for a few minor differences. A comprehensive understanding of the Malundwe pit therefore enhances our appreciation of conditions likely to be encountered during mining at Chimiwungo.

The Lumwana Mine Environmental Department hosts a groundwater and surface water database that yielded a wealth of historical data.

A hydrocensus was carried out to identify existing groundwater and surface water sources and infrastructure. Following the hydrocensus, sites were identified for borehole drilling to develop a denser groundwater level monitoring network. Zones truncated by fault structures were identified by the analysis of the mine geological model, with input from the exploration team.

The intention was to drill three large diameter boreholes and six small diameter boreholes. These were to be drilled in clusters of one large diameter borehole per site, flanked by two small diameter boreholes at each site. The large diameter borehole and one of the small diameter boreholes would target the footwall below the fault structures whilst the remaining small diameter borehole would only be drilled into the hanging wall. The focus of the drilling phase was to identify the individual aquifer units and allow for the estimation of aquifer hydraulic properties through pumping tests.

Pumping tests were to be conducted on the newly drilled boreholes in order to assess potential yields and estimate aquifer hydraulic parameters such as hydraulic conductivity and storativity. Results of pumping tests carried out by previous consultants were analysed and used as a guideline for the pumping tests on the newly drilled boreholes. The resultant data is necessary to attain a greater understanding of the hydrogeology at Chimiwungo and the subsequent numerical modelling.

Groundwater samples were to be collected and submitted to an accredited laboratory for chemical analysis. Results of these analyses were to be used to characterize the general water quality in Chimiwungo.

This report will outline in detail the steps undertaken in developing a conceptual hydrogeological model for Chimiwungo as a precursor to numerical modelling.

# 2 COPPER

Copper is a metallic element with Atomic number 29. It is a ductile and malleable metal and possesses very high thermal and electrical conductivity. The pure form of copper is reddish-orange in colour. It is mainly used as a thermal conductor, electrical conductor, a building material, and a constituent of various metal alloys. An alloy may be defined as a material possessing metallic properties and composed of two or more elements, at least one of which is a metal (Henstock, 1996).

Some copper alloys are:

- brass: copper + zinc;
- bronze: copper + tin; and
- cupro nickel: copper + nickel

The four major industries that consume most of the world's copper are the electrical engineering, the general engineering, the building and the transport industry. The remaining amount of copper is accounted for in the production of a wide range of domestic goods and other products such as coins, ammunition and copper compounds for agricultural purposes.

The biggest customer of copper is the electrical engineering industry, which provides the equipment for electricity generation, including cables and wires. This industry consumes roughly 55% of the world's copper (Mupimpila and Van der Grijp., 1996).

The term "general engineering" refers to a wide and diverse set of conducts, such as mechanical engineering equipment, water turbines, machine tools and other heavy industrial plant equipment. In the building sector, copper is mainly used for plumbing and roofing. Copper's use in the transport industry is for conduction of heat. In this use, the major uses of copper are in the motors and generators of electric and diesel-electric locomotives, overhead contact wires and signalling and communications systems. Copper is also used in sea-going vessels, for such applications as propellers, heaters, coolers and air conditioners. The automobile industry is considered to be the biggest user of copper in the transport sector.

Changes in these four industries clearly have a bearing on the world copper trade. In other words, industrial trends are an important component of the demand for copper. Most copper experts expect a growing market in the next years. They believe that copper demand will increase, because of the fast-growing world demand for electrical power. Especially the developing countries will require more power stations, generators, distribution lines, cables, switchgear, and everything else that goes with an increased population and with its demand for domestic and other electrical appliances. According to Thompson (1997), a 3% trend for annual copper consumption growth is today considered to be conservative.

For copper and its alloys, a comprehensive series of specifications have been drawn up by national standards institutions. In addition, the International Standards Organisation has its ISO recommendations, to which the principal national standards now comply. Besides industrial trends, there are other determinants of world demand for copper. These factors include: (1) population, (2) stock movements, (3) efficiency in use, and (4) availability of substitutes, mainly aluminium (Mupimpila and Van der Grijp., 1996).

## 2.1 Copper in the World

World copper production patterns have changed over time. In the nineteenth century, Europe was the main producer of copper. Although Japan and Russia were important producers, the greater part of the world's supply was coming from mines in Britain and Germany. North America overtook Europe as the leading producer of copper in the twentieth century. Nowadays, Chile and the US play the leading roles and Chile remains the world's biggest producer of copper. Russia, Canada, China, Australia and Canada are the other important copper producers.

Developing countries are increasingly significant stakeholders in the world copper market. In fact, in several of the developing countries which are copper producers, copper constitutes not only a major economic activity, but in some cases, copper is virtually the only foreign exchange earner. This is particularly true for Zambia. In recent years, the large multinational mining companies have increased their investments in exploration and mining projects in Africa and especially South America.

The mining potential of the South American countries has long been known but only partially exploited, mainly because of their governments' opposition to foreign investment. This has now changed and new mining codes in the early nineties in Peru, Bolivia and Argentina have sought to emulate Chile's success in attracting investment with its 1981 mining law that ended discriminatory treatment of foreign firms (The Economist, 9/2/1995). The new codes offer more stable and generous tax treatment and allow repatriation of profits. In addition, these governments have also speeded up the granting of four exploration permits. Furthermore, privatisation has helped to attract foreign investors to the South American mining industry. Table 2 shows the world's top copper producers of 2009.

**Table 2. World Top Copper Producers 2009**

| Rank | Country/Region | Copper Production (tonnes) |
|---|---|---|
| 1 | Chile | 5,320,000 |
| 2 | United States | 1,310,000 |
| 3 | Peru | 1,260,000 |
| 4 | China | 960,000 |
| 5 | Indonesia | 950,000 |
| 6 | Australia | 900,000 |
| 7 | Russia | 750,000 |
| 8 | Zambia | 655,000 |
| 9 | Canada | 580,000 |
| 10 | Poland | 440,000 |

Source: *Copper Investing News 2010*

## 2.2 Copper in Zambia

Zambia is Africa's top copper producing country and copper production is one of the major sources of the gross domestic product (GDP), formal sector employment as well as government revenue. Furthermore, copper and cobalt (a by-product of copper) account for more than 90 percent of Zambia's total foreign exchange earnings, with an additional 5 percent derived mainly from lead, zinc and tobacco (Mupimpila and Van der Grijp., 1996).

Figure 2-1 shows the trend in the total annual Zambian copper output. The chart reveals that copper output of Zambia has been increasing rapidly since 2001. Lumwana Mine first contributed to the total copper output in 2008, giving rise to the conspicuous jump in the chart from 2008 to 2009. Zambia produced a total 681 000 metric tonnes of copper in 2010 and output is expected to rise to 1.44million tons by the year 2015.

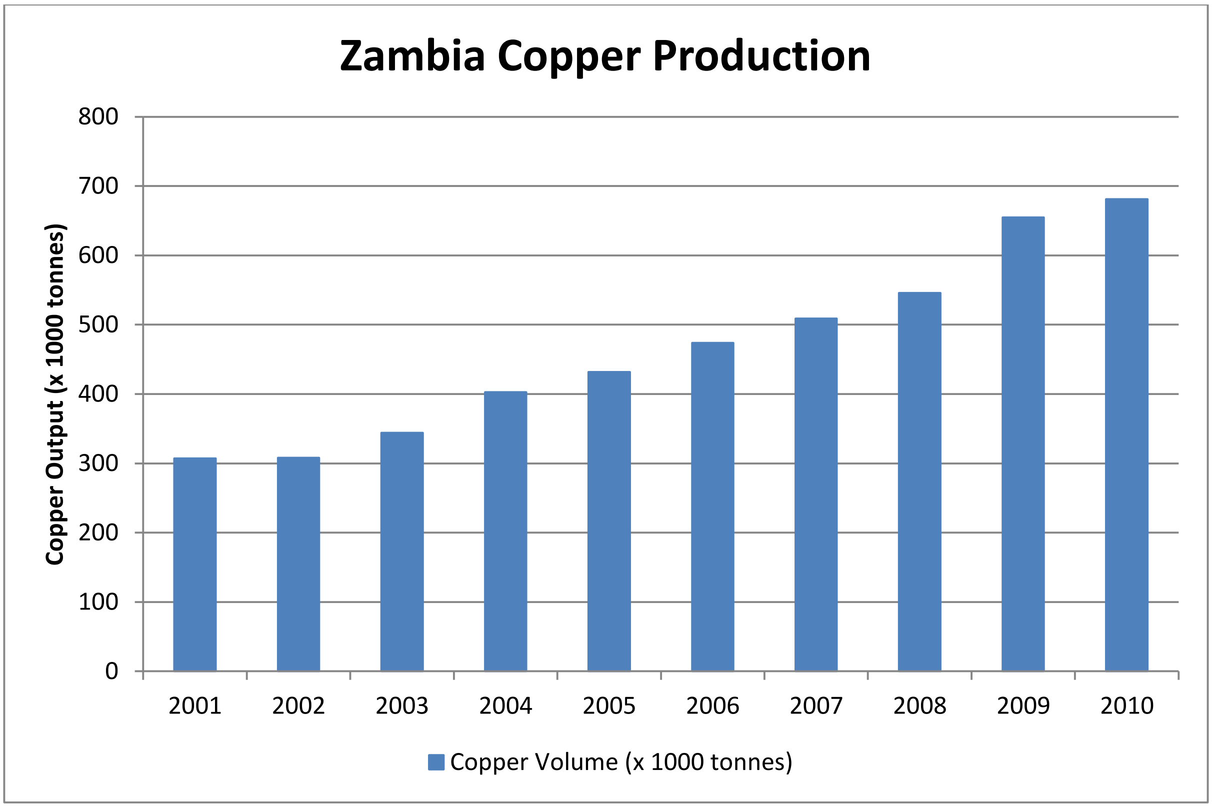



Figure 2-1. Zambia Annual Copper Production

### 2.2.1 Proposed Mining Method - Open Pit Mining

The following excerpt is taken from the website ehow.com and describes open pit mining.

"During open pit mining excavation is performed from the surface to access the ore. Benches of ore are drilled, blasted, loaded on haul trucks and transported to surface. Backfill of the pit is generally not required or feasible. Most open pits are designed in a step-like structure, with each step (sometimes called ledge or bench) dug deeper into the earth to reach the area to be mined. A bench may be defined as a ledge that forms a single level of operation above which mineral or waste materials are mined back to a bench face. The mineral or waste is removed in successive layers, each of which is a bench. Several benches may be in operation simultaneously in different parts of, and at different elevations in the open pit mine. The steps include access roads, and as more material is removed, new steps can be built. The goal is to remove the valuable material, but that involves first removing large quantities of rock at the lowest possible price.

Open pit mining does offer some advantages over traditional deep shaft mining. Pit mining is more cost effective than shaft mining because more ore can be extracted and more quickly.

The working conditions are safer for the miners because there is no risk of cave-in or toxic gas. Open pit mining offers an advantage over shaft mining in that it is mechanically simpler to do. Space is not restricted in open pit mining. Trucks and mining machinery are free to move around as they need to. More machines can move more ore and haul off waste rock more quickly.

Because an open pit mine is open to the air, larger machinery can be used to operate the mine. This is a real advantage to mining companies who often use large trucks to carry debris away from the mine.

The cost advantage of open pit mining to investors is a matter of scale. It is accepted in the mining industry that an open pit mine is cheaper, safer, and mechanically easier to operate. It is cheaper to operate an open pit mine because less manpower and equipment is required. Strip mining, or open pit mining is profitable sooner than a shaft mine because more ore can be extracted from an open pit mine and more quickly." Figure 2-2 is an aerial view of the Malundwe pit, showing the pit outline and benches.

**Figure 2-2. An aerial view of the Malundwe Pit where open pit mining methods are employed**

#### *2.2.1.1 Potential sources of water*

At Malundwe pit small seepages occur from high walls along horizontal features. This is also expected at Chimiwungo where drilling intersected shallow seepage zones (see borehole logs, Appendix A). Exposure of these seepage zones is anticipated to allow the gradual release of water. Upon commencement of mining (excavation of pit) the following are expected to be the main sources of inflows into the pit:

a) Direct rain fall ( into pit and as storm water/sheet flow);

b) Through flow via the Zone of Relaxation (a zone of increased permeability formed around an open pit due to extension strains) and excavated benches;

c) Seepage water from dams and channels;

d) Groundwater (shallow, unconfined); and

e) Groundwater (deep, confined).

Figure 2-3 shows typical water inflows into an open pit mine.

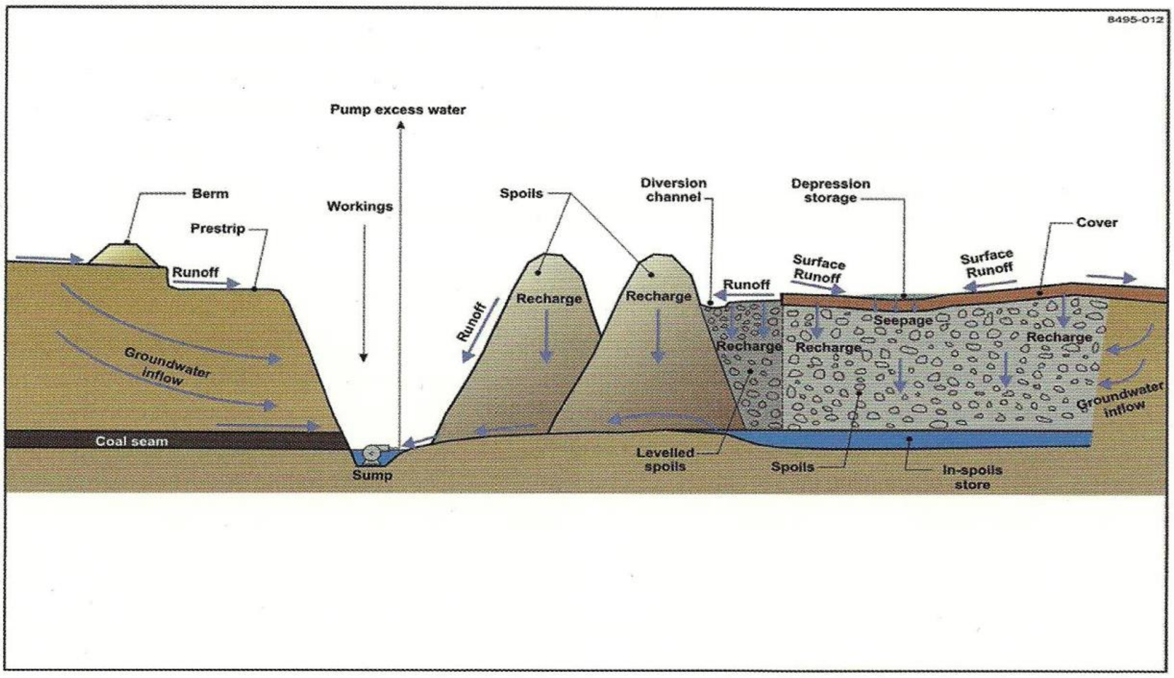



**Figure 2-3. Typical water inflows into an open pit mine (Dept of Water Affairs-RSA)**

#### *2.2.1.2 Dewatering in Copperbelt mines*

As in the rest of mines throughout the world, variety of methods have been used and are still in use within mines on the Zambian Copperbelt. The methods include dewatering drilling, sumps, surface exclusion of water, interception of water, simple drainage, breakthrough methods and grouting. Dewatering presents a critical cost within a mining environment.

E. J. Naish, a consulting Geologist, presented a paper outlining the main methods used in dewatering within Zambian Copperbelt mines:

- **Surface exclusion** of water includes the use of canals and pipelines to carry water over hydrological hazard zones, herringbone ditches to speed up run-off, stream gauging to locate hydrological hazard zones and weirs to quantify flow rates, and the judicious geological siting of dams and other surface water structures.
- **Interception** methods revolve around the concept of interception of the potential mine drainage at the extremities of the mines in order to ensure that the cone of dewatering is lowered before it intercepts the main mining areas.
- **Simple drainage** is the mining of drives into aquifers at reduced hydrostatic pressures in order to drain specific aquifers.
- **Breakthrough** methods involve the mining of drives into aquifers but in a more controlled manner than in simple drainage. In this instance drives are mine directly into aquifers utilising watertight doors or puddle pipes to protect the main mine workings.
- **Dewatering** drilling is the most widely used method of dewatering used on the Copperbelt. It may be conveniently divided into surface and underground dewatering boreholes. Surface dewatering boreholes may either be pumped, utilising borehole pumps, used for piezometric measurements, or used in open pit situations to drain aquifers under hydrostatic pressure. Underground dewatering boreholes are the most widely practised method of dewatering on the Copperbelt and involve the drilling of boreholes into aquifers, in order to lower the hydrostatic head in a particular aquifer.
- **Grouting** to exclude the inflow of water to the mines of the Copperbelt has long been a tried and trusted method of groundwater exclusion. Both cementitious and resin grouts have been utilised on the Copperbelt

(Naish, 1993)

- **Sumps** are constructed in such a manner that seepage from pit walls flows to the low points and gets collected within the sumps and subsequently pumped into drainage channels, away from the pit.

# 3 SITE CHARACTERISTICS OF THE STUDY AREA

## 3.1 Location of the study area

Lumwana Mine is located in the North-Western Province of Zambia, approximately 65 km west of the town of Solwezi and 220 km west of the well-known Zambian Copperbelt (Figure 3-1). The project is having a significant positive impact on Zambia, being the largest new mine in a generation and the largest single capital investment in Zambian history. At full capacity, it is expected that Lumwana will provide around 20% of the country's total metal copper output.

The concession area, covering 1,350 $km^2$, encompasses two ore bodies, Malundwe and Chimiwungo. The Chimiwungo ore body covers a larger surface area. The two ore bodies are structurally controlled deposits of Central African Copperbelt type. Of the two deposits, Malundwe is smaller, but with higher copper grade, and contains discrete zones of uranium and gold mineralisation. Chimiwungo is much larger and lower in copper grade, but has higher overall cobalt grades and contains some uranium mineralisation. Mining is currently taking place at the Malundwe ore body, now at pit floor depths below 127 metres below ground level (mbgl). The mine is currently processing copper and stockpiling uranium.

## 3.2 Current Mine Infrastructure/Mine layout

The mine layout is dominated by the Malundwe pit where mining is currently taking place and clearing of the Chimiwungo area is in progress. The mine is serviced by a large number of well-maintained haul roads (R1, R2, R3, R4, R5). These haul roads are graded and molasses are poured onto the surface to suppress dust and minimize damage to vehicles. Gravel (graded) roads branch off from each of these major haul roads into various working areas of the mine. The process plant to the east of Malundwe pit receives ore from the pit via a conveyor belt.

The Chimiwungo will initially be subdivided into two mining centres, separated by the Chimiwungo River. Chimiwungo South or Main Pit will be to the south of Chimiwungo River and Chimiwungo North Pit to the north. The two mining centres will eventually be joined together to form one pit as mining progresses.


**Figure 3-1. Location of Lumwana Mine (United Nations, 2004)**

## 3.3 Climate

The study area is characterised by a sub-tropical climate, with cool to cold winters and hot rainy summers. The rainy season typically lasts from November to April and rainfall events are often accompanied by thunder and lightning. The regional Mean Annual Precipitation (MAP) varies between 1100 mm/yr and 1400 mm/yr from records obtained from the two towns of Solwezi and Mwinilunga (Garnham and Wright, 2003). A series of weather stations around the mine show a mean annual precipitation of 1240 mm (Figure 3-2). This was calculated from daily rainfall data collected from the five rain gauges installed around the mine (Figure 3-3).

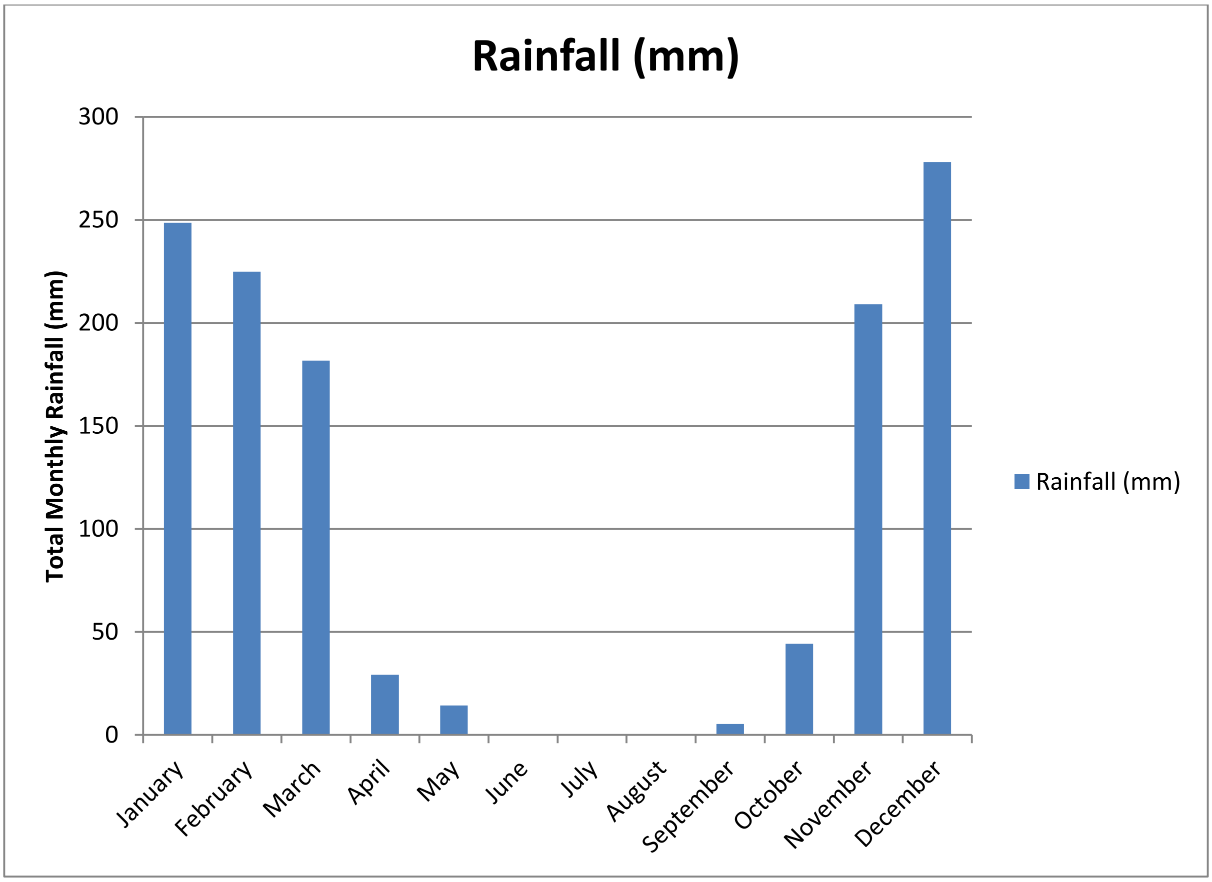



**Figure 3-2. Monthly Rainfall Averages At Lumwana Mine**

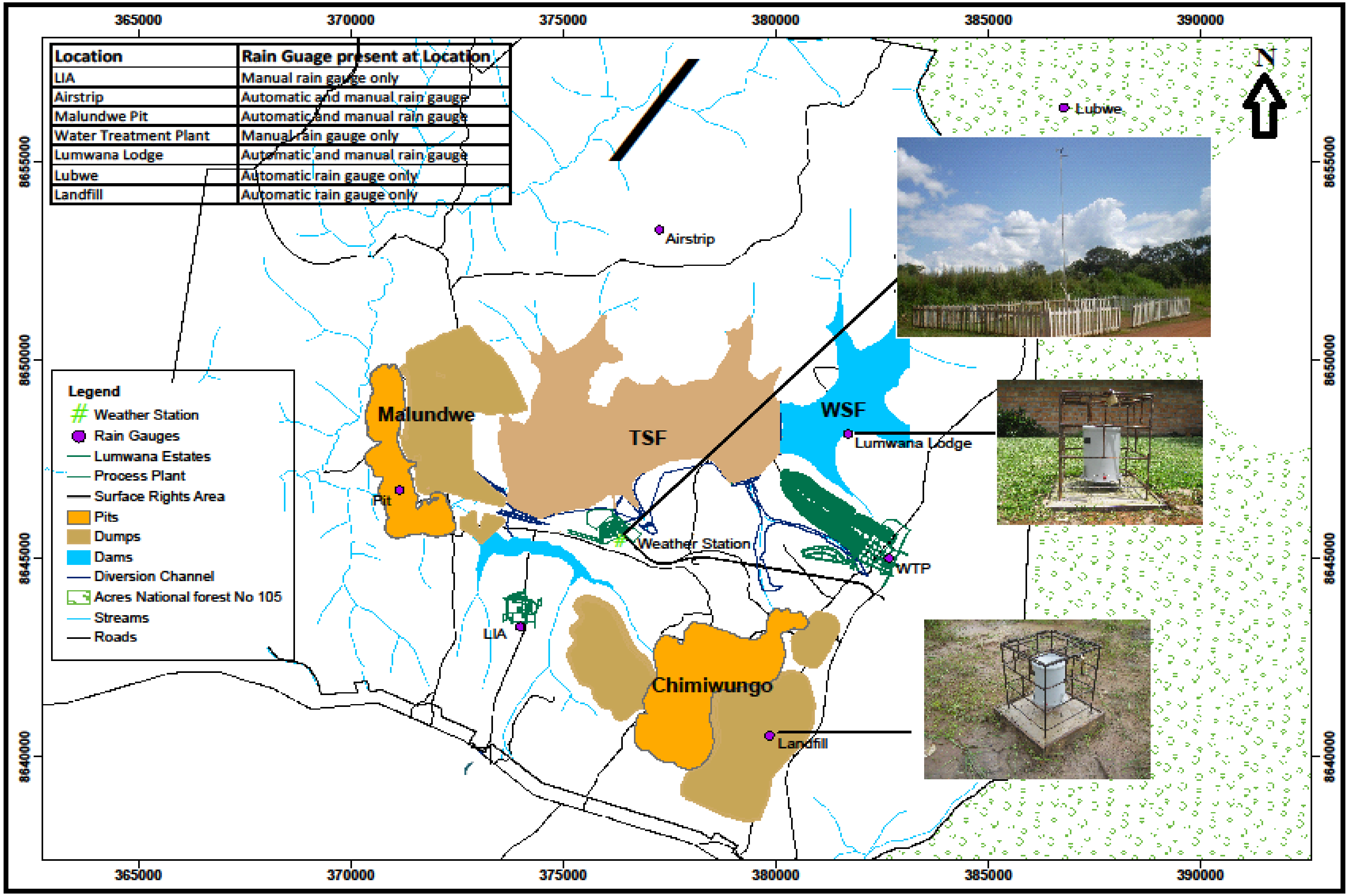



Figure 3-3. Weather Stations at Lumwana Mine

Humidity levels vary from a low of 45% during the winter to a peak of 90% in October, leading into the rainy season. Temperature levels range from a night-time minimum of 4°C in June to a maximum daytime temperature of 34°C in October. The prevailing wind direction in the dry season (July) is from the south east and is from the north-north-west in the wet season (January) (Garnham and Wright, 2003).

## 3.4 Topography and Surface Drainage

The topography of Lumwana mine is defined by the overall drainage pattern of the Lumwana East River and its tributaries (Malundwe and Chimiwungo streams). The area is dominated by gently rolling hills, remnants of an eroded upland plateau. The Malundwe and Chimiwungo copper deposits derive their names from streams which pass close to, or over the deposits. Topographic elevations in the vicinity of the Malundwe copper deposit vary between 1,280 and 1,380 metres above mean sea level (mamsl), while they are higher at Chimiwungo where they vary between 1,340 and 1,380 mamsl. In spite of the little discernible difference in altitude across the immediate project area, many of the watercourses flow through deeply incised valleys. In forested areas away from rivers and streams, slopes are gentle with gradients of between 1.5 and 3.0% (Garnham and Wright, 2003).

As in much of northern Zambia, the topography around Lumwana Mine is dotted with dambos. A dambo is a seasonally waterlogged, predominantly grass covered, depression bordering headwater drainage lines (McCartney, 1998). The definition may be accepted as a seasonal wetland but does not include other types of wetlands, such as marshes or swamps, which are permanently flooded or waterlogged.

Interaction between groundwater and wetlands is similar to that of rivers and lakes. It is accepted some wetlands are independent of groundwater systems (i.e. disconnected). However, most wetlands are either fed by groundwater in-flows, lose water by seepage into the subsurface, or both. In recent years, the ecological value of wetlands has been widely recognised. Amongst others, wetlands help prevent floods, improve water quality, reduce river sediment loads and provide fish and wildlife habitat. It is less well recognised, however, that many wetlands are groundwater driven and without understanding their drivers and functionality, it is difficult to manage and conserve these components of the hydrological system (Parsons, 2004). The dambos around the study area are suspected to be groundwater driven.

Wetlands are characterised by being permanently, frequently or seasonally wet; are underlain by poorly drained (hydric) soils that are usually saturated and under anaerobic conditions; and favour the growth of hydrophytic (water-loving) plants that can tolerate flooded or saturated anaerobic conditions (Stone and Lindley Stone, 1994).

Figure 3-4 is a photograph of a typical dambo in Chimiwungo.

**Figure 3-4. A dambo in Chimiwungo (12°16'16.10"S 25°52'54.93"E)**

The Chimiwungo River flows north-westwards and has its origins in the centre of the study area. It converges into its confluence with the south-westerly flowing Lumwana East River at the Malundwe pit margins. The Chimiwungo River noticeably responds very rapidly to each rainfall event as witnessed regularly at the low bridge across the river. A few major tributaries feed into the Chimiwungo River before the confluence with the Lumwana East River. These tributaries flow from south to north and add to the flow volume of the river (Figure 3-5).

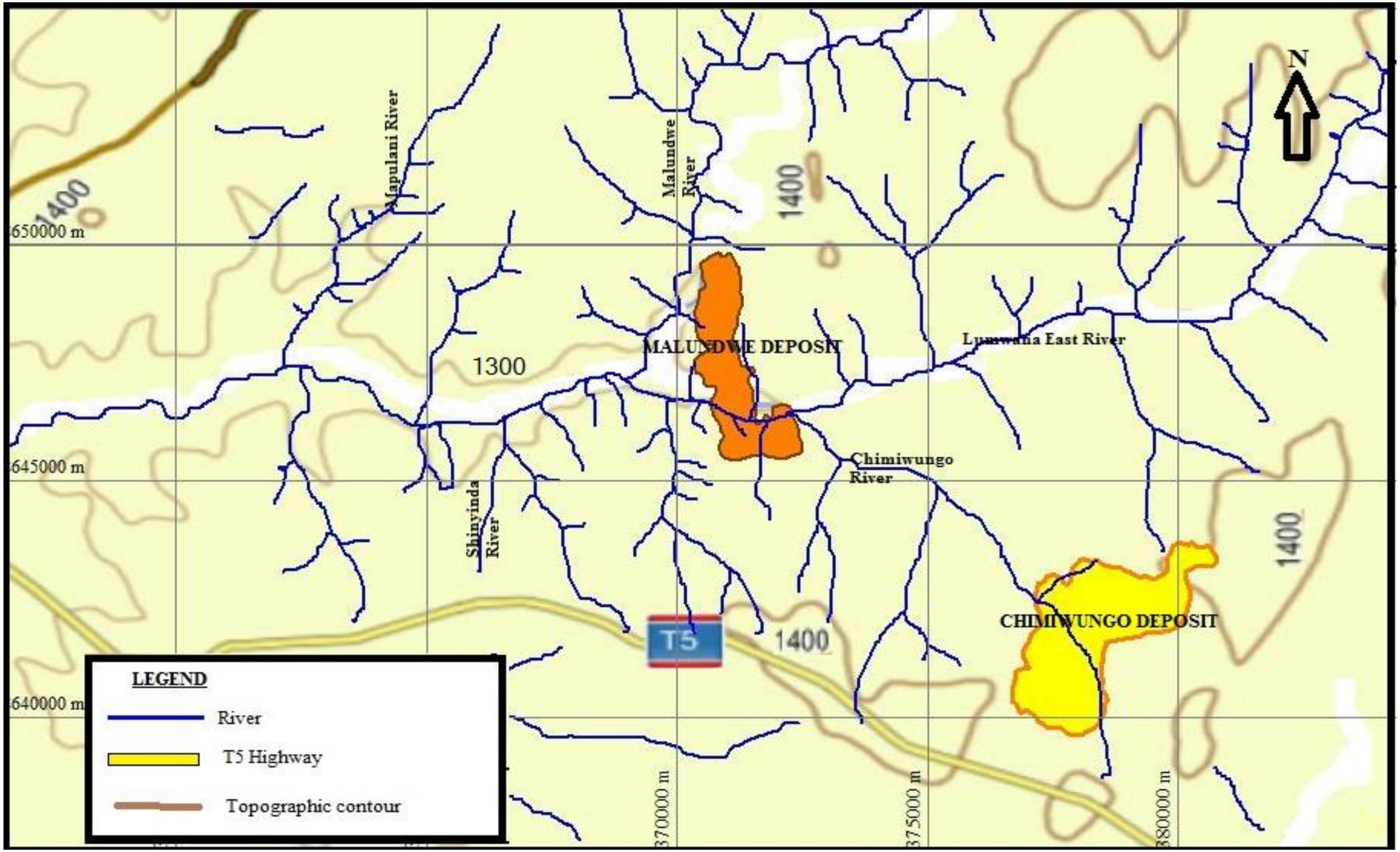



Figure 3-5. Topography and drainage of Lumwana Mine

## 3.5 Soils and Vegetation

Miombo woodland is the dominant vegetation type in the surface rights area, covering at least 85% of the total area before development took place (Knight Piésold, 2008). This type of vegetation is dominated by the genera *Bracchystegia*, *Julbernardia*, and or *Isoberlinia* (Figure 3-6). Miombo woodland is the dominant vegetation type in the Zambezian floristic region (White, 1983). Miombo woodlands provide resources that are vital to the livelihood of millions of rural and urban people living in and around them in central, eastern and southern Africa. In fact, people obtain from these woodlands a multitude of products including food, energy, shelter, medicines and a number of invaluable environmental and spiritual services (Campbell *et al*.,1996).

**Figure 3-6. Miombo Woodland (12°16'31.51"S 25°51'30.15"E)**

The soils in Chimiwungo are extremely weathered, brownish yellow, well drained but with a fine clayey texture. These occur on the gentle slopes. The dambo soils are seasonally waterlogged, deeply weathered, poorly drained with a fine clayey texture.

# 4 GEOLOGY

The geology governs the mode and occurrence of groundwater, runoff and infiltration (recharge), geotechnical conditions, as well as the controls for water-related environmental impacts (seepage and quality). Groundwater occurs within the pore spaces and fractures within a rock. The permeability of a rock depends on the connectivity of pores and fractures. Recharge is a function of the ability of the overlying soil cover and lithologies to allow the infiltration of water from surface to underlying aquifers. The composition of a rock defines the groundwater chemistry as dissolution of geological material takes place as the water percolates downwards. Highly soluble minerals add to the salt content of groundwater and may ultimately define its fitness for human consumption or other purposes.

Bernau (2007), Garnham and Wright (2003) and Knight Piésold (2005) consulted a range of previous reports and described the regional and local geology as presented in the following sections, based on the mine geological model.

## 4.1 Regional Geology

The Chimiwungo and Malundwe ore bodies lie on the margins of the Mwombezhi Dome which forms part of the Katanga sequence. Figure 4-1 shows the regional geological setting within which the mine lies.

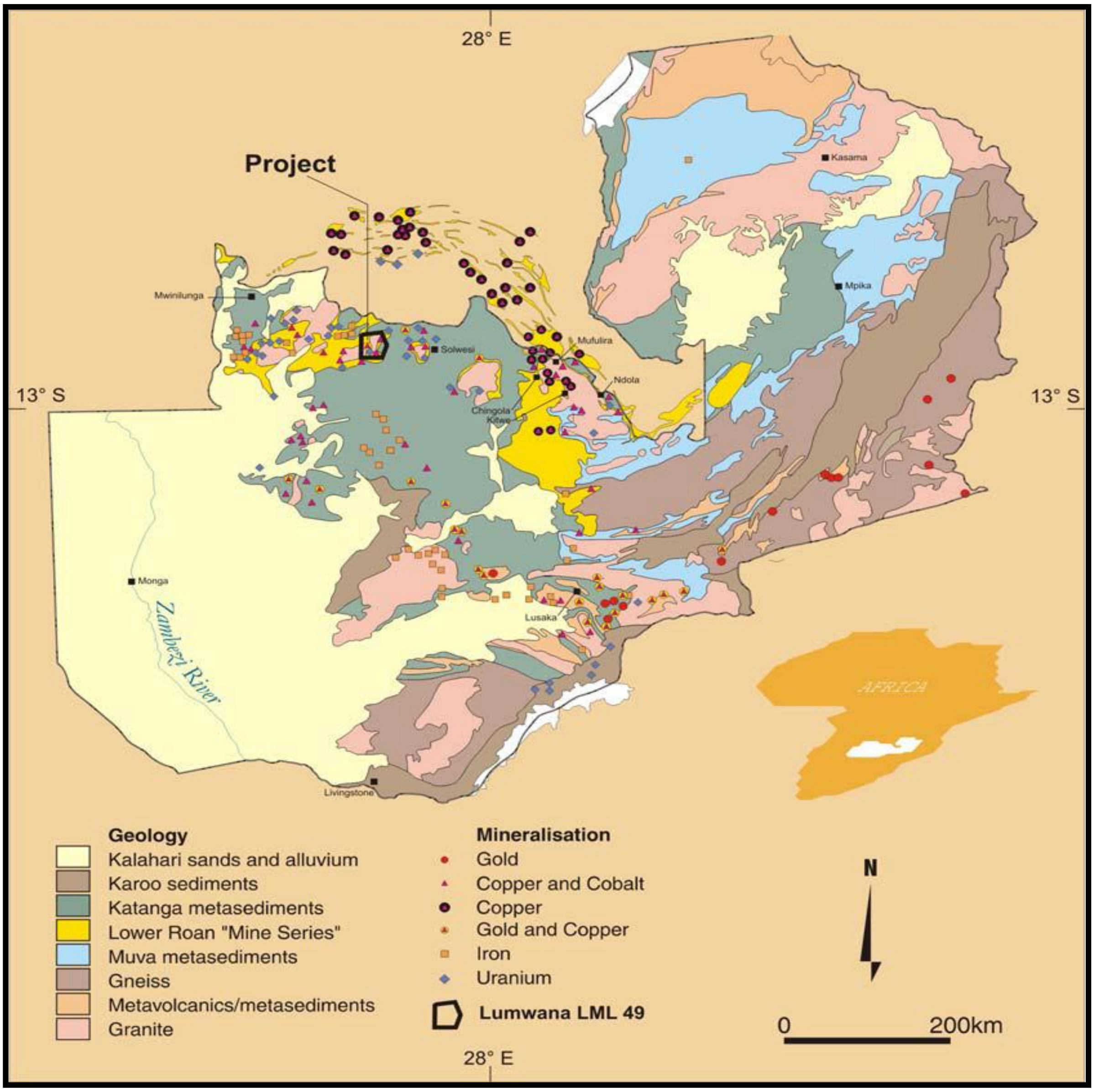



Figure 4-1. Regional geology (Bernau, 2007)

### 4.1.1 Geology of the Mwombezhi dome.

The Mwombezhi Dome Basement Complex that hosts the Lumwana deposits comprises biotite-feldspathic gneiss, hornblende-gneiss, granite gneiss, migmatites and schists. The basement units are intruded by younger granites (Mulela and Seifert, 1998) which have not been dated and are likely to be synchronous with either the 883 ± 10 Ma Nchanga Red Granite (Armstrong *et al.*, 2005) located in the Copperbelt or the 559 ± 18 and 566 ± 5 Ma Hook Granite Complex to the south of Mwombezhi Dome located on the northern contact of the Mwembeshi Shear-Zone (Figure 4-2) (Hanson *et al*,. 1993).

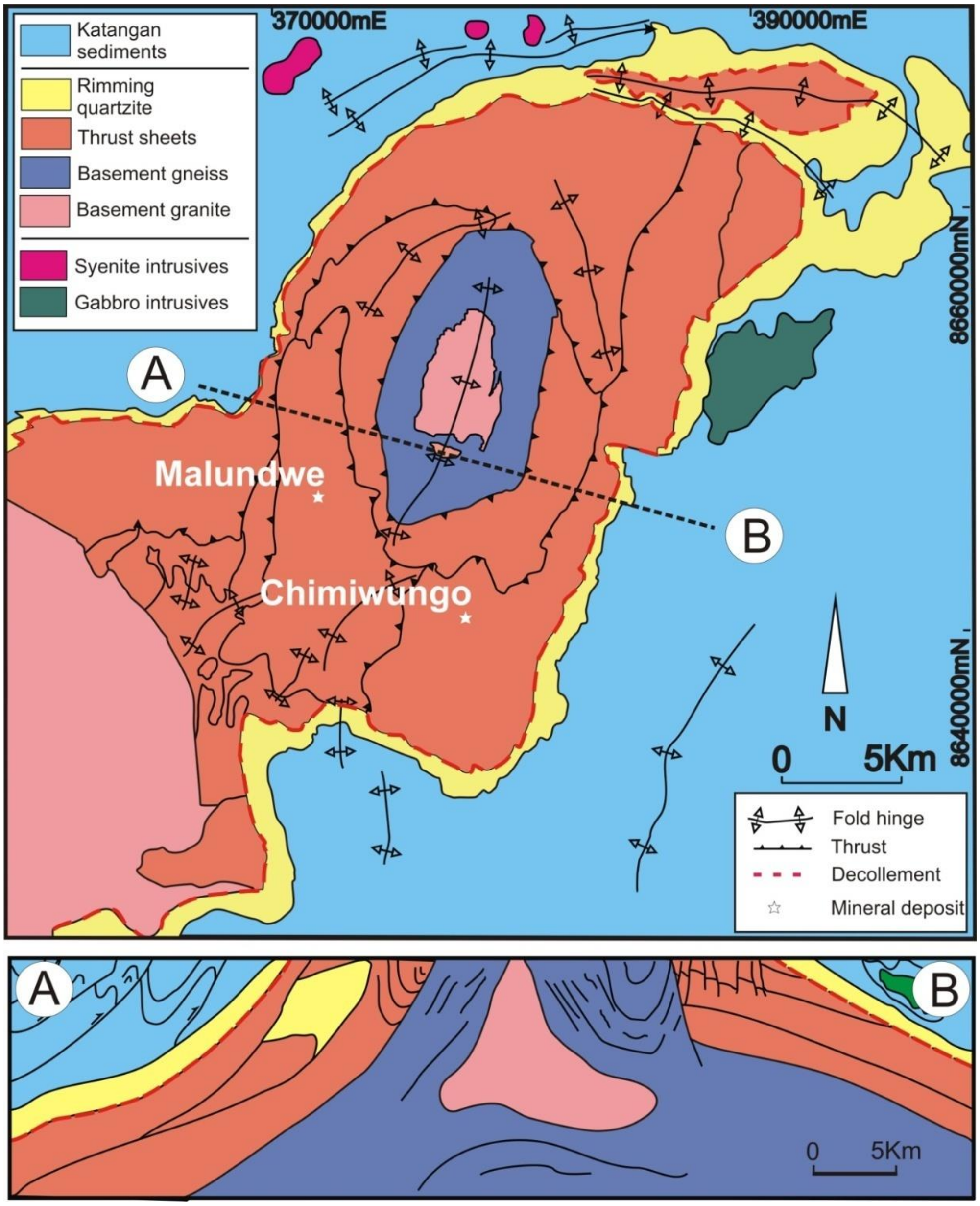



**Figure 4-2 Simplified geology of the north-eastern lobe of the Mwombezhi Dome basement complex. (Bernau, 2007)**

Logging of diamond drill core has revealed that the granites at the core of the north-eastern lobe of the Mwombezhi Dome, exhibit less deformation than the highly deformed granite gneiss units, which host the Chimiwungo and Malundwe deposits. This observation supports the concept that the granites at the core of the north-eastern lobe of the Mwombezhi Dome post date the deformation (Garnham and Wright, 2003).

The Mwombezhi Dome basement complex is separated from the overlying Katangan stratigraphy by a major décollement. The décollement comprises magnesium rich quartzite to muscovite-quartz-talc-kyanite-hematite schist that grades to whiteschist at the contact with the basement units and are collectively known as the “Rimming Quartzite”. The décollement, shown by the dashed red line in Figure 4-2 separates the Palaeoproterozoic thrust stratigraphy from the overlying thin-skinned tectonic regime of the Katangan sedimentary rocks. The décollement is marked by an L-S tectonite that exhibits an intense north/south mineral lineation.

The “Rimming Quartzite” has been correlated with the Lower Roan lithologies but their protolith is enigmatic as their chemical composition is extremely rare in nature and indicates a metasomatic origin (Johnson and Oliver, 2002). The fluids responsible for the metasomatism of the “Rimming Quartzite” are possibly derived from the pore fluids of shallow water sediments, driven off the Congo plate by the over-riding Kalahari plate during continent-continent collision at 530 Ma (John *et al.* 2004).

The whiteschist mineral assemblages observed in the Mwombezhi Dome basement complex and the garnet-hornblende association indicate temperatures of 700° to 750°C, and pressures of 11 to 13kbar, which correlate to burial depths of approximately 50 km (Cosi *et al.* 1992; John *et al.* 2004). Monazites have been dated from assemblages representing peak metamorphism at 524 ± 3 Ma to 532 ± 2 Ma using U-Pb dating (John *et al.* 2004).

## 4.2 Local Geology

The 2003 BFS outlined the geology of Malundwe and Chimiwungo (Garnham and Wright, 2003):

"The copper mineralisation at Lumwana occurs as disseminated coarse-grained sulphides hosted within biotite-muscovite-kyanite-quartz schist, referred to as the Ore Schist, which exhibits a strong N-S stretching lineation and an intense shear fabric. The schist is interpreted to have been formed in a major shear zone. The hanging wall to the Ore Schist is a sequence of pink to grey quartz-feldspar-biotite gneisses to schists, which stratigraphically underlie Lower Roan quartzites and carbonates flanking the Mwombezhi Dome and are dated as pre-Katangan (Cosi *et al*, 1992). The footwall to the ore schist varies between the three deposits. At Malundwe it consists of various kyanite-mica-quartz schists passing into a generally sheared micaceous quartzite to muscovite-quartz schist (footwall quartzite). This lithology is interpreted to be either basal Lower Roan, or a hybridised and metasomatised tectonic mélange composed of both Lower Roan Basement lithologies. The footwall quartzite overlies a sequence of altered and brecciated Upper Roan dolomites and calcsilicates intruded by amphibolites.

At Chimiwungo and Chimiwungo North the footwall consists of dominantly grey sometimes amphibolitic quartz-feldspar-biotite gneisses to schists with interbands of kyanite-mica-quartz schists (Garnham and Wright, 2003).

The mineralisation at Malundwe extends for approximately 6.0 km in the north-south orientation and up to 1.5 km wide (east-west). The mineralisation outcrops at surface to the east, and extends to maximum depth of approximately 200 m below surface to the west and south and is open to the south. The ore schist is tabular to gently folded, has an average thickness of 14 metres, (ranging from 1 to 70m) and dips gently to the west at between 10° and 20° and plunges to the south at around 15°.

Chimiwungo Main mineralisation extends 1.5 to 2.4 km north-south, and 4.2 km in the east-west orientation, extending to approximately 460 m below surface down-dip and down-plunge to the south. At its southern limit the Chimiwungo Main deposit is truncated by the Chimiwungo South Fault.

Chimiwungo South is the up-faulted continuation of the Chimiwungo Main mineralisation. The mineralisation extends up to 1 km north-south, open to the south and east and 1.7 km in the east-west orientation, extending to the limit of drill definition at approximately 370 m below surface to the south and east.

Chimiwungo North is very similar in style to Chimiwungo Main being the northern extension of the Chimiwungo deposit, which has been down faulted by approximately 80 m by the Chimiwungo North Fault Zone. This fault zone is similar in style to the Chimiwungo South Fault and consists of two major splays which host some mineralisation. The orebody consists of a single, 5 -10 south dipping zone, up to 60 m thick, currently extending over an area of 800 m north-south by 500 m east-west. In summary the Malundwe, Chimiwungo and Chimiwungo North tectono-stratigraphy can be considered a highly sheared and altered tectono-stratigraphic sequence produced by major D1 shear zone thrusts.

The ore schists and the footwall quartzite/muscovite-quartz schist units appear to be the most strongly sheared and metasomatically altered portions of the shear zone. Both deposits contain lenses (Malundwe) or internal horizons (Chimiwungo) of quartzfeldspar – biotite gneiss to schist, similar to the hanging wall gneiss. This suggests the Ore Schist is not a different lithology, but instead a hybrid tectonic rock produced by intense Lufilian age shearing and alteration of the basement hanging wall gneiss just below the Basement – Katangan contact. The Malundwe, Chimiwungo and Chimiwungo ore contains typically 5% sulphides dominated by copper-iron sulphides. Typically sulphide assemblages are:

- Chalcopyrite ($CuFeS_2$) - pyrite ($FeS_2$);
- Chalcopyrite ($CuFeS_2$) - bornite ($Cu_5FeS_4$);
- Chalcopyrite ($CuFeS_2$) - pyrrhotite (FeS) - cubanite ($CuFe_2S_3$); and,
- Chalcocite ($Cu_2S$) - bornite ($Cu_5FeS_4$).

Malundwe has all four assemblages but is dominated by the chalcopyrite – bornite assemblage. Chimiwungo has all except the chalcocite – bornite assemblage but is dominated by the chalcopyrite pyrite and chalcopyrite - pyrrhotite – cubanite assemblages. Barren rocks are commonly enriched with iron. Nickel is associated with the more pyritic zones of the ore bodies. High cobalt concentrations are related to carrolite ($Cu\ (Co,\ Ni)_2\ S_4$) enclosed in chalcopyrite, cobalt pentlandite $(Fe, Ni, Co)_9S_8$ and cobaltiferous pyrrhotite hosted predominantly in the upper and main ore schist units at Chimiwungo. Gold and uranium are present as discrete zones mainly within the Malundwe ore schist or immediate footwall, although sporadic zones of uranium and gold mineralisation are observed at Chimiwungo (Knight Piésold, 2008). Figure 4-3 shows the geology of the Malundwe and Chimiwungo ore bodies.

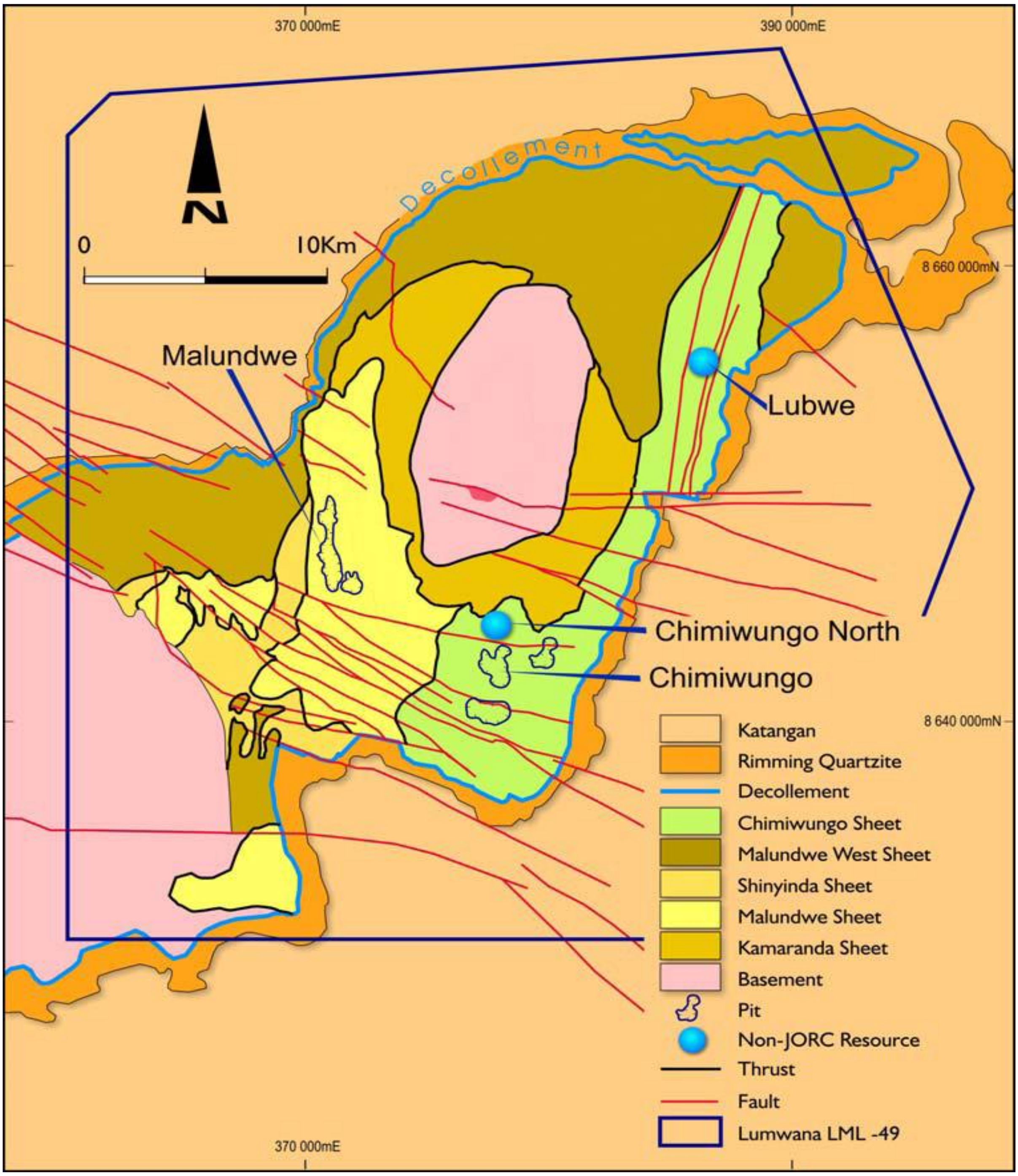



Figure 4-3. Geology of the Malundwe and Chimiwungo deposits (Knight Piésold, 2008)

The Chimiwungo deposit ore body is partitioned into two zones by the Chimiwungo River. These mineralised zones are referred to as Chimiwungo South/Chimiwungo Main and Chimiwungo North. The mineralisation consists of a package of three Ore Schist horizons: Upper Ore Schist, Main Ore Schist and Lower Ore Schist separated by two continuous barren gneiss zones the Middle Gneiss and the Lower Gneiss. The mineralised package and the individual Ore Schist and Gneiss zones have a gentle south dip and plunge. The mineralisation extends up to 4.2 km east/west (along strike) and 4km north/south and is open to the south. The limit of drill definition of the mineralisation in the south is down to approximately 370 m below surface.

The three Chimiwungo Ore Schist units are similar to the Malundwe mica-quartz-kyanite sulphide Ore Schist although there are some mineralised sulphidic gneiss zones. The sulphides are also very similar to Malundwe mineralisation, although pyrite is more abundant and the dominant copper sulphide is chalcopyrite with bornite only being found mainly in the Lower Ore Schist unit. This dominance of chalcopyrite is why Chimiwungo is lower grade. Metallurgically the Chimiwungo Ore Schists behaves in the same way as Malundwe although the concentrate will be lower grade at around 30% because of the dominance of chalcopyrite (Garnham and Wright, 2003).

Figure 4-4 shows the a typical cross-section through Chimiwungo

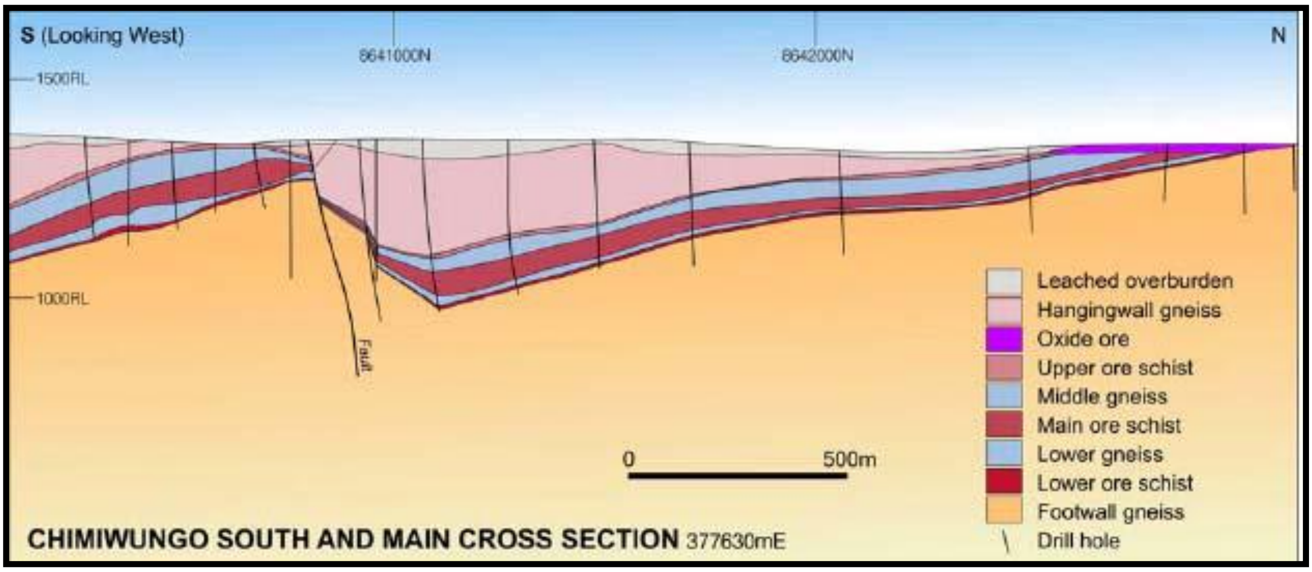



**Figure 4-4. Chimiwungo South and Chimiwungo Main Cross-Section (LMC, 2005)**

## 4.3 Hydrogeology

Geological interpretation, results from drilling (water strikes) and pumping tests are used to identify and characterize aquifers occurring in the study area. The distribution of water strikes in a borehole is evidence of the presence/absence of groundwater and can thus be used as a first assessment of whether the geological units are potential aquifers or aquitards.

The lithological logs from all the drilled boreholes were analysed and recorded. Two aquifer units were recognized within the geology.

**Unconfined aquifer**: This aquifer exists within the highly weathered and leached overburden. It is defined by primary porosity of the poorly sorted material of the near surface geological horizon (Figure 4-5).

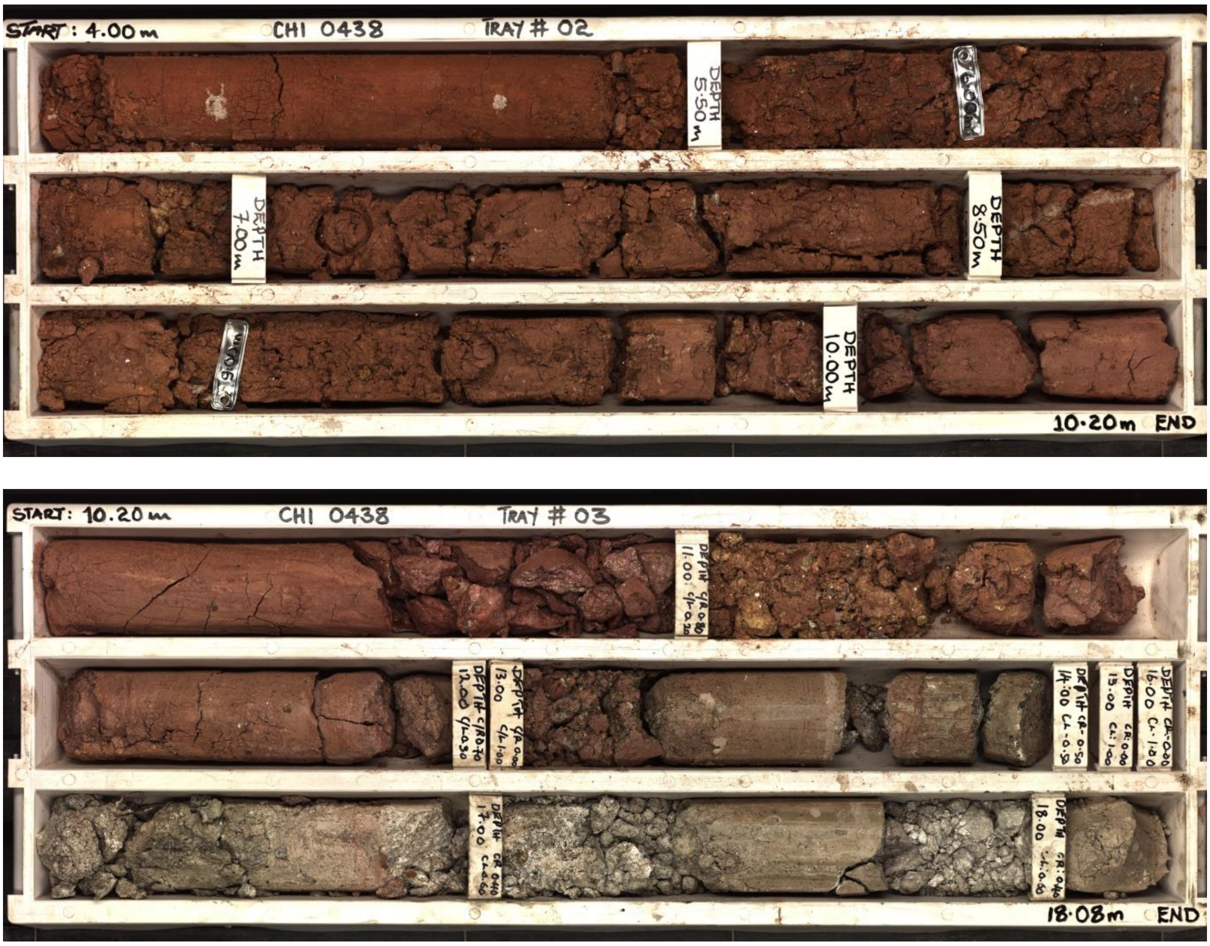



Figure 4-5. Leached overburden

**Confined/fractured aquifer**: The aquifer is heterogeneous, typical of fractured aquifers where flow takes place along fractures, contacts and joints. The fracture zones are associated with high transmissivity values, unlike the rest of the un-fractured rock (matrix) (Figure 4-6).

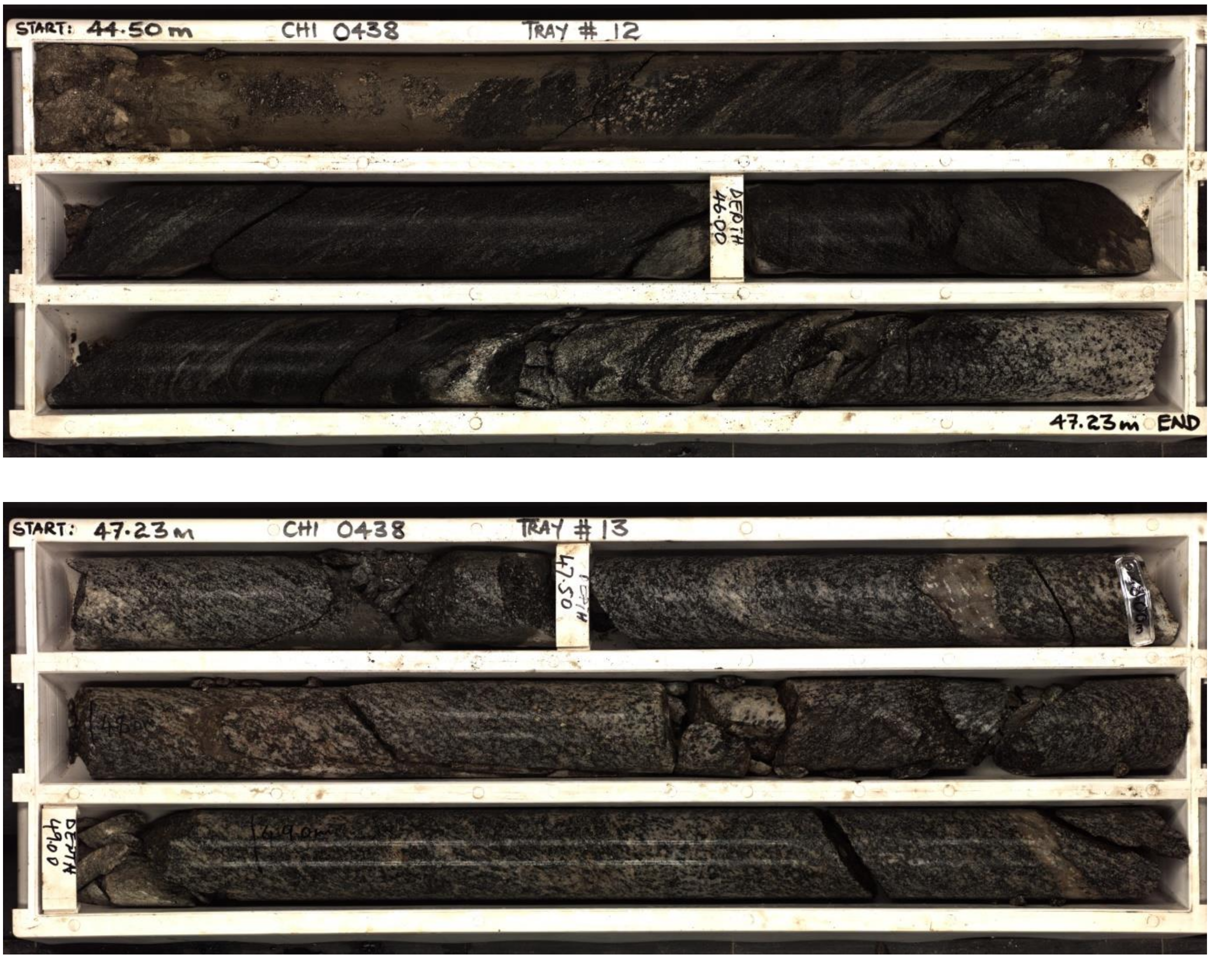



Figure 4-6. Fractured rock horizon

Neither aquifer at Chimiwungo has the potential for yielding large volumes of water, as indicated from the results of the pumping tests carried out during the Bankable Feasibility Study (Garnham and Wright, 2003). This idea is further reinforced by blow yields measured during the latest hydrogeological drilling programme. It is therefore concluded that both aquifers may be classified as minor aquifers.

A more technical analysis of the hydrogeology is described in Chapter 7 in which the conceptual hydrogeological model is discussed.

# 5 FIELD INVESTIGATIONS

## 5.1 Hydrocensus

A Hydrocensus was carried out to establish background hydrogeological conditions and water use patterns within and around the Chimiwungo area. Data collected included the following:

- GPS co-ordinates of the borehole;
- Photograph of the water source;
- Owner;
- Existing equipment;
- Current use;
- Reported yield;
- Reported or measured depth;
- The static water level; and
- Field water quality testing.

The objectives of the hydrocensus were to:

- Conduct an overall reconnaissance survey of the study areas inspecting the surface water, geological and groundwater features;
- Identify the locations of boreholes; and,
- Measure groundwater levels in readily accessible boreholes to develop an up-to-date water level map that could be used to determine groundwater flow directions.

The hydrocensus also served as a reconnaissance tool for the planning of the next phase of the hydrogeological investigation, drilling, pump testing, sampling and analysis of water quality.

## 5.2 Site Selection

It was necessary to collate and examine existing material pertinent to the area. This included geological, geotechnical, hydrogeological and hydrological reports, maps, drilling logs and chemical analyses of water. Additionally, information about stream flows and surface runoff, as well as hydrological and geological data from open pit mining, was also considered.

A total of three drilling sites were selected where one pumping/monitoring hole and two piezometer boreholes would be drilled at each site. Each large diameter borehole was to be flanked by two small diameter piezometer boreholes, one shallow and the other one deep. The shallow piezometer would terminate in the hanging wall whereas the deep one would puncture the fault zone and extend into the footwall. The main objective of drilling boreholes to different depths was to establish the existence or absence of hydraulic connectivity between the weathered and fractured aquifers. Figure 5-1 shows the planned arrangement of boreholes at selected drilling sites.

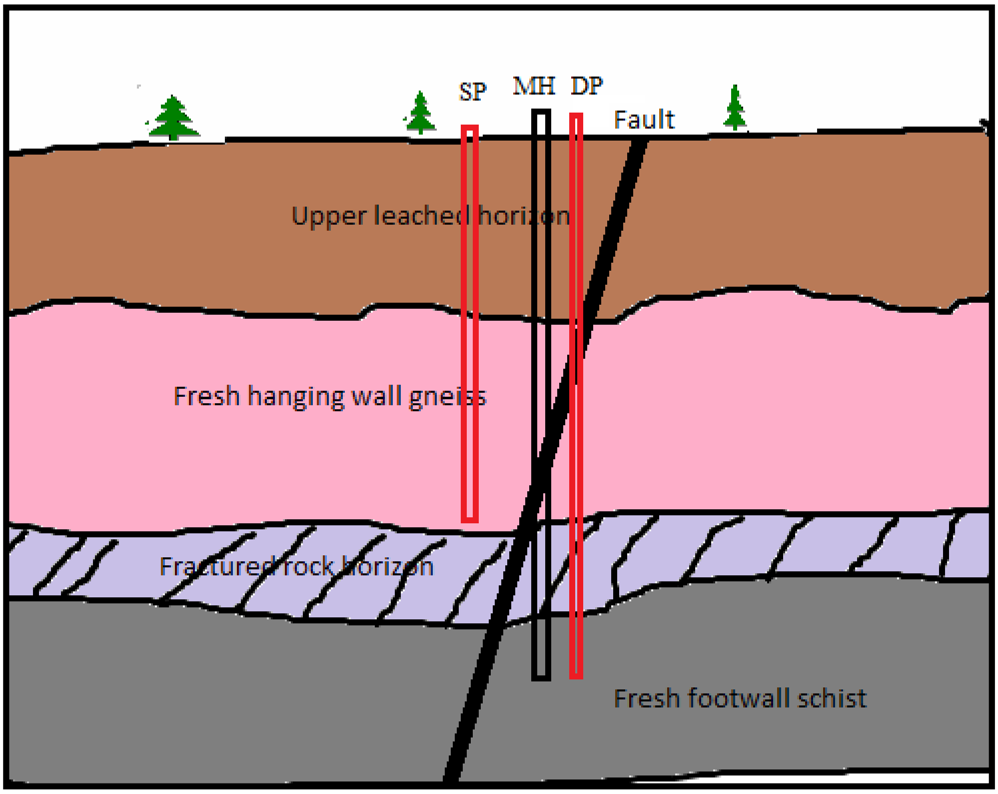



**Figure 5-1. Sketch of borehole positions at drilling sites**

**SP –Shallow small diameter hole. **MH** – Deep large diameter hole. **DP** –Deep small diameter hole*

### 5.2.1 Site Access

A major problem with site access came with the onset of the rainy season. Due to the high rainfall of the 2010/2011 season, the top soil within Chimiwungo became saturated with water. Low lying areas became inundated with runoff from higher topographical areas. Dirt roads that were used most frequently got damaged through the combined action of tyres and the ponding water. Figure 5-2 shows the access road to the drilling area for borehole MH06 in early December 2010.

An LMC contractor on site worked relentlessly to ensure that most of the access roads were rehabilitated. Where alternative access needed to be provided, dozers were brought in to blaze new trails. In instances, huge amounts of crushed rock had to be brought in and compacted onto the problem areas. The road works led to significant delays in equipment movement as rigs incessantly got stuck at several points along the access roads.


**Figure 5-2. Access road to MH06**

## 5.3 Drilling

Capital Drilling (Pvt) Ltd Zambia were contracted by Equinox to carry out the drilling of three large diameter monitoring boreholes and six adjacent piezometers boreholes. The Reverse Circulation (RC) drilling method was used but in instances where near surface geological materials were highly unstable, the Mud Rotary drilling method was employed. Bentonite was used as the drilling additive to aid in hole support.

Figure 5-3 shows the generalised borehole design.

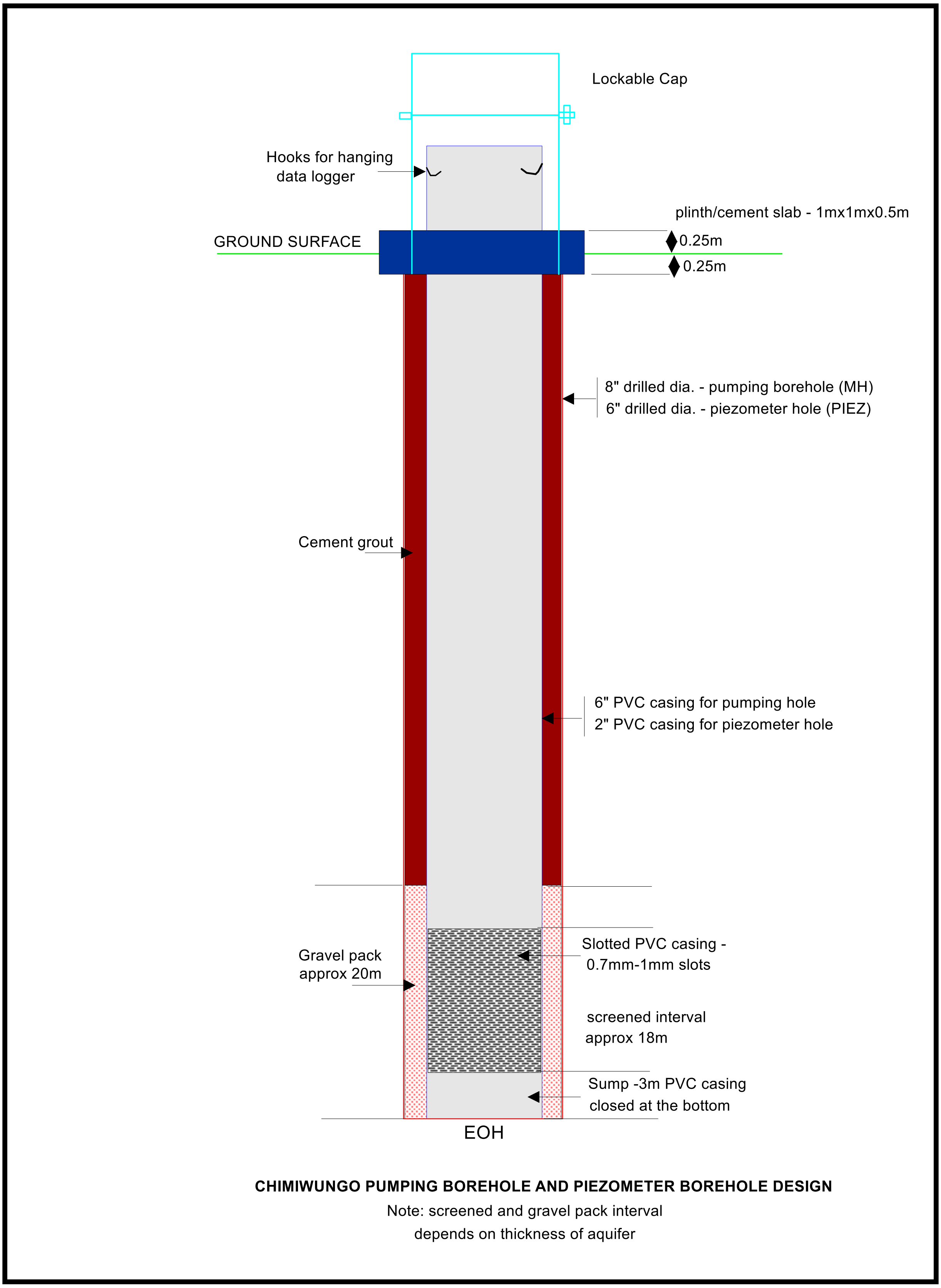



Figure 5-3. Chimiwungo Borehole Design

### 5.3.1 The Reverse Circulation Drilling Method

This drilling method makes use of a rotating bit under controlled loading crushing the geological formation. Cuttings are removed by sucking drilling fluid/air through the drill stem. It is essentially the same as normal rotary drilling except that the formation material around the hole remains generally undisturbed in RC drilling. This allows for rapid drilling through both unconsolidated and consolidated formations, and allows for continuous collection of the cuttings.

Figure 5-4 shows an RC drill rig in action in Chimiwungo and Figure 5-5 shows the diagram of a dual wall reverse circulation rotary method.


**Figure 5-4. RC Drill Rig in action**

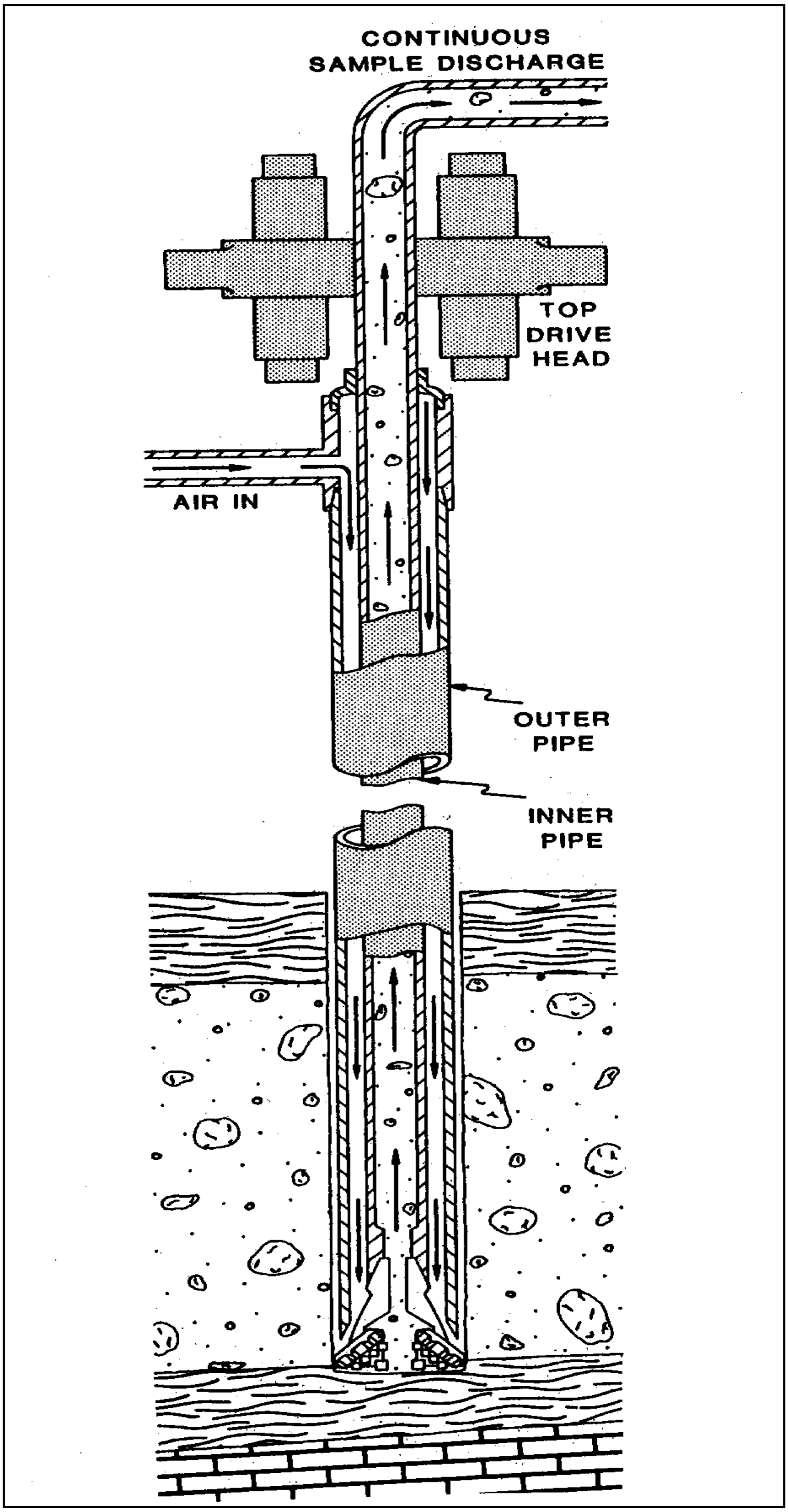



**Figure 5-5.** Diagram of dual-wall reverse-circulation rotary method (Driscoll, 1986)

### 5.3.2 Mud Rotary Drilling Method

In the direct- mud rotary method, the borehole is advanced by rapid rotation of a drill bit mounted upon the end of drill rods. The bit cuts and breaks the material at the bottom of the hole into small pieces (cuttings). The cuttings are removed by pumping drilling fluid (water, or water mixed with bentonite or other fluid enhancers) down through the drill rods and bit and up the annulus between the bore hole and the drill rods. The drilling fluid also serves to cool the drill bit and stabilize the borehole walls, to prevent the flow of fluids between the bore hole and surrounding earth materials, and to reduce cross contamination between aquifers (USEPA, 2003). Figure 5-6 shows a mud rotary drilling rig in action in Chimiwungo.

**Figure 5-6. Mud Rotary Drilling (MH05)**

## 5.4 Pumping Tests

It is essential to determine the hydraulic parameters of the aquifer including transmissivity, storage and well performance (specific capacity). The intention was to carry out pumping tests on all the three monitoring boreholes. The massive delays and the inability of the drilling contractor to complete the drilling programme forced the mine to defer pumping tests to a later date. Drilling was suspended in May 2011 and, by the time of submission of this thesis, still had not resumed.

## 5.5 Water Level Monitoring

*"Ground-water systems are dynamic and adjust continually to short-term and long-term changes in climate, ground-water withdrawal, and land use. Water-level measurements from observation wells are the principal source of information about the hydrologic stresses acting on aquifers and how these stresses affect ground-water recharge, storage, and discharge. Long-term, systematic measurements of water levels provide essential data needed to evaluate changes in the resource over time, to develop ground-water models and forecast trends, and to design, implement, and monitor the effectiveness of ground-water management and protection programs"* (USGS, 2001).

Groundwater level monitoring is necessary to achieve the following objectives:

- Mapping of groundwater flow paths for the study area;
- Estimation of groundwater recharge;
- Detection of long-term trends in an aquifer system; and,
- Detection of long term changes as a result of abstraction or climatic influences.

An electric contact water level meter was used in the regular measurement of groundwater levels. A spreadsheet of the measurements was maintained and updated after each monitoring event.

## 5.6 Water Quality Monitoring

The Environmental Department at Lumwana Mine has been monitoring both surface water and groundwater quality since October 2006. A low flow submersible pump is lowered into each borehole and used to purge the volume of groundwater that is stagnant within the hole. The approach used is dictated by the borehole construction and results in the collection of integrated samples. The sample obtained is integrated over the entire length of the screen as well as over the permeability of the formation. In many cases, groundwater compositions show major variations with depth, even on a small scale. Integrated samples from a screen interval of several meters may accordingly represent mixtures of waters with different concentrations and the mixing process may even induce chemical reactions during sampling. (Appelo and Posthma, 2007).

Figure 5-7 shows a map of groundwater sampling points and Figure 5-8 shows the spatial location of surface water sampling points.

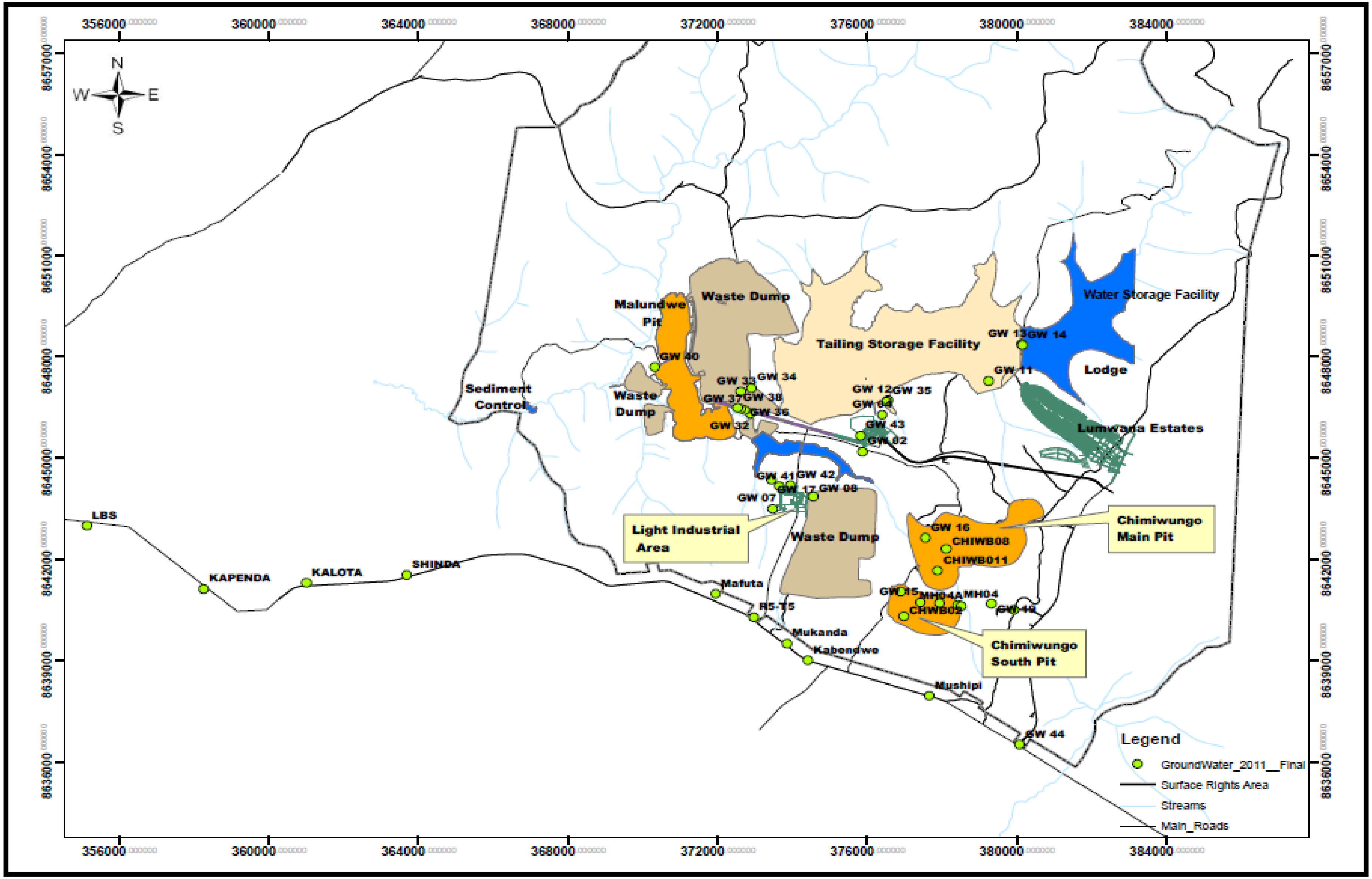



**Figure 5-7. Location of groundwater sampling points (LMC Environmental Department)**

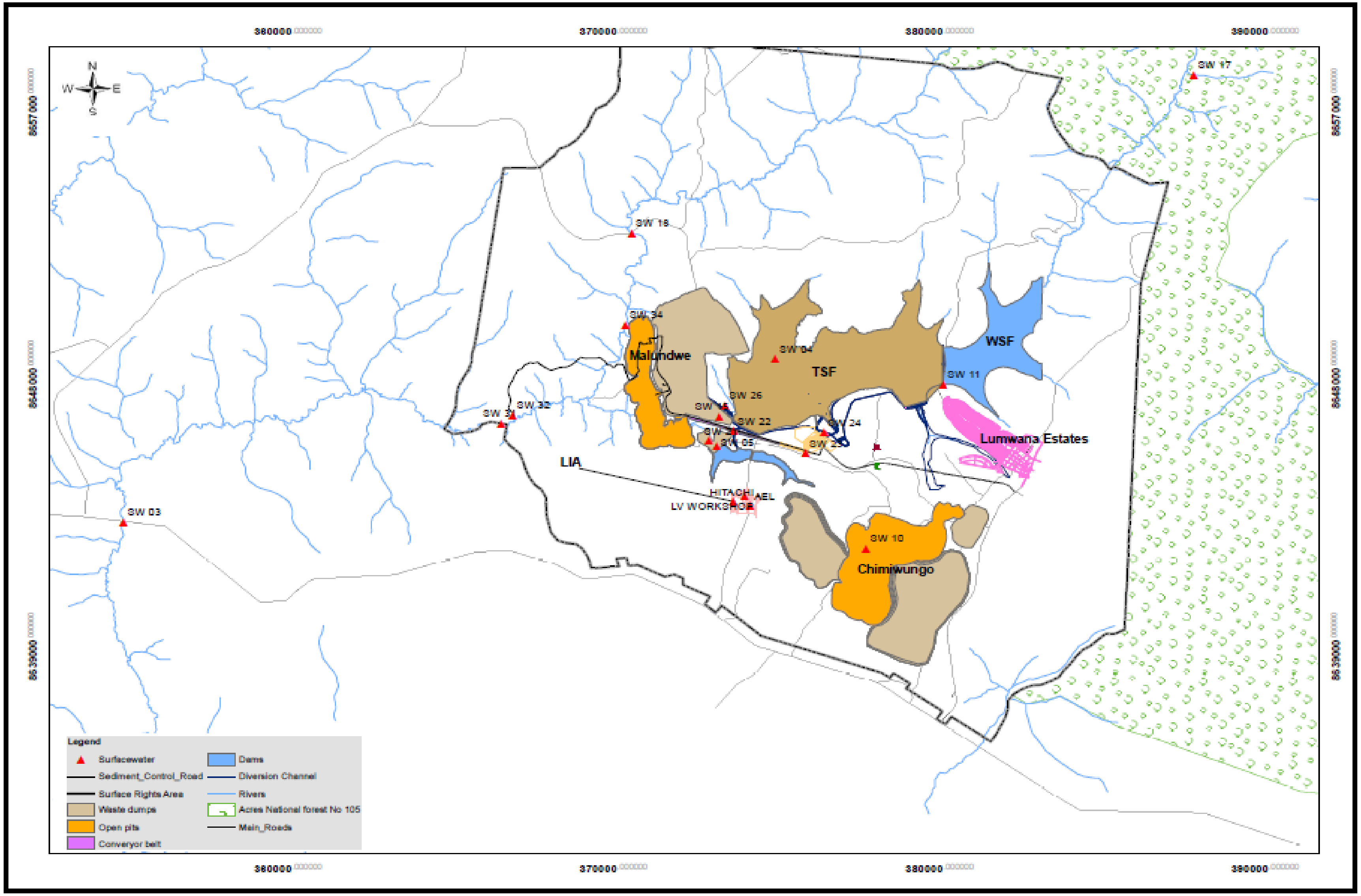



Figure 5-8. Location of surface water sampling site (LMC Environmental Department)

# 6 RESULTS OF FIELD INVESTIGATIONS

## 6.1 Hydrocensus

An initial groundwater source Hydrocensus was carried out at the Chimiwungo deposit in September 2010. The process remained open and ongoing throughout the project period. In September 2010, nine old boreholes were located and used for water level and water quality monitoring (Table 3). The majority of boreholes located during the hydrocensus were those drilled by Golder Associates in the 2003 Bankable Feasibility Study. Figures 6-1 to 6-9 show photographs of the boreholes identified during the hydrocensus, while the positions of these boreholes are shown in Figure 6-10.

**Table 3. Boreholes identified during hydrocensus**

| Borehole | GPS Coordinates (UTM 35L) WGS84 | | Elevation (mamsl) | Depth (m) |
|---|---|---|---|---|
| | X | Y | | |
| **CHWB 002** | 376,980 | 8,640,300 | 1,370 | 150 |
| **CHWB 005** | 377,429 | 8,640,701 | 1,364 | 143 |
| **CHWB 006** | 377,935 | 8,640,677 | 1,355 | 204 |
| **CHWB 007** | 376,897 | 8,641,032 | 1,378 | 132 |
| **CHWB 011** | 377,897 | 8,641,631 | 1,349 | 174 |
| **CHWB 012** | 377,553 | 8,642,615 | 1,346 | 126 |
| **EQ CH 229** | 377,269 | 8,642,914 | 1,338 | 72 |
| **EQ CH 238** | 377,258 | 8,643,098 | 1,346 | 45 |
| **EX M 001** | 377,550 | 8,642,447 | 1,337 | 7 |


**Figure 6-1. Borehole CHIWB002**


**Figure 6-2. Borehole CHIWB005**

Figure 6-3. Borehole CHIWB006

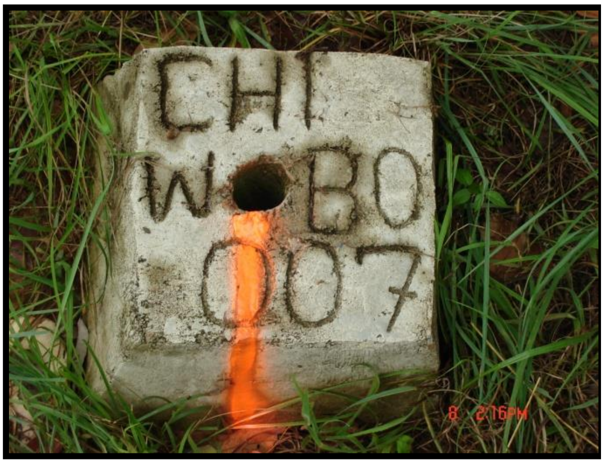



Figure 6-4. Borehole CHIWB007


Figure 6-5. Borehole CHIWB11

Figure 6-6. Borehole CHIWB12

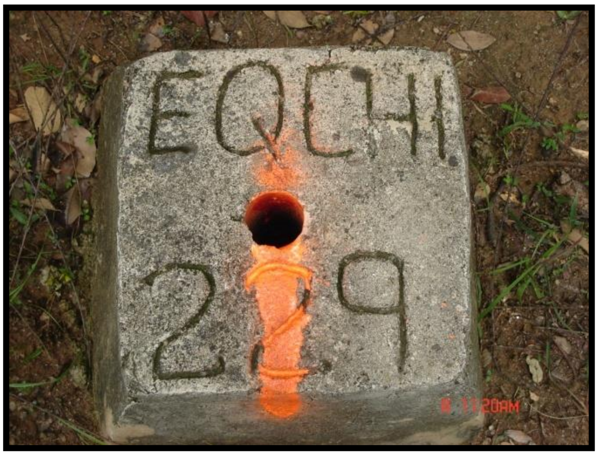



Figure 6-7. Borehole EQCHI229


Figure 6-8. Borehole EQCHI238

Figure 6-9. Borehole EXM001

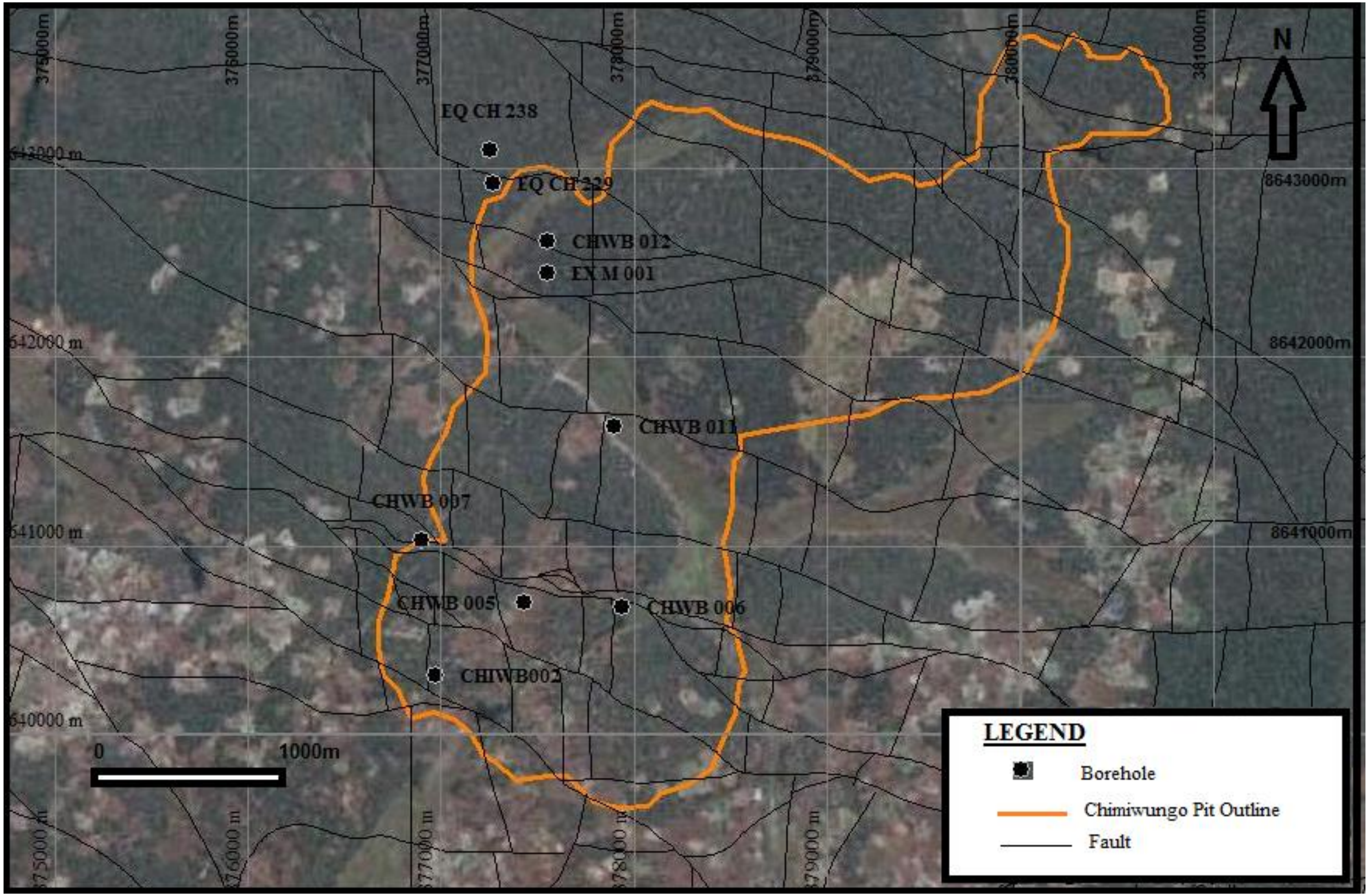



Figure 6-10. Boreholes identified during initial hydrocensus

## 6.2 Site Selection

Borehole drilling targets were selected on the basis of the geological model developed by the Lumwana Mine Exploration team. The geology of Chimiwungo has been defined by a combination of field mapping and exploration drilling. Two exploration drilling programmes were carried out, the first one in 2003 and the second one in 2010/2011. The hydrogeology drilling sites targeted zones of geological discontinuities and weakness such as fault zones. Major fault zones exist in Chimiwungo. Geophysics was not used as the mine felt that the exploration drilling had managed to define the geology to a great degree of certainty.

Table 4 lists the selected drilling positions and the criteria used to target them and Figure 6-11 is a map showing their relative locations.

**Table 4. Site Selection Criteria**

| SITE | TARGET | CRITERIA |
|---|---|---|
| MH04 | Targets on northern margin of Chimiwungo South fault | Evaluation of aquifer characteristics of Chimiwungo South fault |
| MH05 | Targets selected across a fault dipping 55 degrees to the north. | Determine whether fault acts as hydrogeological barrier or groundwater conduit |
| MH06 | Targets selected along a fault dipping 55 degrees to the north | Evaluation of aquifer characteristics of fault |

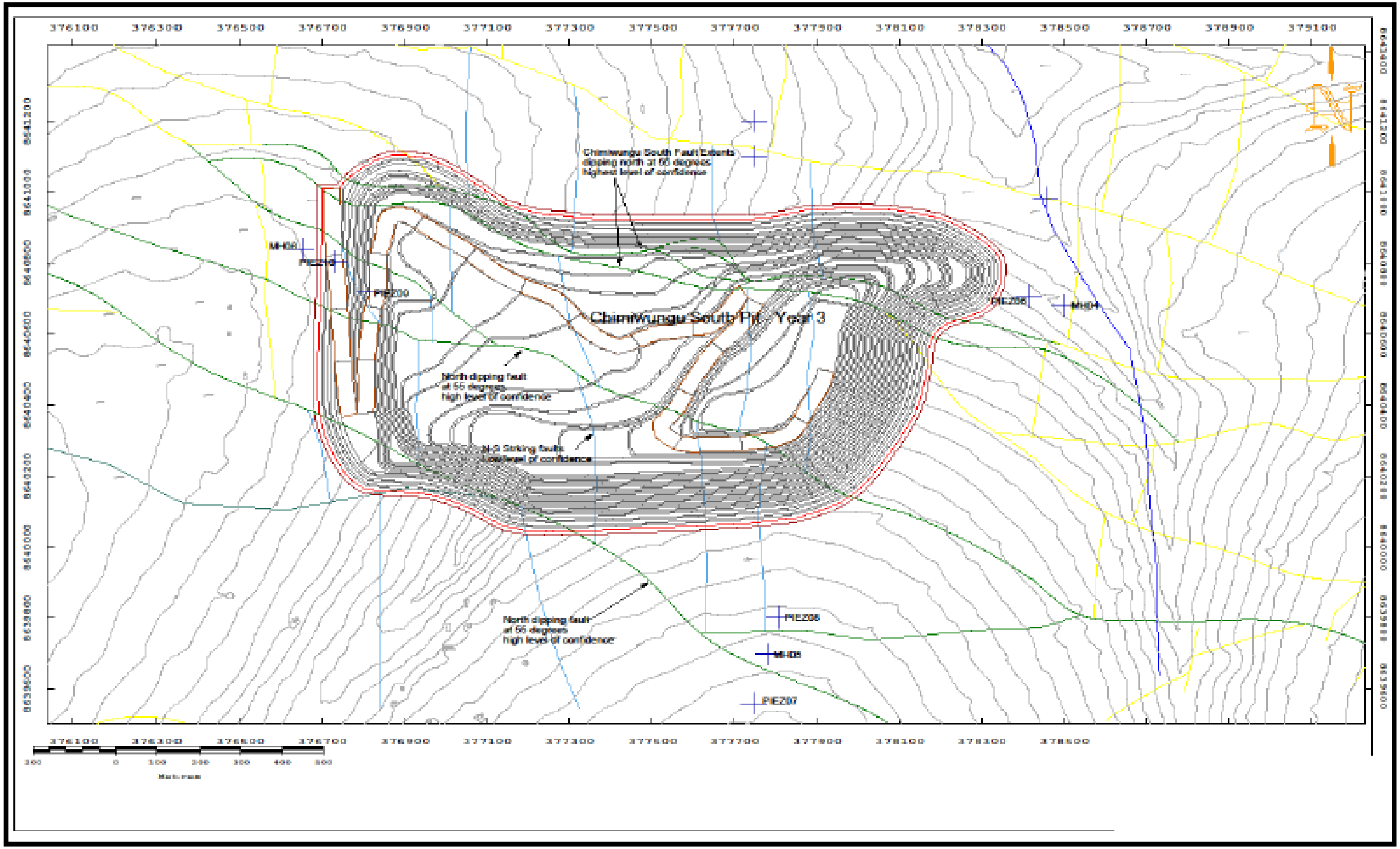



**Figure 6-11. Chimiwungo Drilling Positions (LMC Geotech Department)**

## 6.3 Drilling

The drilling of monitoring boreholes and piezometer holes at Chimiwungo started in September 2010 and Capital Drilling (Pvt) Ltd was the drilling contractor. KLM Consulting Services provided consultancy services and supervision of the drilling process.

The drilling process in Chimiwungo was plagued by incessant collapses of the near surface horizons of the geology. The near surface laterites and clayey formations (highly decomposed schists which make up the top 25 – 35 m of the geology at Chimiwungo) swell due to the intake of water from adjacent aquifers and collapse as water from intersected water strikes destabilizes the material. This impedes the installation of surface casing and makes for difficult drilling as the same lithological material has to be flushed out again and again.

Initially, a strategy was adopted to drill piezometer holes at a 60° angle (30° from vertical) to facilitate the best chance of locating the faults and other water bearing structures. Vertical monitoring holes (for pump testing) would then be located on the basis of the results. After repeated collapses of the inclined boreholes it was decide to drill all the remaining boreholes vertically (90° angle with the surface). A total of three boreholes were abandoned due to collapse and the driller struggled to complete the remaining holes. Three different drill rigs and crews attempted to carry out the drilling process with less than optimal success. The drilling programme was suspended after successive failures and the drilling results presented in this thesis are for those boreholes completed by 9 May 2011. Table 5 presents a summary of the boreholes drilled while Figure 6-11 shows the positions of the boreholes relative to the Chimiwungo South pit.

Borehole MH04 was drilled to a depth of 70 mbgl at a diameter of 10”. A water strike was intersected at a depth of 48 mbgl. Upon attempting to install casing, 16 m of PVC casing fell down the hole and could not be recovered. The hole was abandoned and earmarked for use as a groundwater level monitoring point.

The drilling of a replacement hole, MH04A commenced on 18 September 2010. The borehole was drilled at 12” drilling diameter from ground surface to 31 mbgl and then lined with 21 m of 10” PVC casing. Drilling then continued at 8” diameter down to 56 mbgl. A low yielding water strike was intersected at 48 mbgl. Thereafter the borehole was lined with 6” diameter PVC solid and slotted casings which did not reach the bottom, but stopped at 42 mbgl. A decision was made to declare the borehole complete.

The next borehole to be drilled was a small diameter piezometer well (PIEZO 06), starting on 29 September 2010. It was drilled at an angle of 30° to the vertical, at a diameter of 5.5” to a depth of 80 mbgl. A water strike was intersected at 58 mbgl. PVC casing of 2” diameter was then successfully installed down to the bottom of the hole. A gravel pack was inserted successfully prior to grouting of the overlying annular space and construction of the well head block.

Drilling commenced at PIEZO 09 on 11 October 2010. The borehole was drilled from surface to 140 mbgl, terminal depth. Water strikes were observed at 76 mbgl, 107 mbgl and 123 mbgl. Due to the heavily collapsing weathered regolith, no yield could be measured. After completion of drilling, the borehole was cleaned to the bottom and 2” (51 mm) PVC casing was installed. Screened lengths were installed from 104 mbgl to 134 mbgl to cover the water strike depths. Solid lengths were installed from 0 to 104 mbgl and from 134 mbgl to 140 mbgl. The entire column of casing got stuck inside the drill stem and the driller tried to flush out the drill cuttings using high density drilling fluid to free the casing. It proved impossible to extricate the PVC casing stuck inside the drill rods at PIEZO 09. The casing was eventually removed by cutting it up, rendering most of it unusable. A decision was made to abandon the hole and drill at an alternative position, 30 m to the south of PIEZO 09.

Drilling of the replacement hole (PIEZO 09A) commenced on 19 October 2010. The borehole was drilled from surface to 140 mbgl, terminal depth. Water strikes were observed at 25 mbgl, 56 mbgl, 86 mbgl, 104 mbgl and 115 mbgl. Lithological logging shows that the Chimiwungo South fault zone was encountered at drilling depths of 121 mbgl to 124 mbgl. Due to the heavily collapsing weathered regolith, no yield could be measured. After completion of drilling, the borehole was cleaned to the bottom and 2” (51 mm) PVC pipes were installed. Screened lengths were installed from 104 mbgl to 134 mbgl to cover the water strike depths. Solid lengths were installed from 0 to 104 mbgl and from 134 mbgl to 140 mbgl. The entire column of casing got stuck inside the drill stem and the driller tried to flush out the drill cuttings using high density drilling fluid to free the casing. Similar to what happened at PIEZO 09, it proved impossible to extricate the PVC casing stuck inside the drill rods at PIEZO 09A. The casing was eventually removed by cutting it up, rendering most of it unusable. A decision was made to abandon the hole and drill at an alternative position, 60 m to the south of PIEZO 09A after drilling a monitoring hole.

**Table 5. Summary of boreholes drilled**

| Borehole | Depth(m) | Drilled Diameter (mm) | Casing diameter (mm) | Status | Comments |
|---|---|---|---|---|---|
| MH04 | 70 | 203 (8") | 152 (6") | Salvaged for water level monitoring | 16 m of 6" PVC casing was dropped during installation. Was intended for test pumping hole, now used for water level monitoring |
| **MH04A** | 56 | 203 (8") | 152 (6") | COMPLETE | Replacement for MH04. Test pumping borehole. Cased to 42 mbgl and open from 42-56 mbgl |
| PIEZ06 | 80 | 140 (5.5") | 51 (2") | COMPLETE | Piezometer for water level monitoring |
| | | | | | |
| **MH06** | 113 | 203 (8") | | ABANDONED | Drilling was not successful due to collapsing ground conditions |
| MH06A | 130 | 140 (5.5”) | | ABANDONED | Drilling was not successful due to collapsing ground conditions |
| PIEZ09 | 140 | 140 (5.5”) | | ABANDONED | Drilling was not successful due to collapsing ground conditions |
| PIEZ09A | 140 | 140 (5.5") | | ABANDONED | Drilling was not successful due to collapsing ground conditions |
| PIEZ09B | 78 | 140 (5.5") | | ABANDONED | Drilling was not successful due to collapsing ground conditions |
| PIEZ09C | 95 | 140 (5.5") | 51 (2") | COMPLETE | Drilled to 120 mbgl, Cased to 95 mbgl |
| PIEZ010 | 130 | 140 (5.5") | 51 (2") | COMPLETE | Piezometer for water level monitoring |
| | | | | | |
| **MH05** | 275 | 203 (8") | | ABANDONED | 230 m of drill rods broke off and fell into hole. Fishing unsuccessful |
| PIEZ07 | 275 | | | OUTSTANDING | Piezometer for water level monitoring |
| PIEZ08 | 117 | 140 (5.5") | 51 (2") | COMPLETE | Piezometer for water level monitoring |

Drilling of the monitoring well (MH06) commenced on 30 October 2010. The borehole was drilled (5.5" diameter) and reamed (12" diameter) from surface to 39 mbgl depth. Water strikes were observed at 29 mbgl and 34 mbgl. Plain PVC casing of 10"diameter was installed to a depth of 22 mbgl. The well was then drilled deeper to 111 mbgl at a diameter of 5.5", where the drill rods and bit got stuck on 5 November 2010. They were eventually pulled out on 13 November 2010 and the hole was reamed to 8'' diameter before drilling (8'' diameter) to the current depth of 113 mbgl. The drill bit and rods got stuck again at 113 mbgl depth due to collapsing conditions within a fault zone. A decision was made to swop the rig with a new rig with greater capacity to drill deep holes.

Drilling of the second PIEZO 9 replacement hole (PIEZO 9B) commenced on 22 November 2010. PIEZO 9 and its first replacement PIEZO 9A were lost due to collapse. It was decide that all remaining holes would be drilled vertically, at an angle of 90° to the ground. PIEZO 9B hole was drilled (5.5"diameter) to 42 mbgl and reamed (10.5"diameter) from surface to 29 m depth. Water strikes were observed at 30 mbgl (seepage) and 55 mbgl. Solid PVC casing of 8"diameter was installed to a depth of 22 mbgl. A crew from another rig was brought in to put in a grout seal in the annular space on the evening of 23 November 2010. The crew only cast a surface well head block without the requisite seal. As a result, when drilling commenced, mud started gushing out from under the block, causing collapse of the hole close to surface. The well head block had to be broken to allow re-grouting of the annular space. Drilling (at diameter 5.5" resumed after the grouting was in place but the hole continued to collapse and the hole was terminated at a depth of 78 mbgl. Attempts to install 6" PVC casing down to 29 mbgl were unsuccessful. The driller declared the hole lost and moved to a new position 15 m west of PIEZO 9B to drill a replacement hole (PIEZO 9C).

Commencing on 26 November 2010, PIEZO 9C hole was drilled (5.5"diameter) to 30 mbgl and reamed (8"diameter) from surface to 16m depth. Plain PVC casing of 6.5"diameter was installed to a depth of 16 mbgl. The borehole was then drilled to a depth of 120 mbgl at a diameter of 5.5". PVC casing of 2"diameter was installed in the hole down to 95 mbgl as the hole had collapsed beyond this depth. It was resolved to adopt PIEZO 9C as the shallow hole (tapping into hanging wall) and drill PIEZO 10 as the deeper one (tapping into footwall). Water strikes were observed at 8 mbgl, 21 mbgl (seepage) and 111 mbgl. The presence of additional water strikes is suspected between 40 mbgl and 85 mbgl due to the high degree of fracturing and advanced weathering in this horizon. The high pressures of compressed air used in the drilling process may have masked these water strikes.

The contractor commenced the retrieval of drill rods from MH06 on 12 January 2010. The process progressed very slowly till the last drill rod, hammer and bit emerged from the borehole on 15 January 2010. An assessment of the degree of collapse was made with the view of attempting to complete the hole to the desired depth and diameter, resulting in a decision to abandon the hole and drill a replacement one.

The drilling of PIEZO 10 commenced on 17 January 2010. The hole was drilled at a diameter of 5.5" to 48 mbgl and reamed at a diameter of 8" to the same depth. Plain PVC casing (6" diameter) was then installed down to a depth of 44 mbgl and firmly grouted in place. Drilling continued at a diameter of 5.5"down to the terminal depth of 130 mbgl. PVC casing with a 2" diameter was installed from surface to the bottom of the hole, 30 m being slotted casing. A washed gravel pack was then inserted into the annular space around the 2"casing from the bottom up to 80 mbgl. A cement grout was inserted into the annular space above the gravel pack up to the top of the hole. The drilling rig moved to the site for PIEZO 08 on 23 January 2011.

The drilling of PIEZO 8 commenced on 26 January 2010. The hole was drilled at a diameter of 5.5" down to 48 mbgl and reamed at a diameter of 8" to the same depth. Mud rotary drilling was used to clean and stabilize collapsing top weathered formations before installation of 6 inch casing to a depth of 46 mbgl. Work stoppages were experienced due to rig breakdown, thus delaying the drilling process. The borehole was then drilled to a depth of 117 mbgl at a diameter of 5.5". PVC casing with a 2" diameter was then successfully installed from the bottom of the hole to the surface. A washed gravel pack was inserted up to 60 mbgl and the annular space above it grouted up to the surface.

The next borehole, MH05 was drilled at a diameter of 8" down to 108 mbgl. Mud rotary drilling was used at a diameter of 12" to clean and stabilize collapsing top weathered formations before installation of 10" diameter casing to a depth of 37 m. The annular space was grouted and left to set overnight. The borehole was then drilled to a depth of 275 mbgl at a diameter of 8". On the day targeted for casing installation, the 230 m drill stem sheared off the drill table and fell into the hole. Retrieval efforts were unsuccessful and the hole was abandoned.

Drilling operations moved to the site for the replacement of borehole MH06 on 18 April 2011. The new drilling site was 15 m east of the failed MH06 and lay at the end of the well constructed access road. A 12" diameter hole was drilled to 42 mbgl and plain PVC casing (diameter 10") was installed along the entire length of the borehole. A pilot hole was then drilled at a diameter of 5.5"down to a depth of 131 mbgl. The differences in water strikes between MH06 and MH06A are due to the "rolling" nature of the fault structure and the adjacent lithologies. The fault structure changes its orientation within short distances.

Borehole MH06A was then reamed at a diameter of 8” from 42 mbgl down to 131 mbgl. Difficulties were encountered from 90 mbgl down to 131 mbgl due to collapse of material. The reaming process progressed very slowly due to collapse of material from near surface horizons and from within the fault zone (interpreted to have been intersected at 57 mbgl). Attempts to install 6” PVC casing were unsuccessful and additional cleaning efforts resulted in even greater collapses. A decision was made to try and install 2” PVC casing to convert MH06A into a piezometer instead of a monitoring borehole. The 2” PVC casing was lowered through a hollow drill stem down to the bottom of the borehole. Upon withdrawal of the drill stem, the casing also came up due to mud accumulating in the space between the casing and internal wall of the drill stem. The casing had to be cut out and the hole was declared lost and abandoned on 9 May 2011.

Figure 6-12 shows the massive fracturing within the fault zone. The samples were taken from an exploration hole drilled 60 m to the south of the MH06 site.

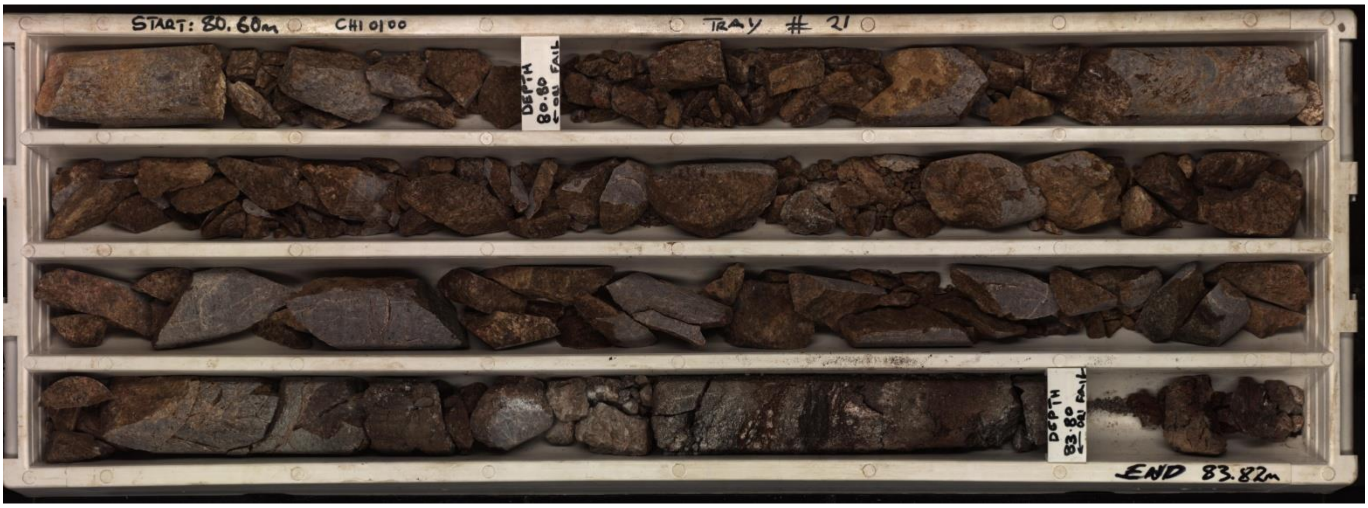



**Figure 6-12. Fault zone lithology**

Borehole construction and lithological logs are presented in Appendix A.

### 6.3.1 Water strikes and blow yields

Intersected water strikes ranged in depth from 4 mbgl to as deep as 123 mbgl. The shallow water strikes were taken to represent the weathered/ perched aquifer whilst the deeper water strikes were intersected within fracture zones. Blow yields were measured by using a V-notch plate across the channel draining water away from the drilling area. Blow yields ranged from minor seepages observed to 5.6 L/s. It is suspected that the drilling method used (Reverse Circulation) and the high degree of fracturing, in conjunction with the high drilling pressures, may also have affected the true blow yields of the water strikes. The high pressure may also have masked the true blow yields of the water strikes. It was not possible to measure the blow yield at PIEZO 6 as only thick mud emerged during drilling. Table 6 is a summary of the information on the water strikes intersected during drilling. Figure 6-13 is a map showing the locations of the boreholes drilled.

**Table 6. Summary of water strike information at Chimiwungo**

| BH ID | X | Y | Z | Depth (m) | Water Strikes Depths (m) | Blow out yield (m³/hr) | Geology at Water strike |
|---|---|---|---|---|---|---|---|
| MH04 | 378,475 | 8,640,601 | 1,352.3 | 56 | 48 | 5.4 | Fractured Gneiss |
| MH04A | 378,465 | 8,640,603 | 1,352.5 | 70 | 43, 48 | 5.5 | Fractured Gneiss |
| MH05 | 377,884. | 8,640,204 | 1,371.4 | 275 | 24, 78-91 | 0.72 | Schist, Fractured Gneiss |
| MH06 | 376,558 | 8,641,059 | 1,380.4 | 113 | 24, 51-62, 76 | 20 | Schist, Fractured Gneiss |
| MH06A | 376,568 | 8,641,058 | 1,380.2 | 131 | 40-41, 66, 93, 96, 98, 108, 120 | 0.5 | Schist, Fractured Gneiss |
| PIEZ06 | 378,395 | 8,640,624 | 1,353.8 | 80 | 58 | | Weathered Gneiss |
| PIEZ08 | 377,900 | 8,640,189 | 1,371.9 | 117 | 66, 84 | 0.72 | Schist, Fractured Gneiss |
| PIEZO10 | 376,603 | 8,641,057 | 1,380.8 | 130 | 28, 50, 114, 122 | 0.72 | Schist, Fractured Gneiss |
| PIEZO9C | 376,687 | 8,641,035 | 1,380.0 | 95 | 22, 111 | 2.52 | Fractured Schist |

## 6.4 Pumping Tests/Slug tests

Due to the massive delays in the drilling programme, it was deemed not feasible to carry out the pumping tests on the only completed monitoring borehole, MH04A. This was the biggest setback of the entire project as it became impossible to acquire reliable estimates of aquifer parameters.

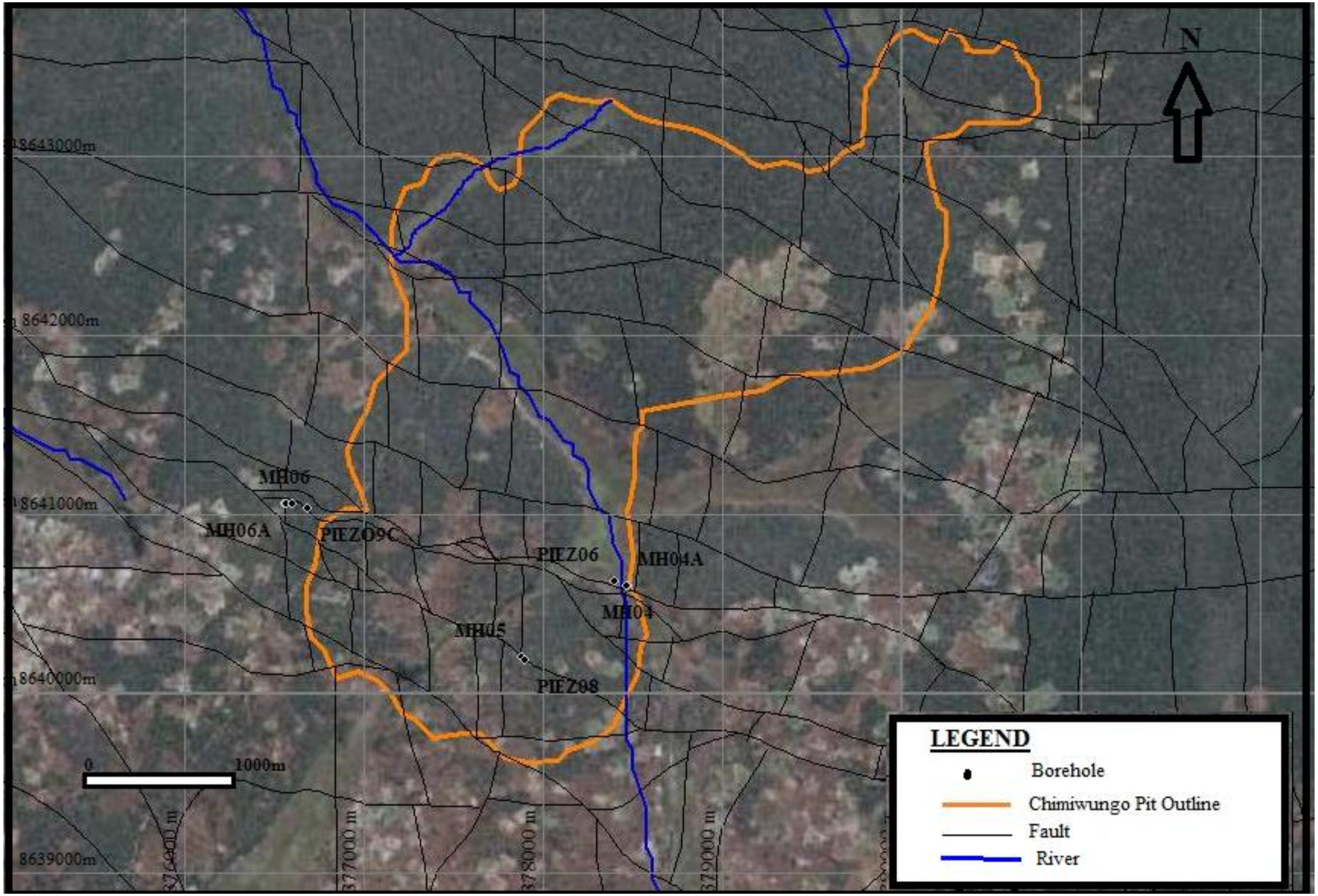



Figure 6-13. Locations of boreholes drilled in 2010/2011

## 6.5 Water level monitoring

Daily water level monitoring was initiated in September 2010 and was subsequently revised to weekly monitoring in December 2010. Boreholes identified during the earlier hydrocensus were all included in the monitoring network (Table 7). Any completed new boreholes were also immediately added to the network.

**Table 7. Boreholes on the Chimiwungo Groundwater level monitoring network**

| Borehole | GPS Coordinates (UTM 35L) | | Elevation (mamsl) | Depth (m) |
|---|---|---|---|---|
| | X | Y | | |
| **CHWB 002** | 376,980 | 8,640,300 | 1,369.9 | 150 |
| **CHWB 005** | 377,428 | 8640,701 | 1,364.438 | 143 |
| **CHWB 006** | 377,935 | 8,640,676 | 1,354.502 | 204 |
| **CHWB 007** | 376,897 | 8,641,031 | 1,377.5 | 132 |
| **CHWB 011** | 377,896 | 8,641,631 | 1,349.401 | 174 |
| **CHWB 012** | 377,552 | 8,642,614 | 1,345.882 | 126 |
| **EQ CH 229** | 377,268 | 8,642,914 | 1,338.283 | 72 |
| **EQ CH 238** | 377,257 | 8,643,097 | 1,346.482 | 45 |
| **EX M 001** | 377,550 | 8,642,446 | 1,336.54 | 7 |
| **EX M 002** | 376,943 | 8,640,604 | 1,375.426 | 26 |
| **GW18** | 379,937 | 8,640,480 | 1,377.867 | 21 |
| **GW19** | 379,326 | 8,640,663 | 1,365.397 | 22 |
| **KPCC_BH001** | 376,113 | 8,641,728 | 1,367.613 | 39 |
| **KPCC_BH004** | 376,333 | 8,645,170 | 1,363.592 | 19 |
| **KPCC_BH005** | 376,292 | 8,644,124 | 1,317.618 | 6 |
| **MH 04** | 378,475 | 8,640,601 | 1,352.25 | 56 |
| **MH 04A** | 378,465 | 8,640,602 | 1,352.463 | 70 |
| **PIEZO 06** | 378,395 | 8,640,624 | 1,353.75 | 80 |
| **PIEZO 08** | 377,900 | 8,640,189 | 1,371.929 | 117 |
| **PIEZO 09C** | 376,687 | 8,641,035 | 1,379.979 | 95 |
| **PIEZO 10** | 376,603 | 8,641,057 | 1,380.765 | 130 |

One of the boreholes drilled by Golder in 2003, CHIWB 007, was destroyed in mid-December 2010 during a bush clearing process (Figure 6-14). The borehole had exhibited a continually declining water level even well into the rainy season. CHIWB007 was situated in the centre of the future mining area and had to be destroyed to enable mining to proceed.

Figure 6-14. Destroyed borehole CHIWB007

Figure 6-15 shows the positions of the monitoring boreholes relative to the Chimiwungo pit.

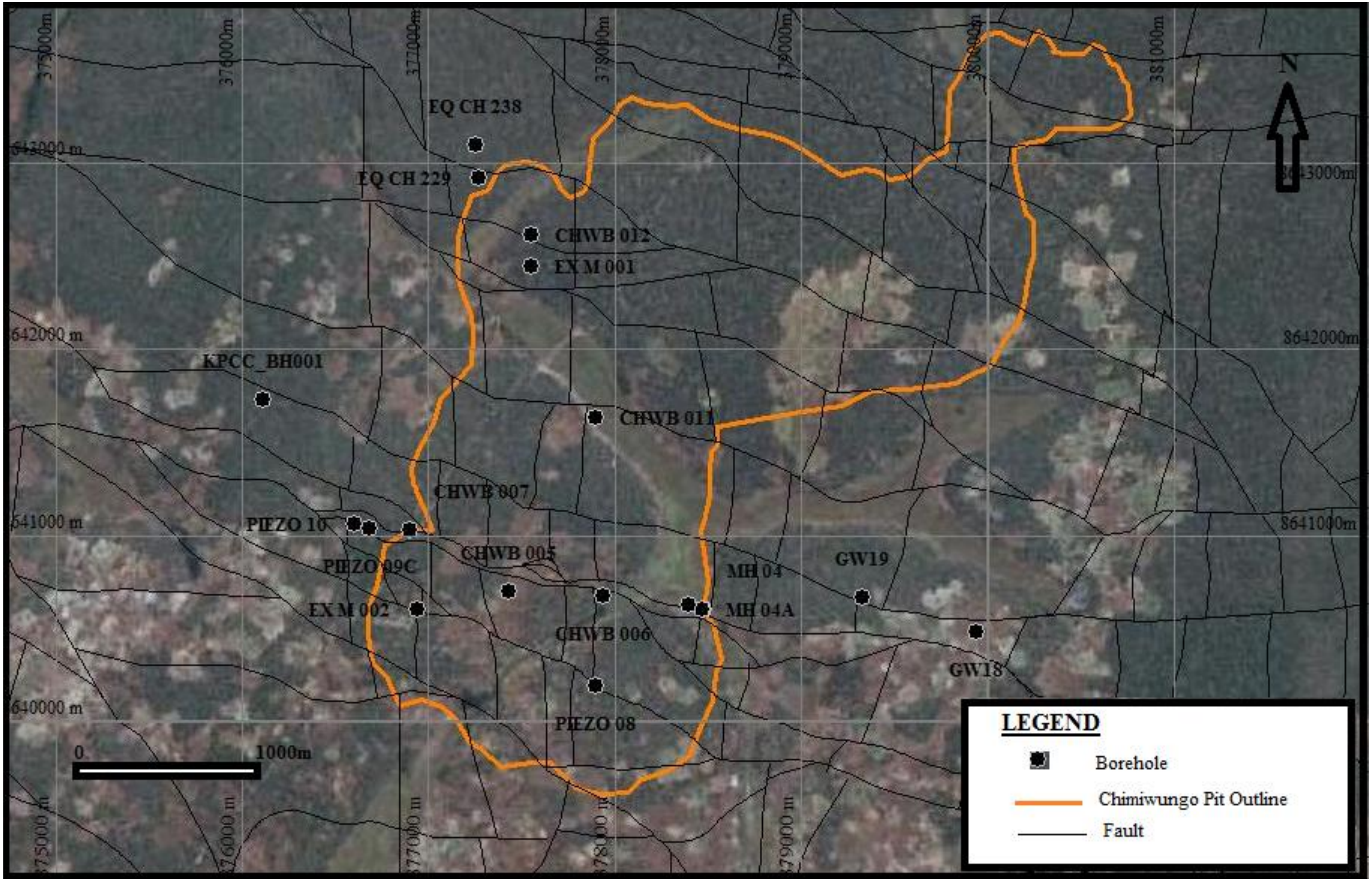



**Figure 6-15. Chimiwungo Groundwater Level Monitoring Network**

A preliminary assessment of the groundwater level trends was carried out on the basis of the overall trends observed during the 2010/11 rainy season and the following groups were defined:

1) Water levels showing continuous rise in water levels since beginning of rainfall season: MH04, MH04A and PIEZ 06 cluster east of Chimiwungo and close to Chimiwungo River and CHWB002 southeast of Chimiwungo (Figure 6-16). This trend was magnified by the large amount of rain that fell in the period mid-December 2010 to March 2011. Individual graphs of groundwater level elevation show that groundwater levels rise subsequent to heavy downpours of rain that are typical of this area.

2) Water levels showing a decline before the rainfall season, levelling off and showing water level rise following the heavy rains in mid-December 2010 to March 2011: CHWB011, CHWB012, PIEZO 09C and CHWB 006 north of Chimiwungo South pit in Chimiwungo North pit, EQCH238. Figure 6-17 shows the response in the groundwater levels in these boreholes from September 2010 to May 2011.

3) Water levels showing fluctuations (Figure 6-18): EMX001 and EQCH229-located close to streams and with water levels less than 2m below ground level. The sharp groundwater level rises indicate rapid recharge following rainfall events and the decreases arise from evaporation (transpiration due to very shallow depths) and discharge to adjacent surface water drainage systems. The fluctuations produced a net groundwater level rise up to the end of March 2011. These boreholes are located north of Chimiwungo South pit, and in Chimiwungo North pit.

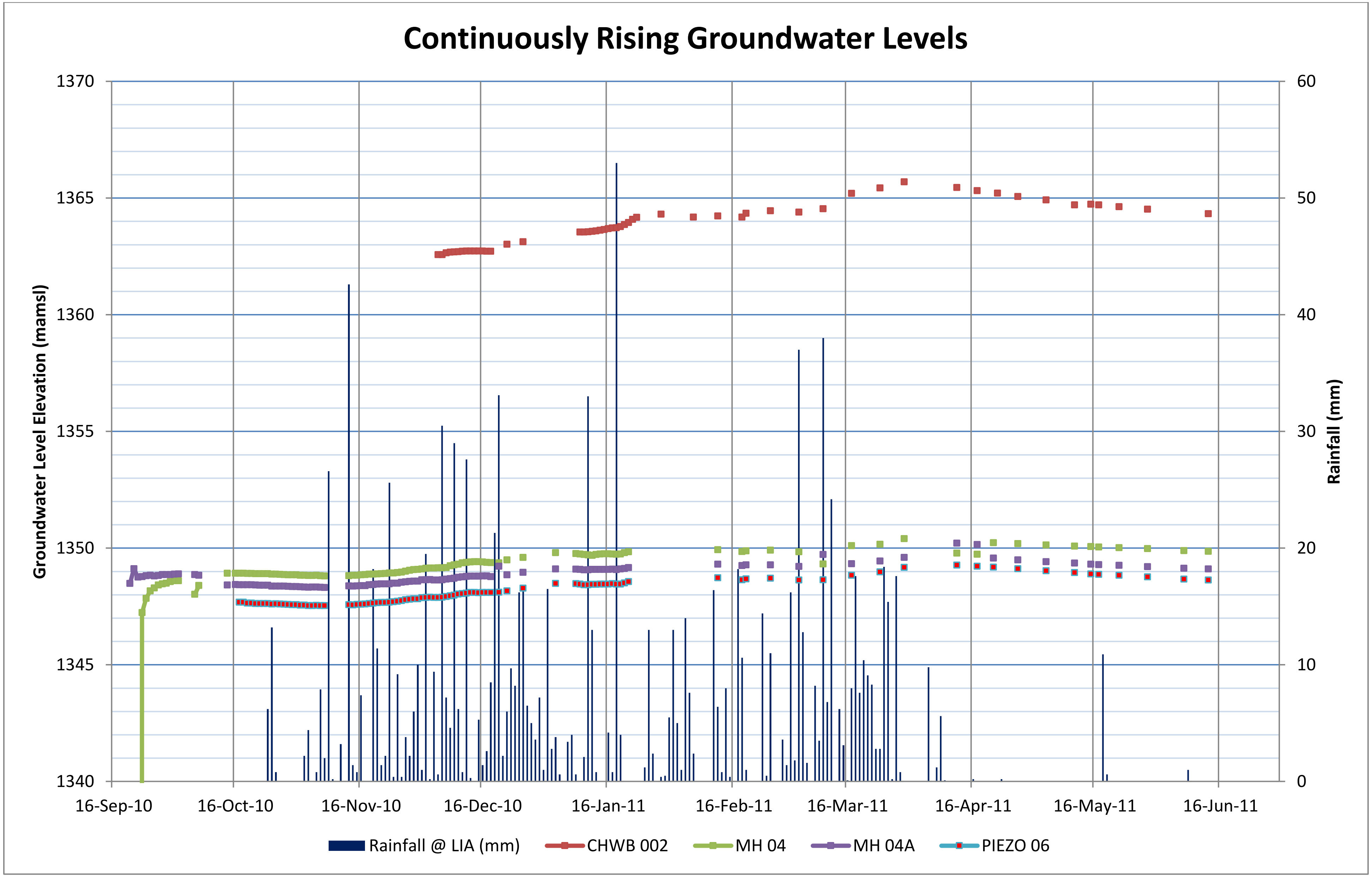



**Figure 6-16. Water levels showing continuous rise since the beginning of the rainy season**

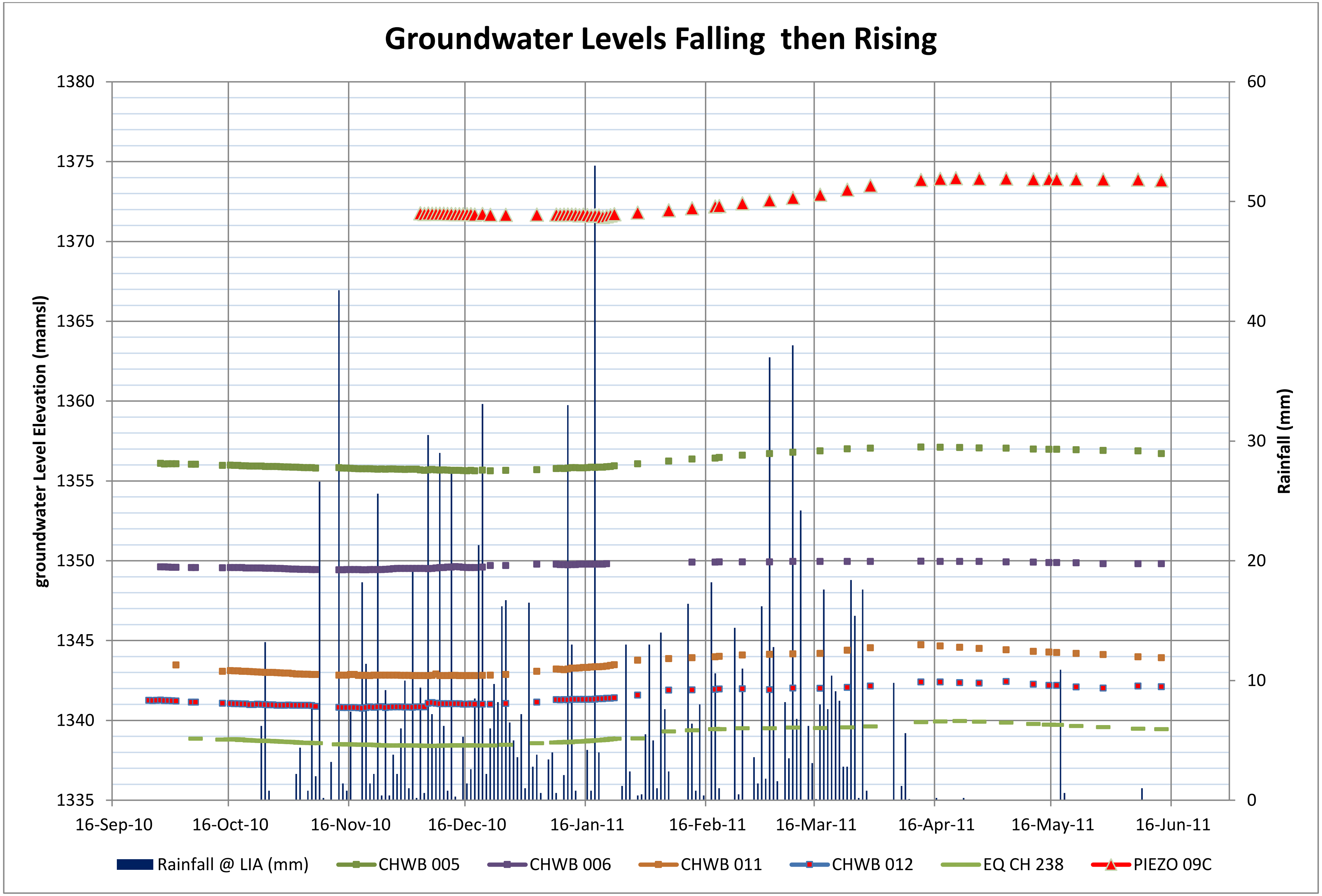



Figure 6-17. Water levels showing continuous decline, levelled off and then rising

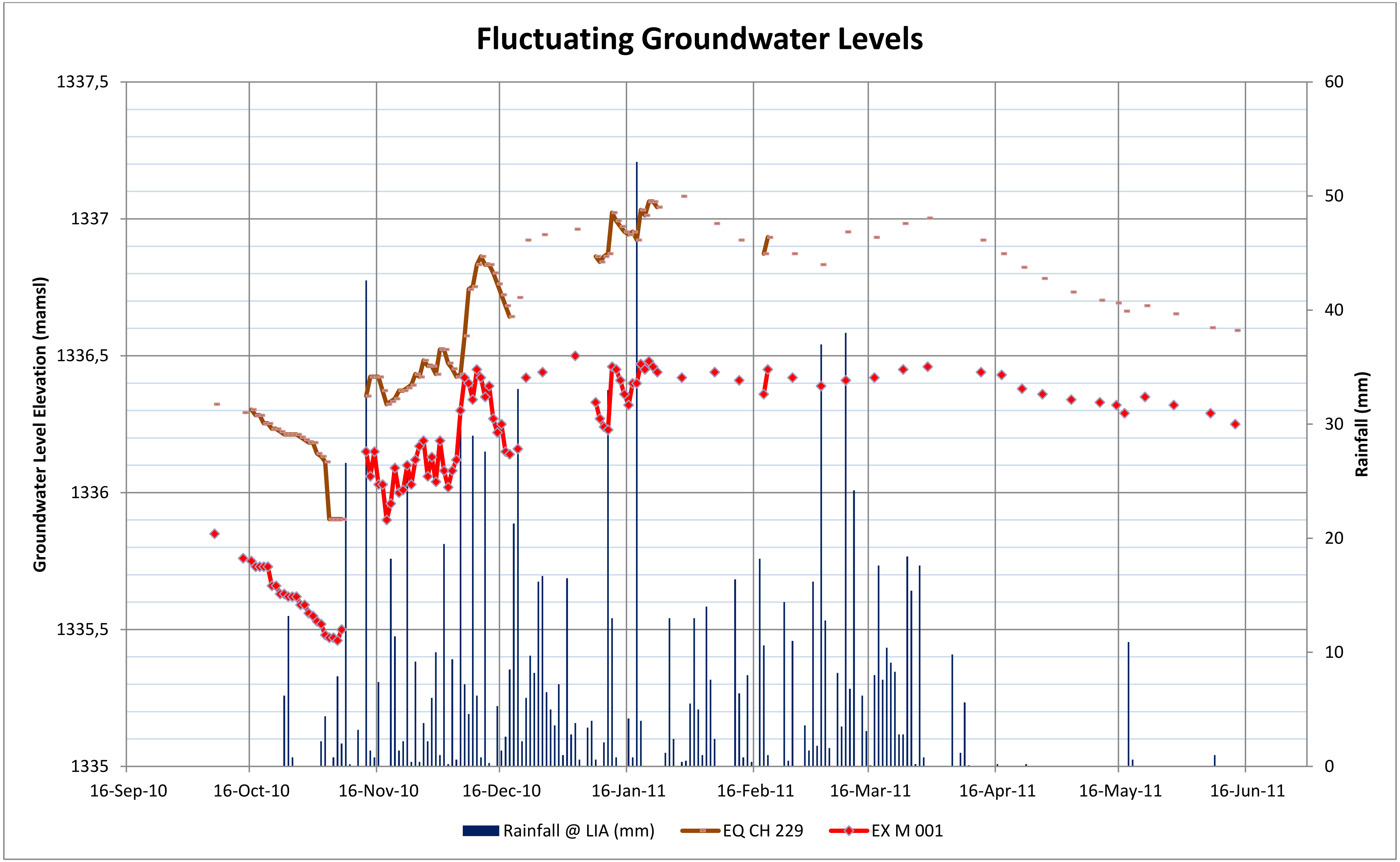



Figure 6-18. Water levels showing fluctuations

A plot of groundwater level elevation against topographic elevation (Figure 6-19) displays a very high degree of correlation (98%), evidence that the groundwater level elevation mimics the topography. This observation suggests that the aquifers being investigated are either unconfined or semi-confined/leaky. The only borehole that does not fall with the correlation line is MH04A which may represent the confined aquifer. This is because solid casing was installed at the top, thus isolating water from the weathered horizon.

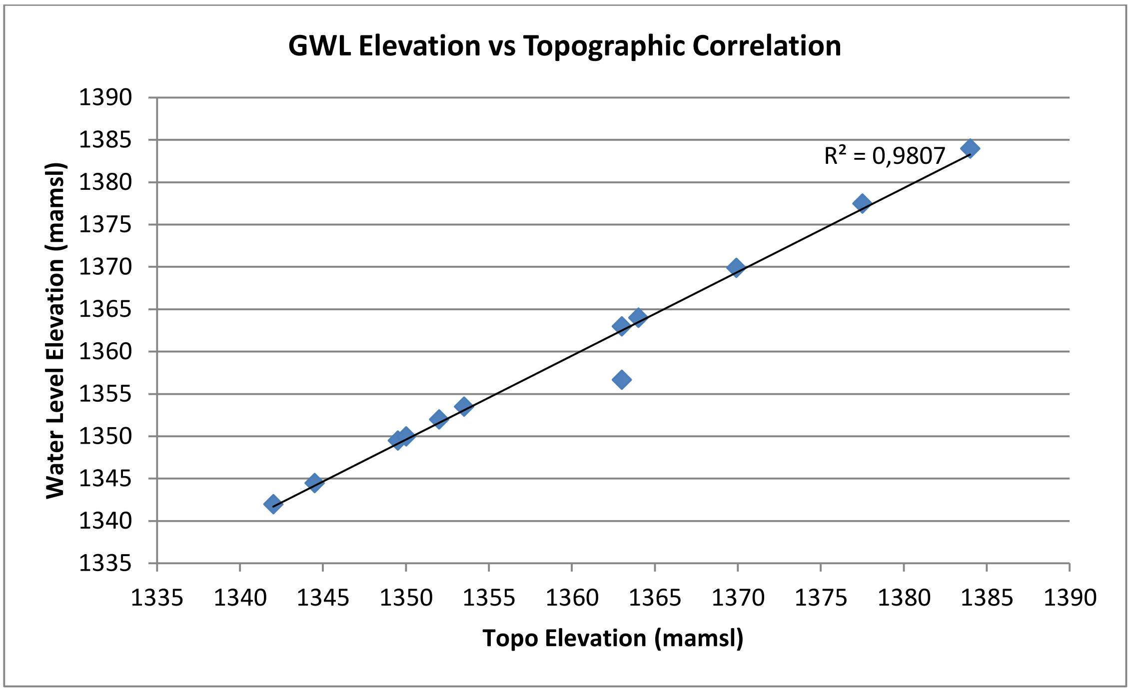



**Figure 6-19. Correlation between groundwater level elevation and topographic elevation**

A piezometric map plotted from the groundwater level data of 15 May 2011 is shown in Figure 6-20. In the south-western part of the study area, the piezometric levels display elevated hydraulic heads and steep gradients to the north and north-east. This lends credence to the hypothesis that this area forms the recharge zone and drains to the north and north east. Recharge is dominant in areas that are truncated by a dense network of fault structures and low lying areas.

The recently drilled boreholes in the south-west and south-east have intersected fault structures during drilling. Groundwater levels throughout the Chimiwungo area rose to levels much higher than at the onset of the rainy season as the rains continued to fall. A delayed response was noted in the northern part of Chimiwungo, signifying that this zone probably receives recharge through lateral flow from the south-western portion of the study area where the groundwater level elevation shows immediate responses to rainfall.

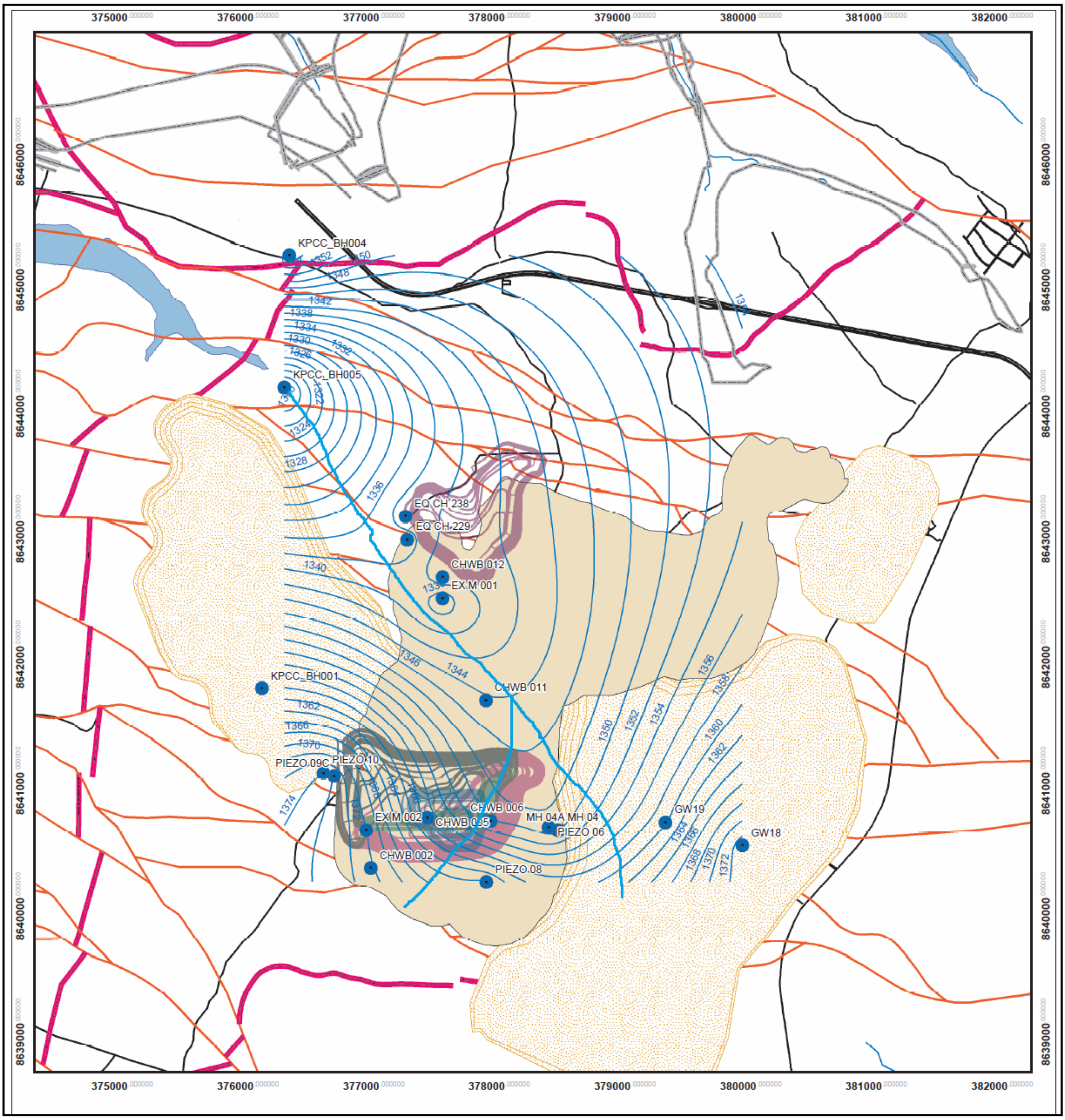



**Figure 6-20. Piezometric map of Chimiwungo (May 2011)**

## 6.6 Long-term groundwater monitoring

Groundwater levels in boreholes CHWB005 and CHWB012 have been monitored on a monthly basis since October 2006 (refer to Figure 6-15 for the positions of these boreholes relative to the Chimiwungo pit). The long-term monitoring data has been updated and plotted together with monthly rainfall totals. The groundwater levels show typical groundwater hydrograph cycles; pronounced rises following periods of heavy rainfall and significant drops during dry periods (Figure 6-21 and Figure 6-22). These responses may be an indication of rapid recharge through preferential flow paths or structures enabling water from rainfall to quickly reach the groundwater table and recharge the aquifers.

Both CHWB005 and CHWB012 fall on minor fault structures within the geology. Groundwater levels fall and rise rapidly within the fault structures, indicating low storativity and immediate discharge to surface water drainage. There exist steep hydraulic gradients between the fault structures and the adjacent fresh rock matrix as shown by the water levels at EQCHI229 (fault structure) and EQCHI238 outside the fault zone.

Both graphs for CHWB005 and CHWB012 show a net rise of groundwater level from October 2006 to October 2010. This may be attributed to recharge from rainfall as there is no abstraction from the aquifers other than discharge via the dambos.

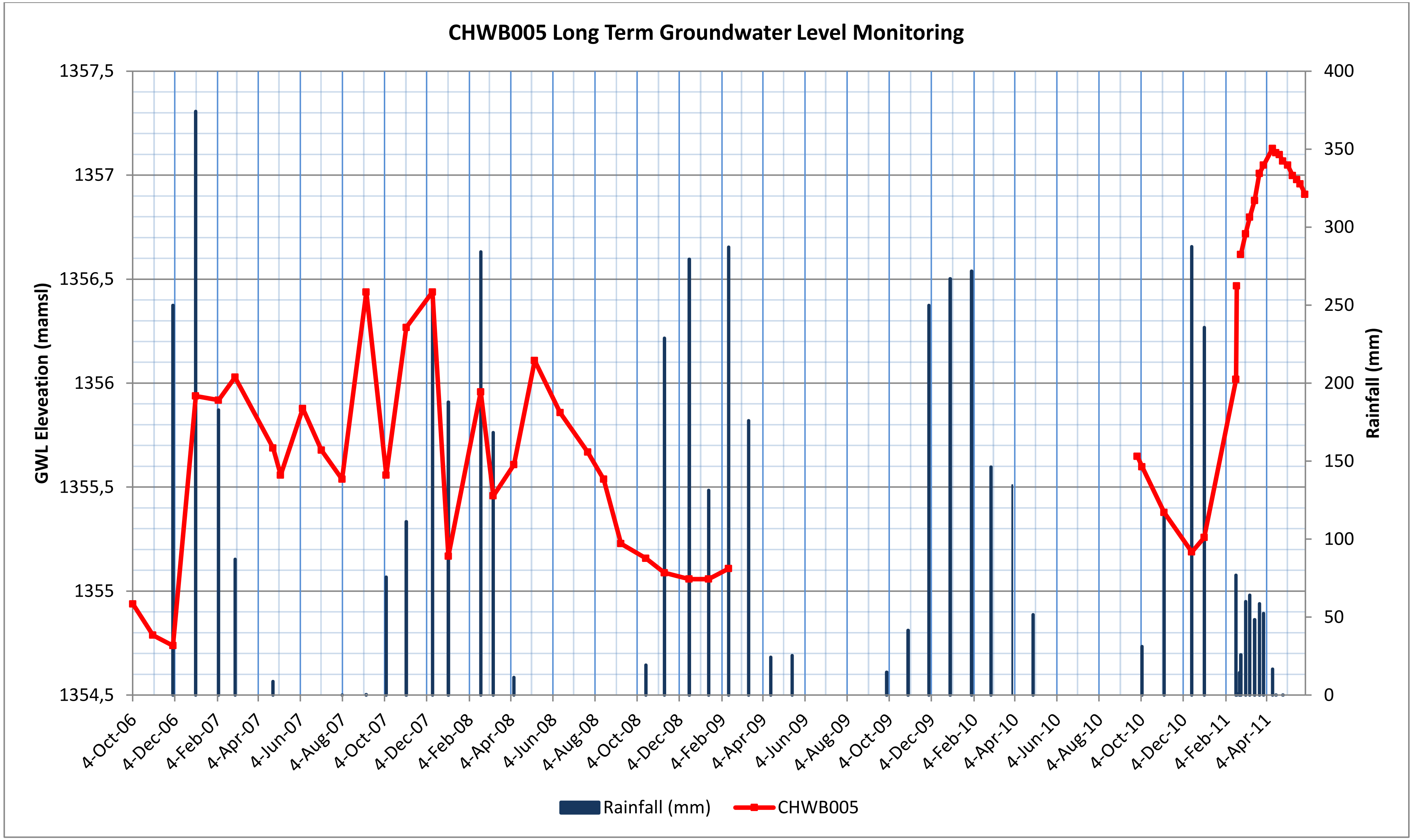



**Figure 6-21. CHWB005 Hydrograph**

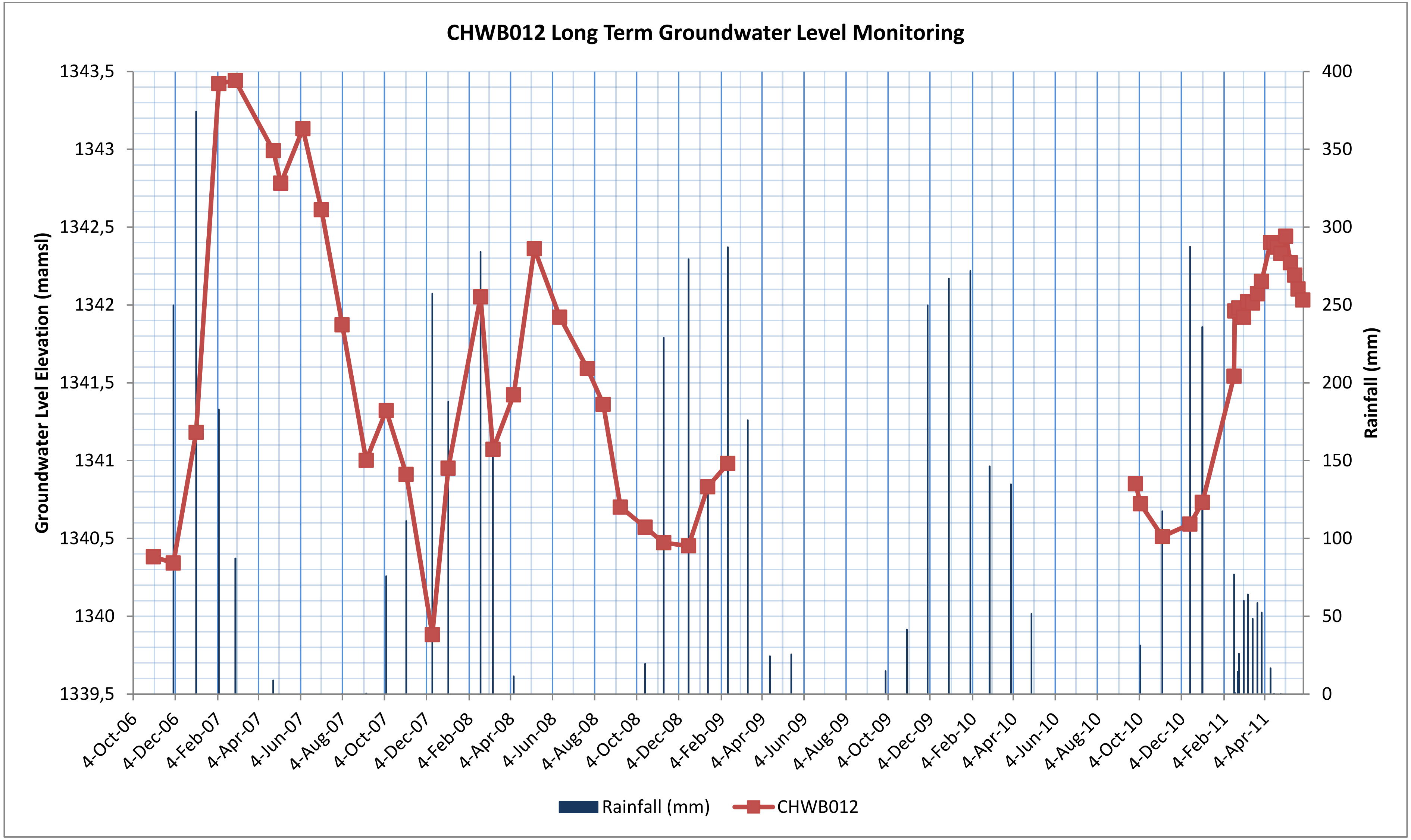



**Figure 6-22. CHWB012 Hydrograph**

## 6.7 Surface water – Groundwater Interaction

Exchange of water between surface water and groundwater bodies is controlled by the relative elevation of the water level in the river to that of the water table. If the water level in the surface water body is higher than that of the groundwater body, water will flow from the surface water body into the groundwater body. Similarly, if the water table or piezometric surface is higher than the water level in the surface water body, the underlying groundwater system is in hydraulic connection with the surface water and groundwater will discharge into the surface water (R Parsons, 2004).

The dambos in Chimiwungo are all at lower water levels relative to the groundwater level. Discharge from the aquifers flows into the surface water drainages and rivers via the dambos. A borehole drilled through an old dambo shows that the dambos are underlain by a thick sequence of silts (Figure 6-23). The silt allows the seepage of groundwater from the adjacent aquifers into the dambo through the base and subsequently into the river system extending from the dambo.

From the piezometric contour map (Figure 6-20) it is seen that the Chimiwungo River occurs at positions of local minima in the piezometric levels. This observation suggests that it is a gaining stream and indicates that the surface water system around Chimiwungo is fed by the groundwater system.

The boreholes that occur adjacent to the dambos have very shallow groundwater levels close to surface. The water levels in boreholes EQCHI229 and EXM001 respond almost instantaneously to rainfall events. This may also signify that most of the groundwater recharge takes place in the upper weathered zone.

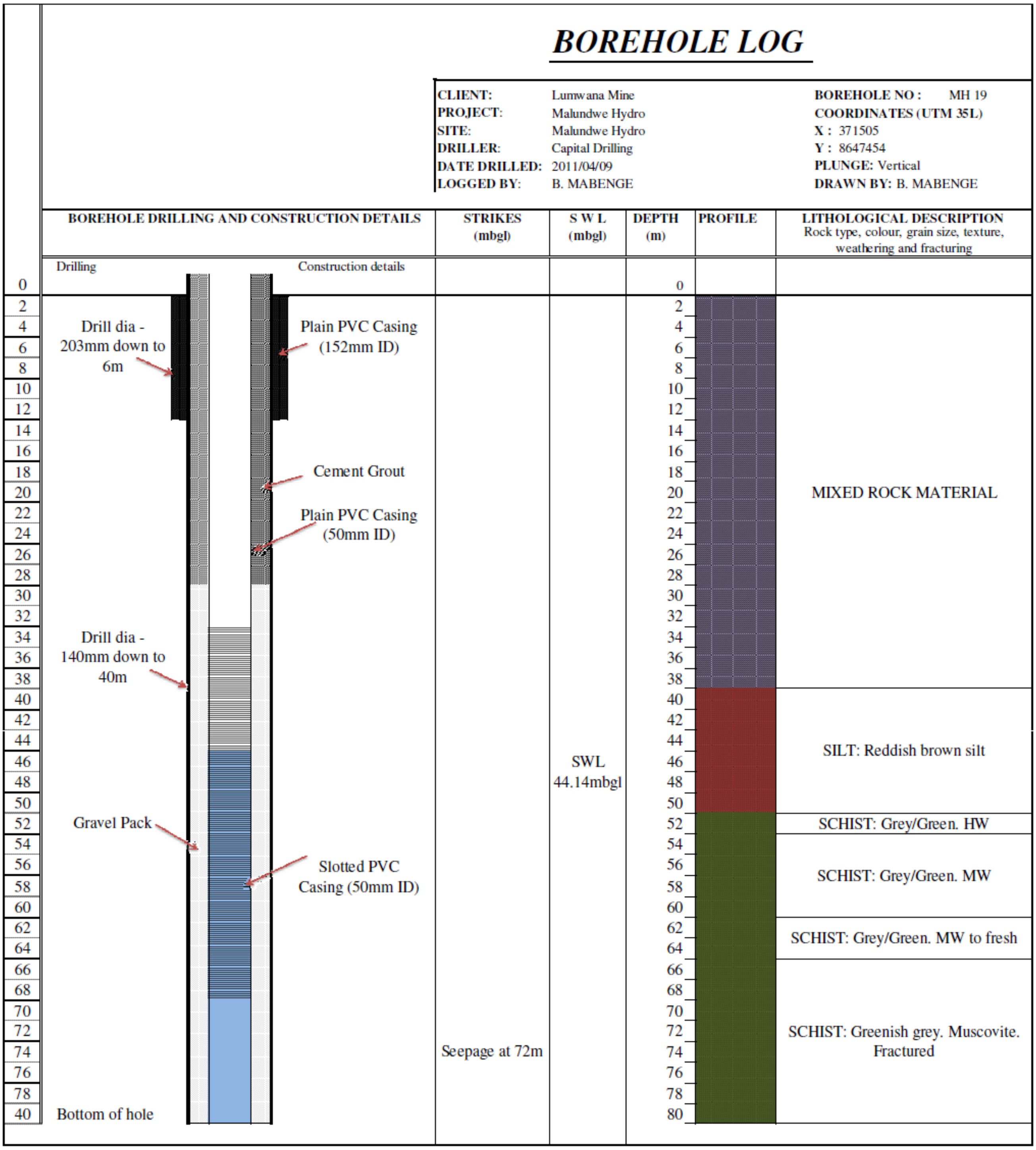



**Figure 6-23. Borehole log of borehole drilled through a dambo**

## 6.8 Water Quality

At the beginning of each month, water samples are collected from nine boreholes and five surface water bodies in the vicinity of the Chimiwungo pit and sent to SGS Laboratory in South Africa for analysis.

Results of water quality data are imported into WISH (Windows Interpretation System for Hydrogeologist). WISH automatically assesses the electroneutrality of the data by calculating the charge balance for each sample. This is done by assessing the contribution of each chemical species to the electrical charge within a water sample which is assumed to be electrically neutral. The sum total of positive electrical charge (cations) must be equal to the sum total of negative electrical charge (anions) for a neutral solution. A charge balance error of more than 5% is deemed unacceptable.

In addition to the electroneutrality analysis, results of split samples and blank samples are used as part of the quality control measures to ensure that the results from the laboratory are credible. Results are also compared to the previous results at each sampling point and differences greater than 10% are flagged and re-analysed, if necessary.

Poor monitoring and quality control of laboratory results have led to most of the water chemistry data being deemed unreliable. The current water quality database contains a significant number of inconsistencies and, in instances, data is missing. Incomplete data, especially where major cations and anions are not analysed, serves virtually no purpose as it is impossible to verify the accuracy of such data. Data from incomplete analyses cannot be plotted on classification diagrams such as the Piper or Expanded Durov diagrams. Such visual classification systems enable the evolution of groundwater to be evaluated and to identify ion exchange processes taking place. Groundwater contamination can easily be identified by plotting the results of a complete water quality analyses onto either of the classification diagrams. Stricter quality control and analysis of results received from the laboratory is recommended.

### 6.8.1 Groundwater Quality

Results of the laboratory analysis of samples taken during May 2011 indicate that the groundwater is of a generally good quality. The groundwater is acidic to neutral (pH 4.8 to 6.8) with the strongest acidity displayed at GW18 (pH 4.8). Laboratory measured Total Dissolved Solids (TDS) concentrations range from <10mg/*l* to 144mg/*l*. It will be necessary to compare the water quality results obtained during the rainy season with those of water samples collected during the dry season in order to determine the degree of any seasonal variations in the water quality. Groundwater quality monitoring has been carried out from June 2006 and is ongoing. The full set of water quality data can be found in Appendix A2.

The general groundwater type can be characterized as a calcium-magnesium-bicarbonate (Ca-Mg-$HCO_3$) type, indicating recently recharged groundwater (Figure 6-24). This is indicative of good quality groundwater which has not undergone intensive ion exchange processes as evidenced by the low TDS. The Expanded Durov diagram (Figure 6-25) shows that the groundwater is generally free of contamination from mining activities. Elevated iron (Fe) concentrations were measured in all the groundwater samples analysed. This may be attributed to the dissolution of Fe bearing minerals within the local geology. The filtration and acidification/preservation of all water samples intended for the analysis for Fe concentration are highly recommended.

A recommendation has been made to widen the groundwater sampling network to include boreholes that are currently on the Chimiwungo groundwater level monitoring network. Three boreholes (XM001, MH04, MH04A) have large diameter casing, providing sufficient access for groundwater sampling. A wider groundwater quality monitoring network is necessary to achieve a better coverage of the groundwater quality mapping of the Chimiwungo aquifers.

Table 8 is a summary of the May 2011 laboratory results. The large charge balance errors highlighted in red show that the laboratory data is unreliable and will also impact on the reliability of the groundwater chemistry analyses outlined in this report.

**Table 8. Summary of May 2011 Groundwater Water Quality Results**

| SAMPLE ID | Date | pH | EC | TDS | TSS | NH3 | F | Cl | MALK | NO3- | PO4 | SO4 | Al | As | Ba | Ca | Cd | Co | Cr | Cu | Fe | Mg | Mn | U | Zn | K | Na | % Error |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mS/m | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L $CaCO_3$ | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | |
| CHWB005 | 2011/05/02 | 5.7 | 7.4 | 60 | <10 | <0.05 | <0.3 | <0.5 | 61 | <0.4 | 0.023 | <0.4 | <0.04 | <0.0001 | 0.12 | 3.9 | <0.002 | 0.03300 | 0.014 | 0.057 | 0.52 | 3.3 | 0.034 | <0.0005 | <0.08 | 4.8 | 6.2 | 2.49 |
| CHWB012 | 2011/05/02 | 6.8 | 27 | 140 | <10 | <0.05 | <0.3 | 0.92 | 40 | <0.4 | <0.02 | 1.8 | <0.04 | <0.0001 | 0.069 | 33 | <0.002 | 0.00700 | 0.019 | <0.0005 | 1.7 | 7.1 | 0.14 | <0.0005 | <0.08 | 7.9 | 12 | 2.53 |
| GW 18 | 2011/05/02 | 4.8 | 1.9 | 92 | 64 | <0.05 | <0.3 | 0.6 | 10 | <0.4 | <0.02 | <0.4 | 0.12 | <0.0001 | 0.053 | 0.85 | <0.002 | 0.00390 | 0.014 | 0.012 | 0.53 | 0.59 | 0.052 | <0.0005 | <0.08 | 0.81 | 1.3 | 10.57 |
| GW 19 | 2011/05/02 | 6.3 | 28 | 144 | 110 | 0.5 | <0.3 | 0.81 | 120 | <0.4 | <0.02 | <0.4 | 0.11 | <0.0001 | 0.28 | 48 | <0.002 | 0.01100 | 0.01 | <0.0005 | 4.2 | 1.7 | 0.25 | <0.0005 | <0.08 | 4.3 | 3.2 | 8.10 |
| GW 44 | 2011/05/02 | 5.1 | 3.1 | 68 | <10 | <0.05 | 0.4 | 3 | 10 | <0.4 | <0.02 | <0.4 | <0.04 | <0.0001 | 0.039 | 0.23 | <0.002 | 0.00180 | 0.0009 | 0.18 | 0.071 | 0.66 | 0.0078 | <0.0005 | <0.08 | 0.93 | 3.9 | 8.21 |
| R5-T5 | 2011/05/03 | 5.6 | 5.8 | <10 | <10 | <0.05 | <0.3 | 2.4 | 51 | <0.4 | <0.02 | <0.4 | <0.04 | <0.0001 | 0.045 | 6.5 | <0.002 | 0.00500 | 0.0016 | 0.0018 | 0.013 | 1.3 | 0.037 | <0.0005 | <0.08 | 0.64 | 3 | 23.01 |
| MUKANDA | 2011/05/03 | 5.2 | 1.8 | 32 | 52 | 0.29 | <0.3 | 0.6 | 20 | <0.4 | <0.02 | <0.4 | <0.04 | <0.0001 | 0.048 | <0.11 | <0.002 | 0.00210 | 0.0006 | <0.0005 | 13 | 0.39 | 0.1 | <0.0005 | 0.14 | 0.28 | <1 | 8.69 |
| MUSHIPI | 2011/05/03 | 5.1 | 2.3 | 60 | <10 | 0.86 | <0.3 | 1.4 | 40 | <0.4 | <0.02 | <0.4 | <0.04 | <0.0001 | 0.01 | 1.1 | <0.002 | 0.00038 | 0.0007 | <0.0005 | 1.8 | 0.21 | 0.03 | <0.0005 | <0.08 | 0.6 | <1 | 66.82 |
| KABENDWE | 2011/05/03 | 5.6 | 5.7 | 136 | <10 | <0.05 | <0.3 | 0.65 | 10 | <0.4 | 0.025 | <0.4 | <0.04 | <0.0001 | 0.12 | 2.6 | <0.002 | 0.00082 | 0.0014 | 0.0021 | 1.4 | 1.4 | 0.026 | <0.0005 | <0.08 | 3.4 | 3.7 | 38.27 |

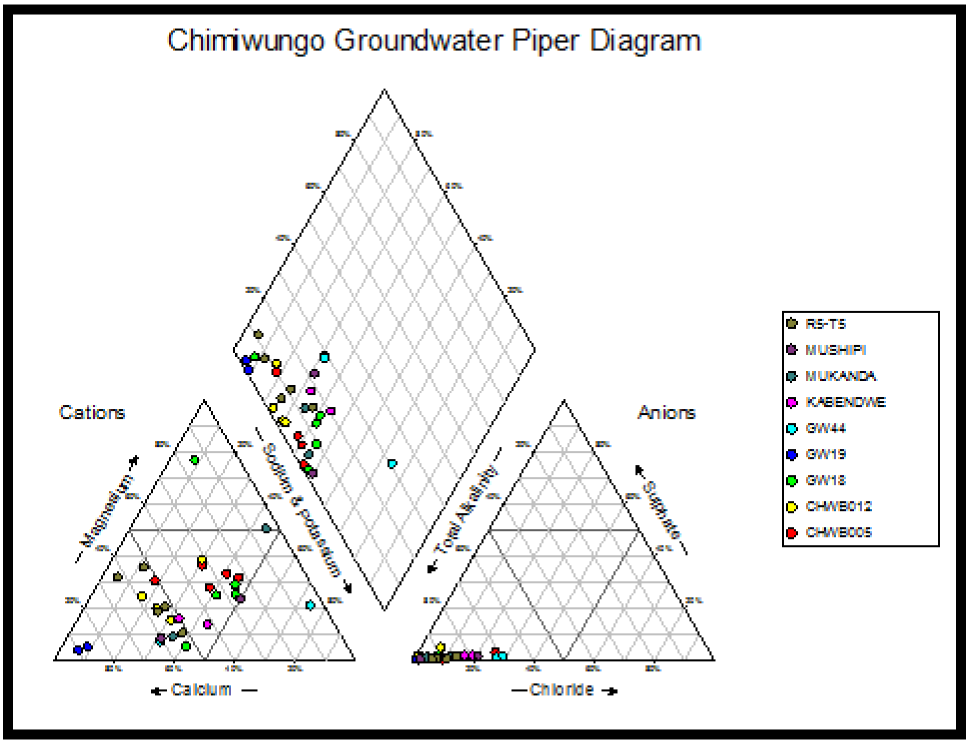



Figure 6-24. Piper Diagram of Chimiwungo groundwater chemistry

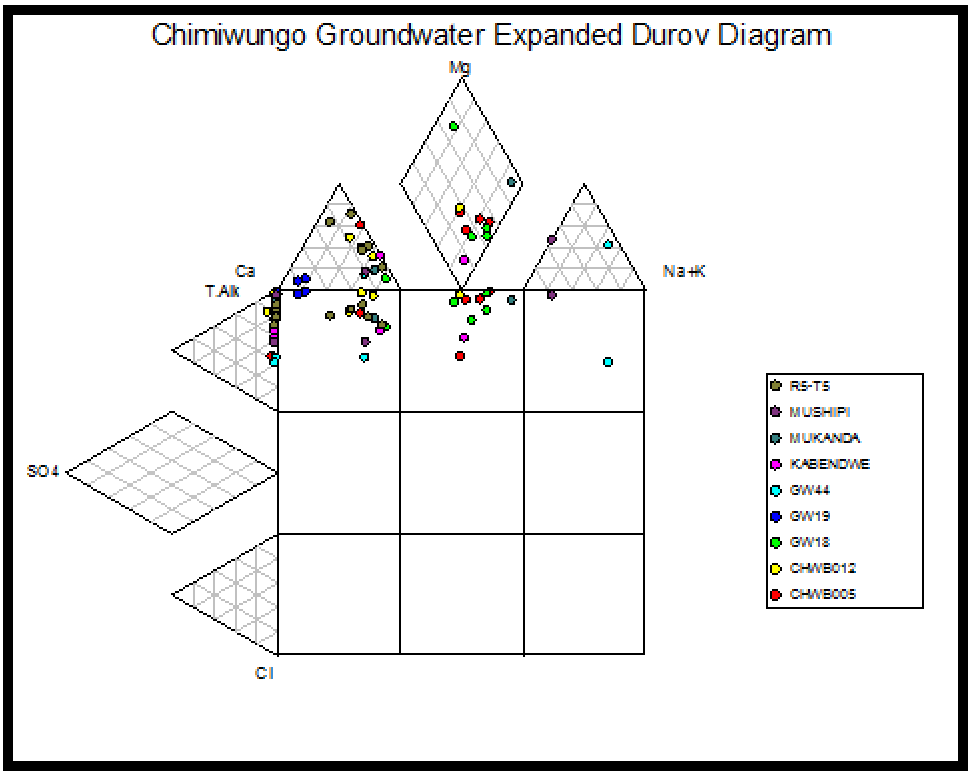



Figure 6-25. Expanded Durov Diagram of Chimiwungo groundwater chemistry

The pH of the groundwater within Chimiwungo has been fairly constant over long periods of time. Most of the sampling points display pH values that are close to neutral. All the boreholes display similar pH trends, with significant lows and highs at essentially the same periods. The pH values measured at GW18 on 3 January 2011 and CHIWB005 on 1 August 2009 are most likely as a result of errors during sampling or analysis. The sudden fall and recovery of the pH is not typical of almost environmentally pristine environments such as Chimiwungo.

TDS concentrations from the groundwater at Chimiwungo are generally constant through long periods. CHWB012 displays a major jump in TDS values from January 2011 and will need to be monitored closely to determine whether upward trend will persist. This may be a consequence of the rapid recharge taking place combined with the leaching effect of slightly acidic rainwater (pH 6.13 – 6.74). The acidic rainfall would be expected to leach already decomposed geological material from surface and quickly reach the groundwater table through fractures. CHWB012 lies adjacent a major fault structure and the borehole is likely to have intersected structures during drilling and construction.

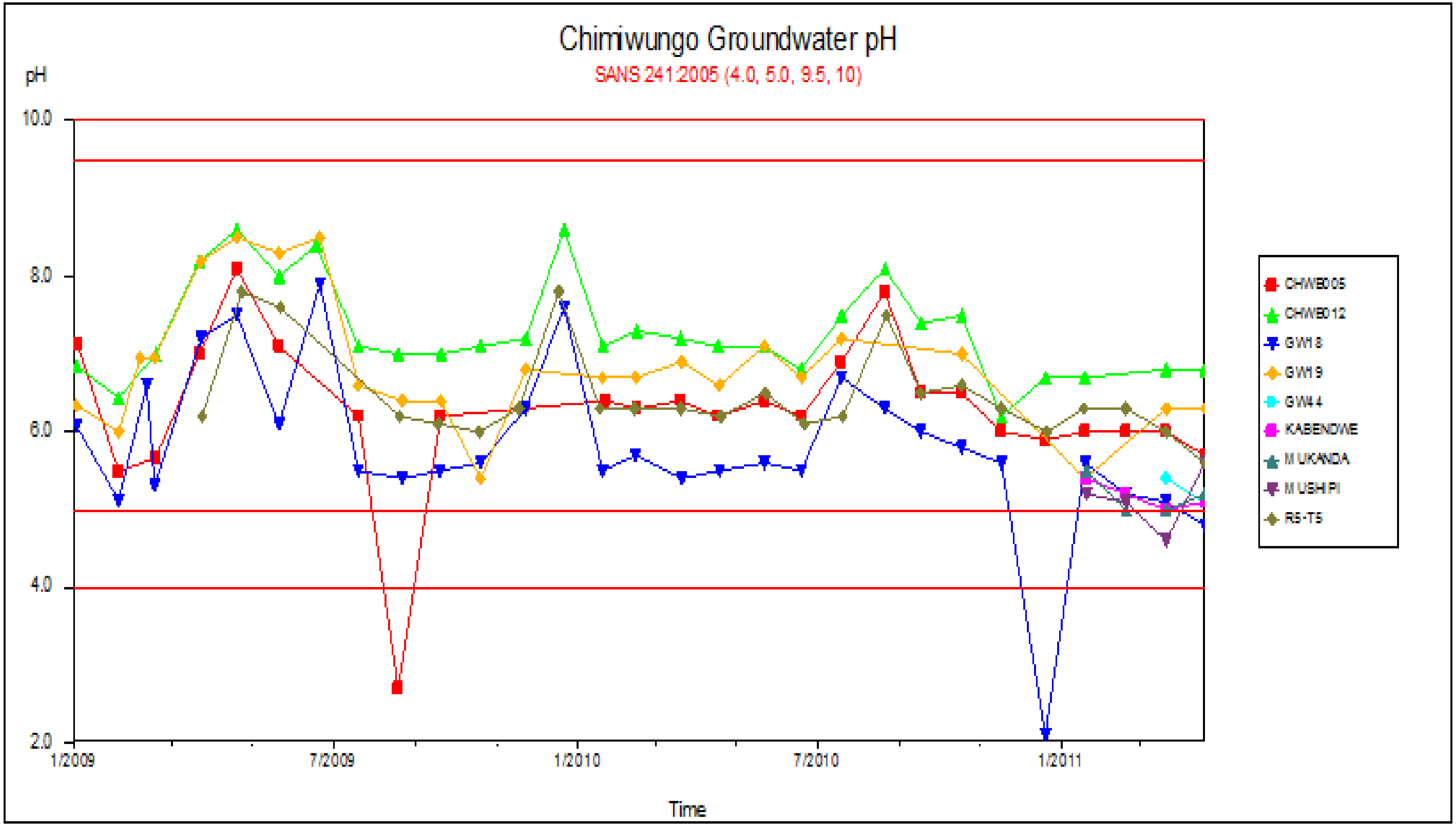



Figure 6-26. Chimiwungo Groundwater pH

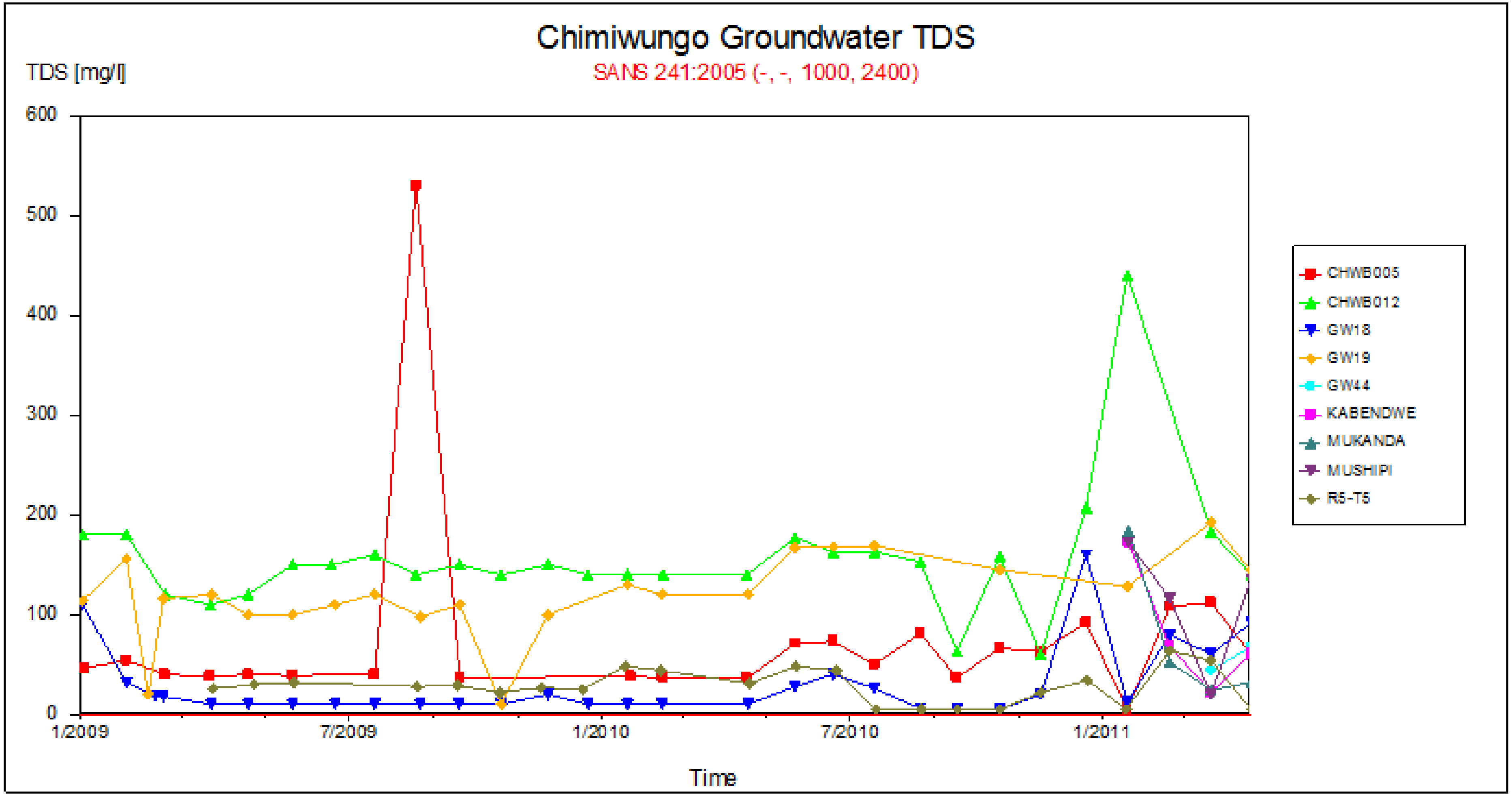



Figure 6-27. Chimiwungo Groundwater TDS

### 6.8.2 Surface Water Quality

Generally surface water quality within the study area is good to moderate with low levels of salinity and limited or low concentrations of dissolved metal species. The distribution of surface water monitoring points is shown in Figure 5-8. Analysis of the surface water quality results for May 2011 (Table 9) shows that the pH ranges from 5.7 to 6.4. The elevated Fe concentration at SW10 may be a result of the high levels of dissolved and suspended solids arising from high runoff during periods of heavy rainfall. The Piper diagram in Figure 6-28 indicates water with a chemical composition dominated by Ca-Mg-$HCO_3$ indicating characteristics of fresh water, an observation supported by the low salinity (TDS in the range of 76 -128 mg/*l*). The Expanded Durov diagram (Figure 6-29) denotes surface water that is generally free of contamination from mining activities. It is inferred that the surface water quality will be more susceptible than groundwater to local seasonal variations in precipitation.

The AEL, Hitachi and LV water samples were collected from vehicle washing bays and represent highly contaminated environments. The high TDS concentrations measured in samples collected at the washing bays are expected. These samples are not representative of the water quality of natural surface water bodies within and around Chimiwungo.

The large charge balance errors highlighted in Table 9 show that the laboratory data is unreliable and will also impact on the reliability of the groundwater chemistry analyses outlined in this report. Unreliable chemistry data leads to erroneous conclusions of the hydrological environment and processes.

**Table 9. Summary of May 2011 Surface Water Quality Results**

| SAMPLE ID | Date | pH | EC | TDS | TSS | NH3 | F | Cl | MALK | NO3- | PO4 | SO4 | Al | As | Ba | Ca | Cd | Co | Cr | Cu | Fe | Mg | Mn | U | Zn | K | Na | % Error |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mS/m | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L $CaCO_3$ | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | |
| SW 10 | 2011/05/01 | 6.2 | 13 | 128 | <10 | <0.05 | <0.3 | <0.5 | 10 | <0.4 | <0.02 | <0.4 | <0.04 | <0.0001 | 0.026 | 0.12 | <0.002 | 0.00077 | 0.0008 | <0.0005 | 0.29 | 0.55 | 0.0022 | <0.0005 | <0.08 | 0.34 | 1 | 6.01 |
| SW 37 | 2011/05/01 | 6.2 | 15 | 76 | <10 | <0.05 | <0.3 | <0.5 | 20 | <0.4 | <0.02 | <0.4 | <0.04 | <0.0001 | 0.033 | 0.43 | <0.002 | 0.00046 | 0.0008 | 0.0007 | 0.39 | 0.67 | <0.0005 | <0.0005 | <0.08 | 0.42 | 1.1 | 28.02 |
| LV WORKSHOP | 2011/05/01 | 5.7 | 54 | 1116 | 470 | 7.4 | 11 | 22 | 180 | <0.4 | <0.02 | 2.5 | 4.8 | <0.0001 | 0.081 | 45 | <0.002 | 0.03000 | 0.06 | 0.23 | 20 | 6.3 | 0.97 | 0.0007 | 1.3 | 27 | 33. | 16.05 |
| HITACHI | 2011/05/03 | 6.1 | 8.4 | 196 | 1200 | 0.17 | <0.3 | 1.9 | 30 | <0.4 | <0.02 | 4.4 | 8.8 | <0.0001 | 0.01 | 10 | <0.002 | 0.00510 | 0.0023 | 0.047 | 11 | 8.4 | 0.1 | <0.0005 | <0.08 | 16 | 4.4 | 38.36 |
| AEL | 2011/05/01 | 6.4 | 2800 | 19068 | 140 | 1500 | <0.3 | <0.5 | 81 | 17000 | 0.18 | 360 | 0.044 | <0.0001 | 0.9 | 420 | <0.002 | 0.01600 | 0.0067 | 0.14 | <0.008 | 50 | 0.37 | 0.0019 | <0.08 | 84 | 100 | 25.38 |

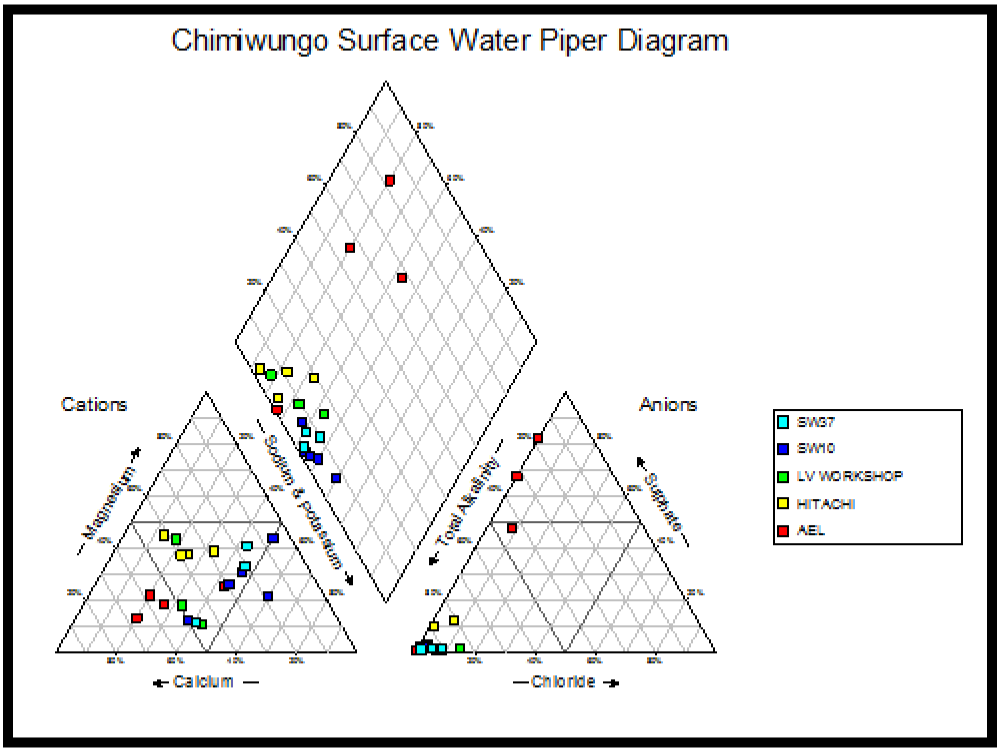



Figure 6-28. Piper Diagram of Chimiwungo surface water chemistry

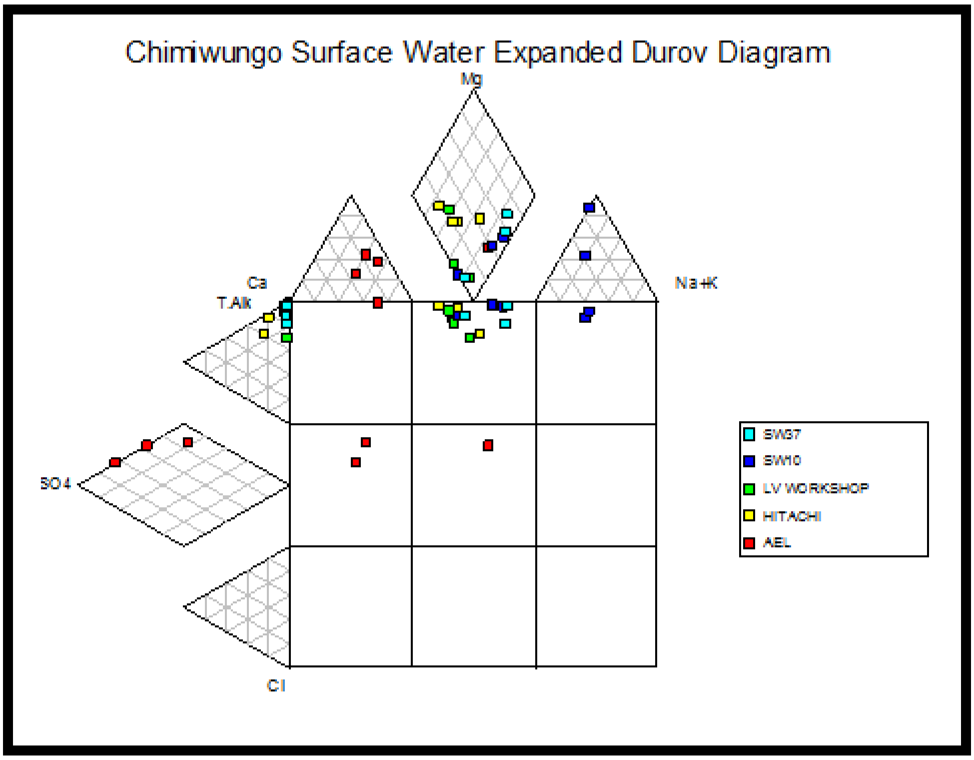



Figure 6-29. Expanded Durov Diagram of Chimiwungo surface water chemistry

The surface water in Chimiwungo shows a generally neutral pH. Only two sampling points (SW10, SW37) may be deemed to be representing true surface water conditions at Chimiwungo. The rest of the sampling points lie at or close to vehicle washing bays within workshops. These sampling points are highly contaminated and are not representative of the true character of the surface water within Chimiwungo. The erratic trend in the TDS concentration at AEL is due to the sampling point which lies at the discharge point of a vehicle servicing area. A variety of substances that are used in vehicle repairs and washed off delivery vehicles contribute to the high TDS concentrations.

The Total Dissolved Solids concentration at the SW10 sampling point in Chimiwungo is highly variable (4mg/*l* to 128mg/*l*). This suggests an environment that is characterized by fluctuating flow volumes. The Chimiwungo River responds very quickly to rainfall events and the rapid runoff contributes to jumps in the TDS concentrations.

Aluminium is almost consistently elevated. It can be mobilised from soils and sediments by natural weathering and accelerated acidification processes.

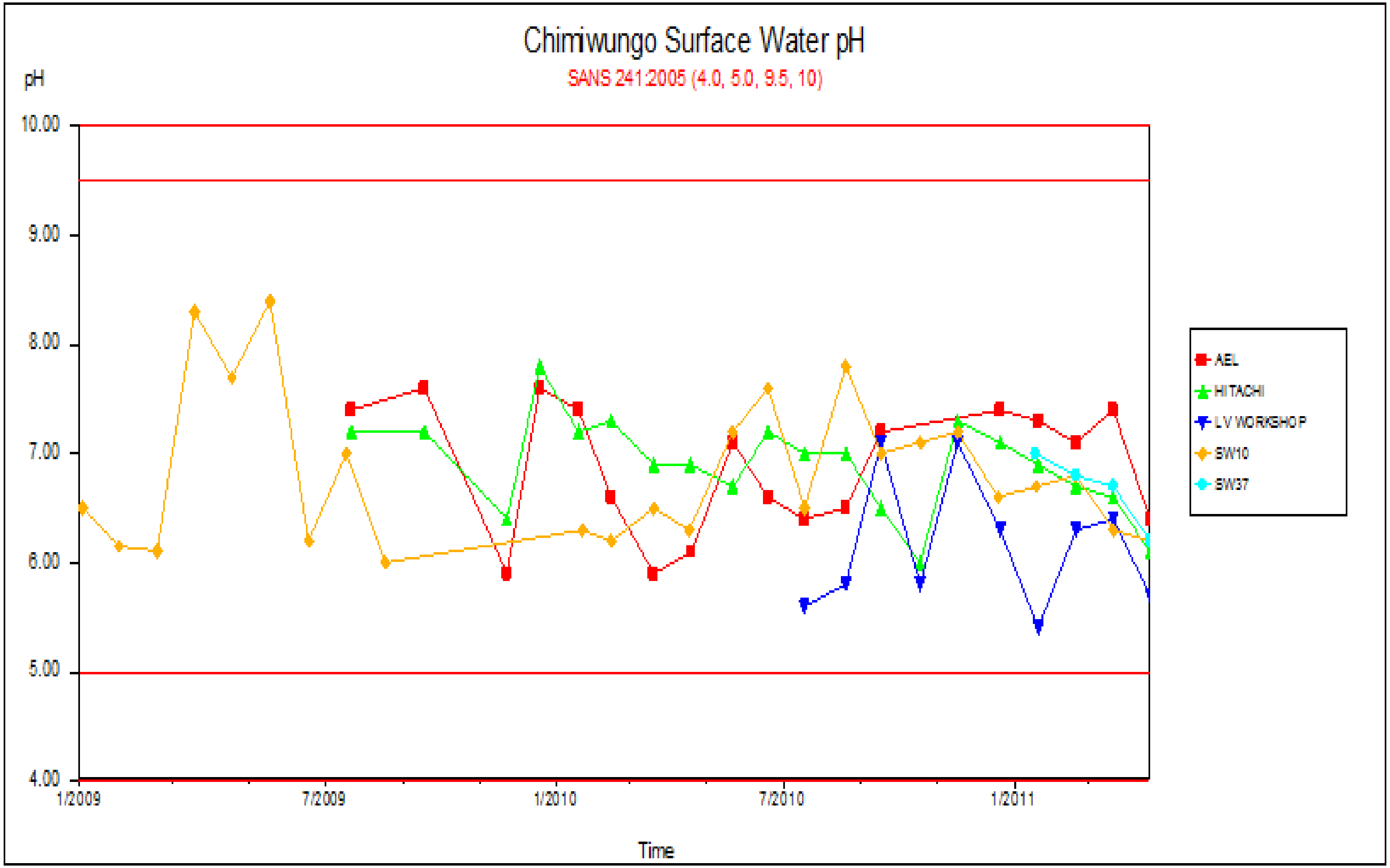



Figure 6-30. Chimiwungo Surface Water pH

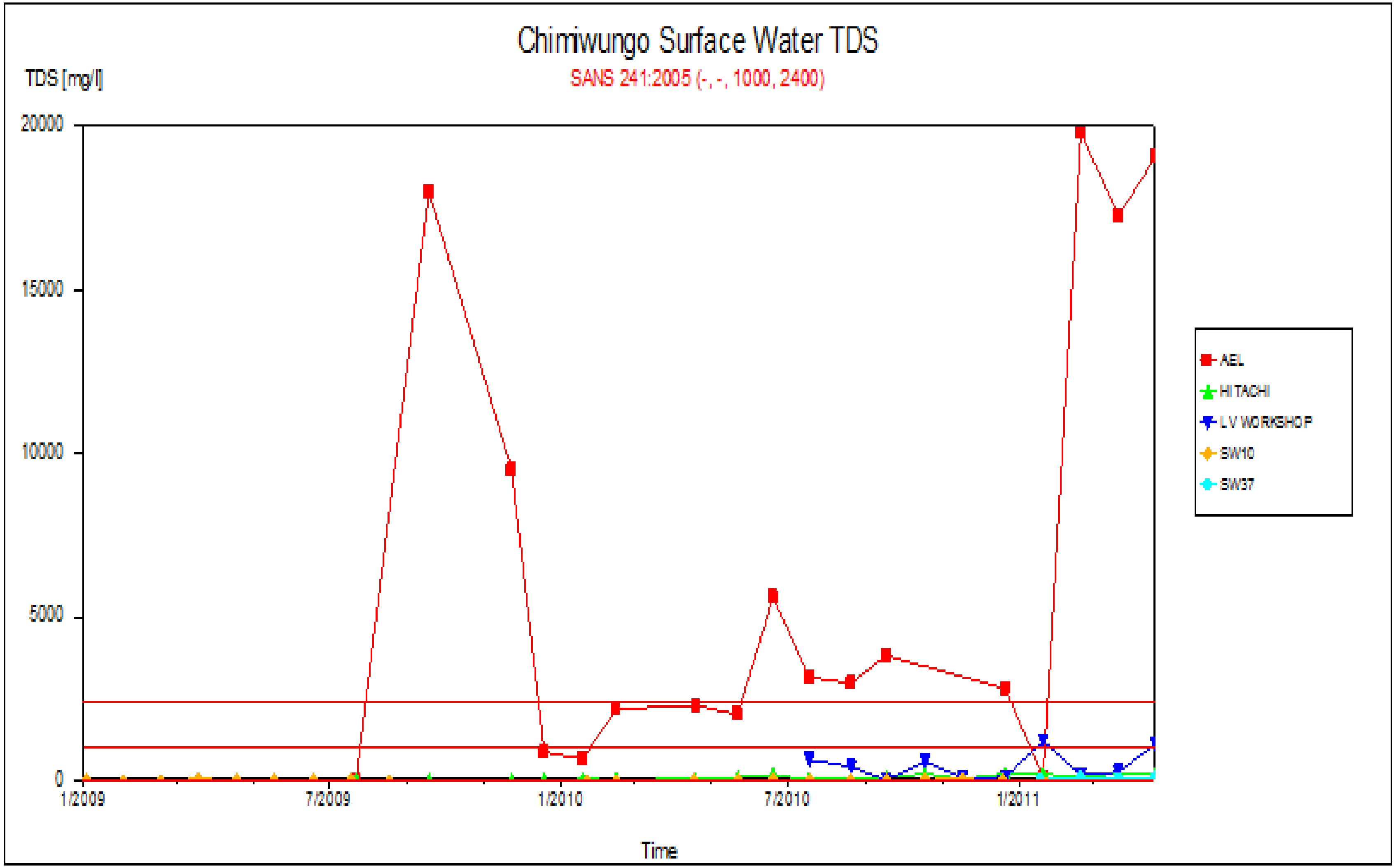



**Figure 6-31. Chimiwungo Surface Water TDS**

## 6.9 Rainwater Quality

Five rain gauges have been installed around Lumwana Mine (Figure 6-32). Three of these are manual stations and the other two are automatic. The different rain gauge locations are intended to cater for any variability of rainfall around the area. The rainwater for the preceding 24hrs is collected and measured at 9 am every day. In March and May 2011, rainwater samples were collected from all the rain gauges and sent to the SGS laboratory for chemical analyses.

The rainwater chemistry is generally bicarbonate ($HCO_3$) dominant. This is expected as it arises from the solution of carbon dioxide in the atmosphere and rainwater as it falls to earth, resulting in a mildly acidic rainwater solution. Sulphate concentrations in the rainwater, as expected, fall below the laboratory detection limit (2.8mg/l). The chemistry of the rainwater is not largely dissimilar to that of the groundwater and surface water. This agrees with the earlier conclusion that that the groundwater is relatively fresh and that recharge is largely from rainwater. Figure 6-33 shows a Piper plot of the rainwater sample results.

Samples collected from rain gauges at the Water Treatment Plant (WTP) and Airstrip may have been subject to anthropogenic activities that give rise to relatively high chloride concentrations. The unusually high concentrations of chloride in rainfall may possibly also be attributed to dry deposition and the rain gauges not being cleaned prior to collecting rainwater. Huge amounts of water treatment chemicals are stored at the WTP for water purification and dust from the stored chemicals may find its way into the rain gauge kept there.

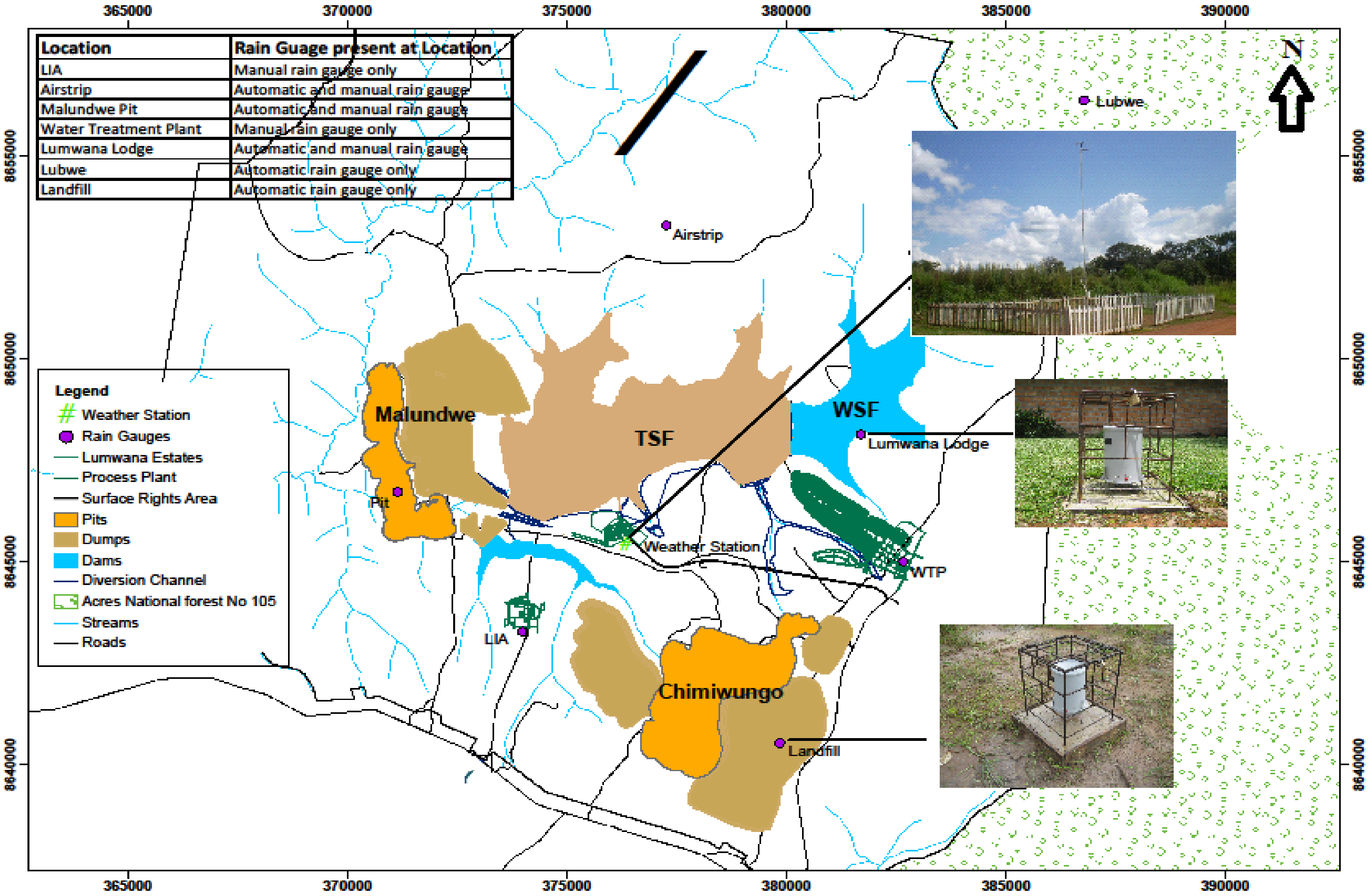



Figure 6-32. Rainfall stations at Lumwana (LMC Environmental Department)

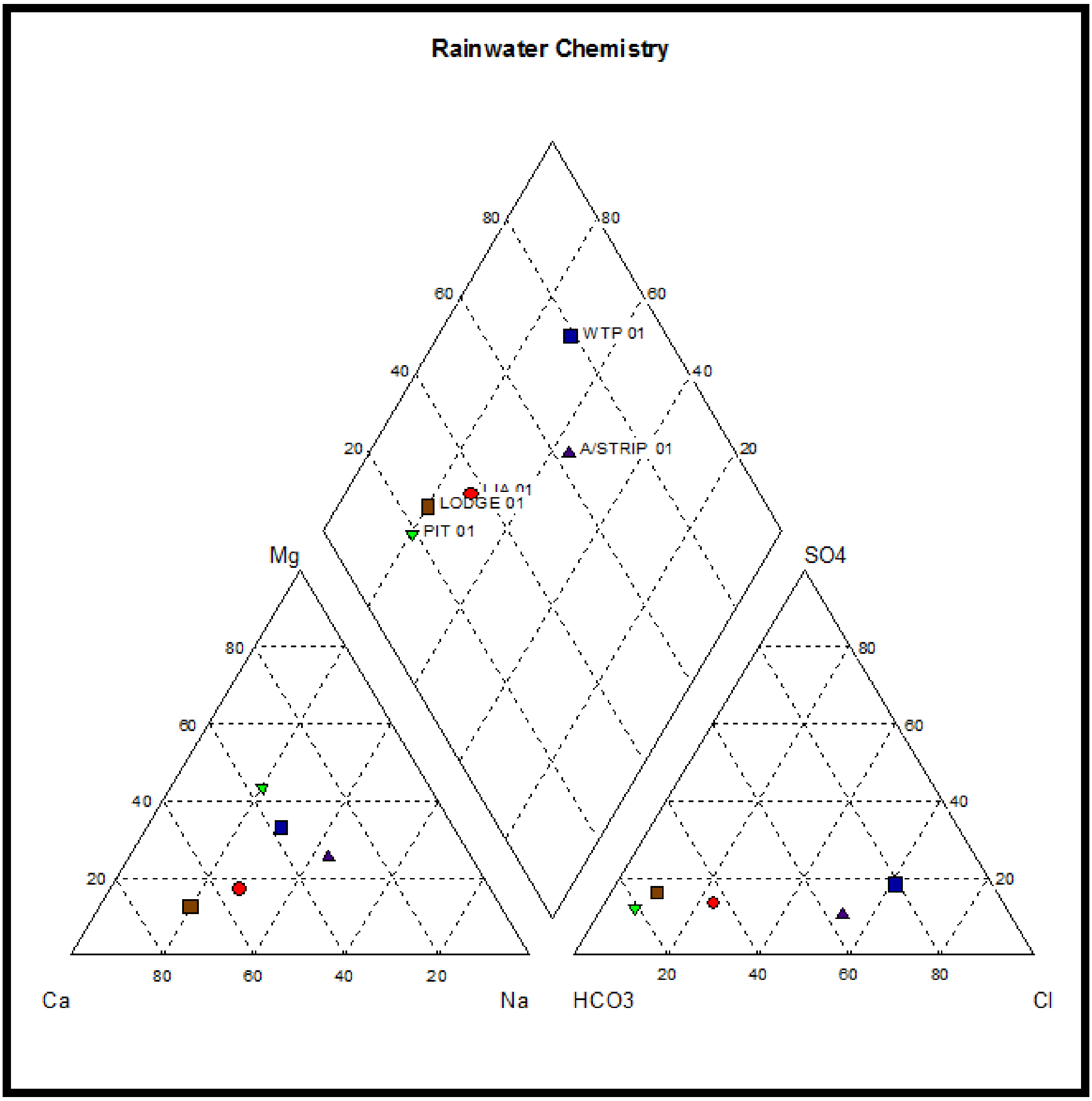



Figure 6-33. Rainwater chemistry at Lumwana Mine

# 7 CONCEPTUAL HYDROGEOLOGICAL MODEL

A conceptual model includes designing and constructing equivalent but simplified conditions for the real world problem. It is an interpretation of the characteristics and dynamics of an aquifer system which is based on an examination of all available hydrogeological data for a modelled area. This includes the external configuration of the system, location and rates of recharge and discharge, location and hydraulic characteristics of natural boundaries, and the directions of groundwater flow throughout the aquifer system (IGS, 2009).

The data gathered during the field investigation phase is used to develop the conceptual hydrogeological model of the area. This conceptual model forms the basis for understanding of the groundwater occurrence and flow mechanisms of the area and is used as the starting point for the numerical modelling discussed later in the report. The conceptual hydrogeological model is discussed in the following sections.

## 7.1 Aquifer Units

The 2003 report by Golder used seven boreholes to characterise the aquifers (Garnham and Wright, 2003). They recognised two hydrogeological units:

- The near surface weathered unit – unconfined (refer to Figure 7-1 for photographs of core samples of the unconfined aquifer)
- The fresh rock unit comprising hanging wall gneiss, ore schists, middle and lower gneiss, footwall gneiss and schist (refer to Figure 7-2 for photographs of core samples of the fractured aquifer)

Boreholes were drilled to a maximum depth of 275m and had yields ranging from 0.2 to 5.6 L/s. However, it is possible that the small sample size means that there are high yielding fractures as yet untapped.

Some of the seven boreholes drilled in 2003 (CHIWB02-12) were found and included in the monitoring programme. New boreholes sited on structures intersected by the core drilling are being considered for use in the hydrogeology investigation to mitigate risk.

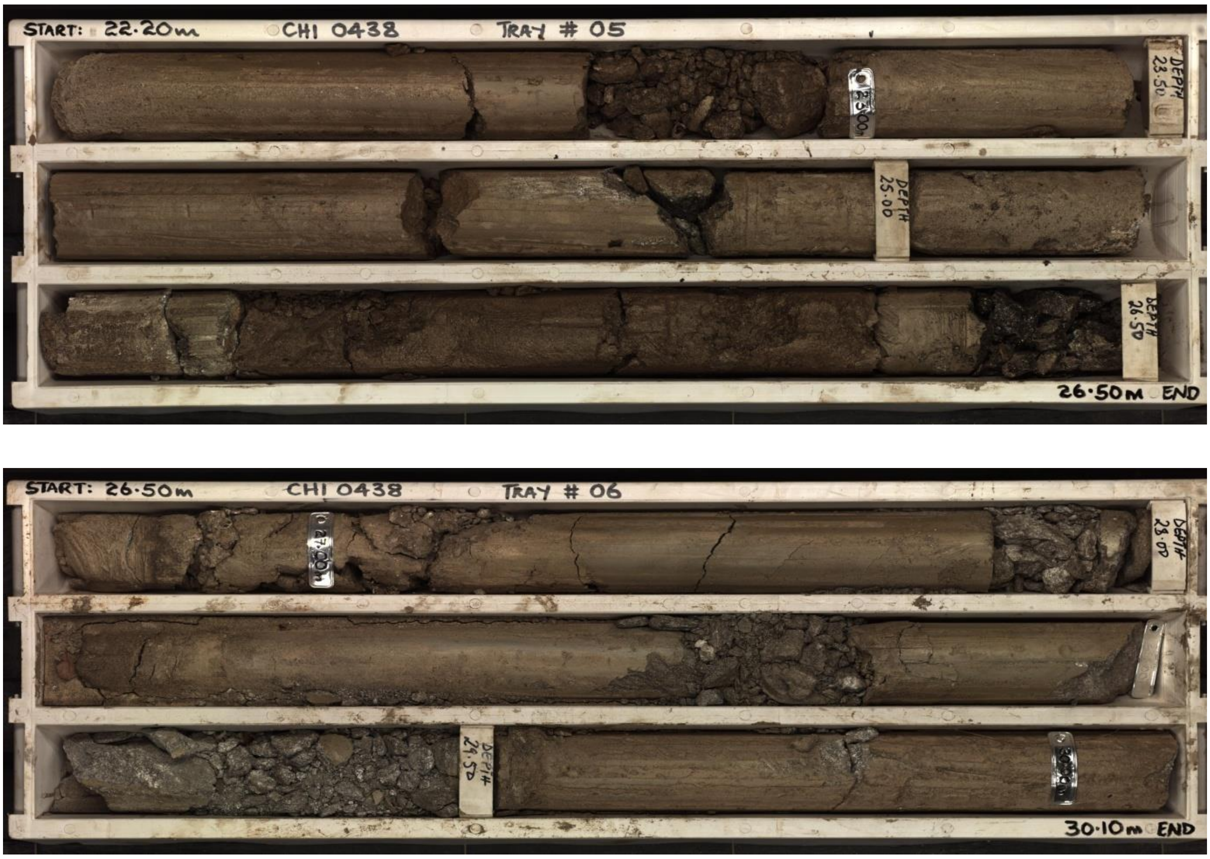



Figure 7-1. Core samples from the upper weathered aquifer

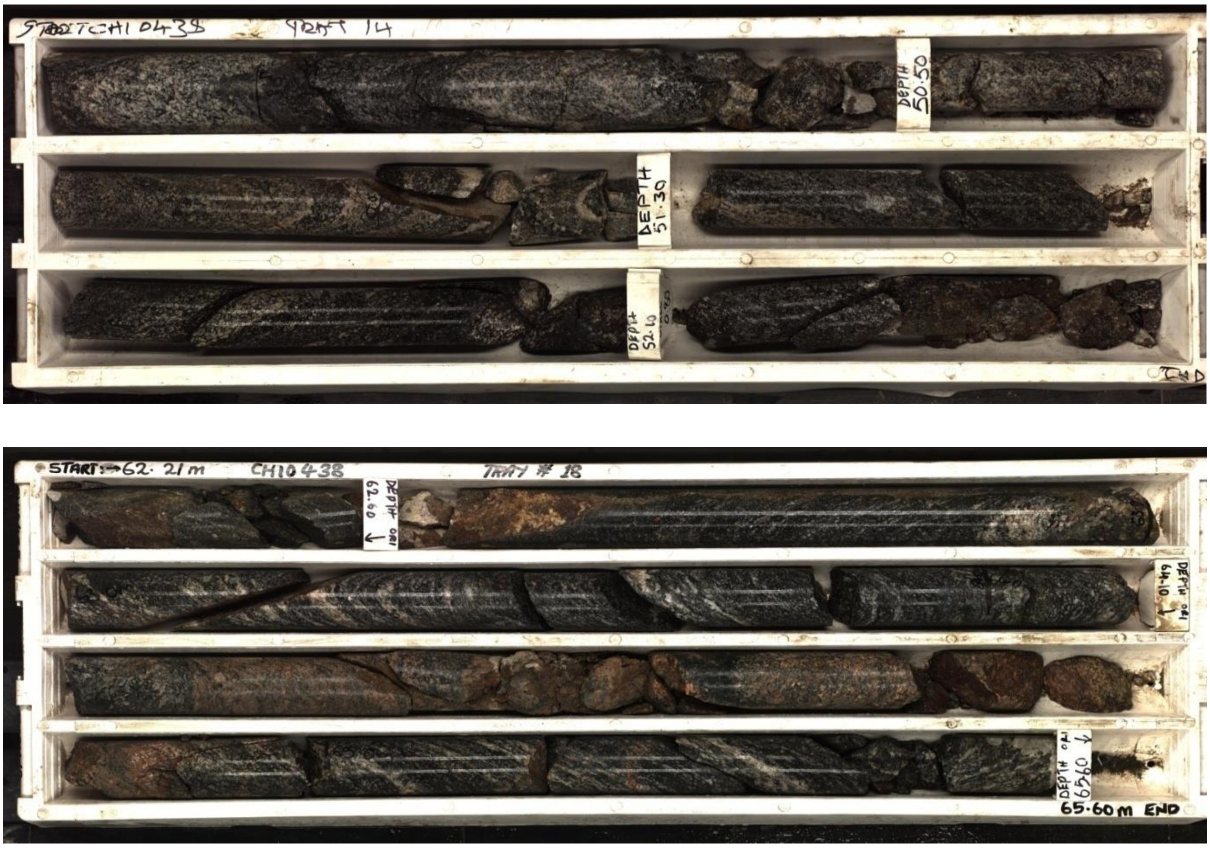



Figure 7-2. Core samples from the fractured aquifer

### 7.1.1 Aquifer classification

An aquifer classification scheme was devised for strategic purposes, allowing the grouping of aquifer systems into types according to their associated supply potential, water quality and local importance as a resource (Parsons, 1995). The South African Department of Water Affairs (DWA) produced a revised version in 1998. The two classification systems are displayed in Table 10

The mine abstracts groundwater as part of their dewatering process to enable mining to proceed safely. The local population in villages surrounding the mine use groundwater for domestic purposes.

The geology underlying the site was classified according to the Parsons (and DWA) system using the information derived from the drilling and estimated aquifer parameters as a minor aquifer system.

**Table 10. Aquifer Classification schemes**

| Aquifer System | Defined by Parsons (1995) | Defined by DWAF Min Requirements (1998) |
|---|---|---|
| Sole Source Aquifer | An aquifer which is used to supply 50 % or more of domestic water for a given area, and for which there are no reasonably available alternative sources should the aquifer be impacted upon or depleted. Aquifer yields and natural water quality are immaterial. | An aquifer, which is used to supply 50% or more of urban domestic water for a given area for which there are no reasonably available alternative sources should this aquifer be impacted upon or depleted. |
| Major Aquifer | High permeable formations usually with a known or probable presence of significant fracturing. They may be highly productive and able to support large abstractions for public supply and other purposes. Water quality is generally very good (<150 mS/m). | High yielding aquifer (5-20 L/s) of acceptable water quality. |
| Minor Aquifer | These can be fractured or potentially fractured rocks, which do not have a high primary permeability or other formations of variable permeability. Aquifer extent may be limited and water quality variable. Although these aquifers seldom produce large quantities of water, they are important both for local supplies and in supplying baseflow for rivers. | Moderately yielding aquifer (1-5 L/s) of acceptable quality or high yielding aquifer (5-20 L/s) of poor quality water. |
| Non-Aquifer | These are formations with negligible permeability that are generally regarded as not containing groundwater in exploitable quantities. Water quality may also be such that it renders the aquifer as unusable. However, groundwater flow through such rocks, although imperceptible, does take place, and need to be considered when assessing the risk associated with persistent pollutants. | Insignificantly yielding aquifer (< 1 L/s) of good quality water or moderately yielding aquifer (1-5 L/s) of poor quality or aquifer which will never be utilised for water supply and which will not contaminate other aquifers. |
| Special Aquifer | An aquifer designated as such by the Minister of Water Affairs, after due process. | An aquifer designated as such by the Minister of Water Affairs, after due process. |

## 7.2 Groundwater Recharge

Groundwater recharge may be defined in a general sense as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir (Lerner *et al*., 1990). There is direct recharge from rainfall through infiltration straight into the ground and indirect recharge from concentration of surface runoff along watercourses.

Groundwater recharge is one of the most important hydrogeological processes to be quantified in both water supply studies and evaluation of toxic waste sites in arid and semi arid areas. Unlike in karstified areas, where the recharge rate may be high, the recharge flux is usually small in these environments, typically ranging from 2 to 15% of the average annual rainfall with the lower values being more common (Beekman *et al*., 1997). Recharge is generally concentrated in playas, arroyos, wadis and other topographic depressions and as preferential flow along fractures and faults and is a difficult process to quantify by the traditional water budget method. Recharge within the Chimiwungo area is primarily from rainfall and the groundwater system discharges to the surface water system via the many dambos that lie within the area.

### 7.2.1 Chloride Mass Balance Method

The chloride mass balance (CMB) method of estimating ground water recharge is often used because of its low cost and reasonable precision. If a steady state is attained between the chloride flux at the surface and the chloride flux beneath the evapotranspiration and the mixing zone (ET/M zone), the following mass balance can be defined (Eriksson and Khunakasem, 1969; Bredenkamp *et al*., 1995; Beekman *et al*., 1997; Beekman, 2000):

$$R = \frac{\text{Total Chloride Deposition}}{\text{Harmonic mean of Cl concentration in ground water}} \times 100 \qquad \text{(Eqn 1)}$$

or

$$R = TD/(Cl_{gw})$$

and $TD = P \times Cl_p + D$

where,

P is rainfall (mm/yr);

$Cl_p$ is the chloride content of precipitation (mg/l);

D is dry deposition of chloride measured during the dry season (mg/m²/yr);

R is Recharge (mm/yr);

$Cl_{gw}$ is Chloride in groundwater (mg/l); and,

TD is total atmospheric deposition of chloride at the surface which originates from precipitation and dry fall out

Chloride deposition during the wet season comprises both dry and wet deposition. In the dry season the chloride deposition can be measured by rinsing the rain gauge with de-ionised water. This enables an estimation of the minimum contribution of dry deposition to the total annual deposition. For this study it was assumed that D=0 (no assessment was carried out to measure dry deposition) and thus $TD = P \times Cl_p$.

The chloride concentration in groundwater at the water table originates from different flow components in the unsaturated zone. Calculation of the recharge rate using chloride concentrations of groundwater at the water table gives an average recharge rate.

For the calculation of average areal recharge, $Cl_{gw}$ is often better represented by the harmonic mean of chloride concentrations in groundwater (Eriksson and Khunakasem, 1969):

$$Cl_{gw} = \frac{N}{\left(\sum_{i=1}^{n} 1/Clgw_i\right)}$$

where, N is the number of measurements. The final calculation is based only on the values of rainfall and chloride concentration

Within the study area, the harmonic mean of the measured rainfall concentrations ($Cl_p$) is 0.95 mg/L, while the harmonic mean of the chloride concentrations in groundwater is 2.45 mg/L. The recharge within the study area may therefore be estimated as:

R = (0.95/2.45) x 100%

Recharge is estimated at 38% of Mean Annual Precipitation, corresponding to 498mm of rainfall per annum.

The seemingly unusually high value of recharge may be attributed to preferential groundwater flow within the fault network, resulting in groundwater and rainfall chloride concentrations of a similar magnitude. Preferential recharge limits the residence times of percolating rainwater in the unsaturated zone, limiting the dissolution of chloride bearing minerals and the concentration of the groundwater by evapotranspiration, at times giving large errors in the estimation of groundwater recharge. A total of five rainfall samples were collected and sent for analysis. The recharge estimate may be skewed by the small number of rainfall samples collected and the fact that all the samples are from one season. Long-term rainfall data would give a more representative value of Cl in rainfall. The quality of the chemistry data is also very poor and makes the estimate potentially unreliable.

The groundwater samples used in the CMB estimate are integrated samples, comprising of water from the weathered zone and the fractured zone. Analysis of recharge and groundwater hydrographs points to the greater portion of recharge being dominant in the weathered zone. The boreholes that occur adjacent to the dambos have very shallow groundwater levels close to surface. The water levels in boreholes EQCHI229 and EXM001 respond almost instantaneously to rainfall events. This may also signify that most of the groundwater recharge takes place in the upper weathered zone.

Seepage mapping in the Malundwe pit has shown that larger quantities of groundwater emanate from the weathered zone than within the fresh rock and fractured zones. The seepage in the weathered zone is greater during the rainy season.

## 7.3 Hydraulic parameters

The hydraulic testing programme was scheduled to commence in November 2010 but, as a consequence of the failure by the drilling contractor to complete the drilling works on time, pumping tests had not been carried out by the time of preparing this thesis. The greatest challenge encountered during the project was the failure to conduct pumping tests.

Golder Associates carried out pumping tests (Garnham and Wright, 2003) on two large diameter boreholes (CHIWB 005 and CHIWB 012) and the values will be used together with additional estimates.

Transmissivity (T) is a measure of the ease with which groundwater flows in the subsurface. Transmissivity is related to hydraulic conductivity (K):

$$T = Kd \qquad \text{(Eqn 2)}$$

where, d is the saturated thickness of the aquifer.

Variable transmissivities are typical of a fractured rock environment. Storativity (S) is a volume of water per volume of aquifer released as a result of a change in head and as no data is available concerning this parameter it is assumed to be 1 x $10^{-5}$ for the fractured rock aquifer, as calculated by Golder Associates in 2003.

Specific Yield ($S_y$) is the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline of the water table. The specific yield for the weathered rock aquifer at Chimiwungo was estimated by calculating the average $S_y$ of silt and clay; $S_y$ at Chimiwungo = 6 (Kruseman and De Ridder, 1994).

Blow yields were measured on some of the boreholes drilled as part of the 2010/2011 programme. These yields were used to obtain estimates of the transmissivities of the aquifers intersected at each drilled site. The following relationship is used to estimate the transmissivity of an aquifer from blow yields (IGS, 2009):

$$\mathbf{T \sim 5Q} \qquad \text{(Eqn 3)}$$

where, T is the transmissivity of the aquifer ($m^2/d$)

Q is the blow yield (L/s)

Estimated values of transmissivities at boreholes drilled in the 2010/11 programme were calculated using the above equation.

Boreholes drilled in the 2010/11 drilling programme intersected shallow water strikes at depths ranging from 4 mbgl to 30 mbgl. These shallow water strikes are defined by average blow yields of 0.1 L/s. The yields are low due the poorly sorted combination of geological materials ranging from very fine clay to medium sized gravel. Deeper water strikes were encountered at fractured horizons within the fresh rock at varying depths. The average blow yield for these deeper water strikes is 0.2L/s.

Using the above relationship (Eqn 3), the following transmissivities (Table 11) have been estimated at each borehole. The intermediate fresh rock units have been considered as aquicludes with transmissivity values lower than one tenth of that of the upper aquifer.

**Table 11. Estimated Aquifer Transmissivities**

| BH ID | Water Strikes Depths (m) | Geology at Water strike | Blow yield (L/s) | Estimated Transmissivity ($m^2/d$) |
|---|---|---|---|---|
| MH04 | 48 | Fractured Gneiss | 1.5 | 8 |
| MH04A | 43, 48 | Fractured Gneiss | 1.5 | 8 |
| MH05 | 24, 78-91 | Schist, Fractured Gneiss | 0.2 | 1 |
| MH06 | 24, 51-62, 76 | Schist, Fractured Gneiss | 5.6 | 28 |
| PIEZ08 | 66, 84 | Schist, Fractured Gneiss | 0.2 | 1 |
| PIEZO10 | 28, 50, 114, 122 | Schist, Fractured Gneiss | 0.2 | 1 |
| PIEZO9C | 22, 111 | Fractured Schist | 0.7 | 4 |
| Average | | | | 7 |
| Minimum | | | | 1 |
| Maximum | | | | 28 |

The values obtained through the estimation are comparable to the values obtained by Golder in 2003. Golder calculated transmissivities of $0.8m^2/d$ at borehole CHIWB05 and $0.6m^2/d$ at borehole CHIWB12. Storativity values obtained in the Golder study have been adopted for the conceptual model.

Transmissivity values were estimated for the two identified Chimiwungo aquifers, using the same relationship (Eqn 3). The average blow yield at each intersected aquifer was used as the basis for the estimation (Table 12).

**Table 12. Estimated aquifer parameters for Chimiwungo aquifers**

| Aquifer Unit | Average thickness (m) | Blow yield (L/s) | Estimated T ($m^2/d$) | Hydraulic conductivity (m/d) | Recharge (mm/y) |
|---|---|---|---|---|---|
| Weathered aquifer | 30 | 0.1 | 0.5 | 0.01 | 498 |
| Fractured/Epidote Schist aquifer | 40 | 0.2 | 1 | 0.05 | 498 |

Figure 7-3 shows a simplified cross-section through Chimiwungo.

### 7.3.1 Influence of structures on groundwater occurrence and flow

Fractures refer to cracks, fissures, joints and faults which are caused by:

(a) geological and environmental processes, e.g. tectonic movement, secondary stresses, release fractures, shrinkage cracks, weathering, chemical action, thermal action; and,

(b) petrological factors like mineral composition, internal pressure, grain size, etc. From a hydrogeological point of view, a rock formation can be considered a multi-porous medium, conceptually consisting of two major components: matrix rock blocks and fractures.

Fractures serve as higher conductivity conduits for flow if the apertures are large enough, whereas the matrix blocks may be permeable or impermeable, with most of the water usually contained within the matrix. Actually, a rock mass may contain many fractures of different scales and the conductivity of the matrix blocks is in most cases only dependent on the presence of smaller or micro-fractures (IGS, 2001). The Chimiwungo area is truncated by a series of sub-vertical faults which, in all likelihood, act as conduits for groundwater flow.

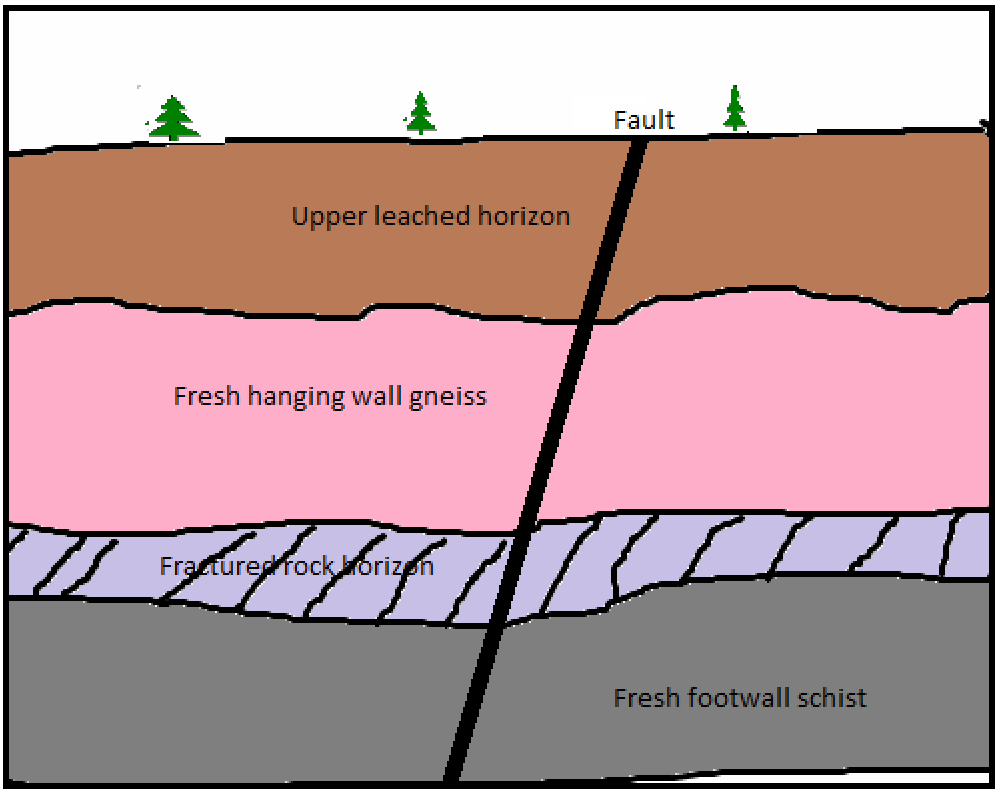



Figure 7-3. Chimiwungo Aquifers

## 7.4 Boundary Conditions

One of the first and most demanding tasks in groundwater modelling is that of identifying the model area and its boundaries. A model boundary is defined as the interface between the model area and the surrounding environment. Conditions on the boundaries, however, have to be specified. Boundaries occur at the edges of the model area and at locations in the model area where external influences are represented, such as rivers, wells, and leaky impoundments.

Criteria for selecting hydraulic boundary conditions are primarily topography, hydrology and geology. The topography, geology, or both, may yield boundaries such as impermeable strata or potentiometric surface controlled by surface water, or recharge/discharge areas such as inflow boundaries along mountain ranges. The flow system allows the specification of boundaries in situations where natural boundaries are at a great distance.

Boundary conditions must be specified for the entire boundary and may vary with time. At a given boundary section just one type of boundary condition can be assigned. As a simple example, it is not possible to specify groundwater flux and groundwater head at an identical boundary section. Boundaries in groundwater models can be specified as:

- Dirichlet (also known as constant head or constant concentration) boundary conditions
- Neuman (or specified flux) boundary conditions
- Cauchy (or a combination of Dirichlet and Neuman) boundary conditions (IGS, 2009)

The Chimiwungo River was set as the northern and eastern boundary (constant head) for the Chimiwungo Main pit. The southern and western boundaries were set as no-flow boundaries due to a topographic high.

Similarly for the Chimiwungo North pit, the Chimiwungo River was set as the southern and western (constant head) boundary and the northern and eastern boundaries were set as no-flow boundaries due to a topographic high that occurs in this area. All other boundaries follow the quaternary catchment boundary and are therefore also assigned no-flow conditions.

Figure 7-4 shows the boundary conditions specified at Chimiwungo.

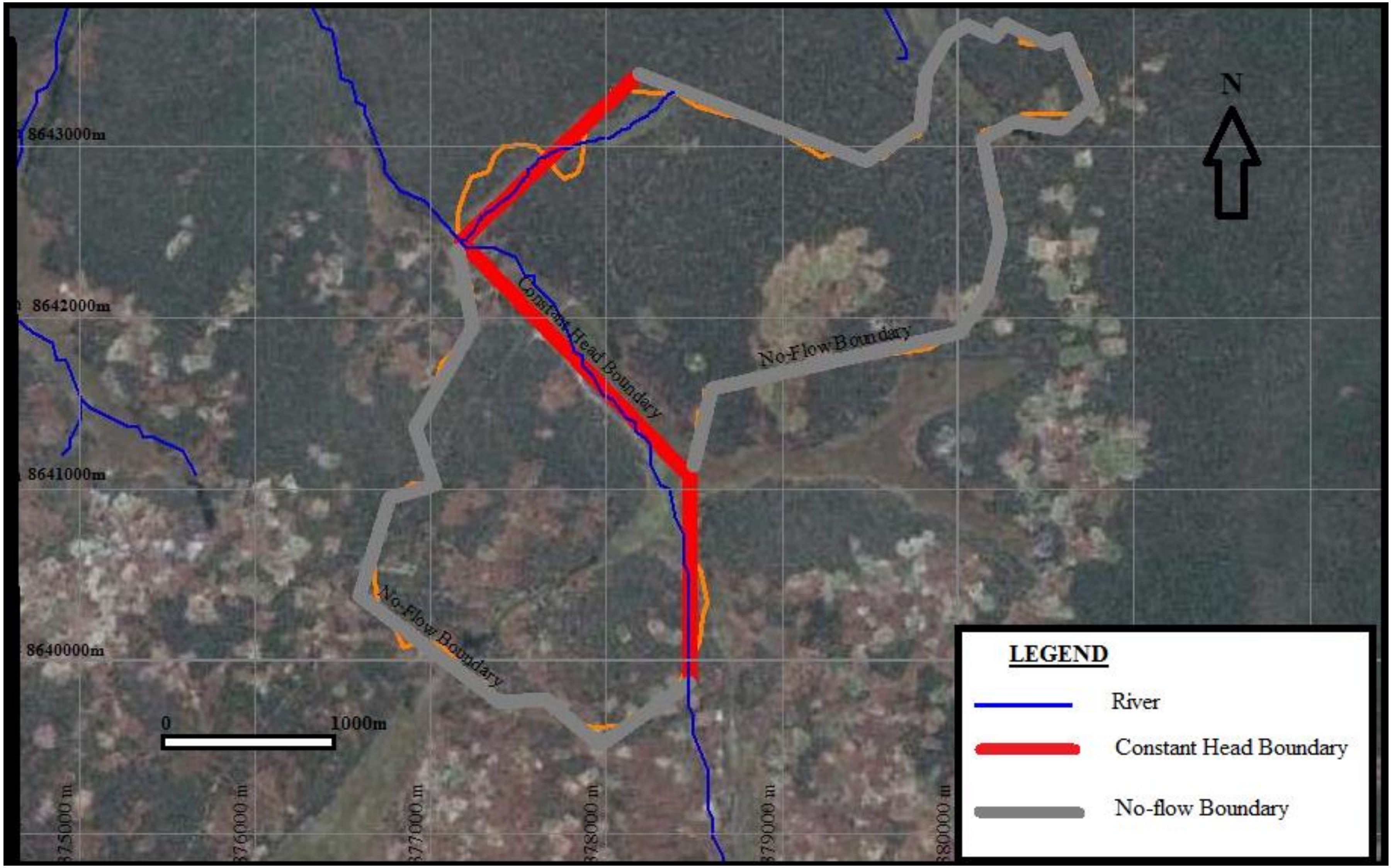



**Figure 7-4. Chimiwungo Boundary Conditions**

## 7.5 Assumptions and Limitations

In order to develop a model of an aquifer system, certain assumptions have to be made. The following assumptions were made during the development of the model:

- The system is initially in equilibrium and therefore in steady state, even though natural conditions have been disturbed;
- The available information on the geology and field tests are considered as correct;
- No abstraction boreholes were included in the model; and,
- Many aquifer parameters have not been determined in the field and therefore have to be estimated.

It is important to note that a numerical groundwater model is a representation of the real system. It is therefore, at most, an approximation, and the level of accuracy depends on the quality of the data that is available and the extent to which the conceptual model describes the actual field conditions. This implies that there are always errors associated with groundwater models due to uncertainty in the data and the capability of numerical methods to describe natural physical processes.

## 7.6 Other sources of water into the pit

Lumwana Mine have a dewatering strategy involving the storage of all abstracted water in the Malundwe pit. However, for effective control it is important that the source of the water is identified. This makes control much more effective and targeted. The water pumped from the Malundwe pit consists of:

- Direct rainfall (into pit and as storm water/sheet flow);
- Through-flow via the Zone of Relaxation (ZOR) and pit benches; and,
- Seepage water from dams and channels; currently, no dams are planned upstream of the Chimiwungo area. The water channels passing through the area will be diverted.

Where possible, each type of water should be controlled at source.

## 7.7 Gap analysis

The following information gaps exist within the information analysed at Lumwana Mine:

- Water quality analyses carried out from 2006 to December 2010 were incomplete. The LMC Environmental Department only requested analyses for some of the major cations and anions. All water quality analysis should include all the major cations and anions (Ca, Mg, Na, K, SO42-, $HCO_3^-$, Total Alkalinity).
- Water levels were not monitored consistently throughout the period of study. The water level meter from the Environmental Department broke down for a six month period. Groundwater levels need to be monitored regularly to build upon the database set up at Lumwana Mine in 2011.
- No pumping data is available in Malundwe which may be used in estimating the potential dewatering volumes for Chimiwungo. Large diameter boreholes need to be drilled and tested within and around both pits at Malundwe and Chimiwungo. Boreholes are required on the major structural features that truncate the pits and on either side of the major fault lines. Pumping tests and analysis are required to determine whether faults act as conduits or barriers to groundwater flow.
- No rain gauge is present in Chimiwungo. High spatial variability of rainfall and rainfall Cl concentrations is observed around Lumwana. At least one rain gauge is required within the Chimiwungo mining area to measure the amount or rain falling around the pit area within one wet season.

# 8 CONCLUSIONS

- The study confirmed the finding by earlier reports that there exist two aquifers; an upper weathered horizon and a lower fractured one.
- Blow yields measured during drilling have shown that Chimiwungo has limited groundwater quantities. The density of fractures appears to be lower and less connected than at Malundwe.
- The geology underlying the site was classified according to the Parsons (and DWA) system using the information derived from the drilling and aquifer testing as a minor aquifer system.
- Recharge within the Chimiwungo area is primarily from rainfall and the groundwater system discharges to the surface water system via the many dambos that lie within the area.
- Recharge is estimated at 38% of Mean Annual Precipitation, corresponding to 498mm of rainfall per annum (Chloride Mass balance Method). Analysis of recharge and groundwater hydrographs points to the greater portion of recharge being dominant in the weathered zone.
- The transmissivity values obtained through the estimation (T ~ 5Q) are comparable to the values obtained by Golder in 2003.
- The Chimiwungo area is truncated by a series of sub-vertical faults which, in all likelihood, act as conduits for groundwater flow.
- The Chimiwungo River was set as the northern and eastern boundary (constant head) for the Chimiwungo Main pit. The southern and western boundaries were set as no-flow boundaries due to a topographic high. Similarly for the Chimiwungo North pit, the Chimiwungo River was set as the southern and western (constant head) boundary and the northern and eastern boundaries were set as no-flow boundaries due to a topographic high that occurs in this area. All other boundaries follow the quaternary catchment boundary and are therefore also assigned no-flow conditions.
- There exits gaps in the water monitoring system and laxity in terms of laboratory analysis.

# 9 RECOMMENDATIONS

- Dewatering will likely be a combination of sumps and depressurization by drain holes. Sumps will collect water that accumulates on the pit floor through seepage via the pit face. The sumps will collect water in quantities that may be used for other purposes within the mining area. Drain holes will allow groundwater trapped within the rock matrix to be released.

- More boreholes need to be drilled and tested to determine hydraulic parameters in each geotechnical sector. This will enhance the understanding of the hydraulic forces at play within the aquifers.

- The general water quality around the mine is reasonably good. Greater control needs to be exercised over the laboratory. Regular checks must be carried out by the use of blank and split samples. Assessments on the electroneutrality of sample results need to be done on each batch of water quality results.

- Chloride deposition should be monitored for several consecutive years to estimate an average annual groundwater recharge rate. The estimation of recharge using the Chloride Mass Balance Method relies on the presence of long term chloride deposition data in order to produce a reliable estimate. A proper rainwater collection and sampling system needs to be put in place to avoid errors.

- Automatic water level recorders should be installed in monitoring holes. The accuracy and consistency of groundwater level measurements will be significantly improved by the use of water level loggers. The failure to regularly measure groundwater levels will be eliminated by the installation of the automatic equipment. The frequency and regularity of groundwater level measurements can also be managed easily.

- A recommendation has been made to extend the groundwater sampling network to include boreholes that are currently on the Chimiwungo groundwater level monitoring network. The four boreholes (CHIWB 012, XM001, MH04, MH04A) have large diameter casing, providing sufficient access for groundwater sampling. A wider groundwater quality monitoring network is necessary to achieve a better coverage of the groundwater quality mapping of the Chimiwungo aquifers.

- It is recommended that a numerical model be developed using the data presented in this conceptual model. Confidence in the numerical model may be enhanced by successfully completing the borehole drilling and testing progamme.

# 10 REFERENCES


Appelo. C.A.J, Postma.D (2007). Geochemistry, groundwater and pollution. *2nd Edition*.

Armstrong RA, Master S, Robb LJ (2005) Geochronology of the Nchanga Granite, and constraints on the maximum age of the Katanga Supergroup, Zambian Copperbelt. *Journal of African Earth Sciences 42: 32-40.*

Beekman, H.E. (2000). Groundwater Recharge: Assessment and Estimation Techniques in Southern Africa, *Lecture notes WREM Hydrogeology Course UZ-Civil Eng. Dept*. Zimbabwe, 17-18, pp 25.

Beekman, H.E, Selaolo, E.T., Van Elswijk, R.C., R.C., Lenderink, N, Obakeng, O.T.O. (1997). Groundwater recharge and resources assessment in the Botswana Kalahari-Chloride and isotope profiling studies in the Letlhaken-Botlhapatlou and Central Kalahari areas, *GRES II Technical Report, pp. 112.*

Bernau. R (2007). The Geology and geochemistry of the Lumwana Basement hosted copper cobalt (uranium) deposits, NW Zambia. PhD thesis. University of Southampton.

Bredenkamp, D.B., Botha, L.J., van Tonder, G.J, van Rensburg, H.J. (1995). Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity. *Water Research Commission Pretoria, South Africa, pp. 407*.

Campbell, B., Forst, P, Byron, N. (1996). Miombo woodlands and their use: Overview and key issues. In Bruce Campbell (Ed.) The Miombo in Transition: Woodlands and Welfare in Africa. *CIFOR, Bogor, Indonesia. pp 1-10*.

Cosi M, Debonis A, Gosso G, Hunziker J, Martinotti G, Moratto S, Robert JP, Ruhlman F (1992) Late proterozoic thrust tectonics, high-pressure metamorphism and uranium mineralization in the domes area, lufilian arc, northwestern Zambia. *Precambrian Research 58: 215-240.*

Demand Media (2011). Advantages of Open Pit Mining. E-How website. E-How.com

Driscoll. F. G (1986) Groundwater and Wells. Subsequent Edition

Eriksson, E. and Khunakasem, V. (1969). Chloride concentration in groundwater, recharge rate and rate of deposition of chloride in the Israel coastal plain, *Journal of Hydrology., Vol. 7, 178-197.*

Equinoxminerals.com

Garnham. R, Wright. A. Golder Associates (2003). Lumwana Bankable Feasibility Study. Volume 4 – *Appendix H. Hydrogeology Study.*

Hanson R.E, Wardlaw M.S, Wilson T.J, Mwale G (1993). U-Pb zircon ages from the Hook granite massif and Mwembeshi dislocation: constraints on Pan-African deformation, plutonism and transcurrent shearing in Central Zambia. *Precambrian Research 63, p189-209*

Henstock, Michael E. (1996). The recycling of non-ferrous metals. The International Council on Metals and the Environment, Ottawa, Canada. 342 pp.

Institute for Groundwater Studies. (2001). Manual on pumping test analysis in fractured rock aquifers.

Institute for Groundwater Studies. (2009). Bachelor of Science Honours Geohydrology *Lecture notes.*

John T, Schenk V, Mezger K, Tembo F (2004). Timing and PT evolution of whiteschist metamorphism in the Lufilian Arc-Zambezi Belt Orogen (Zambia); implications for the assembly of Gondwana. *Journal of Geology 112, 71-90*

Johnson S.P, Oliver G.H.J (2002). High fO (sub2) metasomatism during whiteschist metamorphism, Zambezi Belt, Northern Zimbabwe. *Journal of Petrology, 43, p271-290*

Knight Piésold. (2008) Lumwana Mining Company Limited Uranium Project Environmental Impact assessment. *Report 5249/30.*

Kruseman. G. P, De Ridder. N. A (1994). Analysis and evaluation of pumping test data. Second Edition. *International Institute for Land Reclamation and Improvement (ILRI). Publication 47*

Lerner, D. N., Issar, A, Simmers, I. (1990). A guide to understanding and estimating natural recharge, *Int. contribution to hydrogeology, I.A.H. Publ., Vol. 8, Verlag Heinz Heisse, pp. 345*.

McCartney, M. P. (1998). The hydrology of a headwater catchment containing a dambo: Ph.D Thesis, University of Reading, pp. 266.

Mulela D, Seifert A.V. (1998). Geology of the Mwombezhi Dome and Jiwundu Swamp areas: Explanation of degree sheet 1225NE quarter and 1125, part of SE quarter. *Report of the Geological Survey of Zambia, 83, p28*

Mupimpila. C, Van der Grijp. N. (1998). Copper from Zambia (Draft). *United Nations Environment Program*

Naish. E J. (1993). Dewatering concepts at Zambian Copperbelt mines. *Mine water and the Environment Vol 11*

Parsons. R (2004) Surface Water – Groundwater Interaction in a Southern African Context – a geohydrological perspective. *Water Research Commission Report 116-F1*

Department of Water Affairs. South Africa. Drinking water quality standards. SANS 241:2005

Stone, AW, Lindley Stone AJ (1994). Wetlands and groundwater in the United States; American Ground Water Trust, Dublin.

United Nations (2004). Map of Zambia

U.S. Environmental Protection Agency Environmental Response Team (2003). Response Engineering and Analytical Contract Standard Operating Procedures Drilling and Monitoring Well Installation at Hazardous Waste Sites in South Dakota SOP 2150

U.S Geological Survey (USGS) (2001) Groundwater level monitoring and importance of long term water level data. *USGS Circular 1217*

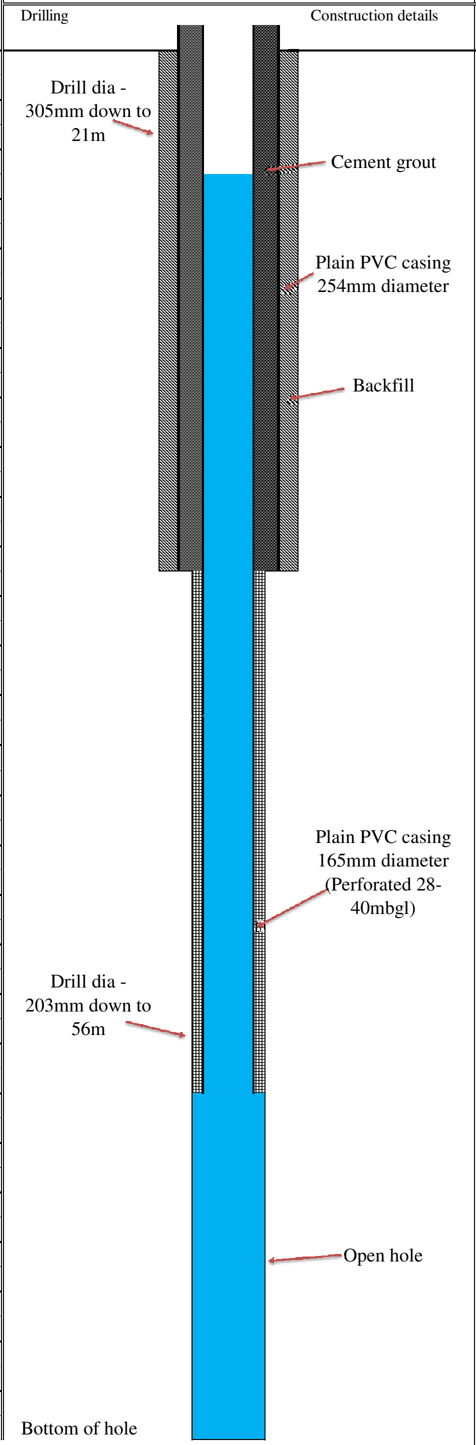
White, F. (1983). The vegetation of Africa. *Natural Resources Research 20, UNESCO, Paris*. 356 pp + maps.

Wiles. S, Garnham. R. Groundwater Resource Management (2007). Hydrogeological study of the Malundwe pit, Lumwana, Zambia.

# BOREHOLE LOG

| | | | |
|---|---|---|---|
| **CLIENT:** | Lumwana Mine | **BOREHOLE NO :** | MH 04 |
| **PROJECT**: | Chimiwungo Hyro | **COORDINATES (UTM 35L)** | |
| **SITE**: | Chimiwungo Hyro | **X :** | 378465 |
| **DRILLER**: | Capital Drilling | **Y :** | 8640603 |
| **DATE DRILLED:** | 2011/09/22 | **PLUNGE:** | Vertical |
| **LOGGED BY**: | B. MABENGE | **STATUS**: | Complete |

**BOREHOLE DRILLING AND CONSTRUCTION DETAILS**



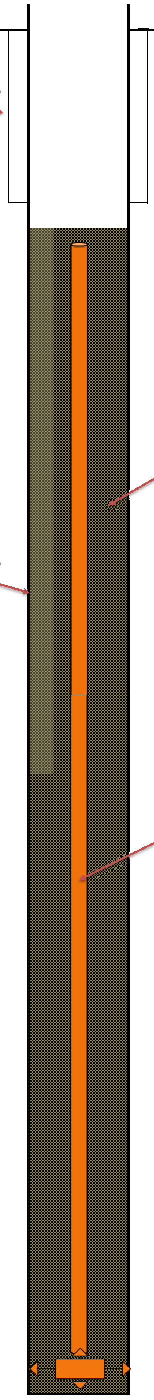

| DEPTH (m) | STRIKES (mbgl) | S W L (mbgl) | LITHOLOGICAL DESCRIPTION Rock type, colour, grain size, texture, weathering and fracturing |
|---|---|---|---|
| 0–1 | | | Topsoil, brown |
| 1–5 | | **SWL 5.04mbgl** | GRAVEL: Clayey gravel |
| 5–10 | | | GNEISS: Yellowish orange, highly weathered gnesiss |
| 10–36 | | | GNEISS: Light brown, moderately weathered gneiss |
| 36–47 | Seepage at 43m | | SCHIST: Grey black, moderately weathered schist |
| 47–56 | W/Strike at 48m *(1.5 L/s)* | | GNEISS: Light brown, moderately weathered gneiss |

# BOREHOLE LOG

| | | | |
|---|---|---|---|
| **CLIENT:** | Lumwana Mine | **BOREHOLE NO :** | MH 05 |
| **PROJECT**: | Chimiwungo Hyro | **COORDINATES (UTM 35L)** | |
| **SITE**: | Chimiwungo Hyro | **X :** | 377885 |
| **DRILLER**: | Capital Drilling | **Y :** | 8640204 |
| **DATE DRILLED:** | 2011/02/15 | **PLUNGE:** | Vertical |
| **LOGGED BY**: | B. MABENGE | **STATUS**: | Abandoned |

**BOREHOLE DRILLING AND CONSTRUCTION DETAILS**

Drilling | Construction details



Drill dia - 305mm down to 37m

Drill dia - 203mm down to 275m

Bottom of hole

Collapsed material

230m of drill rods, hammer and drill bit abandoned down the hole

**STRIKES (mbgl)**: Seepage at 24m; W/Strike at 78m - 91m (0.2L/s)

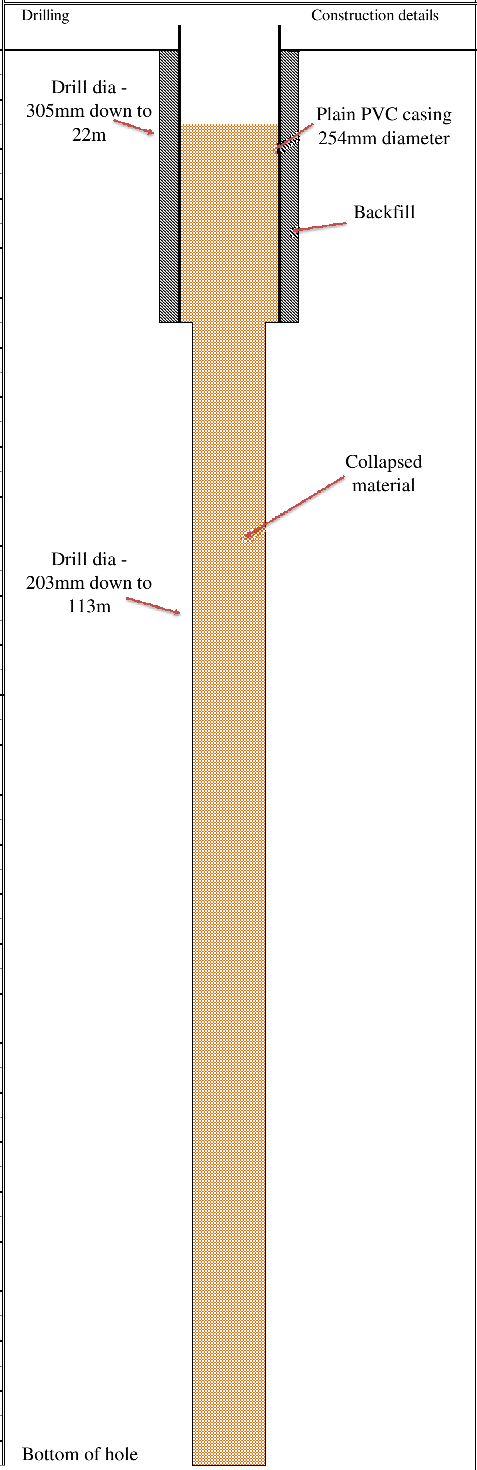
**S W L (mbgl)**: –

| DEPTH (m) | LITHOLOGICAL DESCRIPTION (Rock type, colour, grain size, texture, weathering and fracturing) |
|---|---|
| 0–5 | CLAY/LATERITE: Reddish brown |
| 5–10 | CLAY/LATERITE: Orange brown |
| 10–15 | SAPROLITE: Reddish brown |
| 15–35 | SCHIST: Pale green to grey. Moderately to highly weathered |
| 35–45 | GNEISS: Grey to pink. Moderately weathered |
| 45–60 | GNEISS: Grey to pink. Slightly weathered. Biotite present |
| 60–75 | GNEISS: Grey to pink. Fractured to fresh. Biotite present |
| 75–85 | GNEISS: Grey, Fractured to Fresh |
| 85–90 | SCHIST: Black/ Grey, Fresh |
| 90–100 | BIOTITE GNEISS: Fresh, grey |
| 100–115 | SCHIST: Black/ Grey, Fresh |
| 115–125 | BIOTITE GNEISS: Fresh, grey |
| 125–135 | SCHIST:Greenish Grey, Fresh |
| 135–145 | BIOTITE GNEISS: Fresh, grey |
| 145–160 | SCHIST:Greenish Grey, Fresh. Slight mineralization |
| 160–180 | GNEISS: Grey, Fresh. White feldspar |
| 180–255 | SCHIST: Greeenish grey. Biotite. Mineralized. Fresh |
| 255–260 | GNEISS: Fresh, pink feldspar |
| 260–265 | SCHIST: Grey. Biotite. Mineralized. Fresh |
| 265–275 | GNEISS: Fresh, pink feldspar |

# BOREHOLE LOG

| | | | |
|---|---|---|---|
| **CLIENT:** | Lumwana Mine | **BOREHOLE NO :** | MH 06 |
| **PROJECT:** | Chimiwungo Hyro | **COORDINATES (UTM 35L)** | |
| **SITE:** | Chimiwungo Hyro | **X :** | 376558 |
| **DRILLER:** | Capital Drilling | **Y :** | 8641059 |
| **DATE DRILLED:** | 2011/11/13 | **PLUNGE:** | Vertical |
| **LOGGED BY:** | B. MABENGE | **STATUS:** | Abandoned |

**BOREHOLE DRILLING AND CONSTRUCTION DETAILS**

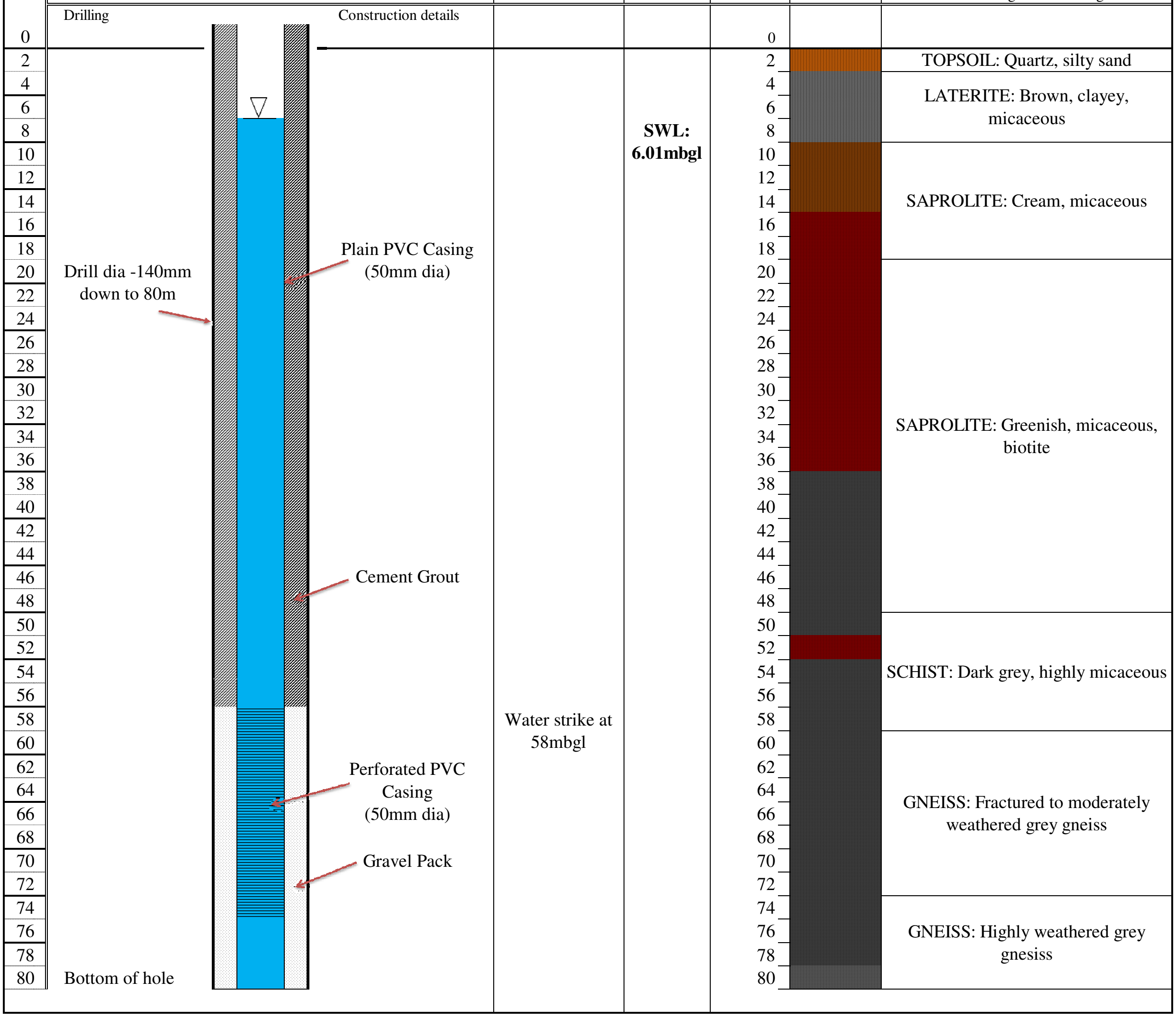



| DEPTH (m) | STRIKES (mbgl) | S W L (mbgl) | LITHOLOGICAL DESCRIPTION Rock type, colour, grain size, texture, weathering and fracturing |
|---|---|---|---|
| 0 – 2 | | | TOPSOIL: Loose, Fine to coarse, |
| 2 – 6 | | | GRAVEL: Clear, grey black, angular, feldspar, clayey |
| 6 – 14 | | | CLAY/LATERITE: Dark brown |
| 14 – 26 | | | GRAVEL: Quartz, Biotite. Fine Angular sand. Iron Oxide. Friable |
| 26 – 32 | W/Strike at 29m - 34m | | GNEISS: Moderately to highly weathered, feldspathic, pink. Subrounded |
| 32 – 42 | | | BIOTITE GNEISS:Moderately weathered. Subangular |
| 42 – 54 | | | GNEISS: Moderately weathered. Quartz Biotite Feldspar. Pink |
| 54 – 60 | | | GNEISS: Slightly weathered. Quartz Biotite Feldspar. Pink |
| 60 – 76 | | | GNEISS: Moderately to highly weathered. Quartz Biotite Feldspar. Pink |
| 76 – 82 | W/Strike at 78m - 91m *(5.6 L/s)* | | BIOTITE GNEISS:Fractured to fresh. Grey |
| 82 – 96 | | | BIOTITE GNEISS:Slightly weathered. Grey |
| 96 – 102 | | | GNEISS: Moderately weathered. Quartz Biotite Feldspar. Pink |
| 102 – 108 | | | BIOTITE GNEISS:Fresh. Grey |
| 108 – 113 | | | MICA SCHIST: Fresh to slightly weathered. Slightly mineralized |

# BOREHOLE LOG

| | | | |
|---|---|---|---|
| **CLIENT:** | Lumwana Mine | **BOREHOLE NO :** | PIEZO 06 |
| **PROJECT**: | Chimiwungo Hyro | **COORDINATES (UTM 35L)** | |
| **SITE**: | Chimiwungo Hyro | **X :** | 378395 |
| **DRILLER**: | Capital Drilling | **Y :** | 8640624 |
| **DATE DRILLED:** | 2010/10/10 | **PLUNGE:** | 60° |
| **LOGGED BY**: | B. MABENGE | **STATUS**: | Completed |

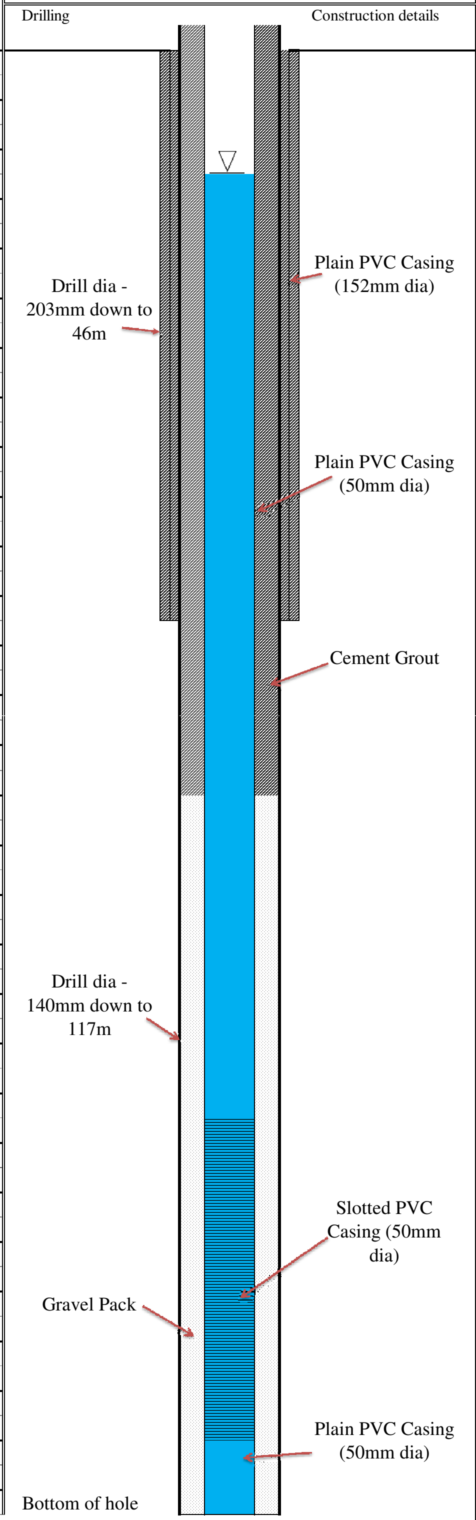
| BOREHOLE DRILLING AND CONSTRUCTION DETAILS | STRIKES (mbgl) | S W L (mbgl) | DEPTH (m) | PROFILE | LITHOLOGICAL DESCRIPTION Rock type, colour, grain size, texture, weathering and fracturing |
|---|---|---|---|---|---|



# *BOREHOLE LOG*

| | | | |
|---|---|---|---|
| **CLIENT:** | Lumwana Mine | **BOREHOLE NO :** | PIEZO 08 |
| **PROJECT:** | Chimiwungo Hyro | **COORDINATES (UTM 35L)** | |
| **SITE:** | Chimiwungo Hyro | **X :** | 377900 |
| **DRILLER:** | Capital Drilling | **Y :** | 8640190 |
| **DATE DRILLED:** | 2011/02/06 | **PLUNGE:** | Vertical |
| **LOGGED BY:** | B. MABENGE | **STATUS:** | Completed |

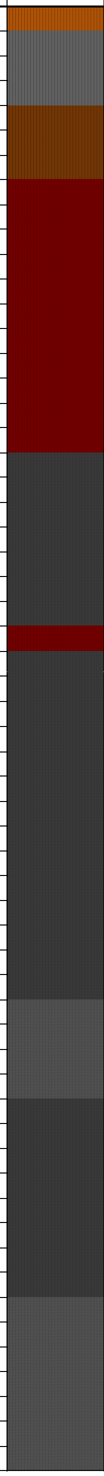
**BOREHOLE DRILLING AND CONSTRUCTION DETAILS** | **STRIKES (mbgl)** | **S W L (mbgl)** | **DEPTH (m)** | **PROFILE** | **LITHOLOGICAL DESCRIPTION** Rock type, colour, grain size, texture, weathering and fracturing




**STRIKES (mbgl):**
- Seepage at 14m
- Seepage at 66m
- Seepage at 84m

**S W L (mbgl):** **SWL: 9.77mbgl**

**DEPTH (m):** 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42, 44, 46, 48, 50, 52, 54, 56, 58, 60, 62, 64, 66, 68, 70, 72, 74, 76, 78, 80, 82, 84, 86, 88, 90, 92, 94, 96, 98, 100, 102, 104, 106, 108, 110, 112, 114, 116, 117



| LITHOLOGICAL DESCRIPTION |
|---|
| TOPSOIL: Loose, Fine to coarse, |
| CLAY/LATERITE: Dark brown |
| SAPROLITE: Reddish brown, clayey. Quartz, feldspar |
| SCHIST: Pale green to grey. Moderately weathered |
| SCHIST: Dark grey to green. Moderately to highly weathered. Pink feldspar |
| SCHIST: Grey/green. Highly weathered |
| SCHIST: Grey/green. Slightly to moderately weathered |
| GNEISS: Grey to pink. Slightly weathered |
| GNEISS: Dark grey, fresh |
| BIOTITE SCHIST: Dark grey |
| GNEISS: Grey, fresh |
| GNEISS: Fresh, pink feldspar. Slight fracturing at 63-66m and 71-72m |
| BIOTITE GNEISS: Fresh, grey |
| GNEISS: Fresh, pink feldspar |
| BIOTITE GNEISS: Fresh, grey |

# BOREHOLE LOG

**CLIENT:** Lumwana Mine
**PROJECT**: Chimiwungo Hyro
**SITE**: Chimiwungo Hyro
**DRILLER**: Capital Drilling
**DATE DRILLED:** 26/10/2010
**LOGGED BY**: B. MABENGE

**BOREHOLE NO :** PIEZO 09A
**COORDINATES (UTM 35L)**
**X :** 376604
**Y :** 8641150
**PLUNGE:** 60 Deg to South
**STATUS**: Collapsed

**BOREHOLE DRILLING AND CONSTRUCTION DETAILS**

Drilling: Drill dia - 140mm down to

Construction details

| DEPTH (m) | STRIKES (mbgl) | S W L (mbgl) | LITHOLOGICAL DESCRIPTION Rock type, colour, grain size, texture, weathering and fracturing |
|---|---|---|---|
| 0–2 | | | TOPSOIL: Loose, Fine to coarse, |
| 2–6 | | | GRAVEL: Clear, grey black, angular, feldspar, clayey |
| 6–8 | | | CLAY/LATERITE: Dark brown |
| 8–16 | | | LATERITE: Pale orange - yellowish. Whitish clay |
| 16–22 | Seepage at 17m | | SAPROLITE: Brown to reddish brown. Fine to coarse. Friable |
| 22–34 | Seepage at 26m | | GRAVEL: Quartz, Biotite. Fine Angular sand. Iron Oxide. Friable |
| 34–38 | | | SAPROLITE: Creamy white. Friable. Angular Quartz. Micaceous |
| 38–44 | | **SWL: ?mbgl** | GRAVEL: Coarse, clear quartz (angular to subrounded) |
| 44–52 | | | GNEISS: Highly fractured, feldspathic, pink.Angular |
| 52–56 | | | BIOTITE GNEISS: Highly weathered. Abundant Iron Oxide |
| 56–58 | | | BIOTITE GNEISS:Moderately weathered |
| 58–60 | | | BIOTITE SCHIST: Moderately weathered |
| 60–72 | | | GNEISS: Moderately weathered. Quartz Biotite Feldspar. Pink |
| 72–76 | Water srike at 76m | | BIOTITE SCHIST: Fractured. Biotite, Feldspar |
| 76–78 | | | BIOTITE GNEISS:Fractuerd to fresh |
| 78–80 | | | SAPROLITE:Fine to coarse. Friable |
| 80–104 | | | BIOTITE GNEISS:Fractured to fresh. Grey |
| 104–108 | Water srike at 107m | | MICA SCHIST: Fresh, grey |
| 108–118 | | | MICA SCHIST: Highly fractured. Grey Iron Oxide staining |
| 118–120 | | | MICA SCHIST: Fresh, grey |
| 120–124 | Water srike at 123m | | SCHIST: Highly weathered. Mineralized (Fault zone) |
| 124–130 | | | SCHIST: Fractured. Grey |
| 130–140 | | | SCHIST: Fresh. Grey |

# *BOREHOLE LOG*

| | | | |
|---|---|---|---|
| **CLIENT:** | Lumwana Mine | **BOREHOLE NO :** | PIEZO 09A |
| **PROJECT**: | Chimiwungo Hyro | **COORDINATES (UTM 35L)** | |
| **SITE**: | Chimiwungo Hyro | **X :** | 376604 |
| **DRILLER**: | Capital Drilling | **Y :** | 8641150 |
| **DATE DRILLED:** | 26/10/2010 | **PLUNGE:** | 60 Deg to South |
| **LOGGED BY**: | B. MABENGE | **STATUS**: | Collapsed |

**BOREHOLE DRILLING AND CONSTRUCTION DETAILS**

Drilling: Drill dia - 140mm down to

Construction details

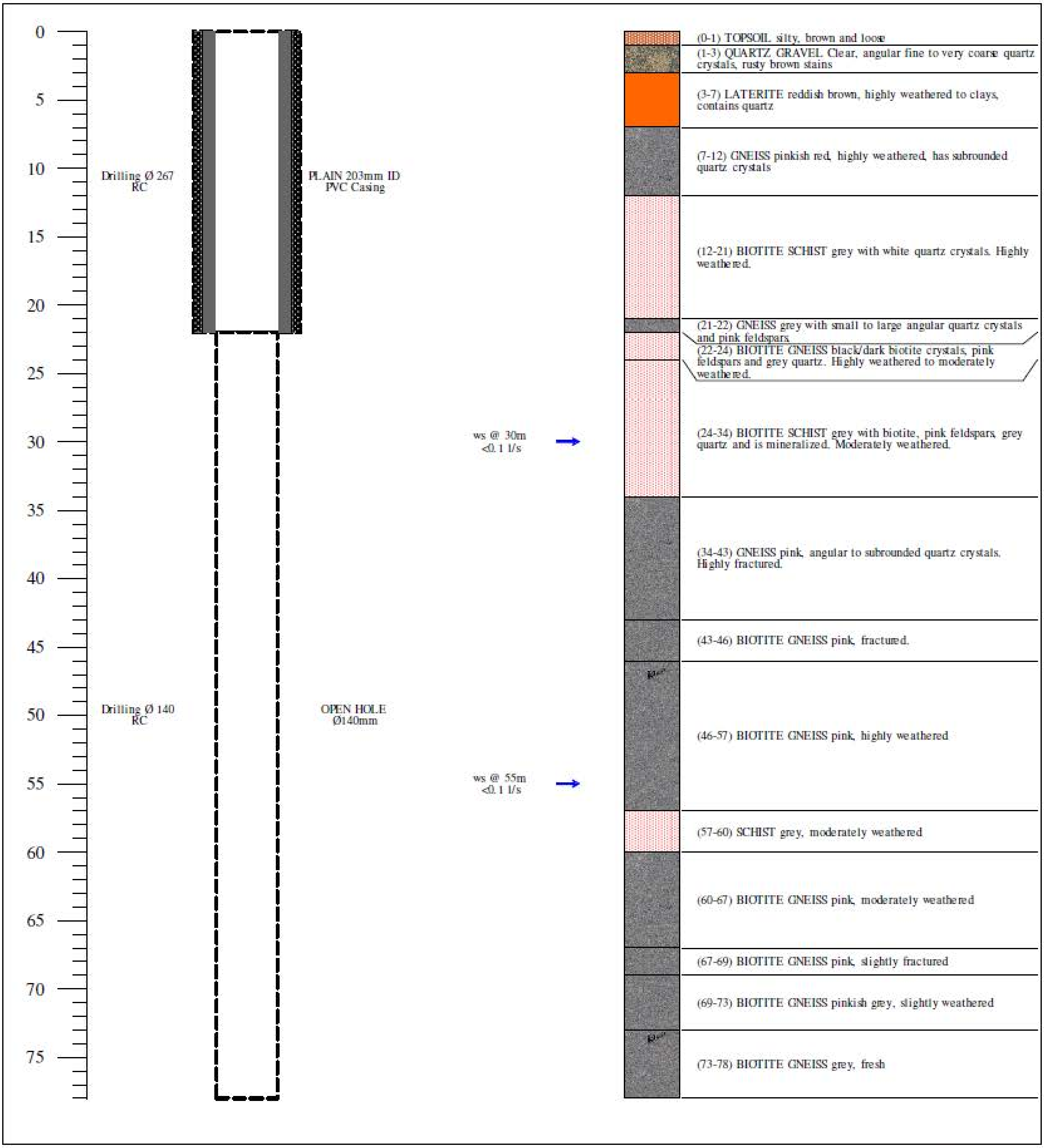
**SWL:** ?mbgl

| STRIKES (mbgl) | DEPTH (m) | LITHOLOGICAL DESCRIPTION Rock type, colour, grain size, texture, weathering and fracturing |
|---|---|---|
| | 0 – 2 | TOPSOIL: Loose, Fine to coarse, |
| | 2 – 6 | GRAVEL: Clear, grey black, angular, feldspar, clayey |
| | 6 – 8 | CLAY/LATERITE: Dark brown |
| | 8 – 16 | LATERITE: Pale orange - yellowish. Whitish clay |
| Seepage at 17m | 16 – 22 | SAPROLITE: Brown to reddish brown. Fine to coarse. Friable |
| Seepage at 26m | 22 – 34 | GRAVEL: Quartz, Biotite. Fine Angular sand. Iron Oxide. Friable |
| | 34 – 38 | SAPROLITE: Creamy white. Friable. Angular Quartz. Micaceous |
| | 38 – 42 | GRAVEL: Coarse, clear quartz (angular to subrounded) |
| | 42 – 52 | GNEISS: Highly fractured, feldspathic, pink.Angular |
| | 52 – 56 | BIOTITE GNEISS: Highly weathered. Abundant Iron Oxide |
| | 56 – 58 | BIOTITE GNEISS:Moderately weathered |
| | 58 – 60 | BIOTITE SCHIST: Moderately weathered |
| | 60 – 72 | GNEISS: Moderately weathered. Quartz Biotite Feldspar. Pink |
| | 72 – 76 | BIOTITE SCHIST: Fractured. Biotite, Feldspar |
| Water srike at 76m | 76 – 78 | BIOTITE GNEISS:Fractuerd to fresh |
| | 78 – 80 | SAPROLITE:Fine to coarse. Friable |
| | 80 – 104 | BIOTITE GNEISS:Fractured to fresh. Grey |
| Water srike at 107m | 104 – 108 | MICA SCHIST: Fresh, grey |
| | 108 – 118 | MICA SCHIST: Highly fractured. Grey Iron Oxide staining |
| | 118 – 120 | MICA SCHIST: Fresh, grey |
| Water srike at 123m | 120 – 124 | SCHIST: Highly weathered. Mineralized (Fault zone) |
| | 124 – 130 | SCHIST: Fractured. Grey |
| | 130 – 140 | SCHIST: Fresh. Grey |

# BOREHOLE LOG

| | | | |
|---|---|---|---|
| **CLIENT:** | Lumwana Mine | **BOREHOLE No.:** | *PIEZO 09B* |
| **PROJECT:** | *Chimiwungo Hydro* | **COORDINATE SYSTEM:** | *UTM 35L* |
| **SITE:** | *Chimiwungo Hydro* | **X:** | *8641031* |
| **DRILLER:** | *Capital Drilling* | **Y:** | *376704* |
| **DATE DRILLED:** | *22/11/2010* | **PLUNGE:** | *vertical hole* |
| **LOGGED BY:** | *B. Mabenge* | **STATUS:** | *Lost/Abandoned* |

Depth (m) | Well Construction: Drilling, Casing | Water strike depth and yield | Lithology | Lithology Description

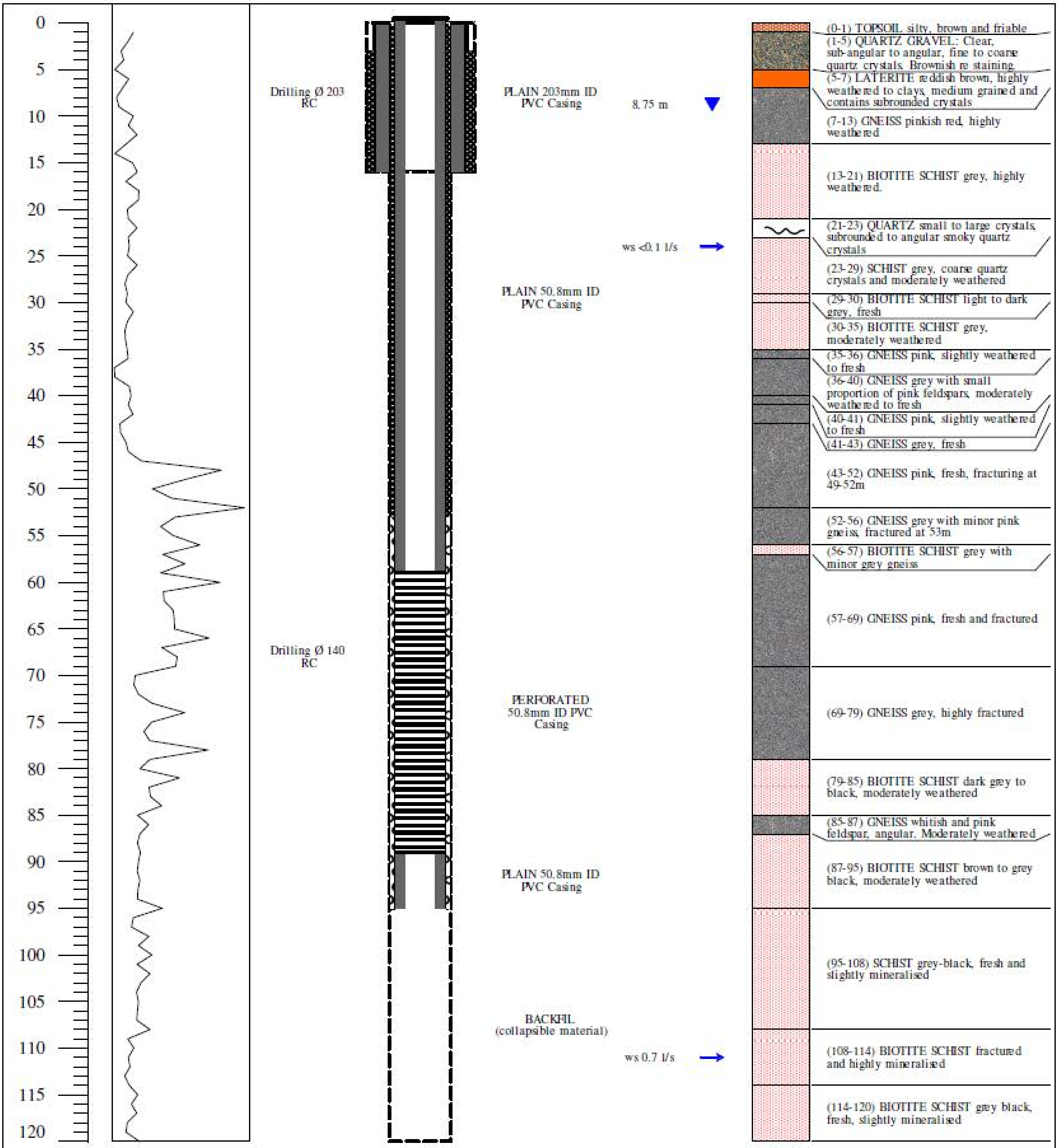



***LEGEND***

Grouting

# BOREHOLE LOG

| | | | |
|---|---|---|---|
| **CLIENT:** | Lumwana Mine | **BOREHOLE No.:** | *PIEZO 09C* |
| **PROJECT:** | *Chimiwungo Hydro* | **COORDINATE SYSTEM:** | *UTM 35L* |
| **SITE:** | *Chimiwungo Hydro* | **X:** | *376711* |
| **DRILLER:** | *Capital Drilling* | **Y:** | *8641058* |
| **DATE DRILLED:** | *27/11/2010* | **PLUNGE:** | *vertical hole* |
| **LOGGED BY:** | *B. Mabenge* | **STATUS:** | *Complete* |




***LEGEND***

Grouting

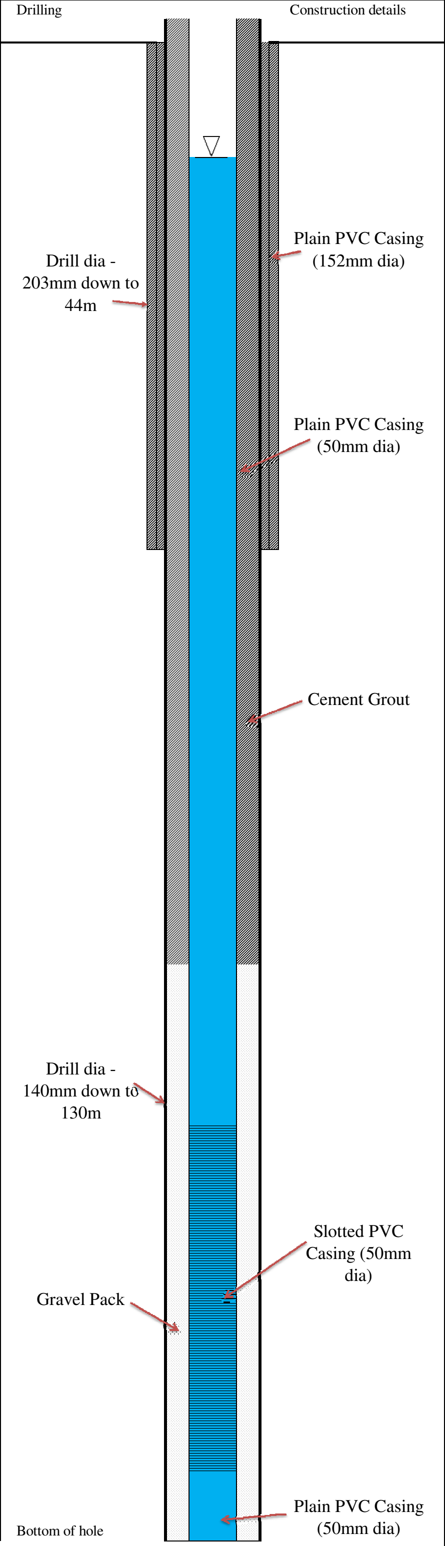
Gravel pack

Sanitary seal

# BOREHOLE LOG

| | | | |
|---|---|---|---|
| **CLIENT:** | Lumwana Mine | **BOREHOLE NO :** | PIEZO 10 |
| **PROJECT**: | Chimiwungo Hyro | **COORDINATES (UTM 35L)** | |
| **SITE**: | Chimiwungo Hyro | **X :** | 376606 |
| **DRILLER**: | Capital Drilling | **Y :** | 8641054 |
| **DATE DRILLED:** | 2011/01/23 | **PLUNGE:** | Vertical |
| **LOGGED BY**: | B. MABENGE | **STATUS**: | Completed |

**BOREHOLE DRILLING AND CONSTRUCTION DETAILS**




| STRIKES (mbgl) | S W L (mbgl) | DEPTH (m) | LITHOLOGICAL DESCRIPTION Rock type, colour, grain size, texture, weathering and fracturing |
|---|---|---|---|
| | | 0–2 | TOPSOIL: Loose, Fine to coarse, |
| | | 2–6 | GRAVEL: Clear, grey black, angular, feldspar, clayey |
| | **SWL: 9.34mbgl** | 6–14 | CLAY/LATERITE: Dark brown |
| | | 14–26 | GRAVEL: Quartz, Biotite. Fine Angular sand. Iron Oxide. Friable |
| Seepage at 28m | | 26–32 | GNEISS: Moderately to highly weathered, feldspathic, pink. Subrounded |
| | | 32–42 | BIOTITE GNEISS:Moderately weathered. Subangular |
| Water strike at 52m <0.1L/s | | 42–54 | GNEISS: Moderately weathered. Quartz Biotite Feldspar. Pink |
| | | 54–60 | GNEISS: Slightly weathered. Quartz Biotite Feldspar. Pink |
| | | 60–76 | GNEISS: Moderately to highly weathered. Quartz Biotite Feldspar. Pink |
| | | 76–82 | BIOTITE GNEISS:Fractured to fresh. Grey |
| | | 82–96 | BIOTITE GNEISS:Slightly weathered. Grey |
| | | 96–102 | GNEISS: Moderately weathered. Quartz Biotite Feldspar. Pink |
| | | 102–108 | BIOTITE GNEISS:Fresh. Grey |
| Water strike at 114m <0.1L/s | | 108–114 | MICA SCHIST: Fresh to slightly weathered. Slightly mineralized |
| | | 114–118 | BIOTITE GNEISS:Fractured to fresh. Grey |
| Water strike at 122m 0.2L/s | | 118–130 | SCHIST: Fresh. Grey |

| | | | | | |
|---|---|---|---|---|---|
| **Job Number** | **JB11-01479~~Bdpj.pjc.Pro_job~~** | | | | |
| **Order** | **LMC16497 May 2011** | | | | |
| **Project** | | | | | |
| | | **Sample Name** | **JB11-01479.001** | **JB11-01479.002** | **JB11-01479.003** |
| | | **Description** | **SW03** | **SW04** | **SW05** |
| **Analyte Name** | **Units** | **Reporting Limit** | **Result** | **Result** | **Result** |
| **pH** | **-** | **0,1** | **6,6** | **8,** | **6,8** |
| **Conductivity** | **mS/m** | **1** | **6,6** | **28,** | **3,4** |
| **Total Dissolved Solids** | **mg/l** | **10** | **408,** | **252,** | **76,** |
| **Total Suspended Solids Dried at 105C** | **mg/l** | **10** | **12,** | **<10** | **<10** |
| **Chloride** | **mg/l** | **0,5** | **0,54** | **4,1** | **<0.5** |
| **Fluoride** | **mg/l** | **0,3** | **<0.3** | **0,3** | **0,36** |
| **Nitrate** | **mg/l** | **0,4** | **1,5** | **<0.4** | **<0.4** |
| **Nitrite** | **mg/l** | **0,7** | **<0.7** | **<0.7** | **<0.7** |
| **Sulphate** | **mg/l** | **0,4** | **5,2** | **17,** | **<0.4** |
| **Total Nitrogen** | **mg/l** | **0,5** | | | |
| **Aluminium** | **mg/l** | **0,04** | **0,099** | **0,098** | **<0.04** |
| **Calcium** | **mg/l** | **0,11** | **5,8** | **16,** | **2,** |
| **Potassium** | **mg/l** | **0,09** | **1,5** | **39,** | **1,7** |
| **Magnesium** | **mg/l** | **0,08** | **3,2** | **4,4** | **1,8** |
| **Sodium** | **mg/l** | **1** | **2,** | **13,** | **1,1** |
| **Zinc** | **mg/l** | **0,08** | **<0.08** | **<0.08** | **<0.08** |
| **Ca hardness as CaCO3** | **mg/l** | **1** | **14,53** | **39,76** | **5,11** |
| **Arsenic** | **mg/l** | **0,0001** | **<0.0001** | **<0.0001** | **<0.0001** |
| **Barium** | **mg/l** | **0,0001** | **0,037** | **0,021** | **0,026** |
| **Chromium** | **mg/l** | **0,0001** | **0,0018** | **0,0051** | **0,0013** |
| **Cobalt** | **mg/l** | **0,0001** | **<0.0001** | **0,** | **<0.0001** |
| **Copper** | **mg/l** | **0,0005** | **0,0011** | **0,0038** | **0,0008** |
| **Iron** | **mg/l** | **0,008** | **0,72** | **0,11** | **0,48** |
| **Manganese** | **mg/l** | **0,0005** | **0,001** | **0,0006** | **0,0016** |
| **Uranium** | **mg/l** | **0,0005** | **<0.0005** | **0,038** | **0,0007** |
| **Cadmium** | **mg/l** | **0,002** | **<0.002** | **<0.002** | **<0.002** |
| **Ammonia as N** | **mg/l** | **0,05** | **<0.05** | **0,06** | **<0.05** |
| **Orthophosphate (Filterable Reactive Phosphorous or PO4) as P** | **mg/l** | **0,02** | **<0.02** | **<0.02** | **<0.02** |
| **Total Alkalinity as CaCO3** | **mg/l** | **10** | **40,** | **91,** | **30,** |
| **Phenolphthalein Alkalinity as CaCO3** | **mg/l** | **10** | **<10** | **<10** | **<10** |
| **Bicarbonate Alkalinity as HCO3** | **mg/l** | **10** | **49,** | **110,** | **37,** |
| **Carbonate Alkalinity as CO3** | **mg/l** | **10** | **<10** | **<10** | **<10** |

| JB11-01479.004 | JB11-01479.005 | JB11-01479.006 | JB11-01479.007 | JB11-01479.008 | JB11-01479.009 | JB11-01479.010 | JB11-01479.011 | JB11-01479.012 | JB11-01479.013 |
|---|---|---|---|---|---|---|---|---|---|
| SW10 | SW11 | SW15 | SW17 | SW18 | SW22 | SW23 | SW26 | SW28 | SW31 |
| Result | Result | Result | Result | Result | Result | Result | Result | Result | Result |
| 6,2 | 6,6 | 7,1 | 6,5 | 6,6 | 6,9 | 7, | 7,7 | 6,4 | 6,9 |
| 1,3 | 4,3 | 39, | 2,5 | 3, | 4, | 9,6 | 32, | 44, | 6,6 |
| 128, | 12, | 340, | 192, | 176, | 52, | 76, | 300, | 384, | 104, |
| <10 | <10 | 20, | <10 | <10 | <10 | 64, | 3300, | <10 | <10 |
| <0.5 | <0.5 | 3,7 | <0.5 | <0.5 | <0.5 | <0.5 | 5,2 | 4,7 | <0.5 |
| <0.3 | 0,34 | <0.3 | <0.3 | <0.3 | 0,36 | 0,39 | 0,64 | <0.3 | <0.3 |
| <0.4 | <0.4 | 24, | <0.4 | <0.4 | <0.4 | 0,54 | 1,7 | 27, | 1,1 |
| <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 |
| <0.4 | <0.4 | 64, | <0.4 | <0.4 | <0.4 | 26, | 31, | 77, | 7,9 |
| | | | | | | | | | |
| <0.04 | <0.04 | 0,14 | <0.04 | <0.04 | <0.04 | 2,3 | 17, | 0,08 | 0,04 |
| 0,12 | 2,8 | 35, | 1,2 | 1,7 | 2,6 | 12, | 34, | 40, | 6, |
| 0,34 | 2,5 | 15, | 0,41 | 0,44 | 2,3 | 8,4 | 61, | 18, | 1,9 |
| 0,55 | 2,2 | 12, | 1,5 | 1,5 | 2,1 | 3,6 | 14, | 14, | 2,6 |
| 1, | 1,1 | 11, | 1,5 | 1,8 | 1,1 | 1,9 | 19, | 12, | 1,9 |
| <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 |
| <1 | 6,87 | 86,30 | 3,06 | 4,30 | 6,41 | 28,98 | 86,06 | 99,32 | 15,03 |
| <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| 0,026 | 0,019 | 0,22 | 0,026 | 0,039 | 0,022 | 0,013 | 0,023 | 0,29 | 0,11 |
| 0,0008 | 0,0015 | 0,005 | 0,0013 | 0,0013 | 0,0014 | 0,0014 | 0,0054 | 0,0056 | 0,0016 |
| 0,001 | <0.0001 | 0,047 | 0,001 | 0, | <0.0001 | 0,008 | 0,004 | 0,095 | 0, |
| <0.0005 | <0.0005 | 0,041 | <0.0005 | <0.0005 | 0,0009 | 0,029 | 0,067 | 0,1 | 0,0026 |
| 0,29 | 0,3 | 1,6 | 0,28 | 0,37 | 0,21 | 2,5 | 26, | 0,59 | 0,68 |
| 0,0022 | 0,0017 | 1,9 | 0,0024 | 0,0017 | 0,0021 | 0,041 | 0,03 | 2,7 | 0,0025 |
| <0.0005 | <0.0005 | 0,15 | 0,0041 | <0.0005 | <0.0005 | 0,0006 | 0,049 | 0,13 | 0,0076 |
| <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 |
| <0.05 | <0.05 | 0,3 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | 0,42 | <0.05 |
| <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 0,041 | <0.02 | <0.02 |
| 10, | 20, | 110, | 20, | 20, | 40, | 20, | 120, | 20, | 20, |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | 10, | <10 | <10 |
| 12, | 25, | 140, | 25, | 25, | 49, | 25, | 120, | 25, | 25, |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | 12, | <10 | <10 |

| JB11-01479.014 | JB11-01479.015 | JB11-01479.016 | JB11-01479.017 | JB11-01479.018 | JB11-01479.019 | JB11-01479.020 | JB11-01479.021 | JB11-01479.022 | JB11-01479.023 |
|---|---|---|---|---|---|---|---|---|---|
| SW34 | SW35 | SW36 | SW37 | SW38 | SW39 | HITACHI | AEL | LV WORKSHOP | HITACHI BORROW PIT |
| Result | Result | Result | Result | Result | Result | Result | Result | Result | Result |
| 6,9 | 8,2 | 6,8 | 6,2 | 5,8 | 4,6 | 6,1 | 6,4 | 5,7 | 6,6 |
| 3,1 | 69, | 2,4 | 1,5 | 1,3 | 1,2 | 8,4 | 2800, | 54, | 11, |
| 120, | 556, | 72, | 76, | 120, | 60, | 196, | 19068, | 1116, | 116, |
| <10 | <10 | 12, | <10 | <10 | <10 | 1200, | 140, | 470, | 48, |
| <0.5 | 3,7 | <0.5 | <0.5 | <0.5 | 0,58 | 1,9 | <0.5 | 22, | 2,5 |
| <0.3 | <0.3 | 0,37 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | 11, | 0,45 |
| <0.4 | 180, | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | 17000, | <0.4 | <0.4 |
| <0.7 | 3,3 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 |
| <0.4 | 97, | 1,2 | <0.4 | <0.4 | <0.4 | 4,4 | 360, | 2,5 | 2,3 |
| | | | | | | | | | |
| 0,059 | <0.04 | 2,3 | <0.04 | <0.04 | 0,058 | 8,8 | 0,044 | 4,8 | 1,4 |
| 2, | 69, | 1,3 | 0,43 | 0,29 | 0,12 | 10, | 420, | 45, | 17, |
| 0,56 | 26, | 1,1 | 0,42 | 0,35 | 0,12 | 16, | 84, | 27, | 6,4 |
| 1,7 | 17, | 1,5 | 0,67 | 0,47 | 0,45 | 8,4 | 50, | 6,3 | 2,8 |
| 1,9 | 19, | <1 | 1,1 | 1, | <1 | 4,4 | 100, | 33, | 4,1 |
| <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | 1,3 | <0.08 |
| 5,05 | 172,81 | 3,28 | 1,08 | <1 | <1 | 25,42 | 1057,97 | 111,49 | 41,42 |
| <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| 0,038 | 0,096 | 0,009 | 0,033 | 0,037 | 0,017 | 0,01 | 0,9 | 0,081 | 0,017 |
| 0,0014 | 0,0051 | 0,001 | 0,0008 | 0,0008 | 0,0009 | 0,0023 | 0,0067 | 0,06 | 0,0038 |
| 0, | 0,003 | 0,001 | 0, | 0,001 | 0,001 | 0,005 | 0,016 | 0,03 | 0,002 |
| 0,0018 | 0,011 | 0,0036 | 0,0007 | <0.0005 | 0,0038 | 0,047 | 0,14 | 0,23 | 0,017 |
| 0,4 | <0.008 | 0,72 | 0,39 | 0,6 | 0,079 | 11, | <0.008 | 20, | 1,6 |
| 0,0015 | 0,0052 | 0,015 | <0.0005 | 0,004 | 0,0023 | 0,1 | 0,37 | 0,97 | 0,091 |
| <0.0005 | 0,23 | 0,0049 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0,0019 | 0,0007 | <0.0005 |
| <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 |
| <0.05 | 1,1 | <0.05 | <0.05 | <0.05 | <0.05 | 0,17 | 1500, | 7,4 | 0,087 |
| <0.02 | 0,022 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 0,18 | <0.02 | 0,032 |
| 91, | 40, | 10, | 20, | 30, | 20, | 30, | 81, | 180, | 61, |
| <10 | 20, | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| 110, | <10 | 12, | 25, | 37, | 25, | 37, | 99, | 220, | 74, |
| <10 | 24, | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |

| JB11-01479.024 | JB11-01479.025 | JB11-01479.026 | JB11-01479.027 | JB11-01479.028 | JB11-01479.029 | JB11-01479.030 | JB11-01479.031 | JB11-01479.032 | JB11-01479.033 |
|---|---|---|---|---|---|---|---|---|---|
| SP1 | SP2 | GW02 | GW04 | GW07 | GW08 | GW11 | GW12 | GW15 | GW16 |
| Result | Result | Result | Result | Result | Result | Result | Result | Result | Result |
| 7,2 | 4,4 | 5,3 | 5, | 5,7 | 4,9 | 6, | 5,4 | 5,7 | 6,8 |
| 29, | 340, | 1,9 | 1,4 | 9,1 | 1,2 | 18, | 15, | 7,4 | 27, |
| 168, | 3472, | 728, | 124, | <10 | <10 | 260, | 56, | 60, | 140, |
| <10 | 36, | 680, | 60, | 150, | 44, | 28, | 72, | <10 | <10 |
| 2,2 | 8,3 | <0.5 | 0,5 | 0,59 | <0.5 | 2,7 | 8,7 | <0.5 | 0,92 |
| <0.3 | 2,4 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | 0,58 | <0.4 | <0.4 | <0.4 | <0.4 |
| <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 |
| 4,5 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | 1,8 |
| | | | | | | | | | |
| 11, | <0.04 | 1,2 | 0,24 | 0,075 | 0,38 | <0.04 | 0,081 | <0.04 | <0.04 |
| 410, | 28, | 0,89 | 0,15 | <0.11 | <0.11 | 27, | 4,7 | 3,9 | 33, |
| 92, | 20, | 0,97 | 0,13 | 4,4 | 0,54 | 4,5 | 6,9 | 4,8 | 7,9 |
| 78, | 10, | 2,6 | 1, | 11, | 1,4 | 5,2 | 1,5 | 3,3 | 7,1 |
| 52, | 8, | <1 | <1 | <1 | <1 | 1,1 | <1 | 6,2 | 12, |
| 0,27 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 |
| 1014,12 | 70,08 | 2,22 | <1 | <1 | <1 | 66,68 | 11,63 | 9,79 | 82,40 |
| <0.0001 | 0,01 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| 0,078 | 0,064 | 0, | 0,035 | 0,078 | 0,015 | 0,16 | 1,5 | 0,12 | 0,069 |
| 0,007 | 0,0013 | 0,0001 | 0,0036 | 0,0045 | 0,0068 | 0,0052 | 0,0069 | 0,014 | 0,019 |
| 0, | 8,2 | 0,029 | 0,004 | 0,01 | 0,006 | 0,028 | 0,3 | 0,033 | 0,007 |
| 0,0034 | 13, | 0,052 | 0,0042 | 0,0005 | 0,0054 | <0.0005 | 0,0008 | 0,057 | <0.0005 |
| 0,062 | 0,15 | 1,4 | 0,48 | 0,26 | 0,34 | 20, | 25, | 0,52 | 1,7 |
| <0.0005 | 13, | 0,054 | 0,022 | 0,019 | 0,014 | 2,2 | 30, | 0,034 | 0,14 |
| 0,019 | 0,36 | 0,0079 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 |
| <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 |
| <0.05 | 0,47 | <0.05 | <0.05 | 0,55 | <0.05 | 0,64 | 1,8 | <0.05 | <0.05 |
| <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 0,023 | <0.02 |
| 130, | 40, | 20, | 20, | 61, | 10, | 110, | 61, | 40, | 140, |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| 160, | 49, | 25, | 25, | 74, | 12, | 140, | 74, | 49, | 170, |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |

| JB11-01479.034 | JB11-01479.035 | JB11-01479.036 | JB11-01479.037 | JB11-01479.038 | JB11-01479.039 | JB11-01479.040 | JB11-01479.041 | JB11-01479.042 | JB11-01479.043 |
|---|---|---|---|---|---|---|---|---|---|
| GW17 | GW18 | GW19 | GW34 | GW35 | GW37 | GW42 | GW43 | GW44 | R5-T5 |
| Result | Result | Result | Result | Result | Result | Result | Result | Result | Result |
| 5,2 | 4,8 | 6,3 | 6,1 | 6, | 5,7 | 5,5 | 6,7 | 5,1 | 5,6 |
| 2,8 | 1,9 | 28, | 2,4 | 35, | 11, | 2,4 | 28, | 3,1 | 5,8 |
| 68, | 92, | 144, | <10 | 104, | 84, | <10 | 196, | 68, | <10 |
| 64, | 64, | 110, | <10 | 64, | <10 | <10 | 750, | <10 | <10 |
| 0,85 | 0,6 | 0,81 | 0,68 | <0.5 | 0,69 | 0,69 | 6,9 | 3, | 2,4 |
| 0,43 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | 0,41 | 0,4 | <0.3 |
| 0,48 | <0.4 | <0.4 | 0,85 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 |
| <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 |
| <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | 0,67 | <0.4 | <0.4 |
| | | | | | | | | | |
| 0,23 | 0,12 | 0,11 | <0.04 | 0,067 | <0.04 | <0.04 | 10, | <0.04 | <0.04 |
| 0,16 | 0,85 | 48, | 0,32 | 18, | 6,4 | <0.11 | 34, | 0,23 | 6,5 |
| 0,56 | 0,81 | 4,3 | 0,49 | 14, | 1,9 | 0,48 | 15, | 0,93 | 0,64 |
| 3,2 | 0,59 | 1,7 | 2,1 | 18, | 9,6 | 2,9 | 15, | 0,66 | 1,3 |
| <1 | 1,3 | 3,2 | <1 | 1,6 | 1,8 | 1,1 | 19, | 3,9 | 3, |
| <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | <0.08 |
| <1 | 2,11 | 120,25 | <1 | 46,09 | 15,98 | <1 | 83,66 | <1 | 16,35 |
| <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| 0,022 | 0,053 | 0,28 | 0,023 | 0,18 | 0,048 | 0,009 | 0,9 | 0,039 | 0,045 |
| 0,004 | 0,014 | 0,01 | 0,011 | 0,013 | 0,012 | 0,0011 | 0,021 | 0,0009 | 0,0016 |
| 0,004 | 0,004 | 0,011 | 0,004 | 0,015 | 0,004 | 0,002 | 0,004 | 0,002 | 0,005 |
| 0,004 | 0,012 | <0.0005 | 0,0025 | <0.0005 | 0,0008 | 0,0062 | 0,019 | 0,18 | 0,0018 |
| 0,66 | 0,53 | 4,2 | 0,23 | 26, | 0,8 | <0.008 | 23, | 0,071 | 0,013 |
| 0,021 | 0,052 | 0,25 | 0,047 | 1,1 | 0,055 | 0,0085 | 0,38 | 0,0078 | 0,037 |
| <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 |
| <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 |
| <0.05 | <0.05 | 0,5 | <0.05 | 3,4 | <0.05 | <0.05 | 1,3 | <0.05 | <0.05 |
| <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 0,091 | <0.02 | <0.02 |
| 10, | 10, | 120, | 20, | 150, | 51, | 10, | 130, | 10, | 51, |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| 12, | 12, | 150, | 25, | 190, | 62, | 12, | 160, | 12, | 62, |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| | | | | | | | | |
| **JB11-01479.044** | **JB11-01479.045** | **JB11-01479.046** | **JB11-01479.047** | **JB11-01479.048** | **JB11-01479.049** | **JB11-01479.050** | **JB11-01479.051** | **JB11-01479.052** |
| **KAPENDA** | **LBS** | **KALOTA** | **SHIINDA** | **MAFUTA** | **MUKANDA** | **KABENDWE** | **MUSHIPI** | **MBS** |
| **Result** | **Result** | **Result** | **Result** | **Result** | **Result** | **Result** | **Result** | **Result** |
| 5,5 | 6, | 5,1 | 4,8 | 5,7 | 5,2 | 5,1 | 5,6 | 4,8 |
| 4,1 | 6,5 | 2,9 | 1,7 | 6,9 | 1,8 | 2,3 | 5,7 | <1 |
| 24, | 132, | <10 | <10 | 312, | 32, | 60, | 136, | 100, |
| <10 | <10 | <10 | <10 | 48, | 52, | <10 | <10 | 76, |
| 1,9 | 1,8 | 3,1 | 0,99 | <0.5 | 0,6 | 1,4 | 0,65 | <0.5 |
| <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 |
| 0,55 | 2,6 | 0,78 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 |
| <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 | <0.7 |
| <0.4 | 1,1 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 | <0.4 |
| | | | | | | | | |
| <0.04 | <0.04 | <0.04 | 0,047 | <0.04 | <0.04 | <0.04 | <0.04 | 0,16 |
| 5,4 | 6,1 | <0.11 | 0,23 | 1,7 | <0.11 | 1,1 | 2,6 | <0.11 |
| 0,82 | 2,1 | 1,9 | 0,92 | 2,9 | 0,28 | 0,6 | 3,4 | 0,11 |
| 0,11 | <0.08 | 0,22 | 0,22 | 5,2 | 0,39 | 0,21 | 1,4 | 0,28 |
| 2, | 6,6 | 3,5 | 1,1 | 1,3 | <1 | <1 | 3,7 | <1 |
| <0.08 | <0.08 | <0.08 | <0.08 | <0.08 | 0,14 | <0.08 | <0.08 | 0,12 |
| 13,53 | 15,27 | <1 | <1 | 4,18 | <1 | 2,65 | 6,58 | <1 |
| <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| 0,035 | 0,019 | 0,035 | 0,034 | 0,036 | 0,048 | 0,01 | 0,12 | 0,009 |
| 0,0014 | 0,0015 | 0,0008 | 0,0006 | 0,0019 | 0,0006 | 0,0007 | 0,0014 | 0,0005 |
| 0,002 | 0,001 | 0, | 0, | 0,006 | 0,002 | 0, | 0,001 | 0, |
| 0,0074 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0,0021 | <0.0005 |
| <0.008 | 0,13 | 0,34 | 0,15 | 27, | 13, | 1,8 | 1,4 | 0,013 |
| 0,012 | 0,01 | 0,0059 | 0,0052 | 0,16 | 0,1 | 0,03 | 0,026 | 0,0046 |
| <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | <0.0005 |
| <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 |
| <0.05 | <0.05 | 0,052 | <0.05 | <0.05 | 0,29 | 0,86 | <0.05 | 0,076 |
| <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 0,025 | <0.02 |
| 30, | 30, | 20, | 10, | 30, | 20, | 10, | 40, | 10, |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| 37, | 37, | 25, | 12, | 37, | 25, | 12, | 49, | 12, |
| <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| | | | | | | | | |
| | | | | | | | | |

Photograph C1. Signs of high wall instability in Malundwe pit

Photograph C2. Cracks behind the high wall at Malundwe pit

Photograph C3. Slope failure at Malundwe pit


Photograph C4. Lithological chips collected during drilling at Chimiwungo

# Thesis Summary

A deep and clear understanding of the hydrogeology of an area is paramount in any dewatering project. The development of a detailed conceptual hydrogeological model goes a long way in creating an appreciation of the prevailing groundwater situation in active and proposed mining areas. The influx of water during mining and the collapse of pit walls present perennial problems and dangers to those involved. Over recent years, dewatering has evolved into a highly specialized field of hydrogeology.

The proposed Chimiwungo mine pit is expected to go to depths beyond 300m by the year 2040. A series of interconnected fractures are suspected to be the main conduits for groundwater movement and storage. In order to achieve pit slope stability, pore water depressurization will need to be carried out alongside the dewatering of the main fractures and faults.

The study focused on the steps undertaken in the development of a conceptual hydrogeological model of the Chimiwungo ore body. The report also outlines the problems encountered in the process and the shortfalls in the final conceptual model developed.

Existing information and projected mine plans were analysed as a basis for the field investigations undertaken. A hydrocensus was carried out to establish existing groundwater and surface water monitoring points. Suitable positions for the drilling of new monitoring boreholes were selected on the basis of the mine geological model and exploration drilling. Drilling was problematic from the onset due to difficulties in accessing drilling sites, the highly unstable weathered material near the surface. Only one of the three large diameter boreholes and four of the six small diameter boreholes were completed in a period of eight months.

The intention was to carry out pumping tests on the three large diameter monitoring boreholes. The massive delays and the inability of the drilling contractor to complete the drilling programme forced the mine to defer pumping tests to a later date. Drilling was suspended in May 2011 and, by the time of submission of this thesis, still had not resumed. Aquifer parameters had to be estimated by consulting literature and using accepted approximations.

The study confirmed the existence of two aquifers; an upper weathered zone and a lower fractured zone.

The high level of correlation between the groundwater level elevation and topographic elevation (98%) is evidence that the groundwater level elevation mimics the topography. This observation suggests that the aquifers being investigated are either unconfined or semi-confined/leaky. Analysis of the piezometry defines the south-western part of the study area as the recharge zone and the discharge is to the surface water drainages in the middle of the area. Boreholes drilled into the weathered zone have very shallow water levels and respond very quickly to rainfall events. This may signify that most of the groundwater recharge takes place in the upper weathered zone.

The general groundwater type can be characterized as a calcium-magnesium-bicarbonate (Ca-Mg-$HCO_3$) type, indicating recently recharged groundwater. This is indicative of good quality groundwater which has not undergone intensive ion exchange processes as evidenced by the low TDS. Generally surface water quality within the study area is good to moderate with low levels of salinity and limited or low concentrations of dissolved metal species.

Groundwater recharge was estimated at 498 mm/yr (38% of Mean Annual Precipitation) for the study area. The Chloride Mass Balance Method was used to estimate the average recharge value.

The specific yield for the weathered rock aquifer at Chimiwungo was estimated by calculating the average $S_y$ of silt and clay; $S_y$ at Chimiwungo = 6 Storativity was assumed to be $1 \times 10^{-5}$ for the fractured rock aquifer, as calculated by Golder Associates in 2003. The transmissivity values obtained through estimation (transmissivity is approximately equal to five time the blow yield) are comparable to the values obtained by Golder in 2003.

The Chimiwungo River was set as the northern and eastern boundary (constant head) for the Chimiwungo Main pit. The southern and western boundaries were set as no-flow boundaries due to a topographic high. Similarly for the Chimiwungo North pit, the Chimiwungo River was set as the southern and western (constant head) boundary and the northern and eastern boundaries were set as no-flow boundaries due to a topographic high that occurs in this area. All other boundaries follow the quaternary catchment boundary and are therefore also assigned no-flow conditions.