# OPEN PIT FLOODING AS A POST-CLOSURE OPTION:
# A GEOCHEMICAL APPROACH

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# Declaration

I, André Abel van Coller, declare that the dissertation hereby submitted by me for the Magister Scientiae degree at the University of the Free State, is my own independent work and has not previously been submitted by me at another university/faculty.

I furthermore cede copyright of the dissertation in favour of the University of the Free State.

André A. van Coller

29 May 2013

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# Abbreviations

| Abbreviation | Description |
| --- | --- |
| ABA | Acid Base Accounting |
| AGES | African Geo-Environmental Engineering and Science |
| AP | Acid Potential |
| BFS | Bankable Feasibility Study |
| BH | Borehole |
| Coeff. Var. | Coefficient of variance |
| DMR | Department of Mineral Resources |
| DoH | Department of Health |
| DTM | Digital Terrain Model |
| DWA | Department of Water Affairs (previously DWAF) |
| DWAF | Department of Water Affairs and Forestry |
| EC | Electrical Conductivity (mS/m) |
| EIA | Environmental Impact Assessment |
| EMP | Environmental Management Plan |
| $fCO_2$ | Carbon dioxide fugacity |
| $fO_2$ | Oxygen fugacity |
| GIS | Geographical Information System |
| GW | Groundwater |
| GWB | Geochemist's Workbench |
| IGS | Institute for Groundwater Studies |
| km | kilometre |
| ℓ/s | litres per second |
| LoM | Life of Mine |
| LoP | Life of Project |
| MAE | Mean Annual Evaporation |
| mamsl | meters above mean sea level |
| MAP | Mean Annual Precipitation |
| MAR | Mean Annual Run-off |
| mbcl | meters below collar height |
| mbgl | meters below ground level |
| mg/k | milligrams per kilogram |
| mg/ℓ | milligrams per litre |
| $Mm^3$ | Mega cubic meters (1 $Mm^3$ = 1 000 000 $m^3$) |
| NAG | Nett Acid Generation |
| NNP | Nett Neutralising Potential |
| NP | Neutralising Potential |
| NPR | Neutralising Potential Ratio |
| NTU | Nephelometric Turbidity Units |
| PGE | Platinum Group Elements |
| PPM | Pilanesberg Platinum Mines (Pty) Ltd |

| Abbreviation | Description |
| --- | --- |
| RoM | Run of Mine |
| RW | Rain water |
| SANAS | South African National Accreditation System |
| SANS | South African National Standards |
| SABS | South African Bureau of Standards |
| Std. Dev. | Standard Deviation |
| STP | Sewage Treatment Plant |
| SW | Surface water |
| SWD | Storm Water Dam |
| TCLP | Toxicity Characteristic Leaching Procedure |
| TDS | Total Dissolved Solids |
| TSF | Tailings Storage Facility |
| TSS | Total Suspended Solids |
| TWQR | Target Water Quality Range |
| UFS | University of the Free State |
| UG2 | Upper Group 2 Reef |
| USA EPA | United States of America Environmental Protection Agency |
| USGS | United States Geological Survey |
| WMA | Water Management Area |
| WRC | Water Research Commission |
| WRD | Waste Rock Dump |
| XRD | X-ray Diffraction |
| XRF | X-ray Fluorescence |

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# CHAPTER 1:

## 1 INTRODUCTION

This document is a written dissertation for research performed to evaluate the use of mine open pit flooding as a post-closure option from a geochemical approach and evaluation. Research and literature reviews were undertaken to evaluate previous work, both nationally and internationally, on open pit flooding and pit lakes. Case studies similar to the project undertaken for this study as well as general mineralogical and geochemical literature research applicable to the study area were also reviewed.

This document with literature reviews and case study covers research and experimental data collected on all aspects of the project from geology through to modelling and the geochemical evaluation of the feasibility for pit flooding as a mitigation method. With the conclusion and submission of this dissertation, a systems thinking and modelling guideline for similar projects in the future will be one of the outcomes. This model is provided to guide hydrogeologists and hydrologists with limited chemical ability through similar studies.

It should be noted by the reader that the main focus point of the study is the geochemical modelling aspect of the project with assumptions made on the geohydrological components of the flooding to accommodate the scientific research. Emphasis of this dissertation lies in the fluid-rock and fluid-fluid interaction in a pit environment through geochemical and hydrochemical modelling, further referred to in this document as hydrogeochemical modelling.

### 1.1 Background

Australasian, European, Canadian and American geo-environmental specialists have long been involved with pit lake studies in the physical processes and dynamics as well as the geochemical aspects of these mitigation methods and events (Castendyk & Webster-Brown 2007; Ramstedt 2003). The use of pit flooding as an environmental post-closure option has however been studied and used to a limited extent in Southern Africa and Africa to a whole, with some recorded cases mostly being by accident rather than a planned mitigation (Bell, Bullock, Halbich & Lindsay 2001; Nixdorf, Uhlmann & Lessmann 2010).

The owning company of the Pilanesberg Platinum Mines (PPM) north of the Pilanesberg initiated such a study to evaluate the feasibility of using surface water and groundwater to flood an open pit as a post-closure environmental management option. The project involved various methods and geohydrological tools to evaluate the possible impact of partially backfilling and flooding the open pit platinum mine

situated in Bushveld Igneous Complex geology. The largest component of the project involved groundwater flow modelling and probably the most important tool being the evaluation of the hydrogeochemical changes and impacts such a mitigation method will have through the implementation of a hydrogeochemical model.

The purpose of the investigation was to determine the various elements and processes involved in the hydrogeochemical system expected in the flooding of the PPM pit. And to evaluate the environmental impact and the feasibility of using the pit as a recreational environment post-closure with the water body also to be used for livestock and game watering and to a lesser extent irrigation of agricultural crops.

This document is for an MSc dissertation in geohydrology, concentrating on the geochemical modelling aspect, to further this study of flooding open pit mines through literature reviews and a detailed hydrogeochemical model in the case study of the PPM pit flooding project.

For the case study and geochemical model various data sources from the pit flooding project and monitoring programs in place at the mine were used to evaluate and interpret input data. Water levels, groundwater quality, surface water quality, rainfall data and climate data have been collected and monitored since 2007 before the start-up of the open pit mine. This formed part of monitoring protocol as set out by the Department of Water Affairs (DWA) and the Department of Mineral Resources (DMR).

Furthermore geological, geohydrological, geochemical and groundwater flow model data from the specialist consultant project were evaluated and served as the basis for the case study project to flow into the geochemical approach to pit flooding and research dissertation. The specialist geohydrological model and study serves as the corner stone and source of assumptions made in the construction and simulation of the hydrogeochemical models.

## 1.2 Terms of reference

### 1.2.1 Research questions

The following questions summarise the goal of this dissertation:

1. What are the main processes or factors dictating the characteristics of groundwater in the project area?

2. What is the expected water quality that will be the final product within the planned pit lake?

3. What are the risks identified during modelling of the proposed pit flooding to the environment and to human/animal use?

4. What mitigation methods/modifications to the planned post-closure option can be applied to decrease or remove risks?

5. Is pit flooding as a post-closure option feasible and can it be used for various recreational and agricultural/wildlife applications?

### 1.2.2  Objectives

The objectives of this MSc project and dissertation are:

- To evaluate the feasibility of flooding an open pit mine as a post-closure environmental mitigation method;

- To set up and simulate a detailed hydrogeochemical model of the pit flooding project to evaluate the chemical impact as well as to determine whether such a mitigation method can be used in future (Case study);

- To develop and illustrate a step-by-step systems thinking template for future work, to help specialist in the environmental mining industry with limited geochemical ability to execute similar studies; and

- To recommend possible future research topics and fields.

### 1.2.3  Scope of work

1. Component A: Literature review and research topics (Chapter 2)

   a. Reviewing of various regional, national and international documents and articles that are in reference with the dissertation and case study

   b. Literature study of the geological setting and mineralogy of the project area and similar national and international cases

   c. Literature study of the geohydrological aspects of the project area and similar national and international cases

   d. Literature study of various dynamic aspects involved in pit flooding and pit lakes both nationally and internationally

   e. Literature study of geochemical and aqueous geochemical studies and modelling as well as a comparison between software packages with a motivation to substantiate the package used in this study

2. Component B: Project data (Chapter 3)

   a. Presentation and review of data captured and used in the case study and geochemical modelling of the pit flooding scenarios

3. Component C: Case study and model interpretations (Chapter 4 and 5)

   a. Interpretations and evaluations of data

   b. Conceptual model

       c. Geochemical model setup and calibration

       d. Speciation modelling

       e. Weathering model

       f. Mixing model

4. Component D: Discussions, water quality (Chapter 6)

       a. Discussion on the model outcomes

       b. Evaluation of the model outcome based on the expected water quality that will influence whether the pit lake can serve as an environmental mitigation to be used for human and agricultural activities.

       c. A sensitivity discussion on the impacts that can occur if the flooding of the open pit does not occur as in the conceptual plan.

       d. A system template describing the steps to follow in future pit lake modelling

5. Component E: Conclusions, recommendations and future topics (Chapter 7)

       a. Conclusions

       b. A system template describing the steps to follow in future pit lake modelling

## 1.2.4 Case study area and location

The Pilanesberg Platinum Mine Tuschenkomst open pit is situated in the North West Province, South Africa (Figure 1-1). The nearest town to the project is Saulspoort with the coordinates listed in Table 1-1 indicating the position of the PPM open pit and central point of the case study area.

**Table 1-1     Project coordinates**

| Latitude | -25.103061 |
|----------|------------|
| Longitude | 27.006502 |

4
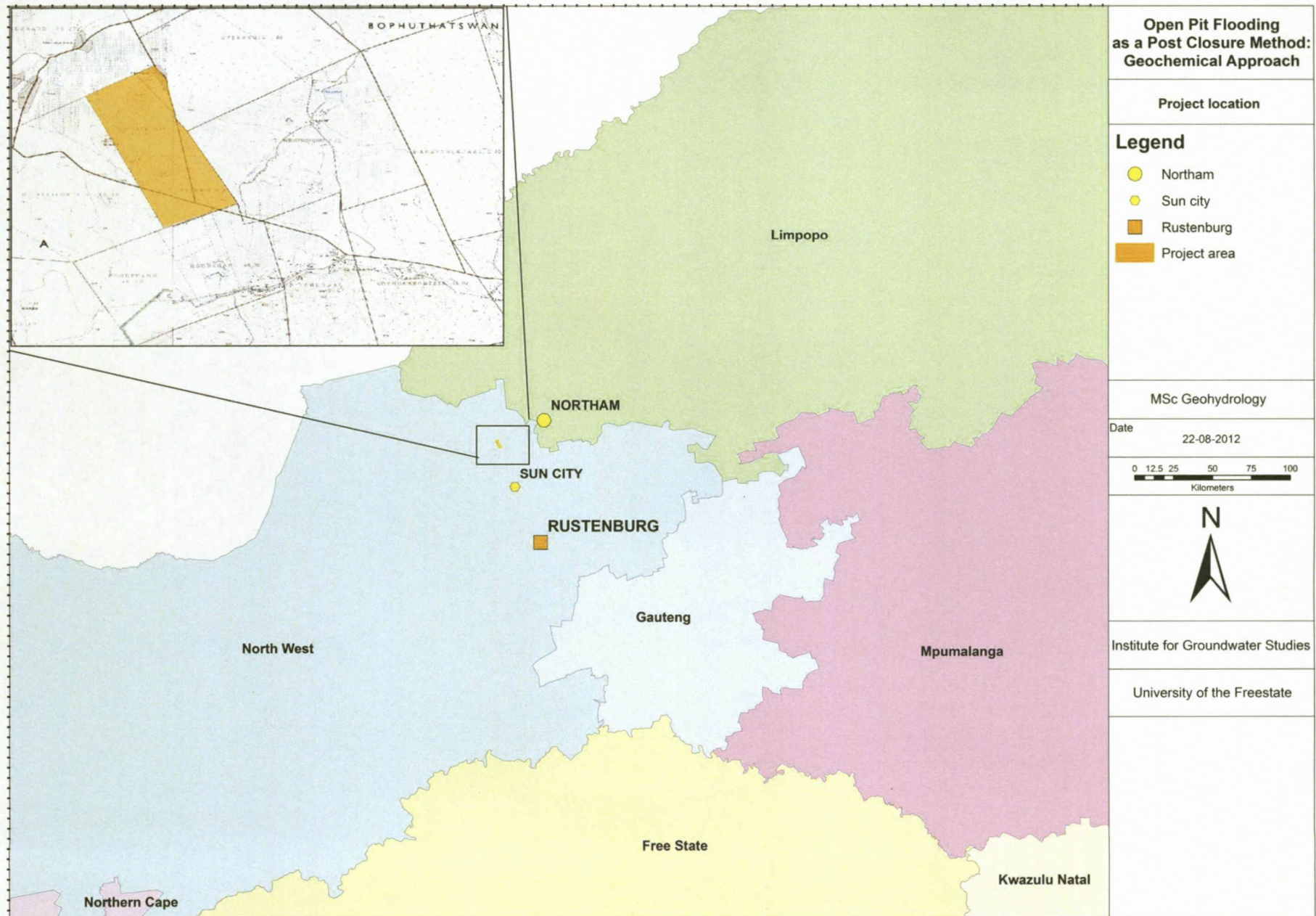
**Figure 1-1    Regional map showing the case study location**

## 1.3    Information sources and software

The following information sources were used in the completion of this dissertation and topic related case study:

- Spatial and GIS data;

- Published literature and articles on various aspects and fields involved in the project all referenced according to the Harvard reference format with in text citations indicating reference author and date of document;

- Historical reports on the PPM project;

- Monitoring data (water quality and water levels of both surface water and groundwater) from the AGES monitoring unit from 2008 until June 2012;

- TCLP, Acid Base Accounting, XRD and XRF data on the PPM mine ore rock, waste rock and tailings material from AGES;

- Rainfall data from the Saulspoort weather station; and

- The software package Geochemists Workbench® was used in numerous stages of the case study and geochemical modelling.

All data sets and sources were acquired and used with full consent from all parties involved.

## 1.4    Document outline

This document contains the following Chapters with a short description of each chapter given:

### 1.4.1    Chapter 1: Introduction

A short introduction to the research project and case study with a background description, scope of work and a summary of information sources

### 1.4.2    Chapter 2: Literature Review

This chapter summarizes research done on national and international case studies, articles, books and reports within the context of the aspects involved in the research topic and geochemical modelling.

### 1.4.3    Chapter 3: Project Data

This chapter gives a short description of the project data sources and methodology. Data described in the Chapter will be used in the following case study and modelling chapters as input data.

### 1.4.4 Chapter 4: Case study – Project Site Assessment

Chapter 4 summarizes a site description and characterisation within the context of the case study and research topic. Short geohydrological descriptions and analysis of data and aspects involved in a pit flooding study are given.

### 1.4.5 Chapter 5: Hydrogeochemical Assessment and Models

This chapter gives modelling scenario descriptions, methodology and results with a conceptual model giving a clear guide to the processes and elements involved in a geochemical assessment of a pit flooding event.

### 1.4.6 Chapter 6: Hydrogeochemical model discussion and outcomes

Chapter 6 discusses modelling simulation and research results to evaluate the feasibility of pit flooding as a post-closure option. All results are discussed and linked to research done on the topics at hand in the literature review of Chapter 2. An evaluation of the water quality and turbidity of the expected pit water is done. In addition to the major outcomes of the project discussed, a few paragraphs discussing the possible outcomes of the project through asking, What if?

### 1.4.7 Chapter 7: Conclusions

Chapter 7 summarizes the conclusions of the MSc study as a whole, gives a clear answer to the research topic and questions, as well as a list of possible future studies that will branch from this dissertation. The second to last sub-section gives a systems thinking outline for future studies to be used by hydrogeologists.

### 1.4.8 References

A list of all references used in this research dissertation using the Harvard referencing system.

### 1.4.9 List of Appendices

A list of appendices containing all relevant data stored on the attached DVD.

### 1.4.10 Abstract

Dissertation abstract.

# CHAPTER 2:

## 2   LITERATURE REVIEW

The following sections of Chapter 2 give a description and summary of various national and international articles and scientific works in reference to the case study and research topic at hand. Various journals, articles, handbooks, data sets and publications were referenced and reviewed to form a general idea and background of the questions and problems within the geochemical modelling of pit flooding scenarios and the geological and hydrogeological setting of the project.

### 2.1   Nomenclature: Terms and meanings

This dissertation is written in a basic scientific language with most words and terms used being understandable to most readers and reviewers with a geological/scientific background. However the author thought it necessary to list some terms and give definitions to written terminology as to avoid long descriptions within the dissertation document and to allow the definition of some less frequently used terminology. Not all scientific terms are listed with only the lesser used terms listed:

*Aquiclude:*   A formation with a low permeability, important in controlling flow in adjacent overlying and underlying permeable formations;

*Aquifer:*   A saturated permeable geological unit that is permeable enough to yield economic quantities of water to wells;

*Aquitard:*   A geological unit that is permeable enough to transmit water in significant quantities when viewed over large areas and long periods, but its permeability is not sufficient to justify production wells being placed in it

*Bed:* Smallest unit used in lithostratigraphy;

*Bedrock:* Unweathered rock beneath unconsolidated material;

*Chemocline*:   A line or border of chemical change between two water layers/columns within a lake environment;

*Conceptual model:* A diagram and verbal information source which shows a set of relationships between factors that are believed to impact or lead to a target condition or natural phenomena. It defines theoretical entities, objects and/or conditions of a system and the relationship between them in a visual way;

*Cone of depression:*   A depression in the groundwater table or potentiometric surface that has the shape of an inverted cone and develops around a borehole from which water is being withdrawn. It defines the area of influence of a borehole;

*Confined Aquifer:*   A formation in which the groundwater is isolated from the

atmosphere at the point of discharge by impermeable geologic formations; confined groundwater is generally subject to pressure greater than atmospheric;

*Drawdown*: The distance between the static water level and the surface of the cone of depression;

*Dyke swarm*: A large concentration of dykes created in a small geographical setting by localised magmatism of an intrusive nature;

*Evapolimnion:* The top layer constantly exposed to atmospheric processes. This lake layer is constantly changing with the main impact on the chemical system being evaporation and thus the increase in ionic concentrations. The depth of the layer is determined by the reach of evaporation into the water column;

*Epilimnion:* The upper oxygenated, circulating layer of a stratified lake;

*Fault:* A discontinuity surface along which there has been a shear displacement, serves as pathways for groundwater flow;

*Formation:* A grouping of beds used in lithostratigraphy, the smallest mappable unit on reasonable scale;

*Geochemistry:* The study of the chemistry of the earth's constituents;

*Groundwater:* Water found in porous rocks below the water table;

*Groundwater table:* The surface between the zone of saturation and the zone of aeration; the surface of an unconfined aquifer;

*Group:* A grouping of formations used in lithostratigraphy;

*Holomictic Lake:* A lake that experiences only a partial annual turnover or mixing of the water columns;

*Hydraulic conductivity (K):* The volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured perpendicular to the area;

*Hydraulic gradient*: The rate of change in the total head per unit distance of flow in a given direction;

*Hydrogeology:* Synonymous with Geohydrology, the study of groundwater;

*Hypolimnion:* A lower, colder layer of a stratified lake, undisturbed by seasonal mixing. Found below the epilimnion;

*Limnion:* Lake layer in a stratified scenario;

*Member:* A grouping of beds used in lithostratigraphy;

*Meromictic Lake:* A lake that experiences a full annual turnover event or mixing of the water column with the exception of the monimolimnion remaining static at depth;

*Mixolimnion:* An unknown mix of water that cannot be characterised into a limnion due to mixing of various layers;

*Monimolimnion:* The lowest, coldest layer at the bottom of a stratified lake, undisturbed by any mixing with reducing conditions and high TDS and sulphate concentrations. Found below the Hypolimnion;

*Recharge:* The addition of water to the zone of saturation; also, the amount of water added;

*Static water level:* The level of water in a borehole that is not being affected by withdrawal of groundwater;

*Supergroup:* The largest lithostratigraphic subdivision comprises of a series of groups;

*Thermocline:* A line or border at which two water columns with different temperatures meet;

*Unconfined aquifer:* Also referred to as a phreatic aquifer. An aquifer which is bounded from below by an impermeable layer, the upper boundary is the water table, which is in contact with the atmosphere so that the system is open;

*Wave Fetch:* The length of water over which a given wind has blown in order to create a wave.

## 2.2 Discovery of platinum in SA with special reference to the Bushveld Igneous Complex

The first recorded mention and discovery of Platinum Group Elements (PGE) mineralisation in South Africa was by William Bettel in 1892 with the identification of osmium-iridium alloy particles in Witwatersrand gold mines with later discovery of platinum (Pt) in the chromitite layers of the Bushveld Igneous Complex by Bettel in 1906 (Bartholomew, Hieber and Lee 1989; Cawthorn 2001) and later by Hall and Humphrey in 1908 (Cawthorn 2001; Wagner 1929). In 1923, Wagner concluded that the Pt deposits associated with the Bushveld Igneous Complex will not be economically viable to mine unless the resource was mined along with other commodities (Cawthorn 2001). Furthermore he stated that the geologists exploring South Africa at the time made the mistake of comparing and basing exploration on the association of platinum with chromite as in other parts in the world, specifically the Urals. However later, as known today, the geologists were merely ahead of their time and metallurgical advances as the UG2 chromitite has one of the greatest platinum reserves in the world (Cawthorn 1999; Cawthorn 2001).

In 1924 A.F. Lombaard while panning in a river bed on his farm Maandagshoek, made the first major discovery of platinum in the Bushveld Igneous Complex. Samples were sent by Lombaard to Dr. Merensky who at the time was a consulting mining engineer in Johannesburg. Merensky later that same year along with Lombaard identified platinum in the pyroxenite and norite of the later to be known Upper Critical Zone (Cawthorn 1999; Cawthorn 2001). The first platinum was panned from the Moopetsi River with a geomorphological study of the drainage patterns observed at the time leading to the discovery of the Mooihoek pipe and several other outcrops of platinum bearing formations. The orientation of these outcrops along a line led to the discovery of the Merensky Reef (Cawthorn 2001; McDonald, Vaughan and Tredoux 1995) and at a later stage to other PGE bearing deposits within the Bushveld Igneous Complex as we know it today.

The location and exploration map as drawn by Merensky and illustrated in Figure 2-1 (Cawthorn 2001) culminated in initiating the start of the platinum industry in South Africa. Today the Bushveld Igneous Complex is the greatest source of PGE in the world and is as much an economic resource to South Africa today as gold was in the past.
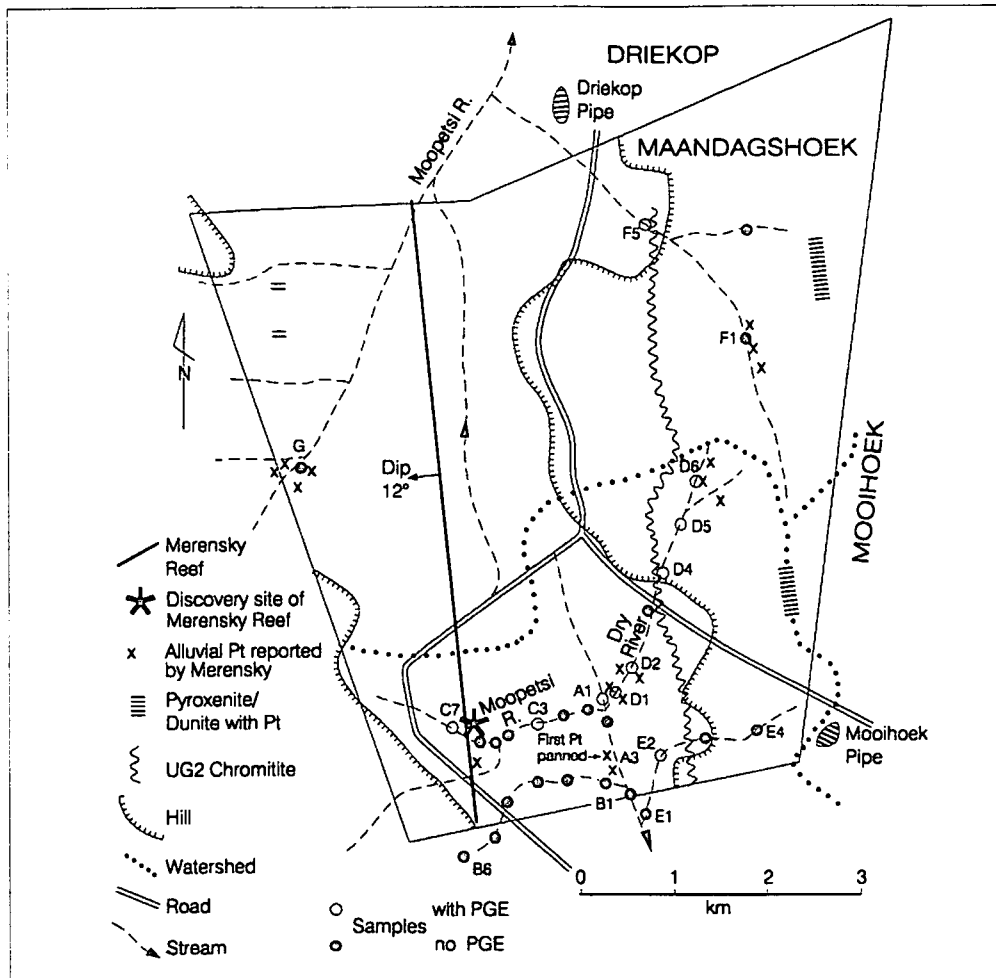
**Figure 2-1     A map of the Maandagshoek farm drawn by Merensky illustrating the discovery locations of platinum on the farm, as sourced from and adapted from Cawthorn (2001)**

## 2.3  Geological setting

The Bushveld Igneous Complex is the largest preserved mafic layered complex in the world both in volume and surface area. The complex covers a surface area of approximately 65 000 $km^2$ and has a maximum vertical thickness of 8 km that holds the world's largest reserves of Platinum Group Elements (PGE) along with chromium and vanadium (Cawthorn, Eals, Walraven, Uken & Watkeys 2006). This layered igneous intrusion which has been tilted and eroded and now outcrops around what appears to be the edge of a large geological basin, contains reserves of platinum, palladium, osmium, iridium, rhodium, and ruthenium; as well as iron, tin, chromium, titanium and vanadium (Smith & Kotze 2010). Accessible PGE reserves in the earth's crust in relation to amounts and production with comparison to other international geological sequences, the Bushveld Igneous Complex holds and produces the most PGE's as described by Naldrett, Kinnaird, Wilson & Chunnett (2008) and shown in Figure 2-2.
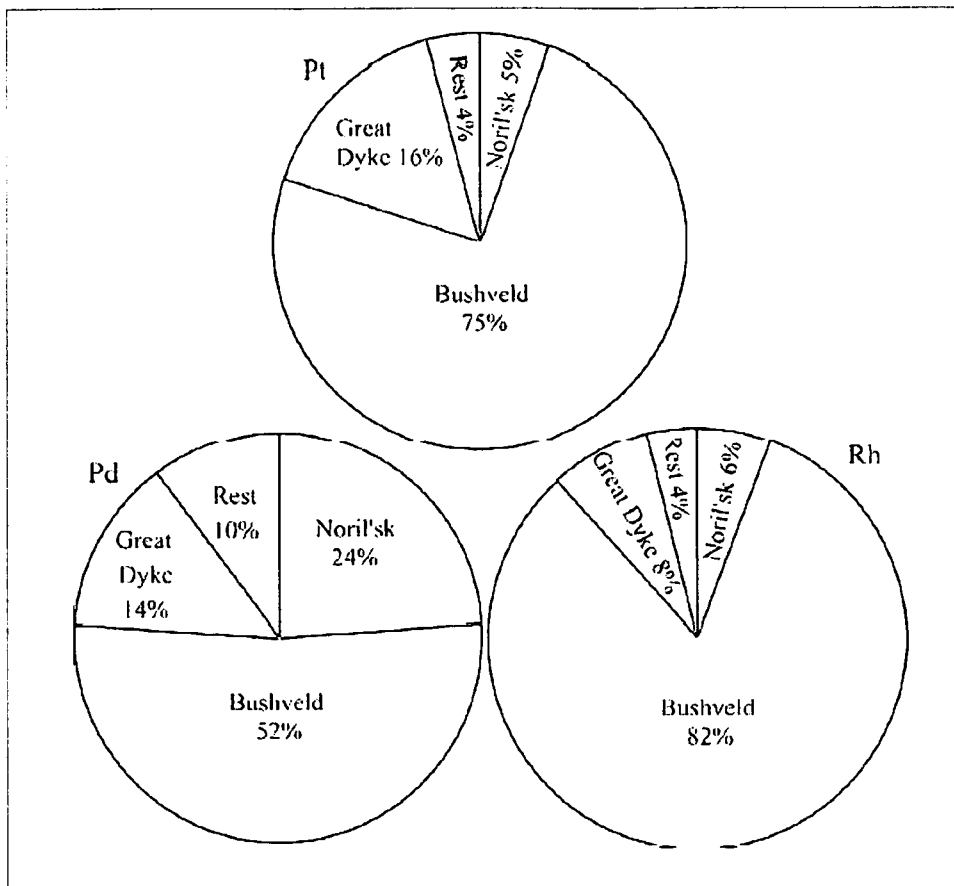
**Figure 2-2    International resource distribution of Pt, Pd and Rh (Naldrett et al. 2008)**

Some of the most well-known igneous intrusions similar to the Bushveld Igneous Complex are the Skaergaard Intrusion, Great Dyke and the Stillwater Complex. These complexes, perhaps excluding Skaergaard, along with other as listed in Table 2-1 are well studied but not one to the extent of the Bushveld Igneous Complex.

The Skaergaard intrusion, similar to the Rustenburg Layered Suite of the Bushveld Igneous Complex, is naturally subdivided into series or layers. The Skaergaard intrusion is divided into 3 lithological series dipping inward at the same trend to a central area where the last magma was crystallised (Andersen & Brooks 2003). The walls of the intrusion are made up of the Marginal border series and the inner part of the intrusion is divided into the Upper border series that crystallised on the roof of the magma chamber and the layered series on the magma chamber floor (Andersen & Brooks 2003). The Skaergaard is a gabbroic intrusion (Farla 2004) similar to certain layers of the Bushveld Igneous Complex and Stillwater Complex.

**Table 2-1      Large igneous complexes and intrusions (Roberts 2008)**

| Name | Age | Location | Area (km²) |
|------|-----|----------|-----------|
| Bushveld | Precambrian | South Africa | 66,000 |
| Dufek | Jurassic | Antarctica | 50,000 |
| Duluth | Precambrian | Minnesota, USA | 4,700 |
| Stillwater | Precambrian | Montana, USA | 4,400 |
| Muskox | Precambrian | NW Territory, Canada | 3,500 |
| Great Dyke | Precambrian | Zimbabwe | 3,300 |
| Kiglapait | Precambrian | Labrador | 560 |
| Skaergård | Eocene | East Greenland | 100 |

The Stillwater Complex is larger than the Great Dyke and Skaergaard intrusion with an aerial extent covering 4 400 km². Similar to other igneous complexes, the Stillwater Complex can be divided into various layers or zones with geological sequences characterised by orthopyroxene, olivine, plagioclase, augite, and pigeonite rich layers (McCallum 2002). Mineralogically the Stillwater Complex is the most similar to the Bushveld Igneous Complex's western limb.

As in the case of the aforementioned international examples, the Bushveld Igneous Complex consists of several units and limbs separated by various other geological units both pre- and post-Bushveld formation age. The Complex is divided into an Eastern-, South eastern/Bethal-, Northern/Potgietersrus-, Western and Far Western limbs stretching from Burgersfort to Zeerust from east to west and from Villa Nora in the north, southward to Bethal (Cawthorn et al. 2006). These tabular shaped limbs are further sub-divided into various groups and layered sequences (Figure 2-3).

The Bushveld Igneous Complex and its layered formations and most significantly the granitic and granophyre formations are commonly known to have formed from a mantle plume with the source rocks melted due to thermal input (Cawthorn 2007, Schweitzer, Hatton & de Waal 1997). The emplacement occurred in a period after the formation of the last Rooiberg Rhyolite Formation.

The general local geology of the study area is dominated by the geology of the Rustenburg Layered Suite; this sequence is described in detail from various referenced articles in the next two sections, along with a second section on the Pilanesberg Complex which had major metamorphic and structural influences on the local geology.
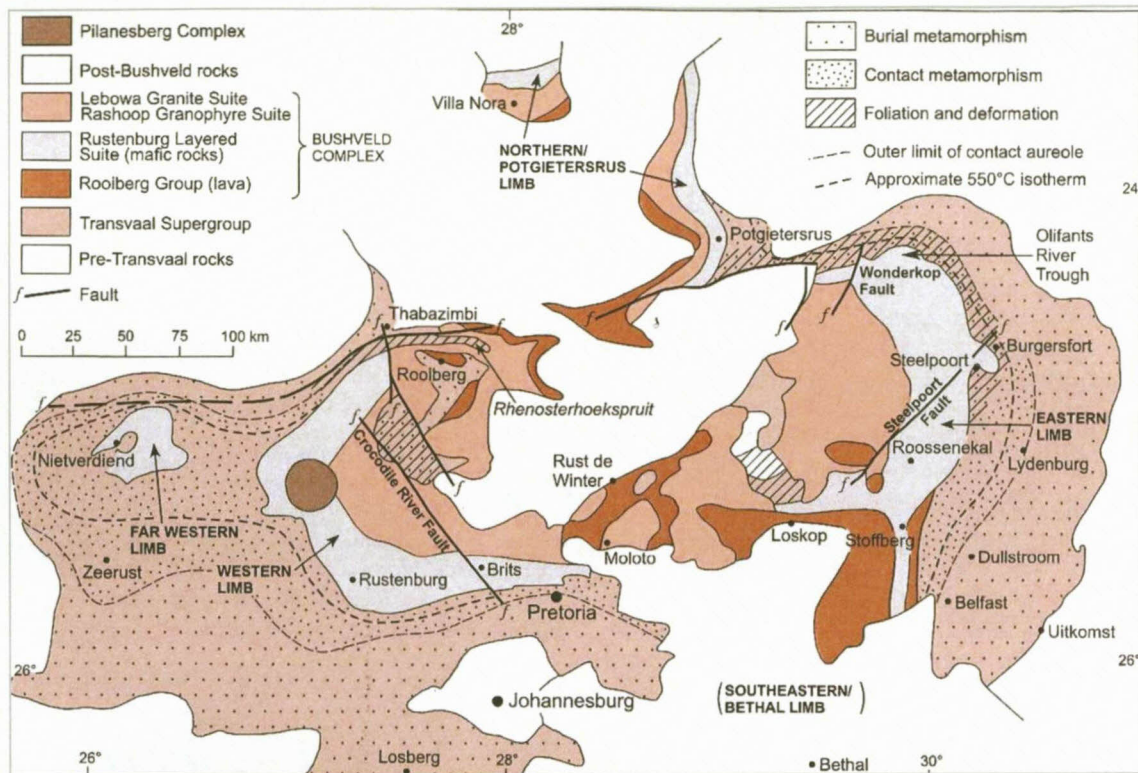
**Figure 2-3    Map of the Bushveld Igneous Complex and its various limbs (Cawthorn et al. 2006)**

## 2.3.1   Rustenburg Layered Suite

The five limbs of the Rustenburg Layered Suite are collectively divided into various zones of stratigraphy based on geology and mineralogy. The suite is divided from the base to the top of the layered intrusion into a Marginal-, Lower-, Critical-, Main- and Upper Zone. Across all the sub-zones of the layered suite a complete differentiation of basic lavas is exhibited from the felsic dunite, pyroxenite and anorthosite to the more mafic norite and gabbros including magnetite- and apatite-rich diorite (Cawthorn et al. 2006). The various limbs of the suite are currently accepted to have been developed out of one common magma chamber. The ore bodies within the complex include the UG2 Reef containing up to 43.5% chromite, and the platinum-bearing horizons Merensky Reef and Platreef (Cawthorn 1999; Cawthorn 2001; Cawthorn et al. 2006; Cawthorn 2007).

The Lower and Critical zones are enriched with Cl relative to F, with the Cl-rich nature of halogens in the complex and layers of the Rustenburg suite, suggesting that the complex and the formation of the Pt and Pd bearing zones were influenced by the exsolution and migration of chlorine-rich volatiles (Willmore, Boudreau, Spivack & Kruger 2002).
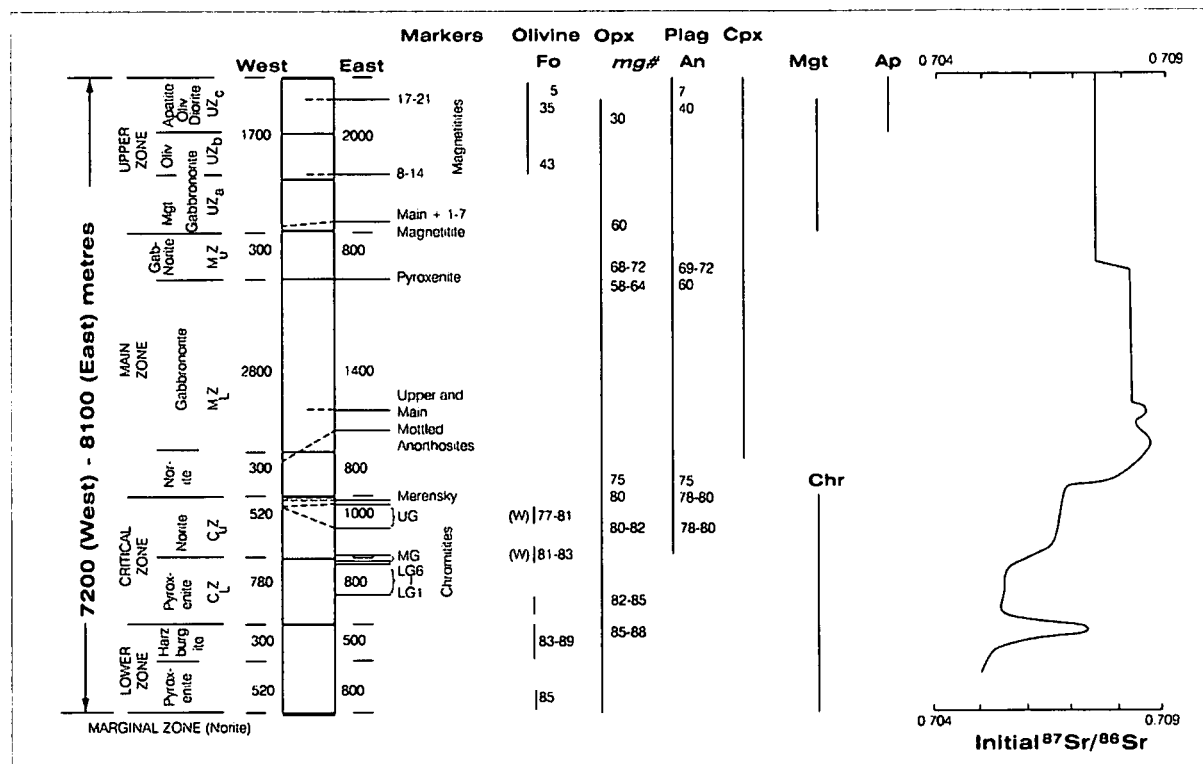


**Figure 2-4    Stratigraphic representation of the eastern and western limb geology of the Bushveld Igneous Complex with the Merensky and UG2 Reefs indicated in the Upper Critical Zone (Cawthorn 2007)**

The Merensky Reef discovered in August 1924 (Cawthorn 2001) is the main ore bearing Reef mined by the PPM mining operations along with sections of the UG2 Reef.  The Merensky Reef originally discovered on the farm Maandagshoek by Dr Hans Merensky (Cawthorn 2001) sits within the Upper Critical zone (Rustenburg Layered Suite) of the Bushveld Igneous Complex along with the UG2 chromite layer and was discovered when traced back to the outcrop location from a stream panning location where Merensky and Lombaard discovered Pt rich sediments.  The UG2 and Merensky Reefs found within the sequence as shown in Figure 2-4 are associated with the formation of plagioclase from the crystallization sequences commonly ascribed to the minerals with Sr isotope studies confirming this model (Cawthorn 2007).

## 2.3.2 Pilanesberg Alkaline Complex

The initial discovery of the Pilanesberg Alkaline Complex, as shown in Figure 2-3, (here after referred to as the Pilanesberg Complex) occurred during the early twentieth century with Molengraaff (1905) and Brouwer (1910) doing the first geological investigations on the complexes geology and structure. Interpretations of the Pilanesberg geology and formation have been relatively unchanged since the first investigation by Shand in 1928 (Verwoerd 2006). The Pilanesberg Alkaline Province was formed during a period of volcanic and plutonic activity after a relatively long geological period with no major depositional or structural activities or deformation, and is today the largest of a number of alkaline complexes in Southern Africa (Lurie 1986). The Pilanesberg Complex that formed within the western limb of the Bushveld Igneous Complex forms part of this alkaline province and formed 1193 Ma (±98) ago (Verwoerd 2006) on the contact between the granitic and mafic phases of the Bushveld Igneous Complex (Lurie 1986).

The Pilanesberg Complex has a circular structure with the topography and drainage of the complex area following the general inward dip of the geology. Sixteen water gaps or out flowing drainages are identified on the outer ring of the complex with the ring shaped hills on the rim of the complex having steeper outward sloping hills than the inward ones (Lurie 1986). The areal extent of the complex occupies 530 km$^2$ (Verwoerd 2006). The complex formed through different stages of volcanic activity and events mainly within the Rustenburg Layered Suite and the Lebowa Granite Suite to the east making up the country rock. The depositional time of the complex has an upper age limit induced by the regional and in some cases local blocks of Waterberg group sandstones present (Verwoerd 2006).

The volcanic geology of the complex is made up of a wide variety of dislocated members and formations made up of lava flows, volcanic tuff, agglomerate and volcanic breccia dipping inwards forming the main form of the ring shaped complex (Lurie 1986; Verwoerd 2006). The plutonic members of the complex are divided into five southward tilting, funnel shaped intrusions one formed within the next. From the centre to the outer fringe the intrusions are made up of red foyaite, white foyaite, green foyaite, second white foyaite and syenite. Other intrusions forming the rest of the complex are the Ledig foyaite, nepheline feldspar porphyry and a tinguaite dyke forming an incomplete ring dyke (Lurie, 1986 and Verwoerd, 2006).

The formational volcanic eruptions or events that formed the complex can be ordered in a sequence as done by Verwoerd (2006) who modified the events after Lurie (1986):

1. Explosive volcanism

2. Intrusion of syenite along ring fracture

3. Extrusion of lavas and pyroclastics

4. Sub-volcanic emplacement of red foyaite plug

5. Renewed volcanic activity

6. Intrusion of white foyaite along conical fractures

7. Intrusion of green foyaite, tinguaite and porphyry

8. Intrusion of Ledig foyaite

9. Intrusion of alkali granite plug

10. Slow subsidence along outer ring fracture

11. Tilting, faulting and thrusting, resulting in rotation

12. Intrusion of parallel and radial dykes

The above sequence of events occurred with volcanic and plutonic nature resulting in the formation of one geological unit around the other in a cone or circular manner. The red foyaite forms the centre and circular formation outwards as volcanic eruptions occurred the other geological units formed and also formed structural dykes and faults due to pressure events.

The Pilanesberg Complex and its intrusions greatest influence on the study area is the fluoride-rich deposits in its outer ring foyaite. The F bearing rock along with the soluble nature of F leads to high concentrations of F in the local surface and groundwater quality. Today the complex and its circular extent form part of a national park and is protected by government to preserve it in its natural state.

## 2.4 Geohydrology

Razowska (2001) in a study of a flooded iron mine indicated the significant changes to the geohydrological environment through mining and the subsequent events implied post-closure. The most significant change to the geohydrology due to mining is the lowering of the water table and the development of a cone of depression that leads to changes in recharge and discharge of groundwater during operational phase with some influences post-closure (Razowska 2001). The same case is found in both shallow and deep mining in the Bushveld Igneous Complex of South Africa. The accepted aquifer model for the whole Bushveld Igneous Complex can be divided into two types namely a shallow perched aquifer in the weathered zone and a deeper, semi-confined fractured bedrock aquifer with areas of partial dewatering near both open cast and underground mines (Titus, Witthueser & Walters 2009). Inflows into mine workings in both cases are variable with leakage from the weathered

north of the Pilanesberg Complex, according to Kriek and Meyer (2010) can be divided into various geohydrological sections or units in correlation with the standardised aquifer system as mentioned by Titus et al. (2009). The local morphology, structural geology and geological units form various hydraulic or groundwater zones with different characterising elements and hydraulic parameters. These five zones are the following (Kriek & Meyer 2010):

1. Perennial river aquifer

2. Weathered and fractured topographically low lying areas

3. Faults and fractured zones forming the major aquifer

4. Weathered norite/gabbro

5. Fractured rock aquifer underlying the weathered zone

The non-perennial river of the study area is the Wilgespruit (Figure 4-3) that is classified as a losing stream with unconsolidated boundaries in the alluvial aquifer and the water level being ±30 mbgl on the river channel lines. The underlying fractured rock and weathered aquifers are recharged from the alluvial aquifer with a surface water-groundwater interaction process allowing the alluvial aquifer to act as a temporary storage zone during rainy seasons (Smith & Kotze 2010).

## 2.5 Hydrogeochemical modelling: Considerations and Software

"Each rock may be regarded, for present purposes as a chemical system in which, by various agencies, chemical changes can be brought about. Every such change implies a disturbance of equilibrium, with the ultimate formation of a new system, which, under the new conditions, is itself stable in turn. The study of these changes is the province of geochemistry. To determine what changes are possible, how and when they occur, to observe the phenomena which attend them and to note their final results are the functions of the geochemist...From a geological point of view the solid crust of the earth is the main object of study; and the reactions that take place in it may be conveniently classified under three heads – first, reactions between the essential constituents of the earth itself; second, reactions due to its aqueous envelope; and third, reactions produced by the agency of the atmosphere." (As quoted from Clarke 1924 and Mason 1966)

At the time of Hutton's geological discoveries, in the nineteenth century during the Scottish enlightenment in the field of geochemistry, one of the oldest scientific fields originated (Repcheck 2003). Geology and geochemistry go hand in hand with emphasis on the reactions, interactions and equilibrium processes of the earth and its environment as phrased by Clarke (1924).

To predict pit lake chemistry various interlinked geochemical and aqueous geochemical models, (mechanistic and empirical), are used to represent hypothetical addition and removal of chemicals to the conceptual lake (Eary 1999). Geochemical modelling and prediction of future pit lakes has the main application of representing chemical equilibria within a conceptual model. The main elements to build an accurate geochemical model are thus to identify the chemical and geochemical reactions that is expected to be in equilibrium and disequilibrium within the predicted system (Eary 1999) and interpret the results accordingly with the real life environment and mechanisms in mind. This is done through the careful analysis and monitoring of the pit lakes geological setting, mineralogy, hydrological and geohydrological mechanisms and hydrochemical data of its groundwater and surface water.
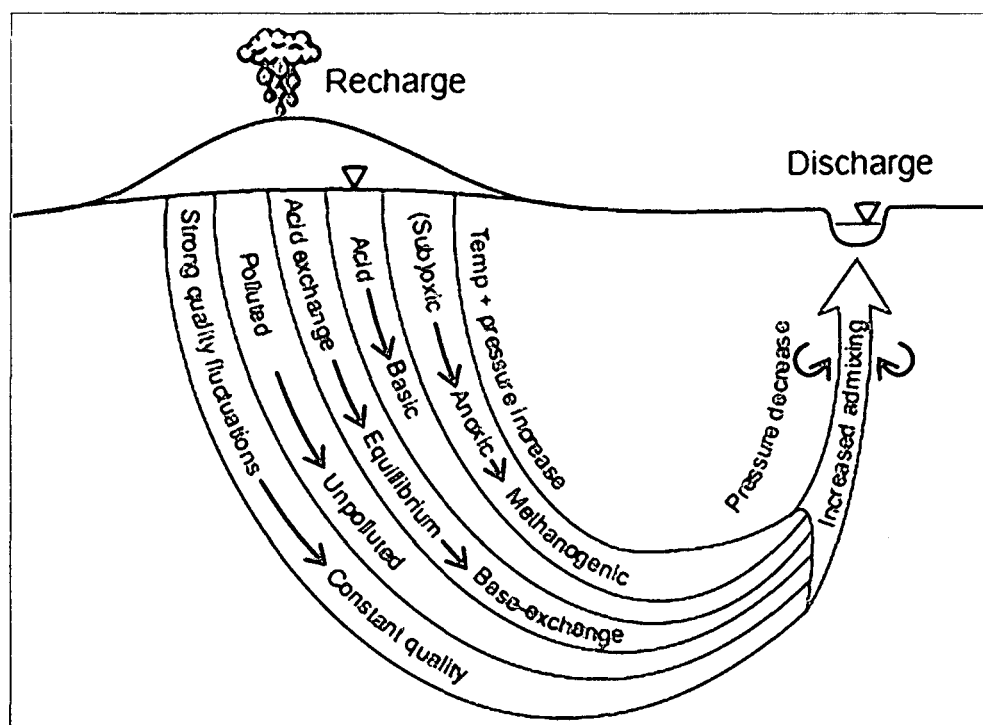


**Figure 2-6** **Important processes to consider during modelling changes in groundwater chemistry (Stuyfzand 1999; Witthueser 2010).**

Physio-chemical parameters like pH, dissolved oxygen content and ion activity are important factors that can govern which reactions take place and at what rate. During the weathering of minerals from the interaction with water, both surface and groundwater, various mechanical and chemical processes should be kept in mind. These processes as shown in Figure 2-6 are important in the conceptualisation of a hydrogeochemical model like a pit lake scenario or open pit flooding (Stuyfzand 1999; Witthueser 2010).

Both groundwater and surface water is derived from rain water. In today's changing

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environment the chemical character of rain is important to consider as the pH and other parameters associated with acid and normal rain can have an impact on mineral weathering (Witthueser 2010). The composition of rain water as well as its pH and various solutes are derived from various sources depending on the environment. However one chemical constituent that is assumed to remain constant for the purpose of geohydrological investigations is the chloride concentration. The most commonly used recharge method is the chloride method in which Equation 1 is used to calculate the percentage of rainwater infiltrating the soil profile and ultimately reaching the water table, replenishing groundwater reserves.

**Recharge% = (Cl in rainwater (mg/ℓ) / Cl in groundwater (mg/ℓ)) x 100**        Equation 1

In this calculation method Cl concentration in rainwater is assumed to be 1.28 mg/ℓ at inland locations and 2.23 mg/ℓ for coastal locations (Van Tonder & Xu 2000), however as seen in a study by Ejelonu, Adeleke, Ololade & Adegbuyi (2011), various anthropogenic and atmospheric processes and factors lead to higher levels of Cl not always accounted for.

From the formation of precipitation to the runoff and recharge of water into various systems, there are various factors that influence the character of the water. These hydrochemical changing factors influencing the characteristics of rainwater before it becomes groundwater includes evapotranspiration; selective uptake of ions by vegetation; organic matter decay; weathering and dissolution of minerals; infiltration rate; ion exchange reactions; adsorption and absorption; mixing with different water types and various socio economic and anthropogenic activities (Witthueser 2010).

| Discontinuous reaction series | | Continuous reaction series | |
| --- | --- | --- | --- |
| Minerals | Structure type | Structure type | Minerals |

High temperature, early

Olivine — Isolated SiO₄ groups

Pyroxene — Single chains

Amphibole — Double chains

Biotite — Sheets

Framework — Anorthite ↓ Bytownite ↓ Labradorite ↓ Andesine ↓ Oligoclase ↓ Albite — Plagioclase series

K-feldspar

(Muscovite)

Quartz ↓ Zeolites — Framework

↓

Hydrothermal minerals

Low temperature, late

**Figure 2-7    Bowen's reaction series with continuous and discontinuous mineral reaction sequences (Klein & Dutrow 2007)**

Weathering reactions and sequences are important factors in all hydrogeochemical modelling scenarios and hydrogeochemistry in general. During the formation of igneous rocks, minerals form in continuous and discontinuous reactions and along with magma separation is called magmatic differentiation (Klein & Dutrow 2007). Both the continuous and discontinuous formation of the rocks through magmatic separation was observed by N.L. Bowen and he developed the Bowen reaction series (Figure 2-7) (Klein & Dutrow 2007). This reaction series is a guideline for the development and formation of minerals during the cooling of a magma with olivine forming at high temperatures, and quartz and hydrothermal minerals forming last under lower temperature conditions and pressure (Klein & Dutrow 2007). This reaction series can also be reversed as observed by Goldich in 1938 in order to develop a mineral weathering sequence (Witthueser 2010). From the Bowens reaction series the minerals forming first under high temperatures are the softest and most unstable minerals at surface conditions and thus the most susceptible to weathering. Quartz and K-feldspars on the other hand form under low temperature conditions closer to those found under surface conditions, thus being hardier minerals that are less susceptible to weathering. This weathering sequence is useful in the development of a conceptual hydrogeological model and weathering simulations.

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The two geochemical software packages suitable for the hydrogeochemical modelling in the pit flooding study are Phreeqc Interactive and The Geochemist's Workbench® (GWB). In this dissertation and research study GWB was used for modelling hydrogeochemical processes. For the purpose of understanding the capabilities and limitations of GWB, a short summary of the program has been compiled with a motivation for the use of the program.

## 2.5.1   The Geochemist's Workbench®

The Geochemist's Workbench®, here after referred to as GWB, is a software package consisting of various program packages aimed at modelling environmental geochemical reaction processes and thermodynamics commonly dealt with in the environmental, geological, biochemical, hydrogeological, energy and pollution management fields. GWB is a set of software tools for manipulating chemical reactions, calculating stability diagrams and the equilibrium states of natural waters, tracing reaction processes, modelling reactive transport, plotting the results of these calculations, and storing the related data (Aqueous Solutions 2012; Bethke & Yeakel 2010).

The software package has the following tools and capabilities (Solutions 2012; Bethke & Yeakel 2010a; Bethke & Yeakel 2010b; Bethke & Yeakel 2010c):

- GSS stores analyte and sample data in a spreadsheet specially developed to work with the GWB set of software tools with capabilities of calculating various constituents and chemical parameters not reported by the laboratory;

- Rxn automatically balances chemical reactions, calculates equilibrium constants and equations, and solves for temperature at which reactions are in equilibrium;

- Act2 calculates and plots stability diagrams on activity and fugacity axes. It can also project the traces of reaction paths calculated using the React program;

- Tact calculates and plots temperature-activity and temperature-fugacity diagrams and projects the traces of reaction paths;

- SpecE8 calculates species distribution in aqueous solutions and computes mineral saturations and fugacity. SpecE8 can account for sorption of species onto mineral surfaces according to a variety of methods, including surface complexations and ion exchange;

- React in addition to having the capabilities of SpecE8, traces reaction paths involving fluids, minerals, waste material and gases. React can also predict

the fractionation of stable isotopes during reaction processes. The simulation results can be rendered with program Gtplot; and

- Gtplot graphs SpecE8 and React results and GSS datasets, including on XY plots, ternary, Piper, Durov and Stiff diagrams. The program allows for the direct copy of data from a graph into a spreadsheet as well as the pot of reaction paths between rocks and fluids on activity-pH diagrams.

The program will be used in this research project and dissertation to model a pit lake and hydrogeochemical environment, however the GWB software package has applications in various other fields as mentioned below (Aqueous Solutions 2012):

**Hydrogeology**

- Hydrochemical calculations, diagrams, speciation and mixing;

- Reaction/mixing path modelling;

- Weathering and adsorption models;

- Seepage and contaminant transport modelling of contaminant plumes;

- Reaction balancing and calculations;

- Environmental mitigation option planning and simulation;

- Pit and mine flooding;

- Simulate laboratory tests with no costs;

- Design solution mines and heap leach operations; and

- Model the attenuation of acid drainage accounting for mixing, neutralization, sorption, and degassing.

**Petroleum and energy (Fracking in South Africa)**

- Model scaling in wellbores and reservoirs, reservoir floods, and formation damage;

- Test the compatibility of fluids before they mix in the formation or wellbore;

- Study how captured carbon dioxide might react with subsurface minerals and engineered materials; and

- Model heat and mass transport and predict reactions accompanying fluid mixing.

**Biophysical/Biochemical**

- Develop quantitative understandings of the mobility and bioavailability of heavy metals in the biosphere, and the persistence of organic contaminants;

- Geo-microbiologists calculate the energy in natural waters available to microbes, how fast bugs respire and ferment, and how they affect their chemical environments;

- Microbial ecologists use the software to design experimental studies of microbial reaction and growth, derive kinetic rate laws, and solve them alone or in combination; and

- Use the package to model the synthesis of organic molecules.

**Environmental and closure**

- Environmental remediators design, test, and optimize environmental clean-up initiatives costing tens of millions of dollars, before deploying remedies in the field.

**Surface water**

- Surface water chemists use the software to account for atmosphere-water exchange, sediment-water transfer, and the effects of biologically mediated reactions.

**Exploration and experimentation**

- Develop genetic models of ore deposition, and interpret patterns in water composition that may lead to undiscovered resources; and

- Use the software package to design laboratory tests that may last months or longer, and to interpret the results of experiments

### 2.5.2 Software motivation

GWB allows the researcher to develop a system and build the processes from start to finish with integrated thermodynamic and geochemical databases, developed by Craig Bethke and students at the University of Illinois (Bethke 2012), referenced by the software to complete reaction paths and give results indicating the processes involved in the modelled system. The main difference in the two packages is the thermodynamic and chemical controls of the software that will not allow processes to take place if the conceptual setup of the model and its element are not accurate to those observed in nature. Thus at the end of a modelled simulation the results are accurate with the software allowing the representation of results on various diagrams and graphs directly from the simulated interface, and this is something other packages do not have.

A study by Pabalari & Sabido (2007) dealt with the comparison of results from simulations using GWB and other software and analytical methods with the following

quote summarising the accuracy of the program, "Overall, the agreement of trends and results between Geochemist's Workbench Version 6.0 database and the various calculational methods used in the model validation exercise indicates that the code is correctly and consistently applying the underlying geochemical theorems and algorithms needed to evaluate the equilibrium and kinetic behaviour of geochemical systems" (Pabalari & Sabido 2007).

## 2.6 Pit flooding, Pit lake dynamics and aqueous geochemistry

### 2.6.1 Pit flooding and lake dynamics

Various studies have been done internationally around the aqueous geochemistry of pit lakes in various mining environments to evaluate the effectiveness of the method in dealing with post-closure environmental mitigation problems. Climatic and geochemical influences create dynamic environments in which pit lakes are not in equilibrium at all times or in the same chemical composition (Bethke & Yeakel 2010a; Castendyk & Webster-Brown 2007). Geochemical modelling and prediction of pit flooding events allow mining companies and governmental mining bodies to evaluate future water chemistry scenario post-closure as well as engineering post-closure mining resources, develop post-closure plans and the assessment of potential environmental risks and effects that could be liabilities in the future (Castendyk & Webster-Brown 2007)

Flooded open pits create artificial lakes called pit lakes with a small diameter to depth ratio (Ramstedt 2003) and along with saline groundwater creates stratification with changes to the layers as seasonal changes affect temperature and the mixing ratios of surface water to groundwater (Ramstedt 2003). The length of free wind action and the wave fetch also plays a role in water circulation of both artificial and natural lakes and dams (Ramstedt 2003). Wind induced physical processes play a large role in shallow water interaction and turnover during seasonal changes and storm events on large water bodies like pit lakes. Wind action over water bodies' transfer energy and momentum to the water creating wave action, turbulence and currents which in turn allow mixing as well as water spray or vapour counting as a water loss (Longo 2012). Wave frequency and momentum is determined by the speed of the inducing wind and thus depth of mixing induced by wave actions of low velocity wind will not have such a great effect on pit lakes (Tolman 2004; Pantuzzo & Ciminelli 2010), especially in locations like the relatively stable conditions of the PPM study area.

The small density changes of input waters that contribute to the flooding of an open pit mine can dictate the development of either meromictic or holomictic lakes (Castendyk & Webster-Brown 2007). Vertical mixing of lake water due to seasonal

changes and different mixing volumes of input water across the water column is called turnover resulting in two different lake types. A meromictic lake is a lake that undergoes a complete turnover annually with a holomictic lake only experiencing a partial turnover (Boehrer & Schultze 2006; Castendyk & Webster-Brown 2007). The study of the effect of turnover events through sensitivity analysis was done by Castendyk & Webster-Brown (2007) in the prediction of pit lake water quality of an open pit mine in New Zealand. The conditions of an artificial lake and the addition of various water sources from groundwater, rain water and runoff surface water causes different temperature signatures to mix and create meromictic pit lakes. Once pit flooding starts to reach equilibrium with the lake water level reaching the same level as the piezometric head of the regional groundwater table, groundwater does not contribute to the inflow of source water into the lake with only rain and surface water contributing (Castendyk & Webster-Brown 2007). This however occurs in areas with higher MAP than MAE.

A case study in which temperature differences and the salinity of the pit water were observed to create stratification and 4 stratified layers was in a pit lake in Udden, Sweden (Ramstedt 2003). The concentrations of heavy metals and $SO_4$ were observed to change with each layer. Most notably the Fe (II) and As showed an increase in concentration with depth and $SO_4$ was the dominant anion increasing with depth to a concentration at the bottom of the lake similar to the solubility concentration of gypsum (Ramstedt 2003). The Udden pit lake was in a sulphide ore deposit with the bedrock dominated by quartz, amphibolite rocks and tuffite. The weathering of these minerals through the interaction with mechanical actions and water lead to a water chemistry that has a much higher metal concentration than natural lakes.

The flooding of an open pit, thus creating a pit lake, minimises oxidation of various minerals in the pit walls and mine waste and the release of heavy metals and acidity due $O_2$ not being allowed to diffuse into the materials (Ramstedt 2003). Oxidation of various minerals can however proceed if Fe (III) acts as the oxidising agent allowing processes to proceed in the absence of $O_2$, as also described by Herbert (2006). The formation of acidic pit lakes is common in various mining industries and areas across the world. According to Nixdorf, Uhlmann & Lessmann (2010) the management of existing acidic lakes through neutralising the water is necessary if the pit lakes are to be used for recreational or fishery use and can be achieved through three methods. Neutral water quality can be achieved by dilution through adding alkaline water from external sources, chemical treatment, and by enhancing the generation of alkalinity through biological measures (Nixdorf et al. 2010).

Another effect that mixing and inflow of different water sources induces is turbidity which is directly caused by the amount of Total Suspended Solids (TSS) in the contributing waters. Suspended solids can clog the gills of fish and other aquatic organisms (Berry & Rubinstein 2003; IWS 2013). TSS reduces the visibility in water bodies and thus the lakes cannot be used for recreational diving. Turbidity is the measurement of the clarity or visibility of water measured in Nephelometric Turbidity Units. Sea water has a turbidity of 50 NTU (Meyer & Hansen 2010) and according to US EPA standards water intended to be used for recreational diving should have a turbidity within 10% of this standard (EPA 2012). Various methods are however effective in mitigating and reducing TSS and in turn mitigate turbidity of contributing water. Upstream sumps, settling ponds and geotextile screens reduces surface water flow velocity allowing suspended particles to settle out and thus the water is cleaned of particles before flowing into the static surface water body (Berry & Rubinstein 2003; GRM 2011).

The flooding of an open pit from contributing waters of surface runoff rain and groundwater as discussed previously leads to chemical variations and stratification of the water column. However, surface runoff contributes the greatest variation of solutes due to episodic releases of oxidation products from surface soils and remnants of mine waste like waste rock dumps and tailings facilities (Herbert 2006). The episodic release of heavy metals and other constituents like discussed TSS in high concentrations from surface runoff occurs during rain events, flood events (one in fifty and one in twenty year floods) as well as in some international cases during snow melt as described by Herbert (2006). Thus the effect of some parameters on water quality expected in pit lakes can be seasonally driven with windows in the changing environment open for various recreation activities and other uses of the water.

Although the most significant impact with hard rock mines, both open pit and underground, are the physical environmental impact and to a certain extent the hydrogeochemical impact of these activities during operations and post-closure. However the principles for these hard rock mines are equally applicable on closed collieries as in the case of the abandoned Middelburg Colliery in the Witbank Coalfield, South Africa (Bell, Bullock, Halbich & Lindsay 2001). The principles of studies done for both open pit and underground mine shaft flooding leads to similar conclusions and challenges. Stratification of flooded water in mine openings can cause upsets and failures of designed treatment facilities due to the unexpected changes in water quality (Nuttall & Younger 2004). Based on the studies of Nuttall & Younger (2004) stratification in flooded mine waters can be caused by various factors of which the following two will be most probable to cause the event to occur in the

case study pit lake:

1. Small inflows and outflows in the pit or shaft wall; allowing

2. Gradual inflow and slow recovery of water levels.

These two stratification causing factors allows for changes in water quality with the bottom layer of the pit lake or flooded underground mine/shaft having metal concentrations of elements like Fe, Zn, Ni and V; 2 to 3 orders in magnitude more than the shallower water column layers (Nuttall & Younger 2004). From this Nuttall & Younger (2004) concluded that in modelling or predicting stratified water column qualities the worst quality modelled or measured will be the concentrations on which long term mitigation designs and treatment plans should be based.

## 2.6.2 Aqueous Geochemistry and Thermodynamics of chemical processes

As mentioned in previous sub-sections, various geochemical processes are involved in fluid-rock and fluid-fluid chemical interaction and is controlled and manipulated through various chemical parameters and elements. The following section gives short descriptions and reviews of elements to consider in modelling aqueous geochemistry as well as various factors and considerations in thermodynamics.

### 2.6.2.1 Thermodynamics

Thermodynamics of natural systems or chemical processes is the study of molecular systems, thus investigating and understanding the properties of individual molecules to ultimately predict the behaviour of the larger system (Price 1998). The previous sentence describing thermodynamics can almost directly be used to describe the purpose of geochemical modelling, with thermodynamics of the environment and its natural systems being the corner stone of any model with chemical processes involved.

The main process and driving force behind any thermodynamic investigation or chemical process is energy and thus thermodynamics can also be described as the study of energy change in chemical processes (Price 1998). Thus in a final descriptive sentence, thermodynamics allows the scientist to evaluate and investigate the chemical building blocks in both anthropogenic and natural systems by understanding the chemical system from the origin of its energy, through the change in that energy and the system phases up towards the ultimate goal of chemical processes, being equilibrium.

Thermodynamics is a corner stone of chemistry and modelling of natural processes, but to fully describe and pull apart the field and its various processes is unrealistic for

the literature study at hand. The system should be studied and understood by any scientist to a competent degree. The main three principles of thermodynamics describing the origin and change in energy of chemical systems are the three laws of thermodynamics (Brown, LeMay, Bursten & Murphey 2006; Price 1998):

1. Matter can neither be created nor destroyed, merely interconverted between forms.

2. An isolated system, if not already in its state of thermodynamic equilibrium, spontaneously evolves towards it.

3. The entropy of a system approaches a constant value as the temperature approaches zero

Thus from the study of thermodynamics all processes can be understood and modelled in terms of system energy and the flow of it. Some examples of thermodynamic modelling is the modelling of solid solutions in the petrology fields as well as fluid partitioning processes when geologists investigate the formation geochemistry of geological structures like the Pilanesberg complex (Ganguly 2001).

Natural systems however rarely achieve perfect equilibrium and are an idealised mathematical model of reality. When using thermodynamics in geochemical modelling we build in variables like ion exchange and dissolution rates to create dis-equilibrium more closely resembling the natural system.

### 2.6.2.2 pH

pH is a well-known physical attribute of most chemical systems and is commonly used to describe the chemical state of a fluid and is measured on a scale from 0 to 14 with 7 being neutral. pH is the negative logarithm of the activity of $H^+$ ions and is a systematic state variable. The acidic or basic level of a fluid and thus the pH level is controlled by the $H^+$ concentration of the water. If the $H^+$ increases pH decreases with an decrease of $H^+$ implying the opposite.
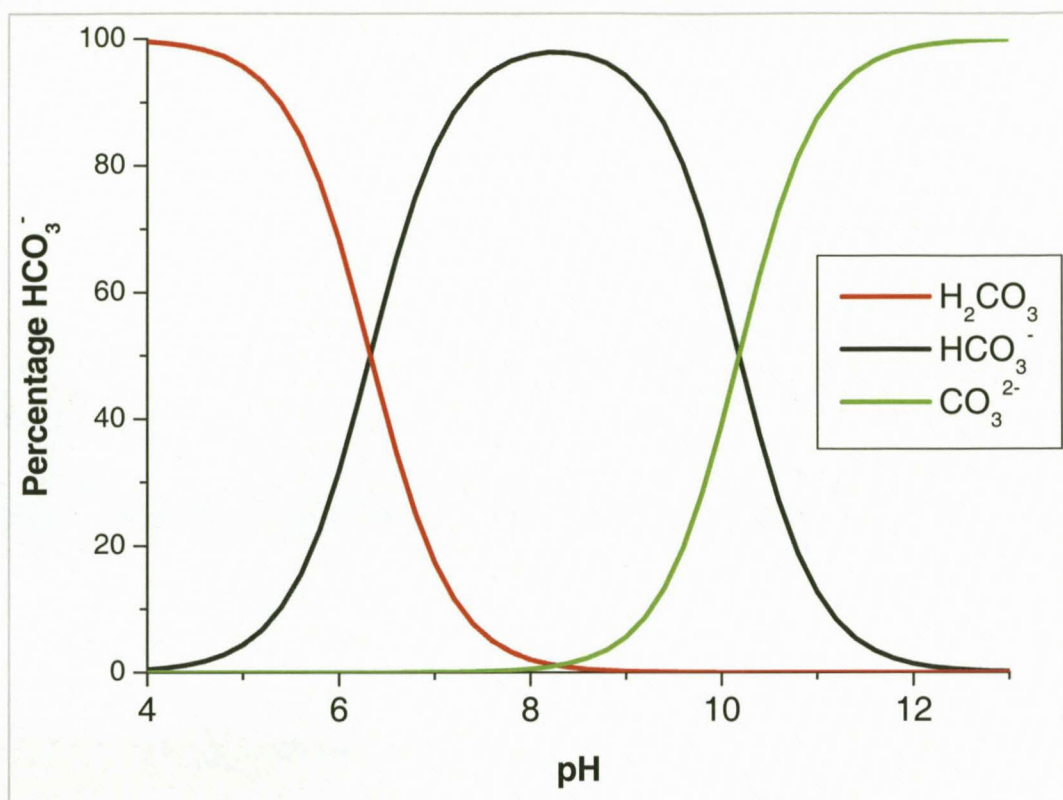
**Figure 2-8    Relationship of pH to percentage HCO₃ (Witthueser 2010)**

The pH of water controls various aspects of the geochemical process leading to both surface water and groundwater quality in nature (Malmstrom & Banwart 1997). A prime example of the effect of pH on a weathering system is illustrated and discussed in the dissolution rate study of biotite under different pH levels by Malmstrom & Banwart (1997). Variables such as pH controls aqueous speciation which in turn plays a role in the bio-availability and activity of ions in the groundwater and soils of a region. Mineral weathering or dissolution rates directly affect the release rate of ions from mineral phases. In the study of biotite dissolution it is evident that minor constituents like $K^+$ and other ions are directly affected by the pH of the system (Malmstrom & Banwart 1997) with a more specific example being the dissolution of galena (PbS) where Pb and S is only released in acidic conditions. An acidic pH allows for faster dissolution with a high basic pH allowing slower dissolution of the main silicate minerals.

Thus in a conservative approach to evaluate normal mineral weathering conditions a pH close to neutral or slightly acidic between 6 and 7 is ideal. pH is largely controlled in groundwater by carbonate and bicarbonate concentrations as indicated in Figure 2-8 (Witthueser 2010). These two cations are dominant in most groundwater facies and also present in the general study area groundwater as well as the whole of the Bushveld Igneous Complex with an average and most common facies of Mg/Ca-

$HCO_3$ (Kriek & Meyer 2010; Meyer & Hansen 2010; Smith & Kotze 2010; Titus et al. 2009; van Coller et al. 2012). From Figure 2-8 the relationship between bicarbonate and pH can be described. Low pH levels have a high $H^+$ concentration bonded in aqueous species of $H_2CO_3$ in dissolution as the system reaches levels with higher $HCO_3$ concentrations $H^+$ is released and pH levels increase until $CO_3$ dominates the system with precipitation of carbonate minerals. This relationship is shown on the graph in Figure 2-9 depicted using sample chemistry from a study on projects in the same catchment as the PPM open pit.
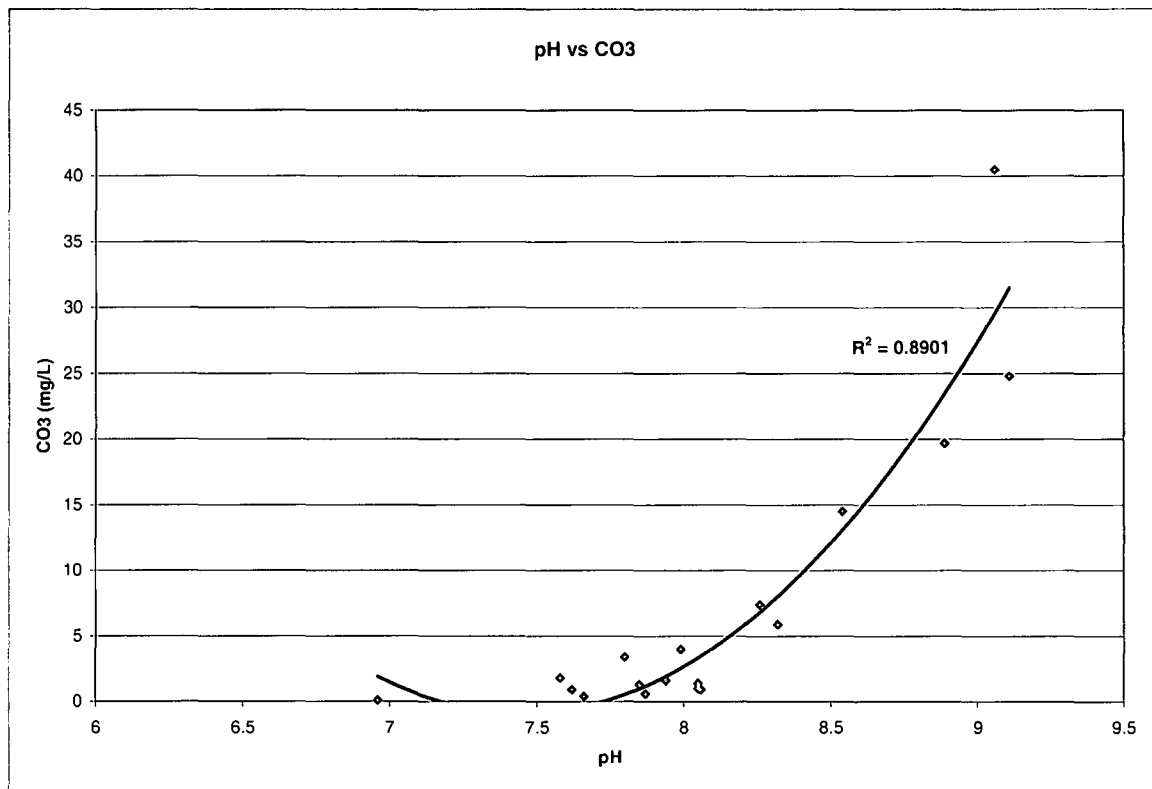


**Figure 2-9    Correlation between $CO_3$ and pH from Meyer et al. (2010)**

### 2.6.2.3  Fugacity

Fugacity, f, is described as the effective pressure, p, of a gas in the system with Equation 2 describing the calculation of fugacity (Price 1998). Thus Φ is a factor describing how the effective pressure of a system deviates from an ideal model in which Φ equals 1. Gas behaviour under most conditions is seen as the ideal model with Φ accounting for differences in pressure due to intermolecular interactions at high pressures (Price 1998).

**f = Φ (p)**                                                                                    **Equation 2**

At atmospheric conditions $fO_2$ is equal to 0.21 under temperatures of 25°C as shown in Figure 2-10 (Merkel & Planer-Friedrich 2008) with $CO_2$ dependent on the local conditions and the dissolved content in the water. $CO_{2(g)}$ and its effect on the environment from greenhouse gas sources is a well-documented topic. $CO_{2(g)}$ infiltrating groundwater systems as dissolved gasses in rainwater has certain effects on the fluid-rock interactions and the chemistry of resultant water. Acidification of water and increased chemical dissolution rates of minerals are the two most important impacts of $CO_2$ to consider with an increasing activity of the dissolved gas in a system (Hellevang, Kvamme & Aagaard 2003).
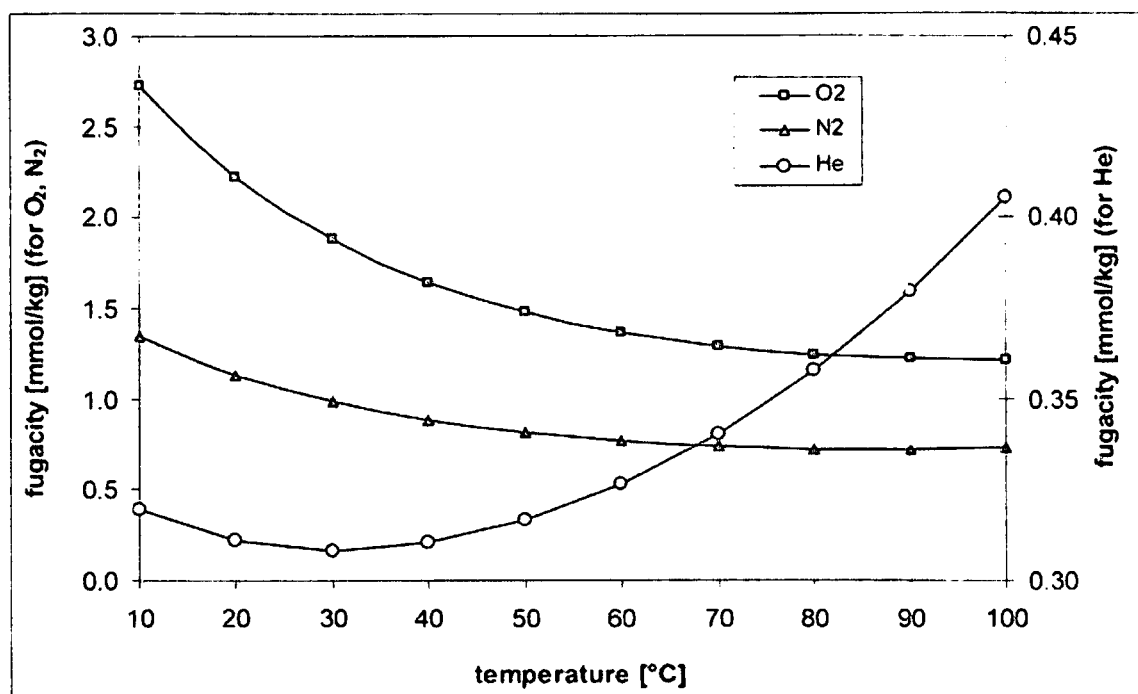


**Figure 2-10    Fugacity trend under increasing temperatures at atmospheric partial pressure (Merkel & Planer-Friedrich 2008)**

The fugacity or gas content of systems of fluid-rock interaction thus is important in controlling pH conditions and mineral weathering rates (Hellevang et al. 2003). Thus the simulation of fugacity is critical to conceptualise and set up an accurate model.

## 2.6.2.4   Activity coefficient

The interaction between ions or molecular compounds forming saturated phases of minerals or aqueous species in groundwater is not necessarily dependent on the concentrations of the constituents but rather the activity of the charged ions. The activity coefficient is a non-linear function of a species concentration with an increase in activity relating to a decrease in ionic strength (Merkel & Planer-Friedrich 2008). In other words, the more compounds interact with each other the lower the ionic activity. An ionic activity thus relates to saturated states of mineral phases in which a diluted

sample not saturated will have high ionic activity with a low ionic activity indicating a saturated state (Merkel & Planer-Friedrich 2008).

The activity coefficient and its application in hydrogeochemical modelling can be applied to the investigation of processes and compounds leading to the saturated or super saturated states of minerals in solution that can possibly precipitate. For example if gibbsite (Al(OH)$_3$) is super saturated in a system the ionic activity of Al and aluminium hydroxides will be low due to their interaction with each other to form gibbsite out of solution. Activity coefficients are fudge factors to relate free energy to concentration so as to be able to calculate effective concentration in thermodynamic terms according to the equation $\Delta G_r^0 = -RT\ln K$.

### 2.6.2.5 Dissolution and precipitation

Dissolution and precipitation are two inseparable processes within a hydrochemical system with the mass action law describing both as reversible and heterogeneous reactions (Merkel & Planer-Friedrich 2008). The dissolution of a compound occurs when the activity product of the free ions is close to 1 with precipitation occurring when the activity is close to 0.

Within the system of the case study various minerals will dissolve into solution in turn allowing the saturation of certain aqueous species to increase and thus forming saturated phases that can precipitate out of solution to form secondary minerals. Both reactions are heavily dependent on pH levels and temperature with certain mineral species not prone to dissolution, only weathering at low or high pH levels (Chen & S. Brantley 1997). $CO_{2(aq)}$ concentration also plays a role in carbon mineral precipitation with organic matter increasing the chances of mineral formations like calcite under high $CO_2$ content (Lebron & Suarez 1996).

Various factors influencing weathering/dissolution rates and formation/precipitation rates can be studied. Standard dissolution rates will however be implemented in this dissertation with precipitation occurring according to thermodynamic laws and activity calculations of aqueous species by the program GWB.

## 2.7 Project mineralogy

The project area geology that will dictate the main mineralogy of the area and the geochemical models are gabbro norite, anorthosite, dunite and pyroxenite of the Bushveld Igneous Complex. A further influence on the area's mineralogy and weathering products in both the hydrochemistry and soils are the foyaite mineralogy in the Pilanesberg Complex's outer ring.

The main minerals of the Bushveld Igneous Complex geology are olivine,

orthopyroxene and plagioclase with chromite, magnetite and apatite as accessory minerals. These sequences tend to weather to kaolinite and smectite clay minerals as evident in the region's dark clay soils (Field work).

The white and green foyaite characterising the outer rings of the Pilanesberg Complex in the northern parts, is responsible for the type of groundwater draining from the hills of the complex. Foyaite are porphyritic per alkaline formations consisting of K-feldspar, nepheline and aegirine-augite in various proportions (Verwoerd 2006). The agpaitic nature of these rocks leads to accessory minerals being highly enriched in rear earth elements (REE) (Verwoerd, 2006). Common accessory minerals in the Pilanesberg foyaite are titanosilicates, titanite, biotite and deposits of fluorite. Heavy metals (Fe and Ti) that occur in these formations become mobile at low pH levels in the groundwater. Fluoride is almost certain to be detected in the areas hydrochemistry.

Based on mineralogical accounts from the geological references of Cawthorn et al. (2006), Verwoerd (2006), Molengraaff (1905), Shand (1928), Lurie (1986), Brouwer (1910), the minerals as listed below are the main mineralogical components in the study area:

- Olivine (Forsterite and Fayalite)

- Pyroxene (Ferrosilite and Enstatite)

- Nepheline

- K-feldspar

- Anorthite

- Phlogopite

- Smectite

- Fluorite

The weathering and dissolution of these minerals has the greatest influence on the groundwater and surface water chemical signatures that will dictate the hydrogeochemical parameters and models of the pit flooding.

## 2.7.1 Mineral descriptions

Based on the geological setting and formations as well as mineralogy derived from the UG2 and Merensky Reef's XRD and XRF results, some main minerals will be used in the geochemical modelling. A short description and review of each mineral used in simulations is given in the next sub-sections with section 2.7.1.8 also describing the expected secondary minerals with chemical formulae, names and

mineral types given. (Mineral colours reported as per hand specimens)

### 2.7.1.1 Olivine

The olivine group and its end-member minerals are nesosilicates with the Mg and Fe rich members; namely forsterite and fayalite being the most common (Klein & Dutrow 2007) and are also found in the study area. Olivine as in the case with pyroxene is commonly found in crystalline rock as a result of settling in magma chambers with the Rustenburg Layered Suite of the Bushveld Igneous Complex being a prime example.

Olivine is mostly found in Mg-rich igneous rocks like gabbro and basalt coexisting with pyroxene and plagioclase. Pyroxene formation can occur from unstable conditions allowing free $SiO_2$ to react with forsterite to form enstatite. Forsterite ($Mg_2SiO_4$) and Fayalite ($Fe_2SiO_4$) will be used in the weathering simulations and details on the olivine end-members are given below (Ralph & Chau 2013):

- Lustre:          Vitreous
- Hardness:        6.5 to 7
- Colour:          Yellow green to olive green
- Weathering rate:  $1 \times 10^{-13.9}$ mole/cm$^2$/s (Wilson 2004)

### 2.7.1.2 Pyroxene

Pyroxene is an inosilicate divided into two sub-groups namely orthopyroxene and clinopyroxene each with its own end-members (Klein & Dutrow 2007). The orthopyroxene end-members ferrosilite ($FeSiO_3$) and enstatite ($MgSiO_3$) are found in project area rocks and is associated with the platinum bearing Reefs of the Upper Critical zone.

Orthopyroxenes are commonly associated with gabbro, norite and basalts associated with crystalline rocks in the same formation processes as olivine. Mg rich enstatite is the most common end-member in crustal rocks however in high temperature and pressure metamorphic formation environments like the Bushveld Igneous Complex ferrosilite concentrations tend to increase (Klein & Dutrow 2007). Both the above discussed end-members will be used in the weathering simulations with details on the minerals given below (Cairncross 2004; Klein & Dutrow 2007; Nesse 2004; Ralph & Chau 2013):

- Lustre:       Vitreous to pearly
- Hardness:     5.5 to 6 on Moh's scale

- Colour:     Grey-yellow to olive green

- Weathering rate:  $1 \times 10^{-16.4}$ mole/cm$^2$/s (Wilson 2004)

### 2.7.1.3 K-feldspar

K-feldspar or Alkali-feldspar is a feldspar sub-group containing potassium rich end-members of the tectosilicates. Microcline ($KAISi_3O_8$) and orthoclase ($KAISi_3O_8$) are the two pure end-members with the more sodium rich sanidine (Ka, Na) $AISi_3O_8$) also found (Klein & Dutrow 2007) in the study area. Mostly found in granites, granitoids and syenite. This potassium rich mineral group and in particular the pure form of $KAISi_3O_8$ will be used in the weathering simulations with some data on the mineral listed below (Cairncross 2004; Klein & Dutrow 2007; Nesse 2004; Ralph & Chau 2013):

- Lustre:     Vitreous

- Hardness:    6 on Moh's scale

- Colour:     White to pale yellow

- Weathering rate:  $1 \times 10^{-16.6}$ mole/cm$^2$/s (Wilson 2004)

### 2.7.1.4 Anorthite

Anorthite ($CaAl_2Si_2O_8$) is a calcium rich end-member of the anorthite-albite series of the plagioclase minerals and tectosilicates. Anorthite along with albite are the most common rock forming minerals in the earth's crust with anorthite being present in anorthosite as 90% of the rock composition with the Ca-rich end-member having a higher melting point than albite. Anorthite is used in the weathering models and data on the mineral is given below (Cairncross 2004; Klein & Dutrow 2007; Nesse 2004; Ralph & Chau 2013):

- Lustre:     Vitreous to pearly

- Hardness:    6 to 6.5 on Moh's scale

- Colour:     Wide range of colours

- Weathering rate:  $1 \times 10^{-12.5}$ mole/cm$^2$/s (White & Brantley 1995)

### 2.7.1.5 Fluorite

Fluorite (CaF) or fluorspar in economic quantities is a halide mineral found in small deposits within the foyaites of the Pilanesberg Complex. Commonly used as a flux in the metallurgic industry and in various household products (Ralph & Chau 2013). The most well-known deposit currently mined in South Africa is the Vergenucht

deposit and mine near Rust de Winter in South Africa, with fluorite deposits associated with the biotite rich syenite of the region (Kriek 2009).

Fluorite is present in the foyaite deposits in the study area and is also found in dissolved quantities within the groundwater and surface water of the region. Thus the mineral was used in the weathering simulation with information on the mineral listed below (Cairncross 2004; Klein & Dutrow 2007; Nesse 2004; Ralph & Chau 2013):

- Lustre:       Vitreous to dull
- Hardness:       4 on Moh's scale
- Colour:       Purple, lilac, golden-yellow, green, colourless, blue, pink, champagne, brown
- Weathering rate:       $1 \times 10^{-12}$ mole/cm$^2$/s (Cama, Zhang, Soler, De Diudici, Arvidson & Luttge 2010)

### 2.7.1.6 Nepheline

Nepheline ($NaAlSiO_4$) is a tectosilicates end-member of the feldspathoid rock forming mineral group (Klein & Dutrow 2007). Nepheline is commonly found in intrusive and extrusive silica deficient rocks like basalt and gabbro. The mineral is a common accessory mineral in igneous complexes.

Data on the mineral is listed below (Cairncross 2004; Klein & Dutrow 2007; Nesse 2004; Ralph & Chau 2013):

- Lustre:       Vitreous to greasy
- Hardness:       6 on Moh's scale
- Colour:       White, grey and yellowish
- Weathering rate:       $1 \times 10^{-20}$ mole/cm$^2$/s

### 2.7.1.7 Phlogopite

Phlogopite ($KMg_3(AlSi_3O_{10})(OH)_2$) is a phyllosilicate clay mineral commonly associated with most crustal rocks as an accessory mineral. Commonly found in Mg rich basic rocks and used in the weathering simulation due to the data base containing only data on phlogopite and not pure biotite. Mineral data given below (Cairncross 2004; Klein & Dutrow 2007; Nesse 2004; Ralph & Chau 2013):

- Lustre:       Vitreous, pearly
- Hardness:       2 to 3 on Moh's scale

- Colour:                 Brown, grey, green, yellow, or reddish brown

- Weathering rate:     $1 \times 10^{-17}$ mole/cm$^2$/s (White & Brantley 1995)

### 2.7.1.8  Smectite

The Smectite $((Na,Ca)_{0.33}(Al,Mg)_2(Si4O10)(OH)_2)$ group minerals are monoclinic clay minerals commonly found in secondary formation or soil profiles in regions like the Bushveld Igneous Complex.  Mineral data listed below for montmorrilonite (Cairncross 2004; Klein & Dutrow 2007; Nesse 2004; Ralph & Chau 2013):

- Lustre:              Dull

- Hardness:         1 to 2 on Moh's scale

- Colour:                 White, buff, yellow, green, rarely pale pink to red

- Weathering rate:     $1 \times 10^{-17}$ mole/cm$^2$/s (White & Brantley 1995)

### 2.7.1.9  Secondary minerals

The following list provides mineral names, groups and chemical formulas of most of the secondary minerals that will be discussed throughout the dissertation project and models:

Table 2-2     Secondary mineral information (Cairncross 2004; Klein & Dutrow 2007; Nesse 2004; Ralph & Chau 2013; White & Brantley 1995; Wilson 2004)

| Mineral name | Formula | Mineral group/type | Comment |
|---|---|---|---|
| Aragonite | $CaCO_3$ | Aragonite group | Polymorph of calcite |
| Calcite | $CaCO_3$ | Calcite group | Polymorph of aragonite |
| Cuprite | $Cu_2O$ | Oxide mineral | Oxidation product of copper sulphide |
| Daphnite | $(Fe, Mg)_5Al(Si, Al)_4O_{10}(OH)_8$ | Chlorite group | Variety of Chamosite |
| Dolomite | $CaMg(CO_3)_2$ | Carbonate mineral | Also regarded as a rock type |
| Fluorapatite | $Ca_5(PO_4)_3F$ | Apatite group | Fluorine end-member |
| Gibbsite | $Al(OH)_3$ | Hydroxide mineral | Polymorph of Bayerite and Doylite |
| Gypsum | $CaSO_4$ | Sulphate mineral | Most common sulphate mineral |
| Hematite | $Fe_2O_3$ | Oxide mineral | Iron analogue of Corundum, Eskolaite, and Karelianite |
| Huntite | $CaMg_3(CO_3)_4$ | Carbonate mineral | |
| Hydroxyapatite | $Ca_{10}(PO_4)_6(OH)_2$ | Apatite group | Calcium end-member |
| Kaolinite | $Al_2Si_2O_5(OH)_4$ | Clay mineral | |
| Magnesite | $MgCO_3$ | Calcite group | Forms a complete solution series with Siderite |
| Nontronite | $(CaO_{0.5},Na)_{0.3}Fe^{3+}_2(Si,Al)_4O_{10}(OH)_2 \cdot nH_2O$ | Smectite clay | Iron (III) rich end-member |
| Phengite | $K(AlMg)_2(OH)_2(SiAl)_4O_{10}$ | Mica group | End-member close to muscovite |

| Mineral name | Formula | Mineral group/type | Comment |
|---|---|---|---|
| Pyrolusite | $MnO_2$ | Oxide mineral | Member of the Rutile group |
| Saponite | $Ca_{0.25}(Mg,Fe)_3((Si,Al)_4O_{10})(OH)_2 \cdot n(H_2O)$ | Smectite clay | |
| Strontianite | $SrCO_3$ | Aragonite group | |
| Whitlockite | $Ca_9(MgFe)(PO_4)_6PO_3OH$ | Phosphate group | |
| Witherite | $BaCO_3$ | Aragonite group | |

## 2.8 PPM pit flooding: Numerical groundwater flow model summary

Before giving a short review of the numerical model done by Meyer and Hansen (2010), it should be clearly noted that this dissertation document is a study of the hydrogeochemical processes involved in a pit flooding event and the modelling of these processes through the use of certain assumptions. To do a research project on a pit flooding event with geochemical modelling the main assumption of the research throughout the process will be that the PPM pit will flood and that the numerical model and its conclusions that the pit will flood over a given period of time is the only outcome. However at the end of the dissertation a discussion on alternative outcomes is done to evaluate the effects of the pit not flooding from a scientific philosophy point of view, on the outcome of the research done in this dissertation.

The PPM Pit flooding project was done with two modelling approaches. The first stage was the numerical flow modelling with the main objective to determine the influence of all parameters associated with surface water runoff, groundwater inflows, evaporation rates, rainfall, pit backfilling and abstraction from the reservoir on the flood curve versus time once mining stopped (Meyer & Hansen 2010). This section of the literature review is a summary and background on the numerical flow modelling of the pit flooding project from the initial study referenced from the specialist report compiled by Meyer and Hansen (2010).

The groundwater flow modelling for the project was conducted in seven stages (Meyer & Hansen 2010):

1. Scenario 1a: Steady state present day setup, water balance and flow conditions. This scenario was used to calibrate the flow model.

2. Scenario 1b: Transient state, 13 years life of mine simulation to obtain flow volumes and hydraulic heads.

3. Scenario 2a: Surface water runoff into the Tuschenkomst pit.

4. Scenario 2b: Influence of initial groundwater inflows on the Tuschenkomst pit flooding.

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5. Scenario 2c: No-backfill versus backfilling.

6. Scenario 2d: Various backfilled volumes and surface reductions.

7. Scenario 2e: Water supply from the flooded pit.

From these seven scenarios certain outcomes and results were obtained based on conservative approaches and assumptions. The Feflow 5.4 modelling package with a finite element triangular mesh was used to compute different scenarios with sensitivity analysis on certain parameters (Meyer & Hansen 2010).

Steady state calibration of the current system was followed by a transient state simulation of the pit dewatering during mining operations. Variable recharge under transient condition were also applied to the model inflows and thus dewatering of the pit had variable influence on the water levels per seasonal and monthly rainfall cycles as seen in Figure 2-11 with wave behaviour of the drawdown curves indicating the seasonal changes of the boreholes surrounding the pit.
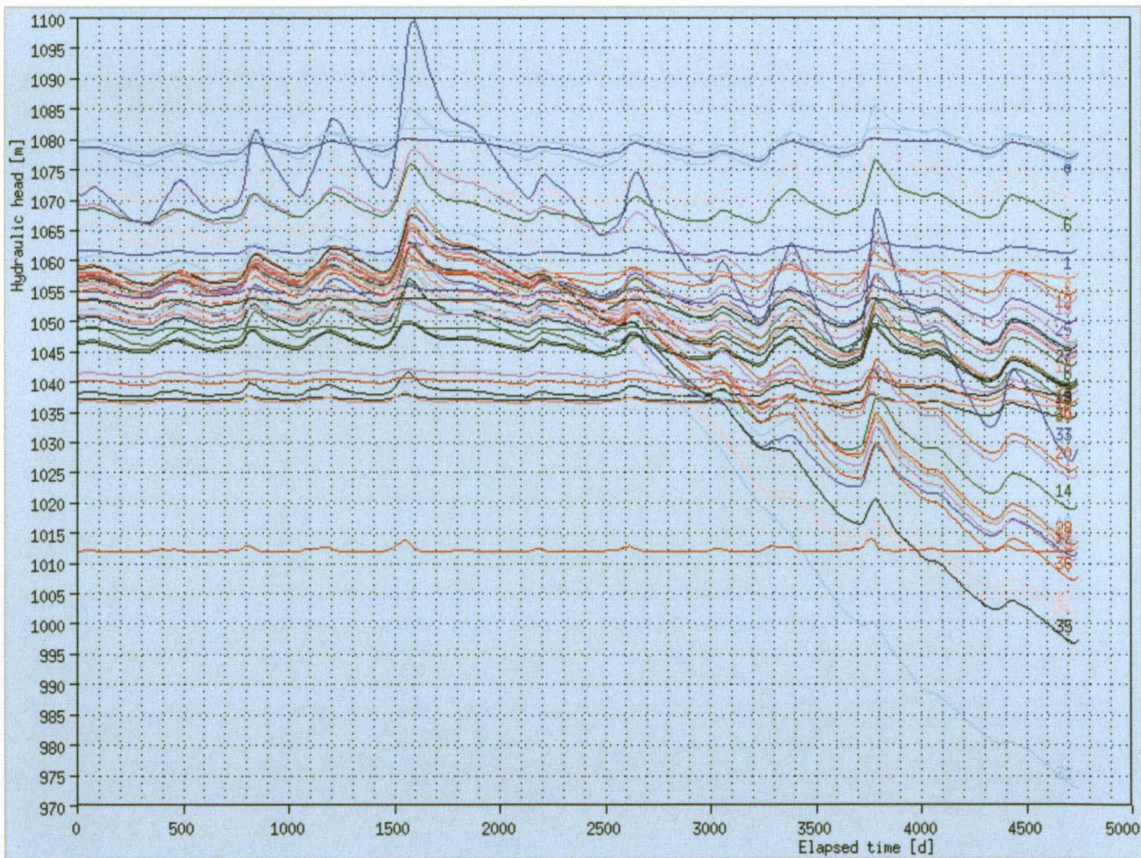


**Figure 2-11    Effect of dewatering during the operational period of the open pit mine on regional observation borehole water levels from Meyer & Hansen (2010)**

Scenario 2 simulated the pit flooding with various influences from groundwater, surface water and rainfall as inflows with evaporation as outflows. Surface water modelling of the sub-catchment shows that if normal inflow from natural drainage patterns are followed the average daily inflows will be 50 ℓ/s. If runoff from an added

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sub-catchment and drainage diversions is implemented the approximate average inflows from surface water will be 68 ℓ/s (Meyer & Hansen 2010). It should be noted that this average rate is based on annual distributions.

An analytical model was then used to evaluate the cumulative effect of surface water, groundwater and rainfall on the pit flooding curve. Scenario 2b showed that a maximum surface water inflow of 50 ℓ/s and a minimum inflow of 0 ℓ/s groundwater along with 2423 mm/y evaporation and an average rainfall directly on the pit of 47 ℓ/s will have the effect as shown in Figure 2-12 on the pit flooding with three sensitivity analyses on the groundwater volumes (30 ℓ/s, 60 ℓ/s and 120 ℓ/s). Groundwater inflow volumes are based on parameters calculated during pumping tests and the maximum inflows derived from the dewatering model (Meyer & Hansen 2010).

Scenario 2c and 2d evaluated the influence of various backfilling options. A sensitivity analysis similar to scenario 2b was done to evaluate the influence of various inflow rates and different volumes of backfilling. The outcome of this scenario is illustrated in Figure 2-13. Scenario 2e was simulated to evaluate the feasibility of the flooded pit as a water supply reservoir for the surrounding communities. This was found to be feasible under normal[1] conditions.

To conclude the following assumptions were made on the pit flooding curve as illustrated in Figure 2-14 (Meyer & Hansen 2010) with these outcomes serving as the assumptions made to accommodate the geochemical research of the post-closure options:

- Surface water runoff volumes equal to an average of 50 ℓ/s or 4 320 m³/d will serve as inflows from surface into the pit;

- An initial inflow from groundwater is 60 ℓ/s or 5 184 m3/d once mining has stopped with 0 ℓ/s as groundwater inflow once the pit water level reached a maximum flooded level;

- Backfilling of at least 23% of the available volume and a surface area reduction of 40% is recommended in order to decrease the needed water volume to flood the pit to 100 Mm³;

- The original groundwater level of 1060 mamsl will not be reached with pit flooding due to high evaporation rates; and

- Increased backfilling and reduction of evaporation will increase the level at which water levels rises to after mining has stopped.

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1 Normal conditions refer to average rainfall and runoff conditions (Meyer & Hansen 2010)
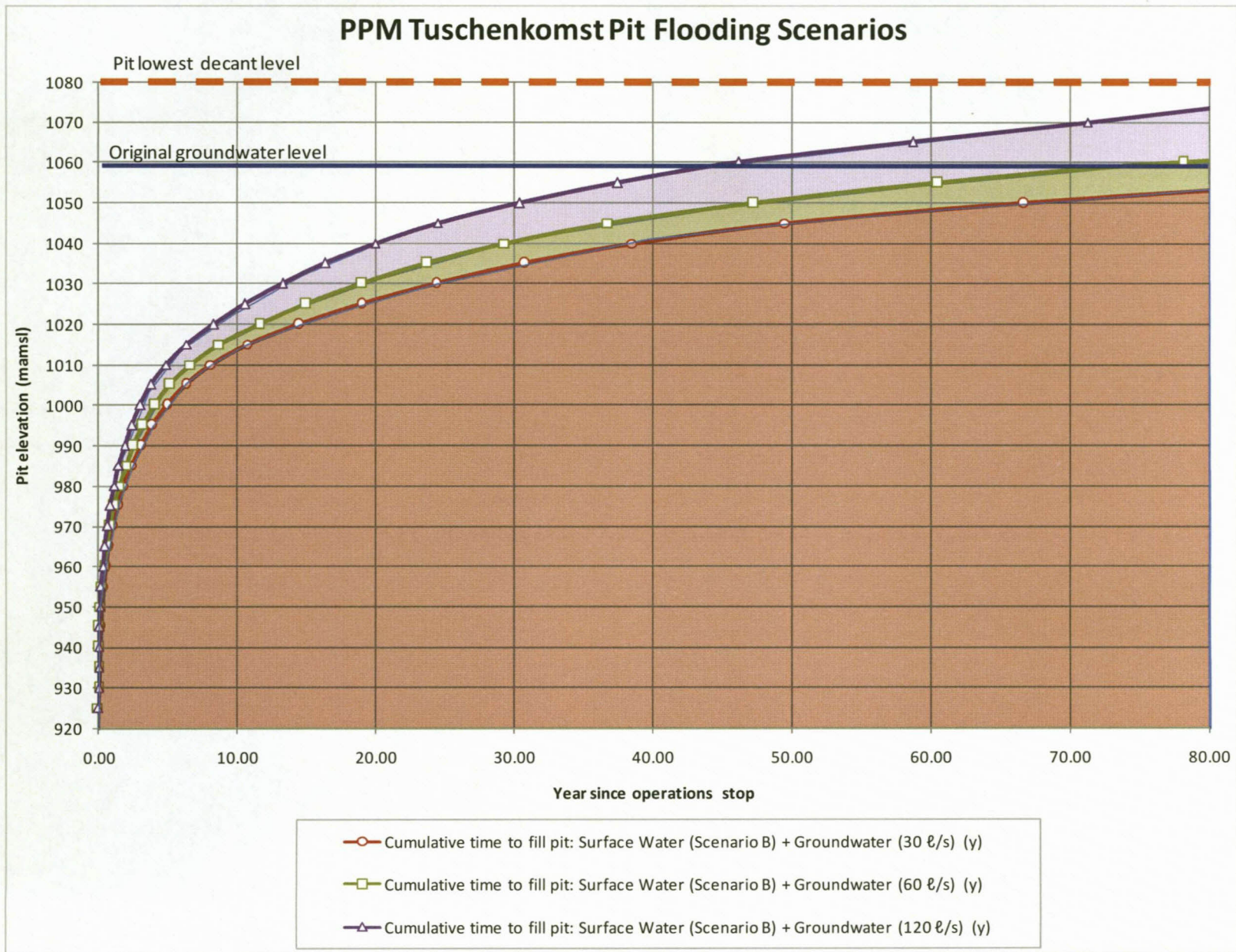
**Figure 2-12    Scenario 2b: Sensitivity analysis of groundwater inflow rates on the pit flooding (Meyer & Hansen 2010)**
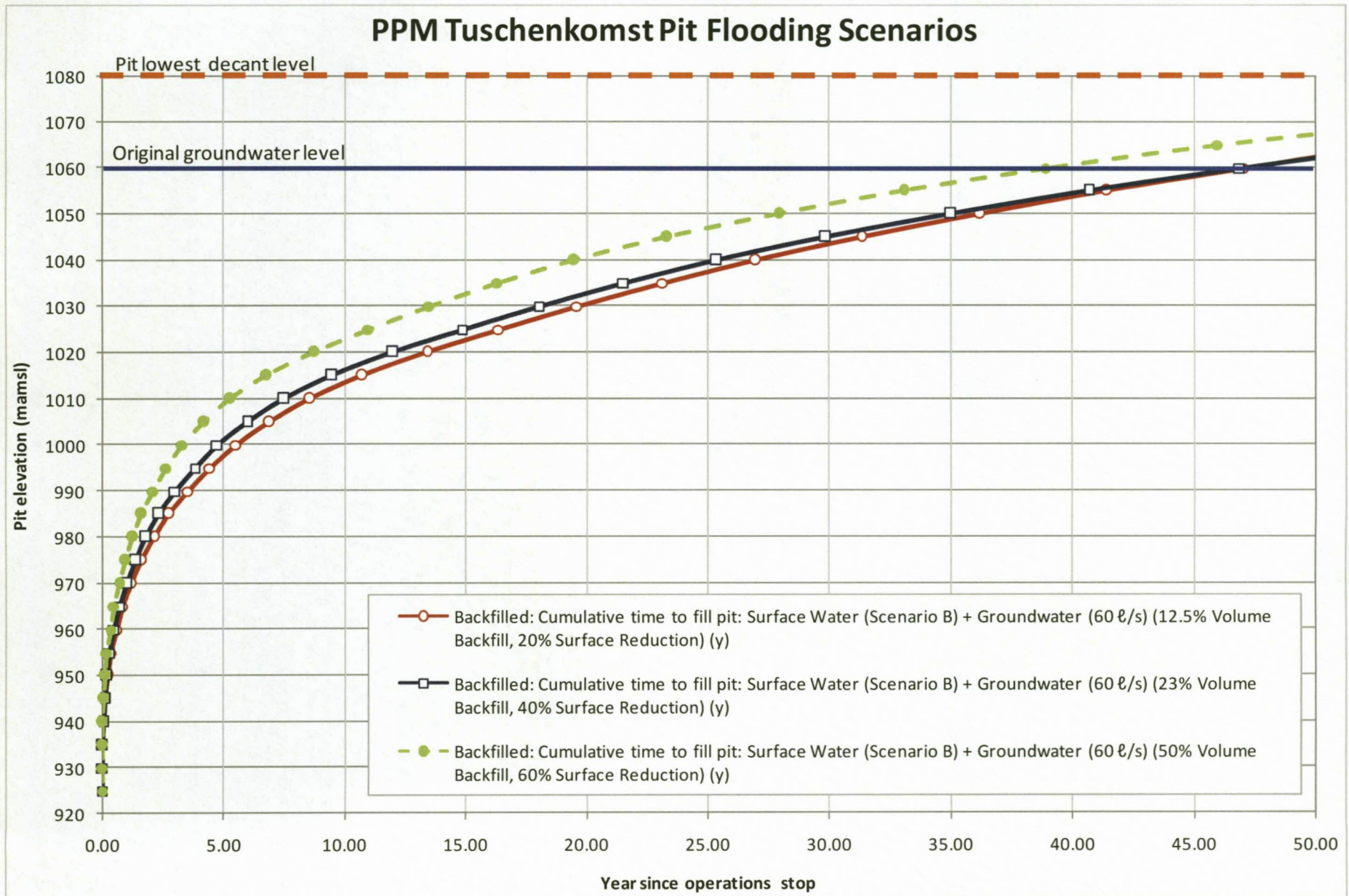
**Figure 2-13    Sensitivity analysis of various backfilled volumes and influence on the flooding curve (Meyer & Hansen 2010)**
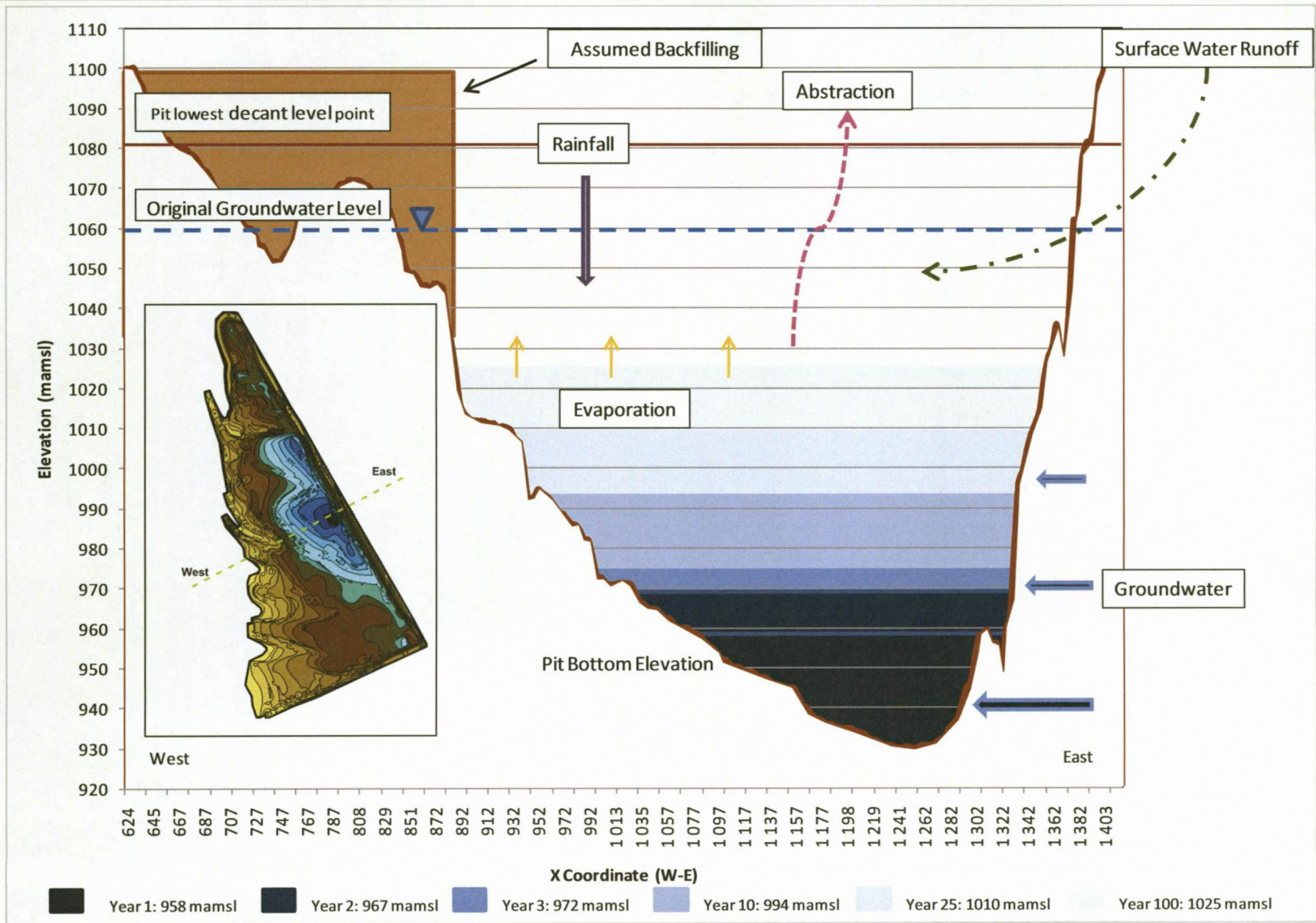
**Figure 2-14   Conceptual illustration of the hydrological impacts on the pit flooding as determined by the flow model (Meyer & Hansen 2010)**

## 2.9 Water Quality Standards

One of the research questions and main outcomes of the research project is to determine whether the expected water quality of the pit lake will be suitable for a variety of human, agricultural and wildlife use. To determine the suitability of the pit lake for water supply, the water quality results as modelled in the pit flooding hydrogeochemical models will be classed and evaluated against national standards. The next 4 sub-sections gives short descriptions of the methodology and terms of reference of each set of national standards and water quality guidelines used in section 6.2 of this dissertation.

### 2.9.1 Domestic and drinking water

The suitability of water use for human consumption with regards to microbiological, physical, aesthetic and chemical determinants that can be harmful and pose potential health risks is based on the standards as set out in the SANS 241:2011 part 1 and 2. These standards were developed by the South African Bureau of Standards (SABS) to have clear guidelines on water quality limits for human use and drinking water, and are referenced in the National Water Services Act of 1997 as a legislative guideline and standard.

Each determinant listed in this standard document (SABS 2011a) has a target limit of which if a water quality complies with these limits the water is suitable for lifetime use and consumption by humans. The water quality guidelines are used by the Department of Water Affairs (DWA) in conjunction with the Department of Mineral Resources (DMR) to recommend and implement target water quality ranges and monitoring programs at various mining and industrial sites. In both SANS 241:2011 part 1 and 2 it is made clear that for water quality testing and classification of the water for its suitability for human consumption, the laboratory and the testing methods must comply with SANAS standards for accredited laboratories.

If the water quality concentrations of water intended for human use do not fall within the target range, the risk involved for the water can be classified into 5 risk categories each with its unique area of risk. These risk categories are listed and explained in Table 2-3 (SABS 2011a; SABS 2011b).

**Table 2-3    Description of risk categories as set out in SANS 241 (SABS 2011a)**

| Risk category | Description |
|---|---|
| Acute health 1 | Routinely quantifiable determinant that poses an immediate unacceptable health risk if consumed with water at concentration values exceeding the numerical limits specified in SANS 241 |
| Acute health 2 | Determinant that is presently not easily quantifiable and lacks information pertaining to viability and human infectivity which, however, does pose immediate unacceptable health risks if consumed with water at concentration values exceeding the numerical limits specified in SANS 241 |
| Aesthetic | Determinant that taints water with respect to taste, odour and colour and that does not pose an unacceptable health risk if present at concentration values exceeding the numerical limits specified in SANS 241 |
| Chronic health | Determinant that poses an unacceptable health risk if ingested over an extended period if present at concentration values exceeding the numerical limits specified in SANS 241 |
| Operational | Determinant that is essential for assessing the efficient operation of treatment systems and risks to infrastructure |

Some determinants were left out in SANS 241:2011 and in the cases where determinants were in detectible values but not dealt with in the newest standards, the SANS 241:2005 edition was used.

## 2.9.2   Irrigation watering

The DWA released a range of documents with each volume describing and listing a range of chemical constituents with Target Water Quality Range (TWQR) for each intended application.  Volume 4: Agricultural Water Use: Irrigation (DWAF 1996b) gives a TWQR for water to be used for irrigational purposes as well as a maximum allowable level and a concentration of which above this level the water will not be suitable for irrigational purposes.  If water is not suitable for irrigation and above the maximum allowable range, either a low crop quality or yield will be experienced or operational infrastructure used in irrigation management will be damaged over time.

The TWQR and two other categories are explained below in Table 2-4 (DWAF 1996b).

**Table 2-4    Water quality categories for irrigation water use (DWAF 1996b)**

| Water quality category | Description |
|---|---|
| TWQR | The No Effect Range, designated in the South African Water Quality Guidelines as the Target Water Quality Range, is highlighted. It must be remembered that the Target Water Quality Range describes essentially what is considered good or ideal water quality and therefore water quality outside of this range may, under certain circumstances, still be acceptable |
| Maximum acceptable range | Maximum acceptable concentration range to be used in most crop types |
| Above maximum acceptable range | Acceptable for irrigation only over the short term on a site specific basis and can either yield low quality and volume crops or damage irrigation management tools |

The above three criterions were used to classify the final simulated lake water quality in section 6.2 for irrigational use.  The overall agricultural activity in the region of the

proposed pit lake is small, self-sustained farming for household food production, thus the maximum acceptable range was used in this dissertation as a suitable level of concentration as the water will only be used for small productions and not large, profitable food crops. Commercial farming in the region is restricted to the banks of the Crocodile River with rural communities only relying on self-sustainability.

### 2.9.3 Livestock watering

The South African Water Quality Guidelines for Livestock Watering Use is essentially a user needs specification of the quality of water required for different livestock production systems (DWAF 1996d). It provides information to make judgements on the fitness of water for livestock watering purposes, primarily for consumption by livestock, but also for water distribution systems. The guidelines are applicable to any water that is used for livestock watering purposes, irrespective of its source (municipal supply, borehole, river, etc.) or whether or not it has been treated (DWAF 1996d).

The water quality guidelines and TWQR is done by means of classifying the intended use of the water and then the effects of each chemical constituent are discussed based on various expected impacts as shown in Table 2-5.

**Table 2-5      Livestock water use characterisation (DWAF 1996d)**

| Characterised use | Effects |
|---|---|
| Livestock consumption norms | Toxicological Effects |
|  | Palatability Effects |
| Livestock watering system norms | Clogging |
|  | Corrosion |
|  | Encrustation |
|  | Scaling |
|  | Sediment |
| Livestock product quality norms | Consumer Health Hazards |
|  | Product Quality |

The livestock water quality guidelines as set out by DWA was used in this dissertation to determine the expected and modelled pit lake quality for the use in livestock water, as well as the suitability for wildlife consumption by antelopes and other animals.

### 2.9.4 Aquatic ecosystems

As directly quoted from The South African Water Quality Guidelines for Aquatic Ecosystems (DWAF 1996c), "The South African Water Quality Guidelines for Aquatic Ecosystems is essentially a specification of:

- The surface water quality required to protect fresh water aquatic ecosystems (the guidelines do not deal with marine and estuarine ecosystems);

- Quantitative and qualitative criteria for chronic and acute toxic effects for toxic constituents;

- Quantitative and qualitative criteria to protect ecosystem structure and functioning, for non-toxic constituents and system variables;

- Quantitative and qualitative criteria to protect aquatic ecosystems against changes in trophic status in the case of nutrients; and

- Modifications that can be made to water quality criteria on a site-specific basis, whilst still providing the same level of protection as the original criteria."

This above scope allows the DWA to give three water quality ranges or categories in which various effects on ecosystems can be the outcome. However as stated in the document, the organisms making up an ecosystem are highly adaptable to various environments and thus species can live and adapt in different water types. The three water quality ranges are given and explained in Table 2-6. These ranges were used to classify the modelled pit lake water quality.

**Table 2-6     Water quality ranges for aquatic ecosystems (DWAF 1996c)**

| Water quality range | Description and effects |
|---|---|
| TWQR | The Target Water Quality Range (TWQR) is not a water quality criterion but is rather a management objective which has been derived from quantitative and qualitative criteria. This is the range of concentrations or levels within which no measurable adverse effects are expected on the health of aquatic ecosystems, and should therefore ensure their protection. These ranges assume life-long exposure. As a matter of policy the DWAF will strive to protect South Africa's water resources by maintaining water quality within the TWQR. |
| Chronic Effect Value (CEV) | The Chronic Effect Value (CEV), is defined as that concentration or level of a constituent at which there is expected to be a significant probability of measurable chronic effects to up to 5 % of the species in the aquatic community. If such chronic effects persist for some time and/or occur frequently, they can lead to the eventual death of individuals and disappearance of sensitive species from aquatic ecosystems. This can have considerable negative consequences for the health of aquatic ecosystems, since all components of aquatic ecosystems are interdependent. It is important to note that: - Even if the concentration of a constituent is always below the CEV there is still a significant risk of chronic effects to a small percentage of the most sensitive organisms; - If the CEV is exceeded the chronic effects will be more widespread, and the likelihood of possible acute effects will increase with increasing concentration, frequency and duration of exceedance of the CEV. |
| Acute Effect Value (AEV) | The Acute Effect Value (AEV) is defined as that concentration or level of a constituent above which there is expected to be a significant probability of acute toxic effects to up to 5 % of the species in the aquatic community. If such acute effects persist for even a short while, or occur at too high a frequency, they can quickly cause the death and disappearance of sensitive species or communities from aquatic ecosystems. This can have considerable negative consequences for the health of aquatic ecosystems, even over a short period. |

### 2.9.5 Recreational water use

The South African Water Quality Guidelines for Recreational Use (DWAF 1996a), is a set of criterion and quality ranges intended to be used for classification of water inland water bodies that will be used for a wide variety of recreational activities. The PPM pit lake is proposed to be used for a variety of full contact recreational activities including scuba diving. The risks involved in recreational water activities is listed and described in Table 2-7 (DWAF 1996a). Various chemical irritants, turbidity, obstacles and plant growth can lead to these risks, however the criteria to classify water for suitability to recreation use addresses TWQR as well as various other classes to identify the suitability of water bodies like a pit lake.

**Table 2-7    Recreational water use risks and descriptions (DWAF 1996a)**

| Risk | Description and examples |
|---|---|
| Human health | Water borne diseases (Bilharzia) |
| | Skin and ear infections |
| | Gastro enteric diseases |
| | Carcinogenic risk |
| Human safety | Poor visibility (Diving and water sport injuries due to obstruction not seen) |
| | Profuse plant growth (Entanglement from over grown vegetation) |
| Aesthetics | Bad odours (Water stinks) |
| | Discolouring and staining of clothes and equipment |
| | Objectionable floating matter (Plastic bags and bottles) |
| | Nuisance plants |
| Damage to equipment | Poor visibility (Damage to equipment due to bumping into unseen obstacles) |

The criterion set out in the above discussed document is used in this dissertation to evaluate the feasibility of using the pit lake for recreational use.

## 2.10 Concluding summary: Chapter 2

Chapter 2 reviewed and compiled a wide base of various data and knowledge sources with relevant national and international references. All geological, mineralogical, hydrochemical, geochemical, geohydrological, and hydrological data relevant to the case study and research objectives were summarised and will feed into the subsequent chapters with knowledge gained being applied.

Chapter 2 served as a desktop study to gain knowledge of various influences and factors to consider in the research project and hydrogeochemical models. This chapter has illustrated one of the steps in compiling a database of knowledge and analogue data as will also be discussed in the systems thinking and modelling template.

Chapter 3 lists the main data sets and sources with short statistical analysis and data discussions without any in depth interpretations.
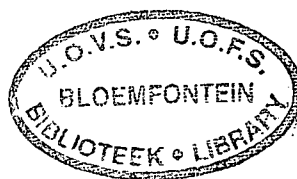
# CHAPTER 3:

## 3 PROJECT DATA AND METHODOLOGY

Various climate, groundwater, surface water and project data sets where used in the case study project and geochemical pit flooding model. This chapter gives sampling and collection methodologies, sources and a description of each data set. No in depth interpretation of the data is given as this is done in Chapter 4.

### 3.1 Data sets and sources

The following data sets with the sources also listed were used as indicated in Table 3-1. All data sets are historical data up to June 2012, which was the cut-off date for this dissertation, thus all historical data end in June 2012 or the closest available date to this.

Table 3-1    List of data sets and sources

| Data set | Source | Description |
|---|---|---|
| Groundwater monitoring data | Client monitoring database (From AGES (Pty) Ltd) | Macro- and Micro chemistry data and Water levels from June 2008 to June 2012 |
| Surface water monitoring data | Client monitoring database (From AGES (Pty) Ltd) | Macro- and Micro chemistry data from June 2008 to June 2012 |
| Rainfall data | WRIMS Database | Rainfall data from 1903 to 2011 for weather station 0548280W Saulspoort (Van Coller et al. 2012) |
| Temperature data | South African Weather Services | Temperature data for weather station 0548375A4 Pilanesberg (Van Coller et al. 2012) |
| Dewatering and pumping rates | Client monitoring database (From AGES (Pty) Ltd) | Monitoring data of dewatering boreholes pumping rates and water levels from June 2008 up to June 2012 |
| Historical reports | Client and AGES (Pty) Ltd | EMP, EIA, BFS and Geohydrological Specialist reports and models |
| Historical hydrocensus data | AGES (Pty) Ltd | Hydrocensus data from 2007 up to 2011 on local and regional scale with chemistry and water level data of surface water and groundwater points |
| Core samples | Client | Samples of overburden, waste layers and ore body from geological exploration of client |
| TCLP and ABA data | AGES (Pty) Ltd | Laboratory results (Water Lab (Pty) Ltd) |
| XRD and XRF data | AGES (Pty) Ltd | Laboratory results (Water Lab (Pty) Ltd) |

| Data set | Source | Description |
|----------|--------|-------------|
| Geological data and maps | Geological survey | 1:250 000 Geological map sheets 2526 Rustenburg and 2426 Thabazimbi |
| Topographical GIS data | Chief Directorate of Surveys and Mapping | 1:50 000 map sheets and data for 2526 and 2426 mapping areas |
| Digital terrain model | Digital data (AGES (Pty) Ltd) | DTM data (XYZ data) for 20m contour intervals |
| Pit DTM | Client | Detailed XYZ data of the open pit area |
| Literature data and analogue values | Various sources referenced accordingly in text | Literature reviews and analogue values were used in some instances. If used, the value was referenced according to the Harvard method of literature reference. |

## 3.2 Methodology

### 3.2.1 Hydrocensus and monitoring data

The author of this dissertation and study was involved with hydrocensus surveys and on a time-to-time basis with monitoring runs during the duration of the PPM Geohydrological studies.

All water samples were taken in accordance with the Department of Water Affairs (DWA), Department of Health (DoH) and Water Research Commission (WRC) "Quality of Domestic Water Supplies: Volume 2: Sampling Guide" (2000).

Volumetric sample bottles (1 Litre PTFE bottles) were used to collect the water samples at each site. Groundwater levels, borehole depth and borehole status were noted. Bailing equipment was used to purge the boreholes and take a representative sample, if the borehole was not equipped with a pump. Approximately two to three times the volume of the water contained within the borehole was purged before a water sample was taken. In most instances during monitoring runs purging of relevant boreholes in accordance with the monitoring protocol set out for the mine was done using a mobile pumping system.

Groundwater samples were stored and cooled in a cooler box, before being submitted to Clean Stream Laboratories now Aquatico (Pty) Ltd in Pretoria, South Africa for analysis.

### 3.2.2 Dewatering and pumping rates

Dewatering volumes and rates were obtained from numerical groundwater flow models conducted by AGES (Pty) Ltd during the various stages of studies conducted for PPM. Numerical groundwater flow models were constructed and simulated using

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monitoring, hydrocensus, drilling, aquifer test and other field data to predict both the dewatering and flooding volumes needed in the operational and post-closure phases of the project. Feflow was used as the software package to conduct this study.

### 3.2.3   TCLP, NAG and ABA data

Two samples from the neighbouring farm from the Merensky and UG2 platinum containing Reefs were sent to the Water Lab (Pty) Ltd for TCLP, NAG and ABA tests.

## 3.3   Data description

### 3.3.1   Rainfall data

Data from rainfall station 0548280W Saulspoort Hospital (Figure 3-1) listed in Appendix A: Climate Data was used to analyse a 108 year period (1904 to 2012) to evaluate rainfall trends and to determine periods of flood and drought.

General statistical distributions and values were calculated on the data set as listed in Table 3-2. The Mean Annual Precipitation (MAP) for the area is 628 mm/a. The data set was also used to calculate dry and wet cycles[2] for one in twenty and one in fifty year events.

### 3.3.2   Temperature data

Temperature data for the Pilanesberg stations was sourced from the South African Weather Bureau for the period from 2005 to 2010. The temperature data is listed in Appendix A: Climate Data.

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2 A dry cycle or dry year (i.e. drought) is defined as the lower 5% of the annual total rainfall, a wet cycle or wet year (i.e. floods) is defined as the upper 5% of the annual total rainfall.
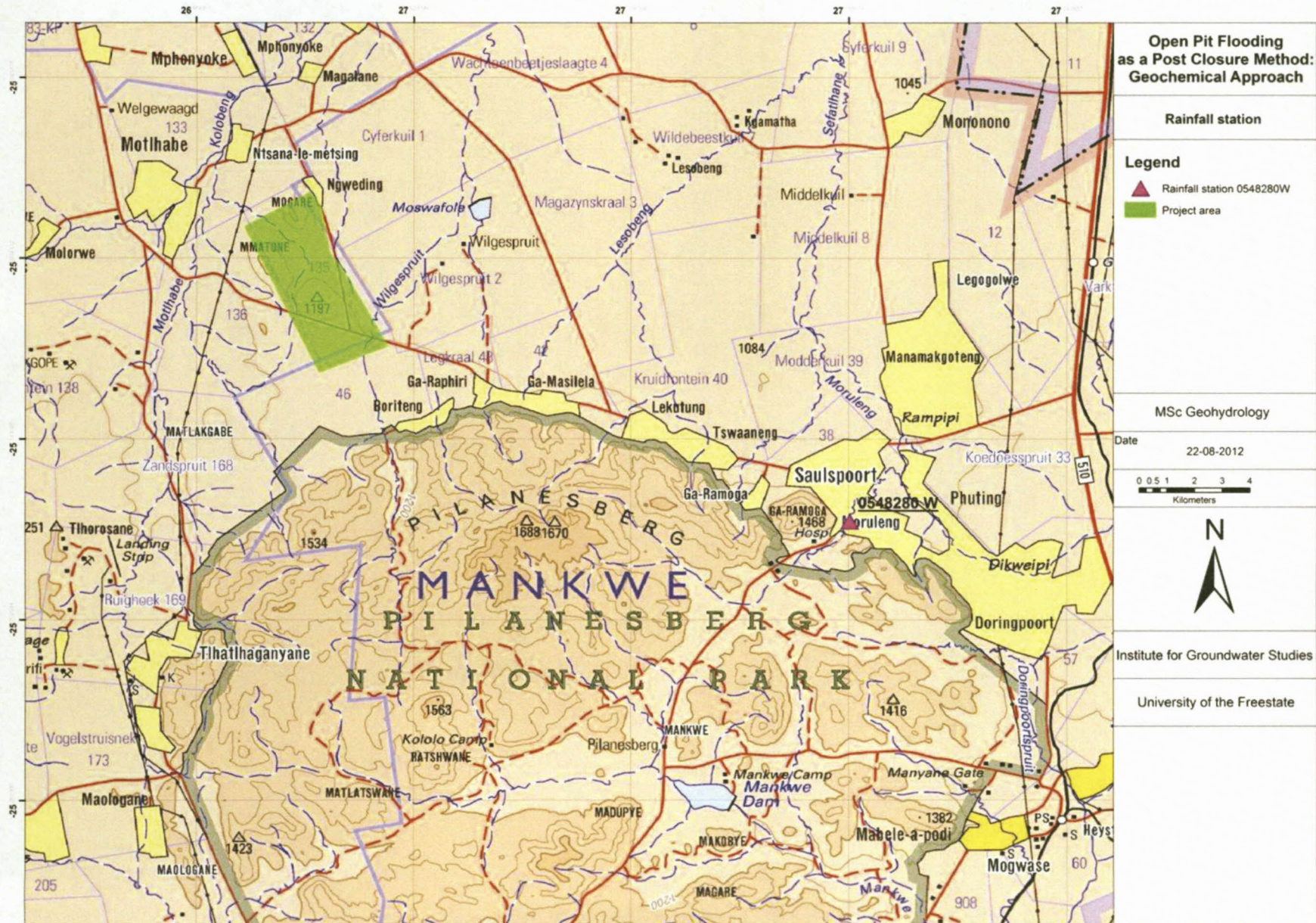
**Figure 3-1    Map showing the location of the Saulspoort Hospital rainfall station**

**Table 3-2    Rainfall statistics**

| Parameter | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Total Annual Rainfall |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average | 127.6 | 90.8 | 84.9 | 44.5 | 15.9 | 3.2 | 4.0 | 5.4 | 11.0 | 50.5 | 76.0 | 113.8 | 627.5 |
| Average - Distribution | 127.6 | 89.5 | 86.1 | 43.8 | 15.8 | 3.2 | 3.9 | 5.4 | 10.9 | 50.4 | 76.9 | 113.8 | 630.6 |
| Maximum | 301.2 | 386.9 | 346.4 | 195.2 | 114.9 | 32.5 | 82.1 | 91.0 | 116.0 | 142.1 | 201.5 | 283.9 | 1043.0 |
| Minimum | 23.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 15.5 | 176.0 |
| Std Deviation | 57.2 | 58.3 | 56.8 | 35.9 | 19.8 | 6.5 | 12.5 | 12.9 | 19.1 | 30.6 | 39.7 | 54.1 | 165.4 |
| 1:20 year flood | 217.5 | 197.1 | 179.1 | 111.4 | 51.6 | 18.8 | 24.9 | 28.0 | 55.8 | 101.4 | 152.8 | 197.3 | 891.0 |
| 50th | 125.2 | 81.7 | 80.6 | 38.8 | 9.3 | 0.0 | 0.0 | 0.0 | 3.4 | 47.8 | 70.5 | 112.4 | 627.5 |
| 1:20 year drought | 42.7 | 18.5 | 13.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 6.6 | 21.5 | 42.1 | 328.0 |
| 1:50 year flood | 275.7 | 237.1 | 225.4 | 154.2 | 62.0 | 26.4 | 56.6 | 39.5 | 70.3 | 113.6 | 185.5 | 275.8 | 968.8 |
| 1:50 year drought | 31.1 | 10.2 | 8.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.4 | 3.7 | 31.0 | 239.2 |

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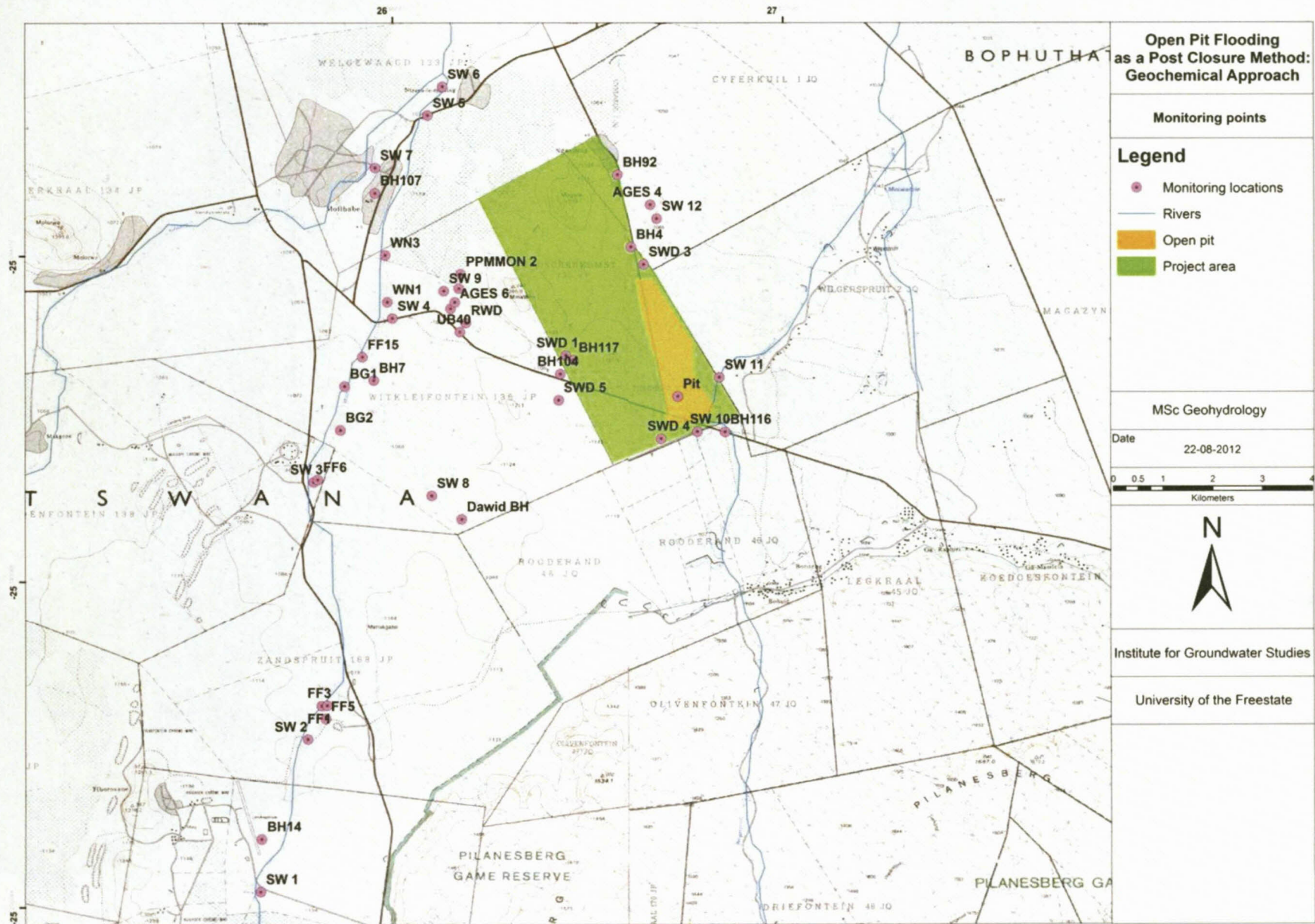
**Figure 3-2    Map showing the project monitoring locations**

### 3.3.3   Monitoring data – Water quality

A monitoring protocol and program has been implemented at the PPM mine since 2008 to evaluate and monitor water levels and water quality. The data set was made available for the study and is used in the case study and hydrogeochemical model.

Monthly, quarterly and bi-annual monitoring of groundwater, surface water, storm water and pit water have been sampled and monitored since 2008 with some data gaps due to drought events, seasonal changes and borehole destruction or theft. The monitoring locations are listed in Appendix C: Monitoring data. Upstream and downstream locations were developed and chosen from historical hydrocensus and drilling to include in the monitoring protocol and data set (Figure 3-2). Some of these boreholes and surface water points will be used to evaluate the regional water quality as well as to include in the hydrogeochemical model.

During data processing and calculations of both groundwater and surface water chemical data, data points at concentrations below the laboratory detection limit was substituted with values half of the detection limit value to complete the data set. The above mentioned processing assumption was made for statistical and modelling purposes due to the fact that the chemical species below detection can still be present in very small quantities which can still cause reactions to occur (Meyer & Hansen 2010). The data sets include parameters that do not match the input values needed for Geochemist Workbench® (GWB) and thus $NO_3$ as N, $NO_2$ as N, $NH_4$ as N and Ortho-$PO_4$ as P was converted to the pure ion form. Laboratory results also report Si concentrations that were converted to $SiO_2$ for aqueous geochemical modelling and analysis reasons.

The general groundwater ion distribution attributes the overall groundwater to be a Mg-$HCO_3$ water type with the exception of BH 7 which falls in the Na-Cl facies as shown on the piper diagram in Figure 3-3.

The region's groundwater has an average pH of 7.8 with a maximum of 8.5 and a minimum pH of 7.2. TDS and EC averages at 545 mg/ℓ and 103 mS/m respectively for the groundwater data set. A calculated charge imbalance error for the most recent lab results shows that some of the samples have errors of more than 15%. A charge imbalance thus exists which could be due to lab errors. Groundwater data to be used for the hydrogeochemical model were therefore chosen from acceptable error ranges and selected with other parameters and statistics in mind. A summary of the groundwater monitoring sample statistics is shown in Table 3-3.
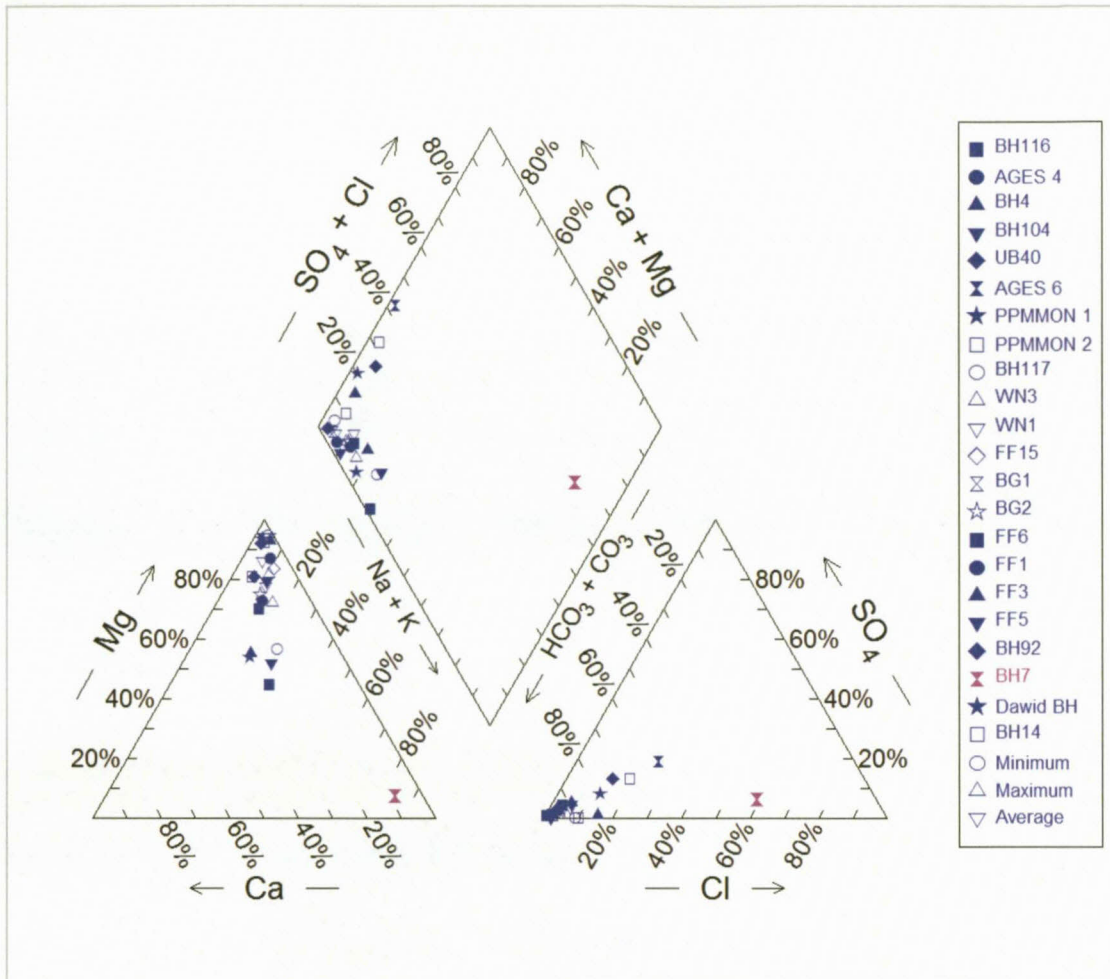
**Figure 3-3**   **Piper diagram showing data points from all groundwater monitoring boreholes in the study area**

**Table 3-3**   **Summary of the groundwater laboratory result statistics**

| Parameter | Unit | Minimum | Maximum | Average |
|-----------|------|---------|---------|---------|
| $HCO_3$ | mg/ℓ | 103.8 | 4989.6 | 727.3 |
| Ca | mg/ℓ | 2.6 | 69.5 | 25.8 |
| Cl | mg/ℓ | 6.1 | 102.8 | 28.4 |
| F | mg/ℓ | 0.1 | 3.5 | 1.2 |
| Mg | mg/ℓ | 5.1 | 260.6 | 114.3 |
| K | mg/ℓ | 0.1 | 4.0 | 1.1 |
| Na | mg/ℓ | 4.2 | 110.1 | 31.9 |
| $SO_4$ | mg/ℓ | 0.1 | 96.6 | 22.0 |
| $NO_3$ | mg/ℓ | 1.2 | 240.3 | 23.9 |
| $NO_2$ | mg/ℓ | - | 0.213 | 0.017 |
| $NH_4$ | mg/ℓ | - | 1.104 | 0.104 |
| $PO_4$ | mg/ℓ | - | 0.438 | 0.078 |
| $SiO_2$ | mg/ℓ | - | 8.471 | 0.476 |
| Al | mg/ℓ | 0.003 | 0.030 | 0.004 |

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| Parameter | Unit | Minimum | Maximum | Average |
|---|---|---|---|---|
| As | mg/ℓ | - | 0.013 | 0.002 |
| Co | mg/ℓ | - | 0.002 | - |
| Cu | mg/ℓ | 0.001 | 0.028 | 0.005 |
| Fe | mg/ℓ | 0.003 | 0.194 | 0.013 |
| Pb | mg/ℓ | 0.001 | 0.015 | 0.003 |
| Mn | mg/ℓ | 0.001 | 0.418 | 0.026 |
| Ni | mg/ℓ | 0.001 | 0.015 | 0.002 |
| Se | mg/ℓ | - | 0.015 | 0.001 |
| Zn | mg/ℓ | - | 0.039 | 0.008 |
| Hg | mg/ℓ | - | 0.001 | 0.000 |
| Ba | mg/ℓ | - | 0.050 | 0.005 |
| Sr | mg/ℓ | - | 2.838 | 0.134 |
| pH | | 7.2 | 8.5 | 7.8 |
| EC | mS/m | 38.1 | 188.2 | 103.2 |
| TDS | mg/ℓ | 192.0 | 1024.0 | 545.0 |
| TSS | mg/ℓ | - | 913.0 | 76.3 |
| Total Hard | mg/ℓ | - | 1131.0 | 477.6 |
| $CO_3$ | mg/ℓ | 0.3 | 13.9 | 4.5 |

**Table 3-4    Summary of the surface water laboratory result statistics**

| Parameter | Unit | Minimum | Maximum | Average | St. Dev. | Coeff. Var |
|---|---|---|---|---|---|---|
| $HCO_3$ | mg/ℓ | 18.400 | 281.600 | 86.285 | 66.2 | 77% |
| Ca | mg/ℓ | 1.658 | 61.464 | 22.296 | 20.2 | 91% |
| Cl | mg/ℓ | 0.700 | 83.800 | 11.915 | 22.3 | 188% |
| F | mg/ℓ | 0.092 | 3.326 | 1.213 | 1.1 | 88% |
| Mg | mg/ℓ | 2.770 | 81.613 | 22.290 | 27.7 | 124% |
| K | mg/ℓ | 0.900 | 10.810 | 5.331 | 3.4 | 64% |
| Na | mg/ℓ | 1.220 | 96.940 | 25.396 | 31.8 | 125% |
| $SO_4$ | mg/ℓ | 0.450 | 212.080 | 36.093 | 58.3 | 162% |
| $NO_3$ | mg/ℓ | 0.735 | 362.440 | 76.696 | 140.5 | 183% |
| $NO_2$ | mg/ℓ | 0.000 | 2.785 | 0.801 | 1.3 | 167% |
| $NH_4$ | mg/ℓ | 0.010 | 1.169 | 0.593 | 0.5 | 83% |
| $PO_4$ | mg/ℓ | 0.038 | 0.038 | 0.038 | 0.0 | 0% |
| $SiO_2$ | mg/ℓ | 2.930 | 3.382 | 3.156 | 0.3 | 10% |
| Al | mg/ℓ | 0.003 | 4.192 | 0.593 | 1.3 | 214% |
| As | mg/ℓ | 0.010 | 0.010 | 0.010 | 0.0 | 0% |
| Co | mg/ℓ | 0.001 | 0.002 | 0.001 | 0.0 | 43% |
| Cu | mg/ℓ | 0.001 | 0.001 | 0.001 | 0.0 | 0% |
| Fe | mg/ℓ | 0.003 | 9.881 | 1.022 | 2.7 | 267% |
| Pb | mg/ℓ | 0.001 | 0.005 | 0.004 | 0.0 | 74% |
| Mn | mg/ℓ | 0.001 | 0.061 | 0.009 | 0.0 | 217% |

| Parameter | Unit | Minimum | Maximum | Average | St. Dev. | Coeff. Var |
|---|---|---|---|---|---|---|
| Ni | mg/ℓ | 0.002 | 0.002 | 0.002 | 0.0 | 0% |
| Se | mg/ℓ | 0.010 | 0.010 | 0.010 | 0.0 | 0% |
| Zn | mg/ℓ | 0.002 | 0.005 | 0.004 | 0.0 | 42% |
| Hg | mg/ℓ | 0.001 | 0.001 | 0.001 | 0.0 | 0% |
| Ba | mg/ℓ | 0.146 | 0.152 | 0.149 | 0.0 | 3% |
| Sr | mg/ℓ | 0.506 | 1.014 | 0.760 | 0.4 | 47% |
| pH | | 7.410 | 8.590 | 7.979 | 0.3 | 4% |
| EC | mS/m | 9.010 | 141.100 | 42.805 | 45.7 | 107% |
| TDS | mg/ℓ | 25.000 | 575.000 | 192.846 | 186.4 | 97% |
| TSS | mg/ℓ | 0.500 | 1826.000 | 292.208 | 500.3 | 171% |
| Total Hard | mg/ℓ | 16.000 | 478.000 | 147.462 | 163.1 | 111% |
| $CO_3$ | mg/ℓ | 0.100 | 4.900 | 1.154 | 1.4 | 125% |

### 3.3.4 Monitoring data – Water levels

Monitoring data is listed in Appendix C: Monitoring data with statistical limits and distributions shown in Table 3-5 and Table 3-6.

During monitoring runs water levels from dewatering, water supply, and static boreholes were taken to evaluate any impacts on the regional groundwater table. Water levels from boreholes not used for water supply or dewatering purposes with static water levels are shown in Table 3-5. The average static water level over the monitoring period in the region is 24.2 mbgl with the largest variation in water levels being 55% in borehole AGES 6.

The average water level in pumped boreholes over the monitoring period was 19.5 mbgl with the largest variation in water level measured in borehole WN 3 with 33% being the coefficient of variance. The shallower average can be described to the large variations in water levels during various abstraction periods.

Table 3-5    Statistical summary of the monitoring borehole water levels (mbgl)

| Date | BH4 | AGES 4 | BH116 | BH92 | BHWK80 | Dawid BH | BH104 | AGES 6 | BH7 | BH107 | UB40 | BH14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Baseline | -30.06 | -27.60 | -30.40 | -33.15 | -25.70 | -25.46 | -40.60 | -28.48 | -9.50 | -11.05 | -35.99 | -22.09 |
| Count | 49.00 | 51.00 | 53.00 | 52.00 | 18.00 | 17.00 | 3.00 | 45.00 | 49.00 | 51.00 | 41.00 | 48.00 |
| Minimum | -22.42 | -27.19 | -28.02 | -32.66 | -25.17 | -25.46 | -40.56 | -5.63 | -8.72 | -10.38 | -14.34 | -19.10 |
| Maximum | -30.12 | -27.73 | -32.51 | -35.72 | -26.32 | -26.31 | -40.63 | -31.86 | -11.22 | -12.62 | -35.99 | -22.58 |
| Average | -27.67 | -27.55 | -30.42 | -33.64 | -25.48 | -25.80 | -40.60 | -14.77 | -10.35 | -11.69 | -20.80 | -21.64 |
| St. Dev. | 3.15 | 0.15 | 1.67 | 0.43 | 0.30 | 0.27 | 0.04 | 7.81 | 0.67 | 0.57 | 4.83 | 1.02 |
| Coeff. Var. | 11% | 1% | 5% | 1% | 1% | 1% | 0% | 53% | 7% | 5% | 23% | 5% |

Table 3-6    Statistical summary of the abstraction borehole water levels (mbgl)

| Site ID | WN3 | WN1 | FF15 | BG1 | BG2 | FF6 | FF1 | FF3 | FF5 | BH117 |
|---|---|---|---|---|---|---|---|---|---|---|
| Start of abstraction | 29-Aug-08 | 29-Aug-08 | 08-Jul-08 | 08-Jul-08 | 29-Aug-08 | 13-Aug-08 | 17-Oct-08 | 03-Oct-08 | 17-Oct-08 | 30-Sep-08 |
| Baseline | -13.96 | -16.38 | -9.43 | -9.46 | -18.02 | -12.60 | -19.10 | -18.10 | -18.20 | -38.33 |
| WL Constraint | -31.00 | -58.00 | -50.00 | -35.00 | -37.00 | -31.00 | -44.00 | -46.00 | -50.00 | -60.00 |
| Count | 56.00 | 62.00 | 51.00 | 52.00 | 58.00 | 55.00 | 59.00 | 59.00 | 57.00 | 36.00 |
| Minimum | -11.94 | -10.81 | -10.35 | -9.77 | -10.70 | -10.20 | -17.35 | -16.57 | -11.00 | -22.21 |
| Maximum | -29.63 | -21.85 | -16.10 | -16.80 | -21.21 | -20.13 | -36.77 | -50.50 | -43.02 | -39.70 |
| Average | -18.56 | -16.20 | -13.10 | -13.15 | -16.18 | -15.17 | -22.62 | -21.37 | -23.12 | -35.71 |
| St. Dev. | 5.92 | 2.69 | 1.93 | 2.44 | 3.57 | 2.53 | 4.11 | 5.98 | 5.74 | 3.92 |
| Coeff. Var. | 32% | 17% | 15% | 19% | 22% | 17% | 18% | 28% | 25% | 11% |

### 3.3.5 Historical hydrocensus data

Historical hydrocensus data as listed in Appendix B: Hydrocensus Data was used in the study of the region as well as certain points that was used in the pit flooding model. From the hydrocensus data only the chemical and water quality data was used with monitoring data of the region being sufficient enough. The water quality data of SEDCH01 and BH27 was used.

### 3.3.6 TCLP and ABA results

Samples from the Merensky and UG2 Reefs were sent for TCLP and ABA tests. TCLP and ABA results are listed and discussed in section 5.3 of this document. The mineralogy and the subsequent reactions caused by the chemistry do not generate acid with TCLP results showing that no risk in any heavy metal contamination will take place due to the relatively neutral pH nature of the environment.

### 3.3.7 Mineralogy data (XRD and XRF results)

The same sample sent to the laboratory for ABA and TCLP were analysed using XRD and XRF with results shown in Table 4-3 and

Table 4-4. The results were used in the weathering model of the case study.

## 3.4 Concluding summary: Chapter 3

The following data sets were used in this research dissertation and case study:

- Rainfall and Temperature data

- Geological and topographical maps

- Literature data and analogue values

- Monitoring data (Water quality and water levels)

- Hydrocensus data

- TCLP and ABA results

- Mineralogical tests and data

Chapter 3 gave short descriptions on statistical summaries of the data mentioned above with the following three chapters (Chapter 4, 5 and 6) using this data within a case study and research modelling to evaluate the possible impact, if any, and feasibility of flooding an open pit platinum mine post-closure as an environmental rehabilitation/mitigation option. All data sets are either listed in the document or provided on the data DVD with appendices.

# CHAPTER 4:

## 4    CASE STUDY - PROJECT SITE ASSESSMENT

### 4.1    Site description

#### 4.1.1    General mine information and infrastructure

The existing mine project at Pilanesberg is the PPM open pit mine with a planned extension of the pit onto the Wilgespruit farm. The mine focuses on Platinum production from the UG2 and Merensky Reefs formed within the western limb of the Bushveld Igneous Complex.

The current operations at the mine receive water from well fields developed by AGES and in the future will rely entirely on water from the Magalies pipeline for water supply. The tailings facilities and plant operations will form part of the mine networks of planned open pit and underground mines in the local vicinity of PPM, and in light hereof tailings material and production will increase.

Mine infrastructure at PPM mine comprises 5 Storm Water Dams (SWD), 2 topsoil dumps, 1 Run of Mine (RoM) stockpile , 2 Waste Rock Dumps (WRD), a process plant with offices and change houses, Tailings Storage Facility (TSF) with a return water dam and a Sewage Treatment Plant (STP). Water supply is delivered via a pipeline from the well field network and another pipe from the Magalies water pipeline with current water supply being 4.5 $Mm^3$/a. Water for change houses, offices, fire control and the plant operations is stored in a 1 $Mm^3$ tank on site near the plant operations. Dirty water from the Southern Pit SWD and Northern Pit SWD is re-used as water for dust suppression when available. Water from the return water dam is re-used in the plant processes.

The mine production for Life of Mine (LoM) is 235 000 tons/month. LoM for current and extended Tuschenkomst operations is currently scheduled to run up to the year 2026.

#### 4.1.2    Study area and surface water catchment

The study area is located north of the Pilanesberg Complex in the North West province, South Africa. The nearest town is Saulspoort approximately 15 km east of the PPM mine (Figure 4-1).

The project falls within the A24D quaternary catchment forming part of the Crocodile West and Marico Water Management Area (WMA). The catchment has an aerial extent of 1262 $km^2$ with the exclusion of 66 $km^2$ of protected area within the boundaries of the Pilanesberg National Park.

**Figure 4-1    Map showing the locality of the case study project**
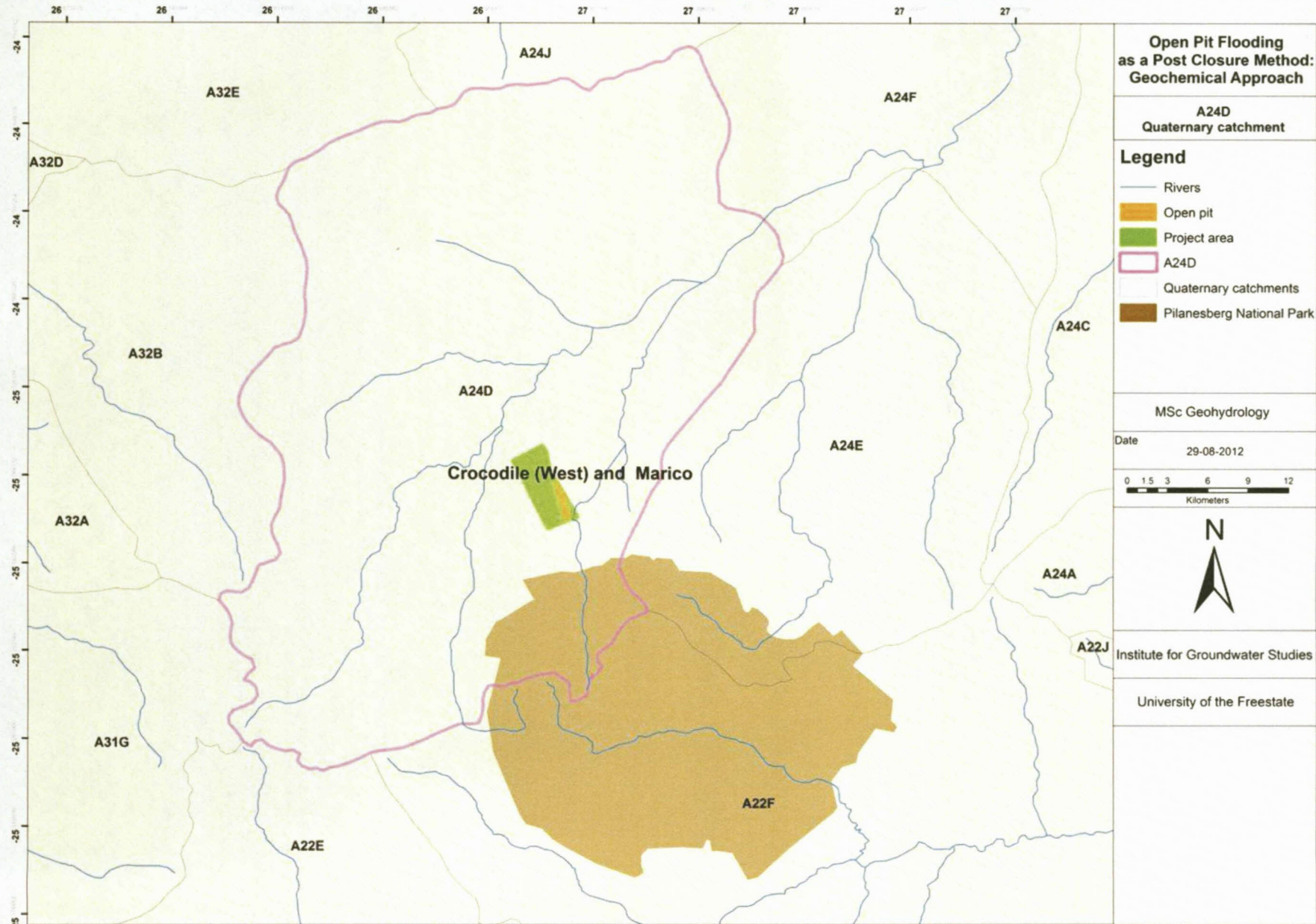
**Figure 4-2     Map showing the project location within the A24D Quaternary catchment (Crocodile West and Marico WMA)**

The A24D catchment has a Mean Annual Precipitation (MAP) of 628 mm/a with a high Mean Annual Evaporation (MAE) rate of 1849 mm/a (Table 4-1). The Mean Annual Runoff (MAR) coefficient for the area is 2.5% of MAP with clay soils increasing the surface runoff of the region (Middleton & Bailey 2008).

**Table 4-1    A24D quaternary information (Middleton & Bailey 2008)**

| Catchment | Catchment area (km²) | | | MAP (mm/a) | MAE (mm/a)) | MAR (% of MAP) |
| --- | --- | --- | --- | --- | --- | --- |
| | Gross area | Protected area | Nett area | | | |
| A24D | 1328 | 66 | 1262 | 628 | 1849 | 2.5% |

### 4.1.3   Topography and drainage

The study area is situated on the north western side of the Pilanesberg Complex and is characterised by a slightly undulating landscape with an average height of 1100 mamsl and occasional peaks with elevations of up to 1330 mamsl. The Pilanesberg Complex's ring structure is the most prominent topographical feature in the region lying just south of the project area. Most of the drainage channels and rivers flow out from the Pilanesberg hills into a northern direction with rivers and streams of the complex itself flowing inwards forming a centripetal drainage pattern (Stone 1999).

The area is drained by several non-perennial streams and drainage lines i.e. Kolobeng-, Mothlabe-, Wilgespruit-, Diphiri-, and Lesobeng River, being the main non-perennial rivers. These rivers flow towards the north, before joining the Bofule River approximately 10 km to the north (Figure 4-3). The Bofule River is joined by other tributaries before it flows into the Crocodile River that forms the main river of the WMA along with the Marico River in the north. The landscape and topography allows for a regional dendritic drainage pattern (Stone 1999). Dry winters lead to streams and rivers only flowing during heavy rain in the summer months with non-perennial rivers. This leads to higher stress being applied on groundwater as a resource due to the non-availability of sustainable surface water reservoirs. During heavy rains the surface run-off over the clay soils increases with a decrease in infiltration and recharge to the groundwater resources.

The Wilgespruit is the river that will contribute the largest part of the surface water component involved in the pit flooding event along with rain water. The natural path of the Wilgespruit, as shown in Figure 4-3, flows through the south-eastern corner of the open pit area. This pathway has however been diverted during the LoM and will be restored once mining has stopped and the pit flooding process is allowed to occur. The Wilgespruit only flows during rain events in the summer months and has a marginal water quality with high fluoride and calcium values from the weathering of fluorite (CaF) containing foyaite in the Pilanesberg Complex geology. The surface

water quality of the Wilgespruit will be a consideration in the hydrogeochemical modelling of the pit flooding process.

## 4.1.4 Climate, rainfall and groundwater recharge

Rainfall data were obtained from station 0548251 (Saulspoort Hospital) for a period ranging from January 1904 to December 2011, covering 108 years. The rainfall and temperature data is reported in Appendix A: Climate Data.

The climate of the area is typical of the bushveld with warm and dry winters and hot and wet summers. The average maximum temperature in summer is approximately 31°C and the average minimum temperature is 18°C, with the highest temperature (of 40.7°C) for the period 2005 – 2010 recorded 03 November 2005. The average maximum temperature in winter is 23°C and the average minimum temp 4°C the lowest temperature (-3.6°C) for the recorded period was in 17 June 2010.

A statistical rainfall analysis was conducted on the weather station data. The station data consisted of monthly rainfall data from 1904 to 2011 with an incomplete distribution of 2012 not included in the current analysis. An analysis on the rainfall data shows that December, January, February and March have the largest positive influence on the MAP and these months are therefore the wettest months in the year and correspond to the summer rainfall region in which the site is located. The driest months, months with the least contribution to the MAP are June, July, August and September that spans through the winter period in the region (Van Coller et al. 2012).

A statistical probability analysis of the data showed that the MAP is 628 mm. As a conservative approach is followed in the analysis using the MAP, the value of 628 mm/a is used for water supply and 891 mm/a for flood analysis to determine base case scenarios. The statistically derived parameters are shown in Table 4-2.

A rainfall distribution chart is shown in Figure 4-4. This chart augmented by a logical test of the data shows that 1:50 year flood events occurred in 1967, 1997 and 2000. One in twenty year flood events occurred in 1939, 1961 and 1991. The 1:50 year drought events occurred in consecutive years from 2005 to 2007, flanked by the 1:20 year drought events in 2003, 2004, and 2008. No other drought events occurred from 1904 to 2003, showing that the drought period from 2003 to 2008 was an exceptional event. This shows that although the probability of drought events may be in the order of 2 times a century (1:50 year drought) when they do occur, they occur for a few years after each other, in this case 3 years. Thus in 104 years, 3 consecutive drought years can be expected (Van Coller et al. 2012).

Recharge in the region based on geological zones and structural influences ranges between 1.5 to 10% of MAP as used for different areas in the calibrated groundwater

flow model for the project. The weighted average recharge coefficient for the area used in general calculations and estimations is 1.3% (Kriek & Meyer 2010).

**Table 4-2    Rainfall statistical parameters**

| Parameter | Value |
|---|---|
| Average | 628 |
| Maximum | 1 043 |
| Minimum | 176 |
| Standard Deviation | 165 |
| 1:20 year flood | 891 |
| 1:20 year drought | 328 |
| 1:50 year flood | 969 |
| 1:50 year drought | 239 |
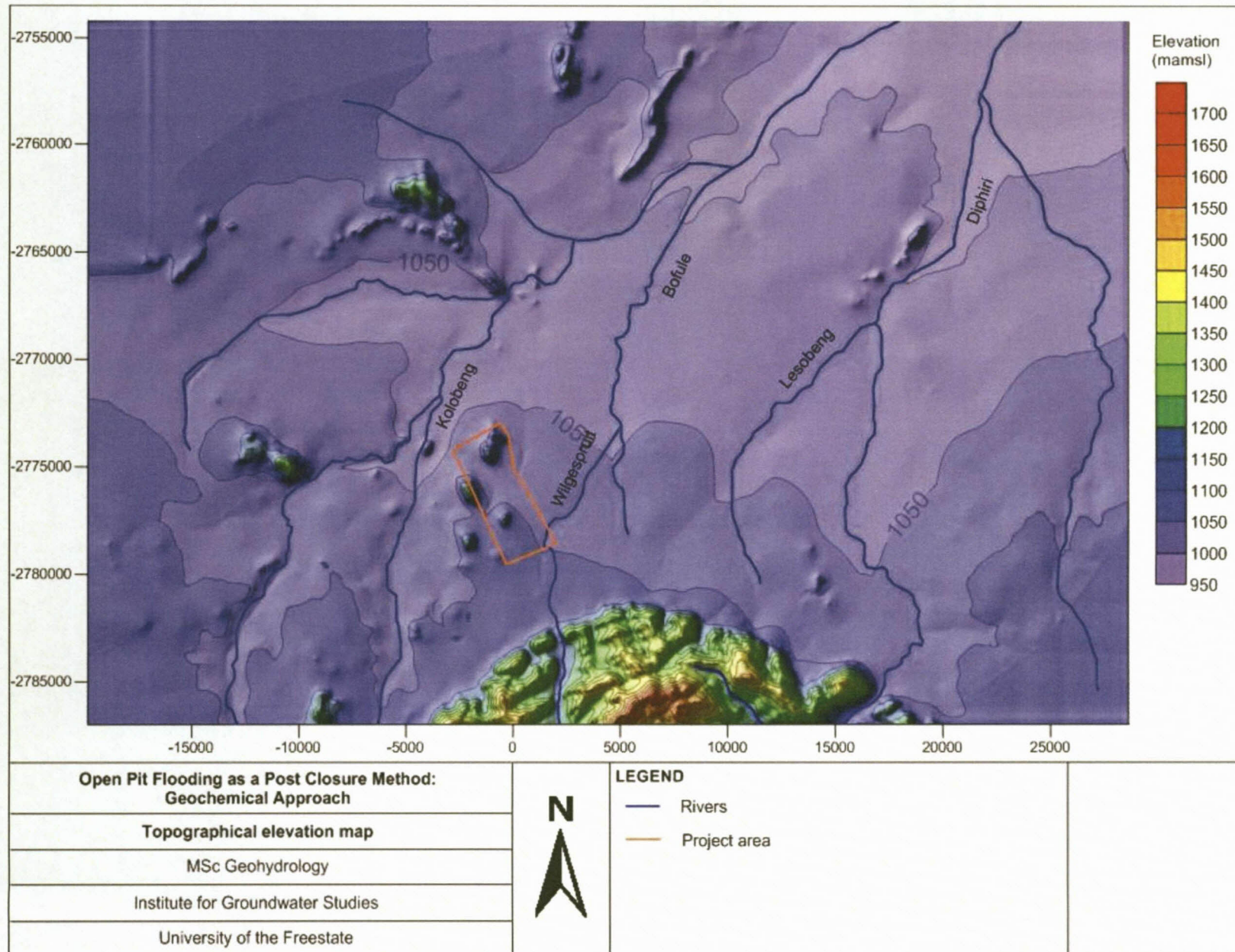
**Figure 4-3    Topographical elevation and drainage map of the regional project area**
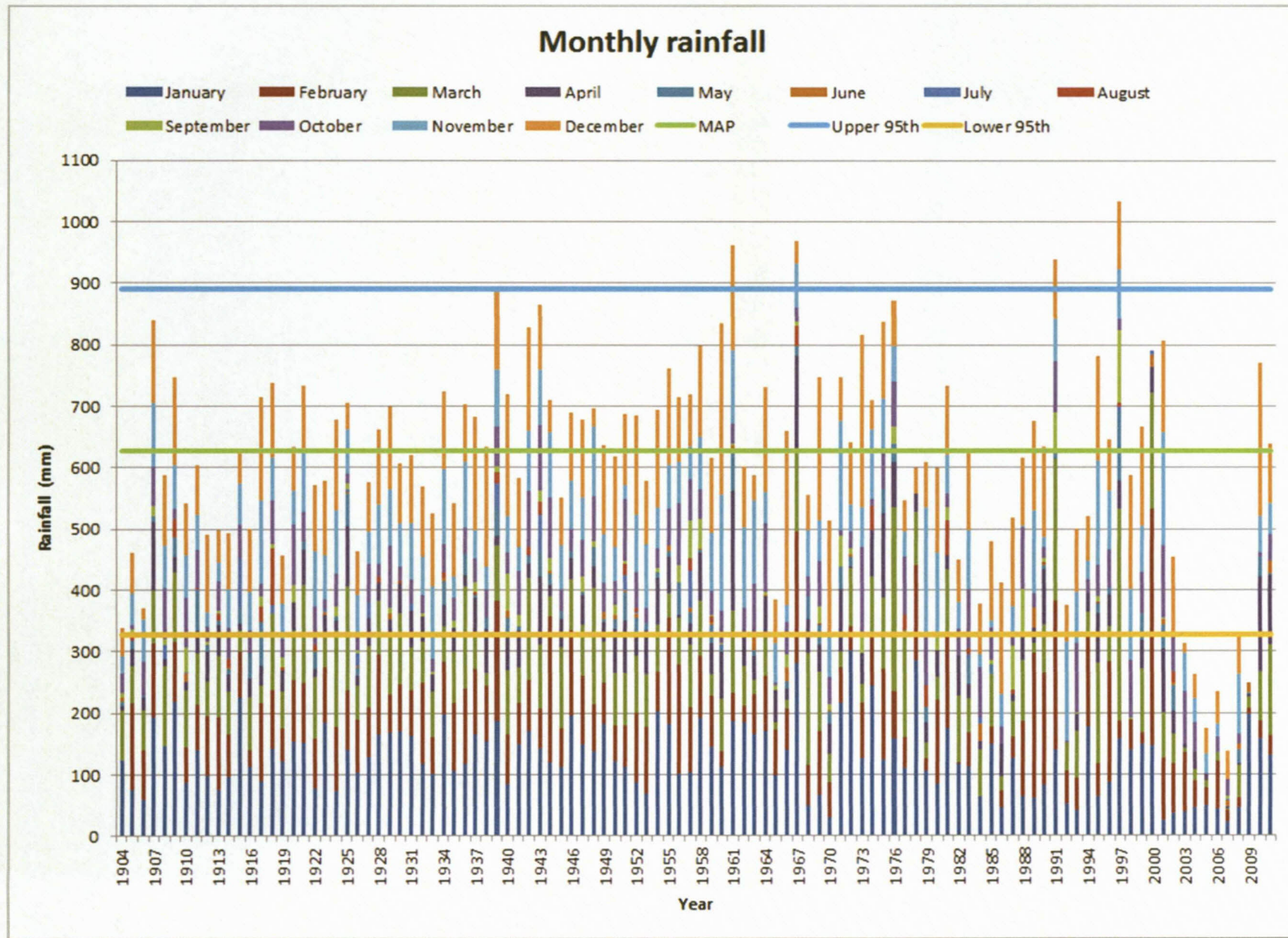
**Figure 4-4    Rainfall distribution chart for Saulspoort rainfall station**

## 4.1.5  Geology

The PPM project development is underlain by the gabbroic formations of the Rustenburg Layered Suite of the Bushveld Igneous Complex. It is located just to the north-west of the prominent Pilanesberg Complex. The Pilanesberg Complex is an alkaline syenite-rich intrusive complex containing rare foyaite and lava tuff. Associated with the Pilanesberg Complex is fluoride which influences the groundwater and surface water quality (Kriek & Meyer 2010).

The Pilanesberg Complex intruded into gabbro norite and anorthosite of the Bushveld Igneous Complex. The Bushveld rocks to the north of the Pilanesberg Complex are overlain by quaternary sediments and sand, between 20 and 40m thick weathered from the Transvaal sequences. The alluvium zones are expected to form localised perched aquifers or zones of higher recharge (Kriek & Meyer 2010), and will act as temporary storage during wet seasons (Smith & Kotze 2010).

The Bushveld Igneous Complex in this area is bounded to the north, west and south by the Pretoria Group Quartzite and volcanic rocks. Archaean rocks are present to the extreme north and are represented by the Swazian Granite Gneiss. These rocks are traditionally considered the basement units of the sub-Saharan African continent.

The layers of the Bushveld Igneous Complex targeted for Platinum Group Elements (PGE's) belong to the Rustenburg Layered Suite that consists of gabbro norite and norite. It contains seams and intrusions of chromitite and the PGE-bearing Merensky and UG2 Reefs (Kriek & Meyer 2010). Samples from the Merensky and UG2 layer has been tested during mineralogical and static laboratory analysis and described in detail.

An extensive network of faults and dykes is associated with the emplacement of the Pilanesberg Complex (Figure 4-5) with the area being characterised by a dyke swarm.

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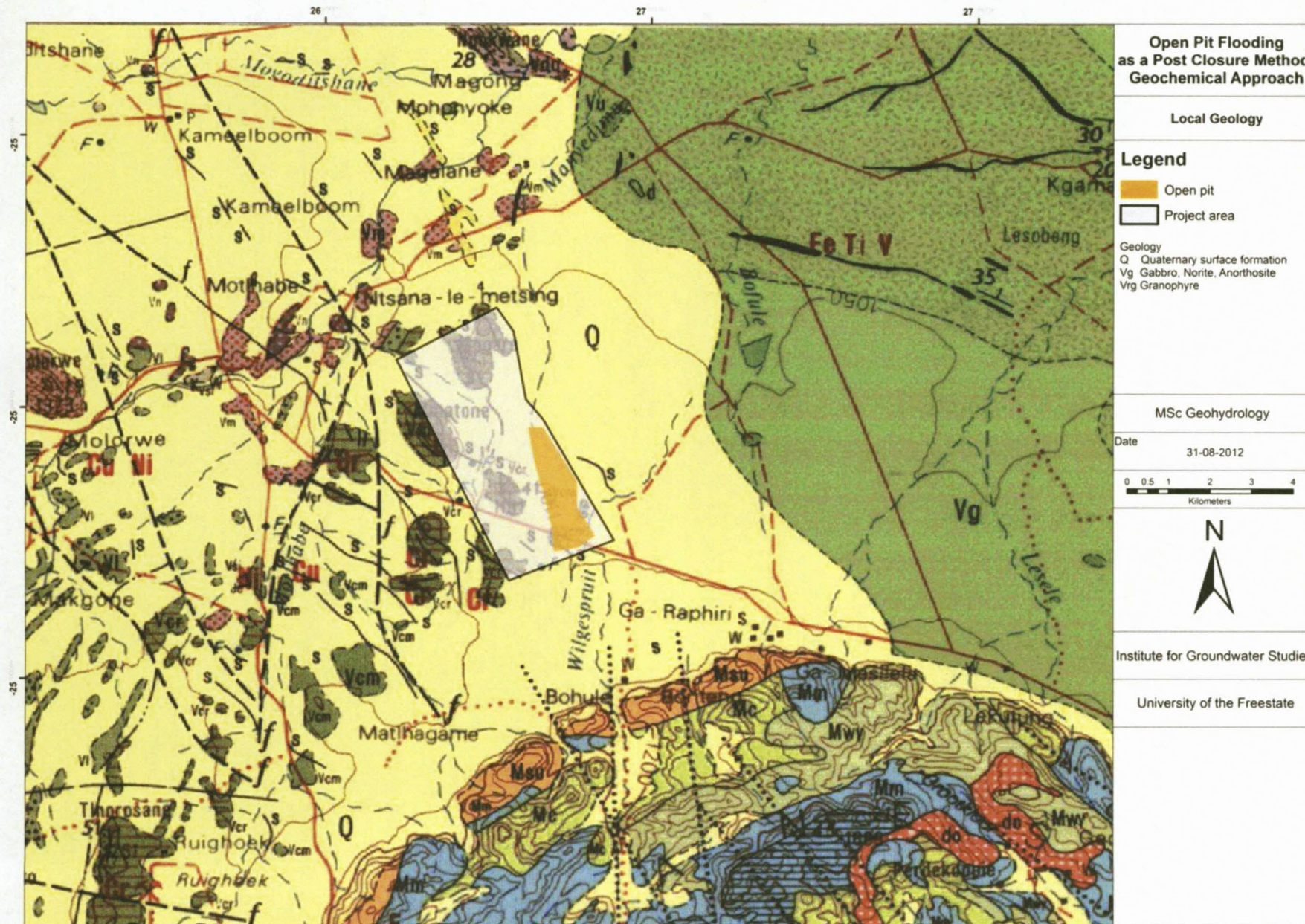
**Figure 4-5    Local geology map of the project area and surrounds**

## 4.2 Site characterisation

### 4.2.1 Mineralogy

The project area geology that will dictate the main mineralogy of the area and the geochemical models are gabbro norite, anorthosite, dunite and pyroxenite of the Bushveld Igneous Complex. A further influence on the area's mineralogy and weathering products in both the hydrochemistry and soils are the foyaite mineralogy in the Pilanesberg Complex's outer ring and is included in the models with the mineral fluorite reacted in simulation.

The economic importance of the region for the mining industry is the PGE minerals in the Merensky and UG2 Reefs, also mined by PPM and neighbouring mines to the south-west and east. Core samples from the Reefs were taken on the neighbouring Magazynskraal farms for exploration on future extension of the current PPM operations. These samples were sent for XRD (Table 4-3) and XRF analysis to evaluate the mineralogy of the host rock containing the platinum. The XRD results and main mineralogy of the two host rock Reefs are shown in Table 4-3.

The olivine is mostly forsterite ($Fo_{83-90}$), with the composition changing to more fayalite-rich ($Fa_{57-95}$) in the northern sector of the eastern limb. The orthopyroxene is mostly enstatite ($En_{75-93}$), but changes to more ferosillite-rich in the upper zone ($En_{30-60}$). The plagioclase is almost exclusively anorthite ($An_{50-80}$) and becomes more albite rich only 30 m from the roof contact (Cawthorn et al. 2006, Meyer & Hansen 2010).

Table 4-3    XRD results showing the mineral distribution percentages of the UG2 and Merensky Reef host rocks

| Mineral | Composition (%) UG2 | Mineral | Composition (%) [s] Merensky |
|---------|---------------------|---------|------------------------------|
| Augite | 3.26 | Augite | 8.07 |
| Biotite | 4.51 | Biotite | 14.01 |
| Chlorite | 7.4 | Chlorite | 7.11 |
| Chromite | 41.55 | Chromite | 3.02 |
| Enstatite | 23.88 | Enstatite | 31.56 |
| Forsterite | 2.03 | Forsterite | 6.95 |
| Hornblende | 1.5 | Hornblende | 1.04 |
| Kaolinite | 0.65 | Kaolinite | 3.23 |
| Lizardite | - | Lizardite | 8.8 |
| Microcline | 3.35 | Microcline | 0.87 |
| Plagioclase | 7.91 | Plagioclase | 11.47 |
| Talc | 3.98 | Talc | 3.87 |
| Total | 100 | Total | 100 |

**Table 4-4    XRF Laboratory results**

| Major Elements | Major Element Concentration (wt %)[s] | |
|---|---|---|
| | UG2 | Merensky |
| $SiO_2$ | 15.69 | 44.07 |
| $TiO_2$ | 1.03 | 0.59 |
| $Al_2O_3$ | 14.43 | 5.78 |
| $Fe_2O_3(t)$ | 25.69 | 14.82 |
| MnO | 0.324 | 0.204 |
| MgO | 12.43 | 27.19 |
| CaO | 1.26 | 3.59 |
| $Na_2O$ | <0.01 | <0.01 |
| $K_2O$ | <0.01 | <0.01 |
| $P_2O_5$ | 0.233 | 0.231 |
| $Cr_2O_3$ | 32.4 | 1.5 |
| **Total** | **100** | **99.92** |
| $H_2O^-$ | **0.12** | **0.28** |

The minerals to consider in the weathering models and which are bound to have an influence on both groundwater and surface water hydrochemistry are the following:

- Olivine (forsterite, fayalite)

- Orthopyroxene (enstatite, ferosillite)

- Plagioclase (anorthite)

- K-feldspar

- Nepheline

- Biotite/Muscovite

- Fluorite

## 4.2.2   Open pit parameters and geohydrological characterisation

Based on the geological, hydrological and geohydrological setting of the area, various influences on the flooding of the open pit will also affect the way in which the geochemical characterisation and modelling of the flooding is approached. Assumptions and data inputs into the conceptual and numerical hydrogeochemical models were largely influenced by the outcomes of the scenarios simulated during the numerical and analytical flow models as discussed in section 2.8 of the literature review.

#### 4.2.2.1 Structural geology and pit wall stratigraphy

The PPM project is situated in a dyke swarm created by the intrusive forces of both the Bushveld Igneous Complex into the Transvaal host rock and at a later stage the Pilanesberg Alkaline complex. Various structures and faults both east-west and north-south create a complicated mining environment with blocks being mined to follow the ore body that was displaced and distorted due to the formation history.

Dolerite dykes rich in magnetite are found in what is called a dyke swarm. A dyke swarm is a large concentration of dykes created in a small geographical setting by localised magmatism of an intrusive nature. The area north of the Pilanesberg is situated in such a setting with intrusive dykes in most cases causing boundary conditions to groundwater flow and causing compartmentalization of local aquifers.

Both east-west and south-north trending faults exist in the area and also run through the open pit area. From mining information and groundwater exploration field data it is evident that the east-west faults and fractures are closed due to the force in the areas formational history being on a north-south direction.

The general wall geology of the pit is gabbro and norite rocks with the mineralogy of the region described in section 4.2.1. The top 5 to 10 m of the wall is characterised by the weathered zone with clay soils dominated by smectite and kaolinite minerals.

#### 4.2.2.2 Water levels

Monitoring of water levels in both unused and used boreholes took place form 2007 up to 2012. Two sets of water levels are analysed, one set represents 12 boreholes with static water levels measured during the period and a second set of 10 boreholes with dynamic water level taken during pumping with a remote monitoring system that is computer based on mine water supply and dewatering boreholes. All monitoring data is given in Appendix C: Monitoring data.
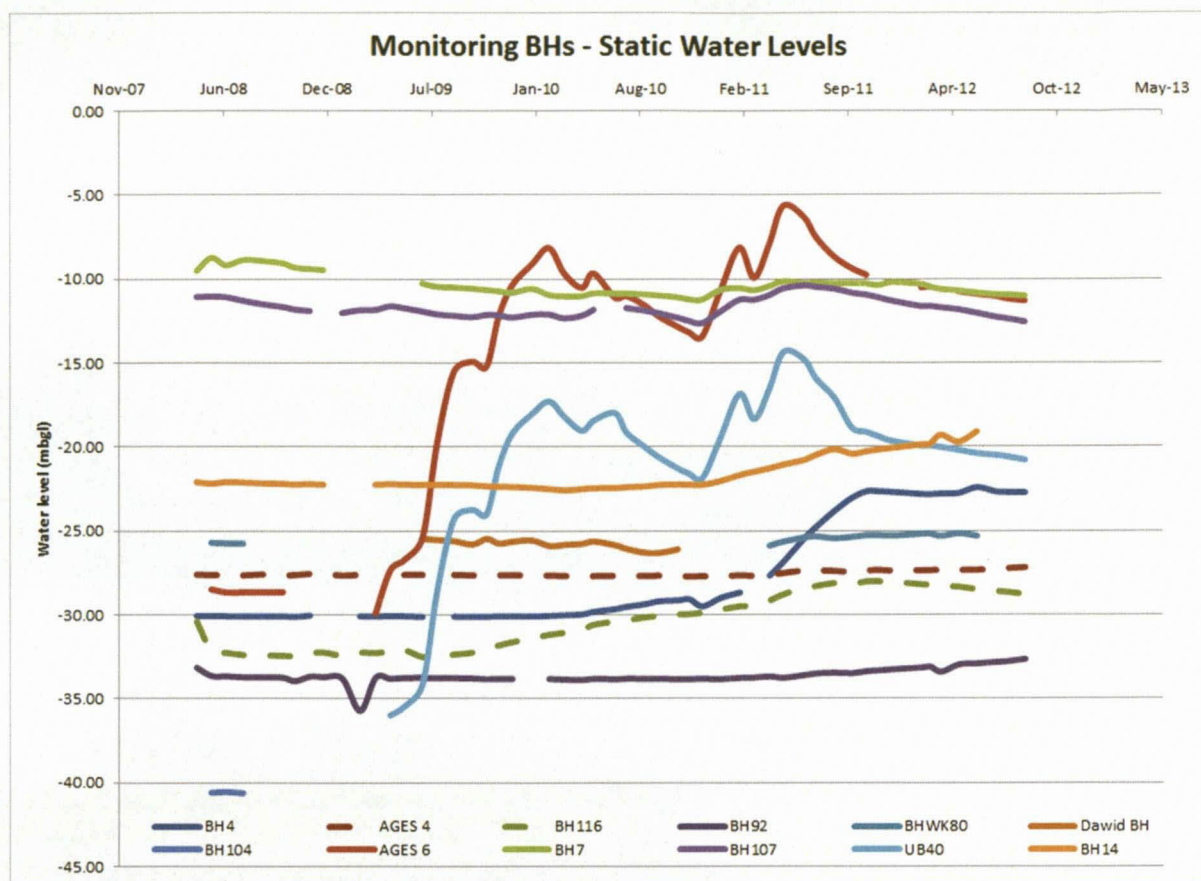
**Figure 4-6      Water level vs. Time trends of static monitoring boreholes**

Static water levels measured did not vary with great significance over the period as shown in Figure 4-6 and Table 3-5 with the exception of AGES 6 and UB40.  Both these two boreholes were occasionally used for water supply.  As illustrated in the graph (Figure 4-6), almost all water levels recovered to higher levels during the first half of 2009 after which they started stabilising as the management plan of the mine started reaping benefits.

Dynamic water levels measured varied with greater significance as would be expected.  Thus a graphical analysis as shown in Figure 4-7 does not allow the other to see any significant trends.  However abstraction data of the abstraction boreholes for the last 5 years (Table 4-5) have been analysed and interpreted to evaluate the efficiency and effectiveness of the current water supply network management from the well field.  Recommended abstraction derived from aquifer tests done by AGES (Pty) Ltd, ranges from 90 $m^3$/d to 210 $m^3$/d for the 10 boreholes used as water supply sources.

**Table 4-5     Abstraction data**

| Borehole ID | | BG1 | BG2 | BH117 | FF1 | FF15 | FF3 | FF5 | FF6 | WN1 | WN3 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Recommended Sustainable rate (m³/d) | | 200.0 | 200.0 | 100.0 | 150.0 | 200.0 | 210.0 | 100.0 | 100.0 | 100.0 | 90.0 |
| Current abstraction stats (m³/d) | Min | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Max | 247.2 | 208.2 | 140.9 | 94.1 | 215.2 | 163.4 | 90.7 | 130.2 | 182.8 | 94.7 |
| | Average | 66.3 | 72.0 | 30.4 | 7.2 | 43.6 | 4.4 | 3.4 | 40.0 | 30.9 | 28.7 |
| | Lower 95% | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Upper 95% | 203.9 | 191.4 | 139.6 | 62.3 | 163.2 | 34.1 | 10.8 | 109.8 | 114.8 | 80.1 |
| Water Level stats (mbgl) | Baseline | 9.5 | 18.0 | 38.3 | 19.1 | 9.4 | 18.1 | 18.2 | 12.6 | 16.4 | 14.0 |
| | Min | 10.0 | 11.4 | 30.7 | 17.4 | 10.5 | 16.6 | 11.0 | 10.2 | 13.5 | 13.7 |
| | Max | 16.8 | 21.2 | 37.7 | 36.8 | 16.1 | 50.5 | 30.8 | 17.8 | 20.8 | 29.6 |
| | Average | 12.9 | 16.1 | 35.5 | 22.8 | 12.8 | 21.4 | 21.7 | 14.6 | 16.1 | 19.6 |
| | Lower 95% | 10.1 | 11.4 | 30.8 | 17.5 | 10.6 | 16.6 | 16.7 | 11.8 | 13.6 | 13.8 |
| | Upper 95% | 16.5 | 20.1 | 37.5 | 32.2 | 15.6 | 28.2 | 28.6 | 17.6 | 20.5 | 29.5 |
| Pump installation depth | | 35 | 37 | 60 | 44 | 50 | 46 | 98 | 31 | 58 | 31 |
| Available drawdown (m) | | 25.5 | 19.0 | 21.7 | 24.9 | 40.6 | 27.9 | 79.8 | 18.4 | 41.6 | 17.0 |
| Maximum achieved drawdown (m) | | 7.3 | 3.2 | -0.7 | 17.7 | 6.7 | 32.4 | 12.6 | 5.2 | 4.4 | 15.7 |
| Average achieved drawdown (m) | | 3.4 | -1.9 | -2.8 | 3.7 | 3.3 | 3.3 | 3.5 | 2.0 | -0.3 | 5.6 |

The abstraction volumes recorded in the system for the last 5 years are kept in the recommended range and thus the system is kept in a good state through aquifer management. Overall, the average abstraction rates are much lower than the recommended yields; however, the maximum yields abstracted in some cases are more than the recommended yields. Given this fact, the water levels respond well and the system seems healthy from a groundwater perspective. This mentioned observation is made through the fact that no drawdown during the 5 years has exceeded the available drawdown recommended. Negative maximum achieved boreholes indicate that the boreholes never reached water levels below the baseline value.
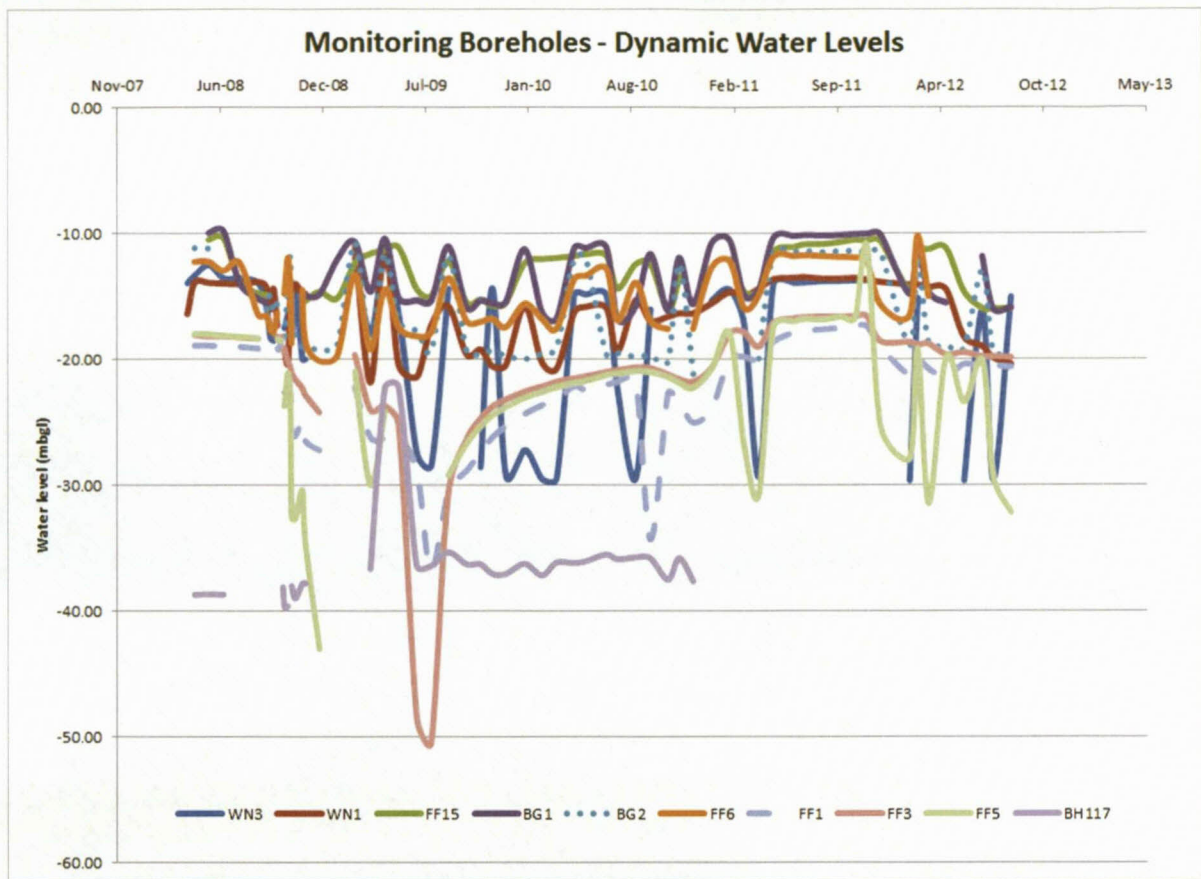
**Figure 4-7    Water level vs. Time trends for water supply monitoring boreholes**

The large variation in the water levels as indicated in Figure 4-7 is due to controlled pumping times and abstraction rates from the mine operators.  Electronic pumping systems with a remote control centre on wireless frequencies allow the mine management to control pumping and dewatering rates.  During winter months drawdown is more significant with low rainfall not allowing any water from surface water sources, however during summer month's water supply demands from groundwater resources are lower thus drawdown is less significant.

The average groundwater level in the region is currently 21 mbgl with deeper levels in the immediate vicinity of the pit as dewatering has an impact with water abstracted within the pit.

## 4.2.3   Water quality

For the purpose of the case study and the aim of the dissertation 5 groundwater samples, 3 surface water and 2 pit seepage samples will be used in the model and site description.  In this section only the water quality of the sample points will be discussed and measured against SANS 241:2011 standards for drinking water with further hydrochemical aspects of the surface water and groundwater discussed in section 5.2.

The water quality assessment is done as set out in the SANS Drinking water guidelines as discussed in the literature review (Section 2.9.1). Some of the unclassified parameters were measured against the SANS 241:2005 guidelines as indicated in Table 4-6 listing the classified samples.

The following conclusions regarding the water quality of input samples can be made:

- None of the sample points has water within a pristine quality range, in other words none of the water samples showed all chemical parameters to be below the TWQR;

- SW8 is not suitable for consumption by humans due to elevated levels of F, Al and Fe above the recommended range;

- SW12 has Fe within levels above the recommended risk limit and is not suitable for domestic use due to an chronic health risk to humans;

- BH27 is not suitable for domestic use or human consumption with Pb concentrations above the recommended limit and can cause chronic health effects in humans;

- SW11 has high concentrations of F and is not suitable for consumption, posing a chronic health risk to humans;

- BH116 is not suitable for human drinking water with high levels of F and Mg potentially posing chronic health effects to humans

- SEDCH01 has unsuitable levels of $NH_4$ with aesthetic risks if consumed;

- BH117 and BH4 have Mg concentrations that falls within the outer limits of guidelines;

- The two samples from the open pit taken from seepage water have high levels of $NO_3$ above the recommended limits. This water is however not used for domestic supply and the $NO_3$ is caused by the explosives during blasting.

### Table 4-6 Water quality classification

| Parameter | Unit | Standard Limits | Risk | SW8 | SW11 | SW12 | SEDCH01 | BH 27 | BH116 | BH117 | BH4 | Pit | Pit North |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $HCO_3$ | mg/ℓ | Not Specified (N/S) | | 95 | 84 | 18 | 205.20 | 95.8 | 4989.6 | 489.7 | 607.8 | 282 | 63 |
| Ca | mg/ℓ | $<150^3$ | SANS 241:2005 | 17.1 | 15.9 | 1.7 | 4.0 | 39.4 | 69.5 | 3.1 | 4.5 | 57.0 | 61.5 |
| Cl | mg/ℓ | <300 | Aesthetic | 15 | <1.408 | <1.408 | 38.6 | 95.8 | 18.2 | 8.8 | 65.2 | 12 | 13 |
| F | mg/ℓ | <1.5 | Chronic health | 2.23 | 1.77 | 0.35 | 0.195 | <0.183 | 2.2 | 0.2 | 0.2 | 0.29 | 0.31 |
| Mg | mg/ℓ | <70 | SANS 241:2005 | 5 | 7 | 3 | 4.083 | 25.573 | 71.6 | 124.5 | 143.1 | 82 | 68 |
| K | mg/ℓ | <50 | SANS 241:2005 | 9 | 3 | 2 | 5.36 | 8.278 | 1.0 | 0.9 | 2.8 | 0.9 | 3.9 |
| Na | mg/ℓ | <200 | Aesthetic | 13 | 17 | 3 | 111.48 | 55.22 | 87.3 | 8.7 | 14.1 | 67 | 97 |
| $SO_4$ | mg/ℓ | <500 | Acute health | 39 | 12 | 3 | <0.132 | 64.31 | 28.2 | 11.3 | 5.7 | 49 | 212 |
| $NO_3$ | mg/ℓ | <50 | Acute health | 0.40 | 0.17 | 0.90 | 0.201 | 1.251 | 27.6 | 5.5 | 3.5 | 64.27 | 81.87 |
| $NH_4$ | mg/ℓ | <1.5 | Aesthetic | 0.323 | -[4] | - | 5.633 | 0.087 | - | - | - | <0.015 | - |
| pH | | 5 - 9.7 | Operational | 7.6 | 7.8 | 7.7 | 9.11 | 8.05 | 7.2 | 8.5 | 8.0 | 8.3 | 8.3 |
| EC | mS/m | <170 | Aesthetic | 16 | 20 | 9 | 59.5 | 72 | 119.0 | 95.2 | 105.7 | 116 | 141 |
| TDS | mg/ℓ | <1200 | Aesthetic | 155 | 107 | 25 | 302 | 348 | 604.0 | 465.0 | 548.0 | 504 | 575 |
| Al | mg/ℓ | <0.3 | SANS 241:2005 | 4.19 | 0.023 | 0.141 | <0.006 | <0.006 | <0.006 | <0.006 | <0.006 | <0.006 | <0.006 |
| As | mg/ℓ | <0.01 | Chronic health | - | <0.023 | - | <0.023 | <0.01 | - | - | - | - | <0.023 |
| Cd | mg/ℓ | <0.003 | Chronic health | - | <0.001 | - | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Tot Cr | mg/ℓ | <0.05 | Chronic health | - | <0.002 | - | 0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 |
| Co | mg/ℓ | <0.5 | Chronic health | - | <0.002 | - | <0.002 | <0.002 | 0.002 | - | <0.002 | 0.002 | <0.002 |
| Cu | mg/ℓ | <2 | Chronic health | - | 0.001 | - | 0.027 | 0.024 | 0.001 | <0.001 | 0.010 | 0.001 | 0.001 |
| Fe | mg/ℓ | <0.2 | Chronic health | 9.881 | 0.020 | 0.320 | 0.02 | 0.008 | <0.006 | <0.006 | <0.006 | <0.006 | <0.006 |

3 The sign < means that a value should be or is lower than the indicated value after the sign
4 A cell with a single – without a value indicates that no data or blank cell

| Parameter | Unit | Standard Limits | Risk | SW8 | SW11 | SW12 | SEDCH01 | BH 27 | BH116 | BH117 | BH4 | Pit | Pit North |
|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|
| Pb | mg/ℓ | <0.02 | Chronic health | - | <0.01 | - | 0.01 | 0.03 | 0.003 | <0.001 | 0.012 | <0.001 | <0.01 |
| Mn | mg/ℓ | <0.5 | Chronic health | 0.061 | 0.003 | <0.001 | 0.007 | 0.004 | <0.001 | <0.001 | 0.027 | | 0.001 |
| Ni | mg/ℓ | <0.07 | Chronic health | - | <0.003 | - | 0.007 | 0.021 | <0.003 | <0.003 | <0.003 | <0.003 | <0.003 |
| Se | mg/ℓ | <0.01 | Chronic health | - | <0.023 | - | <0.023 | <0.01 | - | - | - | | <0.023 |
| Zn | mg/ℓ | <5 | Aesthetic | - | 0.004 | - | 0.037 | 0.017 | 0.014 | <0.004 | <0.004 | <0.004 | 0.005 |

## 4.3   Concluding summary: Chapter 4

Chapter 4 characterised and described the study area with the following main conclusions from the case study site assessment:

- The existing PPM mine is an open pit operation just north of the Pilanesberg Complex currently operating at an approximate 235 000 ton/month from the UG2 and Merensky Reefs;

- The study area falls within the A24D quaternary catchment (Crocodile West and Marico WMA) with the main drainage channel being the Wilgespruit that will also contribute the largest volume of surface water into the pit flooding post-closure;

- The Wilgespruit flows out in a north-eastern direction from the prominent Pilanesberg hills;

- The project area has a warm bushveld climate with maximum average temperatures in summer being 31°C and average minimum temperatures in winter dipping to 4°C;

- The summer rainfall area has a MAP of 628 mm/a with a high 1849 mm/a MAE over the extent of the catchment having and total area of 1328 km$^2$;

- The main geology of the study area is the gabbro norite rocks of the Rustenburg Layered Suite with mineralogical and structural influences from the Pilanesberg Alkaline Complex;

- Complex structural development in the local geology from dyke swarms and faults allows for difficult mining conditions and a wide range of aquifer systems with an average local water table of 21 mbgl; and

- Fluoride and nitrate is the two chemical constituents within the local aquifer deeming most of the sampling locations not suitable for human consumption.

With the conclusion of Chapter 4, allowing the reader a broader hydrogeological understanding of the study area, this knowledge will feed into the setup, conceptualisation and simulation of various hydrogeochemical models as will be discussed in Chapter 5.

# CHAPTER 5:

## 5  HYDROGEOCHEMICAL ASSESSMENT AND MODELS

The following sections of this dissertation are dedicated to the modelling of the pit flooding event to predict the hydrogeochemical outcome of such a post-closure option. Short discussions on the model components, methods, inputs, assumptions and short presentations on the results are given to numerically quantify the impacts, if any, from an environmental geochemistry point of view. With the conclusion of this chapter; it will form part of a full discussion on the results and leave a clear outline, to be finalised in the next chapter for future similar geochemical assessments for hydrogeologists.

All model results are given in Appendix D: Model results, and are available on the data DVD attached to this dissertation document.

## 5.1  Conceptual model

A conceptual model (definition given in section 2.1) with different conceptual subjects has been drafted to model a written and illustrated concept of the expected conditions and processes within the project objectives and the pit flooding event.

Based on the research of Castendyk & Webster-Brown (2007), two types of pit lakes exist with different limnological and chemical characteristics. The main impact on the two types of potential pit lakes is the density and chemical characteristics of pit waters. Another influence is the surface area to depth ratio. Two types of potential pit lakes with one annual turnover event or just partial turnover event can exist. A greater description of lake limnology and the two types of pit lakes is given in section 2.6 of the literature review.

In concept the PPM pit lake will be a meromictic lake due to its large depth to surface area ratio with chemical variation rather than temperature and density changes playing a role. Although the chemical density and temperatures of input water will not differ much (in pre-modelled concept), the morphological structure of the lake, will cause layering of oxygenated and anoxic conditions. As also mentioned in studies by Nuttall & Younger (2004) stratification in flooded mine waters can be caused by various factors of which the following two will be most probable to cause the event to occur in the case study pit lake:

1. Small inflows and outflows in the pit or shaft wall; allowing

2. Gradual inflow and slow recovery of water levels.

A meromictic approach is thus followed in both the conceptual and numerical geochemical models for the PPM pit flooding event to simulate a conservative

approach to the assessment.

The meromictic conditions of the PPM pit lake will dictate the extent of turnover/mixing events of the different lake horizons once flooding of the lake is complete. The input waters will be evaluated through modelled simulations of weathering models under different conditions. The lake input waters will then be modelled based on temperature and calibration data from the samples taken from groundwater.

As indicated by the numerical groundwater flow model discussed in section 2.8, with an acceptable degree of uncertainty the first 40 to 45 years of post-closure flooding will be a mixture of input waters from the groundwater (GW), surface water (SW) and direct rainwater (RW) onto the pit. The input and mixture of these waters is assumed to occur under atmospheric oxygen conditions with weathering products in the field data serving as the chemical range of the waters. During the first phases of flooding the lake will behave in a holomictic way with no distinguishable stratification of the lake waters. However as the water level reaches a greater lake depth over time, a Chemocline will start to develop forming Lake Layer 1 which is termed the monimolimnion.

The monimolimnion is characterised by high total dissolved solids and sulphide mineral concentration as reducing conditions prevail due to a lack of oxygen. The monimolimnion does not overturn annually with oversaturated minerals and products from oxidising reactions causing settling of both sulphide minerals and organic material in the deepest lake layer. Layer 2 termed the hypolimnion on top of the monimolimnion is a layer characterised by a constant groundwater input with flow interaction between the surface and rain water mixing with groundwater. This layer will in concept be the layer with the highest TDS apart from the monimolimnion and the mixing model representing this layer will be used to simulate evaporation reactions as well as any other sensitivity analysis.

On top of the hypolimnion is the epilimnion or lake layer 3 (Figure 5-1) with a SW – RW mix. After approximately 45 years groundwater inflow will stop with the lake water level reaching levels close to 1030 mamsl and the only contribution to the epilimnion will be from the surface. The water level will not reach the original 1060 mamsl datum of the groundwater table within the confines of the lake area due to evaporation being higher than rainfall and groundwater inflow. As the lake fills and layers become distinguishable an epilimnion will always exist with atmospheric conditions allowing for an oxygen fugacity of 0.21. A thin fourth lake layer (Lake Layer 4) will be present and is characterised by an approximate 3 m thick layer of water with a higher TDS value than the epilimnion as well as temperatures close to

that of the atmosphere (Figure 5-1). This $4^{th}$ lake layer is coined and termed in this dissertation as the *Evapolimnion* as it is constantly undergoing changes due to evaporation. Layer thicknesses may vary and is difficult to determine before any flooding with turnover events and their annual frequency also being an uncertainty in the current environment. This layer was added to the conventional pit lake model to give a quantification and indication that small change due to evaporation and atmospheric conditions can lead to chemical variance in the top layer. These changes can be very small or large for short periods with the modelled layer indicating an ideal situation where a definitive layer can be distinguished during static conditions.

A slight thermocline representing a temperature divides will exist once lake and chemical equilibriums has been reached between the epilimnion and hypolimnion. Transition zones between layers represent mixes of water with no real character being definable chemically. Mixing between the evapolinmion, epilimnion and hypolimnion can always occur and the combined layer of these three horizons is called the mixolimnion. A decrease of $O_2$ and increase of $CO_2$ occurs as the depth increases.

The conceptual model as graphically illustrated in Figure 5-1 will be used as a constant guide to the modelling of the geochemical interactions as well as the development of conceptual scenarios.

Weathering models will be done to evaluate the processes and chemical reactions involved in developing the groundwater observed in the field. Mixing models will be developed to simulate the expected lake layer chemical quality and to determine whether recreational activities and other uses of the pit lake can occur once flooding is complete.

The hypolimnion will be simulated by allowing the mixing of GW, SW and RW at atmospheric conditions (Scenario M2). This mixing model will also represent mixing between the epilimnion and hypolimnion. The epilimnion will be simulated (Scenario M1) by allowing the mixing of only surface and rain water. The monimolimnion will be modelled through a reactive simulation of a GW, SW and RW mix (M2) allowing reacting at conditions with depleted oxygen supply and an increase in carbon dioxide. This simulation (Scenario M4) will simulate reducing effects on the water quality. A fourth mixing simulation will illustrate the effect of evapotranspiration within the water quality of the evapolinmion in a 12 hour period in scenario M3.
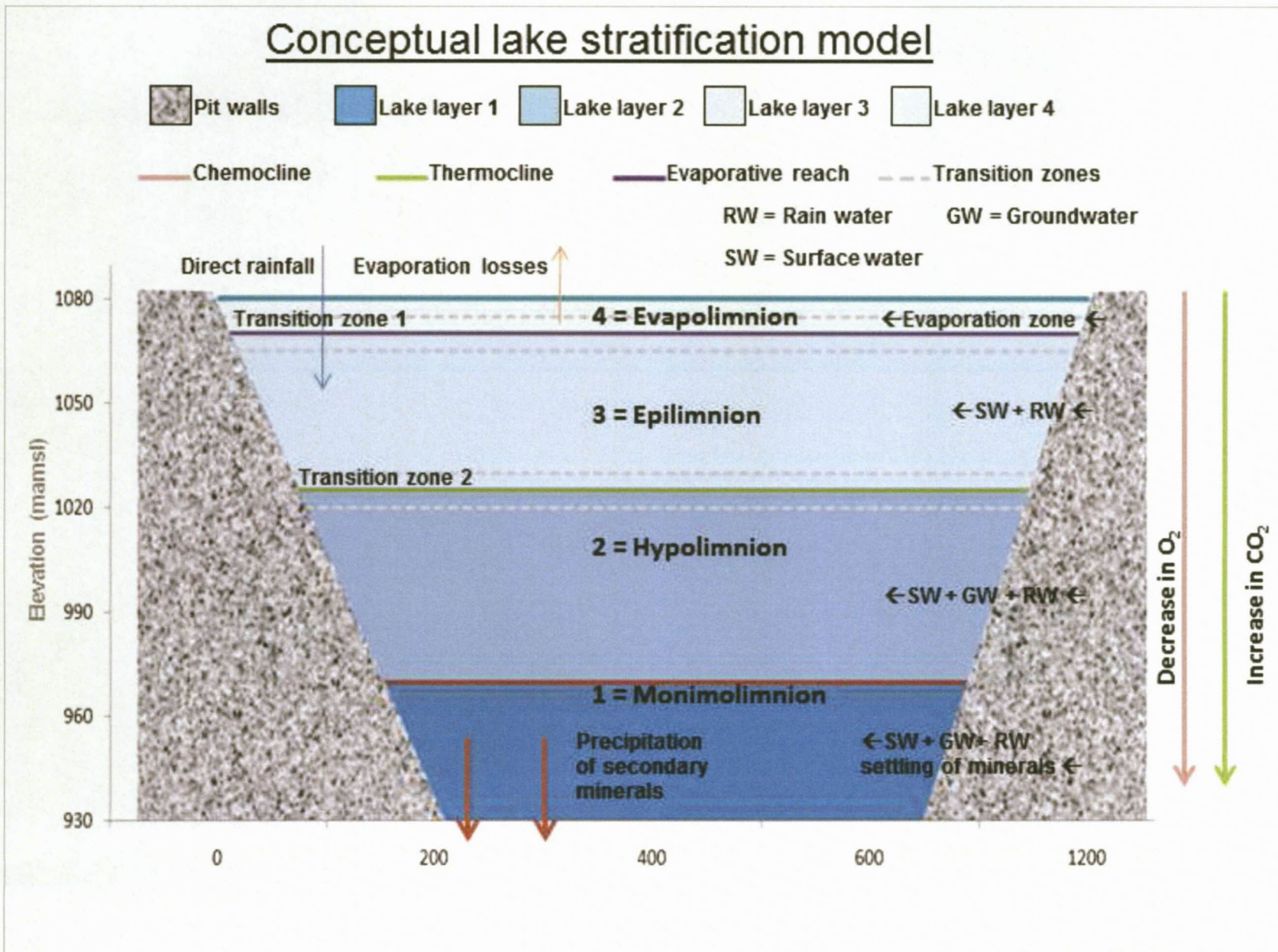
Figure 5-1     Conceptual pit lake stratification model

## 5.2 Groundwater and surface water hydrochemical description

Both surface water and groundwater chemistry in relation to water quality standards were discussed with detail in section 4.2.3 of this document. The groundwater and surface water discussion in this sub-section only looks at the general description of the water that will be used as inputs into the various stages of the geochemical models. The assumptions and input data are discussed in section 5.4.1.3.

### 5.2.1 Surface water characterisation

The surface water samples taken at sampling point SW8, SW11 and SW12 will be used as input parameters for the mixing models. Upstream samples of the Wilgespruit could not be taken as the river is diverted to avoid flooding during operation. SW11 samples the runoff occurring in the Wilgespruit during the wet season and represents the general chemistry of the stream that will contribute most of the surface water that will flood the pit post-closure. SW8 and SW12 are also described and used to cover the regional hydrochemical input from surface water.

SW8 and SW11 have an ion distribution dictating a Ca-HCO$_3$ facies for the two surface water samples with SW12 having an Mg-HCO$_3$ water type. This is evident in the Durov diagram (Figure 5-3) that shows the dominant ions in the surface water are HCO$_3$, Ca and Mg. The triangular plot on the left hand triangle of the diagram also shows that the proportional distribution of Ca, Mg, K, and Na is almost equal. Evapotranspiration has a greater influence on surface water with minerals in higher concentrations due to evaporative processes. The difference in water types and ion distribution is also shown in the Stiff diagrams of Figure 5-2.
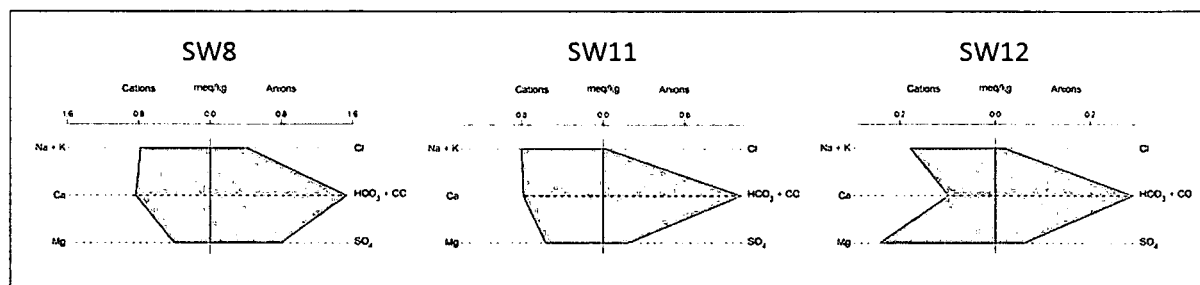


**Figure 5-2    Surface water Stiff diagrams**

The pH of the surface water is neutral with low TDS values averaging at 134.7 mg/l. Evaporation and adsorption processes from the clay minerals in the region soils contribute to the increase in ions like K, Mg, Na and HCO$_3$. These ions are regularly involved in ion exchange reaction between the clay soil minerals and the water. A detailed chemical analysis on the surface water is given during the speciation modelling with saturated and under saturated chemical species discussed.
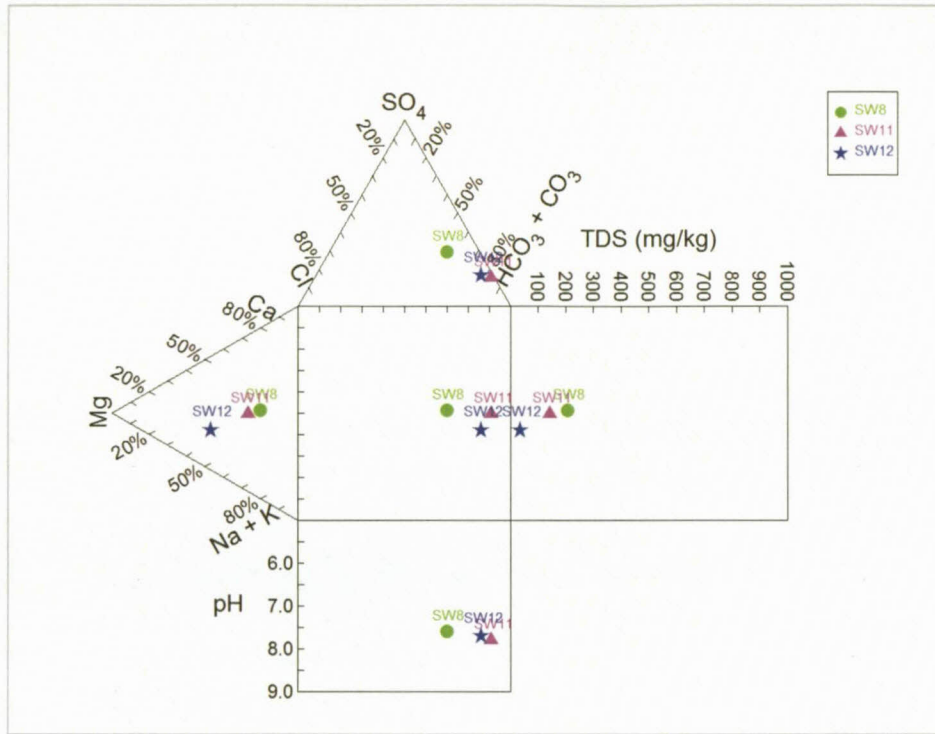
**Figure 5-3    Durov diagram of the input surface water samples**

## 5.2.2   Groundwater characterisation

The groundwater samples taken at sampling point SEDCH01, BH4, BH27, BH117 and BH116 will be used as input parameters for the mixing models. All the boreholes are located in close proximity to the open pit with dewatering allowing for all boreholes sample to be essential upstream from the pit. The 5 borehole samples thus represent a variable distribution of the expected inflows of groundwater into the pit for the first 40 to 45 years.

BH116, BH117 and BH4 has an ion distribution dictating a Mg-HCO$_3$ facies for the three groundwater samples with SEDCH01 having a Na-HCO$_3$ water type and BH27 a NA-Cl distribution. This is evident in the Durov diagram (Figure 5-5) that shows the dominant ions in the groundwater are HCO$_3$, Na, Mg and Cl. The Mg-HCO$_3$ dominating water in most cases correlates with data and observations made by Titus et al. (2009) as water from the weathered aquifers of the Bushveld Igneous Complex, this general signature of the water in the regional geological setting is discussed in the literature review (section 2.4).

The Stiff diagrams (Figure 5-4) also show the difference in water types between the samples. BH116, BH117 and BH4 have the same dominant anion species in concentrations, but Mg is more dominant in BH117 and BH4. The Stiff diagram of SEDCH01 indicates the dominant cation of Na with BH116 showing a full distribution with a slight Na and Cl dominance.
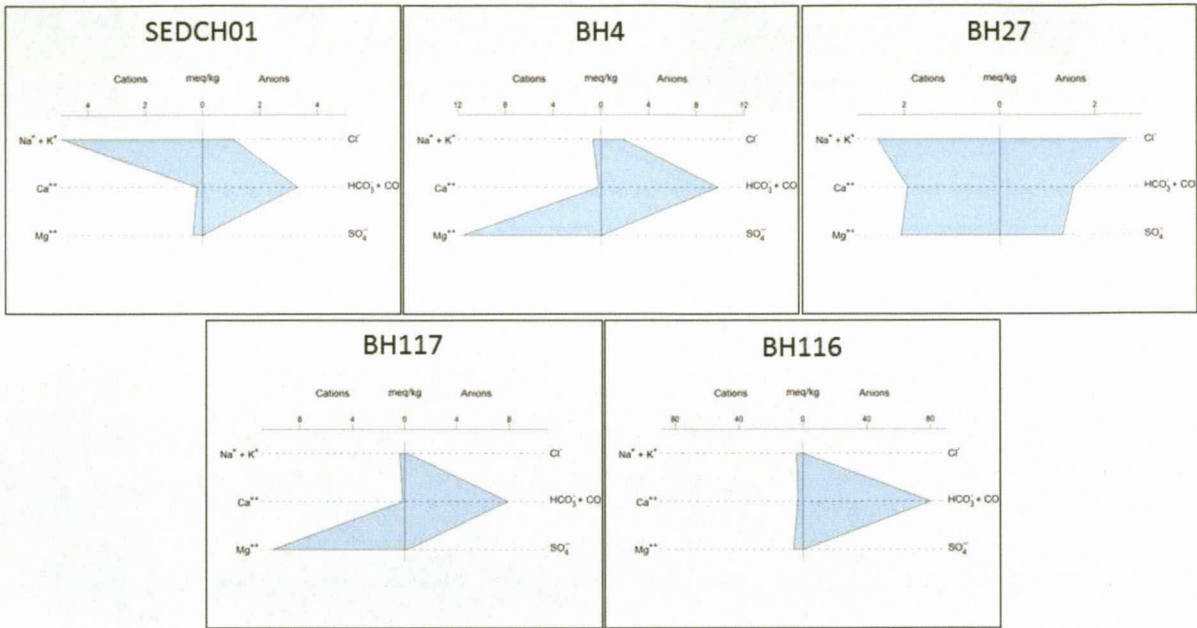
**Figure 5-4    Groundwater Stiff diagrams**

The pH of the groundwater is close to neutral at an average 8.17 with moderate TDS values accept for BH116 with high ion concentrations.  BH27 shows a possible mix of various water sources.  A detailed chemical analysis on the groundwater is given during the speciation modelling with saturated and under saturated chemical species discussed.
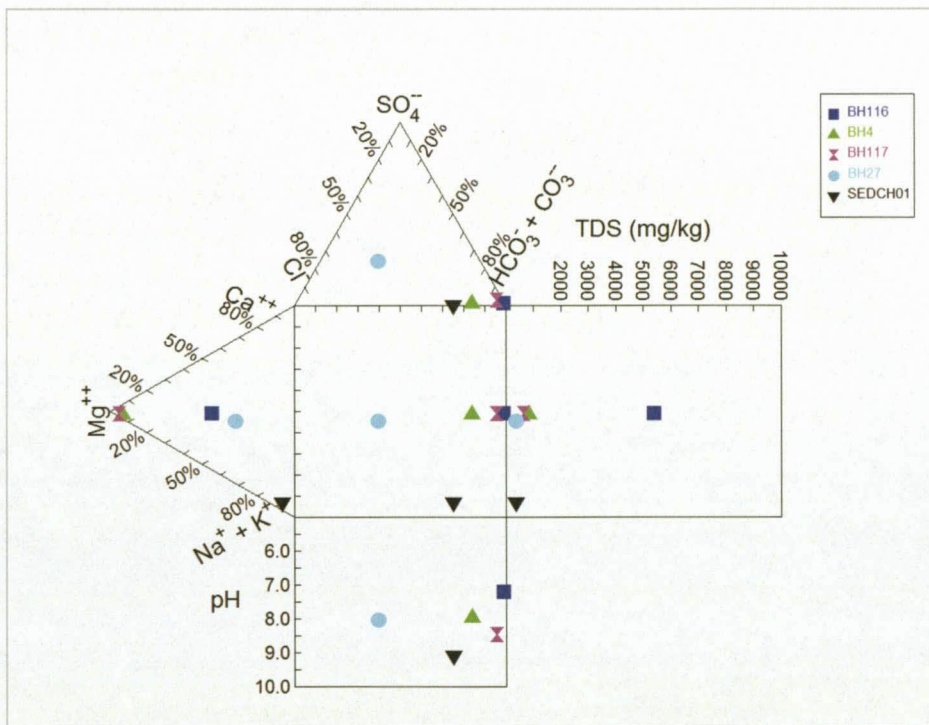


**Figure 5-5    Durov diagram of the input groundwater samples**

## 5.2.3 Rain water

The rain water sample used in the weathering and mixing simulations was compiled using a set of analogue data from Ejelonu et al. (2011) and with some added elements in small quantities to allow for reactions to take place. The added elements allows for the formation of aqueous species as observed in the field data with groundwater ultimately formed through the reactions between the rainwater and minerals. The rain water sample is a Mg-Cl water type with $Mg^{2+}$, $Cl^-$ and $HCO_3^-$ dominating the ion distribution as illustrated in the pie diagram (Figure 5-6). The rain sample has a neutral pH of 7 with a TDS of 22.2 mg/l.
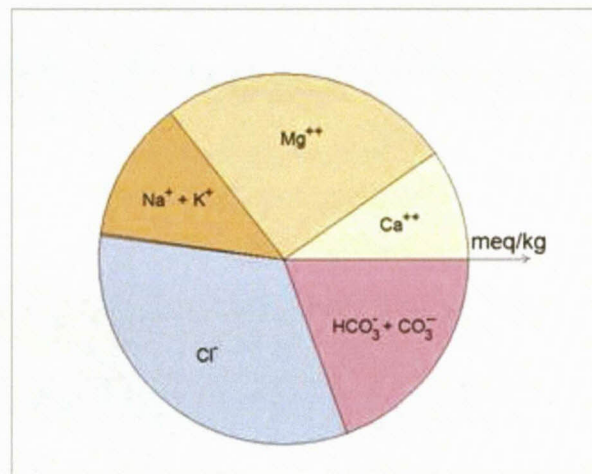


**Figure 5-6      Pie diagram illustrating the major ion distribution in the rain water sample**

## 5.3   ABA and TCLP result discussion and interpretation

Two samples from the adjacent Magazynskraal farm were sent for ABA, NAG and TCLP tests to evaluate the potential for acid generation from the mined rocks as well as any weathering product that will form when ore and the ore bearing rocks are exposed to open atmospheric processes. Sample one was taken from the UG2 Reef and samples two from the Merensky Reef, and is referred to as the UG2 and Merensky samples. The samples were not taken on the PPM property but the Reefs being mined are the same as the sampled Reefs from Magazynskraal that will from part of an extended mining project.

### 5.3.1.1  Acid production potential

Acid-base accounting is a method of determining the acid production potential of an ore body to be mined or of mine waste to be generated. The United States Environmental Protection Agency (US EPA Hessling 2013) has published a method of determining whether mine waste will produce acid. This document states that a net-neutralisation potential of less than 20, a neutralisation potential ratio of less than 1 and a negative neutralisation potential all indicate that a sample could be acid

producing. A positive neutralisation potential indicates that the gangue minerals may be able to neutralise any formed acid (Meyer & Hansen 2010).

Taking the above mentioned standards of evaluating ABA tests into account, the following conclusions regarding the two Magazynskraal samples can be made.

Both samples, GP10619 and GP10620, show a potential to produce acid with both having a Nett Neutralization Potential (NNP) that fits the US EPA criteria (Table 5-1). The positive value of the NNP however indicates that the gangue minerals also present in the samples are of such a nature and concentration that they will neutralize any acid that is produced. This gives the samples a rock type classification of type III. A Type III rock is a non-acid forming rock with a total sulphur percentage of less than 0.25%.

**Table 5-1    Acid-base accounting results**

| ABA | UG2 | Merensky |
|---|---|---|
| Paste pH | 8.3 | 7.9 |
| Total Sulphur (%) | <0.01 | 0.07 |
| Acid Potential (AP) (kg/t) | 0.31 | 2.07 |
| Neutralisation Potential (NP) | 10.21 | 15.12 |
| Nett Neutralisation Potential (NNP) | 9.9 | 13.04 |
| Neutralising Potential Ratio (NPR) (NP : AP) | 32.66 | 7.29 |
| Rock Type | III | III |

The additional buffering capacity of the regional surface and groundwater will also aid in the neutralisation of any acid produced.

## 5.3.1.2   TCLP

The same two core samples used in the ABA testing were sent to the laboratory to conduct TCLP tests on them. Results are shown in Table 5-2. Na, K, Ca, Mg, Fe, Mn are the only chemical parameters that leach in noticeable quantities with Al, Cr, Zn, and Ni also leaching but to a low concentration well in range with drinking water TWQR.

Na, Ca and K are the ions that leach the most significant which is to be expected with the high concentrations of these elements in the areas geology and soil types. The leach ability of Cr out of the sample is low and this is mirrored in the regions groundwater and surface water sample chemistry.

**Table 5-2    TCLP results**

| TCLP | UG2 | | Merensky | |
|---|---|---|---|---|
| Dry Mass Used (g) | 50 | | 50 | |
| Volume Used (mℓ) | 1000 | | 1000 | |
| pH  Value at 25°C | 5.1 | | 5.1 | |
| Electrical Conductivity in mS/m at 25°C | 35 | | 32 | |
| Units | mg/ℓ | mg/ℓ | mg/ℓ | mg/ℓ |
| TDS | 330 | 6600 | 325 | 6500 |
| $CaCO_3$ | 328 | 6 560 | 332 | 6 640 |
| $HCO_3$ | 400 | 8 000 | 405 | 8 100 |
| $CO_3^{2-}$ | <5 | <100 | <5 | <100 |
| Cl | <5 | <100 | <5 | <100 |
| $SO_4$ | <5 | <100 | <5 | <100 |
| N | <0.2 | <4.0 | <0.2 | <4.0 |
| F | <0.2 | <4.0 | <0.2 | <4.0 |
| P | <0.2 | <4.0 | <0.2 | <4.0 |
| CN [s] | <0.01 | <0.20 | <0.01 | <0.20 |
| Na | 12 | 240 | 12 | 240 |
| K | 5.6 | 112 | 9 | 180 |
| Ca | 102 | 2 040 | 69 | 1 380 |
| Mg | 8 | 160 | 22 | 440 |
| Al | 0.44 | 8.8 | 0.347 | 6.94 |
| Sb | <0.025 | <0.500 | <0.025 | <0.500 |
| As | <0.010 | <0.200 | <0.010 | <0.200 |
| Ba | 0.184 | 3.68 | 0.145 | 2.9 |
| B | <0.025 | <0.500 | <0.025 | <0.500 |
| Cd | <0.005 | <0.100 | <0.005 | <0.100 |
| Cr | 0.366 | 7.32 | <0.025 | <0.500 |
| Co | <0.025 | <0.500 | <0.025 | <0.500 |
| Cu | <0.025 | <0.500 | <0.025 | <0.500 |
| Fe | 1.53 | 31 | 1.45 | 29 |
| Pb | <0.020 | <0.400 | <0.020 | <0.400 |
| Mn | 0.741 | 15 | 1.22 | 24 |
| Ni | 0.052 | 1.04 | 0.432 | 8.64 |
| Se | <0.020 | <0.400 | <0.020 | <0.400 |
| Si | 1.18 | 24 | 4.72 | 94 |
| Ag | <0.025 | <0.500 | <0.025 | <0.500 |
| Sr | 0.437 | 8.74 | 0.069 | 1.38 |
| V | <0.025 | <0.500 | <0.025 | <0.500 |
| Zn | 0.049 | 0.98 | 0.032 | 0.64 |

## 5.4 Hydrogeochemical modelling and results

The following sub-sections of the chapter discuss the methodology and ideas behind the models and the scenario setups with simulated results listed and shortly discussed with some interpretations to a low degree. More in depth discussions and reviews of the model results are presented in Chapter 6 of this dissertation to culminate in the final research answers as well as a systems model and final conceptual model.

### 5.4.1 Methodology and scenario descriptions

#### 5.4.1.1 Numerical modelling

Conceptual models as discussed previously give a simplified but complete representation of the observed natural conditions and processes in a conceptual way to understand all aspects of a study area. From the conceptual model most factors or processes is divided into various mathematical models as in the case of groundwater flow with a simple Darcy equation or chemical equations of each mineral being weathered (Vivier 2011). All mathematical models is then combined in a systematic and simplified numerical model with certain assumption being made to accommodate data gaps as well as uncertainties in the models.

These numerical models and there outcomes can be used in either a deterministic or probabilistic manner in scientific fields. The uncertainty and accuracy of these models and the decisions made on their outcomes is however determined by the quality and quantity of the data as well as the assumptions made.

It should however be understood that numerical models does not simulate reality and cannot be seen as accurate with outcomes being true. However the numerical models, like groundwater flow and geochemical models, is important tools in establishing a working and visual understanding of the processes and variables at hand in a certain scenario, ultimately used as a decision making tool. A prime example of this is the deterministic models used in economical sciences to determine share prices of large companies. The economic models are only predictions using mathematical and conceptual knowledge of the economy to predict probable outcomes. They can however not be seen as concrete evidence or predictions of what will happen to a company's share prices, but helps individuals buying and selling these shares to make informed decisions.

#### 5.4.1.2 Data filtering and input samples

Based on spatial position, data quality and relevance to the specific study; five boreholes close to the pit were chosen to be used as inputs into the groundwater

component of the models. The same methodology was used to choose the three surface water samples to represent the chemical signature of surface inputs in the expected flooding of the pit with streams used that will contribute to the inflow post-closure. Data was filtered to eliminate outliers and possible laboratory mistakes with charge imbalance error calculations as well as the substitution of non-numerical values with relevant data.

### 5.4.1.3 Model input data and assumptions

Surface water and groundwater sampling points both upstream and downstream from the pit was selected based on their positions relative to the open pit. They were then speciated and also mixed along with weathering models to predict the chemistry expected in the pit lake. To remain both conservative in approach while remaining accurate and true to the system view as developed in the conceptual model and to compensate for data limitations, certain model inputs and assumptions were made. These assumptions are listed in Table 5-3. The main assumption should however be clearly noted:

**To accommodate the geochemical investigation of the pit flooding, it is assumed by the author that the pit flooding event will occur as noted in the short description of the numerical flow model at an average rate of 50 ℓ/s surface water, 60 ℓ/s groundwater and 47 ℓ/s rainfall, within a period of approximately 100 years.**

Assumptions made during data processing, data input and the model setups and simulations were made to follow a conservative approach to simulate accurate and realistic processes within hydrochemical and geochemical processes within the limits of the software.

**Table 5-3    List of the main model assumptions**

| Data processing | | | |
|---|---|---|---|
| **Assumption** | **Description** | **Data** | **Source** |
| Data on detection limit divided by 2 | All laboratory data for water analysis with values below the lab detection limit were assumed and calculated to be half of the detection limit | All laboratory results | AGES (Pty) Ltd, PPM (Pty) Ltd |
| XRD and XRF data from Magazynskraal used for PPM model | Magazynskraal mine will exploit the same mineral resources and ore as PPM and thus mineralogical data from tests were assumed to be the same as PPM ore mineralogy | Laboratory results | AGES (Pty) Ltd, PPM (Pty) Ltd |
| Elemental compound conversions | $NO_3$ as N, $NO_2$ as N, $PO_4$, $NH_3$ as N and As respectively converted to $NO_3$, $NO_2$, $HPO_4$, $NH_3$ and $AsH$ due to software and simulation constraints on aqueous species | Laboratory results | AGES (Pty) Ltd, PPM (Pty) Ltd |
| **Pit flooding dynamics** | | | |
| **Assumption** | **Description** | **Data** | **Source** |
| Groundwater will only contribute for first 40 to 45 years of flooding up to a water level of 1030 mamsl | As stated in the numerical groundwater flow model and due to permanent impacts from dewatering of the pit, it is calculated that the original groundwater level of 1060 mamsl will not be reached and thus for modelling concept purposes it is assumed that groundwater will only contribute for the first 40 to 45 years of flood water up to ±1030 mamsl. | Numerical groundwater flow model | (Meyer & Hansen 2010) |
| Surface water contribution to pit flooding of 50 ℓ/s | Surface water from drainage lines during summer rainfall season and mostly from the Wilgespruit, will contribute 50 ℓ/s to the inflow of water into the pit | Numerical groundwater flow model | (Meyer & Hansen 2010) |
| Groundwater contribution to pit flooding of 60 ℓ/s | Groundwater from the aquifer in which the pit is excavated will contribute 60 ℓ/s to the inflow of water into the pit | Numerical groundwater flow model | (Meyer & Hansen 2010) |
| Direct rain water contribution to pit flooding of 47 ℓ/s | Direct rainfall during summer rainfall season will contribute 47 ℓ/s to the inflow of water into the pit | Numerical groundwater flow model | (Meyer & Hansen 2010) |
| **Models** | | | |
| **Assumption** | **Description** | **Data** | **Source** |
| Rock mass water volume interaction | 1 l of rain water will be in contact with 200 g of mineralogy during groundwater flow and geochemical interactions | Model input | Author assumption |
| Evaporative losses will be 60% | Evaporative losses will be 60% of top 3 m due to an annual evaporative volume for the catchment of 1849 (1.8 m) | Model input | |
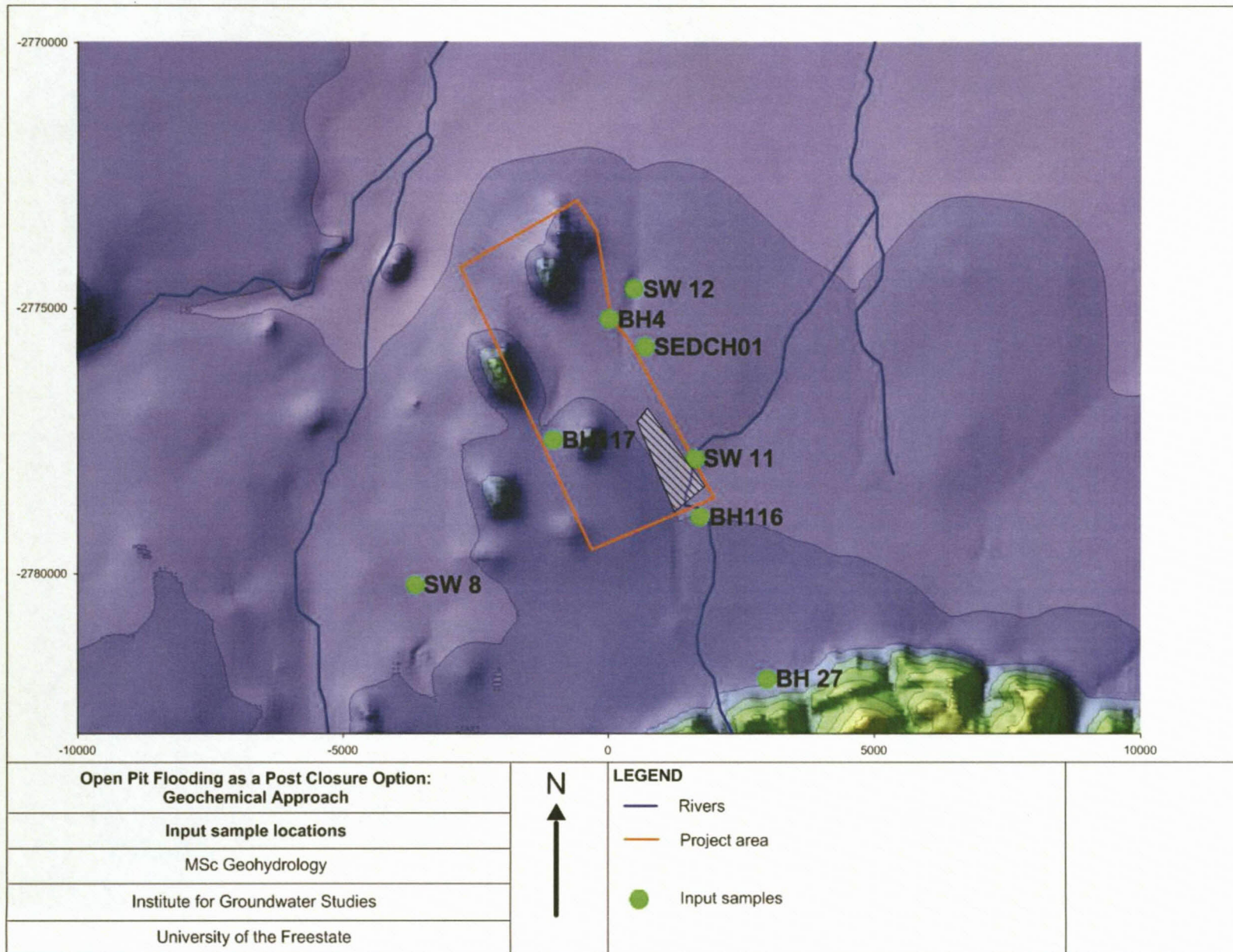
**Figure 5-7    Map showing the locations of sample points used as inputs into the geochemical model**

### 5.4.1.4  Input sampling points and water chemistry

Three surface water and five groundwater samples has been used as input into the flooding model with two pit seepage samples also analysed to compare weathering results with the existing weathering product sampled at the bottom of the pit during operation.  As will be mentioned, the nitrate levels (and TSS in the case of the pit samples) of the samples will not be used for comparison as outside sources like blasting and agricultural activity can lead to these parameters being elevated   A rainfall sample was simulated based on analogue data from Ejelonu et al. (2011) and used as the water to simulate the natural weathering of the main mineralogy of the region.  Rainwater, surface water, groundwater and rainfall chemistry are shown in Table 5-4 with the locations shown in Figure 5-7

### 5.4.1.5  Mineralogical data

The main geology and XRD results from the neighbouring mine core samples were used to set up a proportional set of mineralogy used in the weathering simulations. The minerals were simulated in various different proportions as discussed in the weathering model intro to represent a rock sample from the geological setting.

The minerals used in the weathering models are:

- Fayalite
- Forsterite
- Enstatite
- Ferrosilite
- Anorthite
- K-feldspar
- Nepheline
- Biotite (Phlogopite)
- Fluorite
- Smectite (Montmorrilonite)

**Table 5-4    Input and comparison sample chemistry used in model**

| Water source | | Surface water | | | Rain water | Groundwater | | | | | Pit seepage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample ID | | SW8 | SW11 | SW12 | Rain water | BH116 | BH27 | SEDCH01 | BH4 | BH117 | Pit | Pit North | Minimum | Maximum | Average |
| Water type | | Ca-HCO3 | Ca-HCO3 | Mg-HCO3 | Mg-Cl | Mg-HCO3 | Na-Cl | Na-HCO3 | Mg-HCO3 | Mg-HCO3 | Mg-NO3 | Mg-NO3 | | | |
| $HCO_3$ | mg/l | 95.0 | 84.0 | 18.0 | 9.2 | 4990.0 | 95.8 | 205.2 | 607.8 | 489.7 | 282 | 63 | 9 | 4990 | 631 |
| Ca | mg/l | 17.0 | 16.0 | 2.0 | 1.2 | 69.5 | 39.4 | 4.0 | 4.5 | 3.1 | 57 | 61 | 1 | 69 | 25 |
| Cl | mg/l | 15.1 | 0.7 | 0.7 | 7.3 | 18.2 | 95.8 | 38.6 | 65.2 | 8.8 | 12.2 | 13.0 | 0.7 | 95.8 | 25.1 |
| F | mg/l | 2.2 | 1.8 | 0.4 | 0.1 | 2.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.29 | 0.31 | 0.05 | 2.23 | 0.72 |
| Mg | mg/l | 5.0 | 7.0 | 3.0 | 2.0 | 71.6 | 25.6 | 4.1 | 143.1 | 124.5 | 82 | 68 | 2 | 143 | 49 |
| K | mg/l | 9.0 | 3.0 | 2.0 | 0.7 | 1.0 | 8.3 | 5.4 | 2.8 | 0.9 | 0.9 | 3.9 | 0.7 | 9.0 | 3.4 |
| Na | mg/l | 13.0 | 17.0 | 3.0 | 1.4 | 87.3 | 55.2 | 111.5 | 14.1 | 8.7 | 67 | 97 | 1 | 112 | 43 |
| $SO_4$ | mg/l | 39.0 | 12.0 | 3.0 | 0.1 | 28.2 | 64.3 | 0.1 | 5.7 | 11.3 | 49 | 212 | 0 | 212 | 39 |
| $NO_3$ | mg/l | 1.8 | 0.7 | 4.0 | 0.02 | 122.2 | 5.5 | 0.9 | 15.5 | 24.3 | 284.50 | 362.44 | 0.02 | 362.44 | 74.71 |
| $NO_2$ | mg/l | - | 0.42 | - | 0.002 | - | 0.48 | 0.64 | - | - | - | 2.79 | 0.00 | 2.79 | 0.86 |
| $NH_4$ | mg/l | 0.423 | - | - | 0.010 | 0.009 | 0.112 | 7.253 | 0.829 | - | 0.010 | - | 0 | 7 | 1 |
| $HPO_4$ | mg/l | 0.040 | 0.040 | 0.040 | 0.090 | 0.038 | 0.013 | 0.096 | 0.038 | 0.439 | 0.04 | 0.04 | 0.01 | 0.44 | 0.08 |
| $SiO_{2(a)}$ | mg/l | - | 3.400 | - | 0.100 | - | - | - | - | - | - | 2.9 | 0.1 | 3.4 | 2.1 |
| Al | mg/l | 4.190 | 0.023 | 0.141 | 0.020 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 4.19 | 0.39954 55 |
| $AsH_{3(a)}$ | mg/l | - | 0.010 | - | - | - | 0.002 | 0.012 | - | - | - | 0.010 | 0.002 | 0.012 | 0.008 |
| Co | mg/l | - | 0.001 | - | - | 0.002 | 0.001 | 0.001 | 0.001 | - | 0.002 | 0.001 | 0.001 | 0.002 | 0.001 |
| Cu | mg/l | - | 0.001 | - | - | 0.001 | 0.024 | 0.027 | 0.010 | 0.001 | 0.001 | 0.001 | 0.001 | 0.027 | 0.008 |
| Fe | mg/l | 9.881 | 0.020 | 0.320 | 0.050 | 0.003 | 0.008 | 0.020 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 9.881 | 0.938 |
| Pb | mg/l | - | 0.005 | - | 0.060 | 0.003 | 0.030 | 0.010 | 0.012 | 0.001 | 0.001 | 0.005 | 0.0005 | 0.06 | 0.014 |

| Water source | | Surface water | | | Rain water | Groundwater | | | | | Pit seepage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample ID | | SW8 | SW11 | SW12 | Rain water | BH116 | BH27 | SEDCH 01 | BH4 | BH117 | Pit | Pit North | Minimum | Maximum | Average |
| Water type | | Ca-HCO3 | Ca-HCO3 | Mg-HCO3 | Mg-Cl | Mg-HCO3 | Na-Cl | Na-HCO3 | Mg-HCO3 | Mg-HCO3 | Mg-NO3 | Mg-NO3 | | | |
| Mn | mg/l | 0.061 | 0.003 | 0.001 | - | 0.001 | 0.004 | 0.007 | 0.027 | 0.001 | - | 0.001 | 0.001 | 0.061 | 0.012 |
| Ni | mg/l | - | 0.002 | - | 0.020 | 0.002 | 0.021 | 0.007 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.021 | 0.006 |
| Se | mg/l | - | 0.010 | - | - | - | 0.002 | 0.012 | - | - | - | 0.010 | 0.002 | 0.012 | 0.008 |
| Zn | mg/l | - | 0.004 | - | 0.250 | 0.014 | 0.017 | 0.037 | 0.002 | 0.002 | 0.002 | 0.005 | 0.002 | 0.25 | 0.037 |
| pH | | 7.6 | 7.8 | 7.7 | 7 | 7.22 | 8.05 | 9.11 | 7.99 | 8.48 | 8.3 | 8.3 | 7.0 | 9.1 | 8.0 |

100

### 5.4.1.6 Note on continuous model calibration

In the scientific community modelling of natural systems occurs with calibration of models through evaluating correlation coefficients and mean square root errors between simulated and measured data. However in geochemical modelling the approach is different due to the measurement of change in parameters being controlled by a vast range of factors having impacts on the equilibrium of both the hydrochemical system and the equilibrium of equations with the interaction of the various phases within the model.

TDS, EC and Alkalinity can most of the time be used as parameters to evaluate the calibration level of your model setup. However, errors of up to 500 mg/l in the case of TDS can be accepted due to the concentrated environment in which most models are simulated. An example of the difficulty of calibration is the simulation of a simple weathering model of a specific geology, it will not be practical to simulate the model with large masses of water and material, thus smaller quantities is used. Although smaller quantities is used the rate at which the minerals weather remains the same and thus the amount of weathered material is still the same with a smaller amount of water and thus saturation of certain elements is achieved faster. TDS and EC values are thus expected to be varied in the modelled environment.

Thus in the geochemical discipline it is recommended that constant and continuous monitoring of input parameters and the model results should be done with scientific and chemical knowledge being the main calibration tool. The testing of the accuracy of parameters and variables can also be done through sensitivity analysis evaluating the effect of small changes to the system. The scientific design on whether your system is behaving like it should, will determine the accuracy of your calibration and ultimately your model simulations of real world reactions and systems. It is a systems thinking method that should be maintained throughout the model and in risk assessments of the outcomes with regular model updates during and after life of project also important.

In this dissertation a trial and error approach was followed to the modelling of the system with constant sensitivity analysis and changes to them, parameters and rates to achieve a system in which a close as possible natural environment can be modelled to evaluate the processes involved. In Chapter 6 a systems thinking template, describing in full the modelling path followed and the process of trial and error calibration in this research project, is compiled and illustrated for future use by groundwater specialists with a limited but adequate knowledge of geochemical aspects as in the case with the author and researcher of this document and project.

### 5.4.1.7 Mineral weathering model

The minerals mentioned in section 5.1.2.2 was allowed to react with a rainwater sample as shown in Table 5-4 in both steady state and transient time to allow the assessment of different scenarios and also sensitivity on parameters of the system. Sensitivity analyses were simulated with alterations of mineral weathering rates, allowance and disallowance of precipitation as well as simulations with sliding fugacity of oxygen and carbon dioxide.

The following scenarios and sensitivity simulations were done:

1. Scenario W1: 21 Day laboratory scenario reacting the main minerals with rain water and assessing the processes and outcomes under fixed atmospheric $fO_2$ and solution content $fCO_2$.

2. Scenario W2: Transient state simulation of weathering under atmospheric conditions for 100 years (Simulation W2a) and 1000 years (Simulation W2b) to assess the effect of time on fluid chemistry.

3. Scenario WSens1: Sensitivity analysis on scenario W1 to assess the sensitivity of the system and fluid chemistry on changes in mineral surface areas. An increase of minerals surface area in simulation WSens1a and decrease in surface area in WSens1b.

4. Scenario WSens2: Transient state sensitivity analysis on the reaction of the system and resultant fluid chemistry on change in fugacity of $CO_{2(g)}$ and $O_{2(g)}$ over a period of 100 years. Fixed $fO_{2(g)}$ and increased $fCO_{2(g)}$ in simulation WSens2a and a decreasing $fO_{2(g)}$ and increasing $fCO_{2(g)}$ in WSens2b. Mineralogy and other parameters based on Simulation W2a.

5. Scenario WSens3: Transient state sensitivity analysis on the system on changes in reaction dissolution rates of the silicate minerals including K-feldspar, Nepheline and Anorthite. A decrease in weathering rates in simulation WSens3a and an increase in WSens3b. Parameters based on results of Scenario WSens2b.

6. Scenario W3: Calibrated system with results of transient weathering over 100 years under fixed $fCO_{2(g)}$ and slightly decreasing $fO_{2(g)}$.

### 5.4.1.8 Mixing models

Due to an expected meromictic pit lake environment and dynamic, 4 mixing model scenarios were simulated:

1. Scenario M1: Mixing of surface water and rainwater under atmospheric

conditions at different proportions to simulate the inflow mixing of waters for 50 years to form the epilimnion once groundwater inflow has stopped after the first 40 to 45 years.

2. Scenario M2: Mixing of surface water, rainwater and groundwater at atmospheric conditions at different proportions to simulate the inflow mixing of waters for the first 45 years of pit flooding that will eventually form the hypolimnion.

3. Scenario M3: Evaporation scenario to simulate the effect of evaporation and atmospheric processes on the exposed water chemistry for 12 hours (time in which all natural elements are present during day time) with 66% evaporation of water to form the dynamic evapolimnion. This simulation is done under atmospheric fugacity and higher temperatures.

4. Scenario M4: Mixing of hypolimnion waters under reducing conditions to simulate the expected water chemistry of the monimolimnion under lower temperatures and lower $fO_{2(g)}$ and higher $fCO_{2(g)}$.

## 5.4.2 Speciation model

To evaluate the current system chemical parameters and to compile an understanding of the chemical species involved in the dynamic processes of the hydrochemical environment, speciation models were done on the input samples both surface water and groundwater. The speciation serves a double purpose to evaluate the current state of saturation and potential secondary mineral formation as well as to evaluate which minerals are most frequently dissolved within the geochemical environment. A comparison between the groundwater sample chemistry and the results of the weathering model is also important to understand the dynamics of the system. The geochemical modelling software, Geochemists Workbench®, was used to run a speciation model of the groundwater and surface water of the PPM area in order to determine the potential of mineral formation out of the water.

**Table 5-5    Summary of dominant aqueous species present in the PPM water**

| Aqueous Species | Groundwater | Surface water | Pit seepage |
|---|---|---|---|
| Al(OH)$_4$ | | X* | |
| Ca | X | X | X |
| CaHCO$_3$ | X | | |
| CaSO$_4$ | | | X |
| Cl | X | X | X |
| CO$_{2(aq)}$ | X | | |
| F | X | X | |

| Aqueous Species | Groundwater | Surface water | Pit seepage |
|---|---|---|---|
| Fe | | X | |
| $HCO_3$ | X | X | X |
| K | X | X | |
| Mg | X | X | X |
| $MgCO_3$ | X | | |
| $MgHCO_3$ | X | | |
| $MgSO_4$ | | | X |
| Na | X | X | X |
| $NaHCO_3$ | X | | |
| $NO_3$ | X | | X |
| $SO_4$ | X | X | X |

*Aqueous species present in water marked with X

Table 5-5 shows the dominant aqueous species in the groundwater, surface water and pit samples taken from the PPM area.

In the groundwater samples, the model concludes to a Na-$HCO_3$, Mg-$HCO_3$ and Na-Cl water types as indicated in Table 5-4 with Na, $HCO_3$, Cl, Ca, $SO_4$, Mg and F being the most abandoned ions and this is evident in the dominant aqueous species (Table 5-5). The higher concentrations of the above mentioned ions in combination with the lesser saturated species leads to the supersaturated states of some minerals as indicated in Table 5-6. The following minerals are the main minerals that have the potential to precipitate out of solution in the current groundwater system with super saturated states in at least three of the five groundwater samples:

- Fluorapatite

- Huntite

- Magnesite

- Whitlockite

- Calcite

- Cuprite

- Aragonite

Over time these above mentioned minerals and chemical compounds can precipitate out of solution to form secondary minerals, but the natural environment and kinetic constraints will however prevent this from happening with constant recharge and mixing allowing for dissolution and new reactions. The model indicates absence of clay minerals despite the dominance of clay minerals in the top soil layer and this is

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due to dissolution and exchange reactions with the soils in the region. The pH of the average groundwater is 8.17 that will indicate that the activity and oxidation of heavy metals is unlikely.

The surface water samples used in the model shows lower TDS values than groundwater with the main anions and cations present in lower concentrations. The lower ion content of the surface water could be explained by the periods in which water is present for sampling. Sampling of the surface water streams can only occur during rain periods and in the summer with flood events. The runoff allows for less contact with the geological and pedological environment and thus the solution of minerals into the water is not as prominent as in the slower moving groundwater scenario. The Ca/Mg-HCO$_3$ water type shown in the four surface water samples is typical of stream water chemistry with Ca, Mg, Na and Cl being the most active ions within a natural environment. The water type is dictated and formed through the most prominent ions in the surface water of Na, Cl, HCO$_3$, F, Ca, SO$_4$, Mg and K.

The aforementioned ions are regularly involved in adsorption and exchange reaction with the region clay soils and minerals. Due to these activities the expected secondary minerals forming are not necessarily the minerals present in the highest saturated or super saturated states. The exchange of ions with soil minerals and the formation of clay minerals are more viable in the observed environment of the Pilanesberg area. The minerals in super saturated states within most of the surface water samples are:

- Fluorapatite

- Diaspore

- Whitlockite

However as mentioned due to the observed environment (clay minerals in regional soils along flow channels) and exchange reaction the following minerals will be the most likely to form out of the surface solutions:

- Muscovite

- Strontianite

- Kaolinite

- Cuprite

These last mentioned four minerals are saturated and present in SW11. SW11 will contribute the largest part of the surface water flowing into the open pit during the post-closure flooding. The super saturation of F in both surface water and groundwater and in particular the mineral Fluorapatite can be due to the high fluoride

concentrations in the geology of the Pilanesberg Complex and thus a larger portion of fluorite is simulated to participate in weathering simulations.

The speciation of pit seepage samples indicates a combination between surface water and groundwater.

Table 5-6    Saturated minerals

**Pit seepage**

| Mineral | Log Q/K Pit North | Log Q/K Pit |
|---|---|---|
| HgSe | 29.73 | |
| Fluorapatite | 16.88 | 16.68 |
| Antigorite | 15.39 | |
| PbSe | 9.66 | |
| Hydroxyapatite | 8.15 | 7.99 |
| Saponite-Mg | 3.20 | |
| Whitlockite | 3.15 | 3.05 |
| Saponite-Ca | 3.13 | |
| ZnSe | 2.99 | |
| Saponite-Na | 2.78 | |
| Cuprite | 2.76 | 0.93 |
| Saponite-K | 2.58 | |
| Talc | 2.48 | |
| Dolomite | 2.01 | 3.41 |
| Witherite | 1.90 | |
| Saponite-H | 1.88 | |
| Phlogopite | 1.23 | |
| Chrysotile | 1.17 | |
| Strontianite | 0.78 | |
| Barite | 0.65 | |
| Calcite | 0.40 | 1.05 |
| Aragonite | 0.24 | 0.88 |
| Huntite | | 1.52 |
| Magnesite | | 0.74 |

**Surface water**

| Mineral | Log Q/K SW8 | Log Q/K SW11 | Log Q/K SW12 |
|---|---|---|---|
| Fluorapatite | 14.25 | 15.17 | 10.20 |
| Hydroxyapatite | 3.90 | 5.12 | 0.73 |
| Hercynite | 3.27 | | |
| Gibbsite | 2.74 | 0.29 | 1.19 |
| Diaspore | 1.95 | | 0.40 |
| Vivianite | 1.26 | | |
| Boehmite | 1.11 | | |
| Siderite | 1.05 | | |
| Whitlockite | 0.92 | 1.60 | |
| MnHPO4(c) | 0.03 | | |
| Corundum | 0.02 | | |
| Cuprite | | 1.84 | |
| Witherite | | 1.82 | |
| Muscovite | | 1.07 | |
| Strontianite | | 0.92 | |
| Kaolinite | | 0.56 | |
| Co2SiO4 | | 0.34 | |
| CoSe | | 0.30 | |
| HgSe | | 31.74 | |
| ZnSe | | 2.59 | |
| PbSe | | 9.53 | |

**Groundwater**

| Mineral | Log Q/K BH4 | BH27 | BH116 | BH117 | SEDCH01 |
|---|---|---|---|---|---|
| Fluorapatite | 9.87 | 13.93 | 13.40 | 13.62 | 15.72 |
| Dolomite | 2.58 | 1.47 | 3.21 | 3.16 | 2.40 |
| Huntite | 1.20 | | 1.02 | 2.46 | |
| Magnesite | 0.99 | | 0.59 | 1.33 | 0.16 |
| Hydroxyapatite | 0.98 | 5.68 | 2.76 | 5.25 | 7.94 |
| PbSe | | 9.55 | | | 9.52 |
| ZnSe | | 2.67 | | | 4.88 |
| Whitlockite | | 1.71 | 0.34 | 1.52 | 2.85 |
| Calcite | | 0.26 | 0.99 | 0.20 | 0.61 |
| Cuprite | | 0.11 | 0.49 | 2.53 | |
| Aragonite | | 0.09 | 0.83 | 0.03 | 0.45 |

### 5.4.3 Mineral weathering models

Weathering models were simulated to compare with field results and to evaluate the transient effect of weathering products on the water chemistry. A rainfall sample was compiled based on values sourced from Ejelonu et al. (2011). This rainfall sample as shown in Table 5-4 has an Mg-Cl water type with TDS content of 21.94 mg/$\ell$ and a neutral pH of 7. The rainwater was allowed to react with the main minerals in the local geology of the PPM pit area over different periods with precipitation allowed to occur. The mineral data used in the weathering model is shown in Table 5-7. The mineral abundance and sample mass was determined based on the XRD result weight percentages with a bulk sample used to show a full weathering cycle if water recharges through all layers.

**Table 5-7  Mineral proportions for weathering models**

| Mineral | Input (g) | Surface area[5] (cm²/g) | Dissolution/weathering rate (mol/cm²/s) | Reference/Comment |
|---|---|---|---|---|
| Fayalite | 12.5 | 300 | $1\times10^{-13.9}$ | (M. J. Wilson 2004) |
| Forsterite | 20 | 300 | $1\times10^{-13.9}$ | (M. J. Wilson 2004) |
| Enstatite | 25 | 300 | $1\times10^{-16.4}$ | (M. J. Wilson 2004) |
| Ferrosilite | 12.5 | 300 | $1\times10^{-16.4}$ | (M. J. Wilson 2004) |
| Anorthite | 50 | 800 | $1\times10^{-12.5}$ | (White & S. L. Brantley 1995) |
| K-feldspar | 50 | 800 | $1\times10^{-16.6}$ | (M. J. Wilson 2004) |
| Nepheline | 15 | 300 | $1\times10^{-20}$ | Slightly slower than K-Feldspar |
| Biotite (Phlogopite) | 10 | 300 | $1\times10^{-17}$ | (White & S. L. Brantley 1995) |
| Fluorite | 2.5 | 300 | $1\times10^{-12}$ | (Cama et al. 2010) |
| Smectite | 2.5 | 300 | $1\times10^{-17}$ | Same as Biotite |
| **Total** | **200** | **4000** | | |

Six scenarios in total were simulated in the weathering model to evaluate the sensitivities on parameter change and the processes involved in the general weathering of the regional mineralogy to form the sampled groundwater. Scenario W1 to W3 and sensitivity analysis WSens1 to WSens3 follows the trial and error calibration path as mentioned before to compile a true understanding of the geochemical environment processes. This path is followed to illustrate to non-geochemical orientated scientists the way in which to develop an understanding of the processes involved without a strong chemical background.

The results of all the weathering simulations is summarised in Table 5-8 and is compared to TCLP test results as well as the ranges observed in the groundwater samples from field data.

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5 Surface areas are for fresh samples from whole rock mineralogy as sourced from the listed references

**Table 5-8    Summary of laboratory results, groundwater field data and the results of the weathering model simulations for each scenario**

| Para-meter | Unit | TCLP results | | Groundwater limits | | | W1 | WSens1 | | W2 | | WSens2 | | WSens3 | | W3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | UG2 | Meren sky | Min | Max | Mean | | a | b | a | b | a | b | a | b | |
| $HCO_3$ | mg/l | 400.0 | 405.0 | 95.8 | 4990 | 1277 | 68.1 | 68.2 | 68.1 | 56.5 | 57.0 | 335.6 | 335.6 | 335.6 | 335.8 | 58.9 |
| Ca | mg/l | 102.0 | 69.0 | 3.1 | 69.5 | 24.1 | 24.8 | 24.7 | 24.8 | 11.8 | 11.6 | 0.6 | 0.6 | 0.6 | 0.6 | 10.2 |
| Cl | mg/l | <5 | <5 | 8.8 | 95.8 | 45.3 | 7.3 | 7.3 | 7.3 | 7.4 | 7.4 | 7.4 | 7.4 | 7.4 | 7.4 | 7.4 |
| Mg | mg/l | 8.0 | 22.0 | 4.1 | 143.1 | 73.8 | 1.9 | 1.9 | 1.9 | 8.0 | 7.9 | 79.5 | 79.5 | 79.5 | 79.4 | 7.8 |
| K | mg/l | 5.6 | 9.0 | 0.9 | 8.3 | 3.7 | 0.7 | 0.8 | 0.7 | 1.3 | 1.2 | 3.9 | 3.9 | 3.9 | 3.9 | 6.6 |
| Na | mg/l | 12.0 | 12.0 | 8.7 | 111.5 | 55.4 | 1.4 | 1.4 | 1.4 | 1.5 | 2.2 | 1.5 | 1.5 | 1.5 | 1.8 | 1.8 |
| $SO_4$ | mg/l | <5 | <5 | 0.05 | 64.31 | 21.92 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $NO_3$ | mg/l | <0.2 | <0.2 | 0.89 | 122.2 | 33.68 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| $NO_2$ | mg/l | | | | | | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 |
| $NH_4$ | mg/l | | | | | | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| Al | mg/l | 0.44 | 0.34 | 0.003 | 0.003 | 0.003 | 0.011 | 0.011 | 0.012 | 0.009 | 0.009 | 0.008 | 0.008 | 0.008 | 0.008 | 0.005 |
| pH | | 5.10 | 5.10 | 7.22 | 9.11 | 8.17 | 8.02 | 8.02 | 8.02 | 7.94 | 7.94 | 7.47 | 7.47 | 7.47 | 7.47 | 7.96 |
| $HPO_4$ | mg/l | <0.2 | <0.2 | 0.01 | 0.44 | 0.12 | $7.38 \times 10^{-8}$ | $7.39 \times 10^{-8}$ | $7.38 \times 10^{-8}$ | $2.70 \times 10^{-7}$ | $2.73 \times 10^{-7}$ | $2.23 \times 10^{-4}$ | $2.23 \times 10^{-4}$ | $2.23 \times 10^{-4}$ | $2.23 \times 10^{-4}$ | $3.16 \times 10^{-7}$ |
| Pb | mg/l | <0.020 | 0 | 0.001 | 0.030 | 0.011 | 0.060 | 0.060 | 0.060 | 0.060 | 0.060 | 0.060 | 0.060 | 0.060 | 0.060 | 0.060 |
| Zn | mg/l | 0.049 | 0.032 | 0.002 | 0.037 | 0.014 | 0.250 | 0.250 | 0.250 | 0.252 | 0.252 | 0.252 | 0.252 | 0.251 | 0.251 | 0.251 |
| V | mg/l | <0.03 | <0.03 | | | | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Ni | mg/l | 0.052 | 0.432 | 0.002 | 0.021 | 0.007 | 0.010 | 0.010 | 0.010 | 0.014 | 0.014 | 0.020 | 0.020 | 0.020 | 0.020 | 0.013 |
| F | mg/l | <0.2 | <0.2 | 0.1 | 2.2 | 0.6 | 3.1 | 3.1 | 3.1 | 4.4 | 4.5 | 26.4 | 26.4 | 26.4 | 26.4 | 4.8 |
| $Fe^{2+}$ | mg/l | 1.53 | 1.45 | 0.003 | 0.020 | 0.007 | 0.048 | 0.048 | 0.049 | 0.068 | 0.067 | 0.418 | 0.418 | 0.418 | 0.418 | 0.079 |
| $Fe^{3+}$ | mg/l | | | | | | $1.0 \times 10^{-8}$ | $1.0 \times 10^{-8}$ | $1.16 \times 10^{-8}$ | $1.06 \times 10^{-8}$ | $1.06 \times 10^{-8}$ | $1.11 \times 10^{-8}$ | $1.11 \times 10^{-8}$ | $1.11 \times 10^{-8}$ | $1.11 \times 10^{-8}$ | $1.16 \times 10^{-8}$ |
| $SiO_{2(aq)}$ | mg/l | 1.18 | 4.72 | | | | 6.20 | 6.20 | 5.67 | 6.18 | 6.18 | 6.11 | 6.11 | 6.11 | 6.11 | 6.18 |

## 5.4.3.1  Scenario W1

With an evaluation of the mineralogy at hand in the weathering models and the regional geology of the study area it is shown that precipitation of super saturated states as well as the buffering effect of the hydroxide containing clay minerals are the main influences on the chemical species concentrations and the system parameters.

Minerals at different proportions (Table 5-7) in a 200 g sample were reacted with 1 litre of rainwater over a period of 21 days to assess and simulate the influence of time within a laboratory environment on the weathering reactions and products chemical character.

The buffering reactions of the clay minerals and to a lesser extent the feldspar group minerals allowed for a rapid increase of the pH in the 21 day transient scenario as indicated in Figure 5-8.  During a 21 day simulation the pH rises from 7 to a maximum of 8.03 after which the system stabilises at pH 8.02.
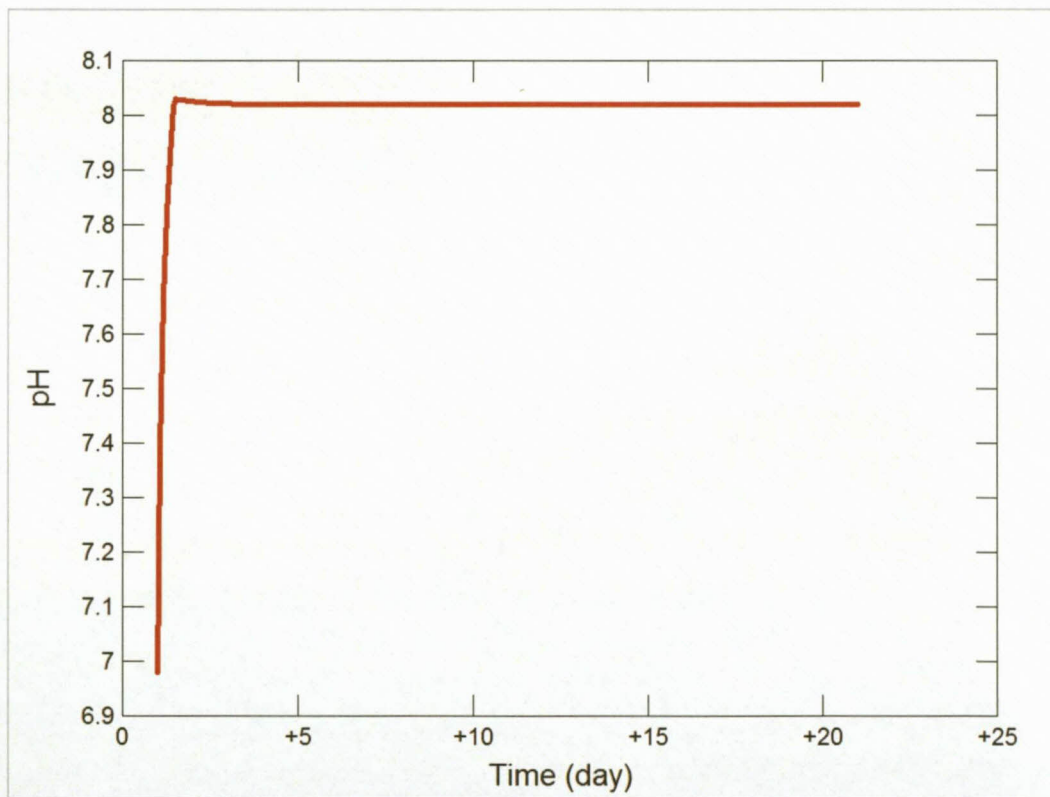


**Figure 5-8**    **Transient evolution of pH during weathering reaction sequence over 21 days at stable atmospheric conditions with the allowance of precipitation to occur in Scenario W1**

The buffering due to increased activity of hydroxides in the system from the clay minerals leads to a low concentration of $HCO_3$ in the system.  Comparing the transient model results with groundwater samples taken from the project area as well as the TCLP results in Table 5-8 shows that $HCO_3$ in the model result ends at 68.1

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mg/ℓ compared to the groundwater ranging between 95.8 and 4990 mg/ℓ and TCLP ranging around 400 mg/ℓ.
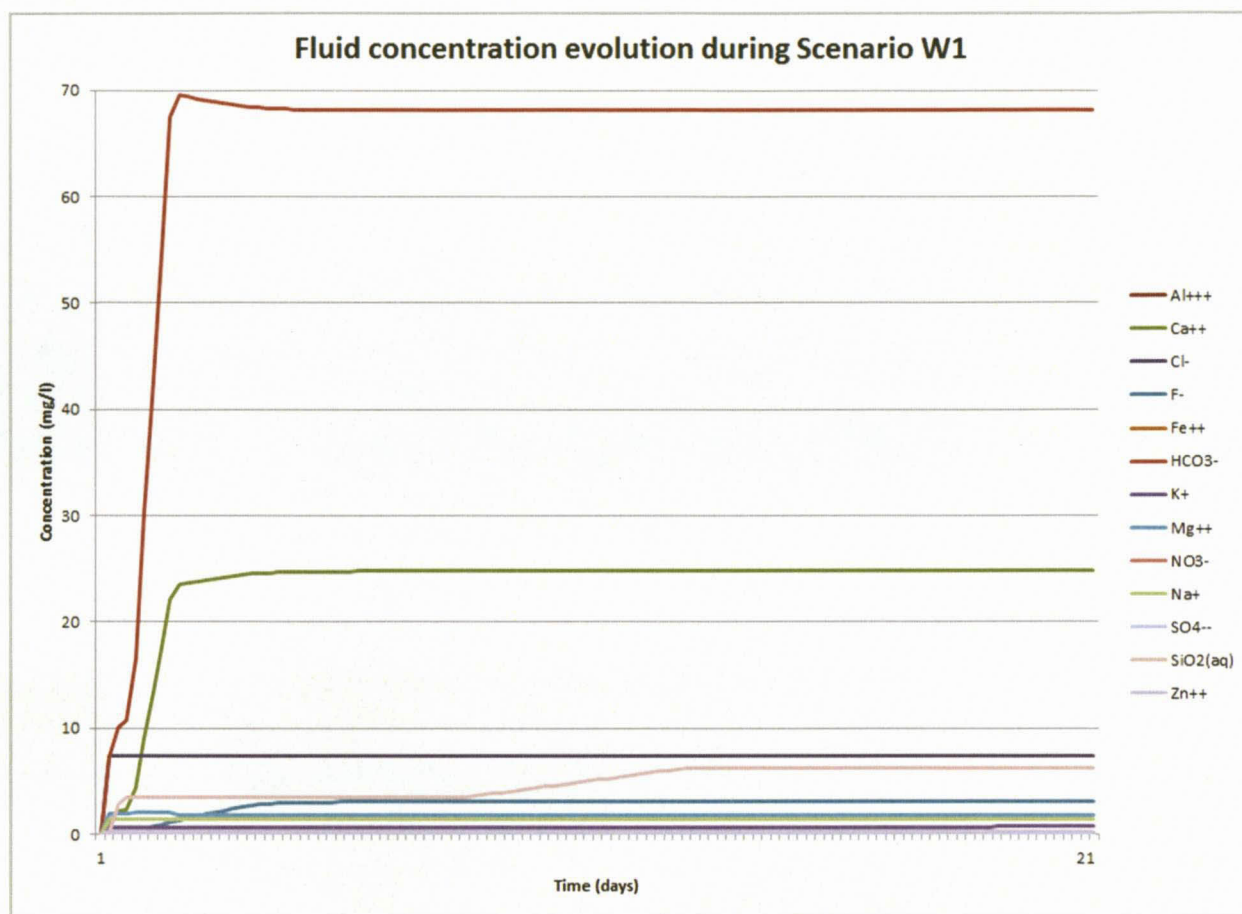


**Figure 5-9    Fluid composition after weathering over a period of 21 days under atmospheric fugacity in Scenario W1**

As explained by Murck et al. (1996) and Witthueser (2010), a decrease in $HCO_3$ correlates with a buffering effect allowing for a higher and more basic pH reading in solution, this is explained and reviewed in the literature chapter. Along with the increase in pH, various other chemical species also reacted and dissolves to be present in various concentrations as shown in Figure 5-9 and depicting the chemical species in concentrations after 21 days of weathering simulating laboratory periods. After an initial period of increased dissolution the system reaches equilibrium with forward and backward reactions balancing with dissolution as well as precipitation. After 21 days the resultant water type migrated from Mg-Cl to a $Ca-HCO_3$ facies as shown in Figure 5-10 with fluorite, daphnite, dolomite, kaolinite, fluorapatite, nontronite, calcite and quartz present in saturated states.

In the modelled scenario results $HPO_4$, $Fe^{3+}$, $NO_2$, V, Ni, Pb and Zn are within the groundwater sample range or present in negligible concentrations. Almost all of the chemical concentrations are within ranges of the groundwater field data but lower than most of the TCLP laboratory results.

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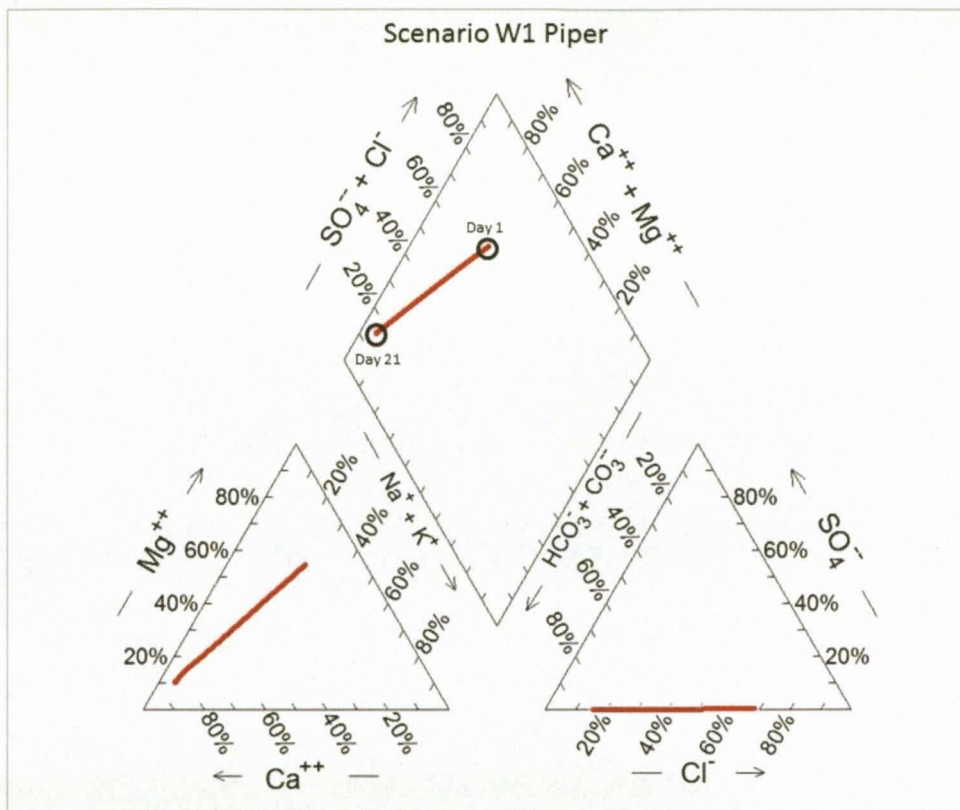
**Figure 5-10    Piper diagram showing the water type development in Scenario W1**

The above mentioned differences can be due to various un-modelled reasons. With the above results of Scenario W1 the discussion of sensitivities of the systems is raised that two factors within the system is most sensitive and controls the outcome of both the resultant groundwater chemistry and the pH of the system after weathering reactions has reached a state close to equilibrium. These two parameters are the weathering/dissolution rates of the minerals as well as the fugacity of $O_{2(g)}$ and $CO_{2(g)}$. This mentioned sensitivity of the system is accurately correlating with observations in other similar studies as also mentioned by Hellevang et al. (2003).

Furthermore the higher concentrations of some chemical species in the TCLP results as well as in some cases of the observed field data can be due to mineral surface area. Residency time within the natural system allows for more time to allow for rock-fluid interaction and thus longer reaction times within the physical limits of the term. In the laboratory mineral surface areas are increased due to milling and grounding of the samples to a fine powder to simulate a conservative scenario with optimal reactions allowed.

Fugacity, weathering rates and mineral surface areas are thus three parameters of the system that will be considered in the subsequent scenarios and sensitivity analysis simulations as discussed in section 2.6.2 of the literature study.

### 5.4.3.2 Scenario WSens1

In laboratory tests to evaluate weathering products as well as ABA and NAG evaluations, the surface areas of the minerals are increased by grounding the samples down to a fine powder before allowing the reaction between the rock mass and fluid. This increase surface areas and thus increases reaction rates with the result being a worst case scenario with high ion concentrations present in the resultant fluid. Based on this above mentioned factor, Scenario WSens1 is a sensitivity analysis on the system to the mineral surface areas.

The same base model was simulated over a period of 21 days as in Scenario W1. However in sensitivity simulation WSens1a the mineral surface areas within the model was changed to a surface area twice that of the analogue value and in WSens1b to half of the analogue values as shown in Table 5-9.

**Table 5-9 Mineral surface area values used in Sensitivity scenario WSens1 a and b**

| Mineral | Input (g) | Analogue Surface area (cm2/g) | Scenario WSens1a (cm2/g) | Scenario WSens1b (cm2/g) |
|---|---|---|---|---|
| Fayalite | 12.5 | 300 | 600 | 150 |
| Forsterite | 20 | 300 | 600 | 150 |
| Enstatite | 25 | 300 | 600 | 150 |
| Ferrosilite | 12.5 | 300 | 600 | 150 |
| Anorthite | 50 | 800 | 1600 | 400 |
| K-feldspar | 50 | 800 | 1600 | 400 |
| Nepheline | 15 | 300 | 600 | 150 |
| Biotite (Phlogopite) | 10 | 300 | 600 | 150 |
| Fluorite | 2.5 | 300 | 600 | 150 |
| Smectite (Low Fe-Mg) | 2.5 | 300 | 600 | 150 |
| Total | 200 | 4000 | 8000 | 2000 |

From these two scenario results as shown in Table 5-8 it is evident that mineral surface area is increased significantly during laboratory tests and that during simulation the system is not that sensitive to the increase or decrease of surface areas. The resultant fluid after weathering remains the same as in Scenario W1 with only minor changes.

From the sensitivity analysis on the mineral surface areas it is evident that the system is dynamic based on other factors.

### 5.4.3.3 Scenario W2

The most influential factor in all geological fields and studies is time, from mineral development and formation, through to the evolution of a fluid from clean rain water into groundwater within the earth's crust. The formation of groundwater as observed in the field with the chemical composition as described in section 5.2 of this dissertation occurs over thousands, if not hundred thousands of years with chemical equilibrium reached after a long fluid-rock interaction leading to forward and backward reaction path periods to develop the observed groundwater.

Scenario W2 is a simulation with the same base values, mineral proportions, surface areas and reaction dissolution rates as used in Scenario W1 with constant atmospheric fugacity of 0.21 $O_{2(g)}$. The scenario was however simulated over two different transient state time periods. Scenario W2a simulated weathering of the main minerals over a period of 100 years, the expected time flooding of the open pit will take, with scenario W2b simulating the fluid evolution over a period of 1000 years. The results is shown and compared to field data limits and averages in Table 5-8
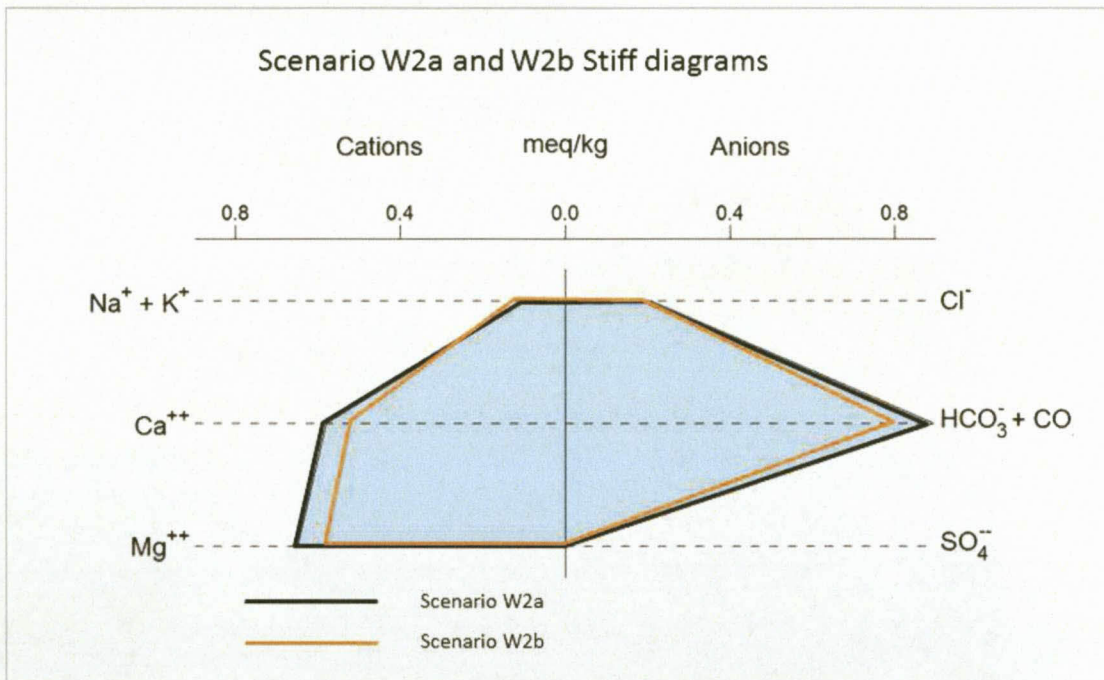


**Figure 5-11   Combined Stiff diagrams of the resultant water for Scenario W2a and b**

During scenario W2a ionic proportions combine to end up with an Mg-HCO$_3$ water type as also in the case with scenario W2b as indicated in the Stiff diagrams of Figure 5-11 correlating with the observation made by Titus et al. (2009) (section 2.4). Weathering over different time periods yield the same results only with slight differences in ionic proportions. Over a 1000 year period the system is allowed more

time to equilibrate with Ca and Mg allowed forming secondary minerals with carbonate and bicarbonate to form dolomite, daphnite, nontronite, muscovite and fluorite. Thus the proportional distribution of the ions in the resultant water type is slightly lower as in the case of a 100 year period of weathering with the system still equilibrating and precipitation of secondary minerals not developed fully.

The pH of the system remains stagnant at 7.94 after 100 years and remains at this level throughout. It can be concluded that weathering and dissolution reactions currently taking place in the natural system will not have an influence on the water quality of the groundwater that will contribute to the pit flooding waters, and field data can be analysed and used to simulate the event.

### 5.4.3.4   Scenario WSens2

Scenario WSens2 evaluates the sensitivity of the system on $O_{2(g)}$ and $CO_{2(g)}$ fugacity, $fO_2$ and $fCO_2$ respectively as this is observed in literature studies to have influences on pH levels and weathering rates (Hellevang et al. 2003; Merkel & Planer-Friedrich 2008; Price 1998). As rainwater infiltrates and flows down into the groundwater system during recharge, the weathering of minerals during the interaction with the water occurs at increasing depths. With an increase of depth from the surface $O_{2(g)}$ supply starts of at atmospheric fugacity of 0.21 and depletes the deeper the water flows with an almost inverse increase in $CO_{2(g)}$ as depth increases . Keeping this in mind the system weathering model was allowed to react with a sliding $O_{2(g)}$ and $CO_{2(g)}$ fugacity to analyse the sensitivity of the system. In simulation WSens2a the fugacity of oxygen was kept constant at atmospheric 0.21 and an increase of $CO_{2(g)}$ from the original fluid basis of 0.00078 to 0.01 was simulated to change linearly over a period of 100 years. In simulation WSens2b the $fO_2$ was allowed to deplete from 0.21 to $1E^{-10}$ and $fCO_2$ was once again increased from basis levels to 0.01 over a period of 100 years. These two sensitivity simulations were done on the original basis minerals and reaction tempos over a period of 100 years with results shown in Table 5-8. Fugacity values as used in WSens2a and WSens2b is shown in Table 5-10.

**Table 5-10   Scenario WSens2a and b fugacity ranges**

| Scenario WSens2 Simulation fugacity | | | | |
|---|---|---|---|---|
| | WSens2a | | WSens2b | |
| Gas | Start | End | Start | End |
| $O_{2(g)}$ | 0.21 | 0.21 | 0.21 | $1.0E^{-10}$ |
| $CO_{2(g)}$ | 0.00078 | 0.01 | 0.00078 | 0.01 |

As observed in the results due to a drop in fugacity and increased $CO_2$ the concentration of elements start to resemble values closer to those observed in the field. The sensitivity on the system with regards to $fO_2$ is however lower than the sensitivity on $fCO_2$, this is observed in the results with both simulation resulting in similar water types with almost no difference in ion concentrations and physical parameters like pH and TDS. All the major ions are present in concentrations within the limits of the groundwater samples with the exception of Ca, Na, $NO_3$, $HPO_4$, and Fe being too low with F also still being present in higher concentrations. pH buffering reactions are less compulsive with pH values for both resultant fluids being 7.47. The resultant water type in both cases is $Mg-HCO_3$ similar to BH4, BH116 and BH117 with the evolution of the water shown in the piper diagram (Figure 5-12).
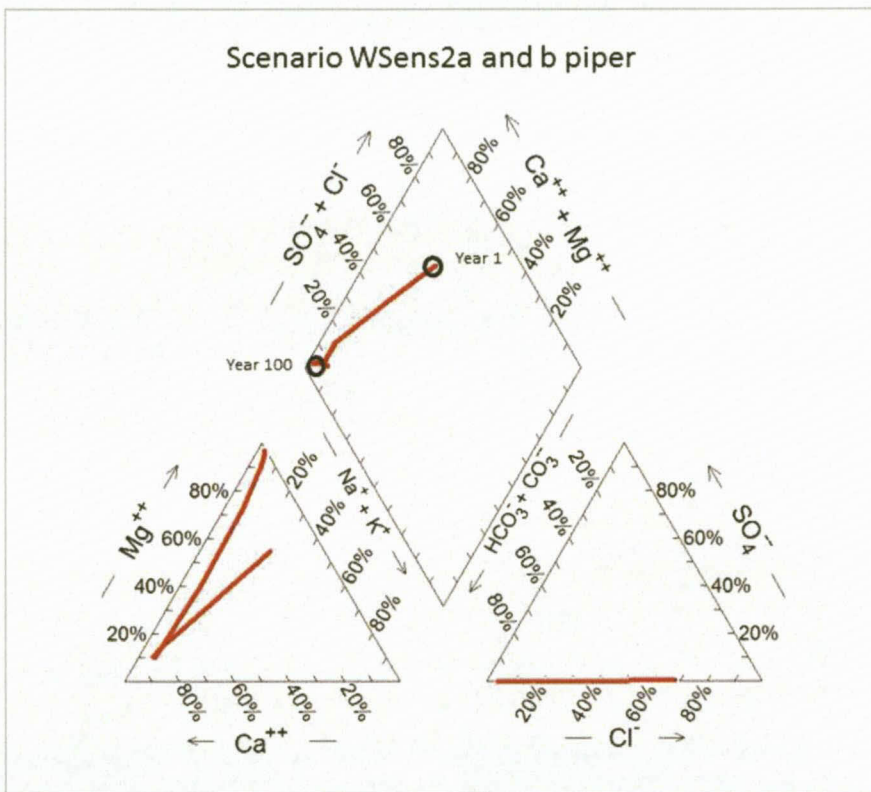


**Figure 5-12    Water facies evolution under sliding fugacity**

The system is most sensitive to $CO_2$ fugacity. On the analysis of the results and the evolution of the fluid during weathering it is shown that an initial increase in Ca, Na, K and Cl occurs after which they deplete with an increase of proportional Mg content leading to the Mg dominated water type. This change in concentrations during the weathering of the regional geology is due to a saturated state of the aforementioned ions leading to the saturation of fluorite, fluorapatite, muscovite, dolomite, nontronite and siderite minerals and thus the ions precipitates out of the system with an increase in carbonate as also observed in the systems modelled by Lebron & Suarez (1996).

The levels of Na, Ca, K, and F being present in levels to low due to the reasons given needs to be calibrated to resemble observed field values to fully understand the current groundwater system geochemistry. The weathering rates of the minerals leads to fast or slow dissolution of the regional mineralogy and thus the increase of ions in the resultant fluid. To analyse the sensitivity of the system and to calibrate the simulated system the weathering rates of the silicate minerals containing the ions has to be changed and adjusted as has been done in WSens3. F concentrations are high due to a conservative approached followed, however once Ca levels increases enough the F will also deplete due to the formation of secondary minerals as described in the speciation of the natural groundwater samples. $NO_3$ levels are lower than the field data but this is due to blasting and agricultural activities in the regional mines and communities leading to an increase of nitrate and thus will not be at the observed levels in a pristine environment.

### 5.4.3.5  Scenario WSens3

Sensitivity analysis on the weathering dissolution rates of the main minerals in the model was simulated to evaluate the effect and calibrate the system to observed data due to concentration differences as mentioned in Scenario WSens2. If weathering rates of the feldspar, plagioclase and other minerals like the clay minerals are too fast the buffering of the system will continue with high concentrations of Al, Ca, Na, K, F and $SiO_{2(aq)}$ and pH levels increasing to over 10. If the opposite is true the pH will be too low and chemical species will not be present in concentrations resembling that observed in the field. During infiltration as rainwater reaches deeper depths and $O_{2(g)}$ decreases with a slight increase in $CO_{2(g)}$ the system will also allow for less dissolution with a migration from an oxidising environment to a reduction inducing one until equilibrium is reached.

Scenario WSens3a and b was simulated with different weathering dissolution rates (Table 5-11) values for K-feldspar, anorthite and nepheline to evaluate the systems sensitivity to the weathering rates of the main minerals as well as to calibrate the system with regards to certain ions contained in these minerals that needs to be present in higher levels within the resultant water. The original weathering rates of feldspar, anorthite and nepheline  was sourced from White & Brantley (1995) as well as Wilson (2004) however at this rate the system reacts to violently in some cases and to slow in others to reach calibrated levels as observed in the field data  To compensate and evaluate the sensitivity of the system to silicate mineral weathering rates, they were adjusted to different values from the original as indicated in Table 5-11.

**Table 5-11    Sensitivity parameter description for Scenario WSens3a and b**

| Scenario WSens3 weathering rates (moles/cm²/s) | | | |
|---|---|---|---|
| Mineral | Original rate | WSens3a | WSens3b |
| K-feldspar | $1.0\times10^{-16.6}$ | $1.0\times10^{-18}$ | $1.0\times10^{-14}$ |
| Anorthite | $1.0\times10^{-12.5}$ | $1.0\times10^{-15}$ | $1.0\times10^{-10}$ |
| Nepheline | $1.0\times10^{-20}$ | $1.0\times10^{-22}$ | $1.0\times10^{-18}$ |

As indicated by the results (Table 5-8) the changes in the system from Scenario WSens2 is not significant with resultant water types being the same. However with a faster weathering rate for the silicate minerals a slight increase of Ca, Na and Fe is observed. This change is small but it does show that a faster rate in conjunction with various other parameter changes can result in a calibrated system.

### 5.4.3.6   Scenario W3

With trial and error used as the main calibrator and to understand the system of the project area with regards to fluid-mineral interaction, the conceptually 'ideal' simulation with the most stable reaction tempos and system parameters were simulated to evaluate the natural modelled system.

This simulation was done with fugacity of $O_2$ and $CO_2$ linearly changing over a 100 year period as illustrated in Figure 5-13. $fO_2$ slides from 0.21 at atmosphere to 0.15, to simulate a environment with depleting $O_{2(g)}$ almost no oxygen accept for $O_{2(aq)}$ already consumed and dissolved by the system. $fCO_2$ slides from the analogue value close to 0.00078 up to a value of 0.01.
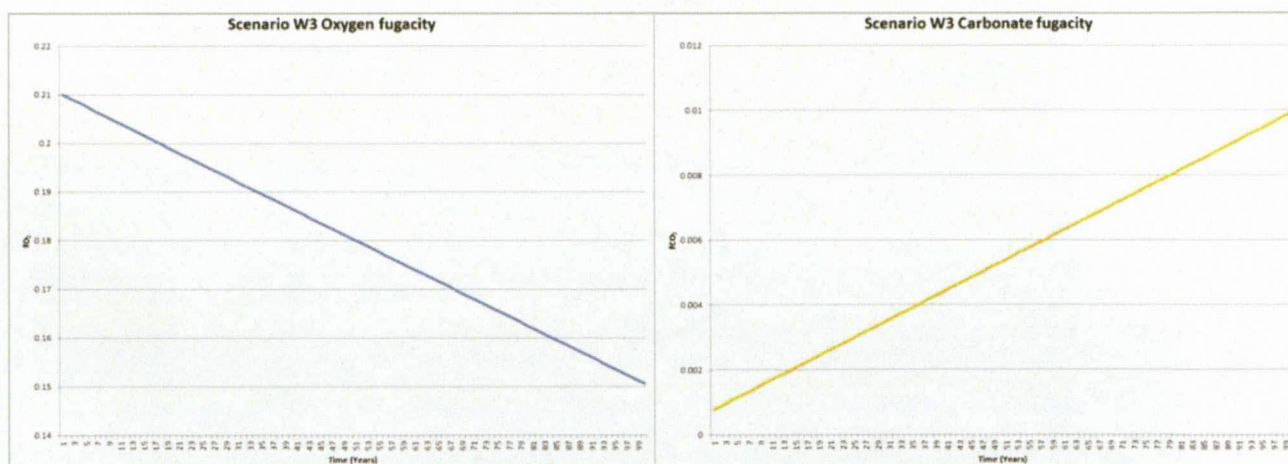


**Figure 5-13   Linear decrease and increase of $O_{2(g)}$ and $CO_{2(g)}$ fugacity**

With a sliding fugacity simulated, the mineral weathering rates in the sensitivity analysis WSens3a and b was analysed and values with results closest to the observed concentrations in the field were used. Table 5-12 shows the weathering rates used in scenario W3 to simulate and analyse the natural system processes.

**Table 5-12    Scenario W3 mineral weathering rates**

| Mineral | Dissolution/weathering rate in (mol/cm²/s) | Reference/Comment |
|---|---|---|
| Fayalite | $1\times10^{-13.9}$ | (M. J. Wilson 2004) |
| Forsterite | $1\times10^{-13.9}$ | (M. J. Wilson 2004) |
| Enstatite | $1\times10^{-16.4}$ | (M. J. Wilson 2004) |
| Ferrosilite | $1\times10^{-16.4}$ | (M. J. Wilson 2004) |
| Anorthite | $1\times10^{-10}$ | WSens3b |
| K-feldspar | $1\times10^{-14}$ | WSens3b |
| Nepheline | $1\times10^{-18}$ | WSens3b |
| Biotite (Phlogopite) | $1\times10^{-17}$ | (White & S. L. Brantley 1995) |
| Fluorite | $1\times10^{-12}$ | (Cama et al. 2010) |
| Smectite (Low Fe-Mg) | $1\times10^{-17}$ | Same as Biotite |

The aim of the sensitivity analysis and preceding scenario was to develop an understanding of the system to conclude with a calibrated system. The calibrated system is then simulated to evaluate the system parameters and processes as they currently and previously took place in the natural system. The calibrated system does not resemble the same concentrations as those observed in the field due to time constraints as well as limits to understanding processes that cannot be seen which is a normal modelling constraint; however the processes and proportional contents of the results do resemble the natural system.

From these above mentioned model setup parameters a weathering simulation for 100 years at an average temperature of 25°C was simulated to evaluate the effect of time and weathering on the fluid (rain water) chemistry and the chemical processes involved. The end result is a water sample resembling a slightly diluted groundwater sample with a pH of 7.96 and a TDS of 109 mg/ℓ (Table 5-8). The calibrated sample has an Mg-HCO$_3$ water type resembling that of the data observed in the field with Ca, Mg, K and Al calibrated to the natural groundwater concentration and F concentrations lower.

A conclusion can thus be made that within the period understandable and measureable to a limit in a human lifespan no significant effect can be observed with regards to chemical concentration changes to recharge water during infiltration and interaction with project area mineralogy. Thus the weathering of minerals in the natural conditions will not have a significant contribution to the flood water that will fill the pit, and current groundwater concentration will prevail. However the system as modelled in scenario W3 allows the evaluation of an accurate representation of the processes involved in the Bushveld Igneous Complex hydrogeochemical interaction resulting in the Mg-HCO$_3$ dominated facies as also observed by Titus et al. (2009);

Smith & Kotze (2010) and van Coller et al. (2012).

### 5.4.4 Pit flooding mixing model

Due to meromictic nature of the planned Tuschenkomst pit lake, as described in the conceptual model, and the different periods of contributing inflows with different water types layering or stratification of the pits water column can occur. During the first 40 to 45 years mixing of groundwater (GW), surface water (SW) and rain water (RW) will occur to fill the initial volume of the lake until the original groundwater levels is reached to form chemical characteristics of water that will form the hypolimnion and monimolimnion after reducing condition prevail at the bottom of the pit lake. The upper epilimnion layer of water will form during the last and continuous stages of the pit flooding with the mixing and interaction of SW and RW without groundwater contributions. A fourth layer on top of the water column called the evapolimnion will continuously change and form due to atmospheric processes and evaporation. These above mentioned mixing of water types during stages of the pit flood event is simulated and described in the next scenarios with the results listed in Table 5-13.

### 5.4.4.1 Scenario M1

Scenario M1 represents the epilimnion with a mix of surface water (SW) and rainwater (RW). This lake layer will develop once the first ±45 years of flooding is done and the maximum groundwater level is reached with groundwater not contributing to the inflow of the flooding event above this datum. Scenario M1 was simulated for 50 years at atmospheric fugacity mixing the surface water and rainwater samples as speciated and described in section 5.4.2. The mixing ratio for this simulation was 51.6% SW and 48.4% RW as derived from the expected inflow volumes from the groundwater flow model. The simulation was thus completed with a SW mass of 5.1 kg and a RW mass of 4.9 kg.

After all reactions has taken place and the two water types has equilibrated the resultant water sample, sample M1, as shown in Table 5-13 has a Ca-HCO$_3$ water type with a TDS of 136 mg/$\ell$ and a final pH of 7.31. The water development is shown in Figure 5-14 on a piper diagram. The mixing model as simulated over the 50 year period allowed the RW to evolve and mix with surface water to develop from an Mg-Cl water and end up as a water type resembling the regional surface water facies of Ca-HCO$_3$.

**Table 5-13    Resultant simulated samples from the four mixing scenarios**

| Mixing scenarios - Simulated samples | | | | | |
|---|---|---|---|---|---|
| Parameter | Unit | M1 | M2 | M3 | M4 |
| Al | mg/ℓ | 0.004 | 0.001 | 0.003 | 0.282 |
| $AsH_{3(aq)}$ | mg/ℓ | 0.005 | 0.003 | 0.007 | 0.026 |
| Ba | mg/ℓ | 0.010 | 0.007 | 0.010 | 0.006 |
| Ca | mg/ℓ | 12.03 | 11.55 | 12.93 | 6.16 |
| Cl | mg/ℓ | 9.91 | 45.33 | 52.55 | 206.21 |
| Co | mg/ℓ | $5.30 \times 10^{-09}$ | $1.54 \times 10^{-08}$ | $1.89 \times 10^{-08}$ | $1.35 \times 10^{-07}$ |
| Cu | mg/ℓ | 0.001 | 0.013 | 0.013 | 0.000002 |
| F | mg/ℓ | 1.44 | 0.57 | 1.79 | 7.04 |
| Fe | mg/ℓ | $6.39 \times 10^{-08}$ | $8.04 \times 10^{-08}$ | $1.14 \times 10^{-07}$ | 0.0008 |
| $HCO_3$ | mg/ℓ | 66.64 | 513.49 | 544.25 | 2443.08 |
| $HPO_4$ | mg/ℓ | $2.20 \times 10^{-06}$ | $4.54 \times 10^{-05}$ | $3.50 \times 10^{-05}$ | 0.000666 |
| Hg | mg/ℓ | 0.0003 | 0.0001 | 0.0003 | 5.00x10-17 |
| K | mg/ℓ | 3.91 | 3.67 | 7.24 | 28.43 |
| Mg | mg/ℓ | 5.41 | 66.22 | 64.74 | 226.97 |
| Mn | mg/ℓ | $3.83 \times 10^{-10}$ | $5.53 \times 10^{-09}$ | $1.05 \times 10^{-08}$ | 0.074 |
| $NH_4$ | mg/ℓ | 0.09 | 1.64 | 1.67 | 6.55 |
| $NO_2$ | mg/ℓ | 0.21 | 0.22 | 0.39 | 1.53 |
| $NO_3$ | mg/ℓ | 1.90 | 33.63 | 34.20 | 134.23 |
| Na | mg/ℓ | 12.05 | 55.36 | 64.60 | 253.53 |
| Ni | mg/ℓ | 0.001 | 0.007 | 0.022 | 0.087 |
| $O_{2(aq)}$ | mg/ℓ | 8.58 | 8.56 | 8.04 | -86.59 |
| Pb | mg/ℓ | 0.003 | 0.011 | 0.059 | 0.231 |
| $SO_4$ | mg/ℓ | 14.77 | 21.92 | 33.31 | 130.72 |
| Se | mg/ℓ | $2.07 \times 10^{-37}$ | $6.55 \times 10^{-38}$ | $5.21 \times 10^{-37}$ | $9.85 \times 10^{-16}$ |
| $SiO_{2(aq)}$ | mg/ℓ | 1.71 | 0.00 | 1.47 | 1.98 |
| Sr | mg/ℓ | 0.50 | 0.26 | 0.47 | 0.38 |
| Zn | mg/ℓ | 0.002 | 0.014 | 0.207 | 0.813 |
| pH | | 7.31 | 6.79 | 6.67 | 6.42 |
| TDS | mg/ℓ | 136 | 717 | 776 | 2985 |
| Water type | | Ca-HCO3 | Mg-HCO3 | Mg-HCO3 | Mg-HCO3 |

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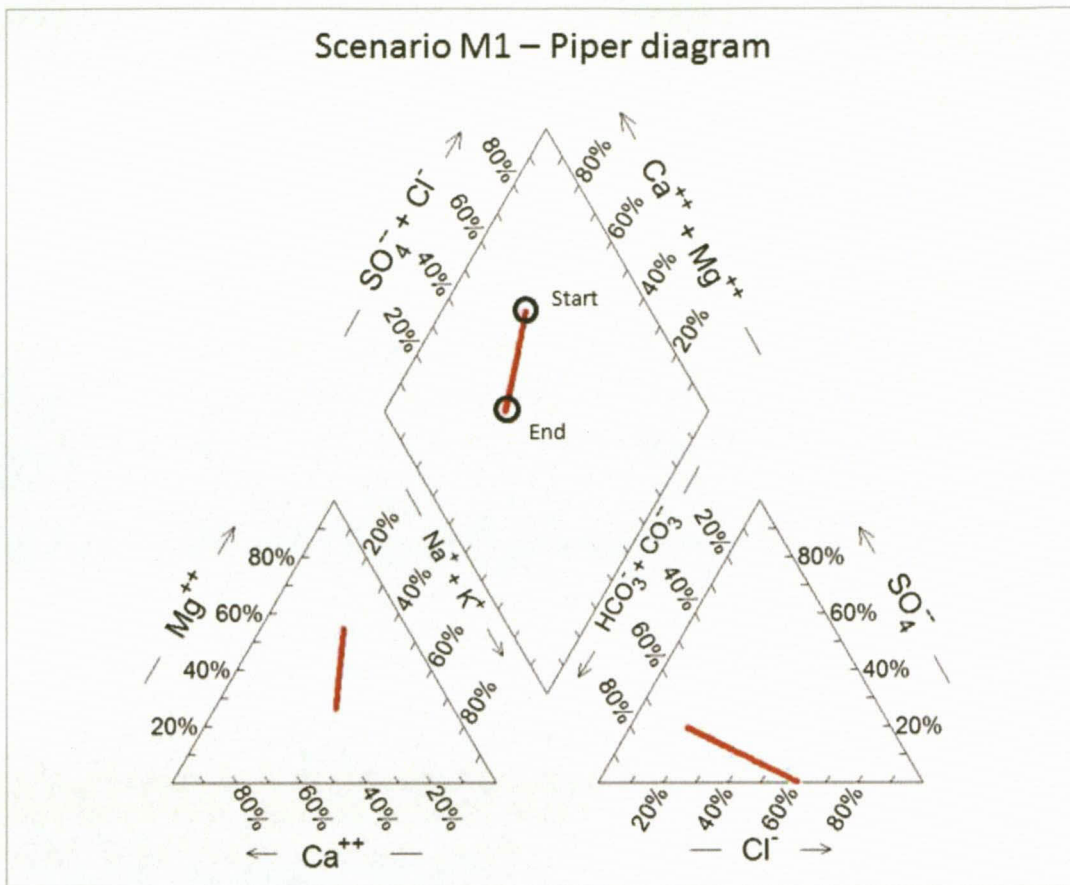
**Figure 5-14    Development of the water mix for scenario M1**

The resultant system does have the potential to allow secondary minerals to form and precipitate out of solution if the water column does not experience turning events as frequently as expected.  The following saturated mineral phases are present in the final sample M1:

- Witherite

- Gibbsite

- Se (black)

- Hematite

- $Co(FeO_2)_2$

- Strontianite

- Fluorapatite

- Pyrolusite

**5.4.4.2   Scenario M2**

Scenario M2 represents the hypolimnion with a mix of surface water (SW), rainwater (RW) and groundwater (GW).  This lake layer will develop from the start of the post-

closure flooding of the pit up to about 45 years into the mitigation process and will stop once the maximum groundwater level is reached and constant inflow/contribution of GW to the system is stopped. Scenario M2 was simulated for 45 years at atmospheric fugacity mixing the surface water and rainwater samples as speciated and described in section 5.4.2. The mixing ratio for this simulation was 32% SW (3.2 kg), 30% RW (3 kg) and 38% GW (3.8 kg) as derived from the expected inflow volumes from the groundwater flow model. The simulation was thus completed with a final sample weight of 10 kg or a volume of 10 litres with the assumption of standard temperature and gas laws allowing 1 Litre to equal 1 Kilogram of $H_2O$.

After all reactions has taken place and the two water types has equilibrated the resultant water sample, sample M2, as shown in Table 5-13 has a $Mg-HCO_3$ water type with a TDS of 717 mg/ℓ and a final pH of 6.79. The water facies for sample M2 is shown on a Stiff diagram in Figure 5-15. The mixing model as simulated over the 45 year period allowed the three water contributions to evolve and mix thus developing a water type resembling the regional groundwater facies of $Mg-HCO_3$.

The resultant system does have the potential to allow secondary minerals to form and precipitate out of solution if the water column does not experience turning events as frequently as expected.
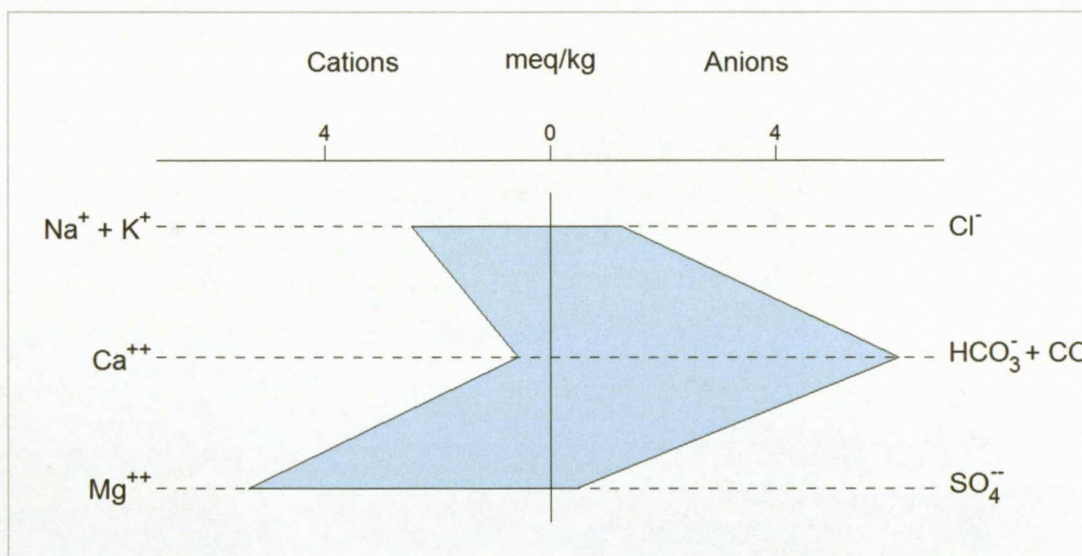


Figure 5-15   Stiff diagram indicating the resultant water type of sample M2 from scenario M2

The following saturated mineral phases are present in the final sample M2:

- Witherite

- Gibbsite

- Se (black)

- Hematite

- $Co(FeO_2)_2$

- Dolomite

- Fluorapatite

- Pyrolusite

### 5.4.4.3 Scenario M3

Scenario M3 simulates the mixing and evaporation processes of the top ±3 m of the water column that will exposed to atmospheric conditions. The water in the top layer termed the evapolimnion will thus be evaporated with the chemical characteristic and concentrations of the water thus changing. This layer does have the potential not to exist as a fully developed limnion but only in small areas or not at all, however for a conservative approach covering all bases it was simulated and allowed to form. For a conservative approach the sample resulting from scenario M2 representing the hypolimnion was used and an evaporation simulation was done to allow 60% of the water to evaporate thus resulting in a sample with conservative results. The M2 sample was used due to its higher concentration of TDS and as noted by Nuttall & Younger (2004) that in the worst water quality observed or modelled can be expected to be the water of the flooded void if the conceptual model fails.

During the year approximately 2 m of evaporation takes place and thus from the 3 m for a conservative approach 60% of the water was evaporated at a rate of 0.555 kg/hour during the assumed 12 hour daylight period, with an initial sample of 10 kg. During the evaporative simulation the temperature of the water was linearly increase from 25°C to 31°C and subsequently allowing the final water sample to have an atmospheric temperature close to the average daily maximum during summer months.

The resultant sample, sample M3, remains a Mg-HCO$_3$ water type but an increase of most of the major ions and TDS values were observed as would be expected from evaporation process. The TDS of M3 ended at 776 mg/ℓ with a slight drop in pH as the H$^+$ of the water increased due to the development of secondary minerals as well as aqueous species mostly combining with OH$^-$. The inverse development of pH vs.

TDS is indicated in Figure 5-16.
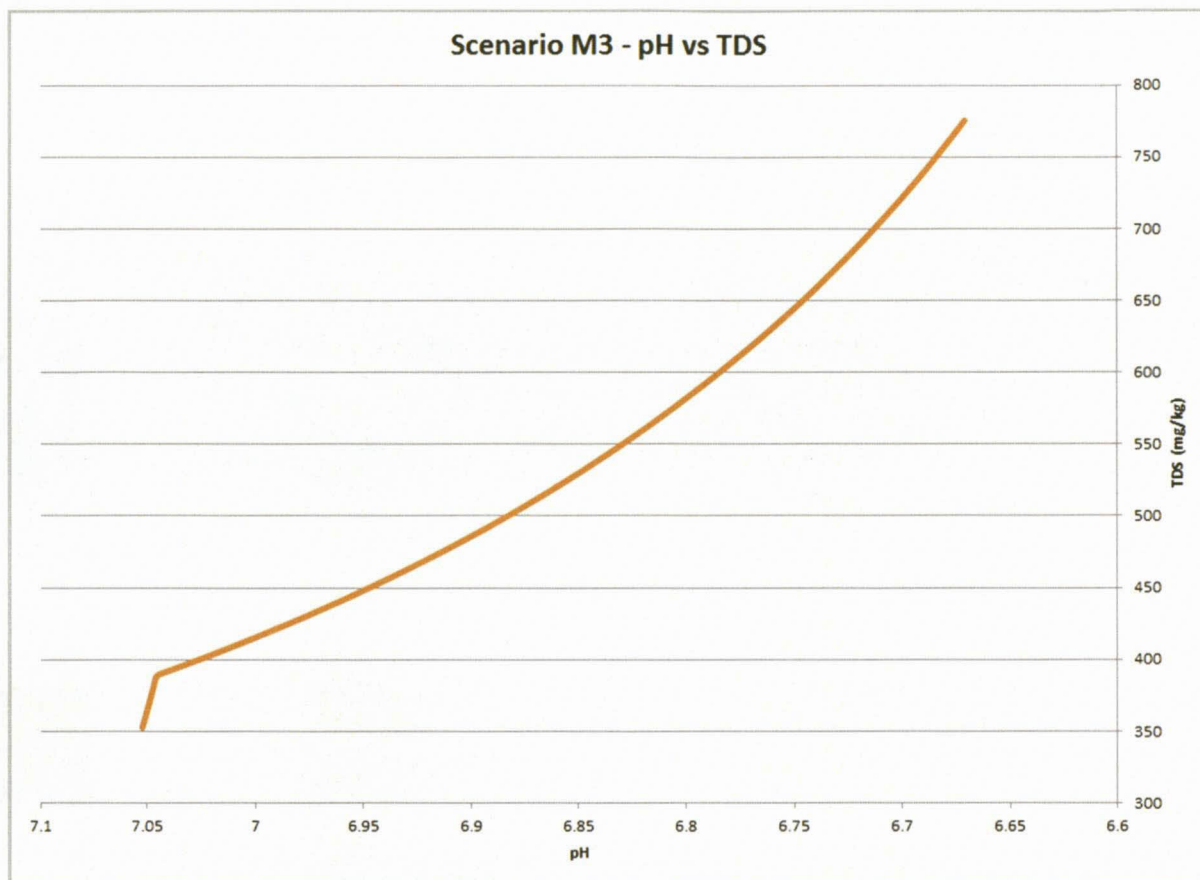


**Figure 5-16** **Graph indicating the inverse relationship between TDS and pH during the development of the water mix in scenario M3**

Sample M3 has the following minerals in saturated states:

- Witherite

- Gibbsite

- Se (black)

- Hematite

- $Co(FeO_2)_2$

- Dolomite

- Fluorapatite

- Pyrolusite

- Strontianite

Although the above minerals are saturated within the system, it is unlikely that they will form out of the evapolimnion and precipitate out of solution due to the constant mixing and change of the top layer from atmospheric processes.

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## 5.4.4.4 Scenario M4

The monimolimnion forms the bottom layer of a pit lake and is present in most lake scenarios. This layer is characterised by water with high TDS and sulphate concentrations in relation to the top water strata with reducing conditions prevailing due to a lack of $O_2$ and an increase of $CO_2$ from decomposing organic matter accumulating on the lake bottom. From this conceptual knowledge of this layer as described by Castendyk & Webster-Brown (2007) discussed in the literature review, scenario M4 was simulated by reacting two samples with the same chemical concentrations as the resultant sample M2, under a fixed oxygen fugacity of $1E^{-50}$ and a sliding carbon dioxide fugacity linearly increasing from 0.00078 to 0.41. Along with a change in fugacity the mixing reactions were allowed to take place under gradually decreasing temperature with a slide from 25°C to 18°C. The fugacity and temperature changes were introduced to the model to allow an accurate simulation of the reducing environment under cold temperatures expected at the bottom of a lake water column. This mixing simulation of the monimolimnion was done for a period of 50 years allowing the precipitation of saturated minerals.

The resultant sample M4 as indicated in Table 5-13 shows that the water remains fixed on an $Mg$-$HCO_3$ facies with a strong increase in most of the major ions. The pH of the system decreased from 7.27 to 6.42 and a TDS increase up to a high 2985 mg/$\ell$. The TDS and pH changes along with an increase of $SO_4$ from 21.92 mg/$\ell$ to 130.72 mg/$\ell$ and an iron concentration elevated by an order of $10^4$ shows that the simulations was successful in modelling the expected reducing environment allowing the processes and systems at work in the monimolimnion to be studied. These system observations correlate with the studies on pit lakes as well as underground mine shaft flooding done by Herbert (2006) and Ramstedt (2003).

The reducing environment and increase in sulphate and iron allows for a system saturated with these two aqueous species as well as other metal compounds to precipitate out and form secondary minerals as listed below and indicated in Figure 5-17:

- $CuFeO_2$
- $Co(FeO_2)_2$
- $CuSe$
- Witherite
- Hematite
- Fluorapatite

- Nontronite

- Gibbsite

- HgSe

- Dolomite

- Strontianite
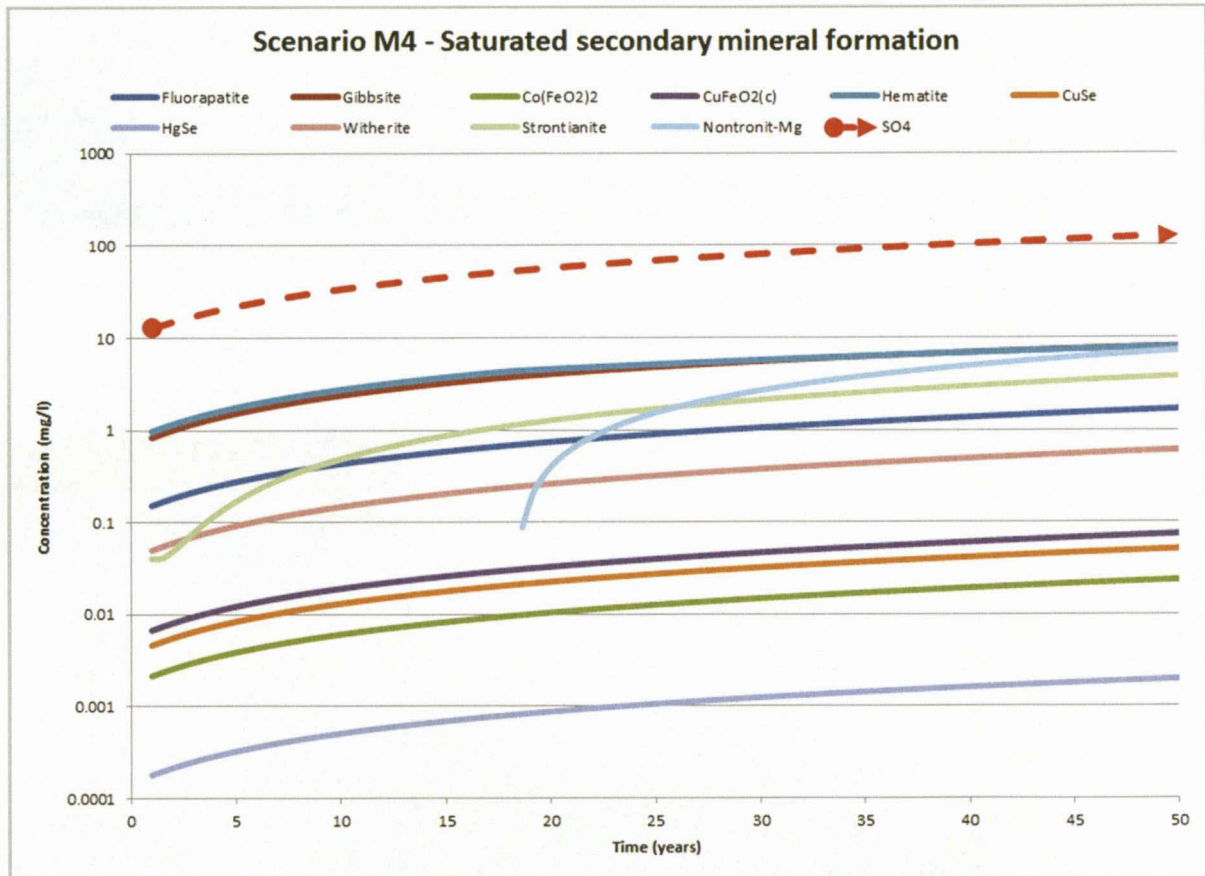


**Figure 5-17** **Graph indicating the increase in mineral concentration over the 50 years of reducing processes and also the increase of SO$_4$ in the fluid**

Figure 5-17 shows the development of the mentioned saturated minerals and also indicates the correlation with SO$_4$ concentration increase in the fluid as the reducing conditions allows for the formation of sulphate and metal containing minerals. The monimolimnion is the deepest lake layer and does not undergo turn over events, thus the formation of these secondary minerals are probable.

## 5.5 Concluding summary: Chapter 5

The following conclusions can be summarised from Chapter 5:

- The surface water of the region has a Mg/Ca-HCO$_3$ water type with the groundwater dominated by a Mg-HCO$_3$ facies;

- A conceptual pit lake model includes the inflow of groundwater, surface water and rainwater mixing during different periods at various fractions allowing the formation of a meromictic pit lake;

- The meromictic PPM pit lake will have 4 lake layers in order from top to bottom termed the evapolimnion, epilimnion, hypolimnion and monimolimnion;

- ABA and TCLP results from an accredited laboratory was interpreted with the samples taken from the core boreholes deemed not to be acid generating with the gangue minerals buffering any potential acidification;

- From the analogue data and field data gathered input samples were selected with weathering and mixing models simulated;

- Speciation models showed that the saturated phases in the groundwater samples are:
  - Fluorapatite
  - Dolomite
  - Huntite
  - Magnesite
  - Whitlockite
  - Calcite
  - Cuprite
  - Aragonite
  - Hydroxyapatite

- The saturated phases within the surface water of the region most likely to form out of solution:
  - Muscovite
  - Strontianite
  - Kaolinite
  - Cuprite

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- Five weathering models were done with sensitivity analysis on various chemical elements in the conceptual system leading to the formation of a calibrated system model (Scenario W3) allowing the interpretation and investigation of processes involved in the formation of the groundwater as observed in the field;

- The final calibrated model indicated a Mg-HCO$_3$ water type with a pH of 7.96 and a TDS of 109 mg/ℓ correlating with field data;

- The four lake layers as discussed and illustrated in the conceptual model was modelled with the following scenarios:

    o Scenario M1: Mixing of surface water and rainwater under atmospheric conditions at different proportions to simulate the inflow mixing of waters for 50 years to form the epilimnion once groundwater inflow has stopped after the first 40 to 45 years.

    o Scenario M2: Mixing of surface water, rainwater and groundwater at atmospheric conditions at different proportions to simulate the inflow mixing of waters for the first 45 years of pit flooding that will eventually form the hypolimnion.

    o Scenario M3: Evaporation scenario to simulate the effect of evaporation and atmospheric processes on the exposed water chemistry for 12 hours with 66% evaporation of water to form the dynamic evapolimnion. This simulation is done under atmospheric fugacity and higher temperatures.

    o Scenario M4: Mixing of hypolimnion waters under reducing conditions to simulate the expected water chemistry of the monimolimnion under lower temperatures and lower $fO_{2(g)}$ and higher $fCO_{2(g)}$.

The results from the weathering and mixing models are discussed in more detail and compared to regulatory values to answer the research questions as listed in Chapter 1, with risks and mitigation methods listed as well as a system model and template for future hydrogeochemical modelling.

# CHAPTER 6:

## 6 HYDROGEOCHEMICAL MODEL DISCUSSION AND RESEARCH OUTCOMES

This chapter serves as a conclusion and summary of this dissertation with all objectives and research questions answered by the discussions in this chapter.

## 6.1 Discussion on model results and outcomes

All model results as used and discussed in the next sections are listed in Appendix D: Model results and available on the data DVD attached to this dissertation document.

### 6.1.1 Mineral weathering

Results of laboratory tests as well as speciation of the current water types of the region simulated within the limits of the software contributed to the mineralogical data and proportions used in weathering, mixing and evaporative models to conclude with a system understanding and answer to the research questions.

Six weathering scenarios were simulated following an analytical calibration path. Scenario W1 resulted in chemical sample with pH value of 8.02 for a transient simulation of 21 days resembling the same time as a static laboratory test. Clay minerals and K-feldspar breaking down allows for buffering reactions to occur as illustrated in model results and Figure 5-8 with the pH of the system increasing to a maximum of 8.02 within the first two days of simulation. These buffering reactions occurred due to a system with disequilibrium within the rate at which reactions took place as well as the simulation of fugacity during the infiltration of recharge waters not taken into account. Allowing for the analogue values used in scenario W1 it is concluded that Ca, Na, K, Mg, Al, $SO_4$ and $NO_3$ was present in the simulated sample with concentration not resembling those observed in the field or in laboratory tests. These above mentioned ions is released mainly by the silicate minerals in the system with k-feldspar, anorthite, nepheline and the clay minerals being the most abundant in the regional geology. Dynamic processes as well as fugacity of certain elements needs to be at ideal natural levels to simulate a true environment along with the correct time frame allowed.

The low concentration of nitrogen containing species can most definitely be described to anthropogenic activity releasing unnatural amounts of N into the system currently observed in the field. $NO_3$ in the groundwater samples are higher than those released in the laboratory leachate tests as well as the simulated values in W1 and the subsequent scenarios and sensitivity analysis. $NO_3$ is a compound readily found in fertilizers and explosives used in the regional area for agricultural and mining reasons. Thus for the purpose of the models $NO_3$, $NO_2$ and other nitrogen

containing aqueous species were not of concern.

The resultant simulated sample for scenario W1 was a Ca-HCO$_3$ water type with a TDS of 121 mg/$\ell$ at a pH of 8.02. The Ca dominated system does not correlate with the region groundwater as well as TDS values being too low. However the analysis of the resultant water as it progresses shows that the final fluid is saturated with minerals similar to those observed in the speciation of both the surface and groundwater samples. This development over the simulation period is shown in Figure 6-1.
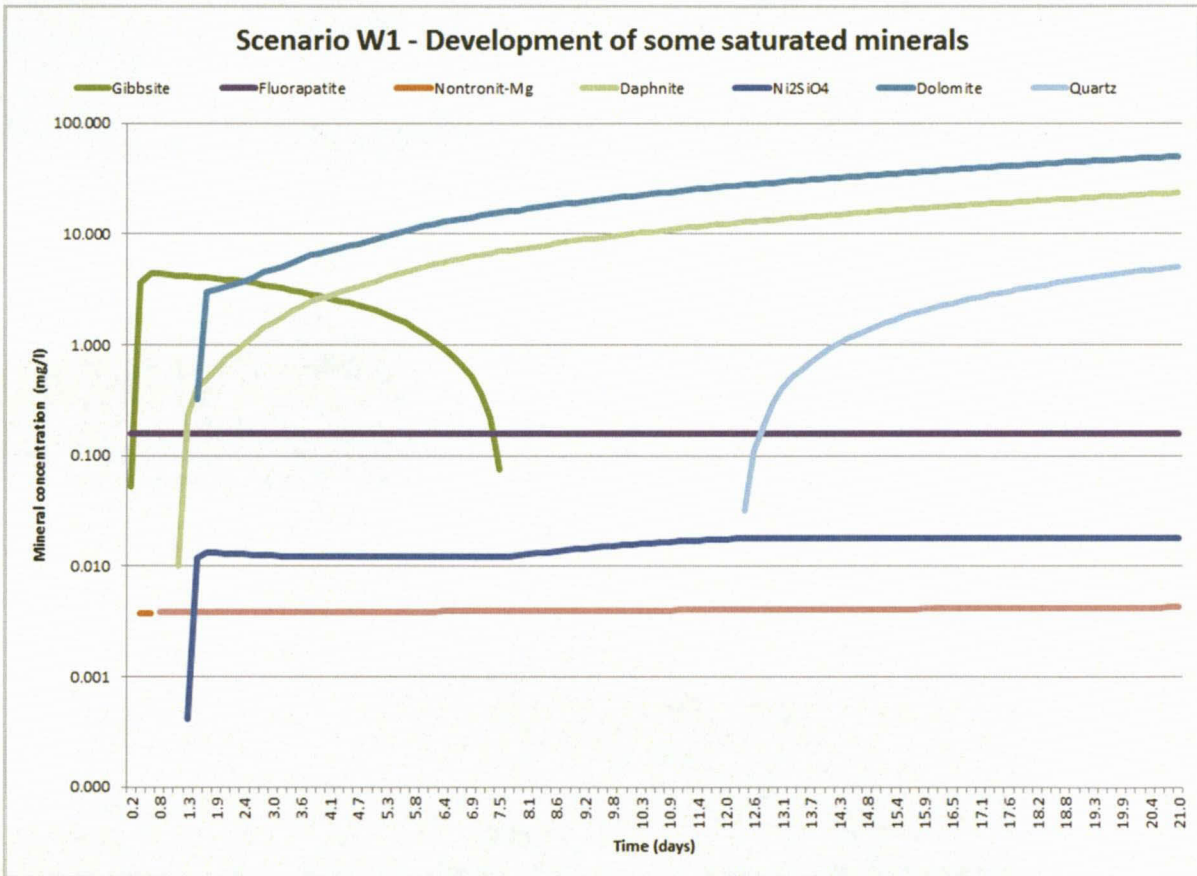


**Figure 6-1** **The development of some saturated minerals within the 21 day period as simulated in scenario W1**

The minerals used in the Scenario W1 and the other weathering models were deduced based on XRD and XRF results with a larger proportion of fluorite allowed to react for conservative purposes, however in a laboratory scenario the milling and grinding of the rock samples to a fine powder increases surface area and thus increase reaction tempos. To evaluate the effect of this the sensitivity of the system with regards to mineral surface area was simulated and analysed in scenario WSens1a and b.

Scenario WSens1a and b were two simulations done with changes to the mineral surface areas as described in section 5.4.3.2. The resultant simulated samples gave

no clear indication on the effect of the surface areas of the minerals with the only observable with significant enough magnitude being the $SiO_{2(aq)}$ concentration within the fluid. A simulation that will show the same results as a laboratory test within realistic natural mineral surface areas are thus not possible. When the surface areas were multiplied almost no changes were observed from the concentrations in scenario W1 results and thus further calculations and simulations were done with analogue mineral surface areas.

As mentioned previously, along with pressure and temperature, time is the most telling and influential factor throughout geological processes from mineral and rock formation as described in the Bowen sequence right up to the formation of groundwater by fluid-rock interaction. Thus the constraint of 21 days on the simulated system had to be changed to more realistic time frames after which a better understanding of the processes and systems involved in the current groundwater environment can be envisaged. Subsequently in scenario W2a and b the same base model was simulated for 100 and 1000 years respectively at atmospheric conditions. Once again the water type and concentration of the aqueous species did not show any significant changes in concentration. However through the extended transient simulation the system in both cases showed a drop in pH. The reaction path allowed for the same buffering and trend for pH as shown in scenario W1 but as the system was allowed to equilibrate and stabilise the pH slowly settled to a lower level. This occurs due to the relationship between $HCO_3$ content of the water and the pH levels as described in the literature review after Witthueser (2010) and indicated in the relevant diagram in Figure 2-8. As $HCO_3$ content of the water reaches proportional levels over 50% in relation to $CO_3$ the pH of the system stabilises between 6 and 8, as the system begins to equilibrate the $HCO_3$ concentrations start to reach stable levels and thus the pH of the system also follows the same trend and stabilises along with it as shown in Figure 6-2. This is explained in the study of this relationship in section 2.6.2 of this dissertation as referenced from Witthueser (2010).

Based on the first three scenarios in the weathering model it is clear that to allow for a simulation with results closer to natural observed data, the fugacity of the system and mineral weathering rates should be adjusted. In the sensitivity simulation of scenario WSens2 the basic system was allowed to react for 100 years at atmospheric $fO_2$ and linearly changing $fCO_2$ from 0.00078 to 0.01 in WSens2a and linearly changing $fCO_2$ in the same way with $fO_2$ allowed to deplete to a level of $1E^{-10}$.

No changes in chemical concentrations between the two scenarios were observed but the resultant water did undergo a significant evolution in water type and

hydrochemistry in comparison to the previous simulations. The resultant water type is Mg-HCO$_3$ facies water correlating with the water types observed in BH04, BH116 and BH117.

Although the water type resembles the natural conditions, concentrations of Ca and Na are still too low as indicated in the Stiff diagram (Figure 6-3), with F being too high. F readily bonds with OH, Ca and other ions to precipitate out of solution once saturated. Thus as the weathering reactions allows for more ions to be released the F concentrations will decrease.
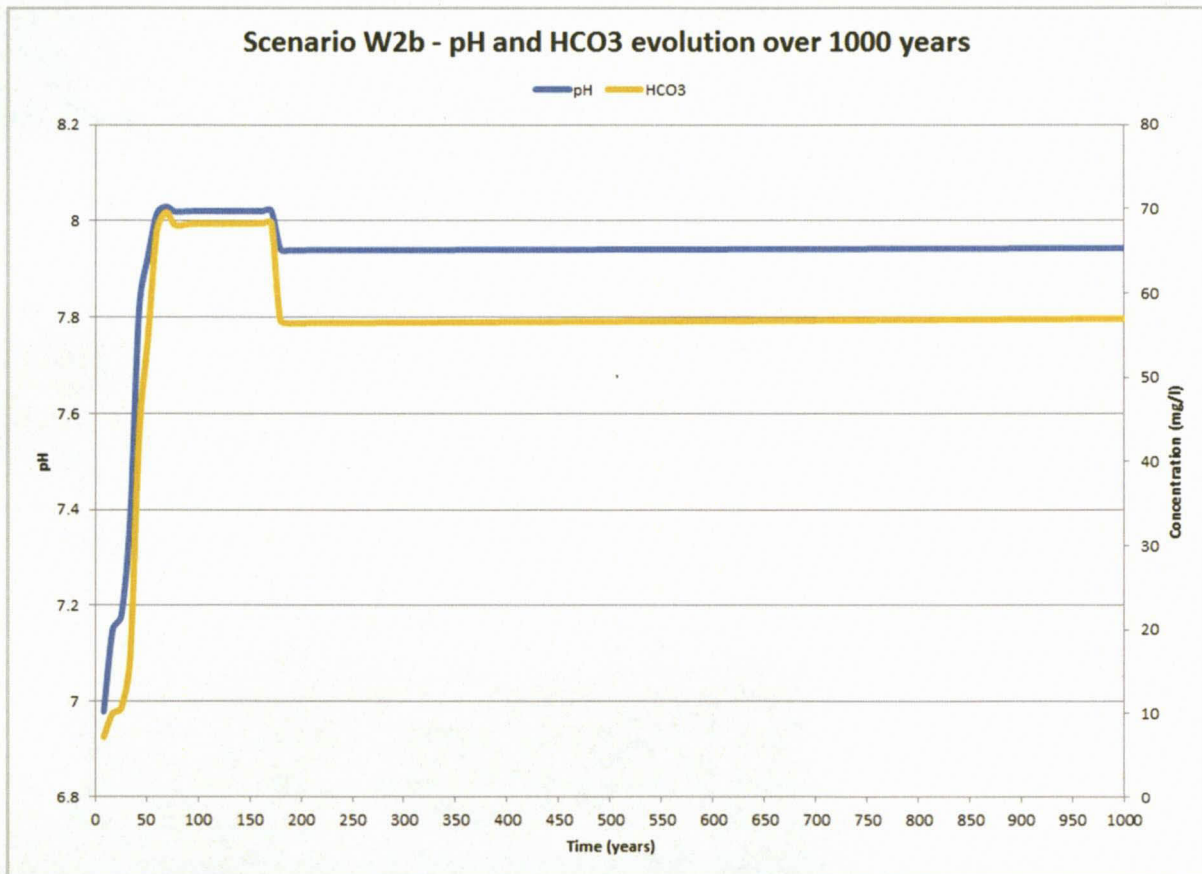


**Figure 6-2    pH and HCO$_3$ evolution over a period of 1000 years**

With this in mind, from the observed scenario of WSens2b and a conceptual knowledge of the geochemical system a sensitivity simulation was done on the weathering rates of the silicate minerals to allow the release of the main ions at a faster rate to calibrate the system at fugacity conditions as modelled in WSens2b.
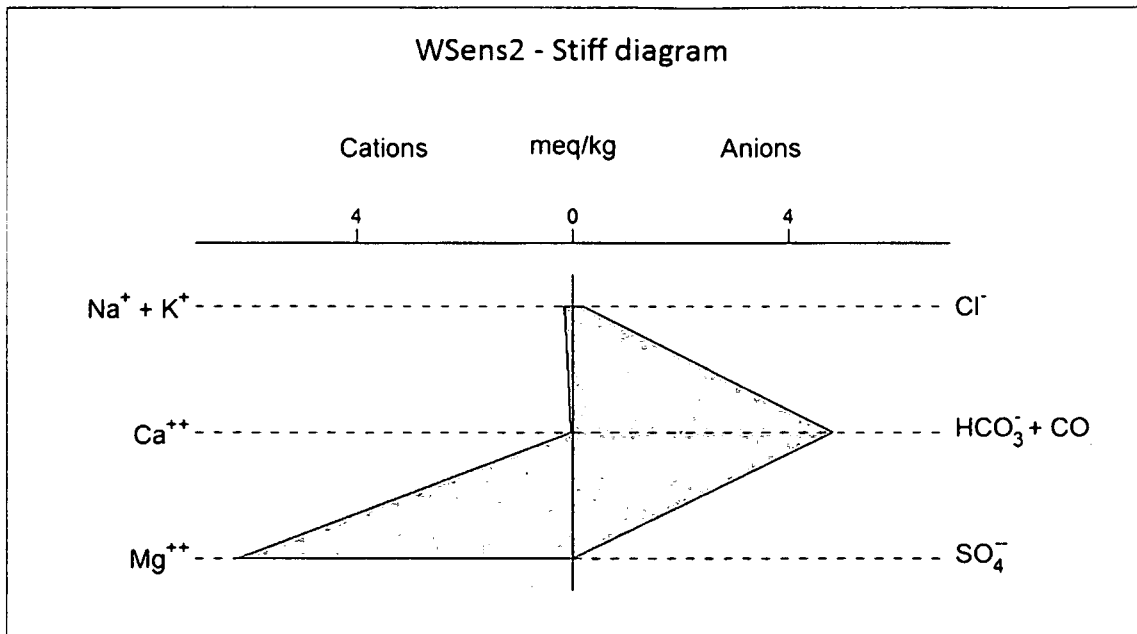
**Figure 6-3    Stiff diagram of the resultant water for scenario WSens2 (Mg-HCO₃)**

The weathering rates of K-feldspar, anorthite and nepheline were adjusted as described in section 5.4.3.5 to analyse the sensitivity of the system to faster and slower dissolution of the Ca, Na and K containing minerals.  Various studies has been done on $SiO_2$ containing minerals and thus accurate weathering rates are available, however in some system physical weathering or formational conditions like metamorphosis, as in the case of the project area geology, mineral alterations occurred that could lead to slower or faster rates.

Once again only small changes and process dynamics was observed in scenario WSens3.  However a slight increase in Na was observed as the nepheline released the ions under faster weathering rates in scenario WSens3b.  Nepheline is a hard mineral with slow weathering due to strong bonds between the ions and the $SiO_2$ molecules, however once the mineral was allowed to react at faster rates Na was released and allowed to dissolve.  Sodium is a highly soluble ion at various activity levels and across a wide pH range as indicated in Figure 6-4 when released from its mother compound usually associated with silicates.  As soon as Na dissolves into the system it bonds with $HCO_3$ at pH levels below 10, once the system reaches carbonate-bicarbonate ratios below 50% $HCO_3$ content the pH increases to levels above 10 and then $H^+$ is released from the aqueous species with Na bonding mainly to $CO_3$ and $SO_4$ in most cases.
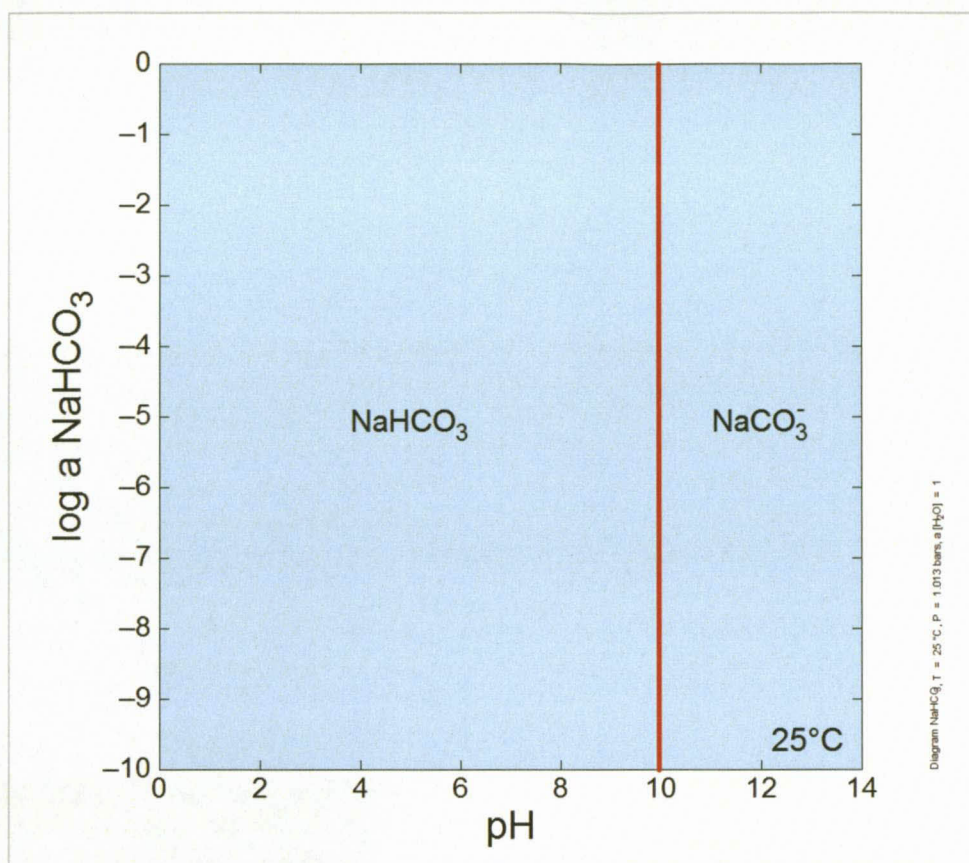
**Figure 6-4    Activity-pH diagram for NaHCO₃**

After the five scenarios with evaluations of the system dynamics as well as the sensitivity of the system to certain parameter changes, the knowledge of the calibration path accumulates to a calibrated simulation of the system in scenario W3. The parameters with the most stable results and that makes the most sense within the conceptual understanding of the hydrogeochemical environment was used to simulate the system in a state closest to that observed in the field groundwater data. The final resultant water sample from the calibrated system will not necessarily have the same chemical concentrations as observed in the field but needs to be proportionally in the same ionic distribution range and the water type should show the same facies.

The model parameters for scenario W3 is described in section 5.4.3.6 of this dissertation. The resultant water is of the $Mg-HCO_3$ facies with a TDS of 109 mg/ℓ with a pH of 7.96. The $Mg-HCO_3$ water type correlates with BH04, BH116, BH117 and surface water sample SW12 with the water indicated on the Stiff and piper diagram in Figure 6-5.
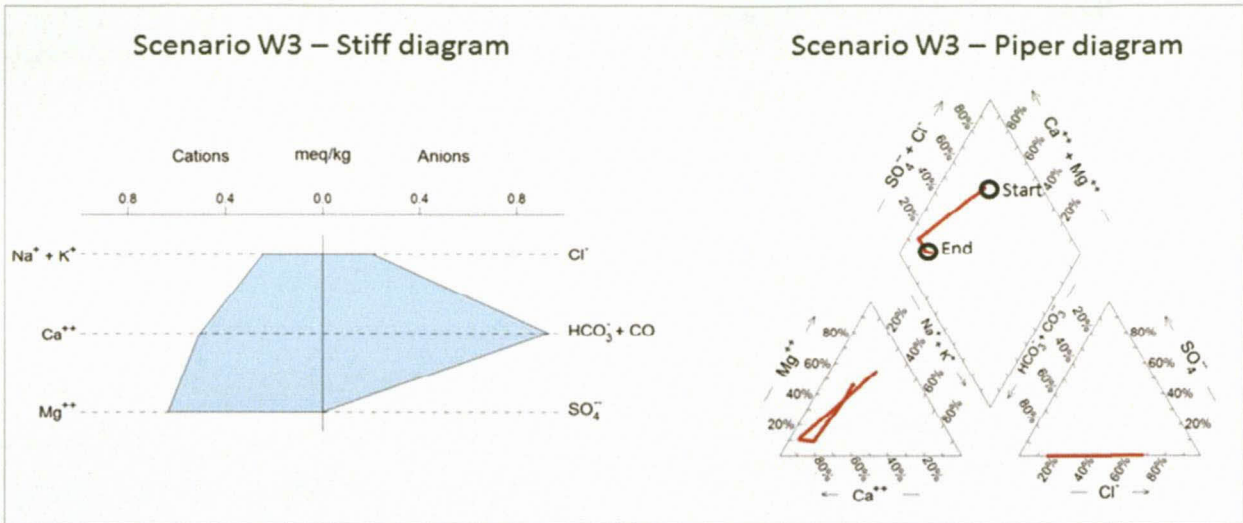
**Figure 6-5    Stiff and Piper diagram indicating the water type of the resultant water for scenario W3 as well as the evolution of the water over the 100 year period.**

The piper diagram indicates the evolution path of the weathering water sample with the initial Mg-Cl facies of the rainwater it follows a reaction path with only $HCO_3$ increasing with a consumption of $SO_4$, Mg and Ca as the saturated species gets precipitated out of solution, once the system equilibrates then only does an increase in Na and K develop to end at a Mg-$HCO_3$ water facies at the position indicated in the piper diagram.  This development of the water hydrochemical signature over 100 years can also be seen in Figure 6-6.  A water sample with a strong Mg/Ca and $HCO_3$ ion distribution in the water can be described as freshly recharged water.
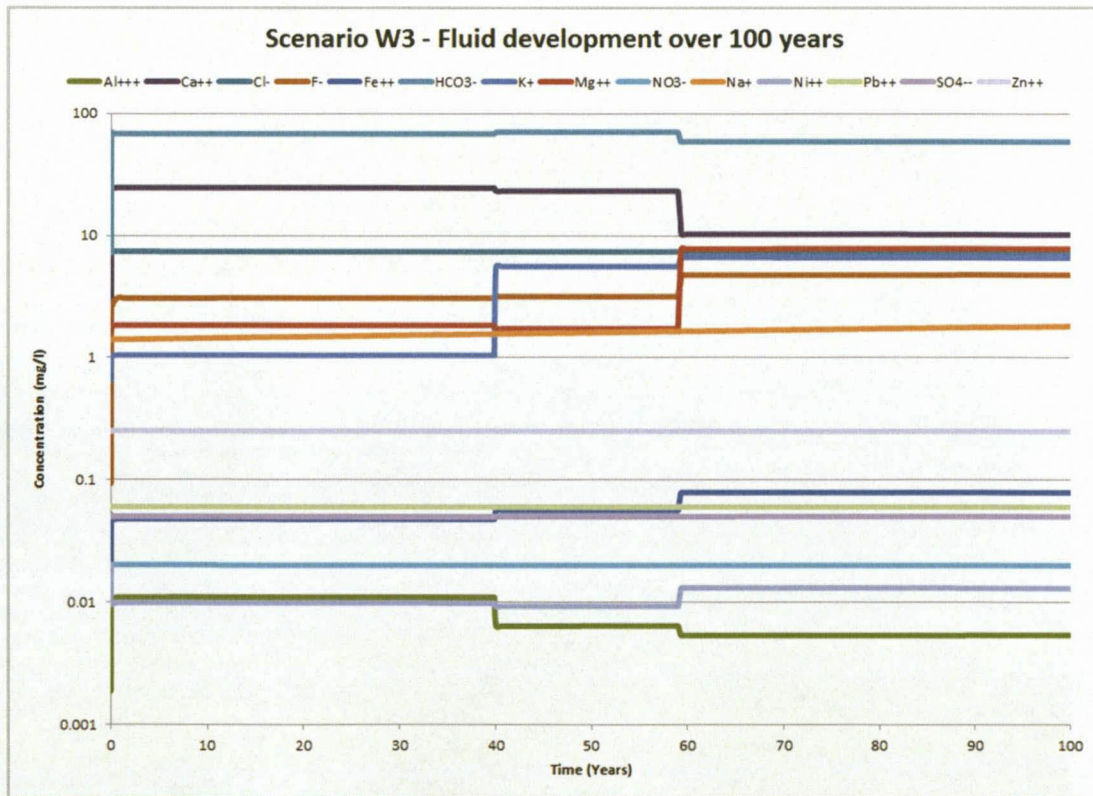


**Figure 6-6    Chemical development of the water in scenario W3**

The resultant water shows elemental concentration content close to that observed in the field with only Na and $HCO_3$ at levels below the groundwater limits and Zn, F and $SiO_{2(aq)}$ above the groundwater limits. $HPO_4$, V and Fe is present in concentration within the ranges observed in the leachate test laboratory results. The development/evolution of the water as indicated in Figure 6-5 and Figure 6-6 and described in the piper diagram discussion, correlates with the saturation levels and development of the minerals present both in solution and solid/precipitated state in the resultant water. The saturated minerals within the system are listed below:

- Dolomite – $CaMg(CO_3)_2$

- Nontronite –

- Muscovite - $KAl_3Si_3O_{10}(OH)_2$

- Phengite – $K(AlMg)_2(OH)_2(SiAl)_4O_{10}$

- Fluorapatite – $Ca_5(PO_4)_3F$

- Saponite -

- Quartz

- Daphnite

The above list of saturated minerals within the final fluid are all clay type minerals containing different proportions of Na, Ca, Mg, K, Fe and $HCO_3/CO_3$. The final model result and speciation indicates that these minerals are all in saturated states, however during the development of the water over the 100 year period these minerals developed to super saturated states allowing for the precipitation of some minerals lowering the concentrations of Ca, $HCO_3$, Al and Fe at about 60 years into the simulation. These observations correlate with the development and precipitation of some secondary minerals as shown in Figure 6-7.

The clay mineral development within the system is indicative in the environmental observations of the site with clay minerals being abundant in the weathered topsoil layer of the region.
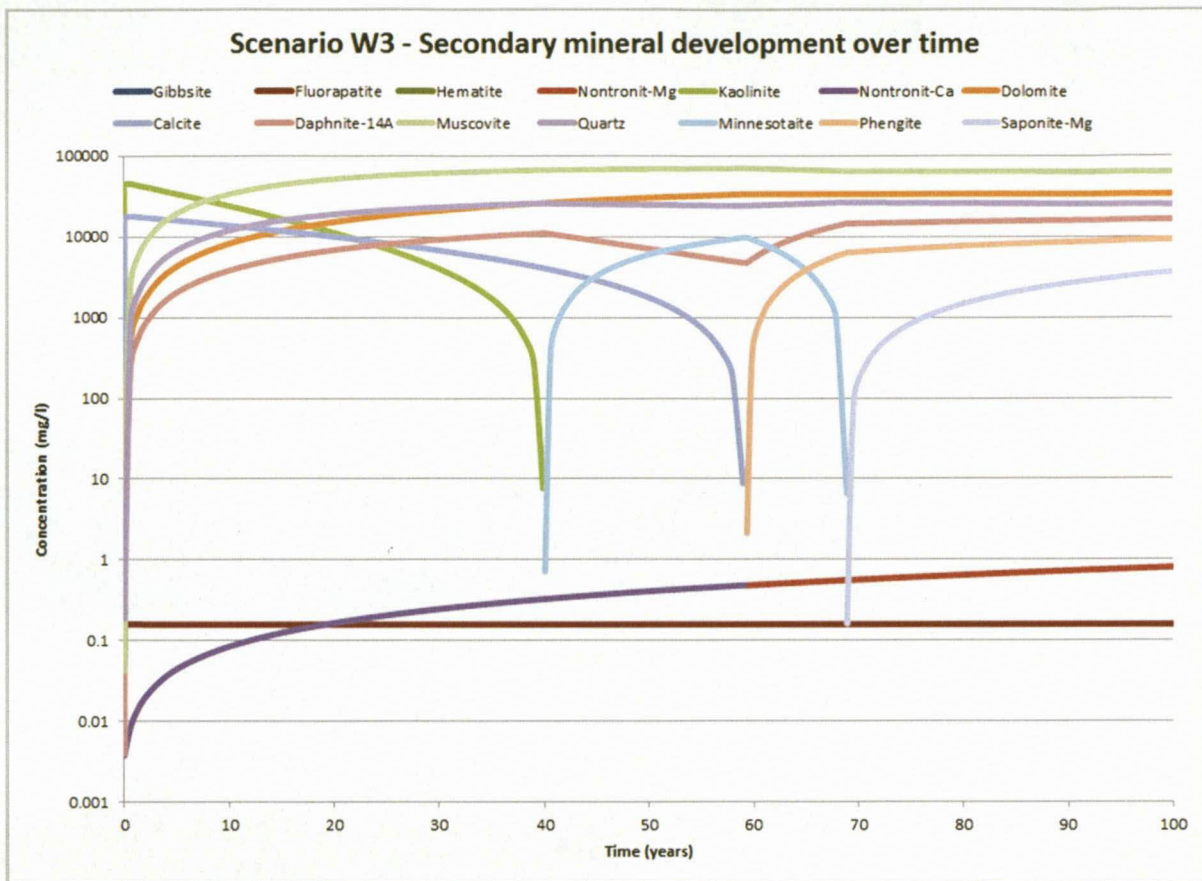
**Figure 6-7** **Diagram showing the development of secondary saturated minerals within the system of scenario W3**

Based on the path followed during the six weathering scenarios the following system observations and model conclusions can be made upon the development and investigation of a calibrated model:

1. The weathering reactions of the mafic, alkaline and to a lesser extent some felsic minerals within the Pilanesberg and Bushveld Igneous Complex geology allows for pH values ranging between 6 and 8 with buffering reactions not allowing any acidic or alkali environments to develop within the regional groundwater.

2. The system is most sensitive to fugacity of $O_2$ and $CO_2$ gasses with simulated values indicating that $fCO_2$ tends to reach levels close to 0.01 in the natural system allowing the dissolution of Al and $SiO_2$ to deplete with a more natural development of Na, Ca, K and Mg waters.

3. Clay mineral soils in the region is abundant due to water speciation in the region in field samples as well as modelled samples showing saturation of clay minerals with development of secondary minerals most likely to be smectite and kaolinite clays.

4. It can be concluded from the weathering models that the weathering period of 100 years with weathering, dissolution and precipitation reactions continuing

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towards a state of equilibrium, does not have a significant enough effect to characterise the chemical composition in concentrations towards that of the data observed in the field relating only to concentrations. Thus the weathering of minerals within a 100 year period will have no effect on the pit lake quality, with older existing groundwater facies dictating the quality long with surface and rain water.

## 6.1.2  Pit flood water mixing

As described in previous sections and the conceptual model, various mixing models were simulated to evaluate the eventual quality and chemical characteristics of the flooded pit layers and to ultimately evaluate whether it will be suitable for recreational, agricultural and wildlife use and serve the purpose as a post-closure environmental mitigation option.

From the four mixing models, samples representing each lake layer were generated with results listed in Table 5-13. Sample M1 represents the epilimnion, M2 the hypolimnion, M3 the evapolimnion and sample M4 represents the monimolimnion water chemistry. From these samples the suitability and feasibility of using pit flooding as a post-closure method as well as the use of the created pit lake for recreational as well as for water supply to agricultural and wildlife activity.

Scenario M1 simulated the sample of water expected when mixing of surface water (SW) and rainwater (RW) occurs to from the epilimnion after groundwater (GW) does not contribute to the top layer of the lake. This layer in relation to the other lake layers is the layer with the lowest TDS in relation to the monimolimnion with a TDS of 2985 mg/$\ell$. The different lake layers are characterised by the main ion concentrations and thus the chemical difference and stratification of the layers are seen in the comparison between ion distributions.

The density between the four layers does not differ significantly enough but the ion distributions and thus the TDS values will allow stratification to a degree. Stratification of the water column in the expected pit lake will thus be significant enough for a thermocline or chemocline to develop, however a transition zone rather than an abrupt change between the layers will exist.
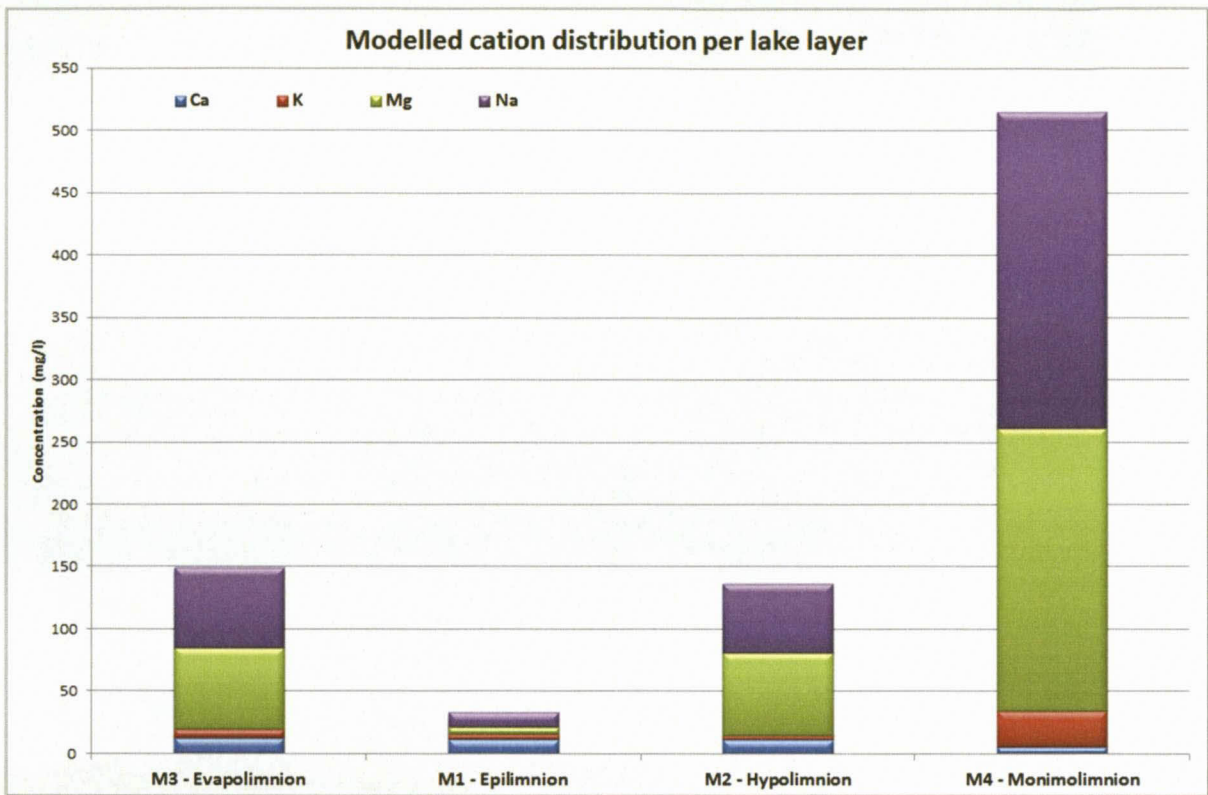
Figure 6-8    Cation distribution per modelled sample
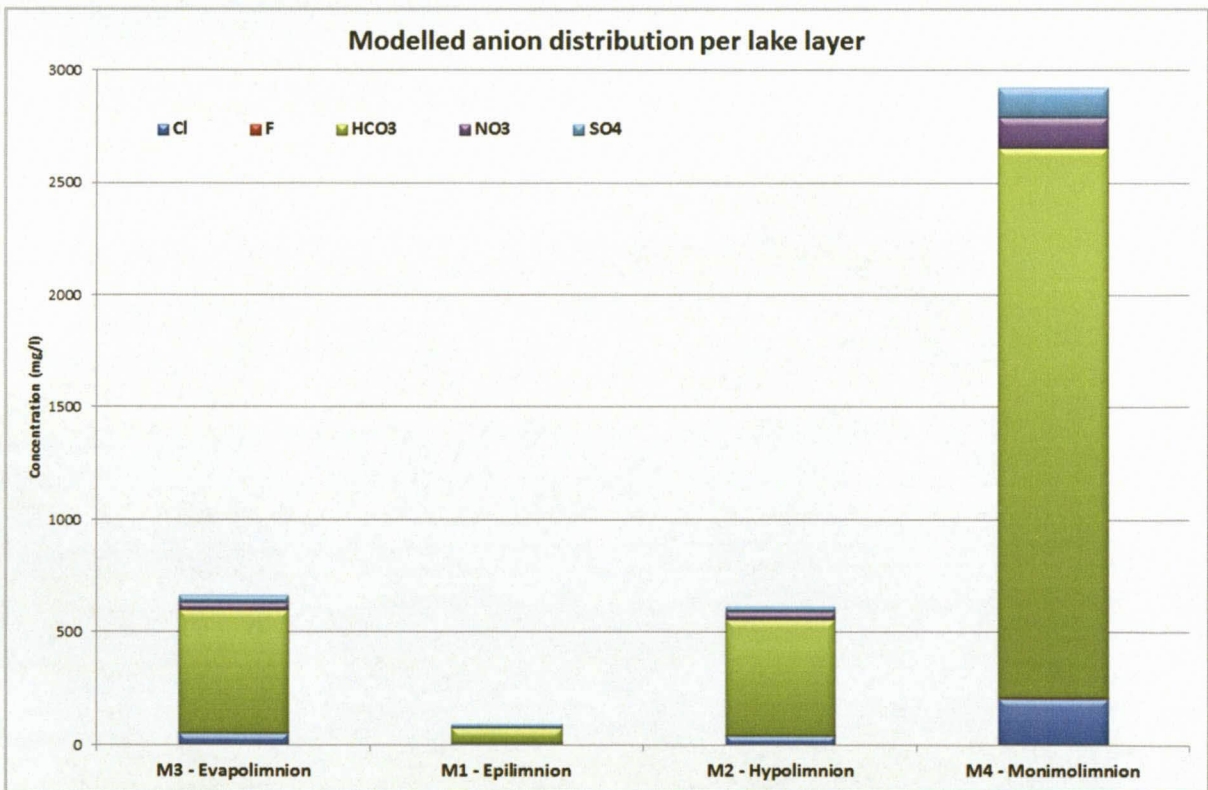


Figure 6-9    Anion distribution per modelled sample

The water types of the four layers all belong to the $Mg-HCO_3$ facies accept for the epilimnion with a $Ca-HCO_2$ facies resembling the surface water signature of the region. The main difference between the four layers is the proportional distribution of the anion and cation distributions. The main cations in the four lake layers are Na, Mg with a higher concentration of K also being dominant in the monimolimnion sample M4 as shown in Figure 6-8. The main anion in all the samples is $HCO_3$ with the reducing conditions in the monimolimnion allowing for an increase in $SO_4$ and $NO_3$.

During the formation of the resultant water samples for each lake layer over the mixing periods used in the transient simulations, allowed for the formation of saturated states of secondary minerals formed from combinations of the most active aqueous species in the chemical concentrations of the waters. The main saturated phases in the four layers are listed in Table 6-1.

**Table 6-1      Saturated phases present in each modelled sample**

| Saturated phases per sample | | | |
|---|---|---|---|
| M1 | M2 | M3 | M4 |
| Witherite | Witherite | Witherite | Witherite |
| Gibbsite | Gibbsite | Gibbsite | Gibbsite |
| Hematite | Hematite | Hematite | Hematite |
| $Co(FeO_2)_2$ | $Co(FeO_2)_2$ | $Co(FeO_2)_2$ | $Co(FeO_2)_2$ |
| Strontianite | Dolomite | Strontianite | Strontianite |
| Fluorapatite | Fluorapatite | Fluorapatite | Fluorapatite |
| Pyrolusite | Pyrolusite | Pyrolusite | Dolomite |
| | Dolomite | Dolomite | $CuFeO_2$ |
| | | | CuSe |
| | | | Nontronite |
| | | | HgSe |

Although the three top lake layers represented by samples M1, M2, and M3 do show the same saturated phases, the formation of these minerals out of solution through precipitation is unlikely due to the annual turnover events expected. The formation of these saturated phases relative to the mixing fractions over the transient simulations along with the saturated phase formation of M4 or the monimolimnion is shown in Figure 6-10. The saturated phases within the monimolimnion are more due to the heavy metal and sulphate increase from the reducing processes. As the mixing continuous over time and the system equilibrates the formation of the minerals in the monimolimnion is possible.

The ionic activity of aluminium hydroxides, iron oxides, sulphates, carbonates and other metal containing species throughout the water column and especially in the

reducing conditions of the monimolimnion allows for the formation of saturated mineral phases. The pH of the water along with the ionic activity of some elements describes these saturated states of some minerals.

The formation of gibbsite, an evaporative deposit, and to a lesser extent the aluminium hydroxides in the clay minerals forms when the log activity of $Al(OH)_4^-$ ranges between -1 and -8 with a pH range between 6 and 14. The activity of $Al(OH)_4^-$ and $Al(OH)_3$ (gibbsite) present in the evapolimnion at log activity of -7.17 and -7.81 respectively with a sample pH of 6.67 shows that gibbsite will only form from the evapolimnion as a secondary mineral. This activity-pH relationship and formation of gibbsite in evaporative environments is indicated in Figure 6-11.

The formation thermodynamics and activity of elements in these processes are clearly described by Merkel & Planer-Friedrich (2008) and also discussed in section 2.6.2 of the literature review.

Gibbsite will form on the lake banks where a shallow water depth allows for the precipitation of the mineral. Gibbsite is commonly associated with the formation of clay minerals like kaolinite and smectite with the $Al(OH)_4$ usually found between sheets of silicates and thus forming these clay minerals as found in the regional soil profiles of the Pilanesberg area.
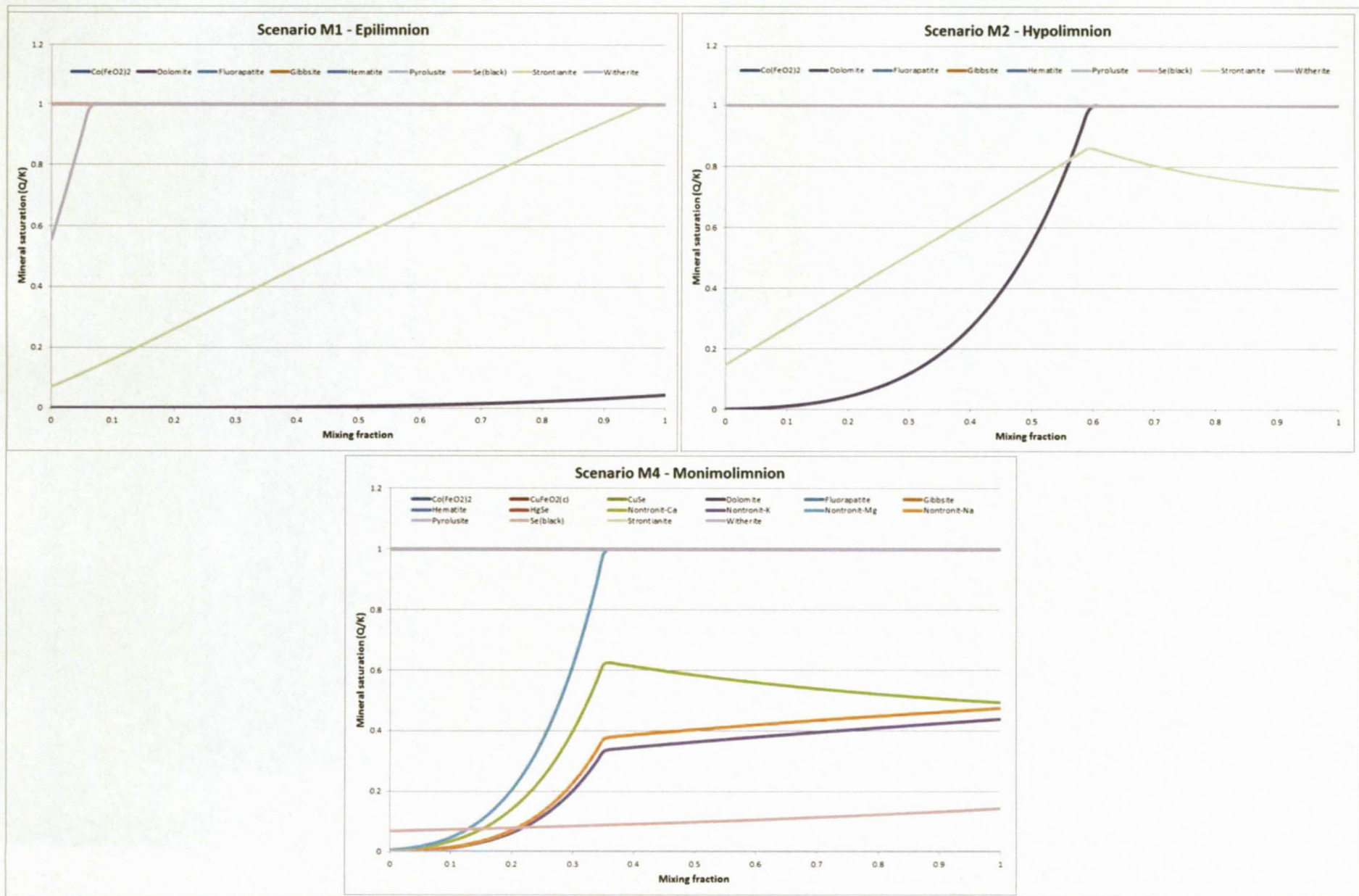
**Figure 6-10    Mineral saturation vs. mixing fraction for scenario M1, M2 and M4**
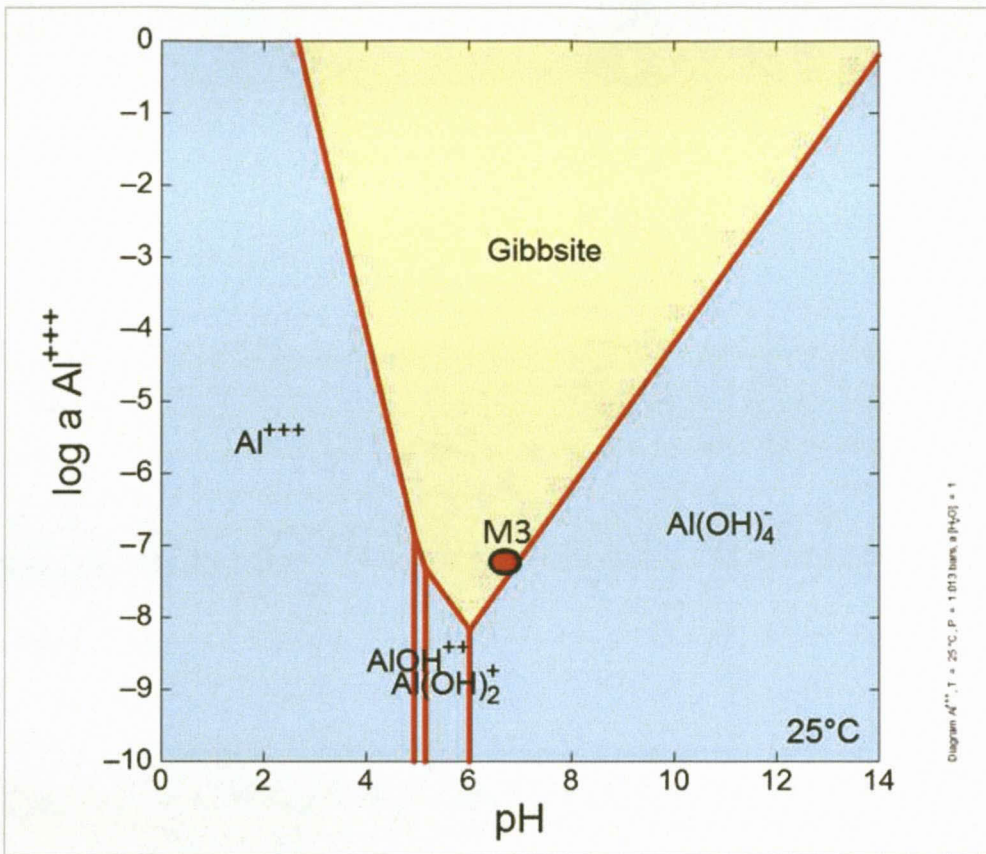
**Figure 6-11    Activity-pH diagram of Al$^{3+}$**
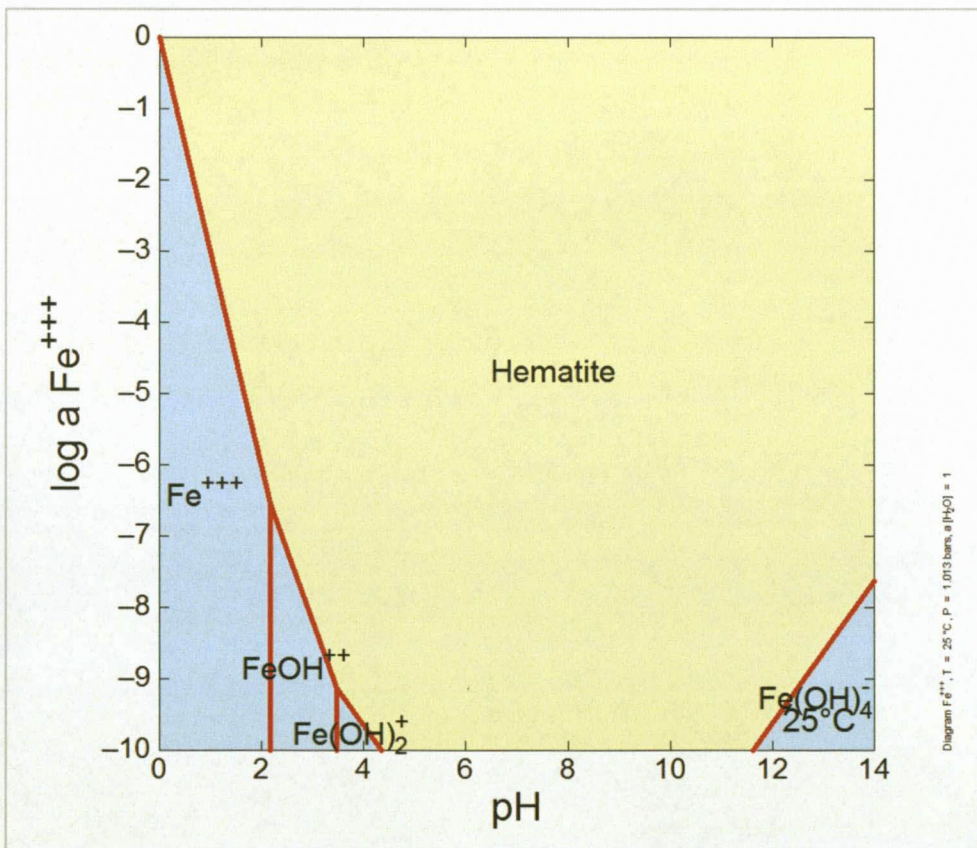


**Figure 6-12    Activity-pH diagram of Fe$^{3+}$**

The evapolimnion will allow mineral formation in shallow water, however the processes during turnover events expected with the epilimnion and hypolimnion will not allow formation of minerals within these two water layers and possibly affecting the precipitation processes in the evapolimnion as well. The monimolimnion on the other hand is saturated with carbonate, sulphate and metal oxide phases. The most likely phases to form from the monimolimnion (M4) are hematite and gypsum. Once the activity of $Fe^{3+}$ reaches pH levels in reducing conditions between 4 and 12 in combination with OH or only oxygen the formation of hematite out of solution will occur as indicated in Figure 6-12.

Gypsum forms once $CaSO_4$ is active at log coefficients between 0 and -2 over a wide pH range. The monimolimnion water shows a $CaSO_4$ activity of -5.21 and thus over the simulated period of 50 years no secondary gypsum will form as indicated in Figure 6-13.
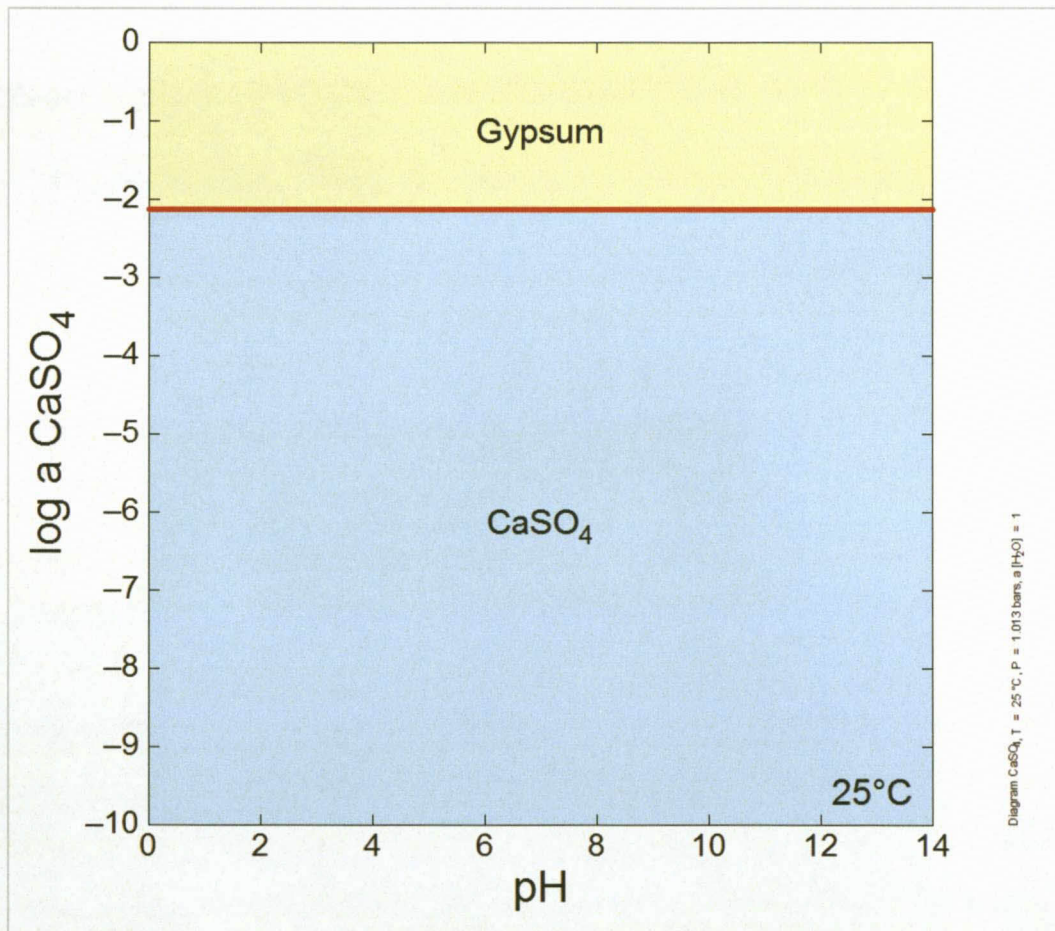


Figure 6-13    Activity-pH diagram of $CaSO_4$

## 6.2 Modelled pit lake water quality and Turbidity

The proposed pit lake at PPM mine post-closure will be used for various water use activities. The lake will be used recreationally for diving and other sports activities, livestock watering and to an extent will supply water to wildlife and support aquatic ecosystems. These activities along with human/domestic water use can only occur if the water quality of the pit lake is of national standards.

The following sub-section compares and summarizes the main chemical constituents in the modelled pit lake waters to the national water quality standards as set out by DWA. The background and criteria descriptions of each standard are summarized in the literature review in Chapter 2 (section 2.9) of this dissertation.

### 6.2.1 Domestic water supply standards

The water sample simulated for each lake layer has been classified according to the SANS Drinking water standards 241-1:2011 (SABS 2011a; SABS 2011b) to evaluate the water for human use and consumption. A review and description of the standards and limits is given in section 2.9 of this dissertation. Some of the standards were still sourced from the SANS 2005 edition for drinking water as indicated.

Table 6-2    Domestic water use quality classification of the simulated lake water chemistry

| Parameter | Unit | Standard Limits | Risk | M1 | M2 | M3 | M4 |
|---|---|---|---|---|---|---|---|
| HCO$_3$ | mg/ℓ | Not Specified (N/S) | | 66.64 | 513.49 | 544.25 | 2443.08 |
| Ca | mg/ℓ | <150 | SANS 241:2005 | 12.03 | 11.55 | 12.93 | 6.16 |
| Cl | mg/ℓ | <300 | Aesthetic | 9.91 | 45.33 | 52.55 | 206.21 |
| F | mg/ℓ | <1.5 | Chronic health | 1.44 | 0.57 | 1.79 | 7.04 |
| Mg | mg/ℓ | <70 | SANS 241:2005 | 5.41 | 66.22 | 64.74 | 226.97 |
| K | mg/ℓ | <50 | SANS 241:2005 | 3.91 | 3.67 | 7.24 | 28.43 |
| Na | mg/ℓ | <200 | Aesthetic | 12.05 | 55.36 | 64.60 | 253.53 |
| SO$_4$ | mg/ℓ | <500 | Acute health | 14.77 | 21.92 | 33.31 | 130.72 |
| NO$_3$ | mg/ℓ | <50 | Acute health | 1.90 | 33.63 | 34.20 | 134.23 |
| pH | | 5 - 9.7 | Operational | 7.31 | 6.79 | 6.67 | 6.42 |
| TDS | mg/ℓ | <1200 | Aesthetic | 136 | 717 | 776 | 2985 |
| Al | mg/ℓ | <0.3 | SANS 241:2005 | 0.004 | 0.001 | 0.003 | 0.282 |
| As | mg/ℓ | <0.01 | Chronic health | 0.005 | 0.003 | 0.007 | 0.026 |
| Co | mg/ℓ | <0.5 | Chronic health | $5.30 \times 10^{-09}$ | $1.54 \times 10^{-08}$ | $1.89 \times 10^{-08}$ | $1.35 \times 10^{-07}$ |
| Cu | mg/ℓ | <2 | Chronic health | 0.001 | 0.013 | 0.013 | 0.000002 |
| Fe | mg/ℓ | <0.2 | Chronic health | $6.39 \times 10^{-08}$ | $8.04 \times 10^{-08}$ | $1.14 \times 10^{-07}$ | 0.0008 |
| Pb | mg/ℓ | <0.02 | Chronic health | 0.003 | 0.011 | 0.059 | 0.231 |

| Parameter | Unit | Standard Limits | Risk | M1 | M2 | M3 | M4 |
|-----------|------|-----------------|------|-----|-----|-----|-----|
| Mn | mg/ℓ | <0.5 | Chronic health | $3.8 \times 10^{-10}$ | $5.5 \times 10^{-09}$ | $1.05 \times 10^{-08}$ | 0.074 |
| Ni | mg/ℓ | <0.07 | Chronic health | 0.001 | 0.007 | 0.022 | 0.087 |
| Se | mg/ℓ | <0.01 | Chronic health | $2.07 \times 10^{-37}$ | $6.55 \times 10^{-38}$ | $5.21 \times 10^{-37}$ | $9.85 \times 10^{-16}$ |
| Zn | mg/ℓ | <5 | Aesthetic | 0.002 | 0.014 | 0.207 | 0.813 |
| Hg | mg/ℓ | <0.006 | Chronic health | 0.0003 | 0.0001 | 0.0003 | $5.00 \times 10^{-17}$ |

Based on the standards for drinking water the following summary of the four lake layers can be given as classified for human consumption and domestic use (Table 6-2):

- Sample M1 representing the simulated water quality of the epilimnion has pristine water quality in all the chemical parameters.

- The hypolimnion (sample M2) has pristine water quality with only $NO_3$ (33.63 mg/ℓ) in elevated concentrations. However once mining stops the nitrate introduced to the system through blasting will decrease and thus $NO_3$ will deplete over time and is not of concern in this study.

- The evapolimnion (sample M3) has elevated levels of $NO_3$ and Pb falling in limits that can cause acute and chronic health risks in humans, the same applies to F.

- The elevated levels of nitrate, Pb and F in the evapolimnion is caused by the evaporation processes.

- The worst water quality is observed in sample M4 representing the monimolimnion. This lake layer is the deepest with reducing conditions with a lack of oxygen allowing the increase in most ionic concentrations.

- Cl, As, F, $NO_3$, Mg, TDS and Pb of the monimolimnion falls in concentrations above the allowed limits for drinking water and is not suitable for consumption and can cause chronic health effects.

The proposed pit lake will not be used for human or domestic use, however due to the rural community in the local area and the proposed use of the lake for diving and swimming, it is important to assess whether the water is safe to humans if consumed accidently. The evapolimnion is a dynamic layer only representing the top 3 m. Based on the summary and classification given above, the lake waters will be suitable with minor treatment and water management practices in place.

## 6.2.2   Irrigation water supply standards

The water sample simulated for each lake layer has been classified according to the DWA water quality guidelines for agricultural use in irrigation (DWAF 1996b). A review and description of the standards and limits is given in section 2.9 of this dissertation.

Based on the classification of the modelled lake water quality for each layer to its suitability for livestock watering (Table 6-3), the following summary of conclusions can be derived:

- Sample M1 has pristine water quality and is suitable for irrigation use with good crop yield and quality expected;

- Sample M2 shows elevated levels of $NO_3$ and TDS. However as mentioned before the nitrate levels in the water should deplete once mining stops and the TDS limit is only applicable on operational infrastructure with scaling being a possible risk. The water is however suitable for irrigation;

- Sample M3 shows the same water quality as M2; and

- Sample M4 or the monimolimnion is not suitable for irrigation due to elevated Na being harmful to moderately and highly sensitive crops.

Table 6-3    Irrigation water use quality classification of the simulated lake water chemistry

| Irrigation - Crop yield and quality guidelines | | | | | | | |
|---|---|---|---|---|---|---|---|
| Parameter | Unit | Max Acceptable | Risk | M1 | M2 | M3 | M4 |
| Al | mg/ℓ | 20 | >20 | 0.004 | 0.001 | 0.003 | 0.282 |
| AsH$_{3(aq)}$ | mg/ℓ | 2 | >2 | 0.005 | 0.003 | 0.007 | 0.026 |
| Cl | mg/ℓ | 350 | >350 | 9.91 | 45.33 | 52.55 | 206.21 |
| Co | mg/ℓ | 5 | >5 | $5.30 \times 10^{-09}$ | $1.54 \times 10^{-08}$ | $1.89 \times 10^{-08}$ | $1.35 \times 10^{-07}$ |
| Cu | mg/ℓ | 5 | >5 | 0.001 | 0.013 | 0.013 | 0.000002 |
| F | mg/ℓ | 15 | >15 | 1.44 | 0.57 | 1.79 | 7.04 |
| Fe | mg/ℓ | 20 | >20 | $6.39 \times 10^{-08}$ | $8.04 \times 10^{-08}$ | $1.14 \times 10^{-07}$ | 0.0008 |
| Mn | mg/ℓ | 10 | >10 | $3.83 \times 10^{-10}$ | $5.53 \times 10^{-09}$ | $1.05 \times 10^{-08}$ | 0.074 |
| NO$_3$ | mg/ℓ | 30 | >30 | 1.90 | 33.63 | 34.20 | 134.23 |
| Na | mg/ℓ | 70 | >70 | 12.05 | 55.36 | 64.60 | 253.53 |
| Ni | mg/ℓ | 2 | >2 | 0.001 | 0.007 | 0.022 | 0.087 |
| Pb | mg/ℓ | 2 | >2 | 0.003 | 0.011 | 0.059 | 0.231 |
| Se | mg/ℓ | 0.05 | >0.05 | $2.07 \times 10^{-37}$ | $6.55 \times 10^{-38}$ | $5.21 \times 10^{-37}$ | $9.85 \times 10^{-16}$ |
| Zn | mg/ℓ | 5 | >5 | 0.002 | 0.014 | 0.207 | 0.813 |
| pH | | 6.5 - 8.4 | <6.5 or >8.4 | 7.31 | 6.79 | 6.67 | 6.42 |
| TDS | mg/ ℓ | 540 | >540 | 136 | 717 | 776 | 2985 |

Although some elements are problematic, the summary and review of the irrigation guidelines in section 2.9 of this dissertation indicated that the suitability depends on the plant species and the irrigation management methods. In conclusion the water of the lake will be suitable for irrigational use.

### 6.2.3 Livestock water supply standards

The water sample simulated for each lake layer has been classified according to the DWA water quality guidelines for agricultural use in livestock watering (DWAF 1996d). A review and description of the standards and limits is given in section 2.9 of this dissertation.

Table 6-4    Livestock water use quality classification of the simulated lake water chemistry

| Livestock Watering | | | | | | |
|---|---|---|---|---|---|---|
| | | | Sample | | | |
| Parameter | Unit | TWQR | M1 | M2 | M3 | M4 |
| Al | mg/ℓ | 0 - 5 | 0.004 | 0.001 | 0.003 | 0.282 |
| AsH$_{3(aq)}$ | mg/ℓ | 0 - 1 | 0.005 | 0.003 | 0.007 | 0.026 |
| Ca | mg/ℓ | 0 - 1000 | 12.03 | 11.55 | 12.93 | 6.16 |
| Cl | mg/ℓ | 0 - 1500 | 9.91 | 45.33 | 52.55 | 206.21 |
| Co | mg/ℓ | 0 - 1 | $5.30 \times 10^{-09}$ | $1.54 \times 10^{-08}$ | $1.89 \times 10^{-08}$ | $1.35 \times 10^{-07}$ |
| Cu | mg/ℓ | 0 - 0.5 | 0.001 | 0.013 | 0.013 | 0.000002 |
| F | mg/ℓ | 0 - 2 | 1.44 | 0.57 | 1.79 | 7.04 |
| Fe | mg/ℓ | 0 - 10 | $6.39 \times 10^{-08}$ | $8.04 \times 10^{-08}$ | $1.14 \times 10^{-07}$ | 0.0008 |
| Hg | mg/ℓ | 0 - 1 | 0.0003 | 0.0001 | 0.0003 | $5.00 \times 10^{-17}$ |
| Mg | mg/ℓ | 0 - 500 | 5.41 | 66.22 | 64.74 | 226.97 |
| Mn | mg/ℓ | 0 - 10 | $3.83 \times 10^{-10}$ | $5.53 \times 10^{-09}$ | $1.05 \times 10^{-08}$ | 0.074 |
| NO$_3$ | mg/ℓ | 0 - 100 | 1.90 | 33.63 | 34.20 | 134.23 |
| Na | mg/ℓ | 0 - 2000 | 12.05 | 55.36 | 64.60 | 253.53 |
| Ni | mg/ℓ | 0 - 1 | 0.001 | 0.007 | 0.022 | 0.087 |
| Pb | mg/ℓ | 0 - 0.1 | 0.003 | 0.011 | 0.059 | 0.231 |
| SO$_4$ | mg/ℓ | 0 - 1000 | 14.77 | 21.92 | 33.31 | 130.72 |
| Se | mg/ℓ | 0 - 50 | $2.07 \times 10^{-37}$ | $6.55 \times 10^{-38}$ | $5.21 \times 10^{-37}$ | $9.85 \times 10^{-16}$ |
| Zn | mg/ℓ | 0 - 20 | 0.002 | 0.014 | 0.207 | 0.813 |
| TDS | mg/ℓ | 0 - 1000 | 136 | 717 | 776 | 2985 |

Based on the classification of the modelled lake water quality for each layer to its suitability for livestock watering (Table 6-4), the following summary of conclusions can be derived:

- The top three lake layers namely the evapolimnion (sample M3), epilimnion (sample M1) and the hypolimnion (sample M2) is suitable for livestock watering and can be consumed safely with no adverse effects by all livestock.

- Concentrations of F, NO$_3$, Pb and TDS in sample M4, representing the water

quality of the monimolimnion, is above the recommended Target Water Quality Range (TWQR) and thus water from the bottom of the lake will not be suitable for livestock watering.

○ Although the Monimolimnion is not suitable for livestock watering, the chances of the last layer to be reached by livestock drinking from the lake, or pumps being deep enough to abstract the last layer is not probable, thus the lake is deemed suitable for livestock watering if managed correctly.

• Based on these classifications, the lake should be suitable for wildlife consumption by antelope and other species.

### 6.2.4  Aquatic ecosystems water standards

The water sample simulated for each lake layer has been classified according to the DWA water quality guidelines for aquatic ecosystems (DWAF 1996c).  A review and description of the standards and limits is given in section 2.9 of this dissertation

Based on the classification results in Table 6-5 the following conclusion summary can be derived:

• The epilimnion has concentrations of F and Pb above the TWQR and within the limits of the chronic effect value (CEV).  This layer can be harmful to some aquatic species but will still be able to sustain aquatic ecosystems.

• The hypolimnion (sample M2) is suitable for the sustainable housing of most aquatic species, however some aquatic life will be affected by $NO_3$ values that is present in concentrations above the acute effect value (AEV)

• The evapolimnion and monimolimnion is classified within the AEV class, however due to the adaptability of some species to these levels, deep water fish and organisms will be able to live and breed in these waters.

Although water quality is not ideal, an aquatic ecosystem with species adapted to the conditions will be sustained by the proposed pit lake.  This conclusion is reached based on the fact that the pit lake will be a new environment formed over a long period of time.  The species adapting and to the pit lake as it floods and reaches the modelled levels will be ideally suited to the final environment due to the natural progression and development of the system.  No existing aquatic ecosystem will exist and thus the new pit lake will host a new ecosystem formed around the environment provided by the flooding event.

Table 6-5    Aquatic ecosystems water quality classification of the simulated lake water chemistry

| | | | | | Aquatic ecosystems | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Sample | | | |
| Parameter | Unit | TWQR | Chronic effect value | Acute effect value | M1 | M2 | M3 | M4 |
| Al | mg/ℓ | 0 - 0.01 | 0.02 - 0.15 | >0.15 | 0.004 | 0.001 | 0.003 | 0.282 |
| AsH$_{3(aq)}$ | mg/ℓ | 0 - 0.01 | 0.02 - 0.13 | >0.13 | 0.005 | 0.003 | 0.007 | 0.026 |
| Cu | mg/ℓ | 0 - 0.0014 | 0.0028 - 0.012 | >0.012 | 0.001 | 0.013 | 0.013 | 0.000002 |
| F | mg/ℓ | 0 - 0.75 | 1.5 - 2.54 | >2.54 | 1.44 | 0.57 | 1.79 | 7.04 |
| HPO$_4$ | mg/ℓ | 5 - 25 | 25 - 250 | >250 | $2.20 \times 10^{-06}$ | $4.54 \times 10^{-05}$ | $3.50 \times 10^{-05}$ | 0.0006 |
| Hg | mg/ℓ | 0 - 0.04 | 0.08 - 1.7 | >1.7 | 0.0003 | 0.0001 | 0.0003 | $5.00 \times 10^{-17}$ |
| Mn | mg/ℓ | 0 - 0.18 | 0.37 - 1.3 | >1.3 | $3.83 \times 10^{-10}$ | $5.53 \times 10^{-09}$ | $1.05 \times 10^{-08}$ | 0.074 |
| NH$_4$ | mg/ℓ | 0.5 - 2.5 | 2.5 - 10 | >10 | 0.09 | 1.64 | 1.67 | 6.55 |
| NO$_2$ | mg/ℓ | 0.5 - 2.5 | 2.5 - 10 | >10 | 0.21 | 0.22 | 0.39 | 1.53 |
| NO$_3$ | mg/ℓ | 0.5 - 2.5 | 2.5 - 10 | >10 | 1.90 | 33.63 | 34.20 | 134.23 |
| Pb | mg/ℓ | 0 - 0.0012 | 0.0024 - 0.016 | >0.016 | 0.003 | 0.011 | 0.059 | 0.231 |
| Se | mg/ℓ | 0 - 0.002 | 0.005 - 0.03 | >0.03 | $2.07 \times 10^{-37}$ | $6.55 \times 10^{-38}$ | $5.21 \times 10^{-37}$ | $9.85 \times 10^{-16}$ |
| Zn | mg/ℓ | 0 - 0.002 | 0.0036 - 0.032 | >0.032 | 0.002 | 0.014 | 0.207 | 0.813 |

## 6.2.5 Turbidity

The definition and use of turbidity is described in the literature review of this document. The turbidity of the modelled pit lake water quality needs to be assessed to evaluate whether the water will be suitable for swimming and especially diving and other recreational uses. Turbidity is measured in Nephelometric Turbidity Units (NTU) by a nephelometer to measure how much light can be detected through a water sample. DWA and other international governmental water bodies set out guidelines to classify weather the turbidity values of surface water bodies is suitable for diving and other recreational activities.

Turbidity or NTU is calculated by using the TSS values of the water in the following equation (Equation 3):

**ln TSS = 1.32 ln NTU + 0.15**                                                                    **Equation 3**

According to USA environmental standards the NTU of waters to be used for recreational purposes should be within 10% of seawater turbidity standards. Marine water has a turbidity of 50 NTU. Another parameter used by DWA is Secchi depth or the clarity/visibility of water. This parameter is calculated by using Equation 4:

**Secchi depth (m) = 5.07/NTU**                                                            **Equation 4**

The calculated turbidity and secchi depths for the PPM groundwater and surface water was done on the maximum and average TSS concentrations for all sites in the monitoring data to allow for a conservative approach. The calculated values are listed in Table 6-6.

**Table 6-6     Turbidity and clarity parameters for surface and groundwater**

| Parameter | Unit | Surface water | | Groundwater | |
|-----------|------|-----|---------|-----|---------|
| | | Max | Average | Max | Average |
| TSS | mg/l | 1826 | 319 | 913 | 76 |
| Turbidity | NTU | 265 | 70.1 | 156 | 23.8 |
| Secchi depth | m | 0.019 | 0.072 | 0.033 | 0.213 |

Based on the USA EPA regulations the turbidity of the maximum SW and GW values is not suitable for recreational use. However as SW will only flow into the system during the summer months during storm events, the water can be suitable for diving during seasonal window periods.

The TSS values of both SW and GW is high but depending on the time between flood events, settling of solids to the lake bottom during these periods will allow the clarity of the water to increase significantly. Thus at modelled level the analytical data shows that the pit lake will not be suitable for recreational use (swimming and diving), but due to certain factors the use of the lake for these activities is still plausible with natural processes being present.

## 6.2.6   Recreational water use standards

The water sample simulated for each lake layer has been classified according to the DWA water quality guidelines for recreational use (DWAF 1996a). A review and description of the standards and limits is given in section 2.9 of this dissertation

Based on the recreational parameters classified in Table 6-7 the following conclusions summary can be deduced:

- Chemical irritants expected in the top 3 layers of the lake water column are suitable for recreational use during full contact activities. Thus swimming and diving in the top three layers can be done.

- Full contact activities in the monimolimnion should however be restricted to short periods with warning notices at surface due to high concentrations of F,

Mg, NO₃ and TDS that can be harmful to humans if consumed in large quantities during recreational activities.

- The pH of the top 3 lake layers is suitable for recreational use.

- Visibility of the water is however poor with the expected waters during storm events not suitable for recreational activity.

- Window periods between flood events can however allow for turbidity to decrease and thus water of the top layers can become suitable for swimming and diving.

**Table 6-7    Recreational use water quality classification of the simulated lake water chemistry**

| Parameter | | Chemical irritants | pH | Secchi depth | Turbidity |
|---|---|---|---|---|---|
| Criteria | | Full-contact | Full-contact | Full-contact | Full-contact |
| TWQR | | N/A | 6.5 - 8.5 | >3 m | 45 - 55 NTU |
| Sample | M1 | Suitable | 7.31 | 0.019 - 0.072 | 70.1 - 265 |
| | M2 | Suitable | 6.79 | 0.019 - 0.213 | 23.8 - 265 |
| | M3 | Suitable | 6.67 | 0.019 - 0.213 | 23.8 - 265 |
| | M4 | F, Mg, NO3, TDS | 6.42 | 0.019 - 0.213 | 23.8 - 265 |

## 6.2.7 Overall pit lake water quality conclusions

Although the pit lake is not planned to be used for domestic and drinking water supply the classified quality of the hypolimnion and epilimnion is suitable for human use as well as agricultural use (irrigation and livestock watering). The suitability of the epilimnion and hypolimnion for the agricultural use is due to the rural community surrounding the pit will only be using it in localised crop areas and for food production to sustain individual families.

Based on the suitability of the pit lake for livestock watering wildlife will also be able to drink the water. Some risks not mentioned in the water quality section will however be raised in section 6.4 and 6.5.

Although water quality is not ideal, an aquatic ecosystem with species adapted to the conditions will be sustained by the proposed pit lake. This conclusion is reached based on the fact that the pit lake will be a new environment formed over a long period of time. The species adapting and evolving to the pit lake as it floods and reaches the modelled levels will be ideally suited to the final environment due to the natural progression and development of the system. No existing aquatic ecosystem will exist and thus the new pit lake will host a new ecosystem formed around the environment provided by the flooding event.

Recreational use will be feasible in the pit lake due to settling and seasonal windows allowing turbidity to decrease as well as visibility to increase. No chemical irritants are present in the water that is harmful to full contact recreational use. Some mitigation methods will however be needed and is discussed in section 6.5.

## 6.3 Final concept models

Based on the literature study, case study and the conceptual model, various scenarios of speciation, weathering and mixing models were simulated to study the current groundwater hydrochemistry and summarise and understand the geochemical processes currently involved in the system as well as those that is expected in the event of flooding the PPM open pit as a post-closure mitigation option.

During the speciation and weathering models various processes were identified that leads to the formation of the surface and groundwater currently observed in the field. As rainwater with an Mg-Cl water facies and a neutral pH recharges into the regional soils and geology, the fluid-rock interaction doesn't only cause physical weathering, but the chemical reactions taking place allows for geochemical weathering of the main minerals leading to the migration of the water from a diluted atmospheric signature towards the groundwater chemistry observed. The groundwater simulated is an Mg-HCO$_3$ water type with a pH of 7.96 formed through various dissolution reaction of the main minerals as listed in Figure 6-14. The Ca, Na, K, F, Fe, Mg, Al and SiO$_2$ rich minerals reacts and forms the groundwater which then over time without any dilution or atmospheric processes can become super saturated with secondary mineral phases and form them through precipitation. However ideal conditions, which are mostly not the case, should prevail for this to occur.

The weathering of the system allowing groundwater to form occurs with depleting fO$_2$ and a slight increase in fCO$_2$. All chemical processes observed and studied, chemical mineral weathering and formation reactions, as well as water type chemistry concluded from this dissertation and case study models are illustrated in Figure 6-14 and this serves as the final concept model for the fluid-rock interaction in the study area.

# Hydrogeochemical fluid-rock interaction

**Rainwater (Mg-Cl)**

**Surface water (Ca-HCO$_3$)**

**Recharge and chemical weathering reactions**

| | |
|---|---|
| Fluorite: | $CaF_2 \rightarrow Ca^{2+} + 2F^-$ |
| K-feldspar: | $KAlSi_3O_8 + 4H^+ \rightarrow 2H_2O + K^+ + Al^{3+} + 3SiO_{2(aq)}$ |
| Anorthite: | $CaAl_2Si_2O_8 + 8H^+ \rightarrow 4H_2O + 2Al^{3+} + Ca^{2+} + 2SiO_{2(aq)}$ |
| Nepheline: | $NaAlSiO_4 + 4H^+ \rightarrow 2H_2O + Al^{3+} + Na^+ + SiO_{2(aq)}$ |
| Ferrosilite: | $FeSiO_3 + 2H^+ \rightarrow H_2O + Fe^{2+} + SiO_{2(aq)}$ |
| Enstatite: | $MgSiO_3 + 2H^+ \rightarrow H_2O + Mg^{2+} + SiO_{2(aq)}$ |
| Forsterite: | $Mg_2SiO_4 + 4H^+ \rightarrow 2H_2O + 2Mg^{2+} + SiO_{2(aq)}$ |
| Fayalite: | $Fe_2SiO_4 + 4H^+ \rightarrow 2H_2O + 2Fe^{2+} + SiO_{2(aq)}$ |
| Phlogopite: | $KAlMg_3Si_3O_{10}(OH)_2 + 10H^+ \rightarrow 6H_2O + K^+ + 3Mg^{2+} + Al^{3+} + 3SiO_{2(aq)}$ |

**Groundwater (Mg-HCO$_3$)**

**Possible secondary mineral formation and precipitation**

$Ca^{2+} + Mg^{2+} + 2HCO_3^- \rightarrow 2H^+ + Dolomite$

$5Ca^{2+} + 3HPO_4^{2-} + F^- \rightarrow 3H^+ + Fluorapatite$

$Ca^{2+} + 4HCO_3^- + 3Mg^{2+} \rightarrow 4H^+ + Huntite$

$Al^{3+} + 3H_2O \rightarrow 3H^+ + Gibbsite$

$2Al^{3+} + Mg^{2+} + 2Fe^{2+} + 3O_{2(aq)} + 22SiO_{2(aq)} + 22H_2O \rightarrow 32H^+ + Nontronite$

$3Al^{3+} + K^+ + 3SiO_{2(aq)} + 6H_2O \rightarrow 10H^+ + Muscovite$

$Ca^{3+} + HCO_3^- \rightarrow H^+ + Aragonite$

$Mg^{2+} + HCO_3^- \rightarrow H^+ + Magnesite$

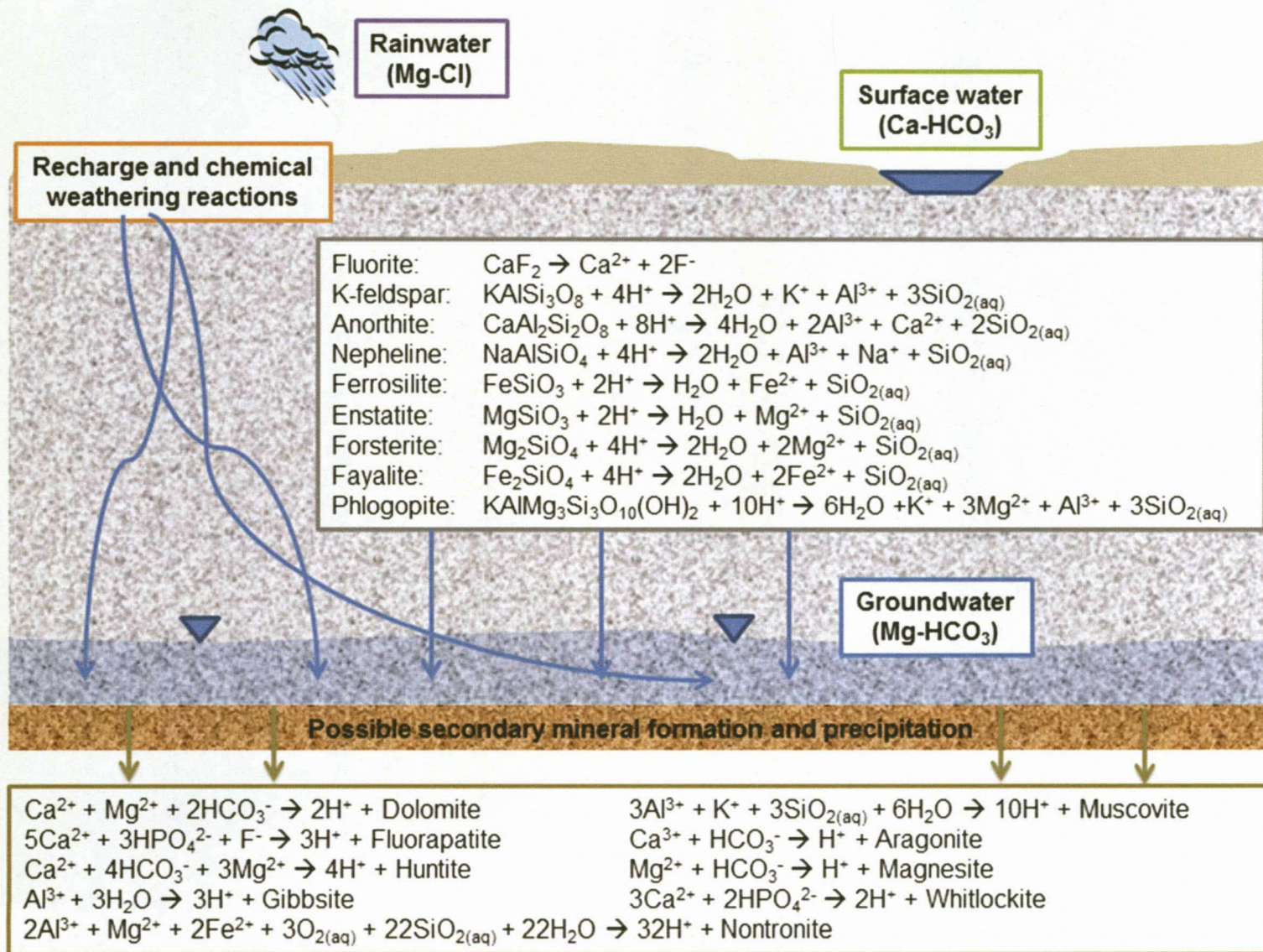$3Ca^{2+} + 2HPO_4^{2-} \rightarrow 2H^+ + Whitlockite$

**Figure 6-14    Final conceptual weathering model**

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The most important simulation during the models were the mixing simulations between groundwater, surface water and rainwater to simulate the expected processes involved as well as the hydrochemistry and water quality of the proposed pit lake. Based on the studies of Nuttall & Younger (2004) stratification in flooded mine waters can be caused by various factors of which the following two will cause the event to occur in the case study pit lake as illustrated in Figure 6-15:

1. Small inflows and outflows in the pit or shaft wall; allowing

2. Gradual inflow and slow recovery of water levels.

These two stratification causing factors allows for changes in water quality with the bottom layer of the pit lake or flooded underground mine/shaft having metal concentrations of elements like Fe, Zn, Ni and V 2 to 3 orders in magnitude more than the shallower water column layers (Nuttall & Younger 2004) also correlating with the modelled PPM water quality in the monimolimnion. From this Nuttall & Younger (2004) concluded that in modelling or predicting stratified water column qualities the worst quality modelled or measured will be the concentrations on which long term mitigation designs and treatment plans should be based. Thus the evapolimnion waters and monimolimnion simulated scenarios were done with the hypolimnion sample as basis.

The waters of the evapolimnion, epilimnion, hypolimnion and the monimolimnion were simulated over different transient periods at different atmospheric conditions. Evaporation processes in the evapolimnion lead to higher TDS values with a slightly lower pH. The SW and RW mix of the epilimnion showed the lowest TDS values with an increase as GW is introduced into the system in the hypolimnion. As the system reaches equilibrium, organic material and high density water accumulates at the bottom of the lake to form the monimolimnion in reducing condition and an increase in $SO_4$ and metal concentrations is observed with a final simulated TDS of 2985 mg/$\ell$ at a pH of 6.42. As the water column increases with depth once again a decrease in $fO_2$ and increase in $fCO_2$ is observed. All the processes observed in the mixing models are summarised in a final mixing concept model as illustrated in Figure 6-15. The increased concentrations of metals in the monimolimnion allows for the formation of secondary minerals out of solution.

# Final Conceptual Pit Lake Model
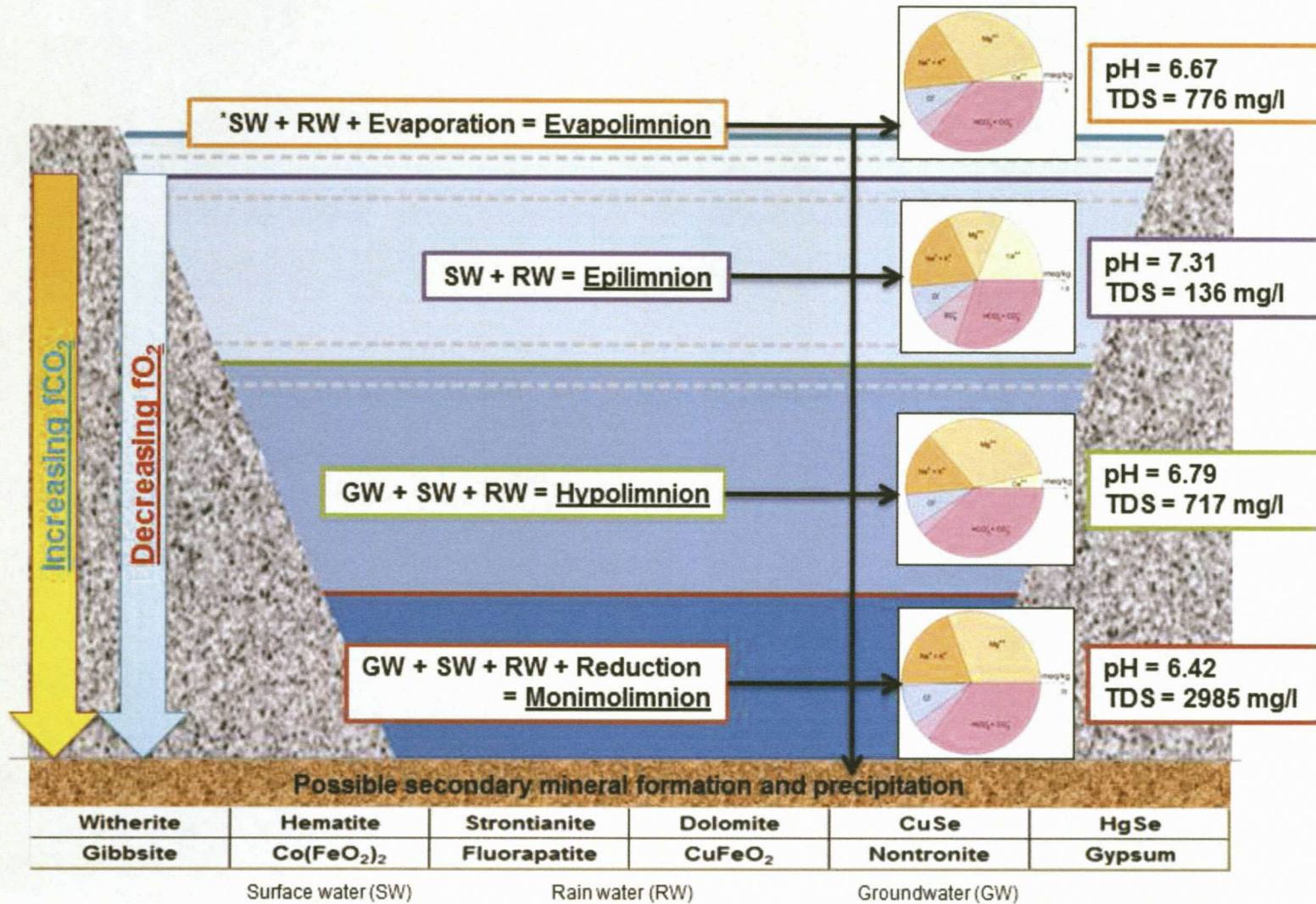


Figure 6-15    Final conceptual hydrogeochemical pit lake model

## 6.4 Short discussion on alternative outcomes

The research outcome and answers to research questions in this dissertation is based on various assumption, limitations and unknowns. Uncertainty is a factor in all models and something that needs to be kept in mind, with research answers addressing all possible outcomes. However in most cases it is unpractical to try and cover all bases through the simulation of models that are time consuming and will generate a wide variety of answers only increasing the uncertainty of the final recommendations and mitigations.

The purpose of modelling be it geochemical or numerical flow modelling is to simulate and generate results that will help in the decision making processes and serve as a decision making and scientific tool in real world situations. However in the context of the research project and case study at hand, the following alternative outcomes to the conceptual scenarios can be possible based on the simple question of What if?

The main assumption made to accommodate the geochemical model is that the pit will flood over a period of 100 years. Now the alternative question and scenario raised will be *What if the pit does only flood partially or not at all?*

However likely or unlikely the above mentioned question and scenario does seem to the researcher, a probability of the event in which the flooding of the pit does not occur as planned is still present and a secondary risk that could lead to various other impacts to consider. If the pit only floods partially the expected lake water quality will be that of the hypolimnion, excluding the water of the monimolimnion as this lake layer will only form if a flooding occurs and a deep enough lake forms. The hypolimnion represents a mixture of groundwater, surface water and rain water which will form the worst case scenario pit water which in the case of a partial flood event can form a holomictic lake with no stratification. If flood events and seasonal inflows do not fill the lake to the expected level, groundwater and surface water will flow into the cavity to approximately the original groundwater level. Although the pit lake quality will still be suitable for various uses as discussed in the water quality analysis of the simulated hypolimnion, recreational use will not be possible due to the shallow depth and access to the water level.

Safety risks will be created due to access to the water table allowing a large part of the pit wall to still be exposed with cliff scenarios created. Thus wildlife, livestock and humans will have a risk of falling a far way before reaching water. In the event that no flooding occurs, which is highly unlikely, the above mentioned risks are extrapolated to even higher levels.

The scenario discussed above can lead to risks as mentioned, thus in the following section (section 6.5) some secondary risks will be identified with possible mitigations listed in the unlikely event of them occurring.

## 6.5 Identified risks and recommended mitigation methods

### 6.5.1 Primary risks

The primary risks identified during the MSc study of the hydrogeochemical environment of the PPM Pit Lake is listed in Table 6-8 with mitigation methods recommended. These risks are based only on the outcomes of the research study with all model outcomes and scenarios taken into account with water quality and possible physical risks.

The risks identified and mitigation methods originate out of following four research questions as mentioned previously:

1. What is the expected water quality that will be the final product within the planned pit lake?

2. What are the risks identified during modelling of the proposed pit flooding to the environment and to human/animal use?

3. What mitigation methods/modifications to the planned post-closure option can be applied to decrease or remove risks?

4. Is pit flooding as a post-closure option feasible and can it be used for various recreational and agricultural/wildlife applications?

### 6.5.2 Secondary risks

In section 6.4 the possibility of an alternative outcome to the proposed and modelled pit flooding scenario as a post-closure option is discussed. From this alternative outcome and the four research questions mentioned in section 6.5.1 the secondary risks, which is much lower in probability to occur, can be identified and is listed with possible recommended mitigation methods in Table 6-9.

**Table 6-8       Primary risks and mitigation options**

| Primary risks and recommended mitigation options | | |
|---|---|---|
| **Risk** | **Impact description** | **Mitigation methods** |
| High turbidity and TSS of the pit lake will render poor visibility unsuitable for recreational use | Low visibility during diving (Cannot dive recreationally in water of turbidity within 10% of 50 NTU) | 1. Upstream sump in the surface water channel flowing into the pit allowing a reduction of flow velocity and settling of TSS<br>2. Settling ponds allowing inflowing surface water to reduce flowing velocity and allow TSS to settle out before flowing into the pit lake<br>3. Only using the pit lake for recreation use during seasonal windows allowing visibility to improve during low inflow periods |
| | High risk of obstacles causing injuries during swimming, diving or other full contact activities | |
| | Clogging of fish gills due to high TSS values reducing respiratory functionality of fish and other water species | |
| Cl, As, F and Pb of the monimolimnion present in concentrations above the allowed limits for drinking water and domestic use | Chronic and acute health effects in humans if consumed. | Treating water with cost effective methods before distribution:<br>4. Anion exchange resin beds in which all significant anions will be removed<br>5. Desalination techniques such as reverse osmosis and electro-dialysis |
| High TDS values of the evapolimnion, hypolimnion and monimolimnion | Damage and impacts on operational infrastructure like pipes and pumps used to source water from the pit lake for domestic and agricultural use with scaling and corrosion being the main impacts | 6. Infrastructure management plans with operational shut downs for maintenance<br>7. Equipment made out of suitable material like plastic pipes and stainless steel pumps |
| Mixing of pristine water layers with the monimolimnion through abstraction activity (pumping) | Mixing of the stagnant monimolimnion with cleaner hypolimnion and epilimnion through turbulence and currents induced by abstraction pumps thus reducing the overall lake quality | 8. Lower abstraction rates for longer periods reducing turbulence from pumping at high rates<br>9. Not abstracting during periods when the lake water level is low<br>10. Pump installation depth should be within the top 50 m of water not allowing the pump to reach levels close to the monimolimnion<br>11. Abstraction for any water use from the pit lake should only occur once the lake is at least 80% flooded |

**Table 6-9     Secondary risks and mitigation options**

| Secondary risks and recommended mitigation options | | |
|---|---|---|
| **Risk** | **Impact description** | **Mitigation methods** |
| Partial flooding creating a holomictic pit lake | High pit lake walls creating difficult access to the water level for humans and animals thus creating a cliff environment that could cause injuries or death | 1. Diverting more regional rivers and drainages to flow into the pit and fully flood to allow water levels to reach capacity<br>2. Decreasing the pit volume and area by increasing the backfill volume<br>3. Fencing of the pit<br>4. Fully backfilling the pit as a post-closure mitigation |
| No flooding with an almost dry pit | High pit walls and large cavity in the ground that can cause injury or death to animals or humans | 5. Fully backfilling the pit as a post-closure mitigation<br>6. Diverting more regional rivers and drainages to flow into the pit and fully flood to allow water levels to reach capacity |

## 6.6 Concluding summary: Chapter 6

Chapter 6 accumulated and gathered the knowledge, information and results from literature studies, field data and model results into an in depth discussion and interpretation, with the research questions and objectives answered and met throughout the chapter.

The mineral weathering models and simulations led to a systematic pathway to a calibrated system with the following parameters yielding the ideal results closest to that observed in the field:

- A simulation period of 100 years with calibrated mineral weathering rates as listed in Table 5-12;

- A fugacity change with $fO_2$ decreasing to $1E^{-10}$ and $fCO_2$ increasing to 0.01.

These results allowed for the conceptualised summary and visual representation to the main processes and chemical reactions involved in the PPM hydrogeochemical fluid-rock interaction forming the groundwater as we observe it in the field. This graphic summary is given in Figure 6-14.

The four pit lake layers were simulated with results for each lake layer and the major processes involved also summarized in a final concept model in Figure 6-15. The pit lake water as summarised in the final concept pit lake model was measured against various water use guidelines to determine the suitability of the water for recreational as well as agricultural uses. All risks and mitigation methods identified is listed with alternative scenarios kept in mind.

The main research conclusions and research answers broadly discussed in this chapter will be listed and given in condensed form within Chapter 7.

# CHAPTER 7:

## 7 CONCLUSIONS

### 7.1 General chapter conclusions

This document is a written dissertation for research done to evaluate the use of open pit flooding as a post-closure option from a geochemical approach and evaluation with emphasis lying in the fluid-rock and fluid-fluid interaction in a pit environment through geochemical and hydrochemical modelling referred to in this document as hydrogeochemical modelling.

Each chapter of this dissertation was a written representation and discussion of various elements within an academic framework to evaluate and answer research objectives and questions. Each chapter was shortly summarised within the document and the following integrated summary gives the main conclusions from each chapter as also listed within this finished research paper for an MSc in Geohydrology under each sub-heading, Concluding summary.

**Chapter 2: Literature Review:**

- The first mention of discovery of PGE minerals in South Africa was by Bettel (1892) with traces of group elements in the Witwatersrand, however the first noteworthy discovery of platinum by A.F. Lombaard and Dr. Merensky was in 1924 on the farm Maandagshoek that later led to the discovery of the Merensky and UG2 Reefs (Cawthorn 1999; Cawthorn 2001);

- Today the Bushveld Igneous Complex has the largest PGE reserves in the world with other similar international examples being the Skaergaard intrusion, Stillwater Complex and The Great Dyke in Zimbabwe;

- Regional and local specialist studies indicated that the general groundwater facies in the Bushveld Igneous Complex is a Ca/Mg-HCO$_3$ water type within the weathered aquifer (Smith & Kotze 2010; Titus et al. 2009);

- Kriek & Meyer (2010) concluded that the local geological strata in the project area geology allows for the following aquifers to from:

  o Perennial river aquifer

  o Weathered and fractured topographically low lying areas

  o Faults and fractured zones forming the major aquifer

  o Weathered norite/gabbro

  o Fractured rock aquifer underlying the weathered zone

- From various international studies on pit lake limnology and factors influencing the pit lake dynamics and aqueous geochemistry, the following elements and factors were studied:

  o Wind effects;

  o pH;

  o Inflow velocity;

  o Thermodynamics;

  o Fugacity;

  o Ionic activity;

  o Depth to area ratio of lake morphology;

  o Chemistry and density of input waters;

- Castendyk & Webster-Brown (2007) in a study on pit lake limnology and stratification developed two conceptual models. The first for a holomictic lake and the second for a meromictic lake on which the PPM pit lake conceptual model was based; and

- A short background and information summary and review of the numerical groundwater flow model done on the PPM pit flooding feasibility was given with the main assumptions on the research study coming from the numerical model.

**Chapter 3: Project Data**

- The following data sets were used in this research dissertation and case study:

  o Rainfall and Temperature data;

  o Geological and topographical maps;

  o Literature data and analogue values;

  o Monitoring data (Water quality and water levels);

  o Hydrocensus data;

  o TCLP and ABA results;

  o Mineralogical tests and data;

- Chapter 3 gave short descriptions on statistical summaries of the data mentioned above with the following three chapters using this data within a case study and research model to evaluate the feasibility of flooding an open

pit platinum mine post-closure as an environmental rehabilitation/mitigation option; and

- All data sets are either listed in the document or provided on the data DVD with appendices.

**Chapter 4: Case study – Project Site Assessment**

- Chapter 4 characterised and described the study area with the following main conclusions from the case study site assessment:

  o The existing PPM mine is an open pit operation just north of the Pilanesberg Complex currently operating at an approximate 235 000 ton/month from the UG2 and Merensky Reefs;

  o The study area falls within the A24D quaternary catchment (Crocodile West and Marico WMA) with the main drainage channel being the Wilgespruit that will also contribute the largest volume of surface water into the pit flooding post-closure;

  o The Wilgespruit flows out in a north-eastern direction from the prominent Pilanesberg hills;

  o The project area has a warm bushveld climate with maximum average temperatures in summer being 31°C and average minimum temperatures in winter dipping to 4°C;

  o The summer rainfall area has a MAP of 628 mm/a with a high 1849 mm/a MAE over the extent of the catchment having and total area of 1328 km$^2$;

  o The main geology of the study area is the gabbro norite rocks of the Rustenburg Layered Suite with mineralogical and structural influences from the Pilanesberg Alkaline Complex;

  o Complex structural development in the local geology from dyke swarms and faults allows for difficult mining conditions and a wide range of aquifer systems with an average local water table of 21 mbgl; and

  o Fluoride and nitrate is the two chemical constituents within the local aquifer deeming most of the sampling locations not suitable for human consumption.

**Chapter 5: Hydrogeochemical Assessment and Models**

- The surface water of the region has a Mg/Ca-HCO$_3$ water type with the

groundwater dominated by a Mg-HCO$_3$ facies;

- A conceptual pit lake model includes the inflow of groundwater, surface water and rainwater mixing during different periods at various fractions allowing the formation of a meromictic pit lake;

- The meromictic PPM pit lake will have 4 lake layers in order from top to bottom termed the evapolimnion, epilimnion, hypolimnion and monimolimnion;

- ABA and TCLP results from an accredited laboratory was interpreted with the samples taken from the core boreholes deemed not to be acid generating with the gangue minerals buffering any potential acidification;

- From the analogue data and field data gathered input samples were selected with weathering and mixing models simulated;

- Speciation models showed that the saturated phases in the groundwater samples are:

  o Fluorapatite

  o Dolomite

  o Huntite

  o Magnesite

  o Whitlockite

  o Calcite

  o Cuprite

  o Aragonite

  o Hydroxyapatite

- The saturated phases within the surface water of the region most likely to form out of solution:

  o Muscovite

  o Strontianite

  o Kaolinite

  o Cuprite

- Five weathering models were done with sensitivity analysis on various chemical elements in the conceptual system leading to the formation of a calibrated system model (Scenario W3) allowing the interpretation and investigation of processes involved in the formation of the groundwater as

observed in the field;

- The final calibrated model indicated a $Mg$-$HCO_3$ water type with a pH of 7.96 and a TDS of 109 mg/$\ell$ correlating with field data;

- The four lake layers as discussed and illustrated in the conceptual model was modelled with the following scenarios:

  o Scenario M1: Mixing of surface water and rainwater under atmospheric conditions at different proportions to simulate the inflow mixing of waters for 50 years to form the epilimnion once groundwater inflow has stopped after the first 40 to 45 years.

  o Scenario M2: Mixing of surface water, rainwater and groundwater at atmospheric conditions at different proportions to simulate the inflow mixing of waters for the first 45 years of pit flooding that will eventually form the hypolimnion.

  o Scenario M3: Evaporation scenario to simulate the effect of evaporation and atmospheric processes on the exposed water chemistry for 12 hours with 66% evaporation of water to form the dynamic evapolimnion. This simulation is done under atmospheric fugacity and higher temperatures.

  o Scenario M4: Mixing of hypolimnion waters under reducing conditions to simulate the expected water chemistry of the monimolimnion under lower temperatures and lower $fO_{2(g)}$ and higher $fCO_{2(g)}$.

## 7.2 Main conclusions and research answers

The conclusions from the first 5 chapters culminated into an in depth discussion and interpretation of the results in a final chapter 6 with conclusions and answers given to all research questions and objectives. By reading chapter 6 of this dissertation a clear understanding of the hydrogeochemical processes in the local study area and the proposed pit flooding options through the evaluation of the hydrogeochemical model outcomes, pit lake mixing models, pit lake water quality and a systems thinking model template.

The following sub-sections give short answers and discussions on the research objectives and refer back to the main discussions on each topic in chapter 6.

### 7.2.1 What are the main processes or factors dictating the characteristics of groundwater, in the project area?

Based on the path followed during the six weathering scenarios the following system

observations and model conclusions can be made upon the development and investigation of a calibrated model:

1. The weathering reactions of the mafic, alkaline and to a lesser extent some felsic minerals within the Pilanesberg and Bushveld Igneous Complex geology allows for pH values ranging between 6 and 8 with buffering reactions not allowing any acidic or alkali environments to develop within the regional groundwater.

2. The system is most sensitive to fugacity of $O_2$ and $CO_2$ gasses with simulated values indicating that $fCO_2$ tends to reach levels close to 0.01 in the natural system allowing the dissolution of Al and $SiO_2$ to deplete with a more natural development of Na, Ca, K and Mg waters.

3. Clay mineral soils in the region is abundant due to water speciation in the region in field samples as well as modelled samples showing saturation of clay minerals with development of secondary minerals most likely to be smectite and kaolinite clays.

It can be concluded from the weathering models that the weathering period of 100 years with weathering, dissolution and precipitation reactions continuing towards a state of equilibrium, does not have a significant enough effect to characterise the chemical composition in concentrations towards that of the data observed in the field relating only to concentrations. Thus the weathering of minerals within a 100 year period will have no effect on the pit lake quality, with older existing groundwater facies dictating the quality along with surface and rain water.

The above mentioned factors in the project area led to the development of a final concept weathering model summarising all processes and chemical reaction in the fluid-rock interaction of the PPM project area in section 6.3 and Figure 6-14.

### 7.2.2 What is the expected water quality that will be the final product within the planned pit lake?

The mixing models as discussed in section 6.1.2 lead to three lake layers with different water qualities and chemical distributions, a conceptual summary of all processes and relative water qualities of the modelled lake is given in section 6.3 and also illustrated in Figure 6-15.

Although the pit lake is not planned to be used for domestic and drinking water supply the classified quality of the hypolimnion and epilimnion is suitable for human use as well as agricultural use (irrigation and livestock watering). The suitability of the epilimnion and hypolimnion for the agricultural use is due to the rural community

surrounding the pit will only be using it in localised crop areas and for food production to sustain individual families.

Based on the suitability of the pit lake for livestock watering wildlife will also be able to drink the water. Although water quality is not ideal, an aquatic ecosystem with species adapted to the conditions will be sustained by the proposed pit lake. This conclusion is reached based on the fact that the pit lake will be a new environment formed over a long period of time. The species adapting and evolving to the pit lake as it floods and reaches the modelled levels will be ideally suited to the final environment due to the natural progression and development of the system. No existing aquatic ecosystem will exist and thus the new pit lake will host a new ecosystem formed around the environment provided by the flooding event.

Recreational use will be feasible in the pit lake due to settling and seasonal windows allowing turbidity to decrease as well as visibility to increase. No chemical irritants are present in the water that is harmful to full contact recreational use. Some mitigation methods will however be needed to reduce turbidity, these potential mitigation options is listed below:

- Upstream sump in the surface water channel flowing into the pit allowing a reduction of flow velocity and settling of TSS;

- Settling ponds allowing inflowing surface water to reduce flowing velocity and allow TSS to settle out before flowing into the pit lake;

- Only using the pit lake for recreation use during seasonal windows allowing visibility to improve during low inflow periods;

### 7.2.3 What are the risks identified during modelling of the proposed pit flooding to the environment and to human/animal use?

The following primary risks have been identified:

1. High turbidity and TSS of the pit lake will render poor visibility unsuitable for recreational use

2. Cl, As, F and Pb of the monimolimnion present in concentrations above the allowed limits for drinking water and domestic use

3. High TDS values of the evapolimnion, hypolimnion and monimolimnion can damage operational infrastructure like pipes and pumps used to source water from the pit lake for domestic and agricultural use with scaling being the main impact

4. Mixing of pristine water layers with the monimolimnion through abstraction

activity (pumping) creating poor water quality in the hypolimnion and epilimnion

### 7.2.4 What mitigation methods/modifications to the planned post-closure option can be applied to decrease or remove risks?

The following mitigation methods are options that can reduce and eliminate the primary risks mentioned in section 7.2.3.

- Improving Turbidity by:
    - Upstream sump in the surface water channel flowing into the pit allowing a reduction of flow velocity and settling of TSS;
    - Settling ponds allowing inflowing surface water to reduce flowing velocity and allow TSS to settle out before flowing into the pit lake;
- Water treatment options:
    - Anion exchange resin beds in which all significant anions will be removed
    - Desalination techniques such as reverse osmosis and electro-dialysis
- Management and maintenance of equipment:
    - Infrastructure management plans with operational shut downs for maintenance
    - Equipment made out of suitable material like plastic pipes and stainless steel pumps
- Preventing the mixing of monimolimnion water with cleaner overlying lake layers:
    - Lower abstraction rates for longer periods reducing turbulence from pumping at high rates
    - Not abstracting during periods when the lake water level is low
    - Pump installation depth should be within the top 50 m of water not allowing the pump to reach levels close to the monimolimnion
    - Abstraction for any water use from the pit lake should only occur once the lake is at least 80% flooded

### 7.2.5 Is pit flooding as a post-closure option feasible and can it be used for various recreational and agricultural/wildlife applications?

Based on the outcomes of this research project and dissertation through the modelling of a proposed pit lake and evaluating the expected water quality and

impacts, it can be concluded that the flooding of the PPM pit as a post-closure option creating a recreational and water supply water reservoir and lake is feasible with the implementation of some mitigating measures.

## 7.3  System thinking and template for future modelling

One of the objectives and research deliverables is to provide a template and thinking system for future geochemical modelling in geohydrology, not just for pit flooding scenarios but for all relevant geochemical topics in groundwater.

A systems thinking template for most scientific research and industry topics is based on three key principles, that allows us in using science to further our study of understanding nature as stated by Krauss (2012), these principles are:

1. Follow the evidence wherever it leads;

2. If one has a theory, one needs to be willing to prove it wrong as much as one tries to prove that it is right;

3. The ultimate arbiter of truth is experiment, not the comfort one derives from one's a priori beliefs, nor the beauty or elegance one ascribes to one's theoretical models.

These three principles on which scientific research is based allow us to think within a system that drives logical exploration of processes and reactions not seen. For this dissertation and future geochemical modelling of groundwater systems and processes a template was developed to allow geoscientists and environmental practitioners to complete similar and more complex models to a relative degree of confidence. The modelling system/template for geochemical simulations is illustrated in Figure 7-1.

This template for geochemical modelling should be used with the three scientific principles as well as common sense in mind. Common sense sounds harsh and out of place in scientific research topics but is needed if a model is to be successful. If your model shows a pH of 14 but no field data comes close to a pH of 14, your model is wrong. Use common sense. The systems model template is divided into ten sub-sections all integrated into a flow of knowledge and research outcomes to allow a final answer to be deduced from a complex system of raw data and observations. This template should not be used as is and should be adopted and moulded to suite each researchers specific thinking system and to his/her unique scientific question/problem.

Each step in the modelling process and template is discussed in the next ten sub-sections. Each description of the steps is accompanied by a step-by-step example of

a scenario in which all aspects is implemented to allow a better understanding of the system and its implementation. The example scenario is the hydrogeochemical modelling of a proposed waste rock dump (WRD) and its impacts and will also describe steps in the system that was not used or necessary in the modelling of the dissertation project.
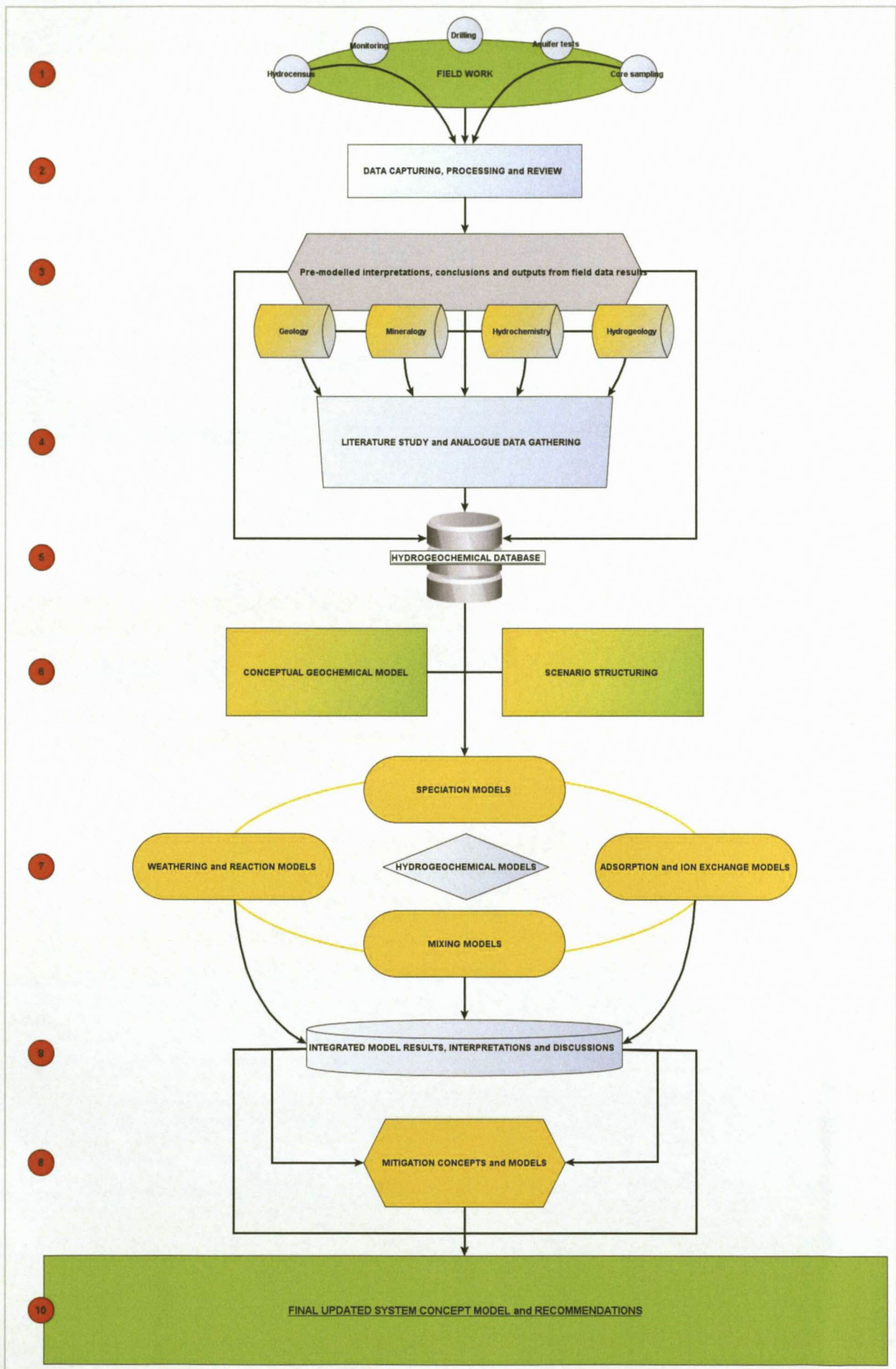
Figure 7-1    System thinking and model template

## 7.3.1 Field work

All scientific studies and modelling processes starts with field work and data gathering to start developing the baseline dataset on which all subsequent decisions and recommendations will be made. The quality and not the quantity of field data are thus important to allow accurate modelling and decisions on project level.

Hydrocensus, core borehole logging, geophysics, percussion drilling logs and data, sampling, aquifer tests and monitoring runs all accumulate data useful and cardinal in analysing the initial/current system in the study area. This initial gathering of data feeds into a flow of data throughout the modelling process, raw and processed.

Data serves as the raw information on which important decisions will be based at the end of a study. Too much data over a wide geographical spread can however create uncertainty if the data is not processed and analysed correctly, thus during planning field work the purpose of the study along with technical knowledge should lead fieldwork into a direction with data quality and deliverable based purpose in mind.

All samples should be sent to accredited laboratories with project timeframe, budget and objectives in mind.

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### (1) TEMPLATE EXAMPLE: FIELD WORK

**Introduction:**

The example project deals with the hydrogeochemical modelling of a proposed waste rock dump (WRD) at a mine in the Bushveld Igneous Complex. The proposed project area directly affected by the proposed WRD is underlain by a soil profile rich in clay minerals and the underlying geology being gabbro. The purpose/objective of the geochemical study is to evaluate the possible impacts, if any, that the emplacement of the proposed WRD will have on the groundwater system and natural environment with a Life of Mine (LoM) being 50 years.

**Available data:**

- Historical reports;
- Geological core drilling logs;
- Monitoring data and reports;
- Planned dimensions of the WRD; and
- Exact location of the proposed WRD.

**Field work:**

- Hydrocensus to evaluate current groundwater levels and quality through sampling and water level measurements;
- Geophysics to delineate any possible structures and faults to serve as drilling targets for monitoring boreholes;
- Drilling of two upstream and two downstream boreholes and logging of the drilling chips;
- Aquifer tests and sampling of water from drilled boreholes;
- Sampling of the geology core samples;
- Sampling the waste material and soil profile;
- Sending water samples to accredited laboratory for hydrochemical analysis; and
- Sending core samples, waste samples and soil samples to an accredited laboratory for ABA, NAG, TCLP, XRF and XRD analysis.

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## 7.3.2 Data capturing, processing and review

Organisation, statistical analysis and project objectives are the most important aspects to keep in mind during data capturing and processing with review and interpretation. Geohydrological, geological, structural, process and hydrochemical data should be captured and cleaned.

Statistical distribution and data quality analysis should be done on the data to review laboratory results and summarise the most important aspects of the data sets. Mean, maximum and minimum values should be calculated and always compared to each other to identify outliers as well as statistically significant attributes. Data sets with large standard deviations and large coefficients of variance (>15%) should be queried and not used in any simulations accept if no other geographically suitable sets are available.

After all statistical data cleaning and processing has been done, a review of all sets and attributes should be done to have a full view of available information and the quality of the data to have a margin of error/uncertainty to apply if necessary in any environmental risk assessments. Once data reviews are done the data sets and points that will be used should be chosen with spatial location and distribution relative to the location of the entity, be it mine dumps, tailings facilities, boreholes or open pit or underground mines that will be modelled in mind.

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### (2) TEMPLATE EXAMPLE: DATA CAPTURING, PROCESSING and REVIEW

Capture all field data, laboratory data and data from report and monitoring reviews and clean statistically to evaluate the quality and accuracy of data. Based on quality and accuracy accumulate a data set of points and information to be used for the rest of the models and simulation. For the example scenario we chose the following processed data sets to use in subsequent steps:

- Water level contour map interpolated using the Kriging method on all hydrocensus, monitoring and aquifer test static water levels measured;
- Geological data from two core boreholes drilled in close proximity to the proposed WRD;
- Water quality and hydrochemical results from the laboratory on the four monitoring boreholes drilled and aquifer tested;
- TCLP/SPLP, ABA, NAG, XRD and XRF results of the tests done on the soil profile, core samples and the waste material; and
- Rainfall data and evaporation rates.

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### 7.3.3 Pre-modelled interpretations, conclusions from field data results

The data sets accumulated and reviewed should lead to some pre-modelled concepts and interpretational conclusions on the research problems/project objectives. Interpretation of laboratory results should occur through evaluating data against concentration standards as set out in the relevant governmental legislation.

XRD, XRF, NAG, TCLP and ABA results should be evaluated and interpreted to

allow a laboratory specific outcome for the project to allow evaluation of modelled results against these data sets to serve as a point of calibration. Conclusions, flagged risks or impacts and recommendations formulated as outputs from data reviews and lab results should be kept in mind to formulate further data sets, research and also the conceptual models and scenario structuring.

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**(3) TEMPLATE EXAMPLE: PRE-MODELLED INTERPRETATIONS and CONCLUSIONS from FIELD DATA RESULTS**

Based on the data sets captured and processed in the example scenario as described in the previous example box, the following pre-modelled interpretations and conclusions on the available parameters can me made:

- The regional water level averages at 12 mbgl with the interpolated level below the proposed WRD sitting at 9.8 mbgl, thus seepage or recharge infiltrating the subsoil and geological strata underlying the WRD, will react and interact with the material for ± 10 m;
- The soil profile of the region consists of clay soils rich in smectite, kaolinite, muscovite and some weathered silica minerals including anorthite, k-feldspar and quartz. The soil profile is ± 4 m deep after which geological units start to show;
- Runoff is high in the region and thus lots of drainage channels exist with extensive calcrete formation along the channels;
- The WRD will be 40 m high;
- From XRD and XRF results the main mineralogy is olivine, amphibole, plagioclase, biotite, muscovite and pyroxene with the waste consisting of similar mineralogy but chrome is in higher concentrations along with various other metals including Fe contained in small amounts of pyrite;
- The water quality and hydrochemistry is suitable for most uses but is slightly acidic;
- The TCLP results show high concentrations of Cr and Fe and other major ions with low sulphur content; and
- The ABA results and NAG show that the waste samples has the potential to produce acidic conditions.

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From the interpretations and conclusions of laboratory and field data the following data sets with interpreted results should be at disposal for the models and further research/project steps:

- Project area geology from geological logs and maps;

- Mineralogy from XRD and XRF interpretations and results on sampled material;

- Hydrochemistry and water quality of the chosen input data sets/points, surface and groundwater;

- Rainfall and climate data with statistical distributions and values;

- Structural data of geology; and

- Data on infrastructure/entities to be modelled (dimensions of TSF and mine dumps)

These interpreted data sets follows the data flow path down the modelling process and feeds into research topics and the final hydrogeochemical database on which

modelling and decisions will be done and made.

### 7.3.4 Literature study and analogue data gathering

Based on all interpretations and the developing picture of the research problem and project terms of reference some research and literature studies should be done on the project area elements and data sets. Literature reviews and analogue data gathering including the following list should be gathered:

- Geological formation processes and geochemistry;

- Mineral descriptions, formulas and chemical composition;

- Expected processes;

- Chemical weathering/dissolution rates; and

- All identified assumptions and data gaps

The literature review needs to be done to fill data gaps and assumptions with meaningful and accurate as possible analogue values. Sensitivity analysis as well as data changes can be made during the modelling process to allow a continuous evaluation and calibration of the system. However the initial conceptual model and model setup will be based on these assumptions and analogue values.

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**(4) TEMPLATE EXAMPLE: LITERATURE STUDY AND ANLOGUE DATA GATHERING**

After data processing and interpretations some data gaps and/or data lists should have been identified. To complete the database and gather enough data to have an accurate conceptual and computed model same literature studies should be done on the data needs and assumptions that will be made. The following analogue data and research information is useful in geochemical modelling:

- Chemical composition and mineral information;
- Weathering and dissolution rates of minerals;
- All chemical processes identified in the data review;
- Project area geology; and
- Similar case studies and models.

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### 7.3.5 Hydrogeochemical database

The first 4 sections in the system template leads to the formulation of a hydrogeochemical database from which data will be sourced to set up and simulate the subsequent steps. Processes and geochemical data gathered from the fieldwork, data processing, analysis, laboratory results and literature reviews feeds into a conceptual model from where assumptions based on data gaps and analogue values will be made to set up scenarios to flow into risk assessments and decision making information from the models.

**(5) TEMPLATE EXAMPLE: HYDROGEOCHEMICAL DATABASE**

All the fieldwork, reviews, literature studies analogue data, lab results and interpretations leads to the formation of a hydrogeochemical database that will be used in the modelling of the WRD system. The following data forms the core of the example scenario database:

- Waste material, soil profile and geology mineralogy and mineral composition;
- Hydrochemistry of the 4 upstream and downstream boreholes drilled during fieldwork;
- Weathering and dissolution rates of minerals;
- Water levels;
- Rainfall chemistry;
- Evaporation rates; and
- Composition of the waste material.

## 7.3.6 Conceptual geochemical models and scenario structuring

From research, data gathering and processing as well as interpretations from lab results accumulated in the hydrogeochemical database, a conceptual theory of the processes involved in the study area on a geochemical level has been made by the researcher. From here a conceptual model needs to be formulated into a structured visual as well as verbal description of the study area and expected processes.

A conceptual model stems from formulated theories. These theories has been developed by the researcher/scientist through the review of the available data, research questions and the flagged risks or data gaps needed to be mitigated or filled. The challenge of the conceptual model is to give a visual representation accompanied by short descriptions to explain the logic and expected processes behind the theoretical ideas of the studied system.

In other words a conceptual model is "a non-software specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions and simplifications of the model" (Robinson 2010 and 2008).

A good conceptual model consists of the following elements and thinking points to be illustrated and described in the simplification of the system (McMahon, A., Heathcote, J., Carey, M., Erskine 2001):

- What is known and understood about the project area and modelled entities;

- What is not known or not understood;

- What are the key physical and chemical processes and how can they be presented;

- Assumptions made and the motivation behind them; and

- Points, processes and all elements to be ignored or simplified due to knowledge gaps or computational limitations.

From the research theories and conceptual model scenario structuring should follow. During the setup and formulation of scenario the research questions, objectives, flagged risks, input data, expected outputs and the conceptually modelled system should be kept in mind along with data gaps, assumptions and software limitations.

**(6) TEMPLATE EXAMPLE: CONCEPTUAL GEOCHEMICAL MODELS and SCENARIO STRUCTURING**

A conceptual model of the example scenario should visually illustrate the following factors and elements as accurately as possible:

- Geology underlying the proposed WRD with all faults and structures indicated as well as the depth of the soil profile (4 m);
- The groundwater level at 9.8 mbgl;
- The WRD with a height of 40 m;
- Mineral composition of the WRD;
- Mineral composition of the soil profile and the geology;
- Chemical facies of the groundwater, surface water and rainwater;
- Expected chemical processes;
- Precipitation, evaporation and runoff;
- Recharge into the soil and geological profile as well as the WRD;
- Seepage from the WRD;
- Mixing of seepage and groundwater;

The above conceptual model along with assumptions and project objective in the geochemical evaluation of the proposed WRD and its impact leads to the structuring of the following model scenarios:

1. Speciation model of groundwater, surface water, rain water and TCLP results of the waste material.
2. Scenario 1: Reaction and weathering of the main project mineralogy to evaluate the processes involved in the formation of the groundwater by allowing rainwater to react with the main minerals at analogue dissolution rates over a period of 100 and 1000 years.
3. Scenario 2: Reaction and weathering of the waste material mineralogy to evaluate the processes involved in the formation of the seepage/leachate from the WRD by allowing rainwater to react with the main gangue minerals at analogue dissolution rates over a period of 50 years (LoM) at depleting $fO_2$ and increasing $fCO_2$.
4. Scenario 3: Evaluation of the adsorption and ion exchange capacity of the underlying geology and soil by allowing the TCLP results from the laboratory to react with the mineralogy over a period of 50 years under both atmospheric oxygenated and reducing conditions with low $fO_2$.
5. Scenario 4: Mixing simulation by allowing the resultant water from scenario 3 to mix with the groundwater over a period of 50 years to evaluate the effect and change seepage will have on the natural groundwater system and quality.

## 7.3.7 Hydrogeochemical models

Based on the conceptual model and scenarios formulated, the input data sets and information will be used to simulate the real world processes within various geochemical and hydrochemical models mimicking the natural processes. These models allow the researcher to evaluate unseen processes and develop an understanding and information network on which environment management decisions will be based, risks will be identified and mitigation methods will be proposed. The following four simulation types are commonly used in geochemical

modelling of geohydrological systems and allow the evaluation of all processes:

- Speciation models
  - o Calculate species distribution in aqueous solutions and compute mineral saturations and fugacity; and
  - o Formulate reaction paths and formulas describing the process involved in the current system forming the fluid sampled in the field.

- Weathering and reaction models
  - o Trace reaction paths involving fluids, minerals, waste material and gases and also predict the fractionation of stable isotopes during reaction processes;
  - o Assess the chemical processes involved in the formation of the fluid observed in the field; be it wastes water, surface water, groundwater, oils or rainwater; and
  - o Deduce reaction paths and chemical reaction formulas describing the chemical processes and system in the natural environment.

- Adsorption and ion exchange models
  - o Model adsorption and ion exchange processes in contaminant transport scenarios, seepage models;
  - o Evaluate the removal of certain elements; and
  - o Investigate whether natural process will remove contamination or is mitigation methods needed.

- Mixing models
  - o Model surface water and groundwater mixing;
  - o Model contaminant and groundwater mixing;
  - o Evaluate the effect of seepage water on the groundwater system;
  - o Simulate and investigate reaction processes, paths, chemical reaction formulas and formation of secondary minerals during mixing events; and
  - o Evaporative processes can also be simulated.

## (7) TEMPLATE EXAMPLE: HYDROGEOCHEMICAL MODELS

Based on the conceptual model and scenarios formulated the following simulations under each model type were simulated with the results to be interpreted:

**Speciation models**

Speciation of groundwater, surface water and rainwater to evaluate the saturated chemical species and processes in the current system

**Weathering and reaction models**

Simulations and sensitivity analysis on Scenario 1 and 2

**Adsorption and Ion exchange models**

Simulations and sensitivity analysis on Scenario 3

**Mixing models**

Simulations and sensitivity analysis on Scenario 4

### 7.3.8 Integrated model results, interpretations and discussions

Results from all modelled simulation should be reviewed, processed and integrated into one system of understanding. The model results should be interpreted as a whole because the natural system acts in a natural cycle from which no element can be removed.

Speciation results allows the researcher/scientist to interpret the current system in its natural state with saturated minerals identified and the formation process by evaluating the aqueous chemistry as well as activity of element under different pH and fugacity values. Weathering results allow for the evaluation of processes involved during fluid-rock or fluid-waste interaction and simulating the processes leading to the formation of groundwater, surface water, waste water and seepage. Ion exchange and adsorption modelling simulates the resultant chemical compositions of fluids once interaction with waste material, construction material, soils and geology has allowed to happen only leaving behind a system with possible exclusion of element due to exchange or sorption processes.

After all the above simulated result interpretations the system was modelled in which waste or clean water was allowed to mix and the processes involved and the impacts going with these mixtures is evaluated.

Once all model results were interpreted and evaluated against standards, lab results and field data. An impact and risk assessment is done on the expected system. During this assessment of the simulated resultant system, the assumptions and model limitations should be kept in mind. Based on the risk and impact assessment mitigation methods should be proposed for implementation.

## (8) TEMPLATE EXAMPLE: INTEGRATED MODEL RESULTS, INTERPRETATIONS and DISCUSSIONS

Based on the simulated results from the geochemical models the following hypothetical interpretations could be made for the example scenario:

- Interpretations on the possible formation of secondary minerals in the groundwater and surface water and whether the saturated mineral phases correlate with the mineral found in the soil profile and along drainage channels;
- Formulation of the most important reactions occurring during the weathering of the main mineralogy and the waste material;
- Graphs and charts indicating the pH and fluid content evolution during weathering of various materials as well as secondary saturated mineral development;
- List of the ions involved in exchange reaction between the clay minerals and the seepage from the WRD as well as adsorbed species.;
- Illustration of the reaction between the seepage from the WRD and the groundwater with a list of the most important reaction;
- Graphs and time series illustrations of the evaluation of the groundwater once reacted with seepage as well as a speciation and description of the final water sample; and
- Identification of problem aqueous species by comparing the simulated water samples to national standards and identifying the risks involved.

### 7.3.9  Mitigation concepts and models

One of the advantages of geochemical modelling and modelling of natural systems in whole, is that mitigation methods can be formulated from simulated results as well as tested before costly application of the methods are done.

Flagged geochemical impacts and risks on the natural environment should be mitigated. Mitigation methods should be formulated and tested with modelled simulations to evaluate the effectiveness of the proposed methods in eliminating or retarding the impacts and its processes.

## (9) TEMPLATE EXAMPLE: MITIGATION CONCEPTS and MODELS

Let's assume that the model results indicated high concentrations of sulphate minerals with metal concentrations of Cr, Cu and Fe above the national limits indicated in the legislation and pH levels between 3 and 5. A high risk and flagged impact is thus possible acid generation and AMD. Possible mitigation methods is lining the WRD or using the calcrete formation along drainage channels as natural geo-liner before the emplacement of waste on the proposed area starts.

However, clients will spend large amount of money to mitigate the possible impacts, thus small model on the recommended mitigation options can be simulated to evaluate the effectiveness of the options. For this two simulations were done:

- Simulation 1 allows the seepage results from the laboratory TCLP results to react with the proposed industrial liner over a period of 50 years evaluating the effectiveness of the proposed method; and
- Simulation2 allows the same reaction to occur with the seepage reacting with the natural geo-liner and evaluating whether the buffering effect of the calcrete will be strong enough to eliminate any acid generation.

A comparison between the results will indicate the best mitigation option.

## 7.3.10 Final updated system concept model and recommendations

The database as well as interpretations, model results and risk assessments and mitigations allow for the flow of data to accumulate into a final decision making tool. From all the information gathered and modelled a final concept model with the processes investigated and observed during the study should be illustrated in which the whole system can be viewed.

This final concept model should include all relevant chemical and physical processes and factors working in on the environment with impacts and mitigation processes also shown. A scientific study will finally not be complete without recommendation that the client should implement.

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**(10) TEMPLATE EXAMPLE: FINAL UPDATED SYSTEM CONCEPT MODEL and RECOMMENDATIONS**

Based on the model results and mitigation simulation a final concept model with more detail is constructed based on the template of the original conceptual model to allow the client to see the whole picture. Based on the model and preceding study, geochemical recommendation can be made towards the EIA or management plans of the project.

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## 7.4 Future research

Possible future research topics branching from this research study and dissertation:

- A biogeochemical investigation and model evaluating the effect of biochemical reactions from algae and plant life on the water quality of the evapolimnion.

- An investigation into the effect of biomass reactions on the $CO_2$ and $O_2$ fugacity in meromictic pit lakes within the reducing conditions of the monimolimnion.

- Hydrogeochemical influence of the Pilanesberg Alkaline Complex on the regional and local aquifers, inside and outside of the ring structure, through detailed field investigations and geochemical models.

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# 9   LIST OF APPENDICES

**All Appendices as listed below are provided on the DVD disc attached to this document**

1. Appendix A: Climate Data

2. Appendix B: Hydrocensus Data

3. Appendix C: Monitoring data

4. Appendix D: Model results

## 10  ABSTRACT

(English)

Australasian, European, Canadian and American geo-environmental specialists have long been involved with pit lake studies in the physical processes and dynamics as well as the geochemical aspects of these mitigation methods and events.  The use of pit flooding as an environmental post-closure option has however been studied and used to a limited extent in Southern Africa and Africa to a whole, with some recorded cases mostly being by accident rather than a planned mitigation.  This document is a written paper on a hydrogeochemical investigation on the feasibility of flooding an open pit platinum mine in the Bushveld Igneous Complex as a post-closure mitigation option.

Various data sets and sources were compiled and processed and served as input data into a hydrogeochemical model of the expected impacts on the conceptual meromictic pit lake environment.  Weathering and speciation models allowed the evaluation of the current system with thermodynamic and chemical reaction processes leading to the hydrochemical composition of the groundwater as we observe it in the field.  Furthermore transient mixing simulations between groundwater, surface water and rain water was allowed to occur under various reducing and evaporative conditions.  The modelled lake chemistry was then evaluated against recreational, agricultural and domestic water use standards to investigate the feasibility of the lake to be used post-closure.

Final recommendations and mitigation methods were proposed with the flooding of the open pit as a post-closure option declared feasible.  A final deliverable of the study was a system thinking and modelling template for hydrogeochemical modelling in various scenarios to guide other scientist through the process of modelling fluid-rock, fluid-waste and fluid-fluid interaction.

(Afrikaans)

Australasiese, Europese, Amerikaanse en Kanadese Geo-omgewingswetenskap spesialiste is al lank betrokke by put meer studies met navorsing op die fisiese prosesse en dinamika asook die geochemiese aspekte van hierdie omgewings versagtende metodes en gebeure. Die gebruik van put oorstromings en vloede as n omgewings post-operasionele opsie word egter min nagevors en ook gebruik tot n beperkte mate in Suider-Afrika en Afrika tot n geheel, met n paar opgetekende gevalle meestal per toeval eerder as n beplande versagtings metode. Hierdie dokument is n skriftelike opstel van n hidrogeochemiese ondersoek na die haalbaarheid van die oorstroming van n oopgroef-platinummyn in die Bosveld Stollings Kompleks as n post-operasionele omgewings versagtings opsie.

Verskeie datastelle en bronne is saamgestel en verwerk en het gedien as invoer data in n hidrogeochemiese model van die verwagte impak op die konseptuele put meer omgewing. Verwering en spesiasie modelle het toegelaat dat die huidige stelsel bestudeer kan word met termodinamiese en chemiese reaksie wat lei tot die hidrochemiese samestelling van die grondwater soos ons dit in die veld waarneem. Verdere meng simulasies tussen grondwater, oppervlakwater en reën water is toegelaat om plaas te vind onder verskillende vermindering en verdamping voorwaardes om die put meer water chemie te simuleer. Die gemodelleerde meer chemie is toe geëvalueer teen ontspannings-, landbou-en huishoudelike watergebruik standaarde om die haalbaarheid van die meer post-sluiting as water bron te kan klasifiseer.

Finale aanbevelings en versagtende metodes is voorgestel met die oorstroming van die oop put as n post-operasionele omgewings opsie as haalbaar verklaar. N finale doel en produk van die studie was n stelsel denk wyse en modellering gids vir hidrogeochemiese modellering in verskeie scenarios en dus ander wetenskaplike te kan lei deur die prosesse van hierdie tipe modellering.