AN INVESTIGATION TO DETERMINE IF SOUTH AFRICAN COAL MINE PITLAKES ARE A VIABLE CLOSURE OPTION

Andrew Johnstone, Lizel Kennedy, Matsatsi Mpetle

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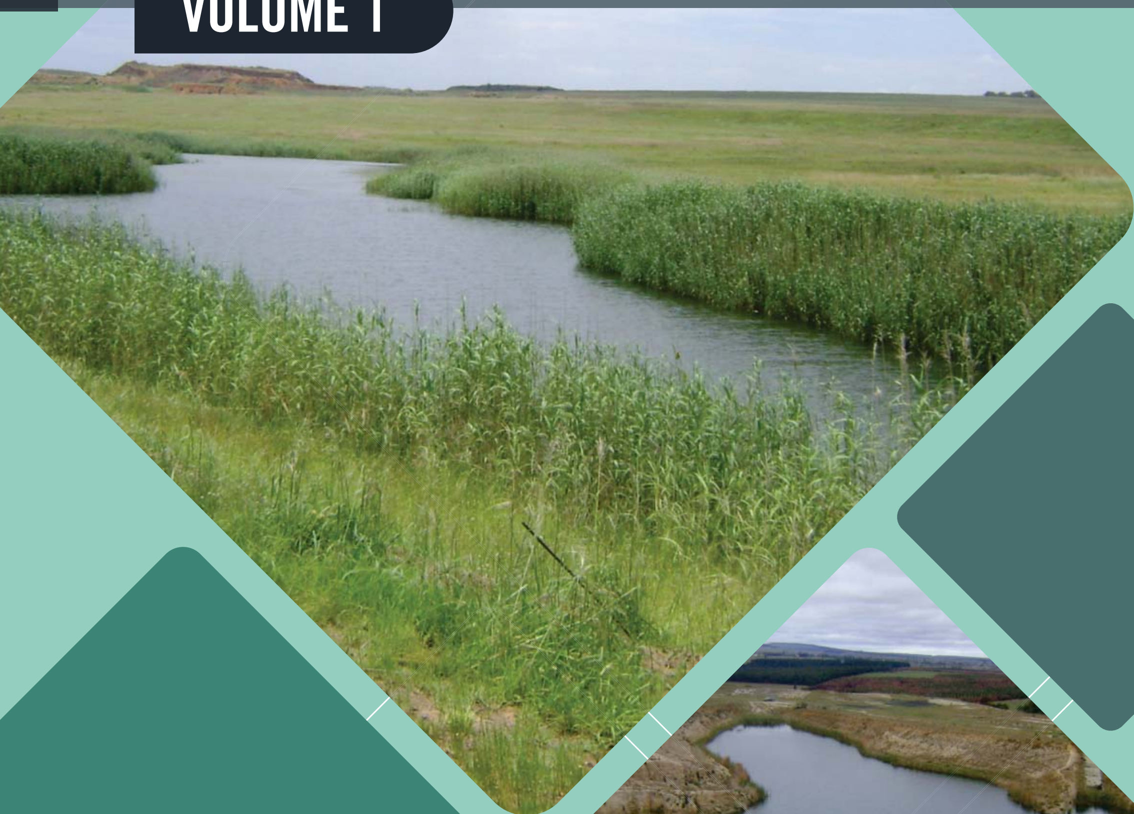

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AN INVESTIGATION TO DETERMINE IF SOUTH AFRICAN COAL MINE PITLAKES ARE A VIABLE CLOSURE OPTION

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Background

South Africa has been mining coal since the early 1800s, initially by conventional underground method, but since 1950 coal production has been mainly from open cast mines. Coal is the major component of the South African Power supply network and this is predicted to continue into the latter half of the 21st century. Open cast coal mines generally leave a final void as a consequence of the mining method, this being the result of insufficient overburden to fill the voids created by removal of the coal and /or to manage water. Once mining operations cease, these voids fill with water forming a lake which is generally referred to as a “pitlake”. The authors have estimated that there are over 200 pitlakes in the three major South African coal fields namely Mpumalanga/Witbank, KwaZulu-Natal and Waterberg.

The study evaluates the environmental sustainability of using pitlakes as a closure option for new and proposed coal mines in South Africa. The current South African mining and environmental legislation states that all pitlakes should be backfilled for the mine to achieve mine closure. This study evaluates the environmental sustainability of using pitlakes as a mine closure option for new and proposed coal mining projects in South Africa.

The major factor of determining environmental sustainability of pitlakes are the water balance and water quality. Positive water balances result in discharge onto surface. A further environmental sustainability consideration is the chemical and biological nature of the water in pitlakes. Pitlake water quality varies depending on the geology, mining method and catchment characteristics. In general, pitlake water quality may not comply with legislated catchment water quality standards resulting in potential threats to the overall catchment water quality.

This investigation concentrated on the two major drivers of pitlake sustainability, whilst investigating four different pitlakes;

- The Mafutha pitlake a stand-alone pitlake in the Waterberg coalfield;
- The Kriel and Kleinfontein pitlakes are associated with open cast operations and in direct hydraulic contact with backfilled material both located in the Witbank/ Mpumalanga coalfield;
- The Rooikop pitlake which is hydraulically connected with both open cast and underground operations located in the KwaZulu-Natal Coalfield.

These pitlakes were selected on the basis that they are representative of the major South African coal fields considering variances in geology and climatic conditions.

The factors affecting pitlake water balances (and as a result the variation in water levels) are groundwater, direct rainfall and runoff; while the losses from the pitlakes are evaporation, surface discharge and flow into the surrounding aquifer. The water balances of each of the pitlakes were evaluated to determine the major inputs and losses. The major input is groundwater, either from the aquifer or backfilled material, and the major loss is evaporation. Pitlake morphology, volumes and surface area are the major design considerations to prevent discharge of pitlake water into the associated catchment area.

The chemical and biological evolution of the water quality in a pitlake determines the long-term ecological sustainability of pitlakes. The inorganic chemistry study concentrated on the water quality and vertical stratification. The measured in-situ were pH, temperature, dissolves oxygen and the redox potential of each of the pitlakes. The organic study determined the phytoplankton, chlorophyll-a and the microbiology of each of the pitlakes.

The study concludes that pitlakes can be environmentally sustainable if they are designed correctly and that the surface discharge of water into the catchment area is managed. The organic and inorganic water quality in the pitlakes showed that the pitlakes are alkaline and have elevated total dissolved solid contents (mainly sodium sulphate) when compared to the natural surface and groundwater in the catchment. These water bodies can support life in terms of chlorophyll-a, phytoplankton and microbiology (bacteria).

The surface area of a pitlake is vitally important to maximise evaporation which directly affects the water balance. In addition, surface runoff should be controlled to avoid excess runoff into the pitlake during storm events that may lead to a temporary positive water balance and uncontrolled discharge into the catchment. Should the pitlake be suitably designed, it forms a water sink to prevent uncontrolled discharge from the mining operations.

A fundamental change in the thinking and legislative requirement is required to view pitlakes as an environmentally sustainable solution to prevent uncontrolled discharge from open cast mining operations to avoid the expense of ongoing water treatment. Correctly designed pitlakes offer an environmentally sustainable closure option for open cast coal mines in South Africa.

Enough data was collected in the study to allow for the development of a guideline for the design of coal mine pitlakes in the South African coal fields. The design manual considered the water balances of the pitlakes and the biological and chemical process that drive the water quality of pitlakes.

Summary of the Study

A summary of the study is provided to give a general overview of the research completed.

Various international studies have shown that inflow water qualities, pitlake morphology, weather conditions and biology play significant roles in the physical and chemical dynamics of the water column. The formation of a stratified water column and circulation pattern in a pitlake is of particular interest in many pitlake studies, as the depth of mixing determines the feasibility of beneficial end-uses of these water bodies. One of the concerns from a water balance and water quality perspective would be if the pitlakes were to discharge poor water quality onto the surface, in which case the quality and volumes of discharge would need to be known and managed.

To determine the viability of pitlakes as an environmentally sustainable closure option, the water quality and water balances of four existing coal mine pitlakes were investigated. The pitlakes were selected on the criteria of having reached steady state water levels, inactive in terms of pumping, access to the pitlakes and data availability.

The study focussed on the following aspects:

- Pitlake morphologies, in terms of relative depth (Zr), determined by bathymetric surveys.
- Physio-chemical characteristics of the water in the pitlakes with depth – pH, EC, DO, TDS, ORP and temperature.
- Inorganic chemistry of the pitlake water, including dissolved major ions and metals.
- Diversity of phytoplankton and chlorophyll-a
- Water balances: Volumes of the water in the pitlakes, water level fluctuations, surface areas of the pitlakes, bathymetry and maximum depths, and potential for discharge or containment of the water.

Three hydrogeological models for pitlakes set in three different types of opencast coal mining operations were investigated. These were:

- Open pit mining which formed a stand-alone pitlake upon flooding,

- Opencast mining by the roll-over method with the pitlake forming in the final void, and lastly,
- An opencast operation connected to underground workings where the pitlake forms in the final void of the opencast operation but also receives recharge percolating through the underground towards the pitlake.

The three pitlakes were situated in the Waterberg, Mpumalanga and KwaZulu-Natal coal fields, where the coal measures that were mined at the specific sites, were the Grootegeluk coal seam, the No. 4 coal Seam and the Alfred and Dundas seams respectively. The climatic conditions for all the sites were similar, indicating water deficit areas where evaporation rates far exceed rainfall, which constitutes an important role in the water balance budget and water quality.

Aims and Objectives

The aim of this study is to understand South African pitlakes and to determine if pitlakes are an environmentally sustainable closure option for open cast coal mines. The study focused on two major aspects of coal mine pitlakes namely, the pitlake water balance and secondly, the pitlake chemistry. This was achieved by the construction of pitlake water balance models to understand site-specific hydrogeological conditions for each study area. The water balance study involved climate analyses, hydrology and groundwater understanding to classify the pitlakes. The determination of pitlake water quality involved a study of the inorganic chemistry, the phytoplankton and the bacteria in the pitlakes. Both aspects of the study are aimed at determining if pitlakes can be an environmentally sustainable option for South African Coal mines. From a water quality perspective, the main aims of the study were to:

- Determine the temperature, pH, EC, DO and ORP with depth in the pitlake water and determine if any significant variability exists with depth. Additional to this, to determine the temperature, pH, EC, DO and ORP of the backfill groundwater and surrounding Karoo aquifer and how these differ from the observed water quality in the pitlakes.
- Determine the vertical stratification and chemistry of the pitlake. Determine if an inactive layer of different chemistry exists at the bottom of the pitlakes. If so, what the chemical composition of this layer is, especially in terms of metal concentrations.
- Determine the diversity of phytoplankton, chlorophyll-a and microbes in the pitlakes.

Approach to the Research:

The objectives for this project were achieved by:

- Extensive literature reviews of relevant documents, articles, journals, websites, theses and previous research.
- Desktop studies of the sites. Data was made available by the respective mining houses.
- Selection of appropriate methodologies of pitlake sampling and monitoring from literature and published guidelines – where, when and how of sampling.
- Field investigation and data collection.
- Water balance calculations with Goldsim and stage curves.
- Evaluation of the water quality and water balances of existing pitlakes.

Field Investigation

Field programmes were initiated at each of the sites to generate information on groundwater levels, groundwater quality and pitlake water quality. Observation boreholes and historical monitoring data were made available by the mining companies. The field investigation aimed to collect data to determine water quality and water balances and included aquifer tests on the boreholes to determine aquifer parameters in the vicinity of the pitlakes.

Four Case Studies

Four end-pitlakes were studied in detail from November 2016 to March 2018, namely:

- Mafutha pitlake
- Kriel pitlakes
- Rooikop pitlakes
- Kleinfontein pitlakes

Each case study is described separately and the basic information if each pitlake is provided in Table 1.

Table 1: Basic information of pitlakes case studies.

Pitlake	Coal Field	Depth	Mining method	Age of pitlake (y)
Mafutha	Waterberg	Single pitlake 70 m	Opencast bulk sample	8
Kriel Colliery Pit 4 (R44, R42)	Mpumalanga	Four Shallow pitlakes 5 m to 12 m	Opencast strip mining with concurrent rehabilitation	13
Rooikop	KZN	Single 12 m	Opencast and underground bord and pillar	12
Kleinfontein	Mpumalanga	Single 3.5 m	Opencast strip mining with concurrent rehabilitation	27

The bathymetric characteristics of all the pitlakes relate to the mining method. The Mafutha pitlake was created by truck and shovel operations, resulting in a deep, round and steep sided pitlake. The Kriel and Kleinfontein pitlakes were mined by dragline operations, resulting in long, narrow basins with cross sections that are steep sided, steeper on the one side than the other, and mainly shallow (<20 m). The Rooikop pitlake is a result initial open cast mining and development up dip of an underground bord and pillar mining operation

Data Collection

Fields data collected consisted of bathymetric mapping of the Mafutha, Kriel, Rooikop and Kleinfontein pitlake and vertical measurement of pH, EC, DO, T and ORP. Samples were collected from inflection points in the parameters measured in the vertical profiling. A summary of the data collected is shown below:

- Water quality profiles: multiple locations were vertically profiles for temperature, electrical conductivity, pH, total dissolved solids, dissolved oxygen and oxidation-reduction potential.
- Secchi depth: measured at the same location as the water quality profiles.
- Water chemistry: samples taken at same location as water quality profiles. The sampling depth was determined from the water quality profiles, (two or more samples taken in the epilimnion and in the hypolimnion).
- Microbial samples collected at same depth as water quality samples.
- Chlorophyll-a: sampled at equally spaced depths over the euphotic zone (estimated as three times the Secchi depth).
- Phytoplankton counts and biomass: sampled at equally spaced depths over the euphotic zone at the same depths as the chlorophyll-a samples. Phytoplankton counts, and biomass were estimated by taxonomic group down to the genus level.
- Relevant mine Environmental Management Plans, monitoring data, relevant investigations and raw data was obtained from the relevant mine owners. This data was used to construction of accurate conceptual chemical- and hydrogeological models of the pitlakes

Water balances

- Climatic data were obtained from the SAWS and WR2012 database
- Digital surface models were used to delineate areas of runoff
- Goldsim Academic software was used for water balance modelling.

Water Quality

- *Pitlake stratification*
  All the pitlakes were holomictic in the 2016-2017 study period. Turnover had occurred by the time sampling was conducted in August 2017. The Mafutha pitlake showed stratification in temperature and dissolved oxygen during the summer months. Kriel and Kleinfontein showed weak thermal stratification with stronger stratification of dissolved oxygen during the summer. Rooikop showed weak thermal stratification and homogeneous dissolved oxygen throughout the depth of the pitlake in the summer. All the pitlakes reached saturation levels for dissolved oxygen in the winter (i.e. 8 mg/l). Most pitlakes in South Africa had a low depth to surface area ratio.

- *Impact on Pitlake Chemistry*
  The modelled water balances showed that groundwater was the main contributor to the inflow in all the pitlakes. The pitlakes are terminal sinks with the groundwater gradient towards the final void. The relative contribution of groundwater to the pitlake decreased as the gradients reduced and the pitlake reached steady state levels. As a result, the two major influences on the pitlake water quality is groundwater inflow and evaporation.

  The Mafutha pitlake is almost exclusively fed by groundwater and there is no discard in the pit. There are however some waste dumps on surface that may have a very slight impact on the groundwater flowing into the open pit. The other source of water is direct rainfall onto the pit. As a result the evolution of the Mafutha pitlake water chemistry is largely influenced evaporation. The relative contribution of leaching of salts from the sidewalls was only evident during the rebound of the water levels in the pit.

  The Kriel and the Kleinfontein pitlake water had similar chemical signatures with high sodium, chloride and bicarbonates. These pitlakes are fed mostly by recharge through the overburden. As a result, the soluble slats in the highly porous backfill material plays a major role in the evolution of the pitlake water qualities.

  Rooikop Pitlake receives recharge from the open cast operation but the major contribution from the underground workings via the highwall adits.

  The neutral to slightly alkaline pH of the pitlakes could be ascribed to soluble salts that act as an immediate buffer against acidification. The acid base accounting (ABA) results for all of the sites indicated enough neutralising potential to act as a buffer against any sulphide oxidation that might occur. An additional factor is that the pitlakes formed relatively rapidly, which submerged acid producing lithologies and excluded any further sulphide oxidation.

  In general, the hypolimnetic water quality in all four pitlakes was similar to their epilimnetic water quality in the pitlakes. Heavy metals were precipitated under the alkaline conditions in the pitlakes and assumed to reside in the clayey sediment at the pit bottom.

- *Lake trophic status, phytoplankton and microbes*
  The sampled pitlakes showed nutrient and chlorophyll-a concentrations corresponding mostly to a mesotrophic status. These results indicated moderate productivity in the pitlakes. The trophic status was variable between pitlakes, but the shallowest pitlakes (Kriel ramp 44 North and Kleinfontein) showed higher chlorophyll-a concentrations that corresponded to higher phytoplankton biomass and higher productivity.

Phytoplankton was dominated by the Chlorophyceae family (Green algae), particularly Ankistrodesmus in Mafutha and Ramp 42 (Kriel). In Ramp 44 North (Kriel) and Kleinfontein, the phytoplankton assemblages were dominated by the Cryptophyceae family, particularly Cryptomonas. Rooikop was dominated by Chlamydomonas and Chlorella of the Chlorophyceae family, although relatively high cell counts for Bacillariophyta were also present in the Rooikop pitlake. The results indicated that pitlakes contain the potential for a diverse set of phytoplankton assemblages that are adapted to environments with relatively high TDS, warm temperatures and ranges of oxygen, pH and ORP conditions.

Microbial samples were mostly dominated by Proteobacteria, but showed unique assemblages for each pitlake, suggesting that the microbes vary with geographic location. Also, results indicated that water chemistry in the pitlake exerts a control on the microbial communities in the water and vice versa.

Conclusions

The conclusion of this study is that pitlakes can be environmentally sustainable if they are designed correctly and that the potential discharge of water into the catchment is managed. The organic and inorganic water quality in the pitlakes showed that the pitlakes are alkaline and have elevated total dissolved solid contents (mainly calcium sulphate) when compared to the natural surface and groundwater in the catchment. These water bodies are able to support life in terms of chlorophyll-a, phytoplankton and microbiology (bacteria). The study did not investigate the biota or vegetation that a pitlake supports.

The most important findings form the case studies are summarised below.

- Mining method and pitlake morphology control the water influx and therefore the water quality of the pitlakes.
- Geology, mineralogy and geochemistry does not differ much between the pitlakes, all show acid neutralising capacity.
- The base potential of the groundwater also acts as an immediate buffer against any acidification. Source water mainly consists of groundwater with high bicarbonate concentrations
- Stratification does not play an important role in the water quality of the pitlakes and neither does overturn. The water quality of the pitlakes was the same after overturn in terms of a homogenous TDS, but better with regards to higher oxygen saturation during the winter.
- Flooding of the excavation as soon as possible after mining ceased is the best management method.
- Climatic controls: Evaporation exceeds rainfall and mitigates the potential for discharge from Mafutha, Kriel and Kleinfontein. However, Rooikop is currently discharging water. Rooikop pitlake discharge water with high sulphates and TDS that exceed water quality objectives for aquatic environments.
- If the pitlakes are constructed where evaporation exceeds all inflow the pitlake acts as a terminal sink. This prevents discharge of water into the catchment.
- The water quality in the pitlakes is able to sustain stable ecological stable communities.

Recommendation

The pitlake design must ensure that the pitlake is a terminal sink.

- To ensure acceptable water quality in the pitlake, it is recommended that the pitlake is flooded as rapidly as possible in order to exclude further sulphide oxidation from occurring.
- If reactive coal seams are submerged, the sulphide oxidative minerals remain in a reduced environment.
- Backfilled overburden areas contribute high TDS water to the pitlakes. The recharge to the backfilled area should be minimised by ensuring free drainage and vegetation cover. Material placed outside the excavation, such as coarse discard rock dumps or coal discard should be capped and vegetated to decrease infiltration and precaution into the subsurface.
- Where pitlakes occur, as a result of opencast strip mining and concurrent rehabilitation, the reactive waste material should be backfilled at the lowest level to ensure rapid flooding and the elimination of oxygen.

- In open cast mining area that result in elongated pitlakes hydraulically connected to backfilled spoils, with hydraulic conductivities, the pitlake should be designed to flood the majority of the backfill.
- In the scenario above, excessive variations in pitlake levels will result in the wetting and drying of the backfill material resulting in excessive salt loads. As a result the design should aim to maintain a relatively constant pitlake level.
- In the pitlakes studied the ambient groundwater has a high alkalinity, which acts as a buffer for possible acid generation.
- Shallow and elongated pitlakes are more conducive to wind-induced mixing dissolved oxygen through the whole water column and the reduction in the solubility of some heavy metals.
- Oxygenated water is also beneficial for pitlake ecological systems, such as algae growth, biota and aquatic vegetation.

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LIST OF ABBREVIATIONS

ABA	Acid Base Accounting
AP	Acid Potential
CDT	Constant Drawdown Test
DEM	Digital Elevation Model
DGGE	Denaturing Gradient Gel Electrophoresis
DO	Dissolved oxygen
DTM	Digital Terrain Model
EC	Electrical conductivity
EMP	Environmental Management Programme
EMPR	Environmental Management Programme Report
GIS	Geographic Information System
MAE	Mean Annual Evaporation
MAP	Mean Annual Precipitation
NNP	Net Neutralisation Potential
NP	Neutralisation Potential
NPR	Neutralisation Potential Ratio
ORP	Oxidation-Reduction Potential
PCR	Polymerase Chain Reaction
RSME	Root mean square error
SAWS	South African Weather Service
SI	Saturation Index
WR (2012)	Water Resources of South Africa
WRC	Water Research Commission
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

Units

m^2	Square metres
m^3	Cubic metres
mamsl	Metres above mean sea level
mbgl	Metres below ground level
mEq/ℓ	Milliequivalents per litre
mg/ℓ	Milligrams per litre
mS/m	Millisiemens per metre
mV	Millivolt

GLOSSARY

Chemocline	Interface between the mixolimnion and monimolimnion in a meromictic lake; in other words, the point where the chemistry and salinity changes drastically with depth.
Epilimnion	The upper, warmer and oxygenated layer of a lake.
Holomictic	Lakes consisting of two layers, epilimnion and hypolimnion, and that mix completely at least once a year.
Hypolimnion	The lower, colder and anoxic layer of a lake.
Metalimnion	The transition layer between the epilimnion and hypolimnion where the temperature changes with a steep gradient.
Meromictic	Pitlakes that consists of three layers and only partially mix due to the large density gradient between the permanent basal layer and the upper mixolimnion.
Mixolimnion	The upper layers of the pitlake – the epilimnion and hypolimnion – that seasonally mix, at least once a year.
Monimolimnion	A bottom layer of highly saline water that has a density too great to mix with overlying layers.
Monomictic	A lake that experiences complete turnover only once a year.
Stratification	The physical separation of a water column into two or more horizontal layers.
Thermocline	The point in the metalimnion where the temperature change is the greatest.
Turnover	The frequency and depth of seasonal mixing periods and homogenisation of pitlake water quality. Turnover occurs when water temperature reaches its maximum density and sink to the bottom of the lake.

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CHAPTER 1: BACKGROUND

1.1 Introduction

Coal is a sedimentary, organic rock which originates from peat. When peat is covered with sediment and is in an anaerobic environment, the peat slowly transforms into hard coal due to compaction, dewatering and increased geothermal heat and pressure (Cairncross, 2004). Coal represents South Africa's major source of energy, and coal mining is still a major economic activity. The first discovery of coal was on the farm Franschhoek in the eighteenth century. The first recognised colliery commenced in the Eastern Cape near Molteno in 1864 (Lurie, 2008). South Africa is globally the sixth largest coal producer, with the main coal producers in South Africa dominated by Anglo American, Sasol, Exxaro, BHP Billiton Energy Coal South Africa and Glencore Xstrata. Currently, coal supplies approximately 94% of energy needed in SA and it is estimated that 200 million tons per annum are consumed in the power stations. Another 97 million tons is mined for export and other local demand. The figure will increase in the next decade as more thermal power stations come on line.

The history of coal in SA and formation of pitlakes

The Karoo Supergroup hosts all of South Africa's coal deposits. In total there are 19 major coalfields are mined in Limpopo, Mpumalanga, KwaZulu-Natal and the Free State, with lesser amounts in Gauteng (Jeffrey, 2005). The coal is mined from two types of coal deposits, namely multiple seam and thick interbedded coal deposit (Deysel, 2015). Multiple seam coal deposit types are common to the Witbank and Highveld coalfields and consist of a discrete number of coal seams between 0.5 and 7 m thick, where coal seams are parted by inter-burden lithologies mostly thicker than the individual coal seams (Deysel, 2015). Thick interbedded coal deposit types are characteristic of the Northern sub basins of the Karoo Supergroup and occur in the Grootegeluk formation of the Waterberg coal field and are commonly referred to as barcoded coal. Barcoded coal deposits are characterised by a succession of multiple thinly interbedded coal and non-coal layers, attaining total thicknesses of between 40 and 70 m (Deysel, 2015).

Extraction of coal in South Africa commenced two centuries ago, with shallow underground bord-and-pillar methods (30 to 200 m below surface) in all the coalfields. The development of large diesel-powered earth moving equipment in the 1960s lead to large-scale open cast mining in the Mpumalanga coal fields (Vermeulen and Usher, 2006). South Africa currently ranks in the top ten of the largest coal producers in the world with opencast operations providing 53% of the run-of-mine (ROM) material (Hobbs et al., 2008). The Witbank coalfields in Mpumalanga produce more than 50% of South Africa's saleable coal (Hancox and Gotz, 2014). In these coalfields up to four of the five the minable coal seams are extracted and typically 4-12 Mt/a is produced from an open cast mine (Hodgson and Krantz, 1998 as cited in Vermeulen, 2003). For each ton of coal extracted, approximately eight tons of overburden or interburden is removed and replaced as spoil (Hodgson and Krantz, 1998; Vermeulen and Usher, 2006).

In South Africa, the most common opencast coal mining method is the role over method with concurrent rehabilitation (Huisamen and Wolkersdorfer, 2015). This method entails the backfilling and rehabilitation of a previously mined strip with the overburden of a currently mined strip (this is commonly referred to as the "role over method"). The overburden is removed in the form of a long, narrow trench which can extend thousands of meters in length and is usually fifty to eighty metres wide (Snyman, 1998). In the large South African opencast coal mining operations, draglines are used to remove the overburden and expose the coal (Snyman, 1998). This usually results in long elongated pitlakes at the end of mining.

Typically, in thick-interbedded coal deposits, coal is mined in benches and the trucks and shovel method is used, which and the results in rounder, deeper pits with consistently steep pit walls (Coal Valley Resources, 2011). The geometry of coal mine end-pitlakes is consequently a function of the mining technique and contrasting to natural lakes, have high maximum depth to low surface area ratios (Boehrer and Schultze, 2006).

Dewatering takes places during the operational phase of opencast mining to ensure a safe work environment. The dewatering causes a drawdown in regional groundwater levels. Once the mine stops, the pit begins to fill with water due to the rebound of water levels. Pitlakes form when groundwater, surface runoff and direct precipitation accumulate in an inactive open pit which extends below the groundwater table.

Many opencast mining operations in South Africa have left final cut end-pits when mining was decommissioned. These final cut end-pits were created where there was insufficient overburden material available to reclaim the natural profile of the landscape, in some cases due to a lack of finances or as an attempt to manage the water (Coal Valley Resources, 2011). An additional reason for the development of pitlakes is due to a lack of proper closure planning. Before the Mineral and Petroleum Resources Development Act (28 of 2002), closure was governed by the Minerals Act (Act 50 of 1991) which provided a basis for environmental management for the first time (Limpitlaw et al., 2005). Prior to the passing of Act 50 of 1991, many mining companies "*used irresponsible mining methods with no regard towards protecting the environment and had often shirked their responsibility towards environmental rehabilitation by leaving an area unrehabilitated prior to them being liquidated or leaving the country*" (Swart, 2003; Limpitlaw et al., 2005). Mine closed before 1956 were not subject to legislative closure requirements and are now the responsibility of the State (Limpitlaw et al., 2005). Today, new mine authorisations, expansions and closure have stringent regulatory requirements and if a pitlake is expected to form after mine closure, a prediction of its future water quality must be conducted as part of an Environmental Impact Study together with suitable methods for closure which should be included in the Environmental Management Plan and the necessary financial provision for closure.

According to Genthe et al. (2017) there are approximately 6000 abandoned or ownerless mines in South Africa. The estimated area of underground coal mining in more than 100 000 ha and opencast mines approximately 40 000 ha (Grobbelaar et al., 2002; Vermeulen and Usher, 2009). Pitlakes, are water bodies that formed in the final voids of opencast mines. A large number occur where mining took place prior to the introduction of environmental legislation in South Africa (De Lange et al., 2018). Hence, most of these lakes are ownerless, with only a crude estimate of their exact number (De Lange et al., 2018). In South Africa the majority of the, pitlakes occur Mpumalanga coal fields, which host the majority of mineable coal. Coal mining is frequently associated with the formation of acid mine drainage (Hancox and Götz, 2014). Consequently, there is generally preconception that pitlakes contain poor quality acid water. Nevertheless, current research of mine water in South Africa has not focused on pitlakes.

1.2 Project aims

The aim of this study is to understand South African pitlakes and to determine if pitlakes are an environmentally sustainable closure option for open cast coal mines. The study focused on two major aspects of coal mine pitlakes, namely; the pitlake water balance and secondly the pitlake chemistry. This was achieved investigating four case studies in different coalfields with different climatic conditions. The study was aimed to determine the pitlake water balance and quality. Both aspects of the study are aimed at determining if pitlakes can be an environmentally sustainable option for South African Coal mines on closure.

Pitlake water Quality: The main purpose of the study was to assess the contributions to water quality of four coal mine pitlakes and assess the hydrogeochemical processes influencing the water quality evolution in the pitlakes namely:

- The temperature, pH, EC, DO and ORP variations with depth in the pitlake and determine if any significant variability exists with depth. Additional to this, to determine the temperature, pH, EC, DO and ORP of the backfill water and surrounding Karoo aquifer to determine how these differ from the observed water quality in the pitlakes.
- The vertical chemical variations in the pitlake.
- Determine the water quality of the backfill groundwater and how this contributes to the final water quality and salinity observed in the pitlake.
- Determine the diversity of phytoplankton and microbes in the pitlakes.

Pitlake water Balance: to determine the main drives of pitlake water balances in the different climatic areas, different mining methods and pitlake morphology.

1.3 Scope and Limitations

- Water balance models were used to determine the inflow, outflow and changes in storage in the pitlakes. A limitation was the overall time duration of the study, which was 2 years.
- The method was intended to provide the information required to assess potential of pitlakes to discharge on surface.
- The groundwater models did not address contamination transport.
- General quaternary catchment climatic data was relied upon for sites that did not have site specific data.
- The long periods for approvals in terms of the mine Health and Safety requirements for launching of boats onto pitlakes.

1.4 Summary of Work Done to Date

Table 1-1 and
Table1-2 summarise the work schedule and deliverables.

Table 1-1: Project Schedule.

No.	Task	Scope of work
1	Desktop Study	
2	First round of sampling	
3	Second round of sampling	
4	Data processing and interpretation	

Table 1-2: Deliverables

No.	Deliverable	Delivery date
1	Desktop and Literature Study	30/11/2016
2	Baseline data of selected pitlakes	26/06/2017
3	Field investigation, results and interpretation and evaluation of data	27/11/2017
4	Pit morphology to determine to evaporation water (l/ha/y), effective depth and seasonal changes.	26/06/2018
6	Draft Final report for review	29/10/2018
7	Final report	04/04/2019

CHAPTER 2: THEORY OF PITLAKES

2.1 Introduction

The theory of pitlakes is based on research completed by Castendyk et al. (2009) and is shown in Figure 2-1, where different elements ultimately contribute to the pitlake evolutions and their sustainability.

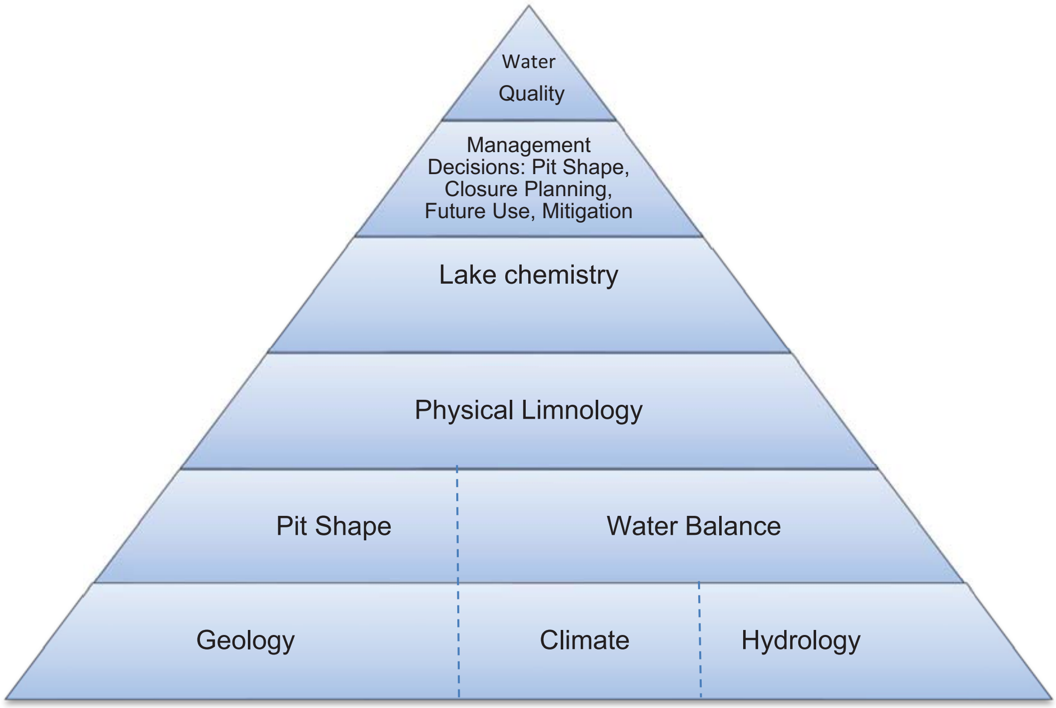


Figure 2-1: Conceptual relationship between the principal factors that affect pitlake water quality considered in the scientific literature (after Castendyk and Eary, 2009)

The classification of pitlakes is primarily based on their interaction with the hydrology of the pitlake as described by Niccoli (2009):

- Flow-through pitlakes – groundwater and/or surface water flows into and out of the pitlake due to rainfall rates that exceed evaporation rates, and where the net water balance surrounding the pit is positive.
- Terminal sinks – Groundwater flows into the pit and the only outflow is evaporation. Accordingly, the net water balance surrounding the pit is negative.

Stratification is often a central theme in international pitlake studies, as it plays a prominent role in the chemistry of pitlakes and can often be beneficial, as it provides opportunities to precipitate heavy metals to the bottom of the pitlake, where it is contained. The formation of this isolated layer depends on the salinity of the inflows from the groundwater, as well as inflows from river diversions and precipitation. Stratification can therefore be defined at the physical processes that separates the water column into layers, sometimes referred to as the physical limnology of the pitlake. The physical limnology of pitlakes can be described by two conceptual models shown in Figure 2-2:

- Holomictic lakes consist of a shallow, oxygen-saturated layer called the epilimnion, resting above a deeper, oxygen-depleted layer called the hypolimnion. Together, these layers are called the mixolimnion. The epilimnion and hypolimnion are separated by a transition zone – the thermocline – which signifies a rapid change of temperature with depth. This type of pitlake mixes completely at least once a year.

- Meromictic pitlakes consist of three layers, namely an epilimnion and hypolimnion that mix completely once a year and rest above a basal layer and the monimolimnion which remains permanently isolated from the surface environment. The incomplete mixing is due to a large density gradient between the mixolimnion and the monimolimnion (Schultze et al., 2016).

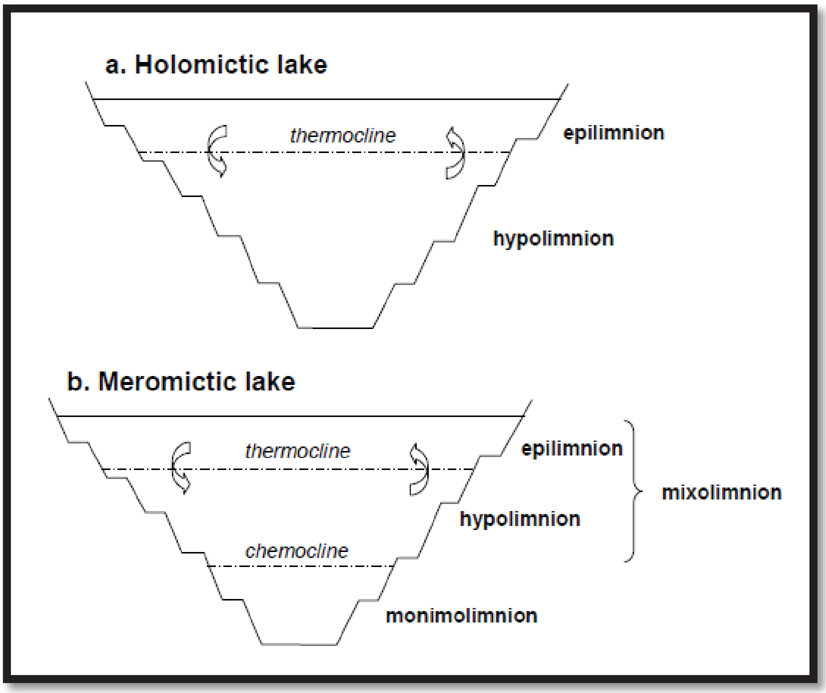


Figure 2-2: Schematic presentation of a holomictic pitlake and meromictic pitlake. (Gammons et al., 2009).

In strongly chemically stratified pitlakes, the downward settling of precipitated minerals is an important internal mechanism causing and stabilising meromictic behaviour (Walker and Likens, 1975 in Schultze et al., 2016). Above this basal layer, there often a fresh water cap that can be extracted for beneficial end uses during regulated periods in the year.

According to Castendyk et al. (2015) the development and stability of meromictic conditions (mixing or inversion) depends on the shape of the basin, wind velocities and climatic conditions. Furthermore, Hutchinson (1957) distinguished three classes of meromixes which describe processes that sustain meromictic behaviour in a dynamic equilibrium. These are:

- Inflow of saline surface water into a fresh water lake – ectogenic meromixes
- Inflow of saline groundwater into a lake – crenogenic meromixes
- Liberation and enrichment of solutes in the deeper part of the lake due to biological activity – biogenic meromixes (Schultze et al., 2016)

Castendyk et al. (2015) found there are exceptions to the most common limnologic behaviour observed in pitlakes with a range of other possibilities including;

- Shallow pitlakes that are perpetually mixed by wind and never develop stratification,
- Pitlakes that develop four or more density separated layers,

- Lakes that begin as holomictic and become meromictic over time,
- Lakes that are initially meromictic that undergo complete top-to-bottom mixing in response to extreme weather events, landslides, or lake management activities such as the Berkerly Pitlake in Montana.

Turnover is described by the frequency and depth of seasonal mixing periods and these events influence water chemistry by mixing dissolved oxygen from the lake surface throughout the water column and by transporting deep, carbon dioxide-rich water to the lake surface where it may exsolve raising epilimnion pH. Geochemical predictive modelling software is aimed at determining the volumes of mixing layers and identifying if a permanently isolated bottom layer will develop (Castendyk et al., 2015).

Most of the deeper pitlakes experience seasonal (or permanent) density stratification, although permanent stratification has been reported in relatively shallow pitlakes (Moreira et al., 2011). Generally, lakes stratify over the summer months, as surface waters become heated by solar radiation. Over the winter months, cooler air temperatures cool surface waters and winds drive convective overturn of the water body. Strong winds associated with episodic storm events can input kinetic energy that can overturn this density stratification. Long-term evaporative losses can exacerbate saline conditions in the lake and salinity-driven long-term stratification may dominate over seasonal temperature-driven stratification. These stratification cycles impact on geochemical processes, including acidification of lake waters and, potential remediation processes, such as sulphate reduction (Müller et al., 2010).

The evolution of water quality in pitlakes, such as redox (oxidation-reduction) potential and pH, is initially determined by the quality of surface and subsurface inflows and how the inflow waters interact with pit mineralogy. However, as the volume of inflows relative to the lake volume decreases (as would be expected as the pit fills), the physical, chemical, and biological processes in the lake itself begin to impact, or even dominate, lake water quality (Castendyk et al., 2015). Therefore, as pitlakes “age” it is likely for the pitlake water quality to become driven by biological controls and processes that affect natural lakes, such as eutrophication and infection by the import of pathogens, may become a greater concern.

To summarise, factors affecting the water quality of pitlakes consist of:

- Geology
- Climate
- Hydrology
- Water balance
- Physical limnology
- Internal and external lake chemical processes

In turn, the water balance of pitlakes is influenced by factors such as

1. Climate
2. Hydrology
3. Pit shape

In South Africa, there are number of typical pitlakes that can be classed according to the mining method and the final pitlake. The pitlakes investigated in this study were;

1. A pitlake as result of a single excavation
2. Pitlakes formed in final void of opencast operations
3. A pitlake associated with hydraulically connected open cast and underground sections of the mine

2.2 Geology and Geochemistry

The geology, in terms of the mineral deposit or ore being mined, as well as the mineralogical characteristics of the host rock, is one of the core factors influencing the final pitlake water quality (Castendyk and Eary, 2009). Geological controls on water quality are determined by the primary minerals and secondary minerals associated with the deposit, whereby the composition of the water is affected, and the pH is either lowered or increased. According to Castendyk (2009), the mineralogy affects the pitlake water quality by the following interactions:

- Groundwater flowing through and reacting with weathered minerals in dewatered pit wall-rock fractures upon rebound and discharges into the pitlake.
- Runoff from rainfall which reacts with minerals on the face of the pit wall and reports to the surface of the pitlake.
- Submerged minerals directly reacting with the lake water at the water-rock interface.

The pitlakes studied in this investigation were coal mine pitlakes, situated in three different coal fields of Karoo Supergroup in South Africa, namely in the Waterberg coal field, Mpumalanga coal field and KZN coal fields. The Waterberg coal field is a northern coal sub-basin where the coal-containing formations comprise the Grootegeluk formation. The Mpumalanga coal field forms part of the Main Karoo Basin where the Vryheid formation is the main coal target and where five different coal seams are mined, but mainly the No.4 coal seam. In the KZN coal fields, the main coal seams comprise the Alfred, Dundas and Gus seams. The coal in these areas ranges from sub-bituminous to bituminous, with anthracite only found in some of the KZN coal fields.

In South Africa, coal seams occur in the Ecca Group of the Karoo Supergroup. Primary and secondary minerals in the Ecca Group and crystalline matter of the coal, identified by Pinetown (2003) include quartz, kaolinite, illite, plagioclase, K-feldspar, calcite, pyrite, and occasionally gypsum, Fe-oxyhydroxides, sulphates, dolomite, ankerite and siderite. The impacts on mine water evolution in SA coal mines can be seen in the elevated TDS, sulphate, alkalinity, calcium and chloride as reported for mine water samples collected in various studies of coal mine water in the Mpumalanga coal fields (Huisamen, 2017).

Quartz and kaolinite make up most of the mineral matter in the coal and are inert, with slow reaction kinetics. Illite, also a clay mineral, is more likely associated with non-coal strata (Pinetown, 2006). Plagioclase and K-feldspar occur as semi-rounded grains with detrital or even pyroclastic origin and are associated with non-coal overburden strata and parting lithologies. K-feldspar weathers to muscovite and is usually also present on bedding planes and sandstone partings between coal layers. The major minerals of concern in the evolution of mine water are the sulphide minerals, pyrite and marcasite, associated with the coal (and often non-coal strata) which occur along cleats and fractures and which have the potential to oxidise with exposure to oxygen and water. Although the sulphur content of South African coal is relatively low, pyrite usually occurs as an accessory mineral (<2%) and is the major cause of acid rock drainage (ARD) in South African coal fields (Gomo and Vermeulen, 2014). The acid buffering minerals such as calcite and dolomite may impact and ARD production and the dissolved solids content and hardness of the water.

When active mining and dewatering of the mine ceases, the secondary mineralisation and secondary salts formed on pit walls and fractured rock zones during the production of the mine are flushed into the pit by water. According to Shafer and Eary (2009) the water quality in the pitlake will therefore be worse during the first few years of flooding but will improve over the long term.

2.3 Water Balance Components

The water balances are calculated based on a generalized mathematical expression, described by Gammons et al. (2009):

$$\Delta S = (P + SWin + GWin) - (E + (T) + SWout + GWout)$$

where

ΔS is change in storage which is the volume of water in the lake,
P is the precipitation falling onto the pitlake,
SWin is the sum of any surface water inputs which includes runoff and diverted streams,
GWin is groundwater entering the lake,
E is the evaporation from the lake,
T is plant transpiration (which is often negligible),
SWout is surface water existing in the pitlake and includes pumpage,
GWout is the groundwater leaving the pitlake.

The water balance of pitlakes is important, as it determines if the pitlake will discharge water into the environment and impact on communities and downstream water courses. Water balances in mines comprise an important role in mine planning and management, where calculations and decisions on best practice are made based on the prevailing climatic and hydrological/ hydrogeological conditions of the mine. If it is decided that a terminal pitlake is the best option for a mine after closure, it should be incorporated into the initial mine plan. If a pitlake is considered for mine closure, then a details study of the water balance and chemistry is critical to determining the environmental substantiality of the pitlake.

2.3.1 Climate

The local climate dictates the volume of water added to a pitlake via direct rainfall (Castendyk et al., 2015) and the volume of water lost by evaporation. The climate and water balances are therefore directly linked and as result the location of the pitlake, determines the behaviour of water in the pit (Castendyk et al., 2015). Two extreme climatic regions exert a control on the water quality as follows:

- Humid climates. Annual rainfall rates exceed annual evaporation rates. When the pit fills in a region with high rainfall, a greater proportion of wall-rock runoff relative to other sources of inflow is received by the pitlake, leaching chemical constituents from the wall rocks and ultimately impacting on the water chemistry. In these regions, it is then often desirable to flood the pitlake artificially, such as diversion of surface water from local rivers, to prevent the initial high concentrations of leached chemicals. When these pitlakes reach steady state conditions, excess rainfall should lead to the dilution of dissolved concentrations over time. It is also these types of pitlakes that are likely to exhibit flow through conditions, where discharge water exhibits relatively good quality because of short residence time of water in the lake, consequently shorter contact time and shorter leaching time with pit wall rocks (Castendyk et al., 2015). The dilution and discharge from through flow pitlakes thus leads to a loss of mass balance from the water instead of the build-up of chemical constituents, such as what is observed in terminal sinks.
- Arid climates. Annual evaporation rates exceed annual rainfall rates. Assuming no other process, other than evaporation removes water from the lake, the lake becomes a terminal point for local groundwater flow and is called a terminal sink (Castendyk et al., 2015). Terminal sinks form where a local groundwater divide surrounds the pitlake, and all groundwater gradients are towards the pitlake. It is evident that for terminal lakes, groundwater provides the largest proportion of inflow during lake filling, with only occasional pulses of rainfall and wall rock runoff during storms (presuming there is no runoff into the pitlake) (Castendyk et al., 2015). In general, larger surface areas lead to higher evaporation losses. Hence, as terminal pitlakes fill with groundwater, the lake surface area increases and so does the volume of water lost by evaporation. Eventually, the rate of evaporation will equal the rate of inflow from the aquifer, which will be when the pitlake has reached steady state water levels. Consequently, as clean water evaporates

from the lake surface and groundwater flows in as background groundwater qualities, evaporation has a concentrating effect on the ionic composition of the water, changing the chemical mass balance and dissolved solids over time, until chemical equilibrium is reached with certain minerals by a process known as evapoconcentration (Castendyk et al., 2015). Terminal pitlakes can become through-flow lakes when the elevation of the lake water exceed the elevation of the surrounding groundwater level or if the lake overflows. If the discharging water is of poor quality, it poses a risk to the environment and needs to be managed.

2.3.1.1 Rainfall

Rain refers to the falling down of condensed water droplets from the atmosphere to the ground as a result of the gravity. Precipitation data may be measured in various ways. There are various weather stations which measure precipitation with the use of a rain gauge. Doppler radar also allows for the measurement of precipitation over a large area without the need to extrapolate observations made at single sites (Neff and Killian, 2003). The water balance modelling requires recorded daily rainfall data from a gauge near the site under investigation in order to obtain a reliable model. The volumes of rainfall into the pitlakes are proportional to their associated surface areas (McCullough et al., 2013).

2.3.1.2 Evaporation

Evaporation is the process in which a liquid changes to the gaseous state at the free surface, below the boiling point through the transfer of heat energy. The rate of evaporation is controlled by the available energy and the ease with which water vapour diffuses into the atmosphere (Finch and Calver, 2008). The evaporation rate increases with an increase in the water temperature. Evaporation pans are probably the most popular devices used in evaluating evaporation. There are two widely used methods of pan evaporation, namely A-pan and S-pan evaporation methods.

Evaporation in a large dam is different from pan evaporation and therefore, water and air temperatures are compensated for by the application of pan factors to the measured evaporation in an effort to obtain dam factors (Haarhoff and Cassa, 2009). Monthly lake evaporation factors applicable to Symons-Pan evaporation are shown in Table 2-1 below.

Table 2-1: Open water evaporation pan factors (Midgley et al., 1994).

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.81	0.82	0.83	0.84	0.88	0.88	0.88	0.87	0.85	0.83	0.81	0.81

Evaporation is applied to pitlake surface areas as the pitlake evolves over time. Evaporation increases with increasing pitlake water elevations due to the increased surface area as a result of increasing water level.

2.3.2 Hydrology

2.3.2.1 Runoff

Surface runoff is the process by which precipitation rates exceed infiltration capacity of the soil (Wagener et al., 2004). Topographical variations are crucial in runoff determination as there is a relationship between surface runoff and surface topography. The runoff coefficient for each quaternary catchment was obtained and used in the volumetric calculation for runoff using the equation presented by (Castendyk, 2009):

$$Q = CIA \qquad [2]$$

Where:

Q is the runoff inflow volume (m^3/day), C is the runoff coefficient, I is the total precipitation (m) and A is the area over which runoff occurs excluding the saturated pitlake surface (m^2). In-pit runoff is expected to have a higher runoff coefficient than the catchment surface and will therefore be calculated separately.

2.3.3 Groundwater Models

Groundwater is pumped out for mining activities to operate in dry conditions and for safety purposes. Once pumping stops, the groundwater rebounds and contributes to the formation of the pitlake. Eventually, water levels in the open mine void will equilibrate with water levels in the aquifer. The purpose of a groundwater model is to characterize the balance of withdrawal or recharge events so that changes in local groundwater flow rate and changes in water levels can be predicted (Ebrahim, 2013).Kruseman and Ridder (1990) provides a wide range of equations which may be used for groundwater inflow calculations and aquifer testing analysis.

Groundwater models are uncomplicated representations of groundwater systems. Mathematical models may be solved analytically or numerically, whereas an analytical model is applied to simple domains and numerical models can be applied to more complex conditions. Groundwater inflow into the open pit may be determined using various equations, but the application of these equations is dependent on the conditions of the site and based on the assumptions on which the equations are based.

2.3.3.1 Analytical *models*

Analytical solutions are reviewed to determine which equations are best suitable for use, given the site characteristics. The pit geometry and aquifer parameters are required inputs in the calculation of groundwater inflow using analytical equations (Singh and Atkins, 1985).

A study by Marinelli and Niccoli (2000) engaged to determine *Simple analytical equations for estimating groundwater inflow to a mine pit*. Two analytical equations for predicting groundwater inflow to a mine pit are presented in this research, based on the conditions given in Table 2-2. Figure 2-3 shows a conceptual groundwater flow model for pitlakes.

Table 2-2: Assumptions for Marinelli and Niccoli approach

Zone 1	Zone 2
Pit walls are approximated as a right circular cylinder	Hydraulic head is initially uniform
Groundwater flow is horizontal	The disk sink hydraulic head equals that of the pitlake water level
Pre-mining water level is approximately horizontal	Flow to the disk sink is three-dimensional and axially symmetrical
Uniform recharge occurs across the site	Materials re anisotropic, and the principal coordinate directions are horizontal and vertical for hydraulic conductivity
Groundwater flow toward the pit is axially symmetrical	

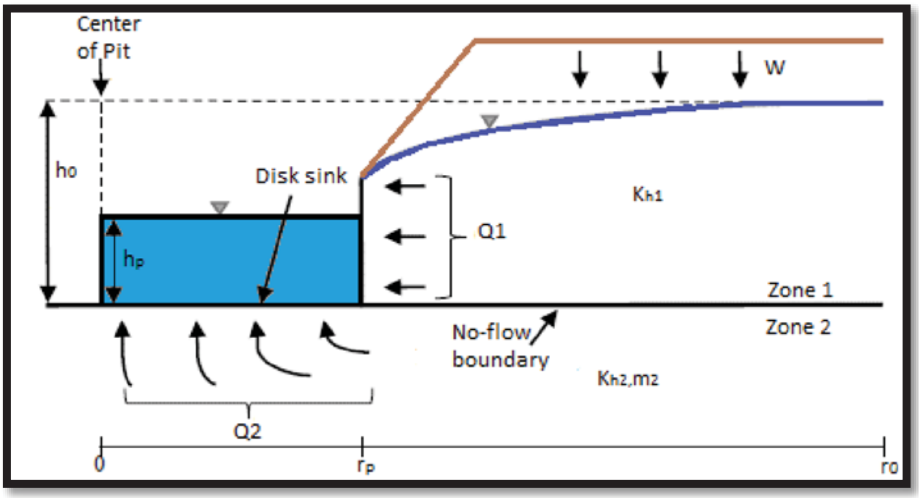


Figure 2-3: Pitlake Conceptual Groundwater inflow model (after Marinelli and Niccoli, 2000).

The analytical solution to calculate groundwater inflow from Zone 1 may be expressed as:

$$Q_1 = W\pi(r_0^2 - r_p^2) \quad [3]$$

Where:
Q_1 is the total inflow from the pit walls in zone 1, W is the recharge flux, r_0 is the radius of influence, r_p is the radius of the pitlake.

Calculating flow into the pit through the pit bottom is determined by the equation:

$$Q_2 = 4 \times r_p \times \left(\frac{K_{h2}}{m_2}\right) \times (h_0 - d) \; ; m_2 = \sqrt{\frac{K_{h2}}{K_{v2}}} \quad [4]$$

Where:
Q_2 is the inflow rate through the pit bottom from Zone 2, K_{h2} and K_{v2} are the hydraulic conductivities for zone 2, m_2 is the anisotropy parameter, h_0 is the pre-mining water table above the base of Zone 1 and d is the depth of the pitlake.

An investigation for the suitability of simple groundwater theorems to calculate groundwater inflow into a mine excavation was conducted by Singh and Atkins (1985) and is illustrated in Figure 2-4. A condition given in this research is one phase flow into a mining surface excavation occurs in the two cases listed below:

a) The mineral deposit is underlain by a no-flow layer and flow is in one horizontal direction.

b) When pressure from the confined aquifer flows vertically through the pit bottom.

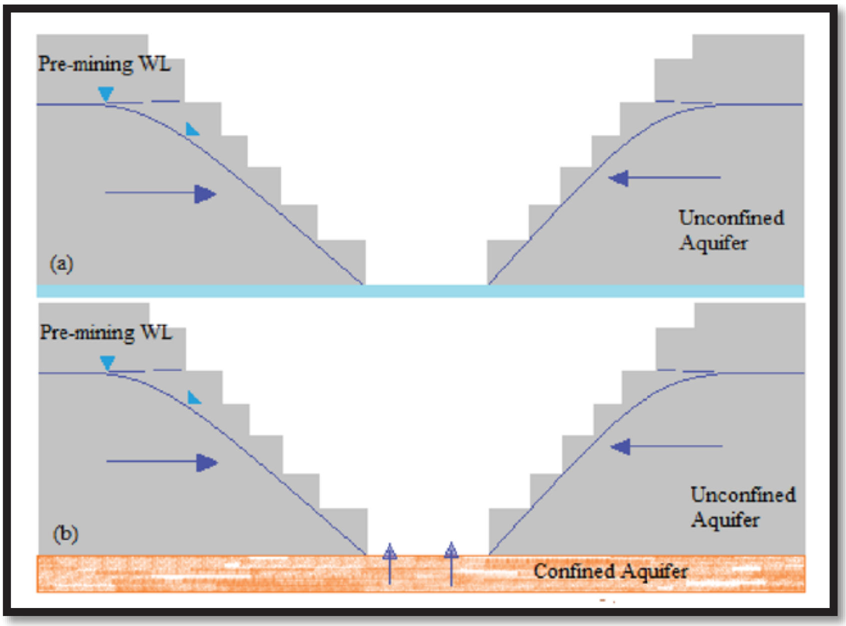


Figure 2-4: Hydrogeological conditions profiles (after Singh and Atkins, 1985)

In the case where the mineral deposit is above the confined aquifer, Singh and Atkins (1985) suggests the application of a well-known formula called Darcy's Law, which is given by:

$$Q = KAi \qquad [5]$$

Where:
Q is the flow rate, *K* is the hydraulic conductivity of the aquifer, *A* is the area of the pit, and *i* is the hydraulic gradient.

Furthermore, Singh and Atkins (1985) suggests the use of the Dupuit solution (modified by to Dupuit-Forchheimer, Figure 2-5) for two-dimensional groundwater flow to an open pit, given the following conditions:

- Excavation is emplaced instantaneously
- Homogeneous and isotropic geology
- Narrow excavation, linear in shape and symmetrical
- Horizontal flow
- Saturated formation below the water table is greater than the thickness of the capillary fringe above the phreatic surface
- Vertical excavation face
- Boundary conditions are very restricted. Dupuit assumes a parabolic shaped depressed water table, while Dupuit-Forchheimer assumes an elliptical depressed water table.

$$Q_g = \frac{\pi \times K \times (h_0^2 - h_w^2)}{\ln\left(\frac{r_0}{r_w}\right)} \qquad [6]$$

Where:
Q_g is the groundwater flow rate, *K* is hydraulic conductivity, h_0 is the pre-mining water level, h_w is the pitlake water level, r_0 is the radius of influence, and r_w is the radius of the pit.

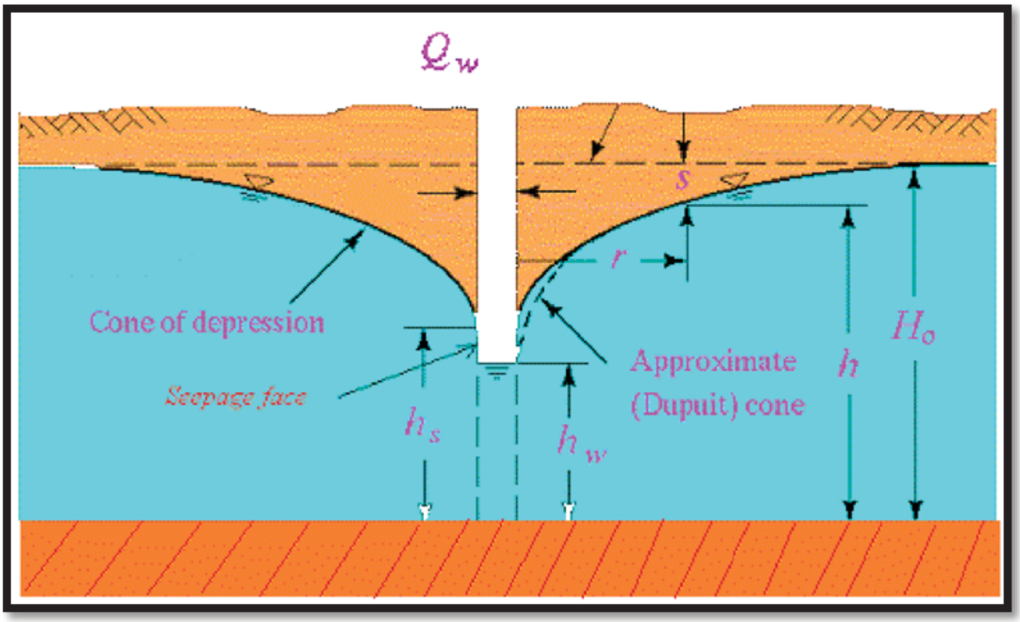


Figure 2-5: Dupuit-Forchheimer illustration.

2.3.3.2 Numerical models

Numerical models mathematically solve groundwater flow models using computers. A mathematical model consists of a set of partial differential equations that are recognised to govern the groundwater flow in the subsurface (Ardejani, 2003). Numerical models provide a more realistic interaction between the groundwater system and the open pits as they are less restricted to assumptions. These assumptions usually include the groundwater flow direction, geometry of the aquifer and the heterogeneity or anisotropy of sediments within the aquifer (Kumar, 2002). Numerical modelling has the advantage of investigating various scenarios without much effort (Bester, 2009).

Computer programs for groundwater flow modelling are based on one of the following methods:

- Finite Difference
- Finite Element, where the spatial domain is divided into a mesh of elements of triangular shape.
- Analytical elements

Groundwater flow is governed by the following equation (Chiang and Kinzelbach, 1998):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)\pm W=S_s\frac{\partial h}{\partial t} \qquad [7]$$

Where:

- K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T);
- h is the potentiometric head (L);
- W is a volumetric flux per unit volume representing sources and/or sinks of water,

With:

- W < 0.0 for flow out of the ground-water system, and W>0.0 for flow in (T^{-1});
- Ss is the specific storage of the porous material (L^{-1}); and
- t is time (T).

2.4 Pit Morphology

The pit shape is important from a water balance and water quality point of view. This is based on the following reasons:

- Large surface area compared to mean depth, linear/ elongated pitlake morphology. These pitlakes are more prone to effects of evaporation and evapoconcentration. Larger surface areas provide larger areas for evaporation, with lower potential for discharge/overflow and ensure a groundwater gradient towards the pitlake, to act as a hydrological sink.
- Small surface area to mean depth ratio or cone shaped pitlakes. These pitlakes tend to form an isolated bottom layer, called the monimolimnion, with inferior water quality to the rest of the lake. If the chemistry and physical structure of the pitlake is stable, the isolated layer may be beneficial to detain heavy metals. Conversely, an isolated layer may not be desirable, as sudden storms events may erode the chemocline and cause this layer to turnover together with the top layers, and mix poor, metal rich water through the whole water column with deleterious effects on overall water quality.

Thus, pitlakes with high depth to width ratios are less susceptible to complete lake turnover (Gammons et al., 2009). Therefore, the relative depth is a good measure for the shape of the pitlake basin (Schultze, 2012). The relative depth is also referred to as the “aspect ratio” and can be described as a comparison of the maximum depth (Z_{max}; m) of the lake to the lake surface area ($A_{surface}$; m^2). The relative depth is expressed as a percentage (Castendyk et al., 2015; Vandenberg et al., 2015). The calculation of relative depth is shown in Equation 1:

$$z_{relative}\,(\%) = \frac{50 \times z_{max} \times \sqrt{\pi}}{\sqrt{A_{surface}}} \qquad [8]$$

Wetzel (2001) indicated that natural lakes have relative depths of < 2%, whereas existing pitlakes have relative depths in the range of 1% to 45% (Figure 2-6). Additionally, Doyle and Runnells (1997) suggested that most pitlakes with a Zr > 25% were more prone to becoming meromictic. However, some contradictions were encountered where a few lakes in this study with a Zr > 25% displayed holomictic circulation patterns, while some other lakes with Zr < 25% displayed meromictic behavior. Thus, although geometry-based comparisons can provide indications on whether a pitlake will become holomictic or meromictic, additional factors may dictate if a pitlake stratifies permanently, such as the water density and windspeed on the pitlakes, should be also be considered when they are applied as predictive measures (Vandenberg et al., 2015, Castendyk et al., 2015).

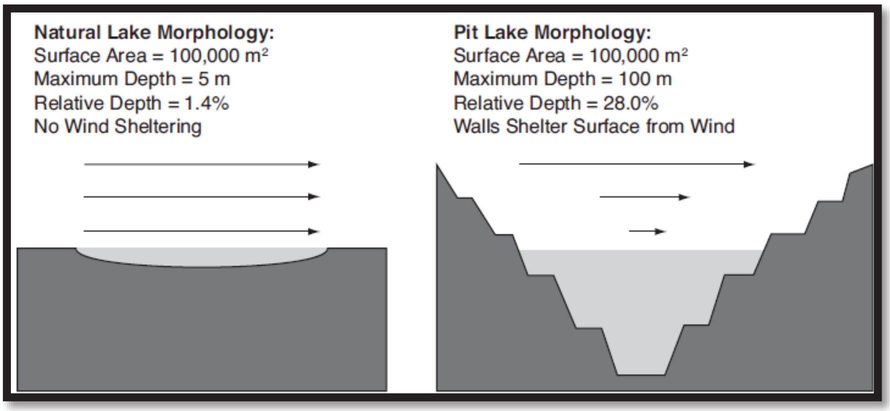


Figure 2-6: Morphology of natural lakes versus pitlakes (Castendyk and Eary, 2009).

In the South African coal fields, where the main coal deposits are in the Main Karoo Basin, the major opencast operations proceed via dragline methods, if the deposit’s characteristics match the draglines’ physical capabilities. The overburden is removed in the form of a long, narrow trench that can extend thousands of metres in length and is usually 50 to 80 m wide (Snyman, 1998). The coal mine pitlakes are left as final voids after the roll over method of mining (also known as concurrent rehabilitation) is completed (Huisamen and Wolkerdorfer, 2015). As a result, the characteristics of pitlakes vary considerably, but they are generally linear in shape, with surface areas of 1 to 30 ha and depth ranging from 2 to 30 m (De Lange et al., 2018).

2.5 Physical Limnology

Wetzel (2001) defines limnology as the study of inland freshwater and saline water bodies, whereby the structural and functional interrelations of organisms are affected by their dynamic, physical, chemical and biotic environment. The limnology of pitlakes is related to their morphometry, which in turn is a function of underwater contour lines, the shape of the lake, and its geologic origin (Slabbert, 2007). Limnological effects are also due to the lake's structure – deep steep sided lakes differ in almost all aspects from shallow lakes. Once the lake basin is formed, physical, chemical, and biological factors interact to produce discernible structures within the water. These structures persist despite the continual movement of the water that is characteristic of all aquatic ecosystems (Slabbert, 2007).

Shown in Figure 2-7 is the terminology and theoretic principles on which the field investigation of the study was based. The schematic illustration shows a cross section through a typical meromictic pitlake experiencing summer stratification, in a temperate climatic zone in Germany. A steep thermal gradient in the mixolimnion, divides the top layer into an epilimnion and hypolimnion with uniform salinity. The mixolimnion is defined as the zone where active mixing of water occurs, whether by wind or seasonal turnover. A drastic increase of the salinity observed at the bottom, indicated the presence of a third layer, the monimolimnion, which is separated from the mixolimnion, by a transition zone termed the chemocline.

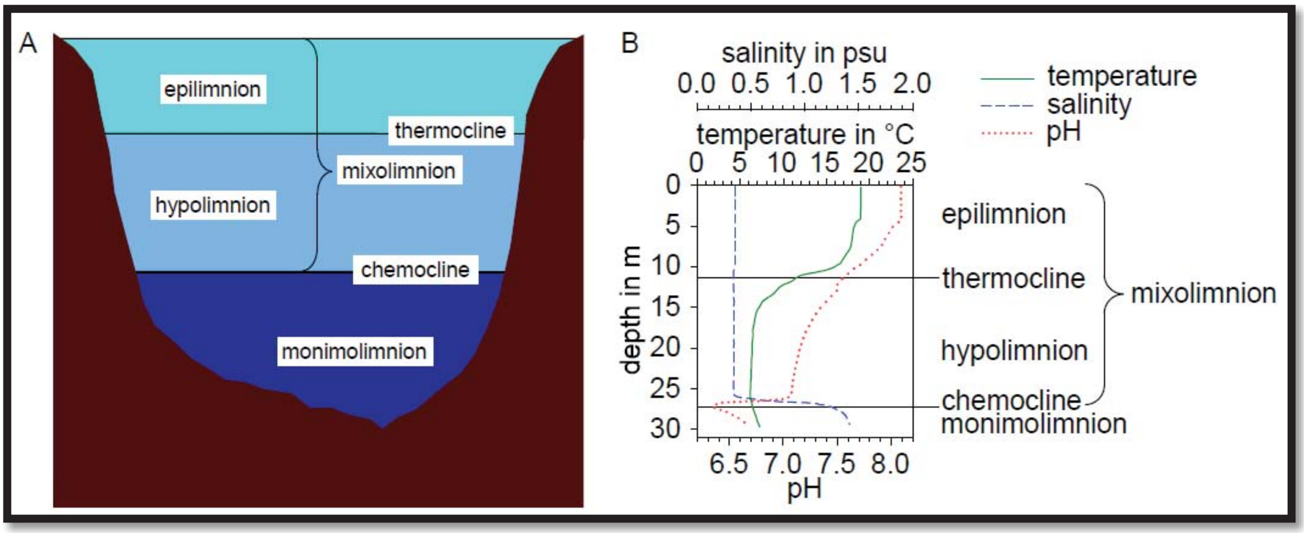


Figure 2-7: The typical terminology used in a meromictic pitlake (Panel A) and the associated profiles (Panel B) for Lake Goische, Germany (Schultze et al., 2016).

The following sets of parameters are thus relevant to measure as an estimation of lake stratification and subsequent turnover:

- Temperature (T) and Electrical conductivity (EC). T and EC combined, the salinity, are the most useful to monitor, as it indicates if the lake will turnover annually (holomictic) or be permanently stratified (meromictic) (Gammons et al., 2009).

- pH and Redox potential. Many studies on mine water consider pH and redox potential the master variables that control water chemistry. The fate and transport of trace metals varies depending on the redox and pH conditions.

Dissolved oxygen (DO). DO gives an indication of the fate and mobility of trace metals in the water.

2.6 Pitlake Chemistry

One of the most pressing concerns about pitlakes is their potential to turn acidic. Conceptual models of pitlake geochemistry are described by external and internal processes, of which many of the internal processes are mediated by algae and microbes (Gammons et al., 2009). External processes have been described as wall rock runoff and wall rock leaching. Figure 2-8 summarises the processes that drive the chemistry in pitlakes.

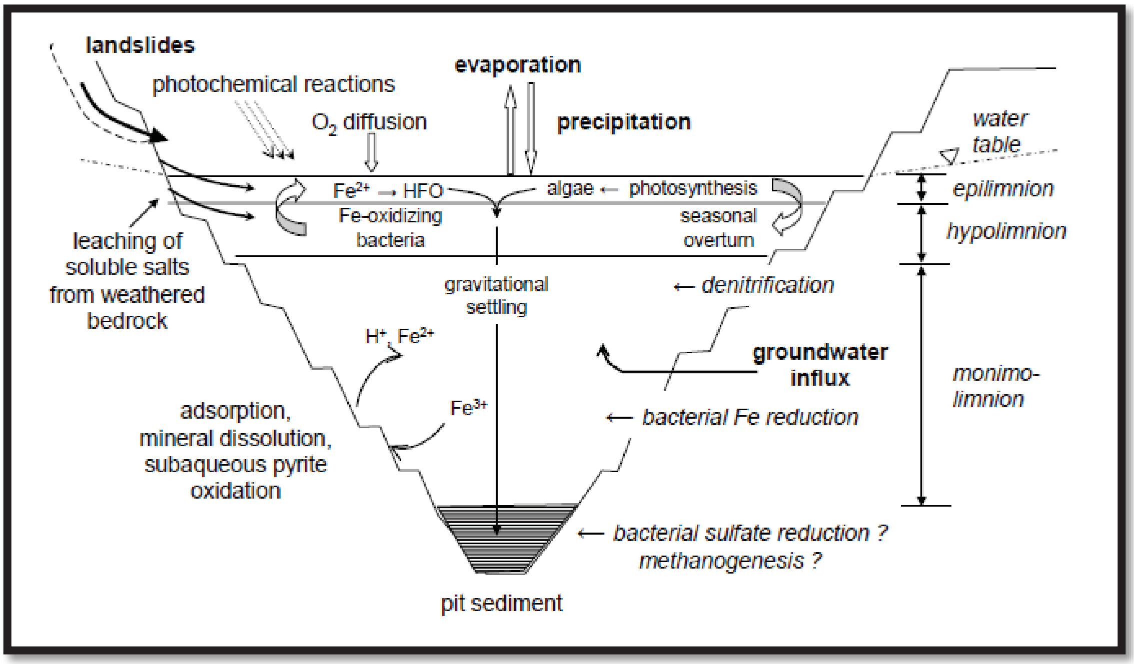


Figure 2-8: Chemical processes in pitlakes (Gammons et al., 2009).

After mining ceased, rebounding groundwater enters the pit by passing through the dewatered strata from where the groundwater transports the products of pyrite oxidation, mainly sulphate, iron, and acidity or dissolves secondary minerals that might have formed, in the backfill material. The hydrochemistry of coal mine pitlakes is thus influenced by the geology of the area, the groundwater and surface water hydrologic characteristics, the amount of sulphur within the strata, the extent of pyrite oxidation, and the mining technology used (Friese et al., 2013).

The most common set of reactions producing acidity in coal mines is the oxidation of sulphide and iron in pyrite (FeS_2) in the following two reactions (Castro et al., 1999 in Sanchez-Espana et al., 2009).

$$FeS_2 + \frac{7}{2}\, O_2(aq) + H_2O \rightarrow FeS^{2+} + 2SO_4{}^{2-} + 2H^+ \qquad [9]$$

$$Fe^{2+} + \frac{1}{4}O_2\,(aq) + \frac{5}{2}H_2O \rightarrow Fe(OH)_3 + 2H^+ \qquad [10]$$

Furthermore, the chemical mass balance in a pitlake is affected by the inflows and outflows from the lake and the contributing water quality of each of these components, together with internal processes in the pitlake, which in turn, is dependent on physical-chemical variables, mainly pH and redox conditions. In general, conceptual models of pitlake geochemistry take external impacts as well as internal processes occurring inside the pitlake into account:

- External processes include pit wall rock runoff and wall-rock leaching (Castendyk et al., 2015).
    - Wall rock runoff is a surface hydrology process mainly generated by rainfall/rain storms at South African coal mines. Wall rock runoff washes dissolves efflorescent salts and oxidation products from the exposed surfaces and transports dissolved components to the pitlake. Data for wall rock runoff can be obtained and quantified by laboratory and fields tests, as well as mineral dissolution kinetics.
    - Wall rock leaching is a groundwater and lake water process and includes direct contact with wall rocks, usually below the water in the pitlake. Chemical leaching occurs in the saturated and unsaturated zone along pore spaces and historic mine adits that intersect the pit wall. Data can be quantified by oxidation modelling and laboratory leaching tests, as well as batch testing with representative water compositions. Data obtained from the laboratory kinetic tests provides a measure of soluble constituents released per mass of rock per unit of time.
- Internal processes to consider in geochemical pitlake conceptual models include (Castendyk et al., 2015):
    - Vertical mixing and turnover of the pitlake water column and redistribution of solutes.
    - Oxygen and carbon dioxide exchange between lake water and atmosphere.
    - Saturation state of minerals – especially in climates were evaporation is a major control
    - Adsorption of metals and metalloids onto Fe-hydroxide and clay mineral surfaces and organic matter and subsequent downward settling of the particles
    - Sedimentation of downward settling solids and the removal of metals from solution
    - Dissolution and oxidation of submerged, and reactive wall-rock minerals.

In natural systems, pH is typically buffered by a carbonate buffer system (at pH of 6 to 8.5); however, pitlakes of lower pH are often buffered by aluminium complexes (pH 4.5-5.5) or iron complexes (pH 2.0-4.0) (Sanchez-Espana et al., 2009).

Previous studies have, however, found that not all pitlakes will turn acidic and that the water quality of coal mine pitlakes can range from extremely acidic, such as the Collie district coal pitlakes in Australia and lignite pitlakes in Germany, to alkaline pitlakes, such as some coal mine pitlakes in India and the USA. The pH of pitlakes can therefore be viewed as a function of the chemistry of the local groundwater, the geology of the coal and country rock (Gammons et al., 2009).

The inflow water qualities therefore exert an important control on the pitlake geochemistry whereby the chemical mass balance of the pitlake water is changed by any inflows and outflows from the lake as follows:

- Groundwater inflow from upgradient aquifer carrying dissolved solids at background concentrations into the lake. The ambient groundwater will have a certain quality but may also pick up certain constituents from weathered rock along the flow path or from meteoric water passing through the dewatered zone.
- Surface water runoff and sediment influx from pit walls which alters the turbidity and chemical input, acidity and ultimately pH.
- Direct rainfall onto the surface of the pitlake that may have a diluting effect.
- Evaporation which has a concentrating effect on pitlake water quality.
- Groundwater and surface water outflows which remove constituents and chemical mass from the water. If the pitlake is stratified, waters of different qualities are removed, which may improve or worsen the water quality and should be managed accordingly.

Table 2-3 is a description of internal processes that can alter pitlake water chemistry.

Table 2-3: Internal pitlake chemical processes (Gammons et al., 2009).

Process	Impacts
Evaporation	Concentration of all solutes in proportion to the fraction of water lost to vapor. May lead to precipitation of gypsum, calcite and other sparingly soluble salts.
Photosynthesis by algae, bacteria or plants	Increase in biomass which provides carbon source for bacteria, animals and other decomposers. Increase in DO. Increase in pH (for non-acidic lakes). Possible uptake of trace metals by plants. Blockage of sunlight if conditions are eutrophic.
Photoreduction	Photoreduction of Fe^{3+} or hydrous ferric oxide to $Fe^{2+.}$ Possible photoreduction
Leaching of soluble salts stored above the water line	Increase in salinity and concentrations of trace metals and metalloids.
Oxidation and precipitation of hydrous metal oxides	Decrease in concentration of dissolved Fe and Mn. Decrease in trace solutes that adsorb onto hydrous metal oxide. Increase turbidity from suspended mineral particles. Possible drop in pH.
Adsorption onto suspended mineral particles or organic matter	Decrease in concentration in heavy metals and metalloids. Enhanced removal of As and Se at low pH. Enhanced removal of Cd, Cu, Pb, Zn at high pH. Important sink for phosphate.
Dissolution of minerals exposed on submerged mine walls	If carbonate minerals are present, they can be an important mechanism for buffering pH to near neutral conditions. If lake is acidic, may see conversion of feldspar and other rock forming minerals to clay.
Sub-aqueous oxidation of pyrite by O_2 and/or dissolved $Fe^{3+.}$	Increase in the concentrations of dissolved heavy metals and sulphate. Drop in pH. Drop in dissolved oxygen and/or dissolved Fe^{3+} concentrations

Evapoconcentration is a major lake process which influence the water quality of pitlakes. For pitlakes situated in semi-arid to arid environments and which are mostly affected by evaporation, geochemical processes are often interpreted in terms of geochemical equilibria. Subsequently, saturation indices are used to define minerals likely to precipitate from solution and limit the maximum dissolved concentrations. Eary (1999) defined equilibrium trends for major ions sulphate, fluoride, calcium, alkalinity and minor ions barium, strontium, aluminium, manganese, cadmium, copper, lead, zinc, arsenic and selenium using chemical data obtained from several hard rock and coal mine pitlakes in the USA.

In terms of metal phases, Al, Fe and Mn are the most prevalent in South African coal fields. Hence, in terms of solubility of Al, Fe and Mn, the following equilibrium trends were observed in existing pitlakes according to the work of Eary (1999) shown in Figure 2-9. For neutral pH conditions, amorphous Al(OH)3 (gibbsite) provides an upper bound for Al at pH>6. At neutral pH conditions, for Fe generally very low concentrations are encountered in existing pitlakes with values between 0.002 and 5 mg/l, making predictions for Fe concentrations under such conditions less important for predictions of water quality. For Mn, at pH > 7.5, rhodocrosite solubility provides a reasonable upper bound for Mn concentrations. These figures indicated that for pitlakes with neutral to slightly alkaline pH waters, Al most likely exist as gibbsite, Fe exist as ferrihydrite solids and Mn as rhodocrosite. Also, the typical concentrations for these metals encountered at neutral pH, is low.

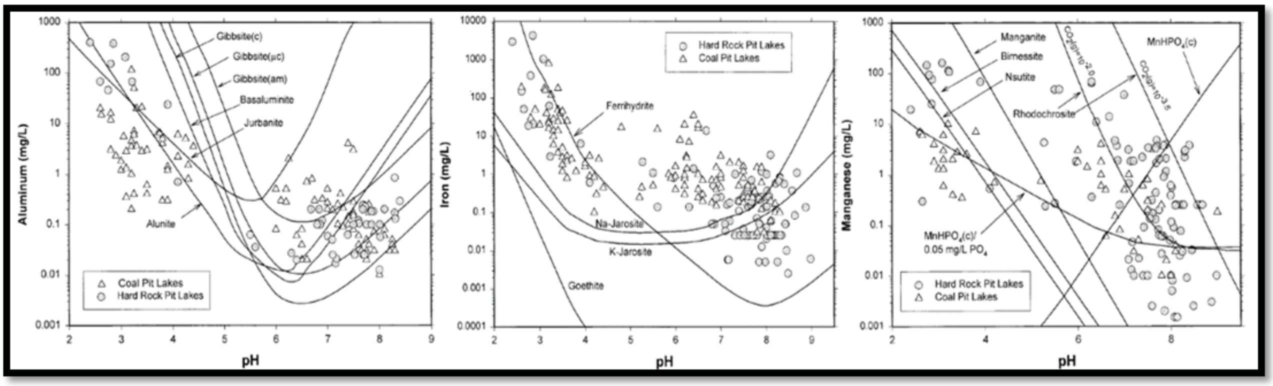


Figure 2-9: Concentrations of Al, Fe and Mn in surrounding geology and coal pitlakes compared to the solubilities of Al, Fe and Mn containing solids (Taken from Eary, 1999).

2.7 Pitlake Biota

The pitlake biota can be assessed by the phytoplankton and chlorophyll-a and microbiology. This study did not include an assessment of any other biota such as fish, amphibians or insects

2.7.1 Phytoplankton and chlorophyll-a

Seven common divisions of algae can be classified from lakes, described by Bellinger and Sigee (2015) and shown in Table 2-4.

Table 2-4: Seven divisions of algae.

Genus	Description
Bacillariophyta (golden brown diatoms)	Usually microscopic, filamentous or unicellular, e.g. Aulacoseira, Nitzschia, Navicula spp.
Chlorophyta (grass green)	Micro- or macroscopic, filamentous, colonial or unicellular, some are flagellated; e.g. Oocystis sp
Dinophyta (red-brown, dinoflaggelates)	Microscopic, unicellular or small chains are all flagellated, cellulose cell wall (when present); e.g. Peridinium, Ceratium spp.
Cyanophyta (blue-green, cyanobacteria)	Micro- or macroscopic, usually filamentous, but also unicellular or colonial, some can float and glide; e.g. Anabaena, Oscillatoria, Chroococcus, Microcystis spp.
Chrysophyta (yellow or brown-green)	Microscopic, unicellular or colonial, some are flagellated; e.g. Mallomonas sp.
Cryptophyta (various colours, various cryptomonads)	Microscopic, unicellular, flagellated; e.g. Rhodomonas sp.
Euglenophyta	Microscopic, unicellular, flagellated; e.g. Euglena sp.

Since phytoplankton communities make up the main algal biomass of a lake and because many planktonic species have defined ecological preferences, most studies have used them as present-day environmental assessments (e.g. Genthe et al., 2017; De Lange et al., 2018). Bellinger and Sigee (2010) further stated that the analysis of phytoplankton communities from a number of sites across the lake also provides information on aquatic conditions in general and is the basis of a broad categorisation of lakes in relation to water quality, particularly trophic states (Figure 2-10).

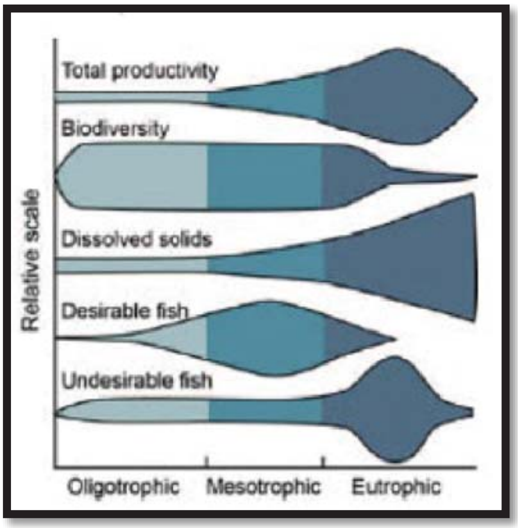


Figure 2-10: Changes in characteristics of lakes with increasing phytoplankton biomass from oligotrophic lakes to eutrophic lakes (Zhu and Schwartz, 2011).

Changes in trophic status accompanied by growth of algae and other aquatic plants in lakes is the norm used to assess the effects of inorganic nutrients (such as nitrates and phosphates) on aquatic ecosystems (Vos, 2001). The trophic status of a lake can also be determined by assessing chlorophyll-a concentrations. According to De Lange et al. (2018) categories used to establish the productivity potential based on chlorophyll-a are as described in Table 2-5.

Table 2-5: Chlorophyll-a concentration and trophic status classification scheme (From De Lange et al., 2018).

Chlorophyll-a concentration (µg/ℓ)	Trophic status classification
>25	Hypertrophic
9-25	Eutrophic
3.5-9	Mesotrophic
<3.5	Oligotrophic

According to the DWAF (1996) the above classification has the following implications for the aquatic ecosystem as described in Table 2-6.Table

Table 2-6: Typical symptoms associated with different trophic status of an aquatic ecosystems (DWAF, 1996; Vos, 2001)

Trophic status	Effects
Oligotrophic	Usually moderate levels of species diversity; usually low productivity systems with rapid nutrient cycling; no nuisance growth of aquatic plants or blue-green algae.
Mesotrophic	Usually high levels of species diversity; usually productive systems; nuisance growth of aquatic plants and blooms of blue-green algae; algal blooms seldom toxic.
Eutrophic	Usually low levels of species of diversity; usually highly productive systems; with nuisance growth of aquatic plants and blooms of blue-green algae; algal blooms may include species that are toxic to man, livestock and wildlife.
Hypertrophic	Usually very low levels of species diversity; usually very high productive systems; nuisance growth of aquatic plants and blooms of blue-green algae, often including species that are toxic to man, livestock and wildlife.

2.7.2 Microbiology

Microorganisms play a significant role in geological and geochemical processes in pitlakes. These organisms include both prokaryotic organisms, such as bacteria, and eukaryotic organisms, such as algae, fungi, protozoa and slime moulds (Castendyk and Eary, 2009).

Bacteria have the ability to couple their survival and growth to a variety of electron donors and terminal electron acceptors. These potential couples are infinitely more complex than coupling organic carbon to oxygen like human metabolism. Bacteria are capable of replacing this redox couple with inorganic compounds such as nitrates, metals and sulphates – this concept is summarized in Figure 2-11 – and is related to the oxidation / reduction potential (ORP) and availability of donor / acceptor pairs of a given environment.

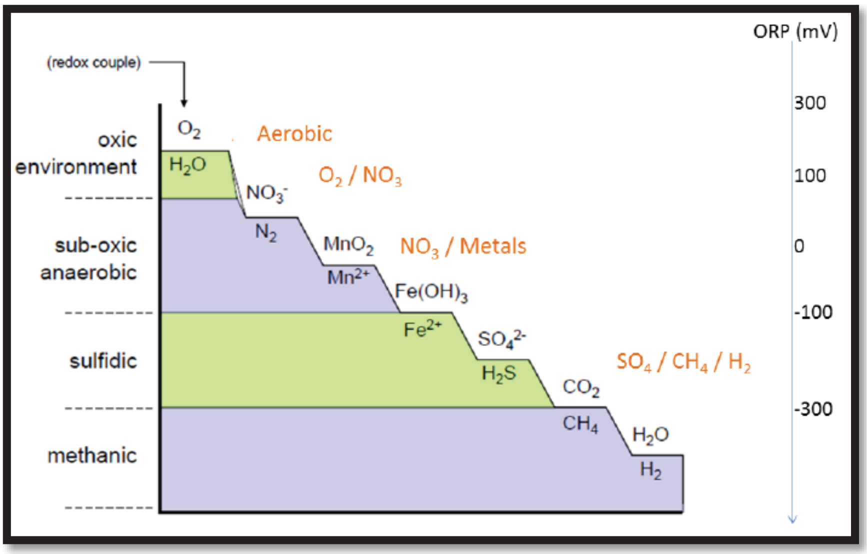


Figure 2-11: Redox tower of microbial metabolism.

Bacteria can also be classified according to their sources of energy, sources of carbon and, in the case of some lower organisms such as sulphur bacteria, the molecule that serves as the electron donor (Vos, 2001). Bacteria in this study was investigated in terms of their phylogenetic diversity, based on operational taxonomic units (OTUs) (Figure 2-12). Previous global studies have found that bacteria can impose a large impact on water quality in pitlakes and similarly, the chemical signature of a pitlake has an influence on the bacterial communities.

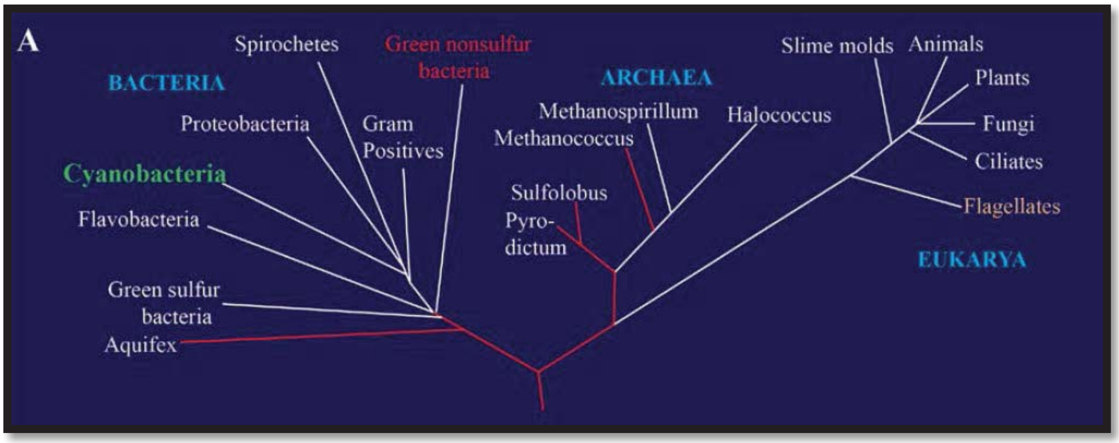


Figure 2-12: Schematic representation of phylogenetic tree based on rDNA data (Druschel and Kapler, 2015).

2.8 Water Quality

One of the fundamental issues regarding mine permits and closure planning, is the final water quality of pitlakes (Shafer and Eary, 2009), especially in terms of environmental impact and environmental sustainability. The final pitlake water balance and water quality will ultimately determine how these water bodies can be incorporated into the original mine plan and form part of the environmental post mine closure. Pitlakes mostly contain groundwater which has evolved through complex water-rock interactions and is subject to hydrological and limnological processes, prevailing under certain climatic conditions. When pitlakes contain poor water quality, the adverse effects of mining in general become a very tangible issue and heightens the public awareness of the impact these water bodies have on communities and the environment (Shafer and Eary, 2009). For a pitlake to be environmentally sustainable, a good or acceptable water quality is key and that the achievable water quality should fit a certain end-use, or uses, which comply with certain criteria. Many studies have shown pitlake water qualities comparable to those of natural lakes in the same geographical area, such as gravel pitlakes in Denmark (Sondergaard et al., 2018), while others, such as the Berkeley pitlake (Davis and Ashenberg, 1989), have shown some of the worst case scenarios of pitlake water quality.

These and various other studies conducted on pitlakes around the globe have found that the final water quality is ultimately a function of a compilation of many factors, as mentioned in sections 2.1 to 2.5. In the current study, the water quality of the pitlakes was examined according to the described factors. The study also considering the different geographical locations and the differing mining methods.

2.9 Mine Spoils

An assessment of the mine spoils considers waste rock dumps, backfill and underground mine voids.

2.9.1 Waste Rock Dumps

Water content in waste rock piles is a function of rock particle size and water infiltration (Smith et al., 1995). The hydraulic conductivity and porosity of the waste rock dumps is greater than the surrounding geology, providing an easier path for water. This is likely to cause groundwater rise beneath the waste rock dump area. In addition the chemistry of the seepage through the waste rock dump will impact on the underlying water quality.

2.9.2 Backfilling of Open Pits

Complete backfilling of open pit mines is a means of entirely avoiding pitlake formation and has frequently been thought of as a solution to many of the environmental issues related with the closure of large-scale open pit mining operations (Williams, 2009). Scenarios of backfill closure designs are described by (Johnson and Carroll, 2015) as follows:

- No backfill – the pit is filled by groundwater and rainfall naturally
- Optimised backfilled – partial backfilling to eliminate the lake
- Complete backfill – backfilling a pit to minimize the exposure of pit walls

Recycling coal waste rejected from processing plants may be used in the form of backfill to avoid environmental problems such as slope failures and air and water pollution. The feasibility of backfilling with coal processing plant waste depends on the geochemistry of the waste material (Donovan, 1999).The movement of water through the backfill will be influenced by the material properties over which flow occurs. It is generally expected that the backfilled material will have a higher porosity and permeability as a result of the pore space created during the backfilling process, compared to the host rock.

The effects of increased porosity of a backfilled mine void on hydrogeological regime is described by Du Plessis (2010) as follows:

- An increase in porosity will often result in an increase in transmissivity and storage. The voids created in the backfilled material will act as preferred flow path for water because of the increased transmissivity
- The porosity of the backfill material will influence the time the pitlake will take to decant.

For backfilled material, the recharge characteristics are listed in Table 2-7 below and for this study the recharge percentages are applied to the Kriel, Rooikop and Kleinfontein sites, as they contain backfilled material.

Table 2-7: Water recharge characteristics for opencast mining in the Mpumalanga area (Hodgson and Krantz, 1998)

Water Source	Water into opencast (%rainfall)	Suggested average value (%rainfall)
Rain onto ramped voids	20-100	70
Rain onto not rehabilitated spoils	30-80	60
Rain onto levelled spoils (run-off)	3-7	5
Rain onto levelled spoils (seepage)	15-30	20
Rain onto rehabilitated spoils (run-off)	5-15	10
Rain onto rehabilitated spoils (seepage)	5-10	8
	(% of total pit water)	(% of total pit water)
Surface run-off from pit surroundings	5-15	6
Groundwater seepage	2-15	10

2.9.3 Underground Mine Workings

Recharge into underground workings is important for the Rooikop site as groundwater recharge from the underground mine impacts the water balance of the pit connected to the underground mine.

Table 2-8: Anticipated recharge to bord-and-pillar mining in the Mpumalanga area (Hodgson, 2009)

Description	Recharge as a % annual rainfall
Influx into bord-and-pillar mining > 100 m	1
Influx into bord-and-pillar mining 60-100 m	1.5
Influx into bord-and-pillar mining 30-60 m	2
Influx into bord-and-pillar mining 15-30 m	2.5
Influx into bord-and-pillar mining <15 m	4-6
Recharge to undisturbed Karoo sediments	3

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter contains a discussion of the different methods used for analysis and sample collection employed in this project, including water quality data analysis and interpretation methods. To obtain a holistic understanding of the observed water quality in the pitlake systems, samples were collected from the pitlakes, as well as from the surrounding natural aquifers and backfilled opencast areas. As the pitlakes were investigated as evaporative sinks (or terminal pitlakes) groundwater flow is towards the pitlakes, hence the water qualities of the aquifer, backfilled pit and pitlakes were deemed important in the investigation. In order to include physical and chemical variations of groundwater and the temporal and spatial variations, historical data from monitoring networks and geochemical characterisation of the study areas were obtained from the mines. Information of the pitlakes studied is presented in Table 3-1.

Table 3-1: Pitlakes investigated in the study

Pitlake	Coal Field	Depth	Mining method	Age of pitlake (y)
Bulk Sample	Waterberg	Deep open pit, 70 m	Opencast bulk mining	8
Kriel Colliery Pit 4 (R44, R42)	Mpumalanga	A number of shallow pitlakes varying 5 m to 12 m	Opencast strip mining with concurrent rehabilitation	13
Rooikop	KZN	Single shallow 12 m	Opencast and Underground Bord and Pillar	12
Kleinfontein	Mpumalanga	Shallow, 3.5 m	Opencast strip mining with concurrent rehabilitation	27

3.2 Site Selection

The field study was aimed at collecting information from existing pitlakes that differ in age, size and depth. The site selection was based on the following criteria:

- Stable water level. There should be no pumping of water from or to the pitlake. Also, no interaction between streams, rivers or tributaries with the pitlake.
- Inactive. The pitlake should be situated in an inactive part of the mine.
- Accessibility. The pitlake should be accessible in terms of launching a boat.
- Data availability. Historical monitoring data of water levels and water quality, site characterisation in terms of geochemistry, typically obtained from previous literature of the sites, EMPRs and the mine monitoring networks.
- Pitlake type. Three scenarios exist within the coal mine sites, namely; 1) Single terminal pitlake, 2) opencast rehabilitated with final void left as a pitlake, 3) rehabilitated opencast with final void as a pitlake and hydraulically connected to underground operations.

3.3 Data Collection

The aim was to collect information for all the variables mentioned in Chapter 2, to quantify the parameters for South African coal mine pitlakes situated in the different coal fields. To understand the water balance of the sites under investigation, climatic data and water levels of both the pitlakes and groundwater were acquired.

Site specific climatic data was considered more reliable in terms of calculating the water balances and where unavailable, published values were used.

Data was acquired in hard copy and data formats. A review of Environmental Management Program Reports for each of the mines was completed to extract the required data. Table 3-2 details the data sets and sources.

Table 3-2: Lists of data sets and sources

Data set	Source	Description
Groundwater monitoring data	Mine data bases Mine EMPR's	Groundwater quality. Groundwater levels.
Pitlake monitoring data	Mine data bases	Pitlake chemistry and levels
Climatic data	Mine data bases, SAWS, WR(2012)	Temperature rainfall, evaporation
Dewatering and pumping rates	Mining houses monitoring data bases (only Mafutha)	Monitoring data from dewatering boreholes, pumping rates and water levels
Historical reports	Mining houses and GCS in-house data	EMPRs – Mafutha, Kriel, Rooikop.
Mineralogical and geochemical data of core samples	Literature reviews, previous WRC reports.	ABA from literature of previous studies in the area or relevant coal field. Mineralogical analysis (XRD)
Geological data and maps	Published maps	1:250 000 geological map sheets
Topographical GIS data	Published data	1:50 000 map sheets, DTM data for 5 m contour intervals
Pit DTM	Mine monitoring data bases and pit bathymetric surveys	Detailed XYZ data for opencast area & bathymetric maps of pitlakes
Literature data and analogue values	Various sources referenced, accordingly in text.	Literature reviews and values for sections of missing data were used in some instances.

3.4 Field Investigation

3.4.1 Water Levels

Groundwater levels data gives indicated of the response of the aquifer to mining and the formation of the pitlakes. These data are essential in calculating groundwater inflow to the pitlakes, as well as model calibration and validation. Of the four sites investigated, the Mafutha is the is the only site with pit water level rebound data as well as well as time-series water levels from surrounding shallow and deep boreholes. Time-series pitlake water level LiDAR data was available from 2013 to 2017 for the Kriel site. Sporadic Rooikop pitlake water levels were provided by the mine personnel.

3.4.2 Climatic Data

In groundwater studies, climatic data are used mainly for estimating the seasonal variations and volumes of precipitation which may be available for groundwater recharge (Block et al., 1995). Site specific rainfall data for Mafutha is available. Kriel site rainfall data were only available for 2016 and 2017 and therefore, WR2012 data were relied upon. Rainfall data for Kleinfontein were available from 1984 to 2001 (after which MAP value from WR2012 was also used as a substitute). At Rooikop only the MAP value was used to calculate rainfall contribution to the pit. Average groundwater recharge rates were obtained from WR90 for each site. Annual average rainfall values for the catchments was used to fill the gaps of missing data.

3.4.3 Aquifer Tests

The purpose of the aquifer tests was to determine the aquifer parameters for the groundwater assessment. Aquifer tests involved constant drawdown and slug tests at Mafutha and Kriel Colliery. Data from the EMPR was used for Rooikop. Literature values were used to estimate the Kleinfontein aquifer parameters.

3.4.4 Sampling and Monitoring

The design of a pitlake sampling programme was based on data from the literature studies which identified the critical values to the monitored. The numbers of samples, frequency of sampling, and parameters were identified from the literature study. Guidelines from a series of reports developed by the Centre for Ecosystem Management at Edith Cowan University, Australia were used as a guide for the pitlake monitoring (McCullough et al., 2010). The report includes guidelines on how, where and when to sample, as well as what variables to sample and analyse. In addition, inland lake sampling guidelines from the Ohio EPA (2010) were consulted as an aid to pitlake sampling methodology. Recommendation from both studies were followed in this studies sampling programme.

Groundwater and Pitlake water quality

The purpose of the groundwater and pitlake water sampling was to determine how the pitlake water quality evolved to current water quality in the pitlakes. Water samples were collected from:

- Karoo aquifers at every site
- Backfilled opencast areas
- Pitlakes

The water sampling did not include surface runoff, wall rock runoff or rainfall water quality.
Groundwater samples from boreholes in the undisturbed Karoo aquifer and in the backfilled/ rehabilitated opencast areas were collected by means of through-flow bailers or collected during the pump tests. The bailer was cleaned with de-ionised water before each sample was taken. The samples were stored in 500 ml plastic bottles and transported to the laboratory for analysis. The samples were taken 5 m below the water level, or at fracture levels that had been determined by means of profiling. In addition to the sampling, the water levels and pH, EC and temperature were measured in the field. Additional groundwater monitoring data was obtained from the mining companies as part of the desktop study.

Pitlake sampling methodology involved:

i. Profiles of T, EC, DO, pH and ORP
ii. Inorganic chemistry
iii. Microbiology
iv. Chlorophyll-a

v. Phytoplankton
vi. Secchi disk transparency
vii. Bathymetric mapping

Microbes and phytoplankton are important components of aquatic ecosystems and through their abundance, density and diversity, the health of a water body can be assessed. The phytoplankton and chlorophyll-a were determined as an additional component to the study with the purpose of determining the trophic state of the pitlakes and the diversity of phytoplankton. Phytoplankton have also been shown to reflect changes in environmental conditions, but due to the time series range in sampling of the phytoplankton in the various pitlakes, insufficient data was obtained to make any deductions regarding seasonal variations. Microbial samples were also collected as a once-off sampling at every pitlake, with the main aim of simply determining the diversity of microbes and if there are any differences of dominant microbes between the pitlake.

A series of 5 sample events was conducted for most of the pitlakes namely November 2016, January 2017, March/April 2017, Aug/September 2017 and November 2017. Microbiology sampling was only conducted on one occasion for every pitlake. A summary of data collected at every site visit for the pitlakes is provided in Table 3-3.

Table 3-3: Sampling dates for the pitlakes.

Pitlake	**Sampling Dates**	**Profile conducted***
Mafutha	Jan 2017 Sept 2017 Nov 2017	i, ii, iii, iv, v, vi i, ii, iv, v, vi i, ii, iv, v, vi
Kriel R44 and 2	March to April 2017 Sept 2017 Nov 2017	i, ii, iii, iv, v, vi, vii i, ii, iv, v, vi i, ii, iv, v, vi
Rooikop	Nov 2016 Sept 2017 Nov 2017	i, ii, iii, iv, v, vi, vii i, ii, iv, v, vi i, ii, iv, v, vi
Kleinfontein	March 2017 Sept 2017	i, ii, iii, iv, v, vi, vii i, ii

Pitlake positions where vertical profiling was completed.

Profiling

The purpose of profiling was to determine the vertical variation in temperature, electrical conductivity, dissolved oxygen, redox potential and pH of the pitlakes. These parameters determine the variations in the pitlake chemistry especially pH and ORP as the single most important variables that determine the solubility and mobility of metals in solution. Dissolved oxygen measurements were important, as DO is essential for aquatic life.

The field investigation of the pitlakes consisted of depth profiling and subsequent sampling specific depths. On each sample event at least two profiles were conducted in each pitlake, at the same deepest location and shallowest location. No significant horizontal variation in water quality was observed and as a result vertical changes were deemed more important. Where applicable, monitoring boreholes in the surrounding Karoo aquifer and backfilled pit area were profiled to determine the groundwater physical-chemical parameters.

The following parameters were measured:

- Temperature (T) and Electrical conductivity (EC).
- pH and Redox potential (ORP).
- Dissolved oxygen (DO).

Depth profiles were conducted using an EXO1 (Yellow Springs Instruments, Yellow Springs, Ohio) multiparameter probe with associated field cable and EXO Classic Hand-held device. The method was chosen as it provides benefits such as allowing for in situ measurement of water quality variables and aids in a better understanding of the systems. Advantages of continuous logging with multiparameter probes include the following:

- In situ measurements of variables without errors induced by atmospheric contact and thus measuring true values as they are in the field.
- Several measurements can be done within a relatively short period.
- The profiler is lowered vertically down the water column, waters from different horizons can be measured without induced mixing of the various layers, if they exist (Usher et al., 2003).

The EXO Classic Hand-held equipment was used to configure the EXO1 sonde and to store and retrieve data. A metered rope was used to cross check the depth reading of the bathymetric device. The EXO1 was lowered in 0.3 m intervals to the bottom of the pitlake, and equilibration time of 5 seconds was allowed for the dissolved oxygen readings. Small intervals were used to ensure any changes in the water quality were captured, thereby enabling the identification of the thermocline (which is a change of at least 1°C per change in 1 m). A mounted sonar and GPS were used to locate complete the bathometric survey and to record the coordinates. Manual rowing by a second person ensured that the boat remained stationary for the sampling, ensuring a fixed location for the vertical profile. For the deeper pitlakes, positioning was achieved by 3-point anchoring.

The data was transferred to a personal computer using a KOR-Interface software. The data were exported in Excel from where the water quality variables were plotted with depth to determine inflection points and depths for sampling.

Pitlake sampling

The purpose of pitlake sampling was to determine the inorganic chemistry of the pitlakes situated in the pitlake and to allow for comparison of the chemistry of the pitlakes to the groundwater quality sampled from the aquifer and in the backfilled spoils.

In additionally, secchi depth measurements were taken with every sampling run to measure the transparency (opposite of turbidity) of the water and depth of the euphotic zone. Based on the secchi data, chlorophyll-a and phytoplankton samples were collected using a sampling pump. Some of the pitlakes had high suspended solids from the surrounding spoils, which entered the pitlakes via erosion channels. As a result, the secchi disc measurements were used with caution when determining depths for chlorophyll-a and phytoplankton sampling, as the influence of suspended solids could lead to misinterpretation of the depth of light penetration and thus the algal biomass. For future research, the turbidity of the water could instead be measured by using a turbidity

Sampling for pitlake water chemistry was conducted based on the bathtub model of the Inland Lake Sampling Manual of Ohio EPA (2010). Variations in the water column profiles, especially temperature and electrical conductivity, were used as guides to sampling depths. Significant changes in temperature are indicative of the depth of the thermocline and changes in EC are indicative of a possible isolated bottom layer with elevated TDS relative to the rest of the water column. A modified method of the bathtub model was used where a thermocline was identified as shown in Figure 3-1 and entails:

- three sampling depths, the epilimnion-a surface sample, epilimnion mid-depth and one metre from the base of the epilimnion,
- one sample in the metalimnion and
- three samples in the hypolimnion, one metre from the top of the hypolimnion, hypolimnion mid depth and one metre from the base of the pit.

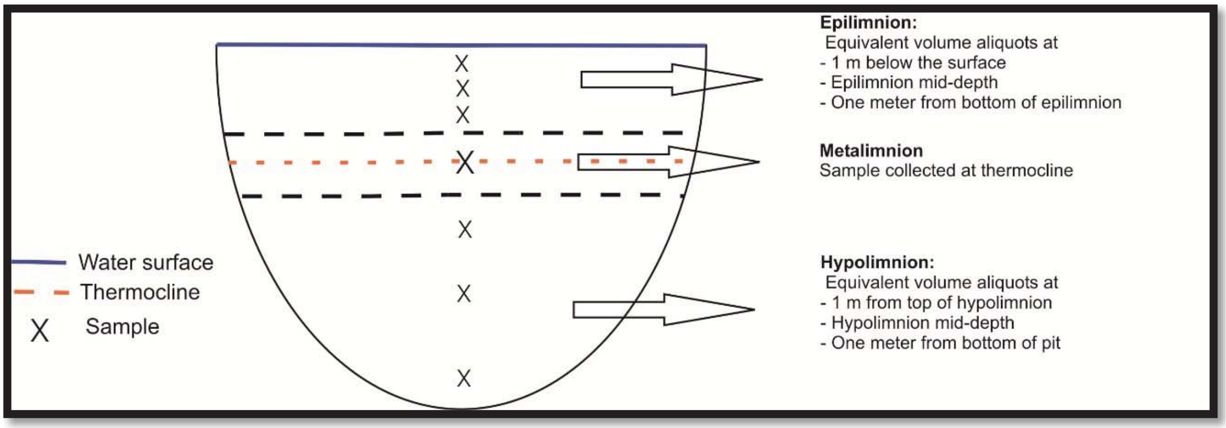


Figure 3-1: Bathtub model for pitlake sampling (Modified from Ohio EPA, 2010).

The sampling device consisted of a Teflon hose coupled to 12 V submersible pump. The samples were collected by lowering the pump to the sampling depth. Sampling containers were rinsed several times with water from the specific sampling depth. The sample for dissolved metal analysis were filtered through 0.45 µm pore size syringe filters into one litre, pre acidified polyethylene bottles. The bottles were filled to the brim, capped, kept at 4°C and transported to the laboratories within 24 h.

Field measurements of each water sample was recorded with a portable, calibrated pH, conductivity and temperature probes. To prevent cross contamination the pumps was run for 3 minutes at each sampling depth, prior to sampling. Sampling equipment was decontaminated between pitlakes.

In summary, the following sets of samples were collected at each depth:

1) a 1 L unfiltered, unacidified sample for pH, EC, alkalinity and major ion analysis;
2) a 1 L filtered (0.45) µm, acidified (1 mL conc. $HN0_3$/100 mL) sample for trace element determinations.
3) a 1 L unfiltered, unacidified sample for the microbiological analysis
4) a 1 L unfiltered, unacidified sample for chlorophyll-a analysis
5) a 100 ml sample for phytoplankton taken at the same depth as chlorophyll-a and preserved with 1% formaldehyde.

Continuous monitoring of pitlake water temperature

The purpose of continuous monitoring of the pitlake temperature in the Mafutha pitlake was aimed at determining the daily and seasonal variations in water temperature and to measure the dates and temperature of the potential inversion in the lake. The Mafutha pitlake was chosen to conduct the continuous temperature monitoring due for the following reasons:

- the pitlake was deep and had a thermocline at 15 m below surface (See Figure 3-2.)
- The pitlake was isolated.

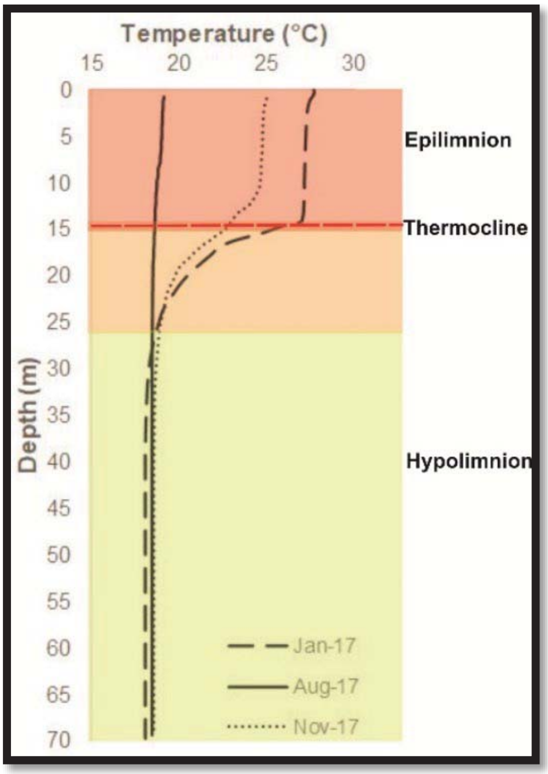


Figure 3-2: Physiochemical profile of Mafutha Pitlake showing the position of the thermocline.

The aim of the study was to determine if the seasonal temperature cycle of the pitlake and whether temperature exerts any control on the chemistry of the water. This was accomplished by the installation of a continuous monitoring system in the Mafutha pitlake from August 2017 to April 2018. The location and depth of the temperature loggers was selected on multiparameter chemical profiles conducted in January 2017. The upper logger situated at 5 m, would define the temperature changes in the top layer (epilimnion) while the second and third loggers, were placed across the thermocline at 15 m and 20 m respectively. The lower temperature loggers were placed in the hypolimnion at 40 m and 60 m.

The monitoring system consisted of a rope with sensors attached at certain depths, extending from the lake surface to the bottom. The loggers used were Onset Hoboware temperature sensors and data loggers. The loggers were attached to the metered rope, which in turn was attached to a surface buoy and a bottom anchor over the deepest point in the pitlake. The buoy was secured with four anchoring ropes attached to the pit walls to minimize both translational and rotational movement (see Figure 3-3). The depth of Hobo Temperature loggers beneath water surface was 5 m (T1), 15 m (T2), 20 m (T3), 40 m (T4) and 60 m (T5). A level logger was placed at 10 m below the water level to determine the water level fluctuations.

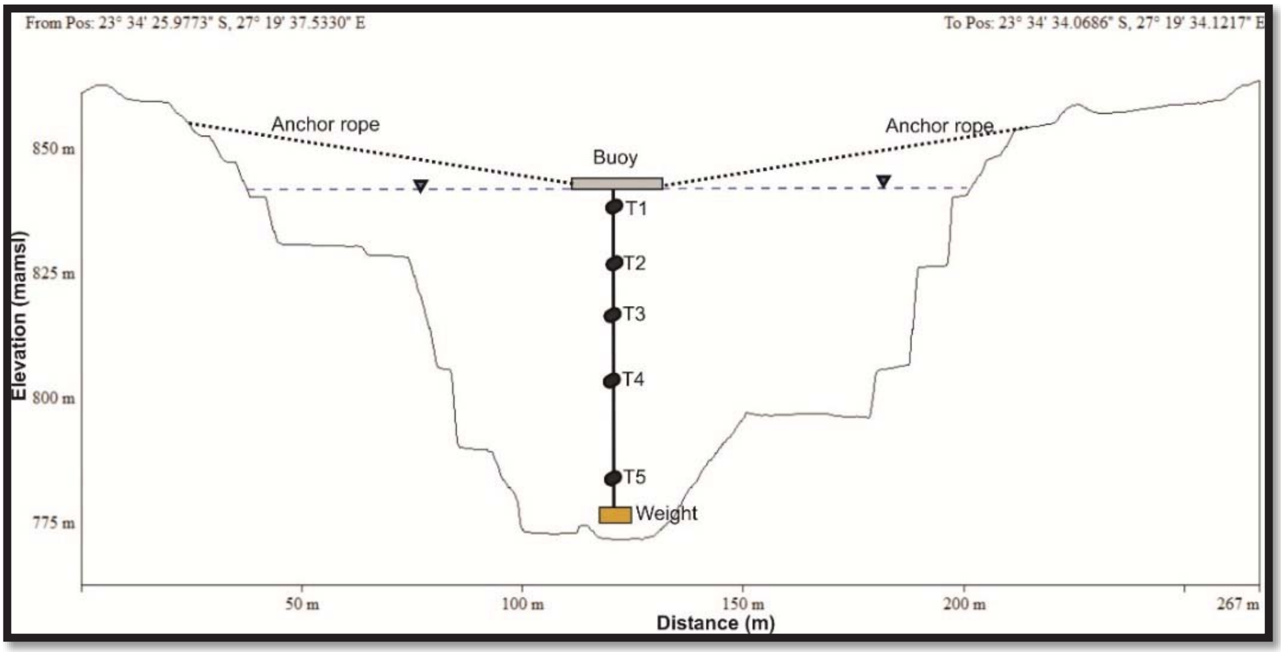


Figure 3-3: Schematic of the Mafutha pitlake temperature measuring system.

3.4.5 Bathymetry

Bathymetric surveys were conducted at each of the pitlakes to determine the pitlake geometry. This enabled locations for profiling and sampling as well the construction of stage curves for water balance calculations. The Lowrance HDS5 Gen 2 echo sounder & chart plotter, along with an HST-DFSBL 600 Watt transducer was mounted onto the vessel and used to continuously log horizontal x and y co-ordinates and corresponding depth z (see Figure 3-4). The system was set to produce sonar-pulses at a frequency of 200 KHz and with a beam width of 8˚ as recommended for relatively smaller, shallow water bodies (Lowrance resources). The internal GPS-system was set to log horizontal co-ordinates using the UTM projected co-ordinate system with the WGS84 reference ellipsoid to ensure that surface and volumetric calculations could be completed in decimal units. The data were then transformed to the Transverse Mercator, Cape 29 model to match the mining companies' survey systems. The semi-ridged inflatable rubber vessel upon which the equipment was mounted, was launched onto the pitlakes for data collection and the vessel was manually powered. The bathymetric models for every pitlake are discussed in each of the case studies.

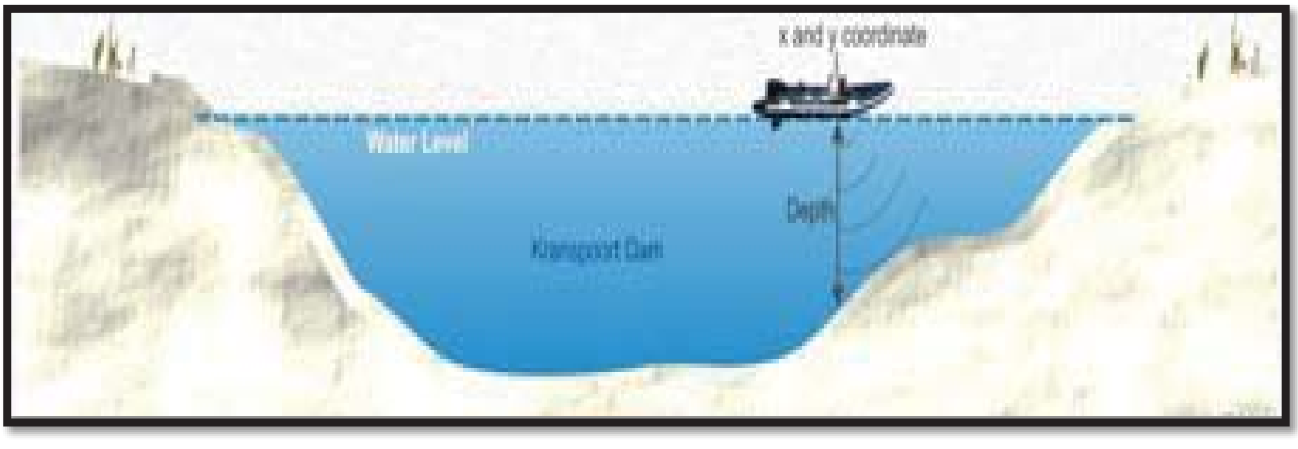


Figure 3-4: Illustration of a bathymetric survey conducted on a pitlake.

3.5 Data Analysis

3.5.1 Aquifer Analysis

The aquifer parameters derived from the pumping and slug testing data were used to in the water balance calculations. Slug test data were analysed using the Bouwer and Rice (1976) method in the FC programme developed by (Van Tonder et al., 2002) to determine hydraulic conductivity of the unconfined aquifers.

$$K = \frac{r_c^2 \ln\left(\frac{R_e}{r_w}\right)}{2dt} \frac{1}{t} \ln\left(\frac{h_0}{h_t}\right) \quad [11]$$

Where:
r_c is the radius of the unscreened part of the borehole where the head is rising
r_w is the horizontal distance from the borehole centre to the undisturbed aquifer
R_e is the radial distance over which the difference in head h_0 is dissipated in the flow system of the aquifer
d is the length of the borehole screen or open section of the borehole
h_0 is the head in the borehole at time $t_0 = 0$
h_t is the head in the borehole at time $t > t_0$

The analysis of the slug test data was based on the following assumptions and conditions (Kruseman and Ridder, 1990):

- The aquifer is unconfined
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the slug test
- Prior to the test, the water table is (nearly) horizontal over the area that will be influenced by the test
- The head in the well is lowered instantaneously at $t_0 = 0$; the drawdown in the water table around the well is negligible; there is no flow above the water table
- The inertia of the water column in the well and the linear and non-linear well losses are negligible
- The well either partially or fully penetrates the saturated thickness of the aquifer
- The well diameter is finite; hence storage in the well cannot be neglected
- Flow to the well is in a steady state

The Pump test data were analysed by means of the (Cooper and Jacob, 1946) and

$$T = \frac{2.3Q}{4\pi\Delta s} \quad [12]$$

Where:
Δs is the change in drawdown over 1 log cycle, Q is the constant discharge rate (m^3/day) and T is the aquifer transmissivity (m^2/day)

The assumptions and conditions for this method are provided by (Kruseman and Ridder, 1990) as follows:

- The aquifer is confined
- The aquifer has a seemingly infinite areal extent
- The aquifer is homogenous, isotropic, and of uniform thickness over the area influenced by the test
- Prior to pumping, the potentiometric surface is (nearly) horizontal over the area that will be influenced by the test
- The aquifer is pumped at a constant discharge rate
- The well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow

The harmonic mean of the calculated aquifer parameters was determined and used as initial input to the models.

3.5.2 Conceptual hydrological Models

Conceptual hydrological models were constructed based on the following features:

- Hydrogeological conditions within the vicinity of the open cast mines,
- Depth and volume of the pitlakes,
- Water levels, and
- Climatic factors

3.5.3 Water Balance Models

Water balance models were developed with the use of Goldsim Academic version 12 to determine the variations volume of water in the pitlakes using climatic and hydrological information (see figure 3-5).

Rainfall data from the mine site, where available, and WR2012, as well as local monthly S-Pan evaporation, and runoff for each site was obtained from the WR90, were input to the hydrological model. Rainfall data were inserted as a time series element. Volumetric contribution values were estimated by making use of the pitlake surface area.

Runoff areas are delineated with the use of digital elevation models with flow direction vectors. Rainfall, together with catchment coefficients and areas over which runoff occurs to calculate the volumetric contribution of runoff.

Monthly S-Pan evaporation and pan factors are inserted in the form of a 'Lookup Table' in the Goldsim program. Lake evaporation in the form of an 'Expression' element is multiplied by the saturated pitlake area to determine the potential evaporation from the pitlake.

The geometry of the pitlake from the bathymetric data were used to develop stage curves in order to determine the relationship between depth, area and volume. The relationship was be nonlinear due to the irregular shape of the pitlakes.

Sensitivity analyses were run for the Goldsim models, where variations in climatic parameters were applied to determine which climatic factor greatly influenced the model. Previous time series water levels were used for calibration purposes, where the data was available.

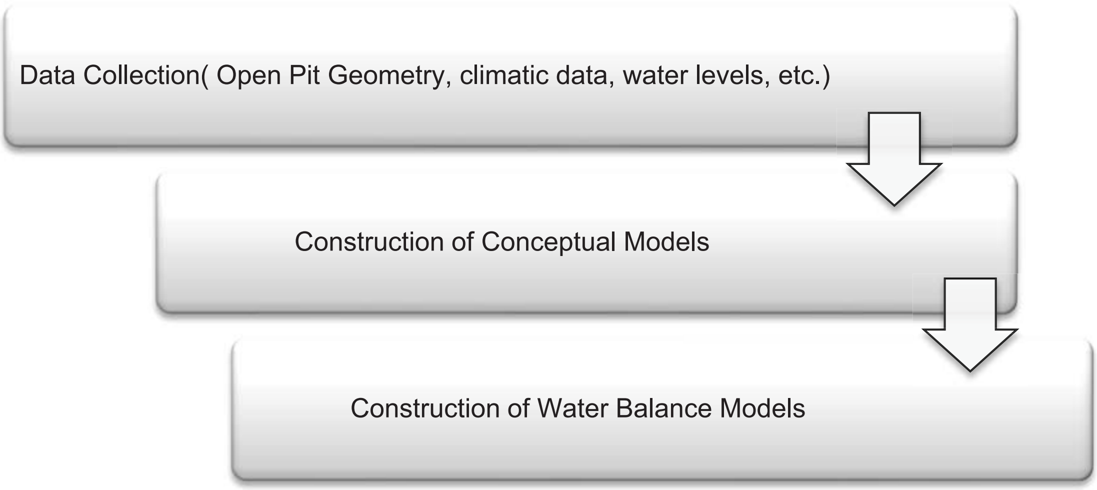


Figure 3-5: Summary of water balance modelling methodology

3.5.4 Geochemical models

Inverse modelling: Saturation index (SI) of pitlake water

The purpose of the calculation of SI for the pitlakes was to determine how the respective pitlakes were saturated in certain minerals and how results might be related to the observed chemical trends seen in other diagnostic plots drawn for pitlake water qualities.

The geochemical code Geochemist Workbench (Bethke, 2018) was used to model saturation indices (SI), where SI for a solid phase is defined as

$$SI = \log (IAP/Ksp) \qquad [13]$$

where IAP is the activity product of the constituents involved in a solubility reaction and Ksp is the solubility product for that reaction (Eary, 1999). The SI output can be explained accordingly:

- Negative SI indicate undersaturation with regards to a particular mineral and potential for dissolution
- SI = 0 indicates saturation for a particular mineral and that it is in equilibrium with the solution,
- Positive SI indicates oversaturation and potential precipitation of a mineral out of solution

The saturation index is used to evaluate the specific processes taking place within a system, by showing the mineral saturation relative to the water.

3.5.5 Water quality analysis

3.5.5.1 Inorganic Chemistry

A full chemical analysis of the sampled waters was performed at Xlab-Earth, a SANAS accredited laboratory. The analysis included dissolved metals, alkalinity, inorganic anions, pH, electrical conductivity and total dissolved solids. Standard APHA (1998) methods were used. Inorganic anions were determined by ion chromatography, while dissolved metals were determined by ICP-OES. Table 3-4 lists the elements analysed. The elements listed cover a wide range and are effective indicators of water quality associated with coal mining. The measurement of the pH indicates the acidity or alkalinity of the water samples, while the EC provides an indication of the overall salt loads of the water, without an indication of type. The water quality determinations were performed using an Inductively Coupled Plasma Spectrometer (ICP). As many constituents were analysed as possible, even though many of the parameters were not critical in terms of regulatory reporting but have the potential to be used in detailed geochemical modelling studies in the future.

Table 3-4: Constituents analysed for during chemical analysis.

Major cations	Ca, Mg, Na, K
Major anions	SO_4, HCO_3, Cl, NO_3, F
Conventional variables	Alkalinity, pH, EC, TDS, total hardness
ICP-OES Dissolved metals scan	Fe, P, S, Si, Ag, Al, As, B, Ba, Cd, Co, Cr, Cu, Li, Mn, Mo, Ni, Pb, Sb, Se, Sn, Sr, Ti, U, V, Zn.
Additional parameters	Total Suspended Solids (Bengtsson), Turbidity

The chlorophyll-a samples were collected and submitted to the Centre of Environmental Management Laboratory of the University of the Free State (UFS) within 24 hours for analysis. A modified method described by Sartory and Grobbelaar (1984) was used to measure chlorophyll-a utilising a VIS-7220 spectrophotometer. This method involves filtering a known volume of water, where after the filter paper was boiled in 10 ml of 95% ethanol at 78 °C. The absorbance was measured at 665 nm and 750 nm with a Philips UV/Visible Spectrophotometer PU8700 Series. After adding 100 µl of 0.3 N HCl the absorbance was measured again after 2 minutes at 665 nm and 750 nm. The following formula was used to calculate chlorophyll-a:

$$\text{Chlorophyll a in extract } (\mu g/L) = (A665 - A665a) \times 28.66 \qquad [14]$$

Where,
A665 = Absorbance of ethanol extract at 665 nm before it was acidified minus the absorbance at 750 nm
A665a = absorbance of the acidified ethanol extract at 665 nm minus the absorbance at 750 nm

The concentration of chlorophyll-a in the original sample:

$$\text{Concentration } (\mu g/L) = \frac{\text{concentration of extract x 10 ml (extract volume)}}{\text{Volume of the smaple in litre}} \qquad [15]$$

3.5.5.2 Phytoplankton analysis

The phytoplankton identification and enumeration were performed by the Centre for Environmental Management at the UFS. The process can be described as follows:

- The dominant algal species were identified with an inverted Zeiss Light Microscope after fixation with formaldehyde (final concentration of 2%) and placed in a sedimentation chamber for at least 24 hours.
- The number of a specific algal species was determined in a known volume of water, counting the individuals (cells, filament and colonies) occurring in 20 blocks of known dimensions.
- The result was multiplied by a constant to obtain the total counts. Algal species were determined as a percentage of the total community.

3.5.5.3 Microbial analysis

Water samples were analysed for microbial diversity using the denaturing gradient gel electrophoresis fingerprinting method. Initial identification of possible micro-organisms present through sequence analysis elucidates possible environmental condition(s). The analyses were conducted by the Department of Microbial, Biochemical and Food Biotechnology at the University of the Free State and included genomic DNA extractions, PCR amplification of the 16S rRNA genes and DGGE analyses (Figure 3-6).

DNA extracts were visualised on a 1% agarose gel stained with ethidium bromide under UV-illumination and the concentration and purity determined using a NanoDrop 3300 fluorospectrometer (Thermo Scientific). 16S rRNA PCR1 was performed on each extracted genomic DNA using a standard procedure developed in the Metagenomics Platform laboratory (SOP_29). The 16S rRNA analyses enabled the identification of specific bacterial species, as well as correlation to broad metabolic groupings. Based on similarity, metabolic capabilities were assigned, and environments identified where these bacteria were prevalent. Results obtained from these studies showed microbial population consisting different types of metabolisms from many different bacterial groups.

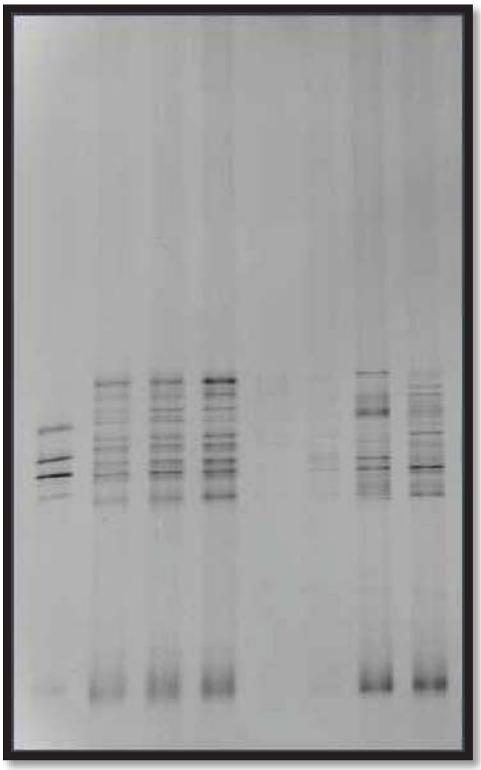


Figure 3-6: Example of a DGGE profile of the partial 16S rDNA products for one of the pitlakes.

3.6 Case Studies

Four case study sites were selected in the Waterberg, Mpumalanga and KwaZulu-Natal coalfields. The sites selected were: Mafutha near Lephalale, Waterberg Coalfield in the Limpopo Province; Pit 4 of Kriel Colliery, near town of Kriel and the Kleinfontein mine near Middelburg in the Witbank-Mpumalanga or Highveld coalfield. A fourth site, Rooikop, was selected to represent pitlakes in the KwaZulu-Natal coalfield. The Rooikop site is situated near the town of Piet Retief, Mpumalanga and geology is typical of the Natal coalfields. The characters if each of the pitlakes is discussed for each site:

- Mafutha
- Kriel
- Kleinfontein
- Rooikop

The location of the sites is shown in Figure 3-7. The sites are situated in the Ecca Group of the Karoo Supergroup, where the coal occurs in the Vrhyheid formation in the Main Karoo basinand the Grootegeluk and Vryheid formation in the Waterberg coalfield.

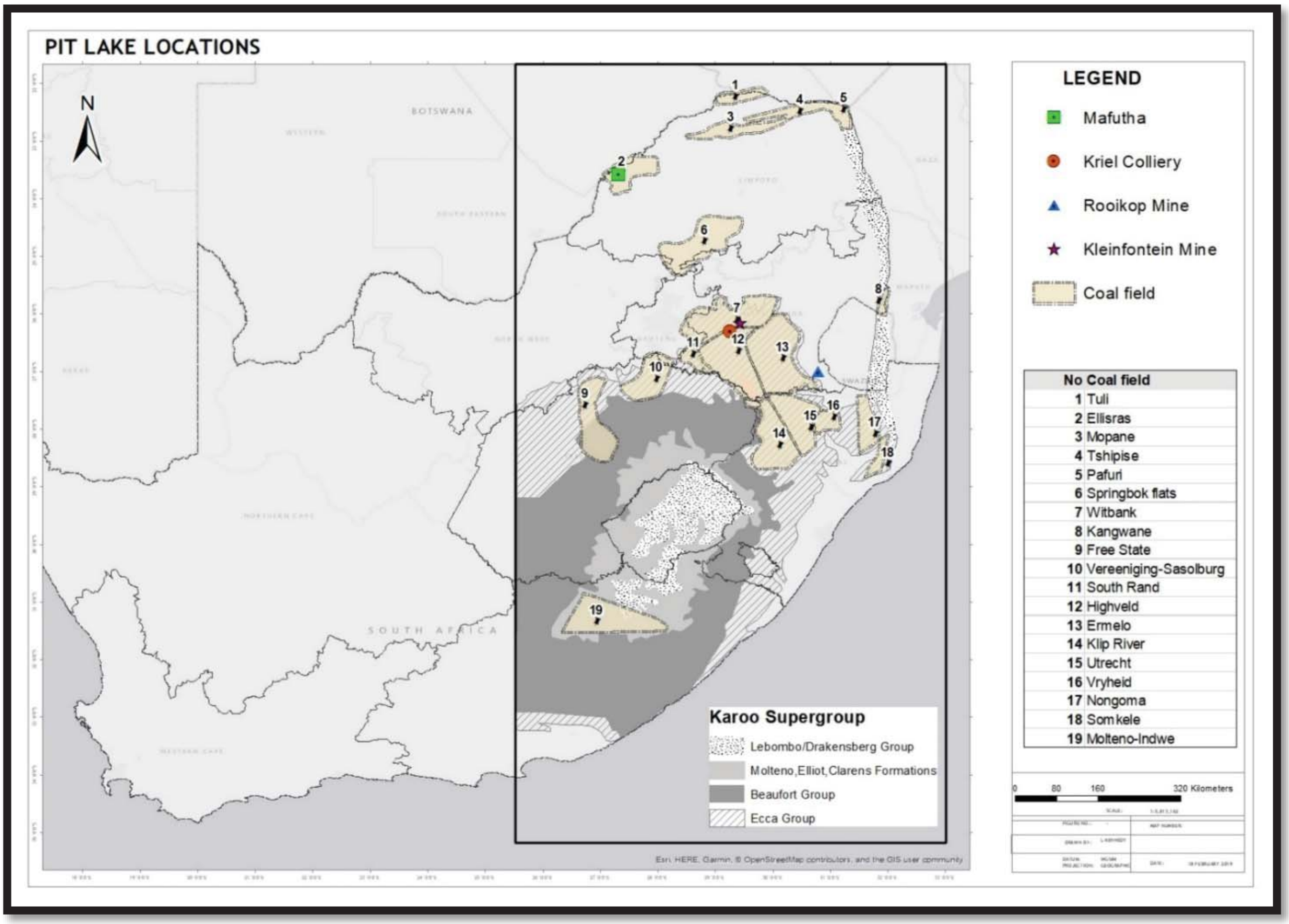


Figure 3-7: Site Locations (Modified from Snyman, 1998).

CHAPTER 4: MAFUTHA PITLAKE

4.1 Introduction

Mafutha pitlake (27° 19' 36.7" E; 23° 34' 21.1" S) is situated on the farm Groenfontein, approximately 40 km to the west of Lephalale, 30 km to the west of Grootegeluk mine, 10 km north of the town of Steenbokpan and close to the RSA/Botswana Border at Stockpoort. The location of the site is shown in Figure 4-1. The study area falls within the Waterberg coal field, in the north western part of the Limpopo Province, South Africa. General activities in the surrounding the site are agriculture and game farming.

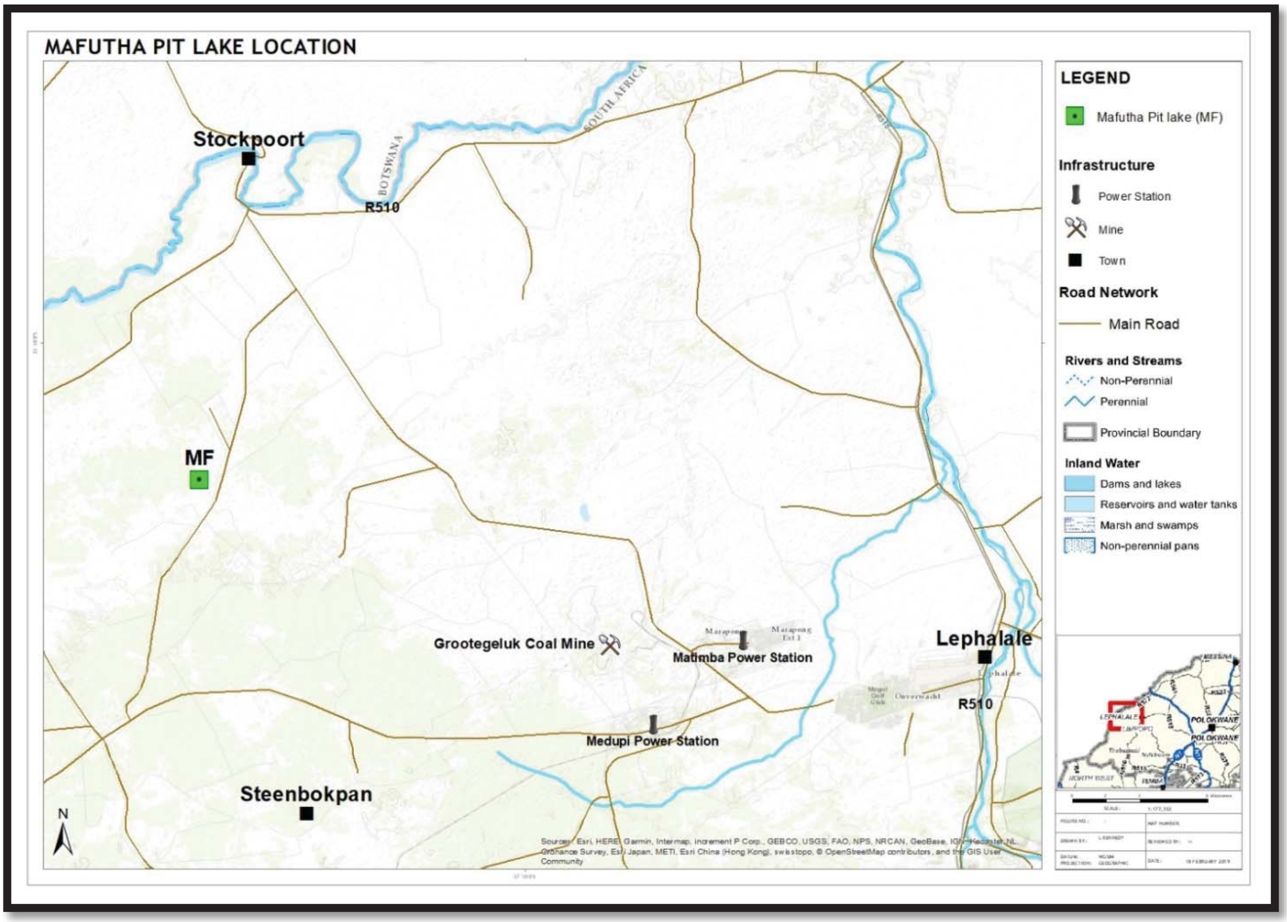


Figure 4-1: Location of Mafutha Pitlake.

A groundwater monitoring program was implemented at the Mafutha from 2008 to evaluate and monitor groundwater quality and levels. The monitoring boreholes consisted of three groups: shallow dedicated monitoring boreholes 30 m boreholes: G250607 to G250614 located around the pit and discard dumps. Deep 200 m monitoring boreholes around the pitlake boreholes namely G250705, G250706 and G250757. And regional deep hydrocensus boreholes located further from the pitlake, on neighbouring farms and of which only the coordinates are provided. The location of the pitlake and monitoring boreholes on the farm Groenfontein and surrounding farms is shown in Figure 4-2 and borehole data on Tables 4-1, 4-2 and 4-3.

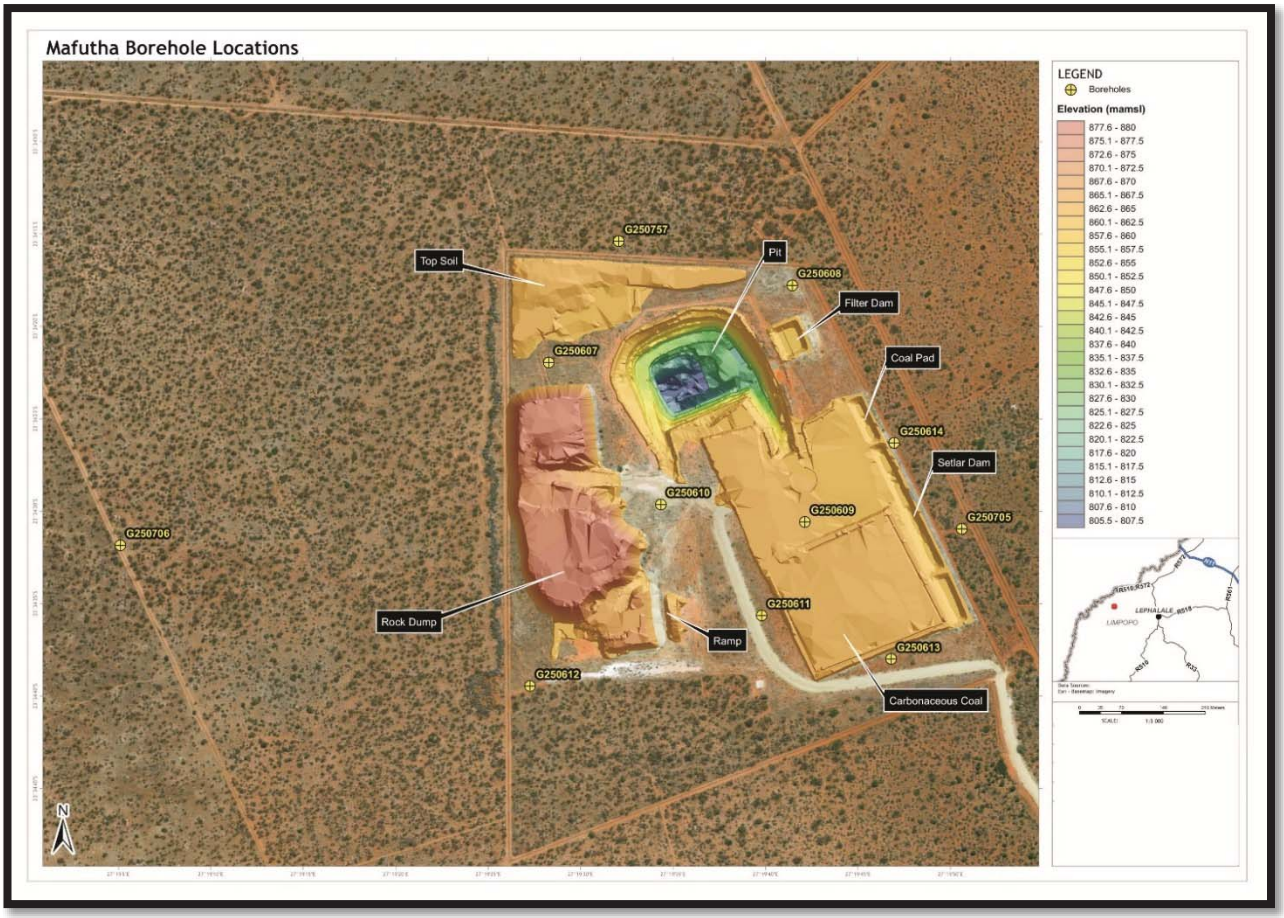


Figure 4-2: Mafutha Pitlake: Topography and location of monitoring boreholes.

4.2 Mining

Mafutha pitlake originated as a result of an open cast bulk mining operation. This mining entailed the removal of all material from a single open pit, selection of material for processing and all the remaining waste material placed on waste dumps outside the mine void. No backfilling was undertaken. The mining allowed for a 40 m by 40 m bulk samples to be taken from the various coal horizons to a final 96 m. The coal samples were beneficiated at the Grootegeluk mine. A total of 1 500 000 m^3 of material was removed from the pit of which consisted of topsoil overburden and a total of 966 000 tons of coal. The mining took place from August 2009 to May 2010. On completion of mining the equipment was removed and the dewatering was terminated allowing the pit allowed to fill with water. Filling occurred groundwater flow along preferential flow paths and along bedding plane fractures, with the net groundwater gradient being towards the pit (Plate 1). Steady state was reached in 2013 at a level of 841 mamsl (Plate 2).

Figure 4-3: Mafutha Pitlake: Pit during operation in 2009.

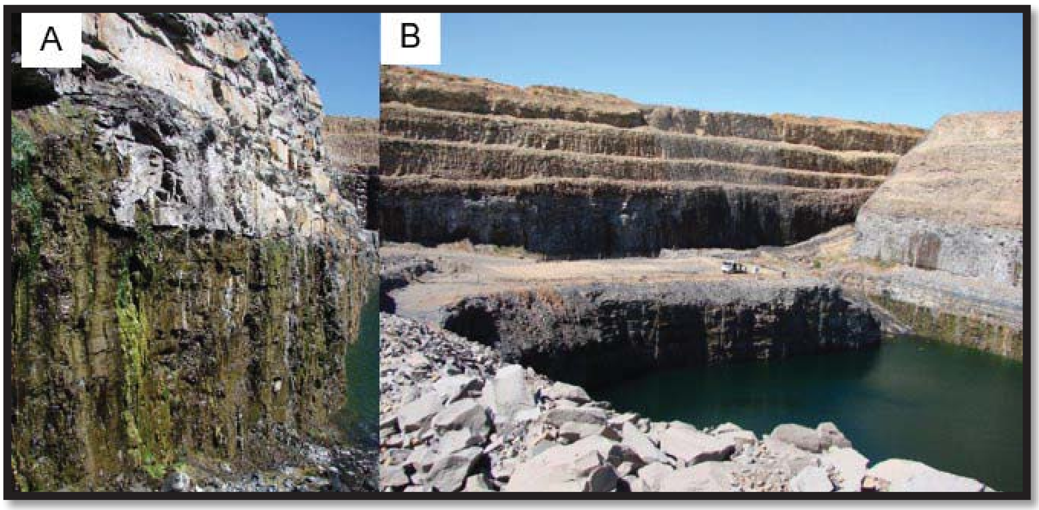


Plate 1: Mafutha Pitlake: Seepage through bedding plane fractures on the pit walls during lake filling (photo courtesy of Botha, 2012).

Plate 2: Mafutha Pitlake: Current status at steady state water level (looking east, September 2018).

4.3 Topography and Drainage

The topography has gentle undulations and shallow drainage lines which flow in a north easterly direction towards the Limpopo River, which is situated approximately 20 km west of the study area. The area is relatively flat with an average slope of 0.25° towards the northeast. The highest and lowest elevation within the study area is 940 mamsl and 820 mamsl respectively, with an average elevation of 868 mamsl.

The study area is situated within the A41E quaternary catchment, which falls in the Limpopo Water Management Area (WMA). The A41E quaternary catchment has an area of 816 km^2 and drains to the Limpopo River.

4.4 Pitlake Morphology

The Mafutha pit has a depth of 89.73 m with the lowest elevation of 771.5 mamsl and a top elevation of 861.23 mamsl. The pit has a surface area of 45 948 m^2. A bathymetric map for the pitlake is provided in Figure 4-4.

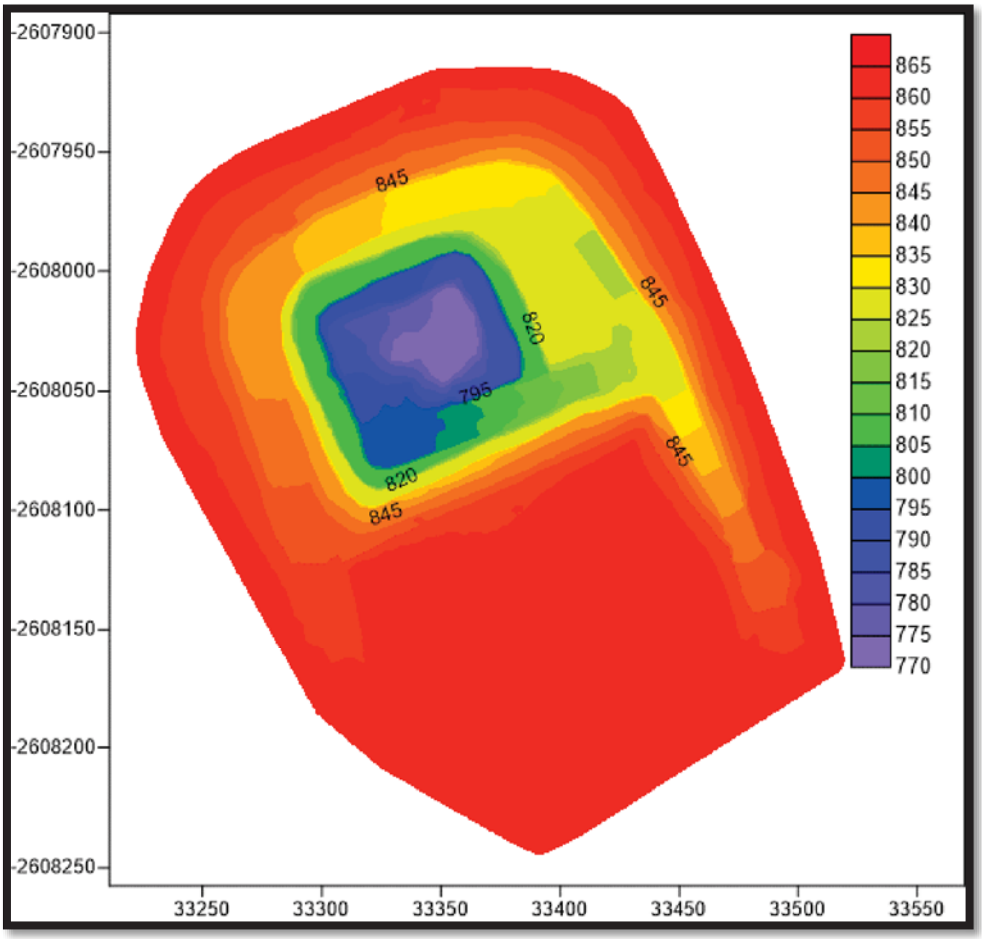


Figure 4-4: Mafutha Pitlake: Bathymetry.

4.5 Geology and Structural Geology

The Mafutha pitlake is situated in the Waterberg coalfield which comprises the Beaufort, Ecca and Dwyka Groups of the Karoo Supergroup. The published A 1:250 000 Geological map of the area is provided in

Figure 4-5. The Beaufort Group has a thickness of approximately 70 m, entirely composed of variegated mudstones and is represented by the Eendragtpan Formation at Mafutha.

The Ecca Group is represented by the Grootegeluk and Vryheid Formations. The Grootegeluk Formation is approximately 60 m thick and is comprised of coal, carbonaceous shale and mudstones. The Grootegeluk Formation is an important unit due to its numerous thick coal seams. The Vryheid Formation underlies the Grootegeluk formation and is approximately 50 m thick, consists of alternating layers of sandstones and siltstones containing coal seams.

The Dwyka Group is represented by the Waterkloof and Wellington Formations. The formations vary in thickness, deepening towards the south-east of the Ellisras Basin. The formation consists horizontally laminated mudstone and siltstone.

The study area is faulted with three major faults and multiple minor faults. The major faults are the Eenzaamheid, Daarby and Zoetfontein faults. The Zoetfontein fault occurred pre/during Karoo depositional tectonism, whilst the Eenzaamheid and Daarby faults resulted from post-Karoo depositional tectonism (Bester and Vermeulen, 2010). The Eenzaamheid fault separates the Karoo Supergroup from the Mokolian Supergroup. The Eenzaamheid fault has a throw of 250 m to the north bringing the upthrown Waterberg Group on the southern side of the fault into contact with the downthrown Beaufort and Ecca Groups on the northern side of the fault (Bester and Vermeulen, 2010). The Daarby fault has a displacement of 200 m to 400 m and divides the coal seams into a shallow opencast mineable western area and a deeper eastern area where the seams will have to be extracted by underground methods (Deysel, 2015). The Mafutha pitlake and Grootegeluk coal mine are located in the shallow opencast minable part of the Waterberg coalfield.

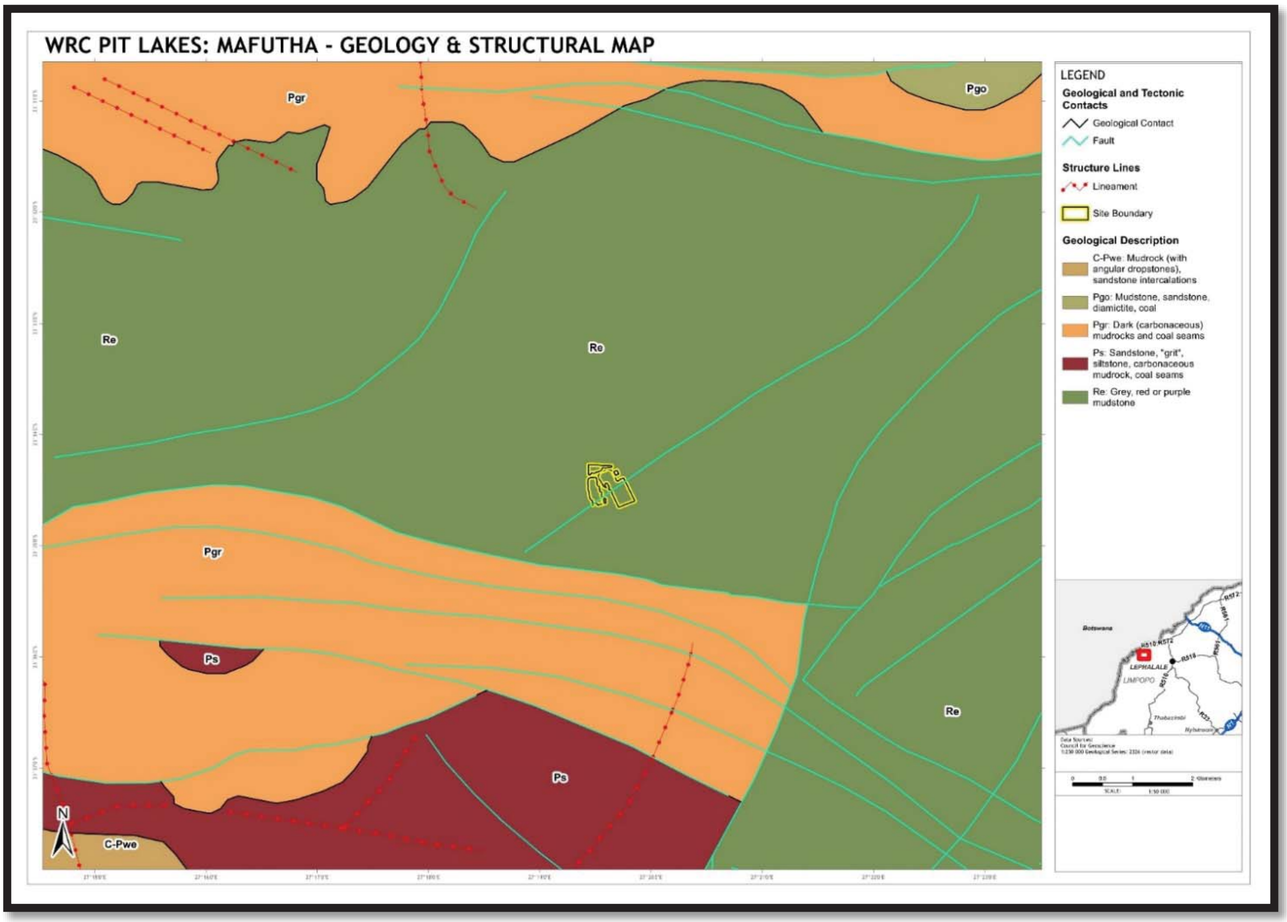


Figure 4-5: Mafutha Pitlake Geology

In the Waterberg the coal is mined in benches with Bench 1-5 in the upper zone (Grootegeluk Formation) and Bench's 6-11 in the Vryheid formation (Figure 4-6Figure 4-6:). The Grootegeluk coal mine is currently the largest operating coal mine in the Waterberg coal field, where benches 2, 3, 4 yield coking coal on beneficiation, while bench 5 produces a thermal grade coal, which has high phosphorous, and benches 6-11 are dull coals and are highly interbedded with mudstone and carbonaceous mudstone. Generally, the run-of-mine coal in these zones has high ash content, ranging from 45% to 65% and has to be beneficiated to obtain a blend of coking coal and middling suitable for power generation (Bester, 2009; Hancox and Götz, 2014). The high number of mudstone intercalations also result in higher beneficiation required for the coal (Deysel, 2015).

At the Mafutha Mine site, the coal was mined to the bottom of Bench 5, which included Zone 11 to 5 and comprised intercalated coal and mudstones of the Grootegeluk formation (Upper Ecca). The coal zones were overlain by a weathered overburden layer of up to 8 m thick, followed by a well-developed mudstone layer of the Eendragtpan Formation (Beaufort Group) of up to 25 m thick. The mine reached a depth of 96 m below the surface.

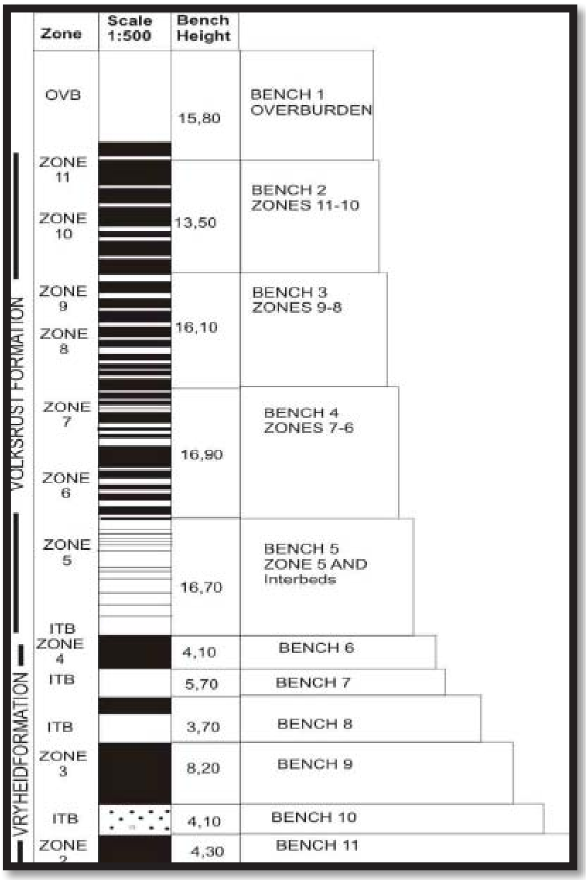


Figure 4-6: Generalised stratigraphic column of the coal bearing intervals of the Waterberg coal field ITB= Interburden; OVB = Overburden (From Deysel, 2015).

4.6 Mineralogy and Geochemistry

The main rock types in the area are purple/green mudstone, shales and white Ecca formation sandstones. These formations are divided into different layers, and the coal is intermixed with the mudstones and shale (Bester, 2009). Deysel et al. (2014) conducted mineralogical analyses on samples from the farms Groenfontein, as well as on two neighbouring farms (Grootwater and Welgelegen). From results of her study Deysel (2015) identified the dominant geological units that have an acid producing potential as the sandstone and the coal units. These units consist of quartz, kaolinite, muscovite, pyrite, siderite and rutile. The mudstone and shale units all showed a neutralising potential and the minerals identified within these units included quartz, kaolinite, muscovite, pyrite, hematite, marcasite and calcite (Deysel et al., 2014). Nevertheless, overall, the majority of 232 tested samples were classified as having a neutralising potential ratio (NPR) of less than 1, implying that the samples have a high potential for acid generation (Deysel, 2015).

Geochemical data for the site obtained from SASOL mining indicated the run-of-mine coal of the deeper Vryheid formation (zones 4A, 4, 3 and 2) generally comprise higher pyritic sulphur content (0.5% to 4.6%) than the upper zones of the Grootegeluk Formation (zones 11-5) (0.1% to 1.5%), also indicating the possibility of a higher acid potential of the deeper coal as seen in Figure 4-7. The Mafutha pit was mined up to a depth of 96 m, which according to exploration logs drilled prior to mining, indicates mining up to zone 5 of the Grootegeluk coal formation. Acid Base Accounting (Deysel, 2015) and detailed sulphur analysis for the Mafutha is documented in Appendix I.

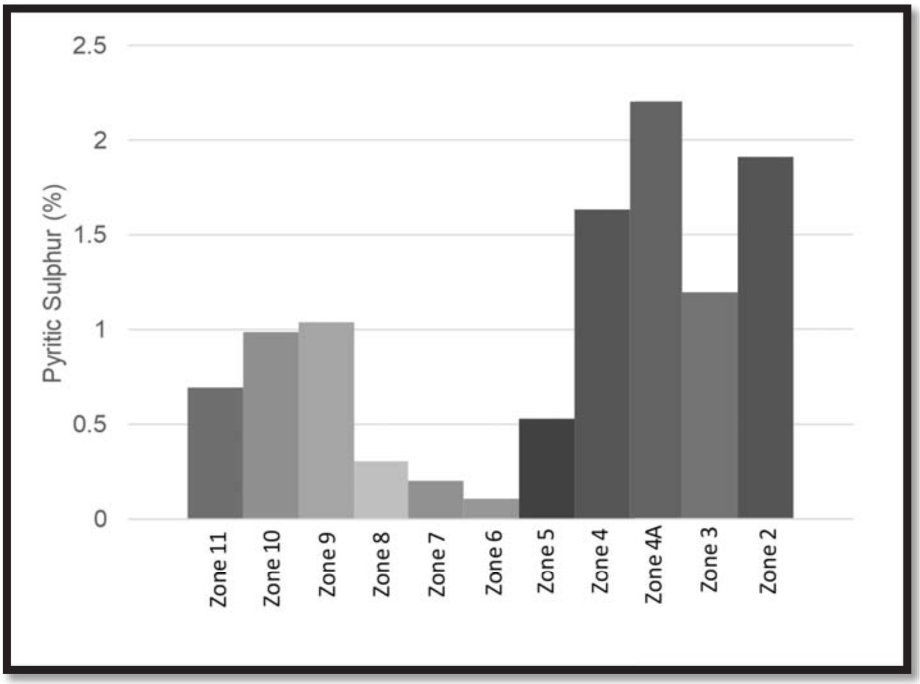


Figure 4-7: Mafutha Pitlake: Pyritic sulphur (%) content of the Grootegeluk and Vryheid coal zones. Coal zones 11 to 5 mined from the Mafutha pit.

A profile of pyritic sulphur from samples analysed by SASOL of core borehole G250006, with the depths (in mamsl) of the coal zones is shown in Figure 4-8. The samples consisted of intercalated coal and mudstone. The highest pyritic sulphur content seems to occur in the contact between coal zone 10 (C10) and coal zone 9 (C09), with 1.5%S. Coal zones 10, 11 and the contact between the overlying mudstone layer (Eendragtpan formation) also showed %S of higher than 1. The overburden comprises a weathered zone of 20-30 m dominated by clay soils with smectite and kaolinite. Samples with S% > 0.3% usually have a high potential for generating acidity (Deysel, 2015). Most of the samples plotted in Figure 4-8 show a potential to generate acid with associated secondary products, such as sulphate, when neutralised.

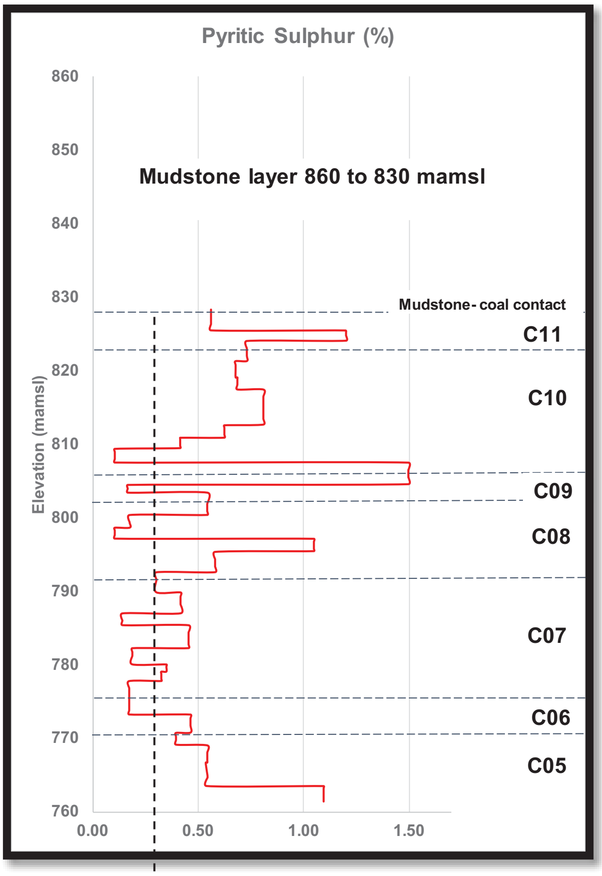


Figure 4-8: Mafutha Pitlake: Profile of pyritic sulphur, sampled and analysed from borehole log G250006

4.7 Hydrogeology

Two aquifers are present in the study area, namely the shallow weathered aquifer and the deeper fractured aquifer. The upper weathered aquifer is associated with the weathered horizon and usually 5-25 metres below ground level (Bester, 2009). The aquifers are recharged by rainfall with recharge estimation for the catchment of 1.6% of the MAP (7 mm). The fractured bedrock aquifer has lower aquifer properties than the upper weathered aquifer. Most groundwater movement occurs along fractures and bedding planes (Hodgson, and Krantz, 1995). These structures are better developed in sandstone resulting in higher yields from borehole in the sandstones (Vermeulen et al., 2011).

Groundwater Levels

The depth to groundwater was obtained from monitoring boreholes within and close to the mining area. Eight shallow boreholes drilled into the weathered aquifer located within the vicinity of the open pitlake were accessible for measurement and the water levels ranged between 2.65 and 22.17 mbgl with an average water level of 18.07 mbgl. Table 4-1 shows the borehole information while Figure 4-9 shows the variation in water levels of the boreholes drilled into the shallow weathered aquifer. Elevated water levels are observed in boreholes G250607 and G250610 which are situated near the waste rock dump. The greater porosity and hydraulic conductivity plus the lack of vegetation increases the rate of recharge through the waste rock dumps resulting in a groundwater mound. Data from the deep boreholes is shown in Table 4-2: with the time-series water levels in Figure 4-10. Data of borehole water levels from neighbouring farms is shown in Figure 4-11; the data shows that the water levels in the regional boreholes were not affected by mining activities.

Table 4-1: Shallow Boreholes information (LO27 Cape Datum)

BH I.D	Longitude	Latitude	Surface elevation (mamsl)	Collar Height (m)	BH Depth (mbgl)	BH Depth (mamsl)
G250607	33128.95	-2608007.46	861.23	0.3	30.54	830.69
G250608	33502.66	-2607880.01	861.12	0.28	30.44	830.68
G250609	33521.43	-2608273.74	862.85	0.3	30.57	832.28
G250610	33300.33	-2608244.16	861.54	0.315	30.51	831.03
G250611	33454.53	-2608429.4	862.12	0.3	30.49	831.63
G250612	33099.26	-2608546.2	861.66	0.26	30.5	831.16
G250613	33652.9	-2608502.33	861.43	0.22	30.46	830.97
G250614	33658.29	-2608142.61	861.4	0.22	30.51	830.89

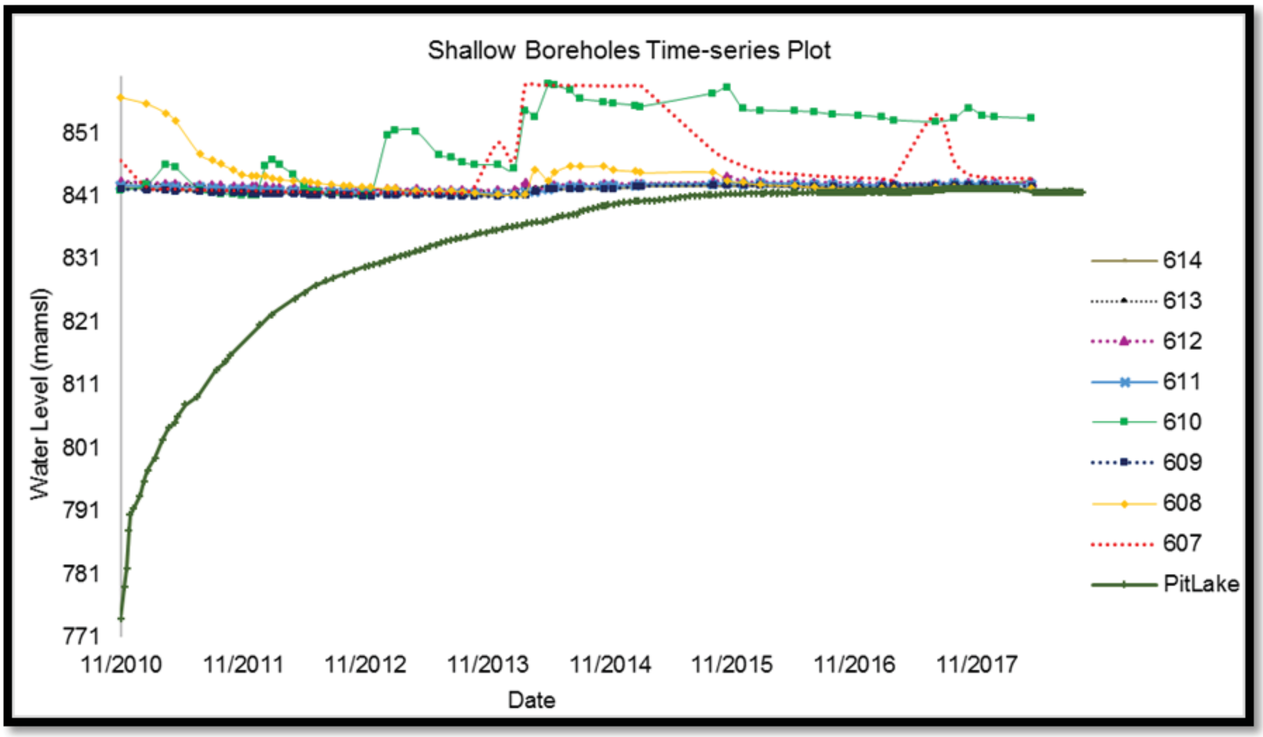


Figure 4-9: Mafutha Pitlake: Water levels in the shallow boreholes and the pitlake.

Table 4-2: Deep Boreholes Information (LO27 Cape Datum)

BH ID	Longitude	Latitude	Surface Elevation (mamsl)	Collar Height (m)	BH Depth (mbgl)	BH Depth (mamsl)
G250705	33761.85	-2608286	861.33	0.3	189.75	671.58
G250706	32471.39	-2608310	860.97	0.32	191.15	669.82
G250757	33236.85	-2607806	860.98	0.34	177.7	683.28

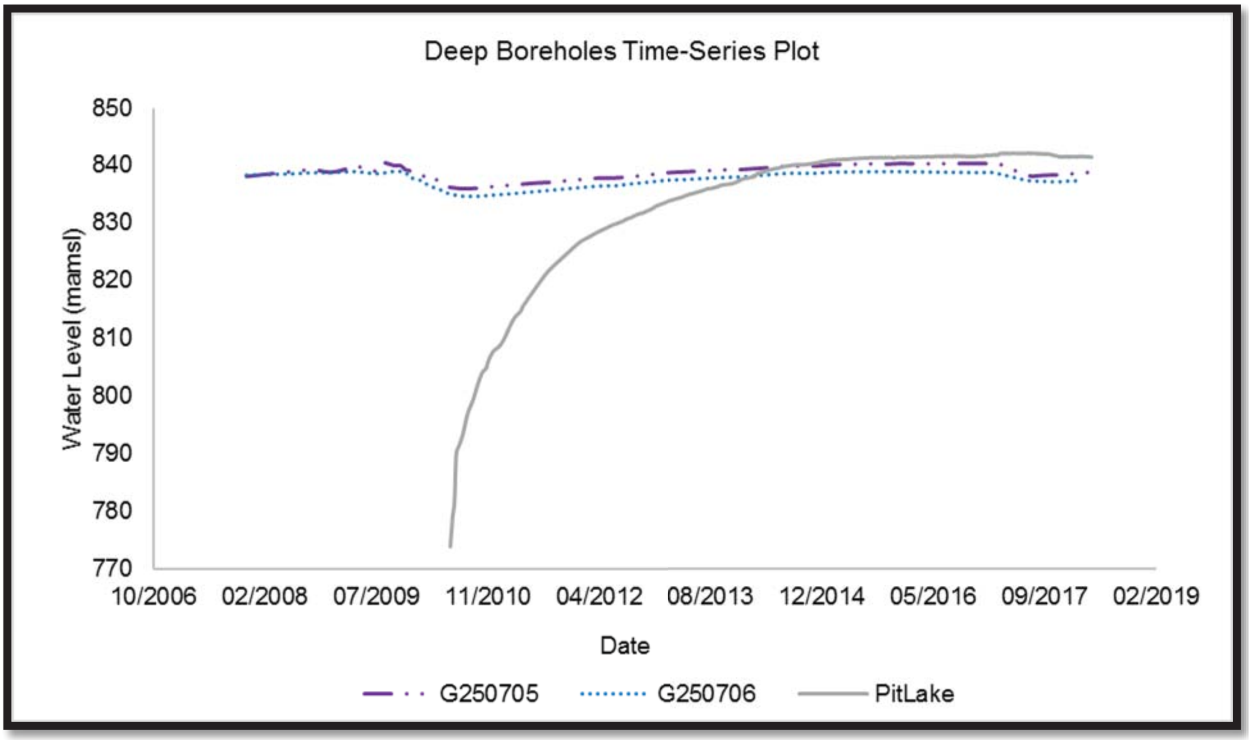


Figure 4-10: Mafutha Pitlake: Time-series plot for deep boreholes and pitlake rebound.

Table 4-3: Neighbouring Farms Monitoring Boreholes (LO27 Cape Datum)

Site Name	Latitude	Longitude	Surface Elevation (mamsl)	BH Depth (mbgl)	BH Depth (mamsl)
G218714	-2605554.53	35565.19	855.60	150.45	705.15
G250703	-2607539.56	31981.26	858.49	166.35	692.14
G250705	-2608285.88	33761.85	861.33	189.75	671.58
G250706	-2608310.30	32471.39	860.97	190.12	670.85
G250720	-2610894.54	34889.06	869.77	156.30	713.47
T261714	-2612346.28	32181.56	875.09	191.00	684.09
W228701	-2603754.58	31744.53	843.47	174.45	669.02
W228709	-2604792.05	34048.94	852.17	162.83	689.34
W228710	-2605799.15	32678.54	853.42	168.56	684.86
W228723	-2606656.01	34466.64	857.98	153.30	704.68
W228724	-2607123.35	34002.14	859.22	170.40	688.82
W228726	-2606436.40	34682.98	857.82	160.49	697.33

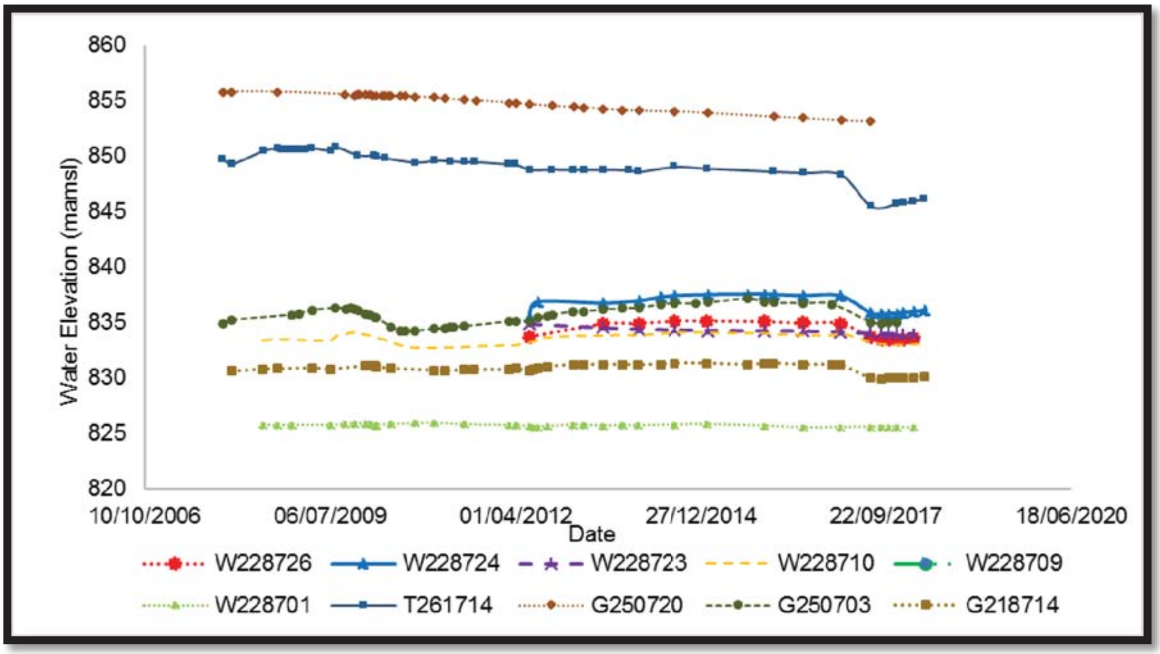


Figure 4-11: Mafutha Pitlake: Time-series data of neighbouring farms' boreholes

A good relationship exists between the topography and ambient groundwater level, as shown in Figure 4-12 below. Figure 4-13 and Figure 4-14 are the groundwater flow maps for both the weathered aquifer and the fractured aquifer respectively. A groundwater mound near the waste rock dump WRD is evident. Figure 4-15 is a time-series plot of pitlake water level and rainfall graphs to determine a relationship between rainfall and pitlake levels

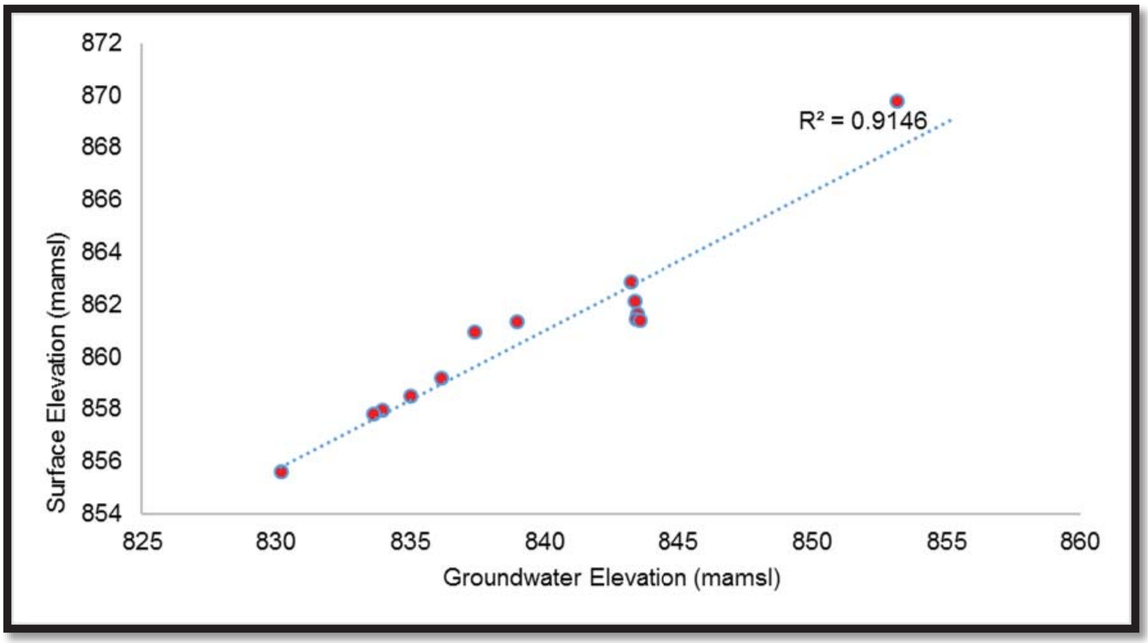


Figure 4-12: Mafutha Pitlake: Bayesian Analysis.

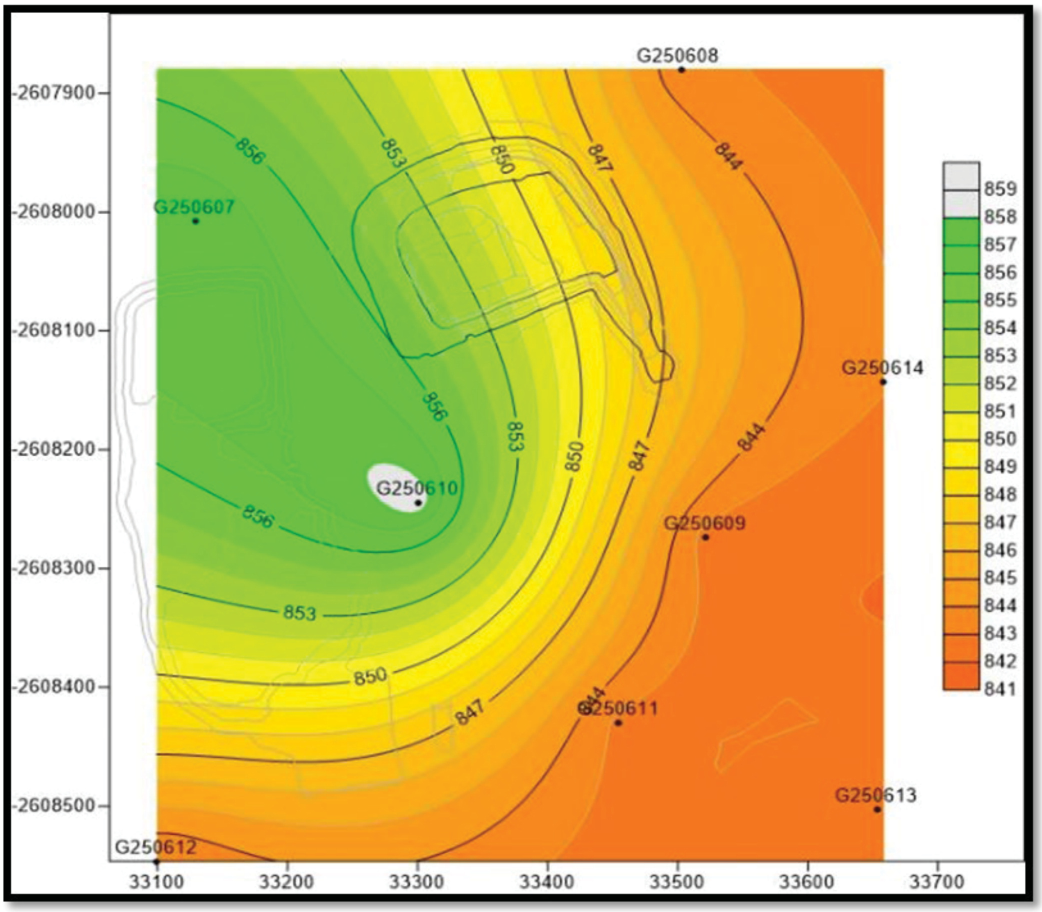


Figure 4-13: Mafutha Pitlake: Weathered aquifer piezometric levels.

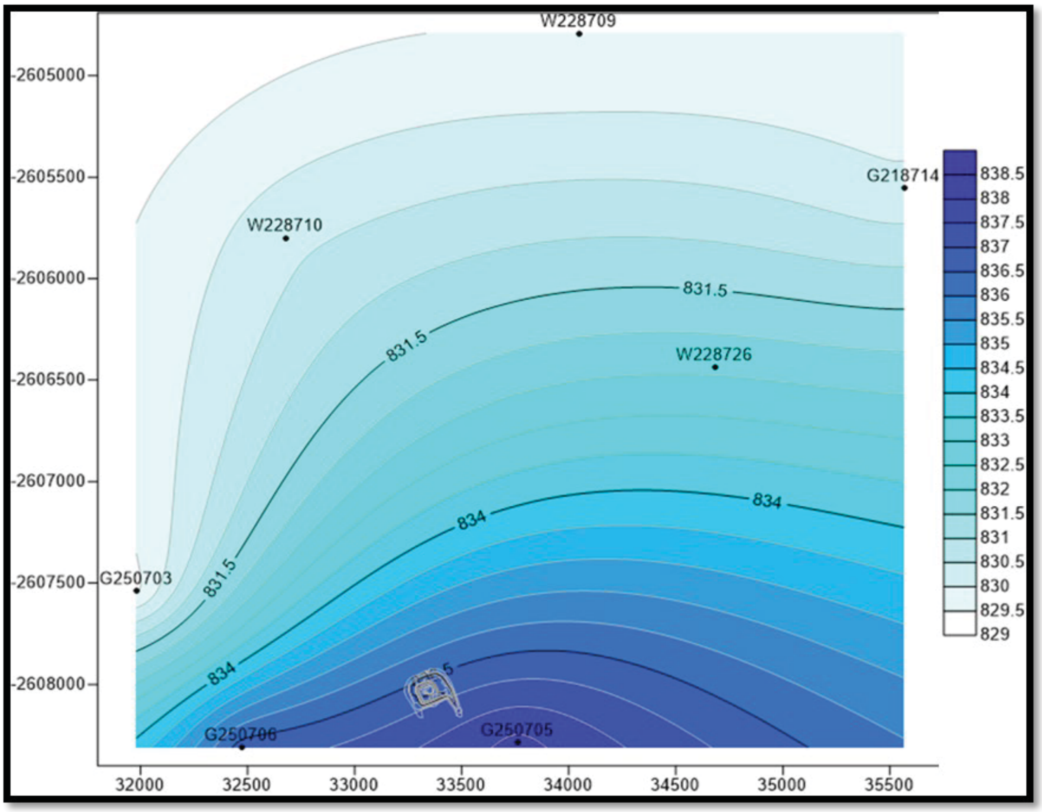


Figure 4-14: Mafutha Pitlake: Fractured aquifer groundwater flow.

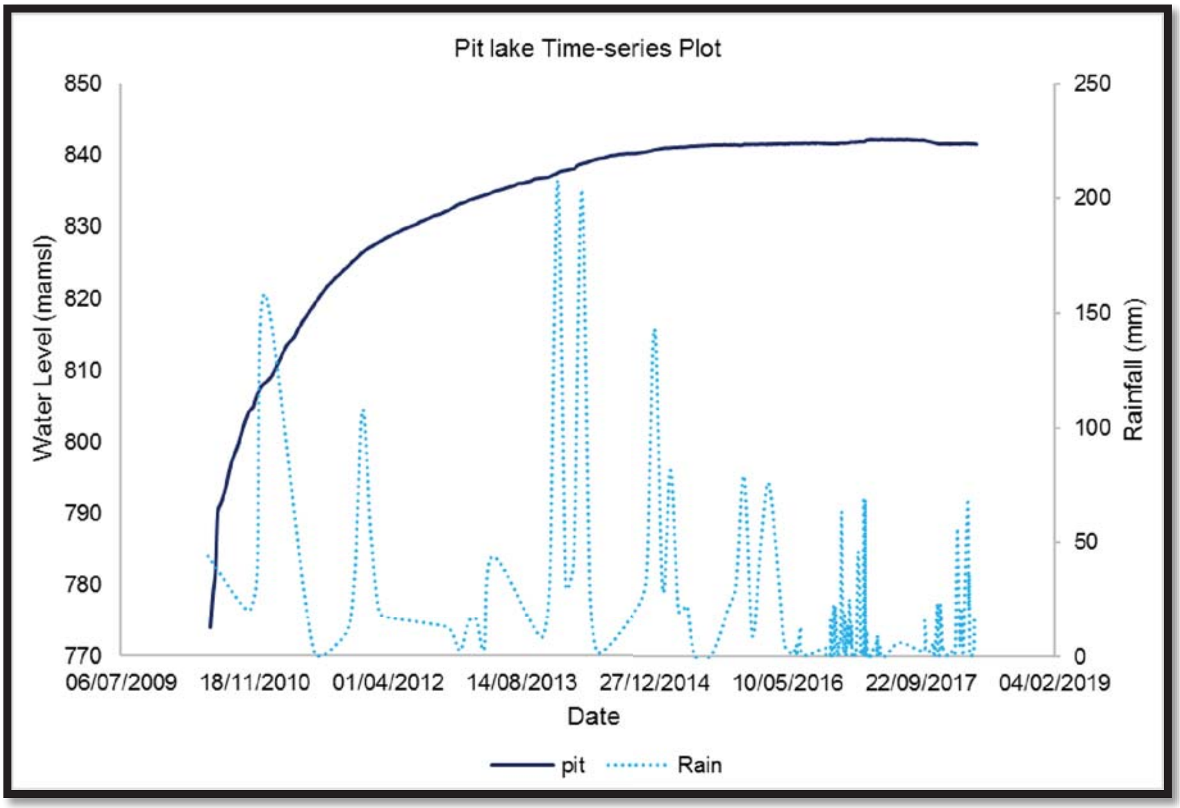


Figure 4-15: Mafutha Pitlake: Water levels and rainfall.

Aquifer Tests

Pump testing was conducted on the three fractured aquifer boreholes. A harmonic mean transmissivity value of 7.7 m^2/day was obtained from the analyzed data, from which a hydraulic conductivity value was estimated and served as a base for model calibration. Recovery data of boreholes G250706 and G250757 were used as they were more reliable than the pumping data.

4.8 Conceptual Hydrogeological Model

There are two aquifers at Mafutha; the shallow weathered aquifer and the deeper fractured Karoo aquifer. The conceptual hydrogeological model is shown in figure 4-16. Four minor faults bound the Mafutha pitlake from the north, east, south and west which serve as preferred pathways for the groundwater flow.

The total excavated volume of the pit is approximately 1 021 600 cubic metres and has a depth of approximately 90 m. A rock dump with an area of 70 092 m^2 and is covered with rocks and comprises approximately 50% coal, is located south west of the pitlake. A filter dam with an area of 3 575 m^2 is located north east of the pit, and a settler dam and coal pad are located south east of the pit with areas of 13 695 m^2 and 41 820 m^2 respectively.

Mafutha pitlake is a standalone pitlake which has not been backfilled and therefore the water balance equation uses the following components:

$\Delta S = GW_{in} + P + R + R_{in\text{-}pit} - E$

Where:

ΔS is the change storage, GW_{in} is the groundwater inflow, P is precipitation is the additional recharge over the waste rock dump, $R_{in\text{-}pit}$ is the runoff from pit walls and E is evaporation.

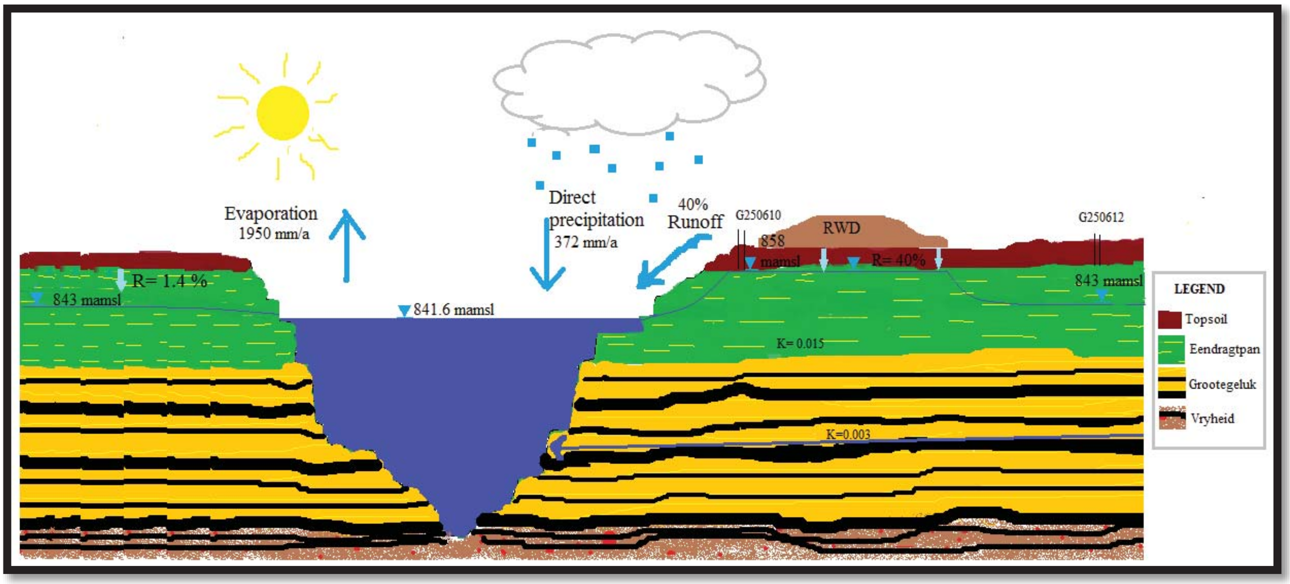


Figure 4-16: Mafutha Pitlake: Conceptual hydrogeological model.

4.9 Conceptual Hydrogeological Model of the Mafutha Pitlake

Rainfall

The A41E catchment has a MAP of 438 mm. A data from a rain gauge located 90 m NNE from the pitlake was made available by SASOL with an average value of 372 mm/year was calculated from the last 10 years of data. Figure 4-17 compares the data obtained from the WR2012 database and the rain gauge placed on site. It is evident that the study area experiences summer rainfall with very low rainfall during the winter months.

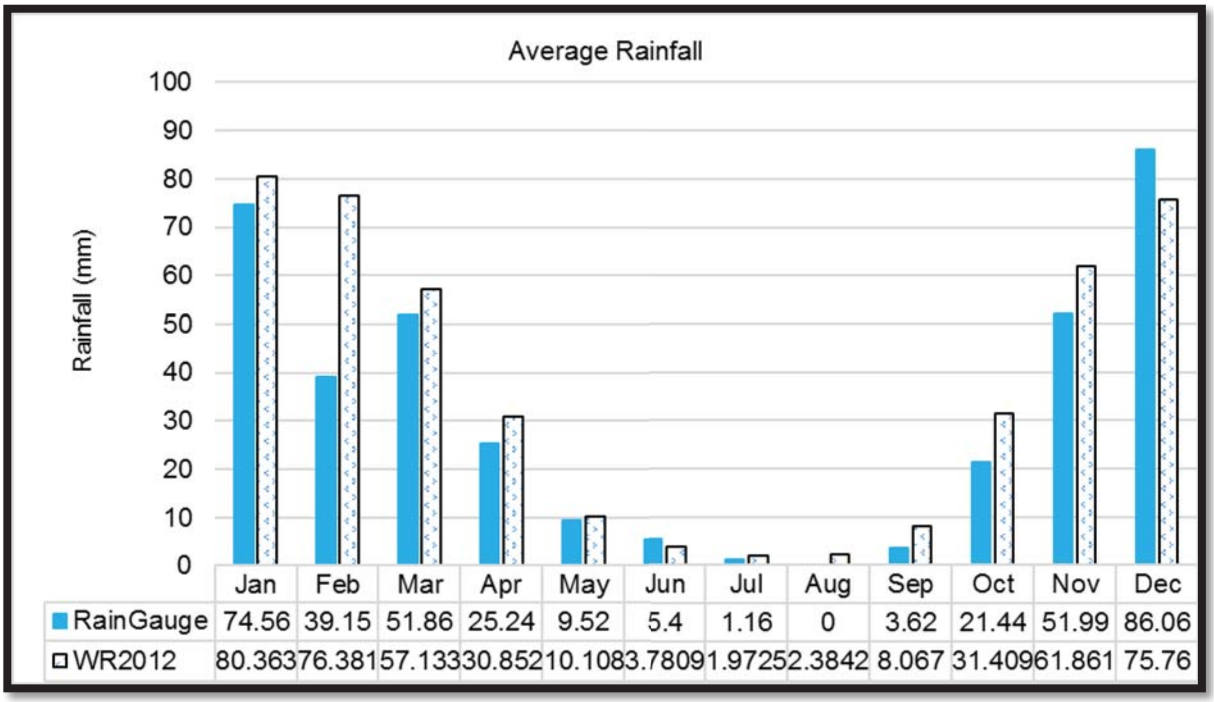


Figure 4-17: Mafutha Pitlake: Average Rainfall.

Runoff

A berm was constructed aroind the pitlake to limit surface runoff inot the pit as show in Figure 4-18. As a result the contribution to the pitlake from runoff is limited to the sidewalls and acess ramp inot the pit.

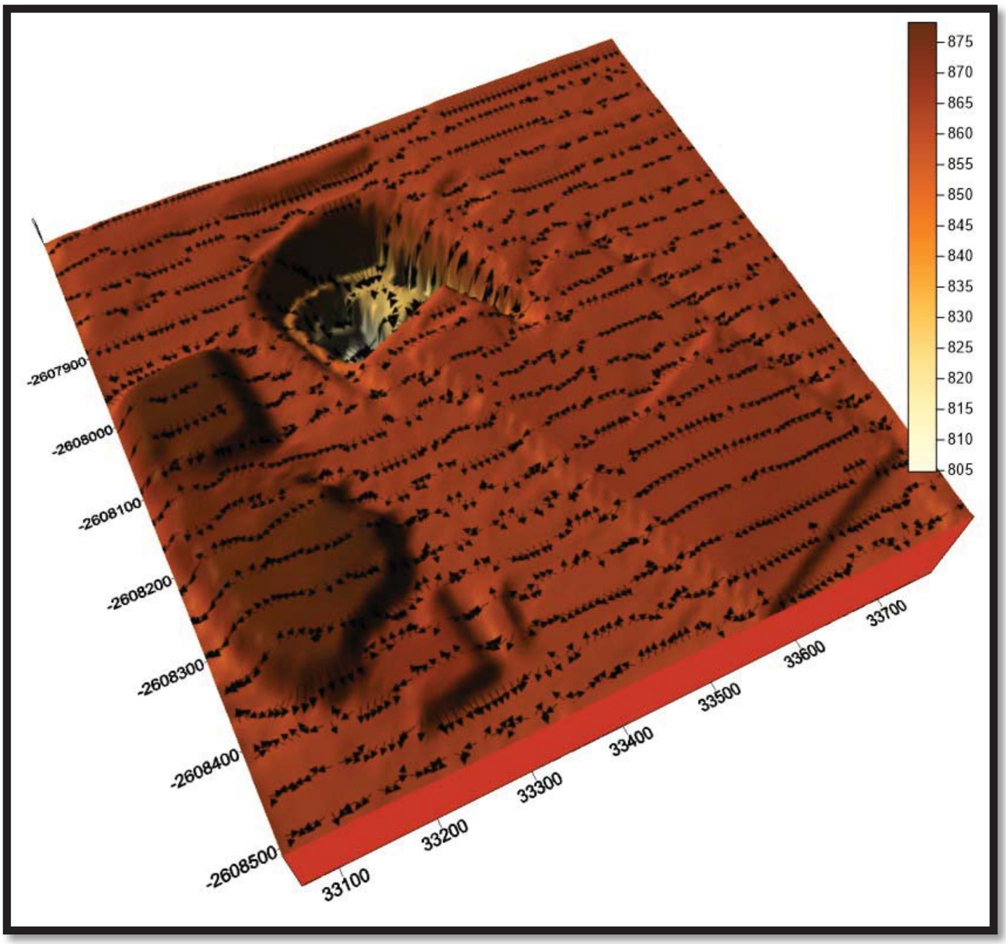


Figure 4-18: Mafutha Pitlake: Surface topography.

Groundwater Inflow

Groundwater inflow for Mafutha was calculated with the use of (Marinelli and Niccoli, 2000) method as discussed in Section 2.3.1 of the report. Pitlake water level were into the model as time series data. Groundwater into the pit was calculated using the derived aquifer parameter with the allowance for additional recharge caused the water level mound at the waste rock dump.

Evaporation

The study area falls within the 1D evaporation zone which has a MAE of 1950 mm/a. Evaporation data obtained from WR2012 showed that the evaporation rate is considerably high between September and March. Local Symons-Pan evaporation for zone 1D is expected to vary as shown in Table 4-4:

Table 4-4: Mafutha Monthly Evaporation (mm)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Evaporation	226.2	210	210	209	174.3	164.8	129.3	110	90.7	102	137	186
Pan Factors	0.81	0.82	0.83	0.84	0.88	0.88	0.88	0.87	0.85	0.83	0.81	0.81
Lake Evaporation	183.222	172	174	176	153.4	145	113.8	95.5	77.1	84.6	111	151

Water balance Model Calibration

The water balance model shows a strong correlation between the simulated and observed pitlake water levels indicating that the model is capable of predicting the future behaviour of the pitlake. The calibration results are provided in Figure 4-19 and Figure 4-20.

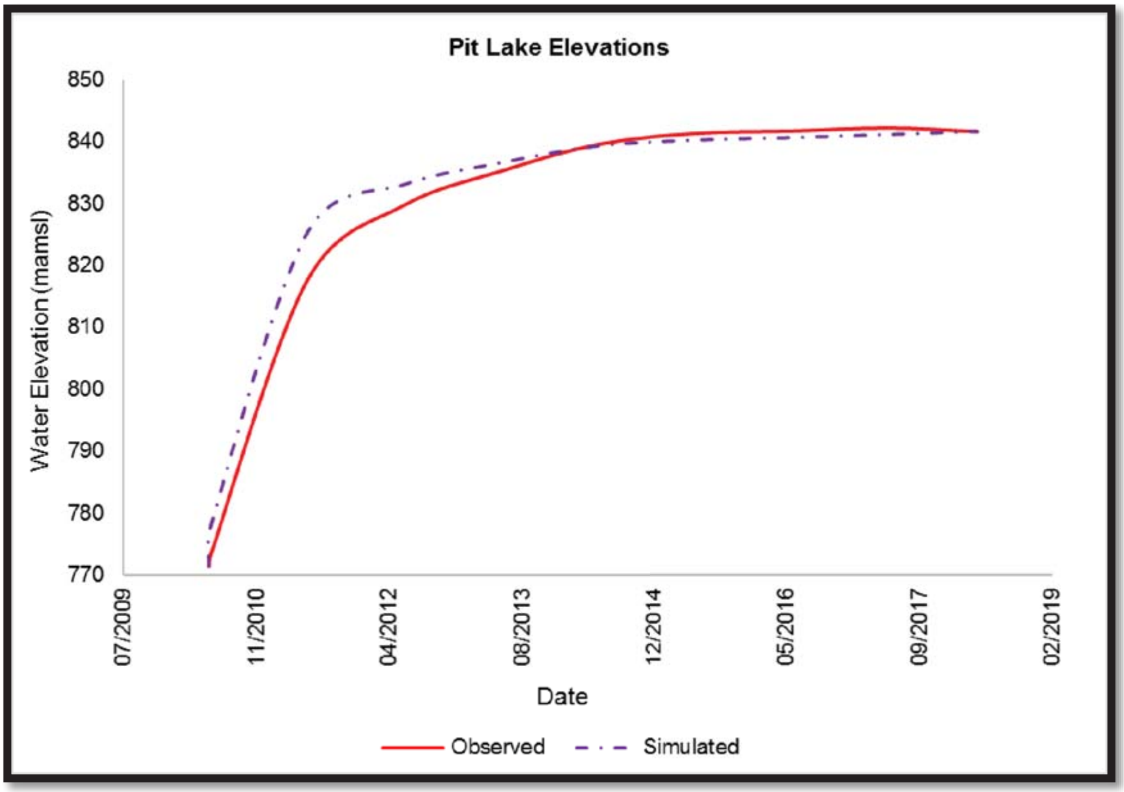


Figure 4-19: Mafutha Pitlake: Comparison of observed data and simulated data.

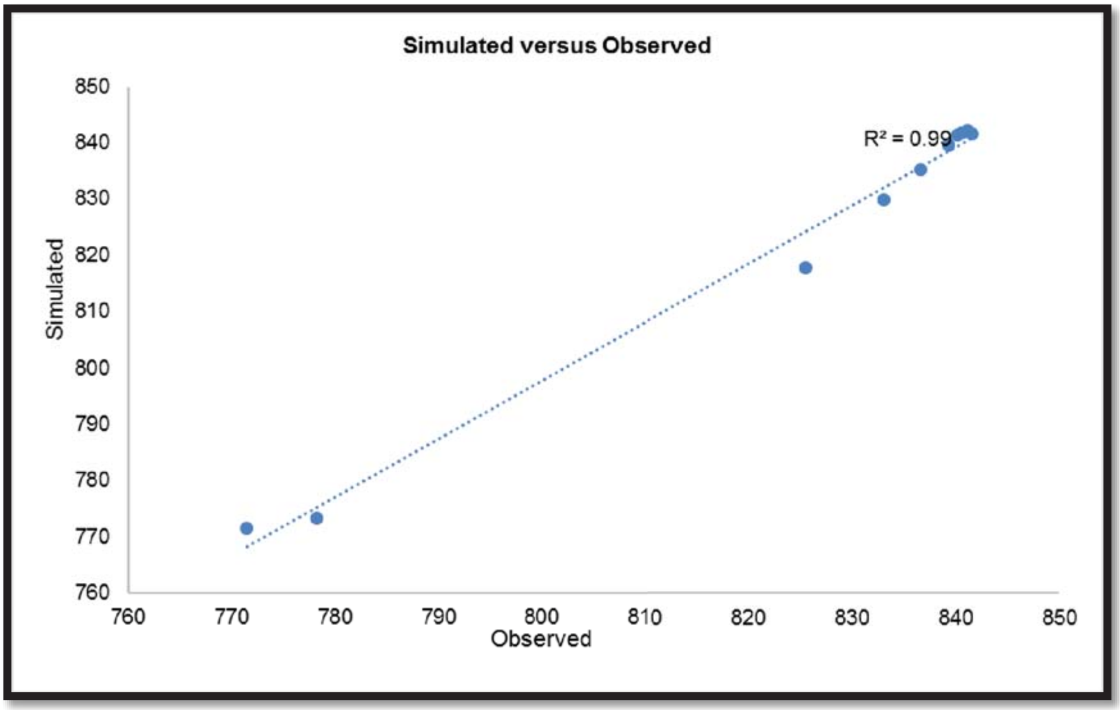


Figure 4-20: Mafutha Pitlake: Calculated versus observed pitlake elevations.

Sensitivity Analysis
A sensitivity analysis Figure 4-21 was undertaken to determine which parameters the model is the most sensitive to. The model is most sensitive to an increase in the evaporation rate. A 100% increase of the annual rainfall would not cause the pitlake water level to reach decant point.

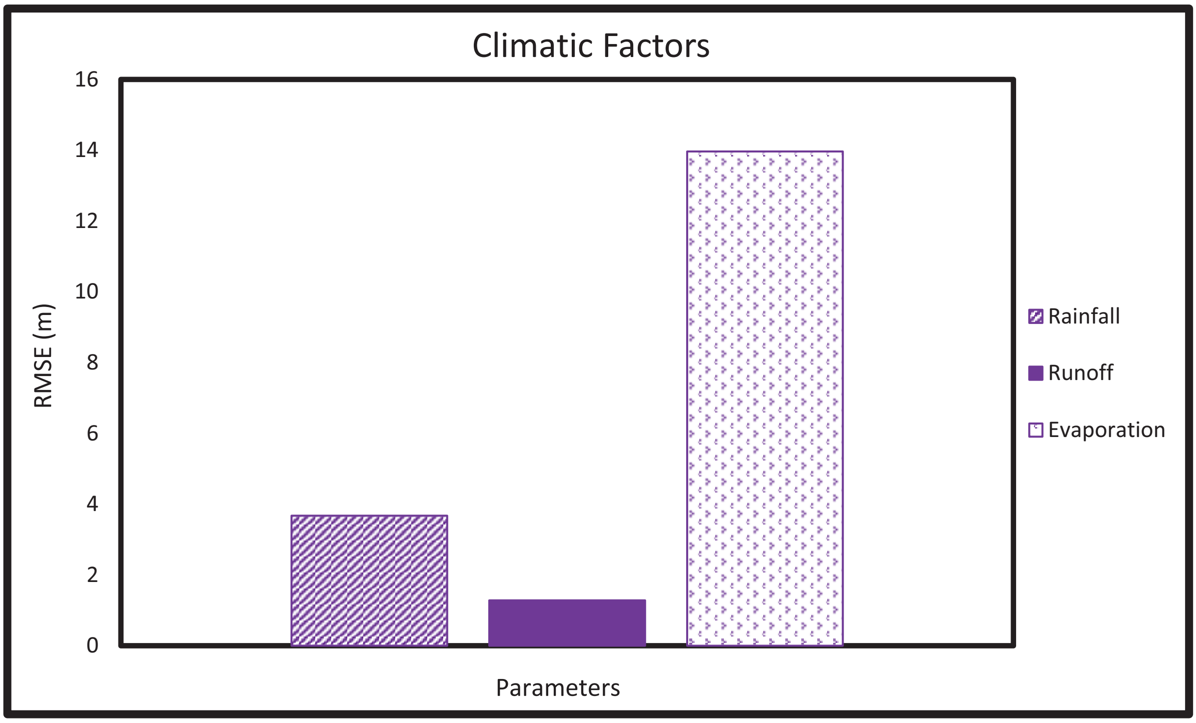


Figure 4-21: Mafutha Pitlake Water balance model – sensitivity analysis.

The Appendix A: Mafutha Water Balance model is shown in Appendix A.

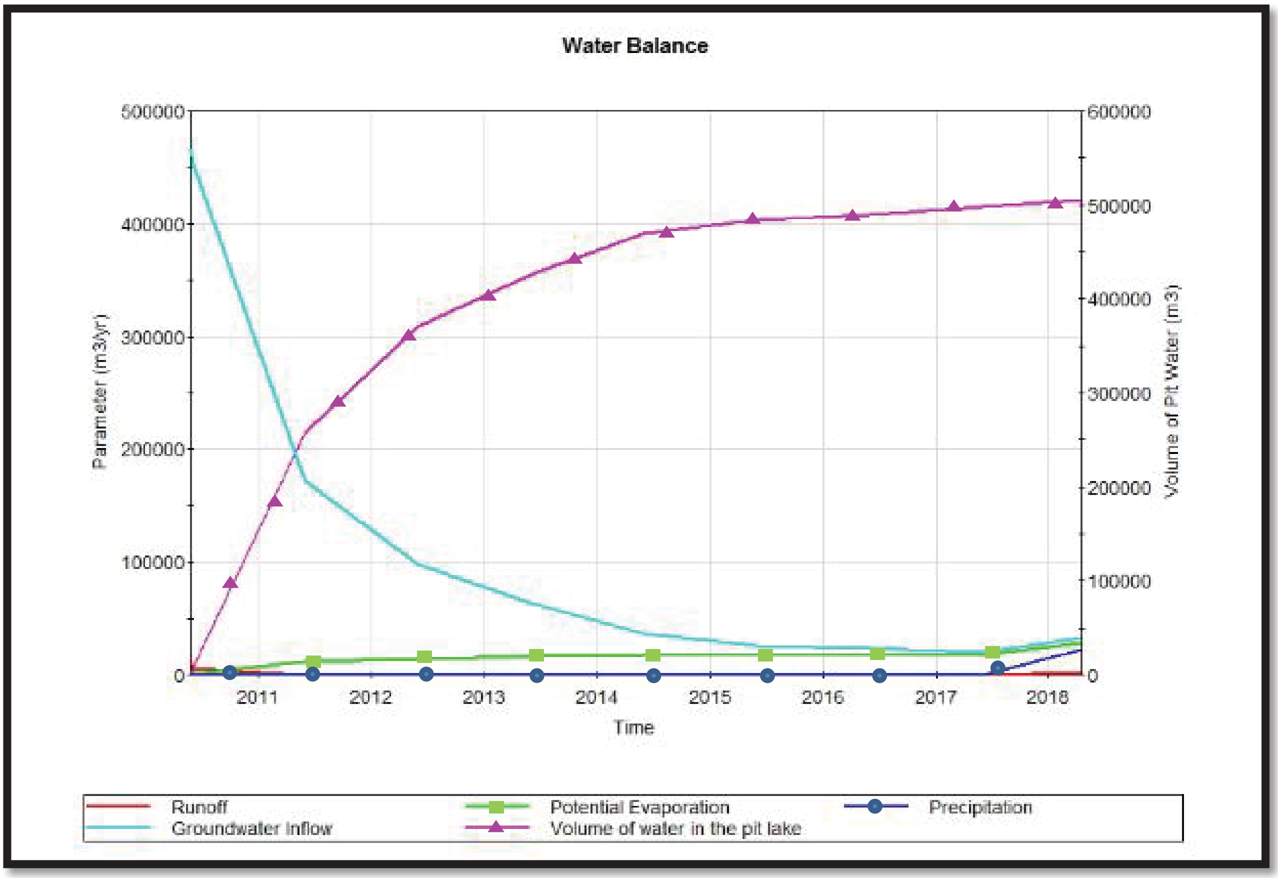


Figure 4-22: Mafutha Pitlake: Water balance.

Figure 4-22 as expected, indicates the Figure 4-22 groundwater contribution to the pitlake decreases as the hydraulic gradient approach's equilibrium. Evaporation rate on the other hand increases as the pitlake fills due the increase in surface area. Groundwater and evaporation values approach a near equilibrium which results in the groundwater levels of the pitlake being marginally lower than the regional groundwater level. The contribution of runoff from the pit walls decreased with increasing pitlake water level due to the decrease in the surface area from which runoff occurs. Direct rainfall contribution increases with the increase in pitlake surface area.

The calculated cumulative inflow volumes from each contributing source was calculated to be:

- 89.6% is from groundwater
- 8.7% is from rainfall
- 1.7% from pit wall runoff

The relative contribution of the sources with time is shown in figure 4-22.

Figure 4-23 is a stage curve plot of Mafutha which demonstrates the water elevation and volume of water of the pitlake at the end of each year. The net inflow decreases as the pitlake approaches equilibrium.

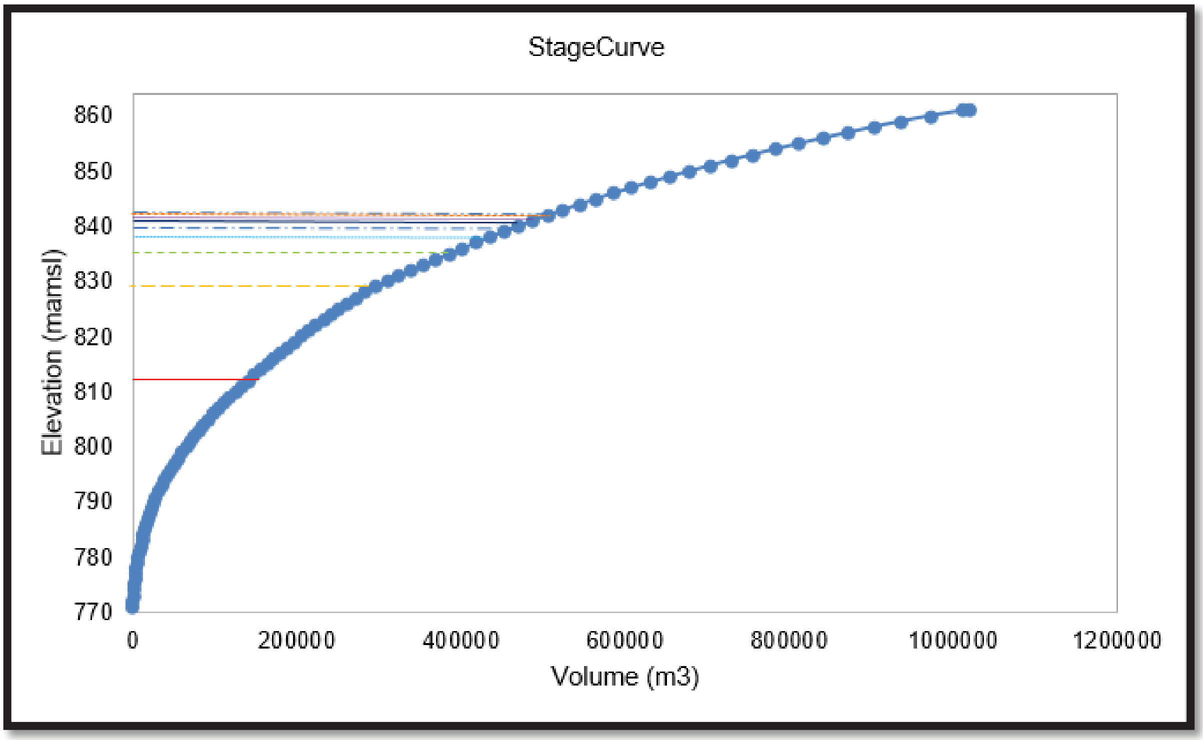


Figure 4-23: Mafutha Pitlake: Stage curve.

4.10 Water Quality

4.10.1 Water Quality Profiles

Karoo aquifer

The groundwater quality was evaluated with borehole profiles to determine the in-situ multiparameter chemical variables. Vertical profiles have been known to provide useful information of flow in fractured rock aquifers. Profiles were conducted in the deep boreholes in the direct vicinity of the pitlake (G250706, G250705 and G250757). These boreholes were influenced during dewatering of the pit during mining which was followed by the subsequent rebound of the water after mining ceased from mid-2010. Profiles were conducted under steady state conditions at the time of the study and the results are displayed in Figure 4-24 for the different profiling events. Subtitle variations in the different profiles can be attributed to the calibration of the equipment between profiling events.

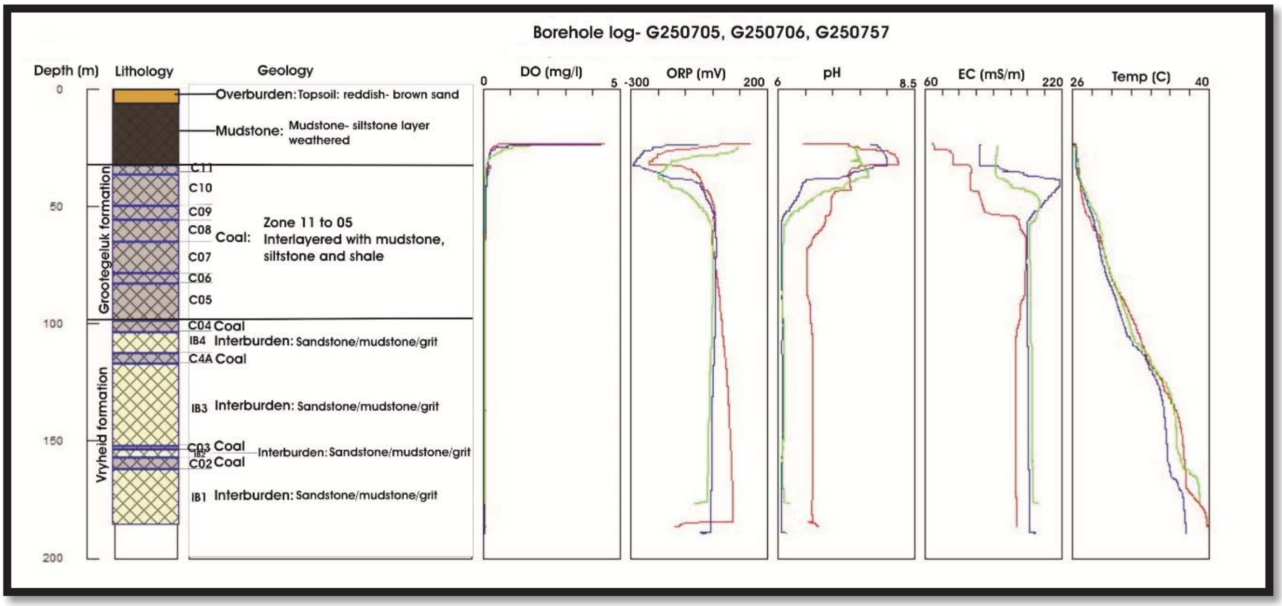


Figure 4-24: Mafutha Pitlake: Multiparameter profile of chemical plots for boreholes G250705, G250706 and G250757.

The general geochemical characteristics of the Karoo aquifer surrounding the Mafutha pitlake that were determined by the through multiparameter probing are detailed below:

- The pH of the Karoo aquifer generally has a near neutral character, which varies from 6 to 8.5 in the top 30 m of the water column. The pH at the coal seam horizon is lower, with a pH of 6.
- The electrical conductivity levels of the Karoo aquifer range from 60 to 220 mS/m above the coal seam horizon, indicating variable recharge to these boreholes. A constant EC of 180 mS/m is evident in all three boreholes over the coal horizons.
- The redox potential of the Karoo aquifer is variable, with mostly reducing conditions in the top 30 m of the water column. The range from -200 to 300 Mv, indicating the stale nature of the top water and possible microbial activity. At the coal horizon, a redox potential is between -50 and 50 mV showing depleted oxygen concentrations over the coal horizon. This should limit any pyrite oxidation to the extent that future sulphate generation should be insignificant.
- The temperature of the Karoo aquifer increase with depth, starting 26°C at 23-25 mbgl and reaches 40°C at the bottom of the boreholes.

Pitlake

The potential for stratification of the water column was investigated through vertical profiles at various depths in the pitlake. In a lateral direction, the profiles showed the same water quality, and therefore only the deepest profiles are reported. Profiling was conducted in January 2017, August 2017 and November 2017; shown in red, blue and green, respectively in Figure 4-25.

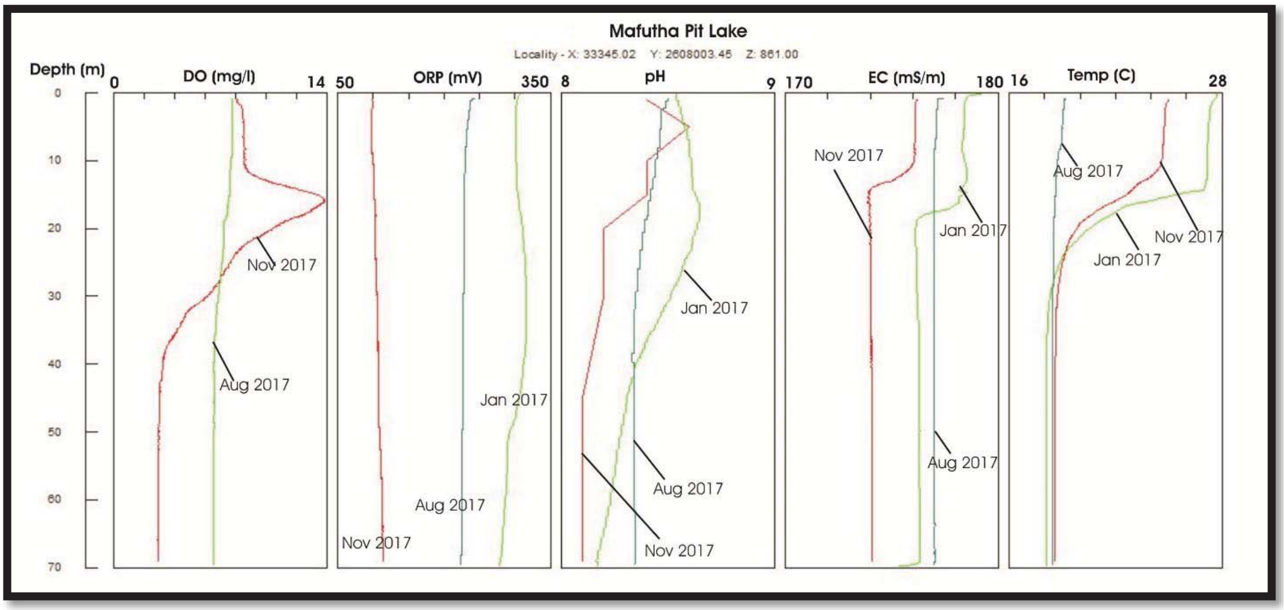


Figure 4-25: Mafutha Pitlake: Multiparameter chemical profile.

The general characteristics of the pitlake water as determined by multiparameter profiling is discussed below namely:

- The temperature profiles indicated a thermocline at approximately 15 m in January 2017 and at approximately 10 m in November 2017.
- The pH of the pitlake water generally has an alkaline character. Oxidation of pyrite is minimal because of the flooded state of the coal zone and the alkalinity of the water.
- An oxygen maximum occurred at the same level as the thermocline, which could be attributed to a chlorophyll-a maximum at that depth (pers. Comm. Lund, 2018). The oxygen maximum could also be suggestive of a "fresh water flow" along that zone (pers.comm. Mullbauer, 2018).
- In August 2017, the pitlake water had already overturned and the water quality variables T and EC homogenised. The temperature remained at 18°C from approximately 25 m from surface throughout the year.
- EC profile showed that the chemistry of the water was homogenous with no isolated layer, or chemocline the bottom of the lake.
- The pitlake displayed holomictic behaviour with turnover occurring throughout the whole water column, once a year.

The temperature profiles showed the formation of a thermocline and the deepening of the epilimnion to a final thickness of 15 m, after which turnover of the water column occurred sometime between June and August, when the top water cooled to 18°C and induced mixing to a homogenous T, EC, DO, pH and ORP. The results of the continuous monitoring of the pitlake water temperature with depth, described in the methodology showed the steady warming of the upper 15 m of the water column until a thermocline was reached. Figure 4-26 demonstrates the temperature changes in the pitlake at various depth over the time from September 2017 to April 2018. The temperature loggers were unfortunately removed prior to the overturn occurring.

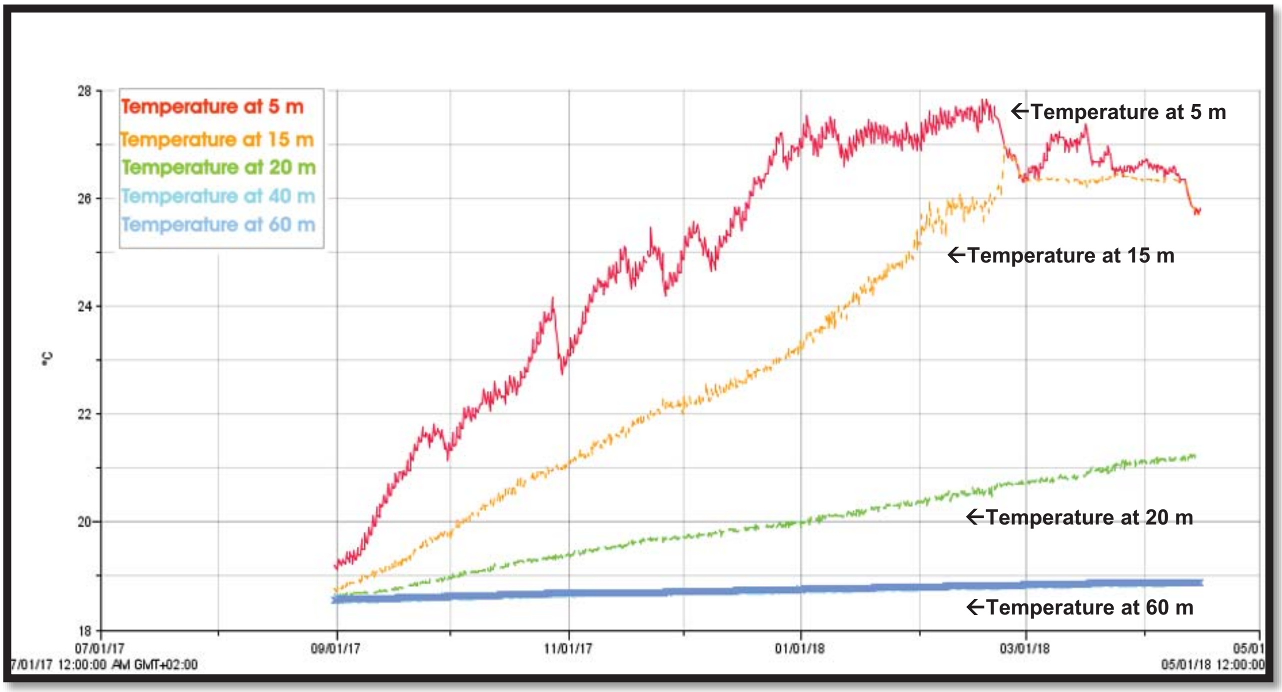


Figure 4-26: Mafutha Pitlake: Continuous monitoring of T.

Source of water for pitlake

Figure 4-27 shows the ionic characteristics of sampled groundwater and the Mafutha pitlake. The median values of samples collected during the 2016 and 2017 study period were calculated and used for the plot. Groundwater from the area is mostly dominated by sodium and chloride ions, with equal amounts of bicarbonate in some of the boreholes, such as boreholes G250607 and G250610 resulting in a sodium-bicarbonate water type. The shallow boreholes, as shown in the water balances study, recharge quicker than the deeper aquifer. The groundwater mound in the vicinity of the coarse waste rock dump is evident from the shallow water level of some of the shallow boreholes around the dump. The shallow boreholes, G250607, G250608 and G250610 around the waste rock dumps showed higher relative bicarbonate concentrations (mEq/ℓ), but overall low sulphate concentrations indicative of the relatively inert nature of the material in the dump.

Sampling depth for the groundwater samples was not consistent and may be a contributing factor to the differences observed in the water qualities among the shallow boreholes. This is particularly evident during the rainy season, when new recharge water overlies “older” lower in the borehole. Some the samples of the shallow boreholes did not plot in a specific water type which could be attributed to mixing of recharge water with deeper groundwater.

The water levels in the deep boreholes G250705 and G250706 show the greatest influence by the dewatering during mining and subsequent rebound of the water levels of the pitlake. These groundwater samples showed an overall sodium-chloride water type (chloride equivalence 63%-75%; bicarbonate equivalence 25%-36% and sulphate lower than 1%). These samples show sodium as the dominant cation (61%-83%), while magnesium (21-25%) is also a major specie.

The pitlake samples show chloride and bicarbonate as the dominant anions (the chloride equivalence 45-59% and the bicarbonate 28-30%) and to lesser degree sulphate (the sulphate equivalence 12-18%). Sodium is the dominant cation in the pitlake samples, followed by magnesium and calcium (the sodium equivalence 65-74%, magnesium 16-21% and calcium 7-11%).

The ionic characteristics of the Mafutha pitlake are very similar to that of the groundwater sampled in close vicinity to the pitlake. These results confirm the water balance study that groundwater is the main source of inflow into the pitlake. The fundamental ionic characteristics of the pitlake, can be expected to change very little, due to the ongoing influence of groundwater as the main source of water for the pitlake. Overall, the groundwater chemistry showed an enrichment of sodium.

Initial pitlake chemistry showed increase in sulphate concentrations which decreased as the pitlake filled. This can be attributed to the dissolution of salts precipitated on the pit wall during excavation and wash off by runoff. The relative concentration of sulphate in the pitlake water decrease over time with the rise in water level

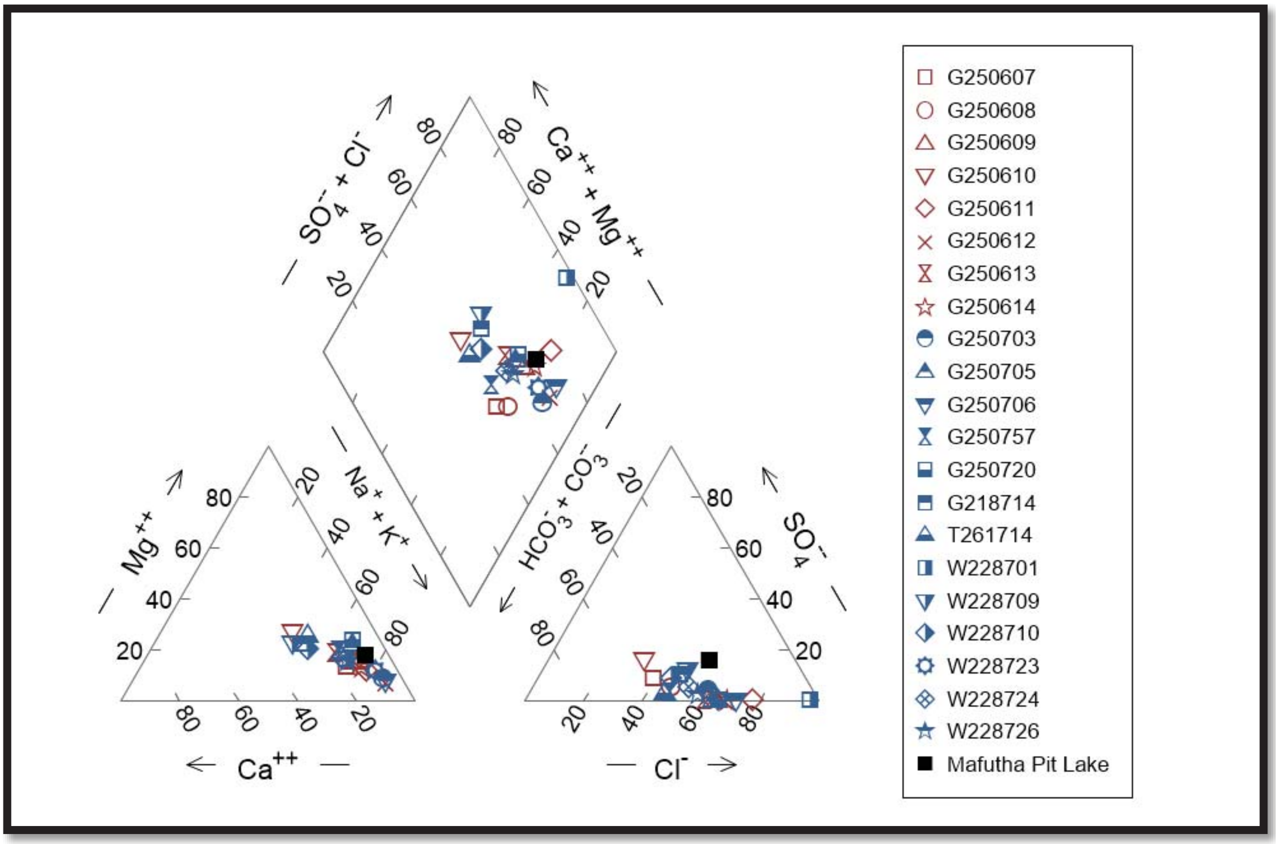


Figure 4-27: Mafutha Pitlake: Piper diagram.

Possible processes in the Karoo aquifer, which lead to the observed Na-Cl signature of the groundwater were investigated by means of bivariate plots. A plot of Na and Cl (Figure 4-28) shows that the concentrations of the Na and Cl ions increases stoichiometrically, with a 1:1 ratio of Na over Cl, suggesting halite (NaCl) dissolution as a source of Na and Cl ions in the water (Hounslow, 1995). Some of the samples plotted above the 1:1 equiline, indicated some additional source of Na, such as ion exchange between the groundwater and host rocks, whereby Ca and Mg is exchanged for Na in clay mineral structures associated with the mudstones and sandstones in the lithology. On the other hand, some samples plotted below the 1:1 line, indicated possible removal of Na by reverse ion exchange.

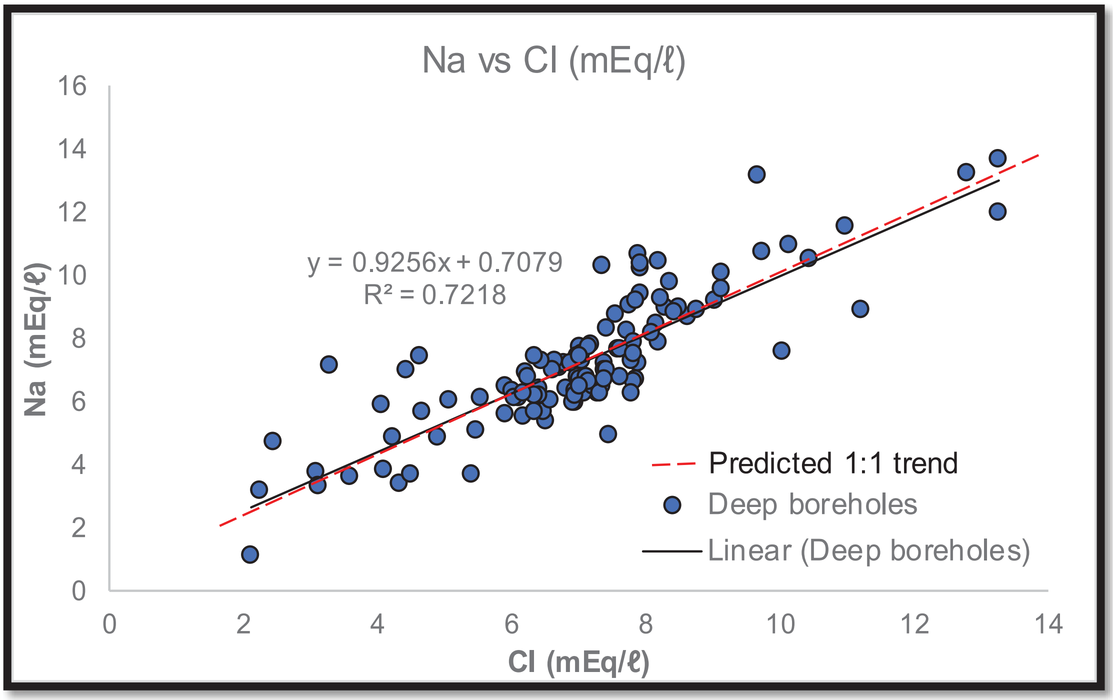


Figure 4-28: Mafutha Pitlake: Scatter plot of Na vs Cl in mEq/ℓ.

A scatter plot of Ca vs Ca+SO_4 of the deep borehole samples (Figure 4-29) indicated that a source for the majority of the Ca was the dissolution or weathering of a mineral other than gypsum; such as carbonates or silicates, with a ratio of >0.5 (Hounslow, 1995). One mole of gypsum dissolves according to the equation to release 1 mole of Ca and 1 mole of SO_4.

$$CaSO_4.2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \qquad [12]$$

According to the molar ratios, gypsum solution plays a minor role in groundwater and this may explain the relatively low concentration of SO_4 observed in the groundwater. If gypsum were to exert a control on the water chemistry, the Ca to Ca+SO_4 ratio would be 0.5, which for a few samples seems to be possible. Samples plotting below the predicted 0.5 ratio, indicate Ca removal by ion exchange or calcite precipitation. The presence of SO_4 in the water could also be explained by pyrite oxidation, but only with a ratio of smaller than 0.5 and at a of pH < 5.5 (Hounslow, 1995). However, the pH of the groundwater was circum-neutral (pH 6-8) and therefore pyrite oxidation was not considered as a driving mechanism for the groundwater quality.

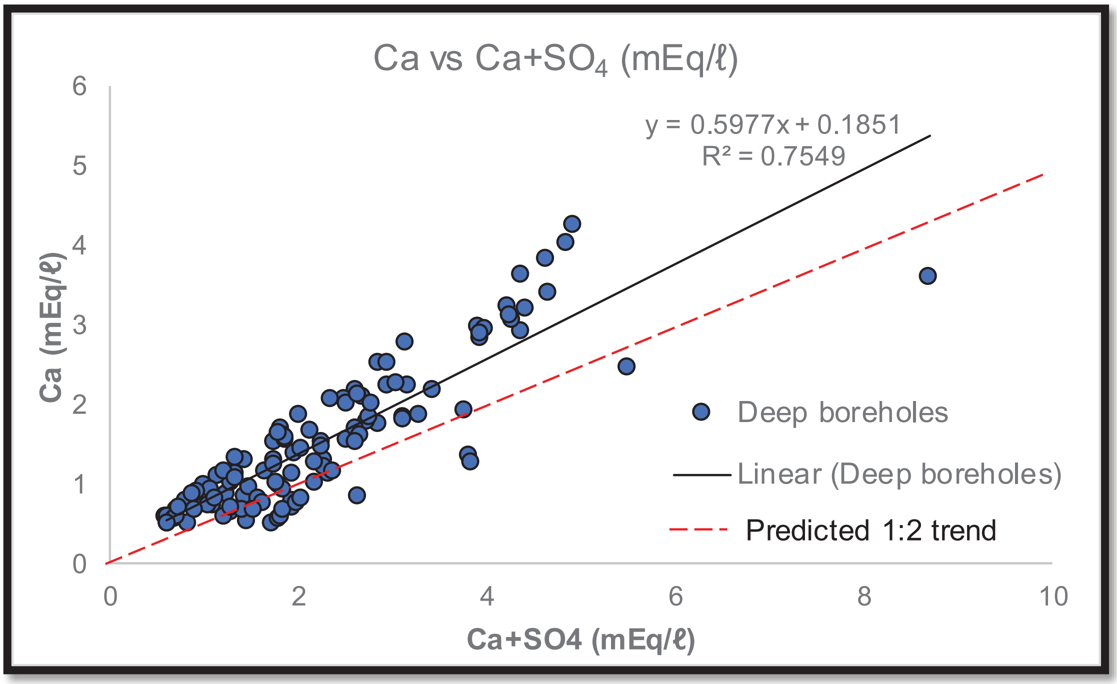


Figure 4-29: Mafutha Pitlake: Scatter plot of Ca vs Ca+SO4.

Lastly, Ca+Mg-HCO_3+SO_4 vs K+Na-Cl plots indicate whether the groundwater chemistry is highly influenced by ion exchange (Lufuno, 2017; Puntoriero et al., 2015). The Na + K-Cl show the quantity added or removed for Na+K in relation to the amount added by dissolved Cl salts, such as NaCl (halite), while Ca + Mg - SO_4 - HCO_3 show the quantity for Ca + Mg added or removed, relative to the amount added by dissolution of gypsum, calcite and dolomite. From the scatter plot in Figure 4-30, it is evident that ion exchange is a major process which alters the groundwater chemistry, as indicated by the slope of -1. It could be deduced that the groundwater ion exchange processes are also one of the sources of additional Na in the pitlake water.

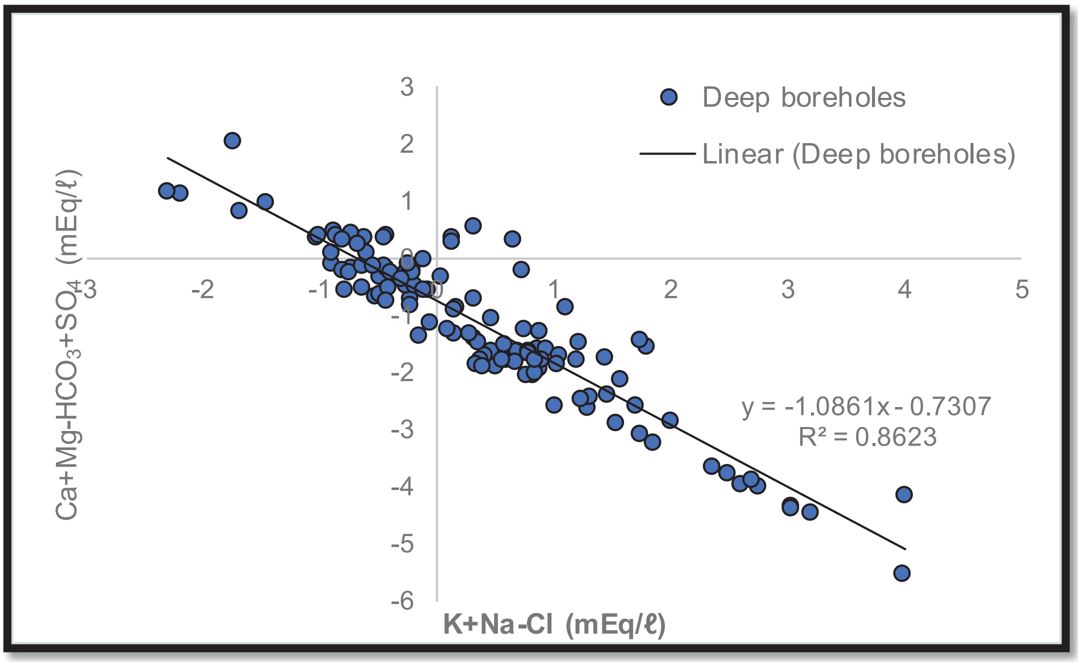


Figure 4-30: Mafutha Pitlake: Scatter linear correlation plot of Ca+Mg-HCO_3+SO_4 vs K+Na-Cl (mEq/ℓ).

4.10.2 Pitlake Chemistry

The results of the pitlake water chemistry collected during the study period are documented in Appendix I: Mafutha Water Quality. The discussion uses monitoring data from 2009 to 2017 in conjunction with collected field data to identify and describe the most likely dominant hydrogeochemical processes and contribution to the pitlake water quality.

A Piper diagram (Figure 4-31) was constructed of pitlake water quality data from 2009 to current and shows how the water quality has evolved towards the Na apex of the cation triangle from the beginning of pit flooding in 2009, to when the pitlake reached equilibrium water levels at the end of 2014/2015 and the current chemical signature. An increase in Na can be suggestive of ion exchange in favour of Na, where a decreasing trend of Ca and Mg occurs with increasing Na (Gomo and Masemola, 2016). The pitlake water classified as Na-Cl water type, similar to the Karoo aquifer in the study area. The "current" water quality includes all samples taken from 1 m to 69 m depth in the pitlake in January, August and November 2017.

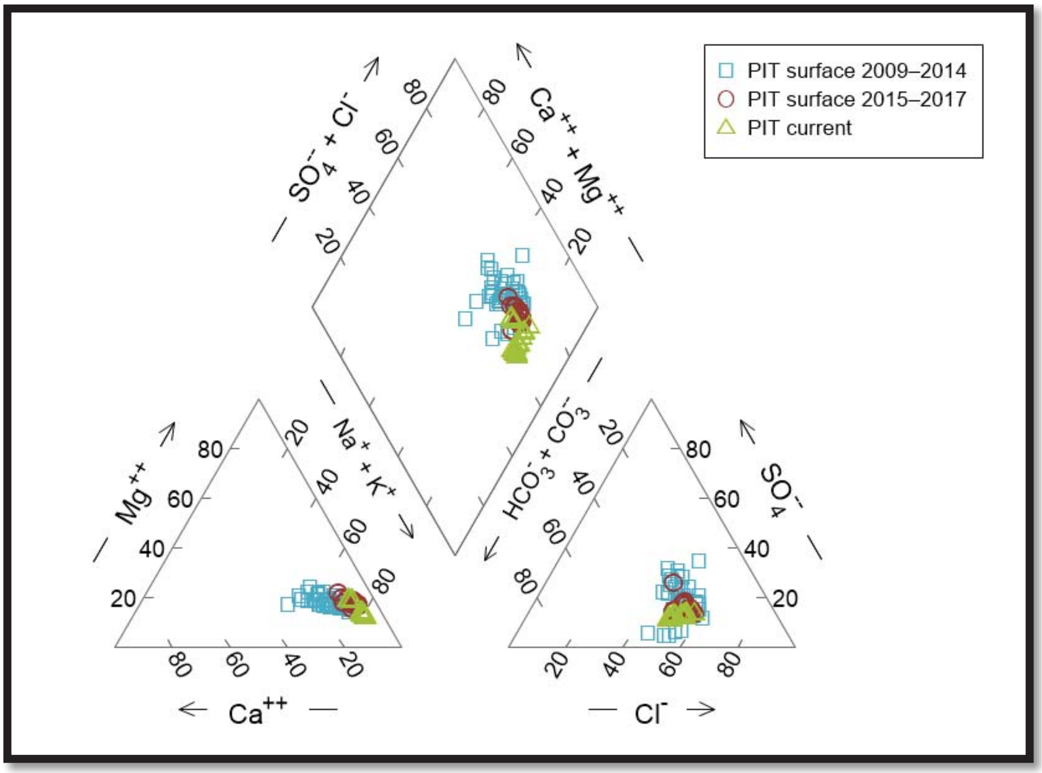


Figure 4-31: Mafutha Pitlake: Piper diagram showing Na enrichment.

According to the classification scheme of Eary (1999), the Mafutha pitlake water quality is defined as circumneutral pH with low TDS, whereby the pit wall rocks and other remnant mining surfaces are minimally reactive and the groundwater inflow in the pitlake contains low solute loads. The TDS of these types of pitlakes comprise of high proportions of base cations and alkalinity. Metal concentrations of this category of pitlakes are usually low, which is consistent with their near neutral pH (Eary, 1999). Monitoring data of water samples taken from the surface of the Mafutha pitlake prior to this study were made available for the study. Figure 4-32 to Figure 4-38 are time series graphs showing the pH, TDS, sulphate, bicarbonate, calcium and sodium of surface grab samples from the pitlake from 2009, as well as the deep boreholes, most influenced by the mining.

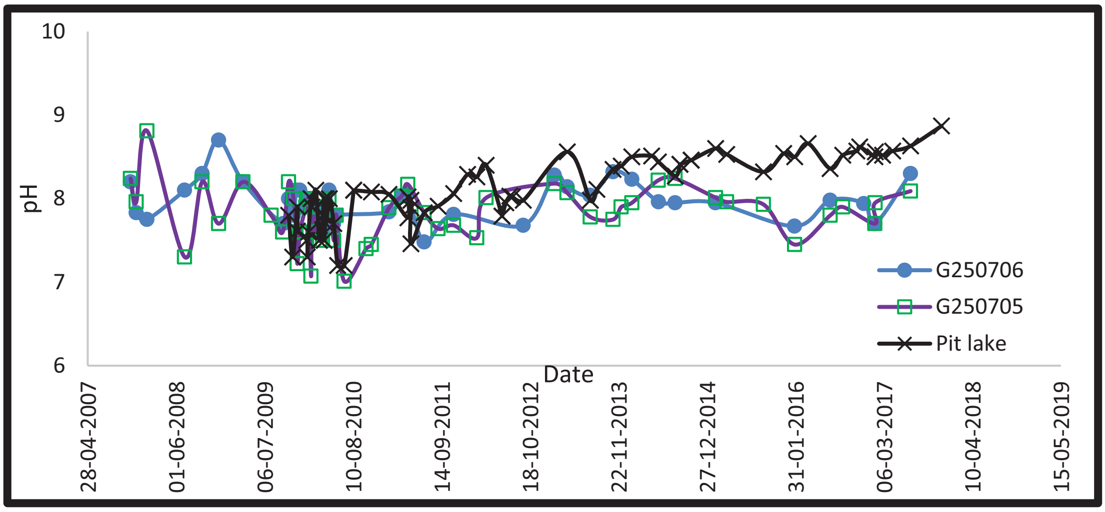


Figure 4-32: Mafutha Pitlake: Karoo aquifer pH levels.

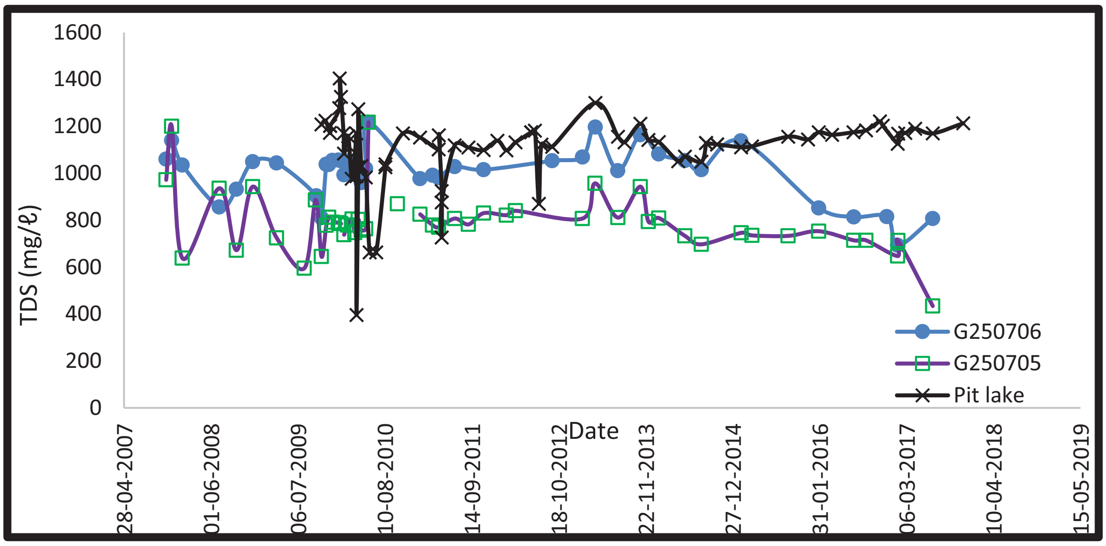


Figure 4-33: Mafutha Pitlake: Karoo aquifer and Backfill water TDS.

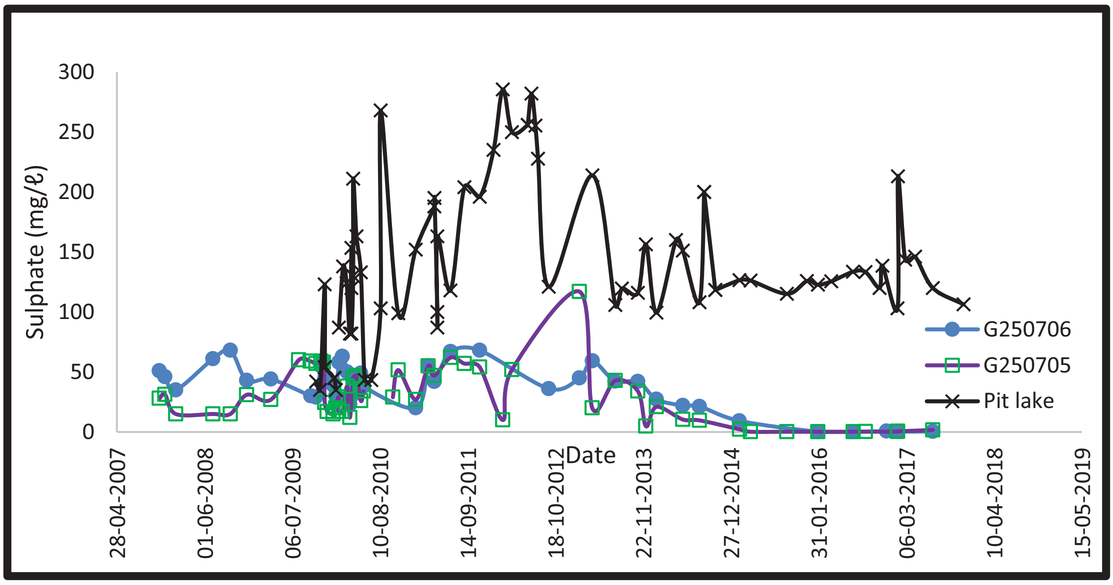


Figure 4-34: Mafutha Pitlake: Karoo aquifer sulphate concentrations.

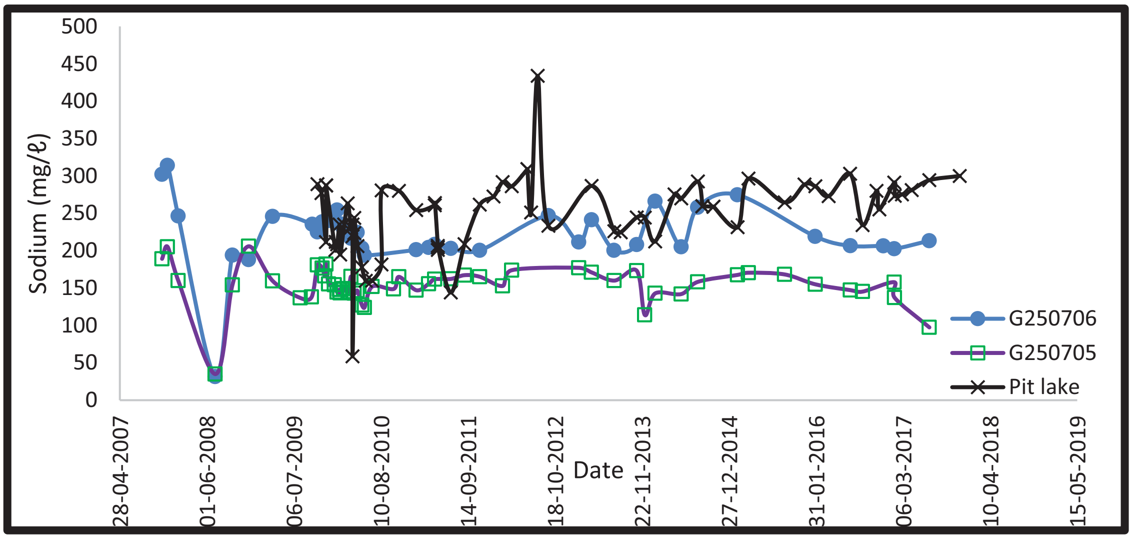


Figure 4-35: Mafutha Pitlake: Karoo aquifer and sodium concentrations.

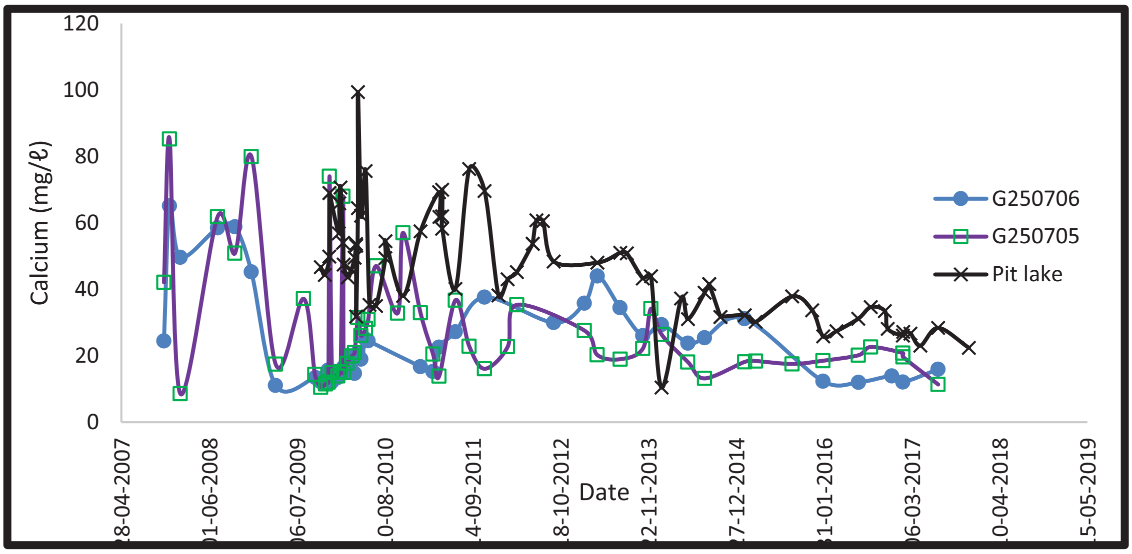


Figure 4-36: Mafutha Pitlake: Karoo aquifer and calcium concentrations.

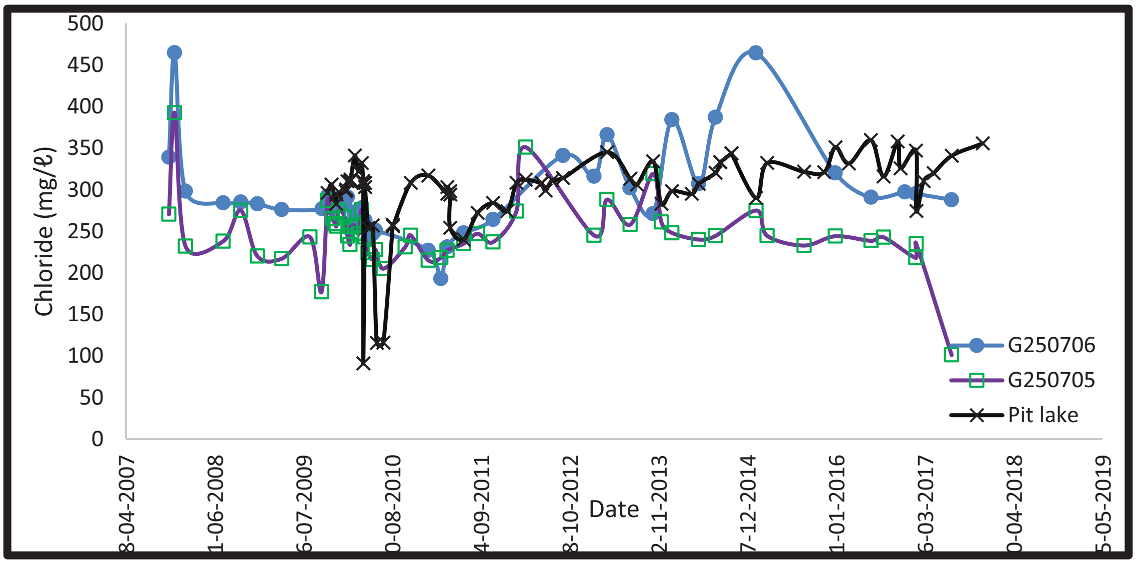


Figure 4-37: Mafutha Pitlake: Karoo aquifer and chloride concentrations.

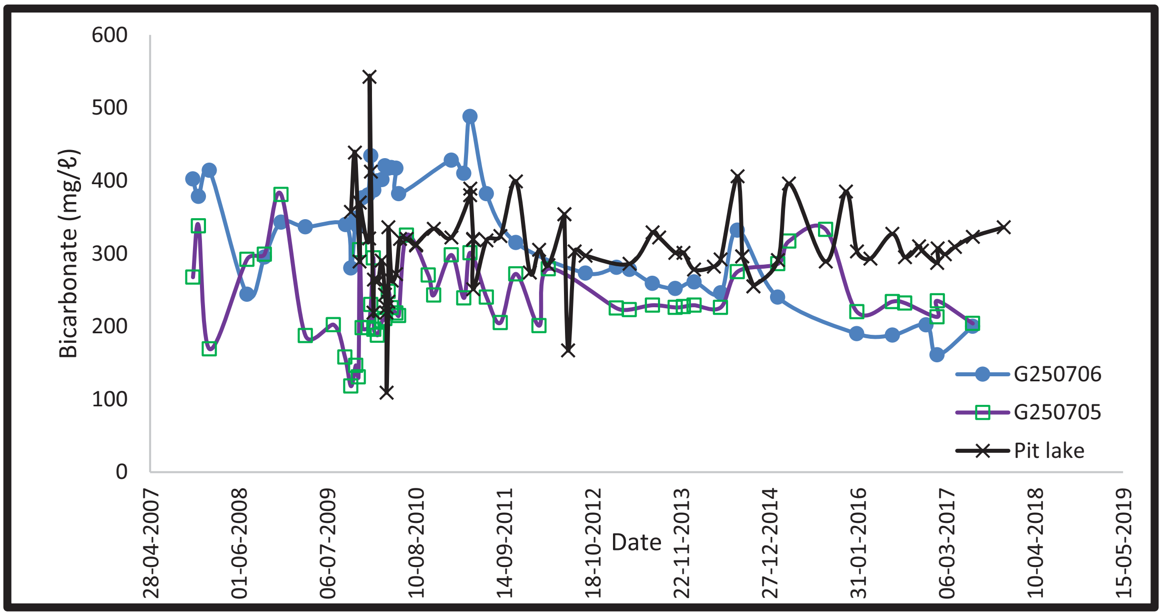


Figure 4-38: Mafutha Pitlake: Karoo aquifer and bicarbonate concentrations.

Time series graphs of the major ion concentrations in the pitlake and Karoo aquifer, showed the following:

- Sodium showed an increasing trend with time while Ca showed a prominent decreasing trend in the pitlake. Calcium in the pitlake decreased to the concentrations encountered in the deep Karoo aquifer.
- Alkalinity was evidenced, as bicarbonate in much higher concentrations than SO_4. Sulphate levels seemed to become constant in the pitlake over time. The sudden increase of SO_4 at the beginning of pit flooding (pumping stopped in May 2010) could be attributed to the flushing of oxidation products (secondary salts) from the damaged rock zone created by blasting and the subsequent exclusion of further sulphide oxidation by flooding. The Karoo aquifer showed very low concentrations of SO_4, indicating that the SO_4 in the pitlake does not have its origin form the Karoo aquifer, but from remnant secondary precipitates that dissolved from the pit wall during flooding.
- Alkalinity was more than Ca and higher concentrations of both constituents were encountered in the pitlake than in the Karoo aquifer.
- Chloride in the top surface water of the pitlake showed a slight increasing trend, indicating some impact from evapoconcentration in the upper 1 m of the water column. Chloride concentrations in the Karoo aquifer were almost equal to that in the pitlake.
- pH showed a steady increase with time, towards a pH of 9.

Prominent trends included a decreasing trend of Ca and an increasing trend of Na. As shown in the groundwater, the removal of Ca could be due to both calcite precipitation and ion exchange between water and rock/ clay particles. Another prominent trend was an increasing concentration of Cl over time. Waters undergoing extensive evaporation show Na and Cl increases in a linear 1:1 ratio, but as indicated in the groundwater at Mafutha. Additional Na can be added to the system by ion exchange processes, which then alters the 1:1 ratio. Thus, chloride concentrations generally increase stoichiometrically with sodium, but in mature mine water, this has been shown to not be the case (Azzie, 2002). Furthermore, the mineral fraction of South African coal has been reported to contain kaolinite and Illite, which with their ion-exchange capabilities, contributes to additional Na in the water (Azzie, 2002). The cation exchange capacities (CEC) of these weathered surface materials and lithologies overlying coal seams have great potential for exchange of Ca and Mg in favour of Na (Usher, 2003). This occurs according to the following reaction (Usher, 2003):

$$2Na^{+} + CaX_2 \rightarrow 2NaX + Ca^{2+}$$

Where X= clay mineral (typically montmorillonite clays such as Illite and kaolinite)

During ion exchange, the anions remain unaffected (Hounslow, 1995). A plot of Na against Cl in mEq/ℓ for the pitlake water in Figure 4-39, shows a major increase of Na relative to Cl, indicating that Na is added to the pitlake water from additional sources or processes. This can be suggestive of the addition of Na by means of ion exchange occurring in the aquifer, fractured pit walls where groundwater seeps into the pit and sediments on the benches of the pit. If evaporation was the only control on the water chemistry, Na and Cl would increase in a 1:1 ratio, as indicated by the 1:1 equiline. Additionally, if halite dissolution (NaCl) was the only control, the data would have plotted on the 1:1 line.

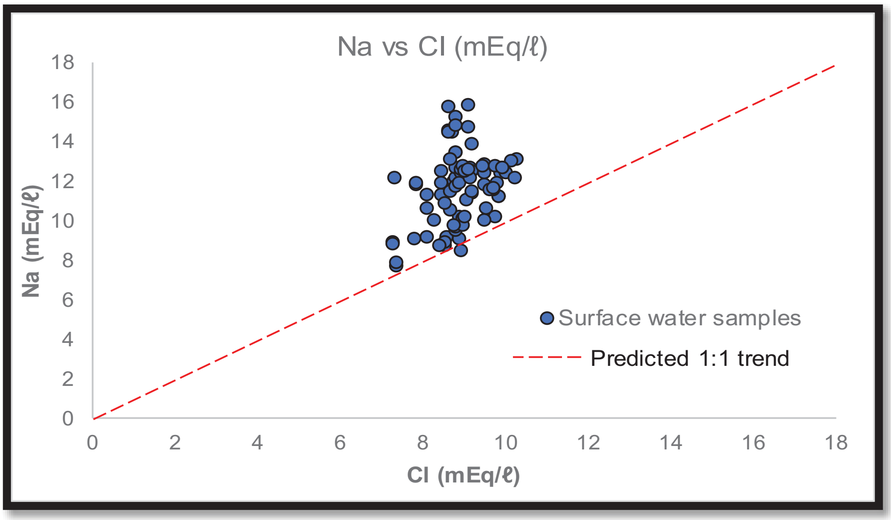


Figure 4-39: Mafutha Pitlake: Sodium concentration plotted against Chloride.

Accordingly, the decreasing trend of calcium concentration was investigated in Figure 4-40. A plot of $\frac{Ca}{Ca+SO4}$ showed ratios largely of <0.5 at neutral pH (linear trend with slope = 0.39), which indicated the removal of Ca from the water by ion exchange and/or calcite precipitation (Hounslow, 1995). The few samples that plotted on the 1:2 predictive line, or above it, could theoretically be indicative of Ca added to the system by means of gypsum dissolution, or above the line, other sources of Ca, such as calcite dissolution.

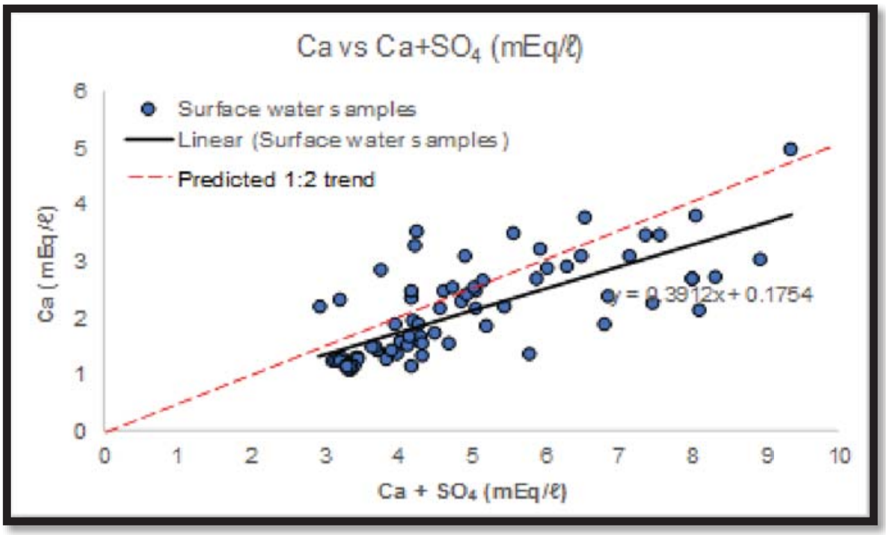


Figure 4-40: Mafutha Pitlake: Scatter plot of Ca vs Ca+SO$_4$ of surface water samples collected during the monitoring period of 2009 to 2017.

According to a plot of Ca+Mg-HCO_3+SO_4 vs K+Na-Cl, the negative slope of -1.85 shows that the pitlake water itself is not undergoing active ion exchange processes (Figure 4-41). Therefore, instead, the additional Na may have its origin from the groundwater-rock interactions, where extensive ion exchange in favour of Na is occurring in the groundwater flowing at background water qualities and reacting with pit wall rocks with flow towards the pitlake.

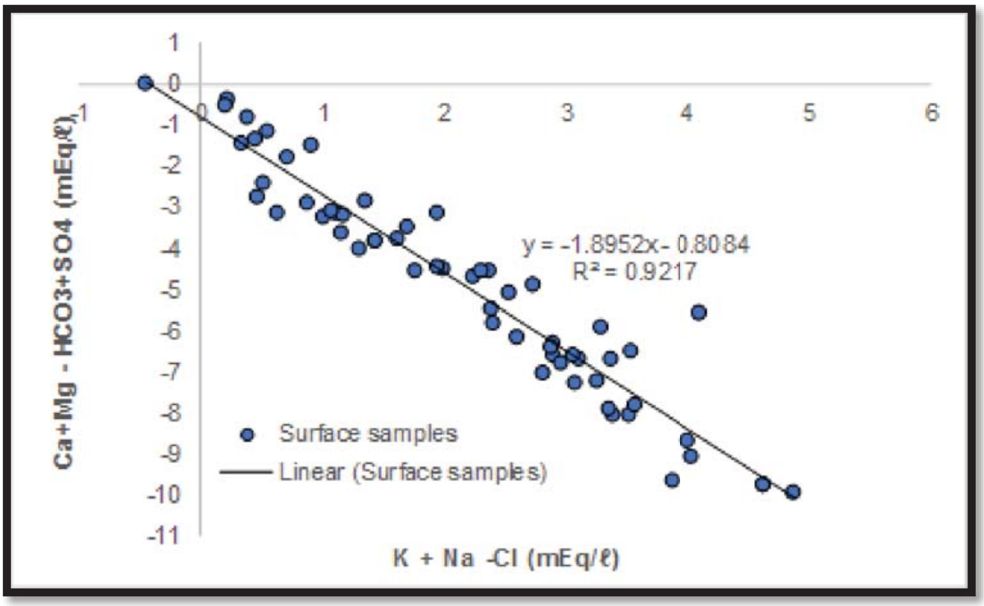


Figure 4-41: Mafutha Pitlake: Scatter plot of Ca+Mg-HCO3+SO4 vs K+Na-Cl.

The hardness of the water at Mafutha pitlake exceeded levels of the accepted limit of 180 mg/ℓ, which indicates very hard water according to the classification system of McGowan (2000) in Table 4-5.

Table 4-5: Water hardness classification (McGowan, 2000).

Hardness class	Total Hardness as CaCO3 (mg/l)
Soft	<60
Moderately hard	60-120
Hard	120-180
Very hard	>180

The total hardness showed a decrease from the initial values when flooding started, indicating enrichment of Na relative to Mg and Ca. The hardness of grab samples collected from the surface of the pitlake are plotted in Figure 4-42.

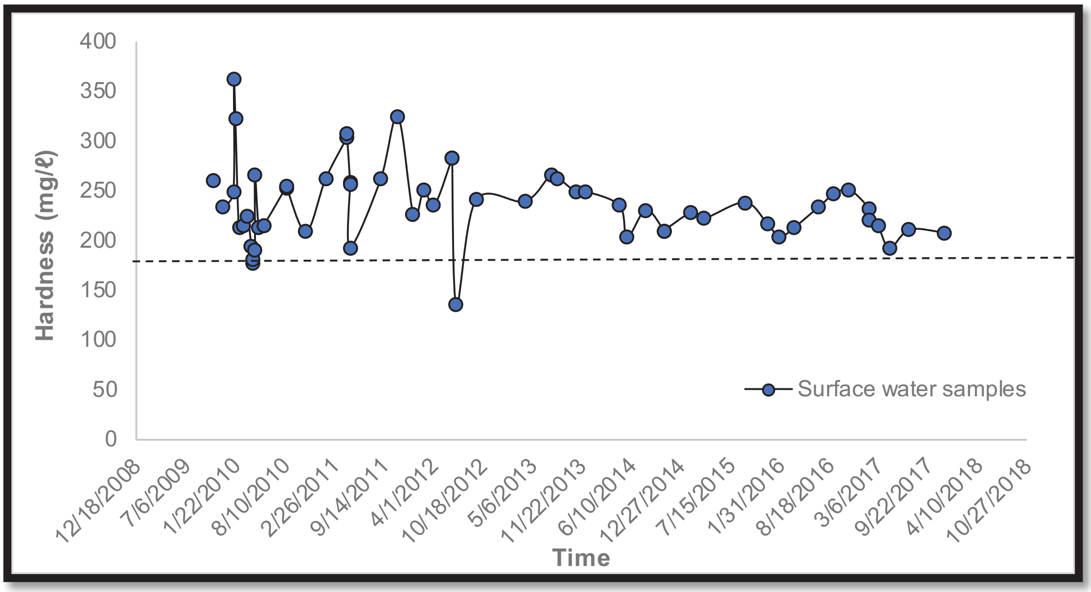


Figure 4-42: Mafutha Pitlake: Total hardness.

Saturation indexes plotted for Mafutha pitlake surface samples indicated oversaturation with regards to calcite, with the potential to precipitate (Figure 4-43). Additionally, the SI also showed oversaturation with CO_2 in the pitlake water (Figure 4-44). Gypsum on the other hand, showed total undersaturation in the pitlake water (Figure 4-45).

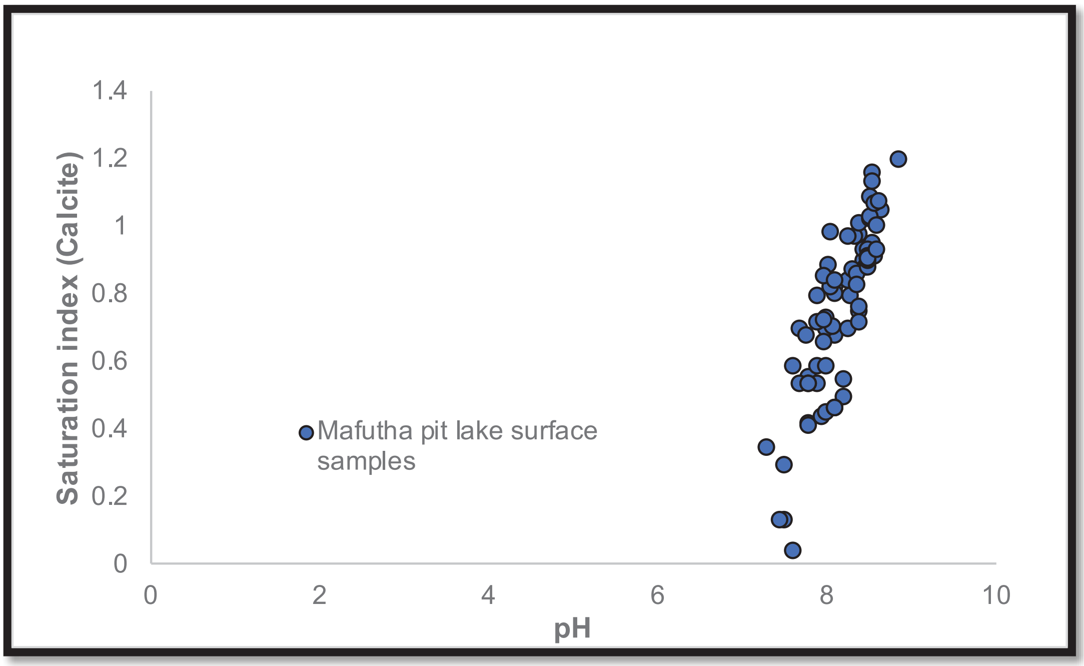


Figure 4-43: Mafutha Pitlake: Saturation index.

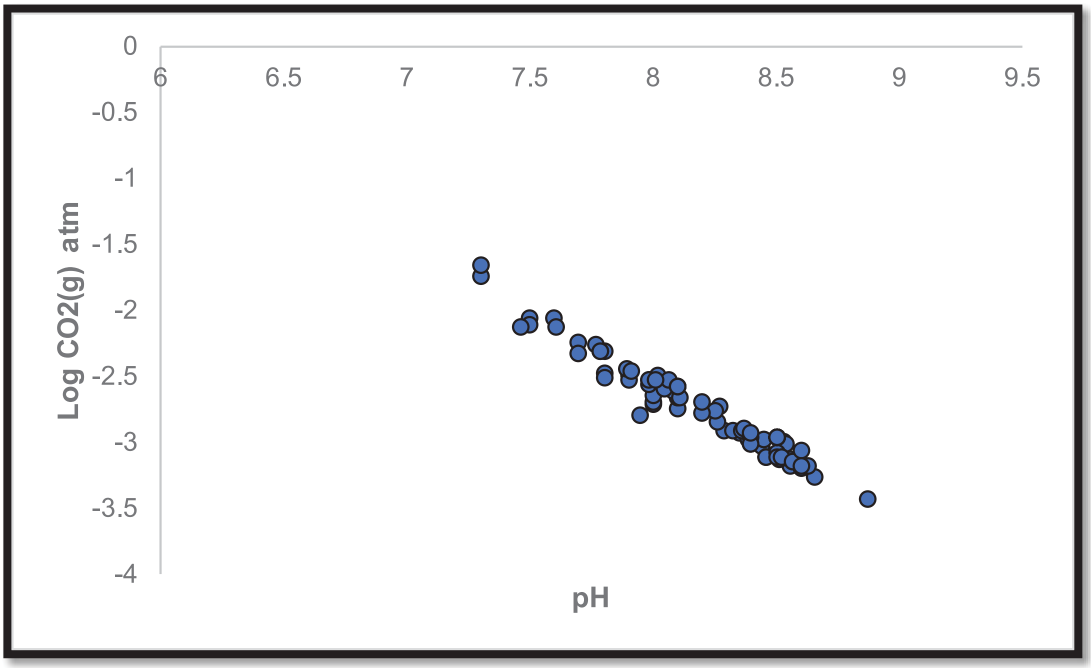


Figure 4-44: Mafutha Pitlake: Saturation index for equilibrium partial pressures of CO2(g).

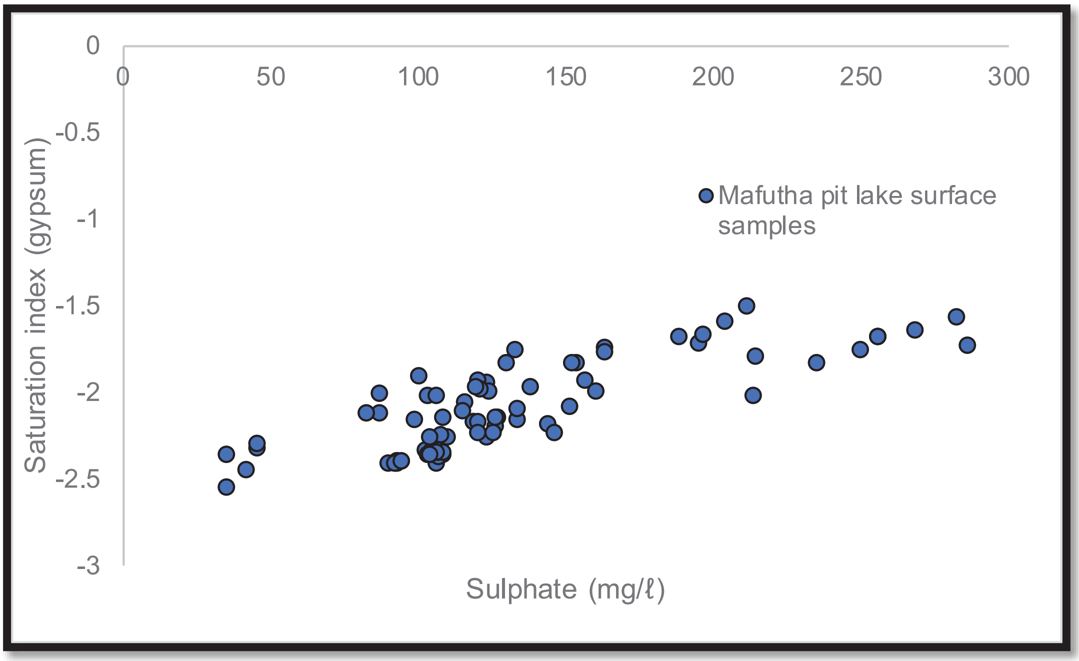


Figure 4-45: Mafutha Pitlake: Saturation index for gypsum.

Together with the temporal variation of the pitlake chemistry, one of the research questions that arose was whether variations of chemical parameters exist with depth at Mafutha. Generally, the hypolimnetic water quality is similar to the epilimnetic water quality. Spatial variability was firstly tested using physicochemical profiles, which showed little variation of the EC, indicating that the mineralisation of the water column was nearly constant with depth. Also, the pH and ORP showed constant values with depth. The only variations were noticed in the temperature, where at 15 m, a thermocline was encountered, with a metalimnetic layer from 15 to 25 m below the surface of the water. At 15 to 20 m below the surface a DO maximum was encountered in the summer. Altogether, 24 samples were collected at various levels during the 1-year monitoring period in the summer, late winter and late spring, at the deepest location in the pitlake.

Plots of the major ions with depth are shown in Figure 4-46. Variations were observed with depth and a shift in the chemistry was observed from the January to the August samples. The first metre of the water column showed higher Cl concentration in the August and November sampling runs. The partial pressure of CO_2 showed a clear increase with depth in the January and November sampling runs, and homogenised, together with the bicarbonate concentration in the August sampling run.

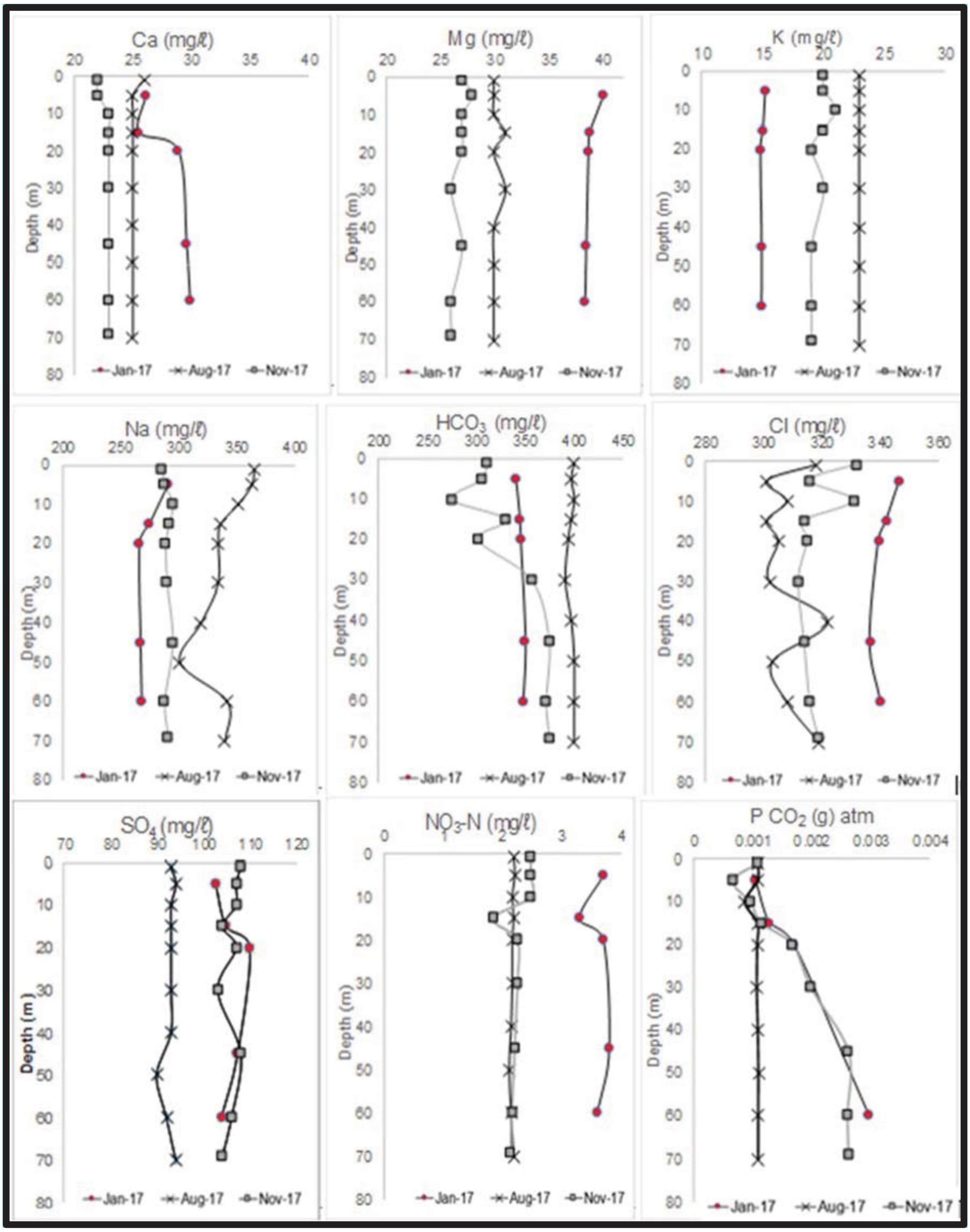


Figure 4-46: Mafutha Pitlake: Plots of major ions and partial pressure of CO_2(g) at of depth samples.

Trace Element Chemistry

At a slightly alkaline pH of the pitlake water, heavy metals are usually not present in significant concentrations. Dissolved Al, Fe and Mn concentrations were below or just above detection limits. According to Hem (1985), Al, in its dissolved form, occurs as the anion $Al(OH)_4$ in waters above neutral pH. Fe usually occurs as colloidal form, while Mn tends to stay in solution at higher solubilities due to Mn being stable over a wider Eh and pH and oxidation of Mn^{2+} is considerably slower than oxidation of Fe^{2+} (Denimal et al., 2005). According to the Eh-pH diagram in Figure 4-47 the Fe in the samples possibly occurs as ferric hydroxides and therefore plot in the $Fe(OH)_3$ field.

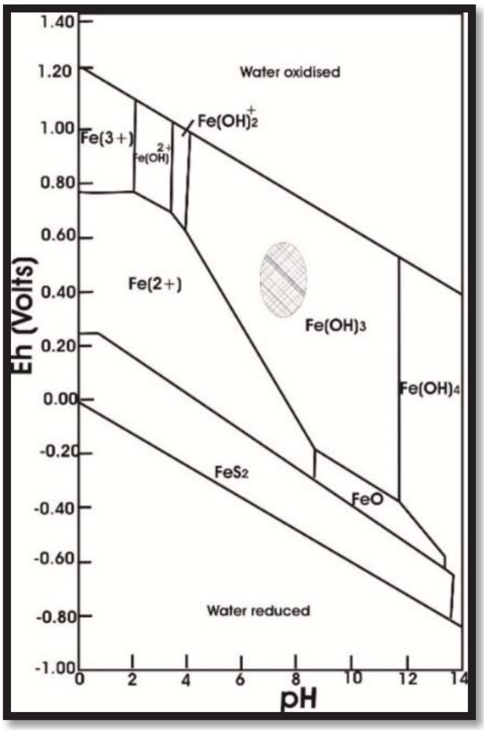


Figure 4-47: Fields of stability of solid and dissolved forms of iron as a function of Eh and pH at 25°C and 1 atmosphere pressure (Modified from Hem, 1985). Pitlake samples plots in the crosshatch area.

Manganese is stable over a wider range of Eh and pH and a massive removal of Mn by precipitation cannot occur in the conditions encountered in the pitlake. The oxidation of Mn2+ is also slower than that of Fe2+(Denimal et al., 2005) and thus explains the occurrence of manganese in the Mn2+ valence state as shown by the Mafutha pitlake samples plotted in Figure 4-48.

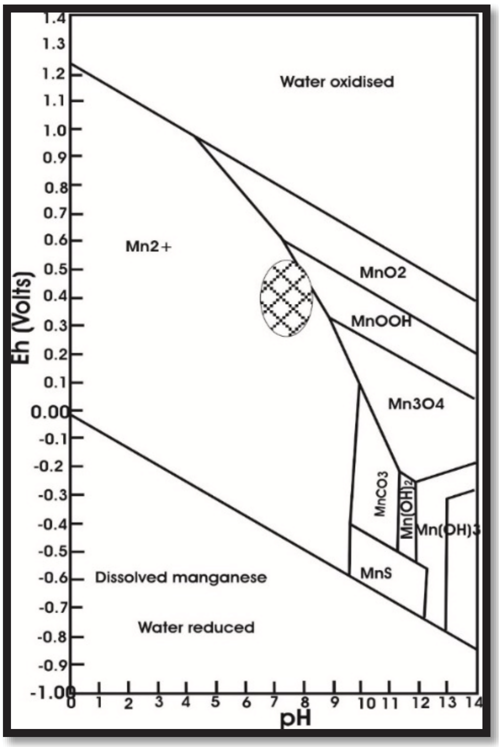


Figure 4-48: Fields of stability of solid and dissolved forms of manganese as a function of Eh and pH at 25°C and 1 atmosphere pressure (Modified from Hem, 1985). Pitlake samples plots in the crosshatch area.

4.11 Pitlake Biota

4.11.1 Phytoplankton

The lake productivity potential of the Mafutha pitlake was investigated by using chlorophyll-a levels, according to the classification scheme of De Lange et al. (2018). Phytoplankton was sampled during the January (summer), August (winter) and November (spring) 2017 sampling events at Mafutha pitlake. The secchi depths were 7 m, 8.5 m and 8 m below the surface for the sampling events, and the euphotic zone was approximately 21 to 24 m (usually calculated as three times the secchi depth). Table 4-6 shows the average nutrient concentrations of nitrogen, phosphorous, silicon in the pitlake measured at the depths where phytoplankton samples were collected. Phosphorous is usually the limiting nutrient, while 'too hard' water may impact on the growth and abundance of certain types of phytoplankton. According to the classification system of McGowan, the water in the Mafutha pitlake is very hard. The phytoplankton population was dominated by the Chlorophyta group during all three sampling events. This is seen in the stack diagram Figure 4-49. During January, the average chlorophyll-a concentration was 3 µg/L and the algal population was dominated by the genus *Ankistrodesmus*. In August, the average chlorophyll-a concentration was 6 µg/L and the algal population was dominated by *Mesotaenium*. In November, the average chlorophyll-a concentration increased to 8.18 µg/L and the algal population was dominated by *Chlorella* and *Chodatella,* as depicted in Figure 4-49, showing the relative abundance of the algal genera analysed in the samples. Algae and chlorophyll-a are mainly influenced by temperature (Vos, 2001). According to the classification scheme of Wetzel (2001), based on the average chlorophyll-a concentration, the trophic status of the Mafutha pitlake is mainly mesotrophic. Results for phytoplankton are presented in Appendix I.

Table 4-6: Mafutha Pitlake: Average concentrations of nutrients, chlorophyll- and secchi depths

Site	Date	Ammonia-N (mg/ℓ)	Nitrate-N (mg/ℓ)	Total Phosphorous (µg/ℓ)	Si (mg/ℓ)	Hardness (as CaCO3 (mg/ℓ)	Average chlorophyll-a (µg/ℓ)	Secchi depth (m)
Mafutha	Jan 2017	-	3.7	-	21.5	230	3	7
	Aug 2017	0.3	2.2	<250	23	187	6	8.5
	Nov 2017	0.1	2.3	<250	22	167	8	8

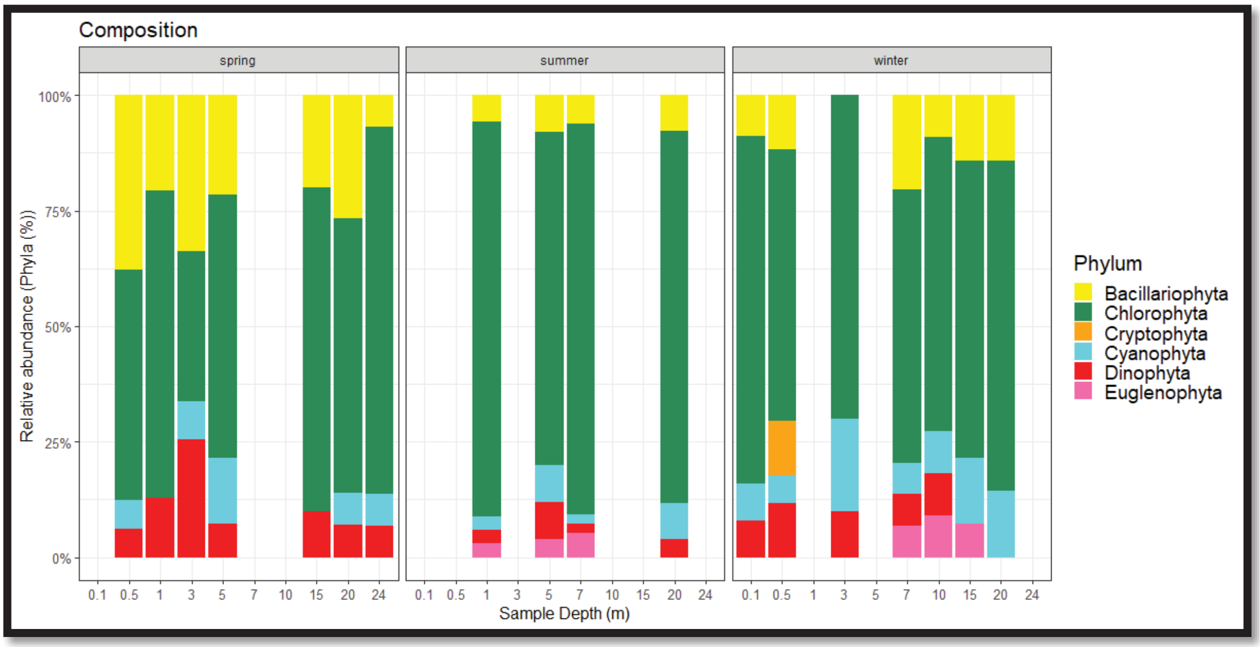


Figure 4-49: Mafutha Pitlake: Stack diagrams of the relative abundance of phyla

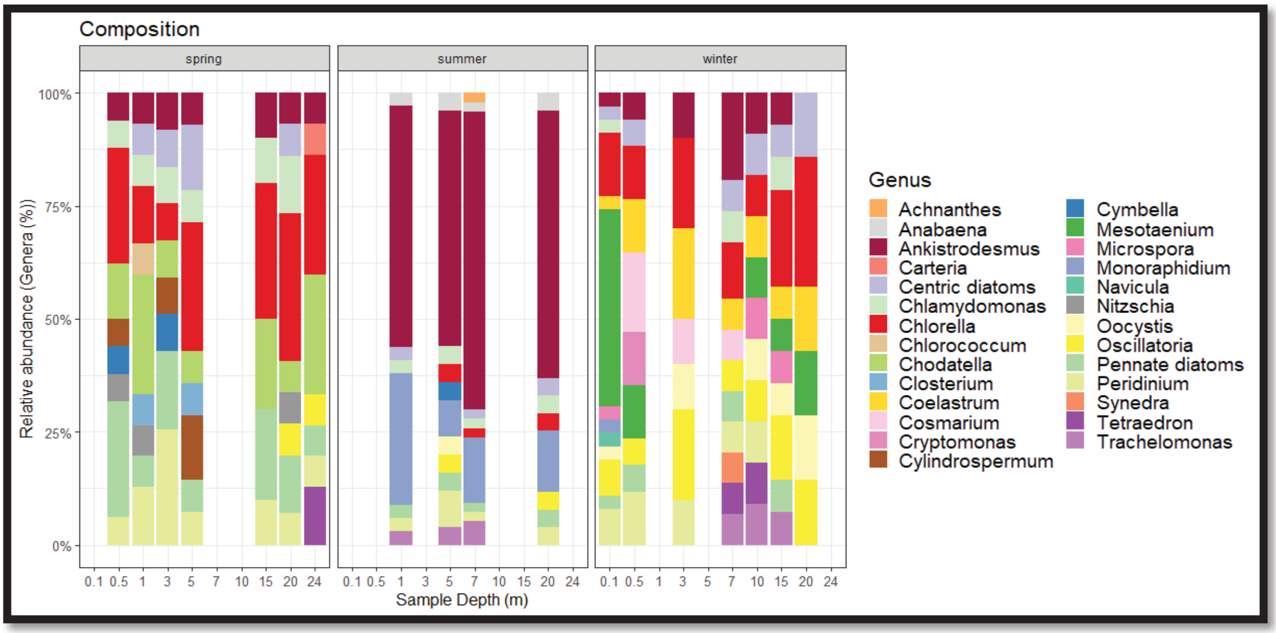


Figure 4-50: Mafutha Pitlake: Stack diagrams showing the relative abundance of genera

4.11.2 Microbiology

The microbial diversity for Mafutha was sampled at 5 m and 45 m, as no significant changes occurred in the ORP or dissolved solids with depth, hence detailed sampling intervals were not applicable. The microbial population was dominated by Proteobacteria, consisting 50% for the 5 m sample and 65% of the 45 m sample (see Figure 4-51). Other relative abundant bacteria included Planctomycetes, Actinobacteria, Bacteriodetes, Chloroflexi and Cyanobacteria. The dominant metabolic functions of the bacteria were aerobic chemoheterotrophs, aromatic compound degradation, human pathogens and animal parasites or symbionts. A full microbial report drawn up by the Department of Biotechnology at the UFS is documented in Appendix M: Microbial Report.

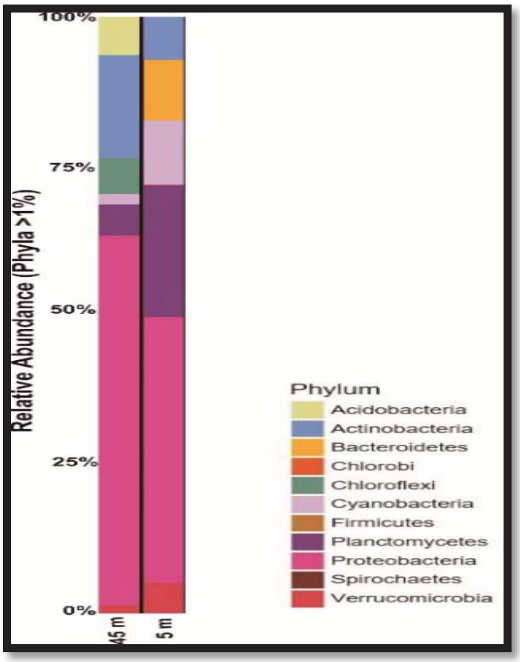


Figure 4-51: Mafutha Pitlake: Microbial diversity (Phylum level) at 5 m and 45 m.

4.11.3 Conclusions

Conclusions drawn from Mafutha pitlake were:

- Mafutha is a terminal sink and no discharge of the pitlake water is expected into the surrounding aquifer.
- The major contribution to the inflow is groundwater 90%. The only outflow from the lake is evaporation
- The groundwater inflow from the surrounding aquifer has a sodium bicarbonate to sodium chloride signature and is the major contributor to the dissolve salts in the Mafutha Pitlake.
- The pitlake water of Mafutha sodium-chloride type which was constant over the period of analyses.
- The groundwater quality shows a dominance of sodium and chloride with TDS of 780 mg/l and a pH of 7.4, while the pitlake had a TDS of 1000 to 1100 and pH of 8.1. The higher TDS in the pitlake is a direct result initially of dissolution of salts on the sidewall of the pit prior to flooding and lately to of evaporation and concentration of salts.
- The pitlake showed thermal stratification which divided the water column into an upper epilimnion of 15 m and lower hypolimnion of 55 m. The epilimnion showed slightly higher TDS than the hypolimnion, possibly evidence of evaporation effects. The thermal stratification and subsequent turnover during the winter did not impact the chemistry of the pitlake but homogenised all the physicochemical parameters.
- An enrichment of Na indicated that possible ion exchange processes were active which added additional Na to the water. Higher initial concentrations of SO_4 were found in the pitlake during early stages of filling are due the dissolution of oxidation products and salts on the sidewalls of the pit.
- The Mafutha pitlake filled within five years to steady state water level. This rapid filling excluded further sulphide oxidation. Hence, the pitlake is not expected to attain much higher sulphate levels or turn acidic.
- The spatial variability of the water in the pitlake is remarkably small. This is be ascribed to high turnover and dynamic circulation of the water in the pit.
- The Mafutha pitlake displayed an overall good water quality and microbial diversity.

In terms of the objectives of the study the author opinion that the Mafutha Pitlake is environmentally sustainable, ecologically stable and requires no remedial action.

We do however recommend that the existing groundwater and pitlake water monitoring program be continued to support the mine closure application

CHAPTER 5: KRIEL COLLIERY

5.1 Introduction

Kriel Colliery (29° 14' 12.33" E; 26° 17' 13.85" S) is an underground and opencast coal mine located either of the R545, between the towns of Ogies and Bethal in Mpumalanga (Figure 5-1). Kriel Colliery lies in the Kriel Magisterial District and is served by the Highveld Regional Services Council, Ga Nala Municipality. The Kriel coal mine lease area spans approximately 25 000 ha and the end of life of mine is expected to be reached in 2019, when it will be revised for further mining until 2026. Extraction of coal started with underground operations in 1975 with the A1 and northwest shafts. During 1978, opencast operations commenced with the mining of Pit 1 and 3. The underground mine employs a combination of continuous mining and conventional mechanised bord and pillar mining. The opencast operation are strip mining. Proven coal reserves in the Kriel Coalfield are the No 2, 4 and 5 seams, but only the No 4 seam is economically extracted. The coal is ranked as low-grade bituminous steam coal and the depth of the coal seam ranges from 6 m to 85 m below the ground, with an average coal seam thickness of 4.9 m. All coal historically and currently produced is dedicated to the Kriel Power station.

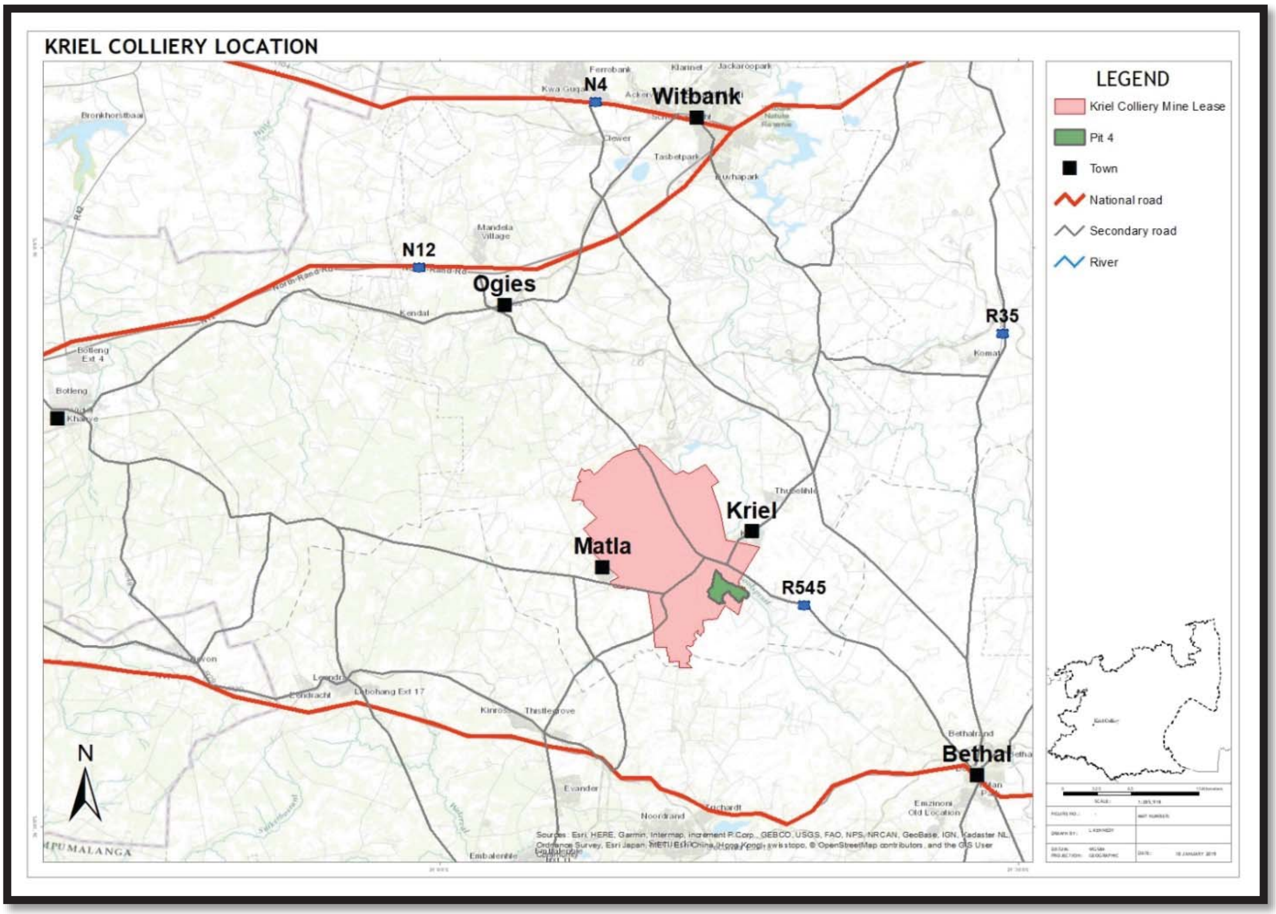


Figure 5-1: Kriel Colliery location.

5.2 Mining

Open cast mining in Pit 4 commenced in 1996 and ended in 2005. The pit was mined by strip mining method using draglines with concurrent rehabilitation. At the end of mining, the final voids were left to fill naturally with water. The lake inflow was groundwater dominated, where the groundwater was made up of a combination of groundwater from surrounding aquifers and rainfall infiltrating backfill reporting to the pit. The early rehabilitation work done in the pits conformed to the requirements of the legislation at that time. The low-lying areas were planned to be utilised as evaporation dams, while the voids in the deeper areas were filled in with spoils to create a free-draining surface. This was done to facilitate free drainage from the area and to minimise the runoff into the pitlakes (AMCOAL Kriel Colliery EMPR, 1993). The shallower areas were rehabilitated by using excess materials from other areas of the pit and leaving final voids as part of an evaporation dam to provide water for agriculturally usable land.

Pit 4 is bound on the west the Dwars-in-die-Weg spruit and on the east the Steenkoolspruit. The confluence of two streams occurs to the north of Ramp 44 North. The pitlakes included in the study are Ramp 44 North, Ramp 44 South and Ramp 42 South, and the locations are shown in Figure 5-2.

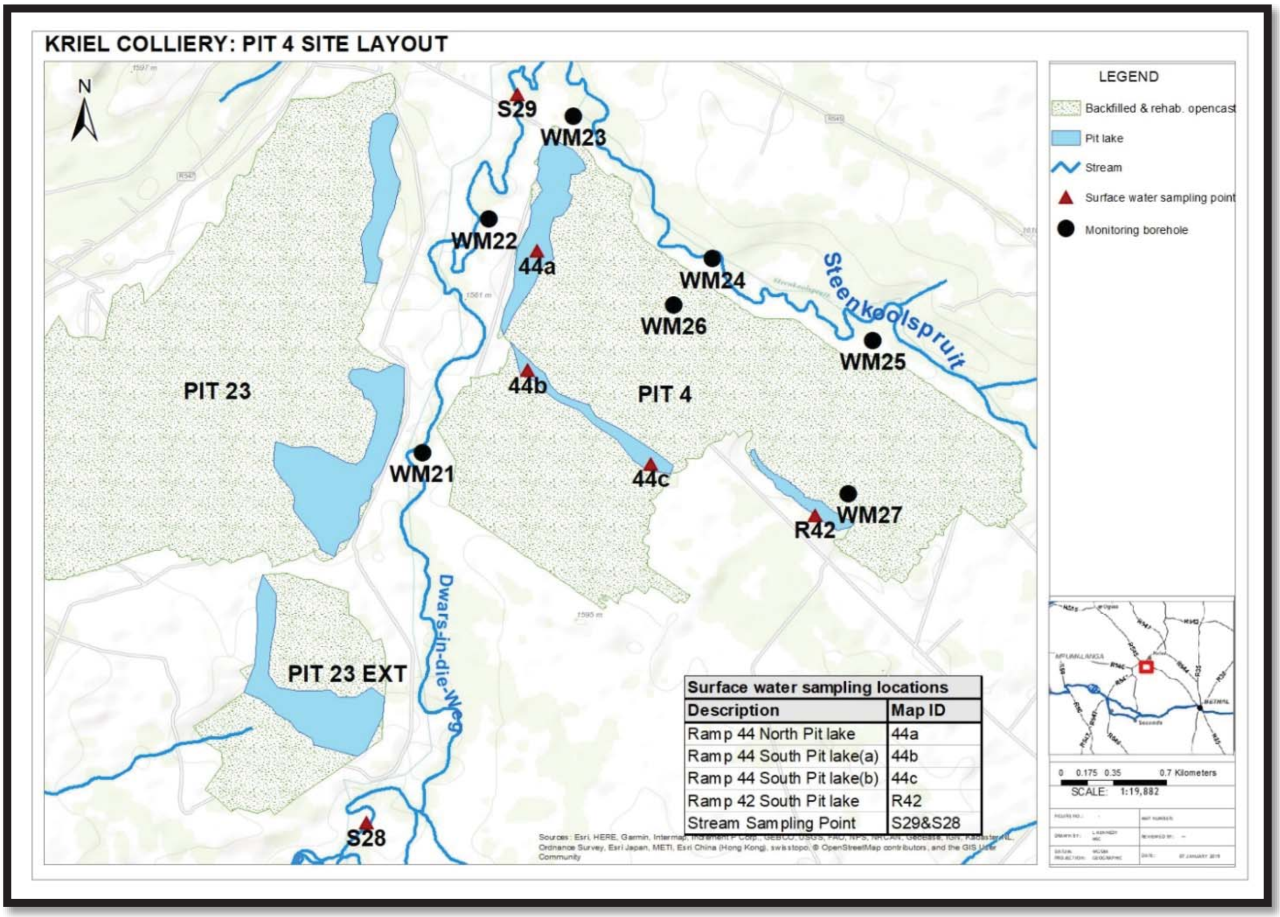


Figure 5-2: Kriel Pitlakes: Groundwater, pitlake and river monitoring locations

The post mining land capability of the pits consists of a mixture of arable, grazing and wetland, with the evaporation dams forming a part of the wetland. Additionally, all the gradients created on rehabilitated areas were designed to allow for free drainage of the backfilled areas. The final rehabilitation for Pit 4 was completed in 2010. The perimeter of the pitlakes was surrounded by this summer vegetation as shown in the photograph of Ramp 44 North (Plate 3). Plate 4 shows the Ramp 44 South pitlake, with the Matla and Kriel Power Stations in the background. The rehabilitation of Ramp 42 South (Plate 5) was not as complete at the time of the study and had side walls of the pitlake had steep sides, a highwall and erosion channels.

Plate 3: Kriel Pitlake 4: Ramp 44 North, looking north, 29 March 2017.

Plate 4: Kriel Pitlake; Ramp 44 South, looking east, 10 May 2017.

Plate 5: Kriel Pitlake: Pit 4 Ramp 42 South, looking North-West, 10 May 2017.

The coal floor dips towards the south-east and as a consequence, the pitlakes in the south-east of the mining area (R42 South) are deeper than the pitlakes in the north-west (Ramp 44 North) as shown in Figure 5-3.

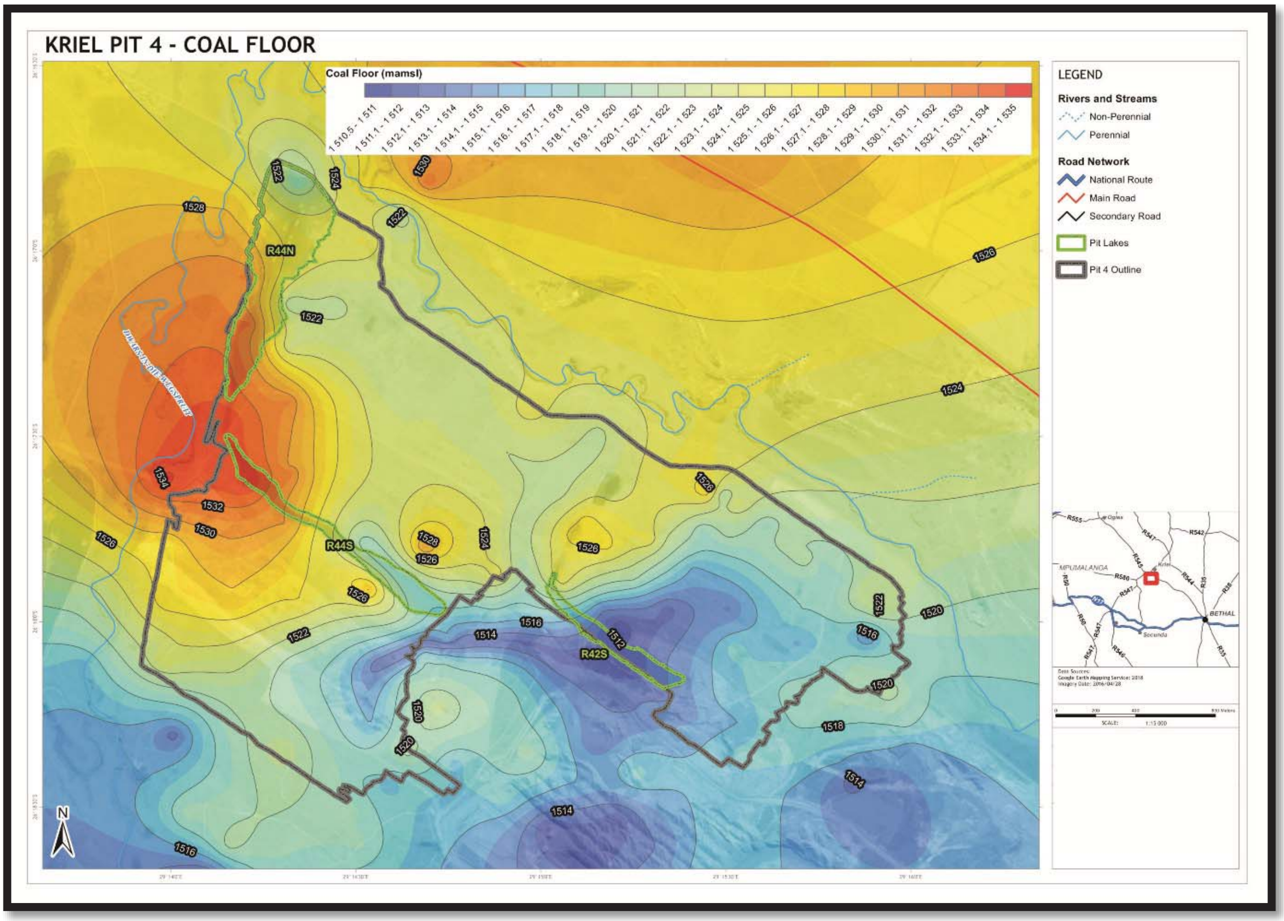


Figure 5-3: Kriel Pitlakes: Coal floor contours for Pit 4 (Data from AMCOAL EMPR Kriel Colliery 1997).

5.3 Pitlake Morphology

The Kriel pitlakes have a rectangular shape with depths of less than 10 m. The bathymetric maps of the three pitlakes investigated at Kriel Colliery, are provided in Figure 5-4 to Figure 5-7. The shapes of the pitlakes reflect their origin, being created by dragline operations which left long, narrow basins with cross sections that are steep-sided and shallow. Contouring during the rehabilitation process have reduced the angle of the sidewalls at Ramp 44 North and South. Ramp 42 has a steep high-wall along the southern shoreline.

44a (Ramp 44 North): Pitlake 44a has a depth of 6 m with the bottom of the pitlake at an elevation of 1531 mamsl and the top of the pitlake at an elevation of 1537 mamsl. The bottom of the pitlake contains backfilled material of 5 m in height from the bottom of the coal floor.

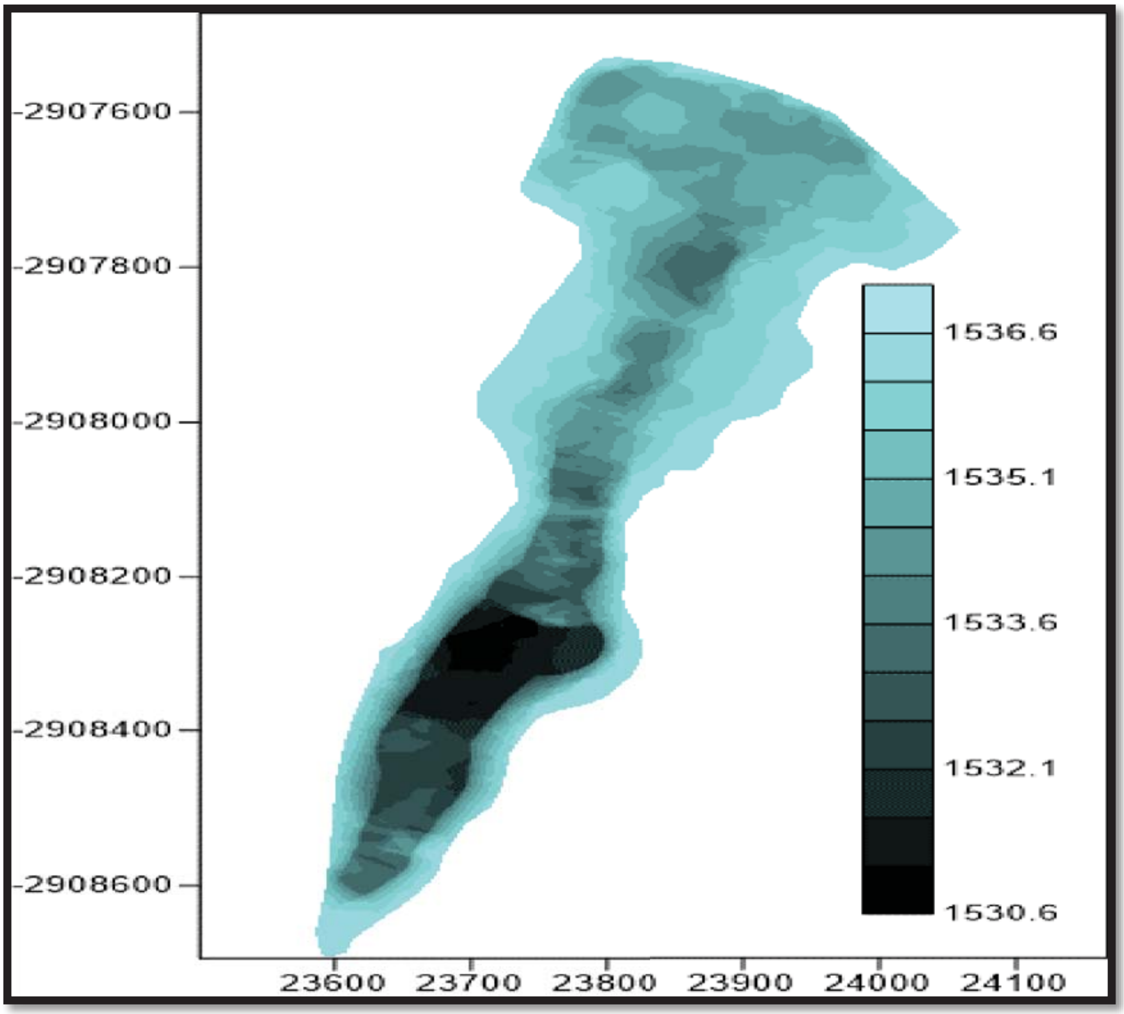


Figure 5-4: Kriel 44 North: Pitlake 44a – Bathymetric map.

44b (Ramp 44 South): Pitlake 44b has a depth of 5.4 m with the bottom of the pitlake at an elevation of 1531.6 mamsl and the top of the pitlake at an elevation of 1537 mamsl. The bottom of the pitlake contains backfilled material of 2 m in height from the bottom of the coal floor.

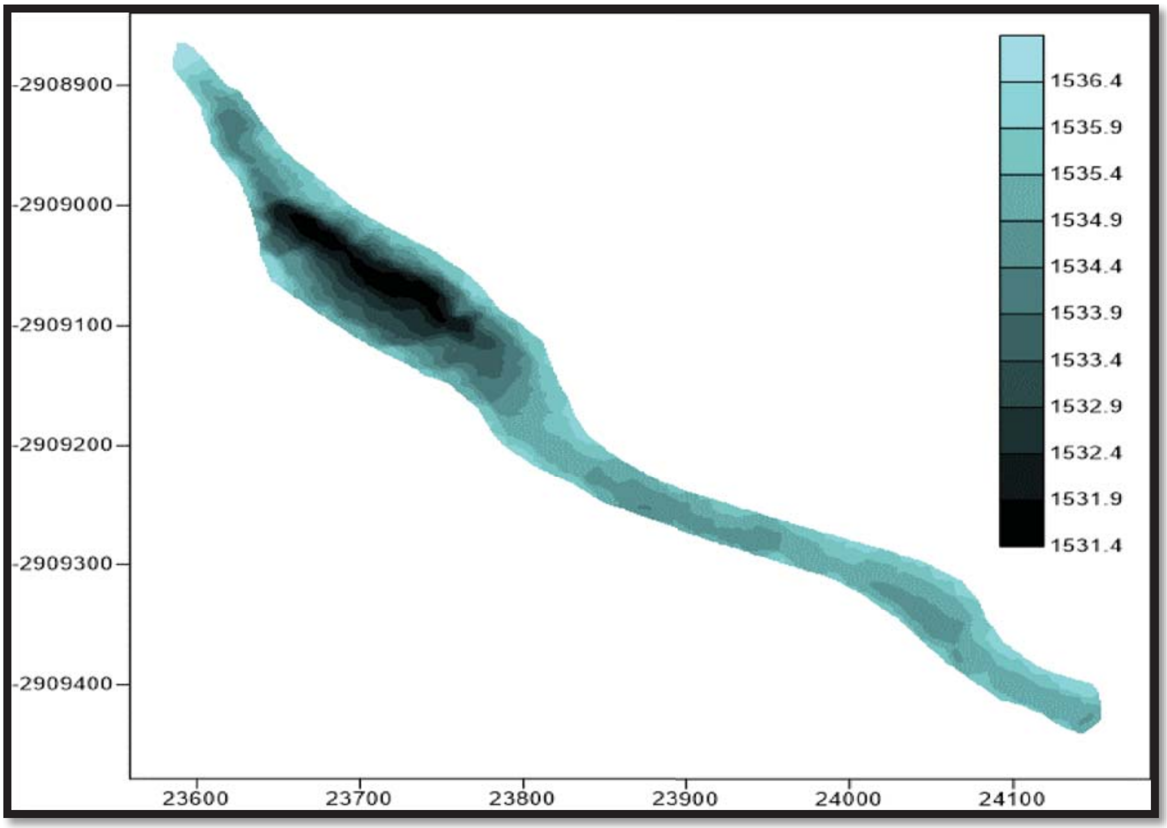


Figure 5-5: Kriel Ramp 44 South Pitlake 44b – Bathymetric map.

44c Ramp 44 South: Pitlake 44c has a depth of 6 m with the bottom of the pitlake at an elevation of 1526.5 mamsl and the top of the pitlake at an elevation of 1537 mamsl. The bottom of the pitlake contains backfilled material of 7.5 m in height from the bottom of the coal floor.

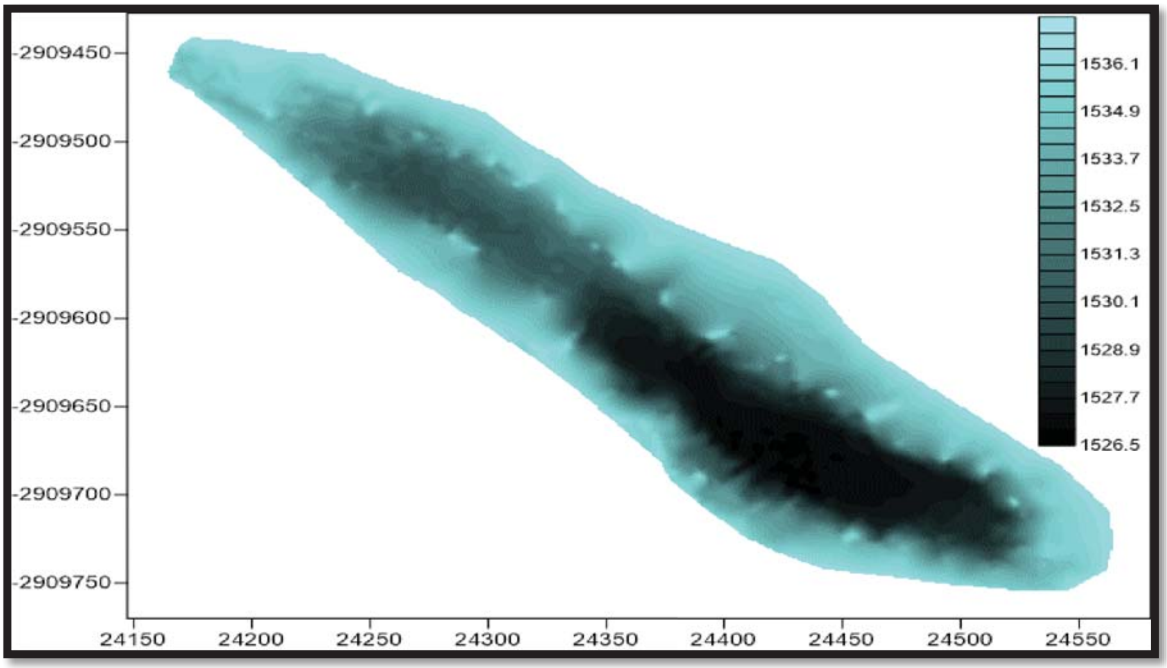


Figure 5-6: Kriel Ramp 44 South – Pitlake 44c Bathymetric Map

R42: Pitlake R42 has a depth of 13.1 m with the bottom of the pitlake at an elevation of 1523.9 mamsl and the top of the pitlake at an elevation of 1537 mamsl. The bottom of the pitlake contains backfilled material of 5 m in height from the bottom of the coal floor.

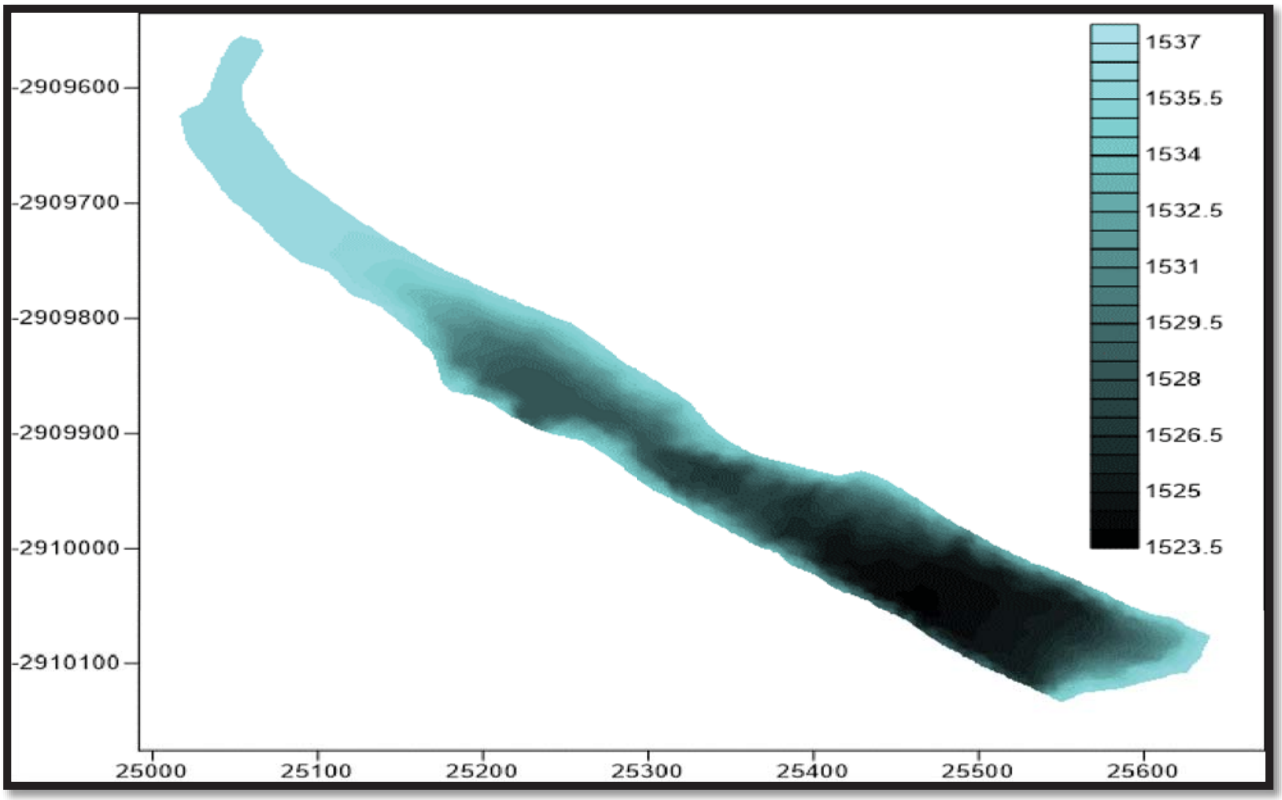


Figure 5-7: Kriel Ramp 42 Pitlake R42 – Bathymetric map.

Table 5-1: Summary of Pitlake physical properties.

Pitlake Name	Age (years)	Depth (m)	Total Volume (m^3)	Area (m^2)
44a	13	6	424932.2	180 770
44b	13	5.4	85956.38	54 154
44c	13	10.5	202428.1	42 750
R42	13	13.1	327638.7	56 197

5.4 Geology and Structural Geology

The Highveld Coalfield in the Mpumalanga Province of South Africa is situated on the northern part of the main Karoo Basin. The Karoo Supergroup can be divided into the Dwyka, Ecca, Beaufort, Stormberg and Drakensberg Groups.

The Highveld Coalfield is underlain by a thin sequence of Dwyka and Middle Ecca strata lying on an undulating floor composed of felsites, granites, and diabase associated with the Bushveld Complex (Buchan et al., 1980). The Dwyka Group consists of tillite (Lurie, 2008), siltstone and sometimes shale (Grobbelaar et al., 2004).

The Vryheid Formation of the Ecca Group, where the coal occurs, conformably overlies the tillite with minor conglomerates, sandstones, shales and coal (Cadle, 1990). In the Highveld (and Witbank) coal fields, the glacial deposits of the Dwyka Group are directly overlain by rocks of the Vryheid formation, as the Pietermaritzburg formation is absent in these coal fields. The overlying Volksrust Formation is also either not developed or completely eroded away in the central Mpumalanga coal fields (Johnson et al., 2006; Huisamen, 2017; Hancox and Götz, 2014).

Pre-Karoo dolerites have greatly intruded the geological sequence of the Highveld Coalfield. There are two main dolerite sills in the coalfield, with more extensive thinner sills 1.5 m to 15 m thick (Buchan et al., 1980). Where a dolerite sill has intruded, the seam is faulted, resulting in a vertical throw ranging from 6 to 25 m (Buchan et al., 1980).

A major dolerite sill of up to 14 m is generally situated below the No. 2 seam in the Pit 4, 23 and 23 extension areas (AMCOAL Kriel Colliery EMPR, 1993). A 1:250 000 Geological map of the Kriel study area is provided in Figure 5-8.

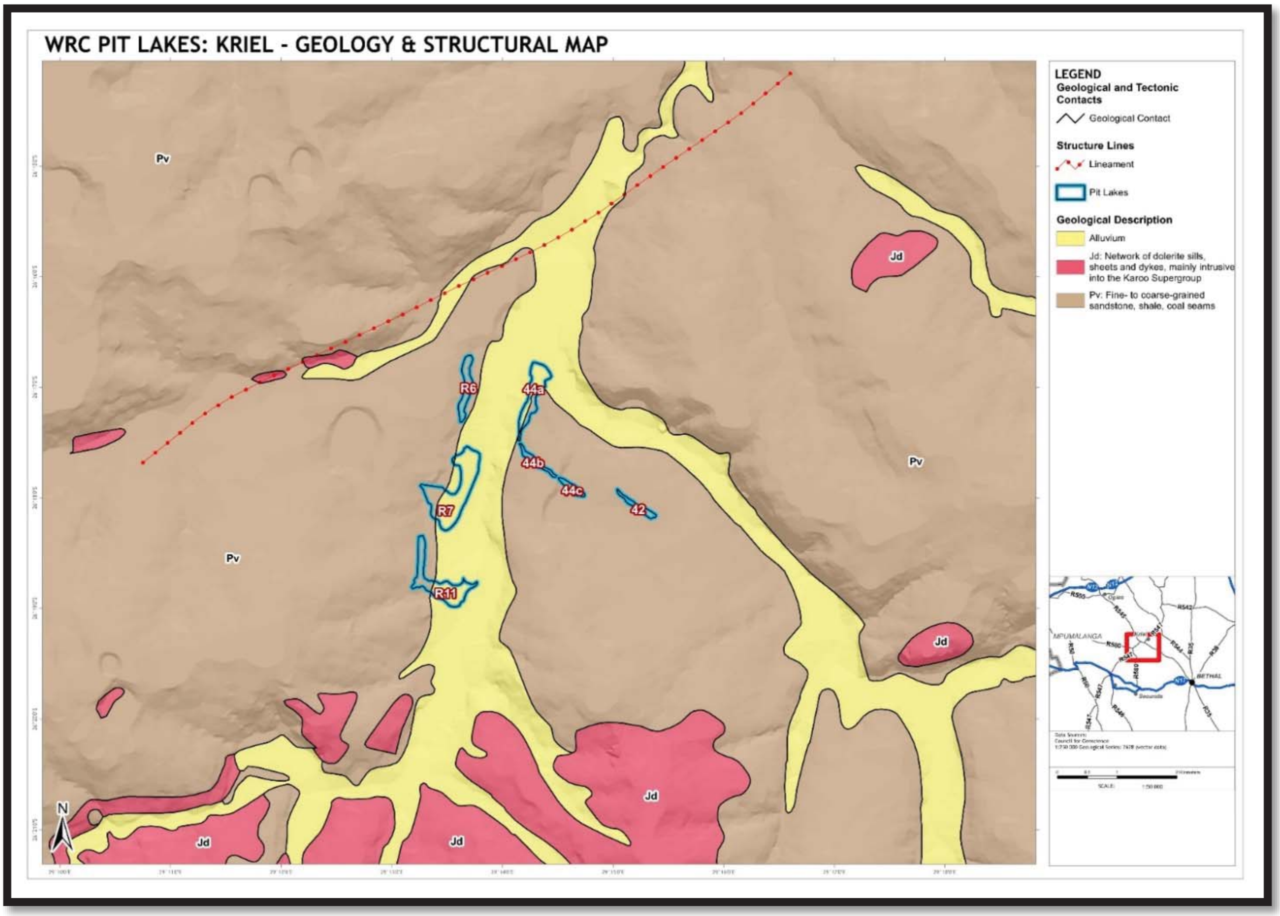


Figure 5-8: Geology of Kriel Colliery.

The basin depth is approximately 300 m (Jeffrey, 2005), with the coal zone approximately 70 m thick. Five major coal seams occur in the Highveld, numbered from the bottom upwards, No. 1, 2, 3, 4, and 5 (Jeffrey, 2005). The coal seams are generally described as follows:

- No.1 Seam is thin and mainly discontinuous
- No.2 Seam is approximately 1.5-4 m
- No.3 Seam is thin and discontinuous
- No.4 Seam is 1-12 m, laterally continuous

- No.4 Upper Seam is 1-4 m thick and is separated from No.4 Lower Seam which is 4-12 m thick by sandstone
- No.4A Seam occurs above the No.4 Upper Seam
- No.5 Seam is 1-2 m thin.

The majority of the coal mined at Kriel Colliery is from the No.4 Seam. The lithological profile depicted in Figure 5-9 shows that sandstone is the dominant sedimentary rock unit. Closer inspection of the No. 4 seam in Figure 5-10 shows that the sandstone adjacent to the coal seam occasionally includes thin alternating layers of carbonaceous shale. The total thickness of the No.4 Seam in the Kriel coal field is generally between 4 and 5 m thick, where the top seam attains a thickness of 1.5 to 2 m. The No 4 seam is regionally overlain by a thick interlaminated shale-sandstone/siltstone and underlain by a typical white Ecca sandstone layer. Glauconitic sandstone, indicative of transgressive marine periods, is present above the Nos. 4 and 5 coal seams, forming useful stratigraphic markers (Zhao, 2010).

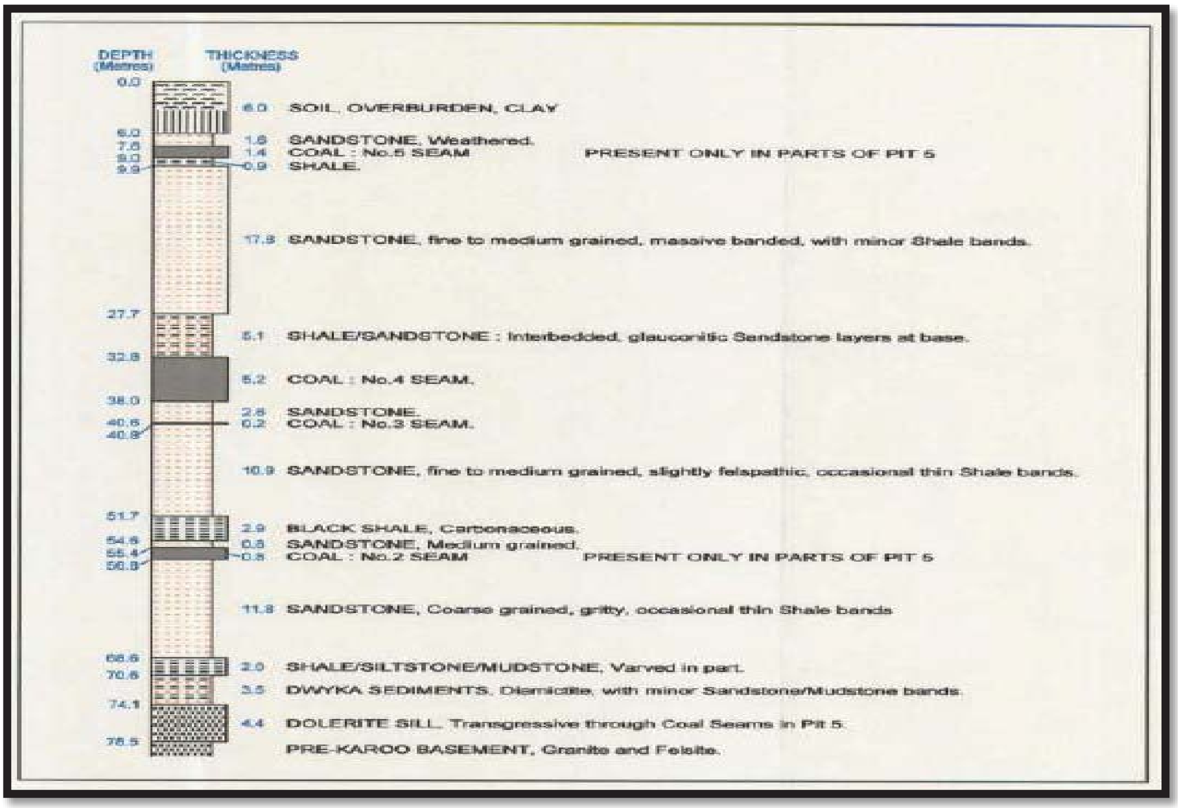


Figure 5-9: Kriel Pitlake: Typical lithological profile.

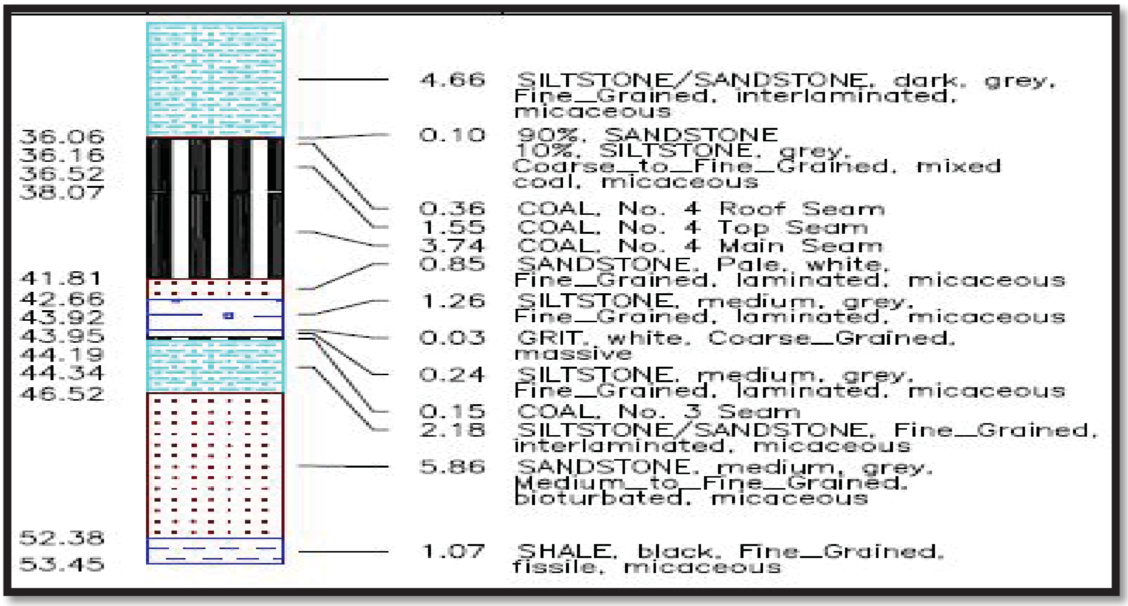


Figure 5-10: Kriel No. 4: Coal seam lithology.

5.5 Mineralogy and Geochemistry

The mineralogy and geochemistry of the Ecca sediments have previously been researched in detail by Azzie (2002). XRD tests were performed on sandstone, shale and silt from the overlying strata, as well as tests conducted on coal from the No 4 seam.

From XRD interpretations Azzie (2002) derived that kaolinite and quartz are the main mineral constituents in all rock samples, while feldspars occur in major to minor proportions. Illite and siderite were present in major to minor amounts while pyrite, calcite and dolomite were present in minor to trace proportions in the shales and siltstones. Table 5-2 shows the mineralogy (wt%) for the number four coal seam, analysed by the Siroquant method, where Ab= albite; An = anorthite; Ant = Anatase; Ap = apatite; Cal = Calcite; Dol = dolomite; Ill = Illite Kln= kaolinite; Mc = microcline; Qtz = Quartz; Sd =siderite.

Table 5-2: Mineralogy of Kriel Colliery sediments and coal (Siroquant analysis) taken from Azzie (2002).

Lithology	Qtz	Mc	Ab	An	Ill	Kln	Cal	Dol	Sd	Ap	Py	Ant	Total
shale	24.6	8.5	5.2	7.7	15.6	36.6	0	0.3	1		0.7		100.2
Sandstone	62.7	13.4	7.7	5.3		5.7	2.5	0.8	1.8		0		99.9
Silt	38.7	11.7	12.1		10.9	17.7	0	0.1	8.5		0.3		100
Coal	41.8					36.9	0	0.8	1.5	16	3.1		100.1
Coal	22.1	1.1				26.5	6	1.1	1.4		41.7		99.9
Coal	51.2					41.5	1.5	2.5			3.3		100
Coal	21.9					36.1	17.5	8.8			14.6	1.1	100
Coal	0.2					18	57.1	8.3	2.3	10.3	2.2	1.6	100

In general, the ABA from previous studies indicated that the lithology at Kriel is not acid producing. Sediments which have been found to have high acid potential were the shales and to a lesser degree the carbonaceous siltstones (Usher et al., 2003). For details of ABA conducted on Kriel, the reader is referred to Usher et al. (2003), an earlier Water Research Commission (WRC) report comprising geochemical data on backfilled opencast mines in the Highveld and Witbank coal mine areas.

The backfill in rehabilitated pits usually consists of waste rock and a small quantity of discard, and the material is covered with a 1 m (or thicker) sandy-loam soil layer. Table 5-3 contains data of ABA conducted in the rehabilitated Pit 23 Extension, adjacent to Pit 4 in the Kriel Mine lease area. From the data, it is evident that the excavated material mainly contains acid neutralising rocks, except for the contact sandstone and shales above and below the No 4 seam that are acid producing (NPR < 1 and negative NNP). These rock units may contain significant sulphide minerals such as pyrite that can oxidise to ultimately form sulphuric acid. Additionally, the No.5 seam has also been found to be strongly acid producing with an NPR < 1 and negative NNP <-20 kg$CaCO_3$/tonne. Even if the acid producing materials at the contacts with the No 4 seam were not removed, enough neutralising potential exists within the other rock materials to buffer the acidity.

Table 5-3: Acid generating potential of rock samples analysed at Kriel Colliery (Data from Usher et al., 2003)

Lithology		Initial pH	Final pH	Acid (open)	Acid (Closed)	Base	NNP (Open)	NNP (Closed)	NPR (open)	NPR (closed)
Soil		7.38	6.91	0.03	0.06	2.52	2.49	2.46	86.83	43.41
Soil	SANDY	7.53	5.46	0.15	0.31	0.99	0.83	0.68	6.40	3.21
Sandstone	MASSIVE	8.33	6.13	0.07	0.13	0.81	0.74	0.68	12.10	6.05
Sandstone/shale	INTERBURDEN	7.24	6.57	0.08	0.15	3.40	3.33	3.25	44.18	22.09
Sandstone/shale	INTERBURDEN	8.04	5.93	0.40	0.81	9.05	8.64	8.24	22.45	11.22
5 SEAM	SEAM	8.52	2.20	24.17	48.35	9.45	-14.72	-38.89	0.39	0.20
Sandstone/shale	INTERBURDEN	8.29	6.42	3.07	6.14	6.37	3.30	0.23	2.07	1.04
Sand		7.84	5.14	0.37	0.75	0.68	0.30	-0.07	1.81	0.91
Shale		6.72	3.17	0.25	0.50	-0.98	-1.23	-1.48	-3.92	-1.97
Sandstone		7.82	4.74	0.85	1.71	1.10	0.25	-0.61	1.29	0.64
Sandstone/shale/siltstone		7.86	4.33	3.86	7.72	12.13	8.27	4.41	3.14	1.57
Sandstone	MASSIVE	8.84	8.88	0.32	0.63	70.79	70.47	70.15	223.30	111.65
Sandstone/shale	INTERBURDEN	8.42	8.77	0.34	0.67	33.01	32.68	32.34	98.25	49.13
Sandstone/shale	INTERBURDEN	8.46	8.27	0.31	0.61	21.63	21.32	21.01	70.45	35.22
Sandstone/shale	INTERBURDEN	8.15	3.46	22.97	45.95	21.95	-1.03	-24.00	0.96	0.48
4 SEAM	SEAM	8.89	6.67	18.36	36.71	46.94	28.58	10.23	2.56	1.28
Sandstone/shale	INTERBURDEN	7.88	4.11	3.12	6.24	0.87	-2.25	-5.37	0.28	0.14

NNP = NP-AP; NPR = NP/AP

5.6 Hydrogeology

Du Plesis (2008) describes aquifers of the Mpumalanga Coalfields as follows:

- Weathered zone aquifer
  The aquifer consists of the weathered Ecca Group material, occurring at depths varying between 1 to 25 mbgl with high transmissivities values.

- Fractured rock aquifer
  The aquifer consists of solid Ecca and Dwyka Group rocks, with higher transmissivities as a result of fractures. Groundwater movement in this aquifer is through fractures.
  During the field investigation, it was observed that the boreholes' yields in the undisturbed Karoo strata varied between 0.14 L/s to 1.35 L/s.

At Kriel Colliery, the pitlakes are situated in the weathered zone, with groundwater levels at 1.25 to 3.48 mbgl for the Karoo aquifer around the excavation. For the in-pit boreholes ("IBH"), the water levels were deeper and resided at 6.46 to 20.84 mbgl. The groundwater flow direction was determined and shows the flow direction towards north east, mimicking the coal floor (Figure 5-11Figure 5-11:).

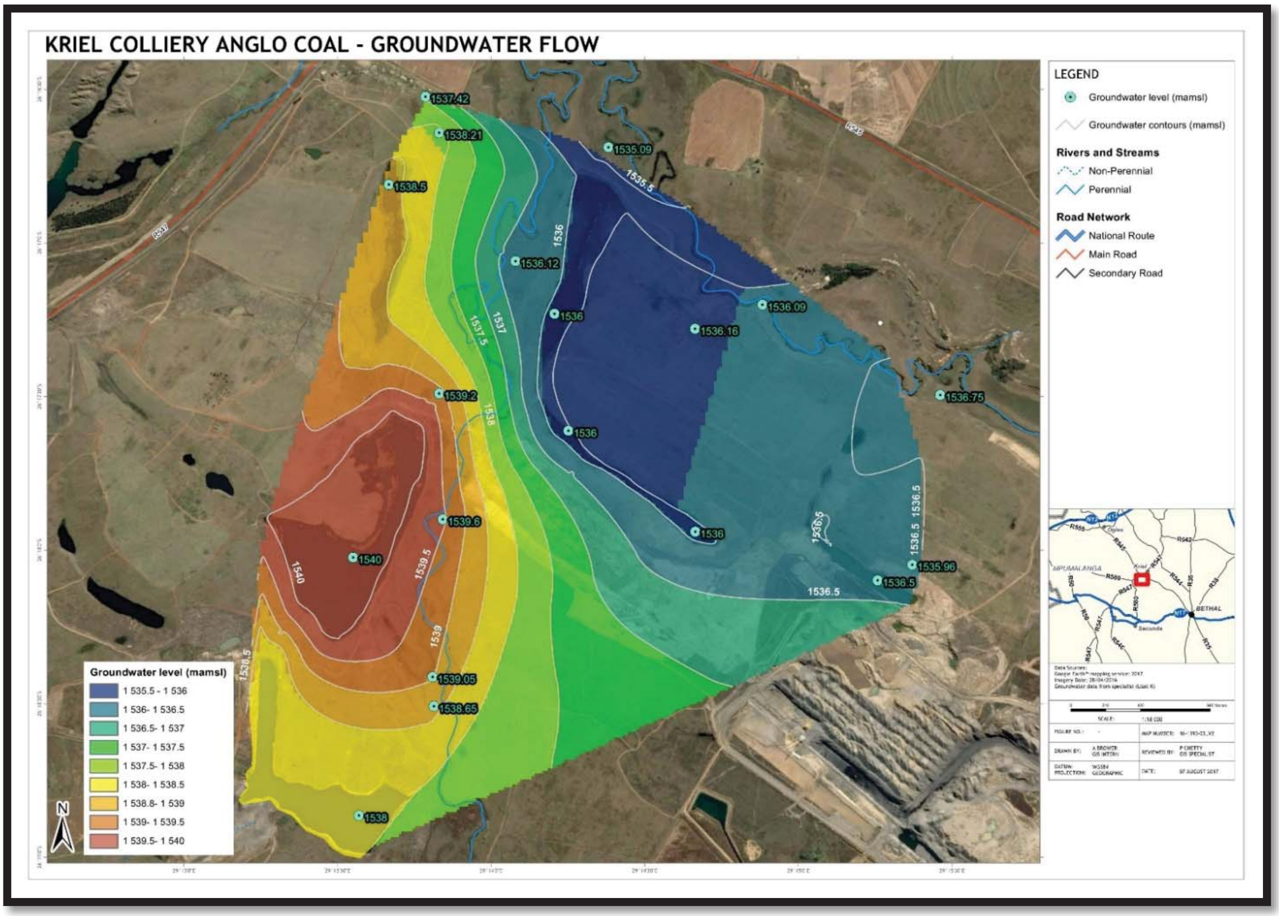


Figure 5-11: Kriel Pitlake: Groundwater flow map.

Water Levels

Groundwater levels were determined by the investigation of seven boreholes (WM21-WM27) located on the site, two of which (WM26 and WM27) are drilled in the backfilled material (called in-pit boreholes “IBH”) and five drilled on the perimeter of the excavation (called out-pit boreholes “OBH”). The range of groundwater levels is 0.9 to 7.56 mbgl in the undisturbed Karoo aquifer. Water levels in the boreholes drilled in the backfilled material are deeper than in the undisturbed ground. The SWL of the seven boreholes ranges from 1.25-20.84 mbgl during the April 2017 investigation. All the boreholes show similar trends (Figure 5-12), where slight variations in water levels are observed and may be associated with seasonal change and rainfall recharge. A poor relationship exists between the surface elevation and groundwater elevation, as shown in Figure 5-11 details of the boreholes and is listed in Table 5-4 below:

Table 5-4: Kriel Boreholes (September 2016).

BH ID	Latitude	Longitude	Location	Depth (m)	Diameter (mm)	Elevation (m)	SWL (mbgl)	SWL (mamsl)
WM 21	-26.29832	29.23072	OBH	26.1	125	1540.85	1.25	1539.23
WM 22	-26.28432	29.23469	OBH	42	123	1537.9	1.78	1535.75
WM 23	-26.278165	29.23973	OBH	29	98	1537.09	2.0	1534.79
WM 24	-26.28669	29.24807	OBH	42.5	123	1539.34	3.34	1535.74
WM 25	-26.29158	29.25771	OBH	29.5	98	1540.23	3.48	1536.23
WM 26	-26.28802	29.24735	IBH	19	75	1542.62	6.46	1535.62
WM 27	-26.30079	29.2562	IBH	33	75	1556.8	20.84	1535.52

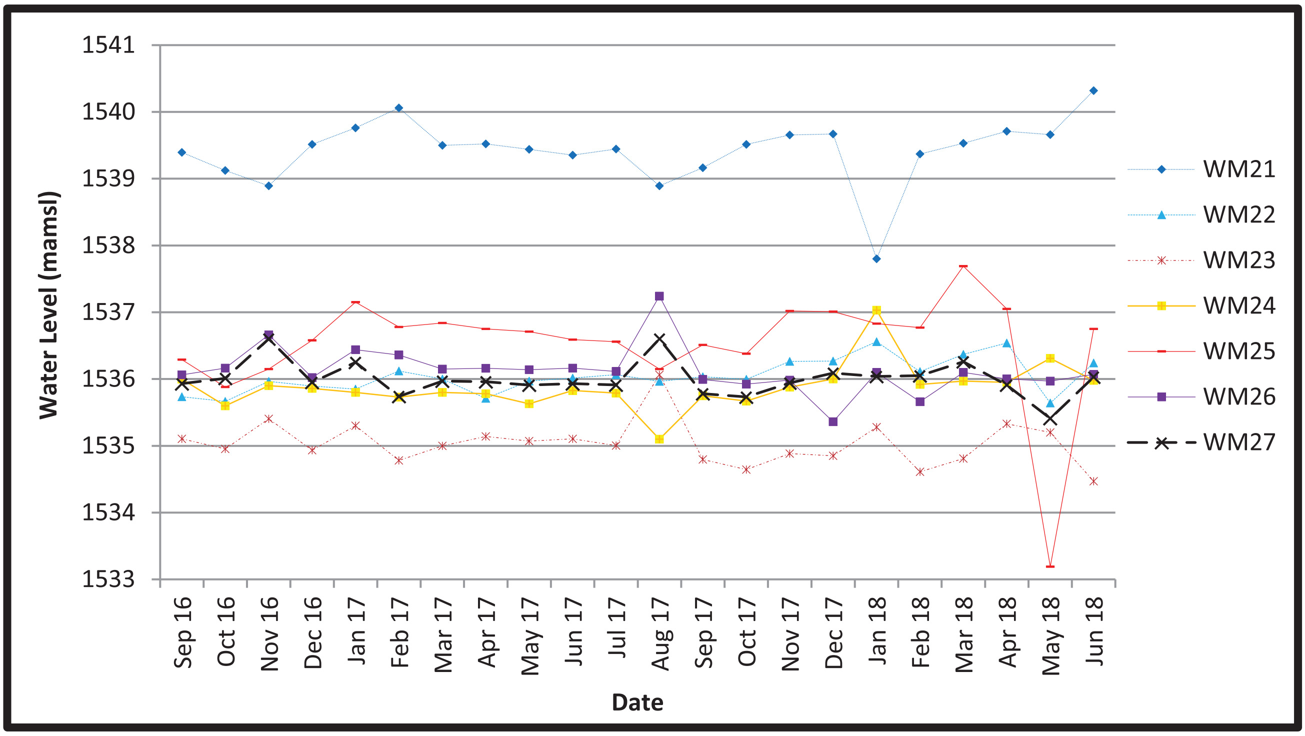


Figure 5-12: Kriel Pitlake: Monitoring boreholes hydrographs

Aquifer Testing

Of the seven boreholes located on site, only one could be tested by means of a CDT due to the small diameters (less than 100 mm) of the boreholes or low yielding results (less than 0.1 ℓ/s). Aquifer tests were conducted to determine the aquifer parameters, viz. transmissivity (T) and hydraulic conductivity (K).

A 6 hour-discharge test was conducted on WM21 at a rate of 0.77 ℓ/s, with the pump setting 24 mbgl. To ensure that the discharge rate of 0.77 ℓ/s remained constant, discharge measurements were taken every 30 minutes. The available drawdown was recorded as 18.67 m. No observation boreholes were at close vicinity to the borehole for monitoring.

Using the Jacob Cooper method, analysis of the results obtained from WM21 CDT, the average transmissivity calculated using the transmissivities of the early-time and late-time is 1.65 m^2/day.

Slug testing was conducted on boreholes with smaller diameters, where a measured volume of water is displaced, and the recovery time was measured. Transmissivity values varied between 0.37 to 8.69 m^2/day. High transmissivities were observed in the boreholes located within the backfill material. Transmissivity values obtained from each of the boreholes are provided in Table 5-5.

Table 5-5: Slug Test T-values (OBH are "outpit boreholes", IBH are "in-pit boreholes")

BH ID	Location	T (m^2/day)
WM21	OBH	1.65
WM22	OBH	0.42
WM23	OBH	3.47
WM24	OBH	0.91
WM25	OBH	0.37
WM26	IBH	6.03
WM27	IBH	8.69

5.7 Conceptual Hydrogeological Model

The Kriel Pitlakes are due to a shortfall in backfill material and insufficient bulk capacity. The Kriel pitlakes vary in age, size and depth, with pitlakes R6, R7 and R11 22 to 27 years in age, and Pit 4 is 13 years. There are two rivers near the study area, the Dwars-in-die-Wegspruit, which forms the southwest to northeast boundary and the Steenkoolspruit, which forms the southeast to northwest boundary. The conceptual hydrogeological model is shown in Figure 5-13 and cross sectional is based on a profile line in Figure 5 12. The undisturbed geology backfilled, and coal floor is incorporated into the conceptual models. The water balance models incorporates the backfilled areas and assumes groundwater inflow from the undisturbed aquifer is insignificant. To account for this, the Dupuit-Forchheimer analytical equation (which assumes an elliptical water table) is used and not the Dupuit equation, which assumes a parabolic water table.

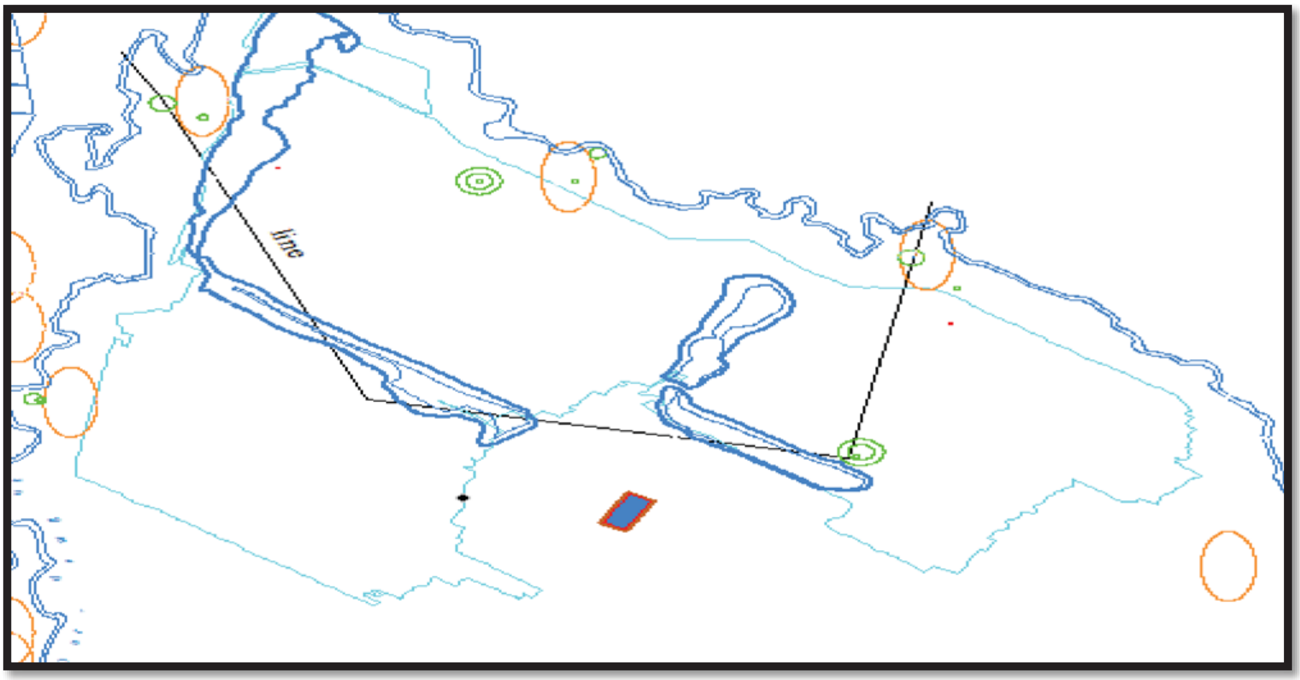


Figure 5-13: Profile line.

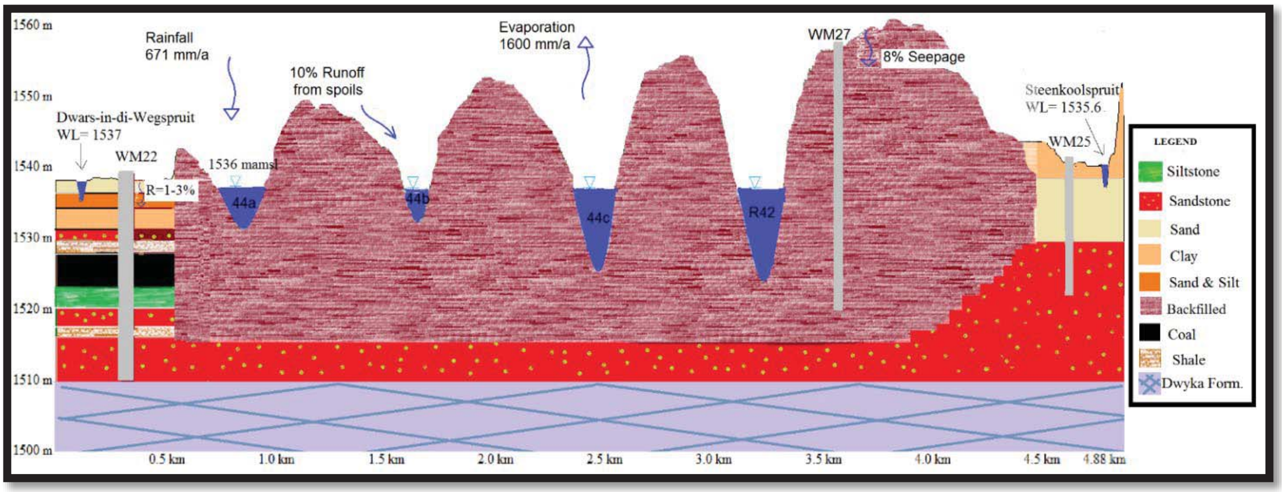


Figure 5-14: Kriel Pitlake: Conceptual hydrogeological model.

5.8 Water Balance Model

The Kriel water balance model used the following equation and solved for the paramentes to determine the water balance of the pitlakes:

$$\Delta S = P + GW_{karoo} + GW_{Backfill} + Ro_{Backfilled} - E - D$$

Where:

ΔS is change in storage, *P* is precipitation, GW_{karoo} is groundwater inflow from the underground workings, $GW_{Backfill}$ is groundwater inflow from the backfiled material, $Ro_{Backfilled}$ is runoff from the backfilled material, *E* is the evaporation and *D* is the surface discharge.

Assumptions and Limitations

- The model assumes that production ceased on the 31st of December 2005, the date on which the pits began to fill with water, and which is the start of the simulation.
- Each of the pitlakes was modelled individually
- No pit water level measurements are available and pit levels were taken from LiDAR data from 2003 to 2017.
- There are no site rainfall records Kriel and rainfall data from the WR2012 database was relied upon and used as input for the model.
- For this study, water balance modelling was only completed on for Ramp 44 pitlakes.

Rainfall

The B11D quaternary catchment falls in the rainfall zone B1A and has a MAP value of 671 mm/a. Groundwater recharge onto undisturbed aquifer is estimated at an average 5% of MAP (Usher, 2003). No reliable site specific data were available for this site and climatic data were obtained from the WR2012 database which has data from 1920 to 2009. Summer rainfall is observed with minimal rainfall during the winter months. Monthly rainfall data from 2005 to 2009 will be used and thereafter average annual rainfall data will be used.

Runoff

The surface topographical elevation across the study area varies, with the minimum elevation at 1512.5 mamsl and the maximum elevation at 1607 mamsl. The topography dips towards the streams at an average slope of 3.72°. The B11D quaternary catchment has a net area of 536.9 km^2. The two main surface drainages in the Kriel lease area are the Steenkoolspruit and the Dwars-in-die-Wegspruit.

Hydrogeological properties of the backfilled material differ from that of the undisturbed ground and were therefore considered during the water balance modelling in terms of recharge and runoff coefficient. Recharge to the backfilled material was assigned a greater value due to the increased porosity. Runoff areas for each pitlake were delineated using digital terrain models (Figure 5-15Figure 5-15:). The runoff coefficient used for the Kriel pitlakes was 10%, as suggested by (Hodgson and Krantz, 1995).

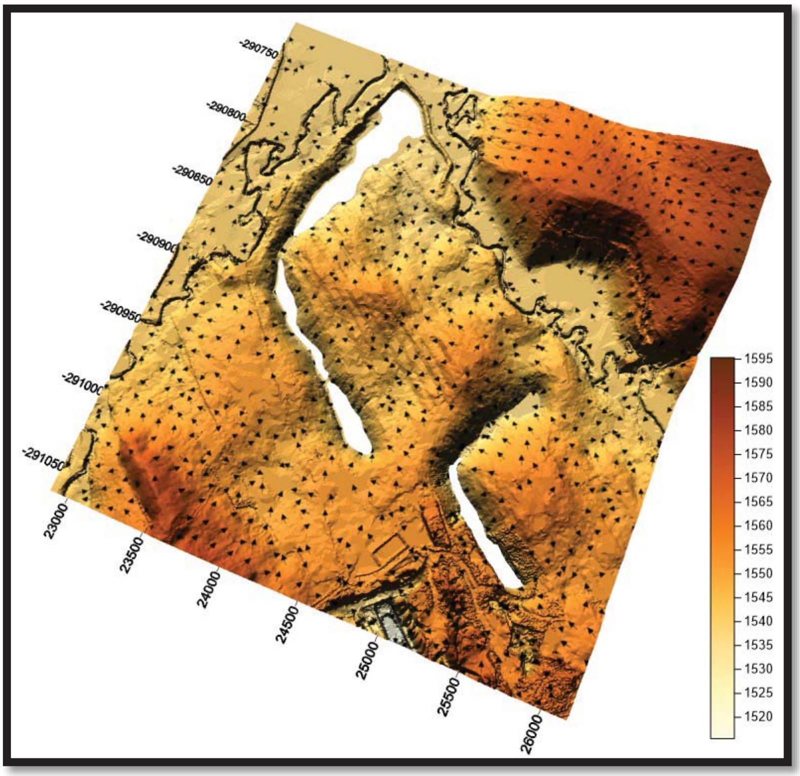


Figure 5-15: Kriel Pitlake: Surface Topography

Groundwater Inflow

Groundwater inflow to the Kriel pitlakes is calculated using the Dupuit-Forchheimer, as discussed in section 2.3.1 of the report.

Evaporation

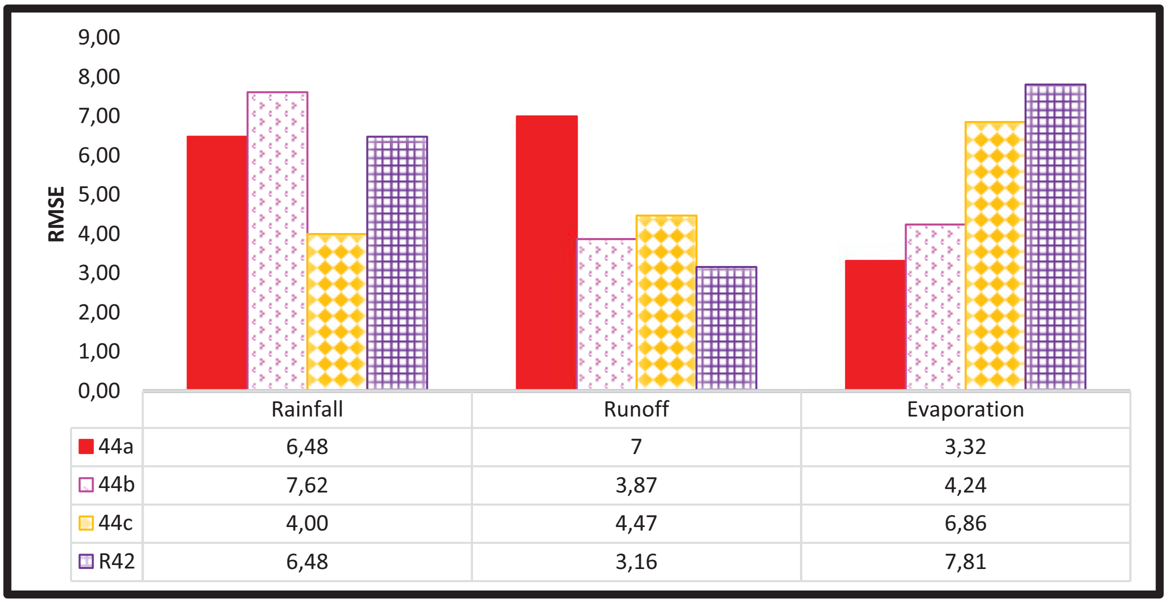
The catchment falls into evaporation zone 4A, and thus has a MAE value of 1600 mm/a. Local Symons-Pan evaporation for evaporation zone 4A is expected to vary as shown in Table 5-6.

Table 5-6: Kriel Monthly Evaporation (WR, 2012)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Evaporation	172	163	179	176	147	145	111	94	76	83	110	143
Lake Evaporation	139.3	133.7	148.6	147.8	129.4	127.6	97.7	81.8	64.6	68.9	89.1	115.8

Sensitivity Analysis

Sensitivity of the pitlake varies for each pitlake model simulation as observed in Figure 5-16. The climatic parameters were increased by 100% to evaluate the effects on the model output. An increase in the evaporation parameter resulted in a water elevation drop of 1 m for pitlakes 44a and 44c, whereas the pitlake water elevation for 44c and R42 were decreased by 4 m (1531 mamsl) and 5 m (1529 mamsl) above the pitlake bottom respectively. The geometry of the pitlakes may be the main influence of this as pitlakes 44c and R42 are slightly deeper than pitlake 44a and 44b.



	Rainfall	Runoff	Evaporation
44a	6,48	7	3,32
44b	7,62	3,87	4,24
44c	4,00	4,47	6,86
R42	6,48	3,16	7,81

Figure 5-16: Kriel Water Balance: Goldsim Sensitivity Analyses

Results

Monthly water balances for the pitlakes are detailed in the Appendices (Appendix B: 44a Water Balance to Appendix E: R42 Water Balance). A summary of the results is given in Table 5-7. The pitlake water balance for all four pitlakes demonstrates similar behaviour. Natural groundwater contribution from the surrounding aquifer into the pitlakes is minimal due to the low hydraulic gradient. Evaporation rate increases as the pitlakes fills due to increased surface areas. Water elevation fluctuations were observed due to seasonal rainfall and once the pitlakes reach equilibrium the majority of flow into the pitlakes is from the backfill material.

If a porosity of 25% is assumed the saturated volume of the backfill material in pit 44 is 3.6×10^{-10} Mm^3.

Table 5-7: Summary of Kriel Pitlakes Water balances

Components	44a	44b	44c	R 42
Groundwater Inflow (%)	46	29	40	58
Rainfall (%)	45	45	38	34
Runoff (%)	10	26	22	8

5.9 Water Quality

5.9.1 Water Quality Profiles

Karoo aquifer and backfilled opencast

The water quality in the Karoo aquifer (out-pit boreholes "OBH") and backfilled opencast area (in-pit boreholes "IBH") were profiled in May 2017 and September 2017 using a multiparameter probe. The boreholes were drilled in September 2016 and the location of the boreholes in shown in Figure 5-12. The results of the vertical profiling and geological logs for OBH boreholes are plotted in Figure 5-17 to Figure 5-21, while the results of the IBH boreholes are plotted on Figure 5-22 and Figure 5-23. The lithological profiles indicated that sandstone is the dominant sedimentary unit in the out-pit boreholes, with varying thickness above the coal seam.

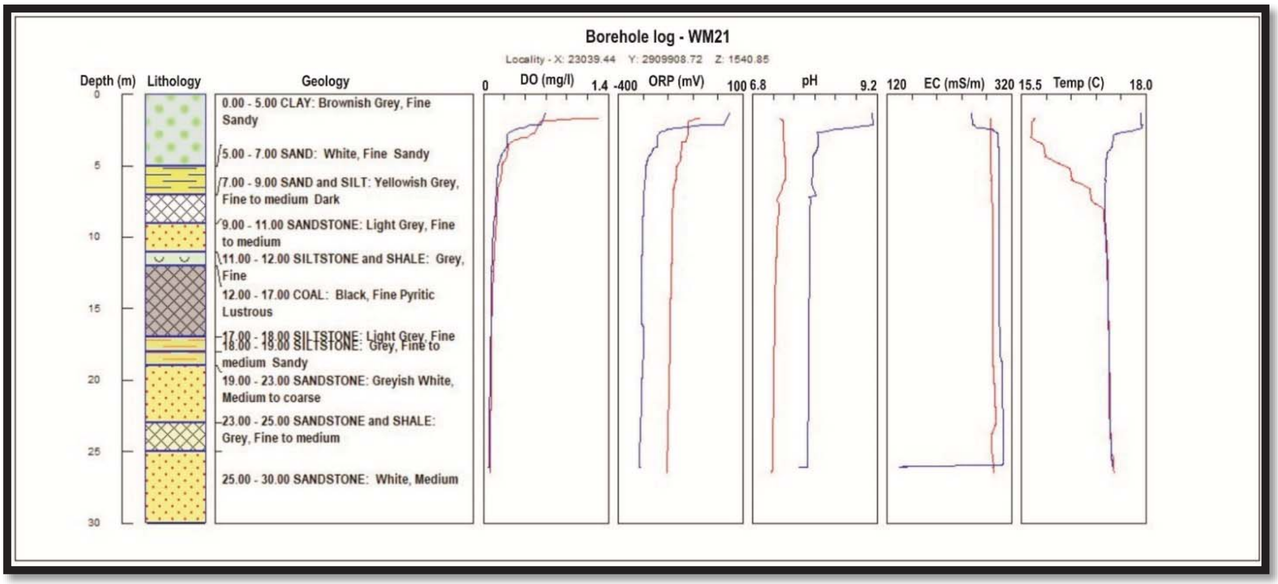


Figure 5-17: Kriel Borehole OBH WM21: Multiparameter Profile.

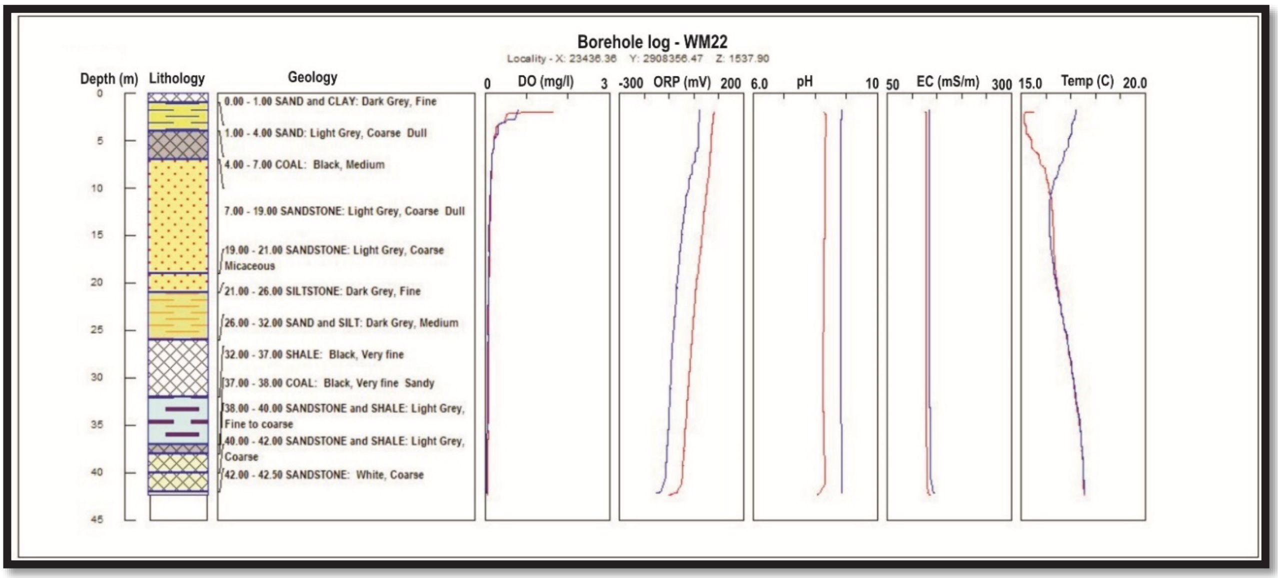


Figure 5-18: Kriel Borehole OBH WM22: Multiparameter profile.

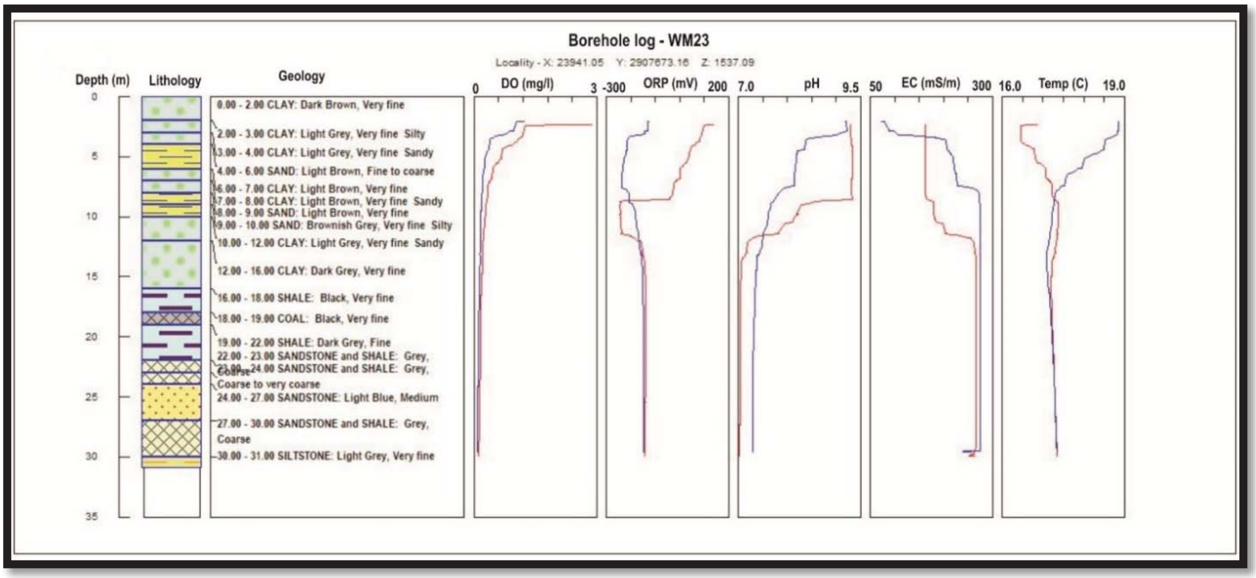


Figure 5-19: Kriel Borehole OBH WM23: Multiparameter profile.

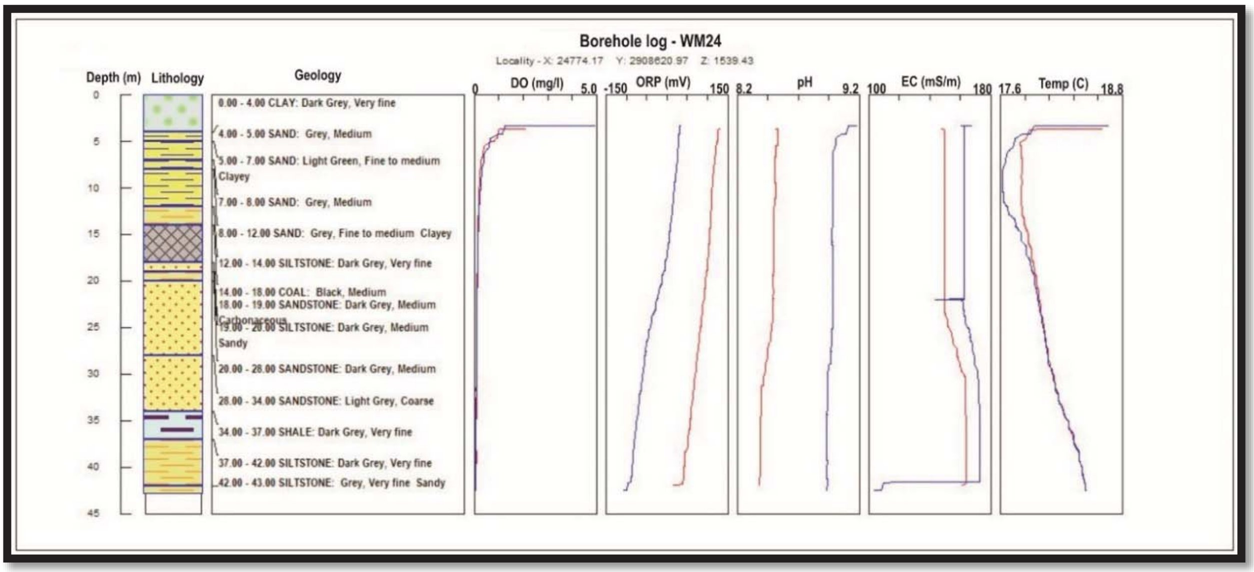


Figure 5-20: Kriel Borehole OBH WM24: Multiparameter profile.

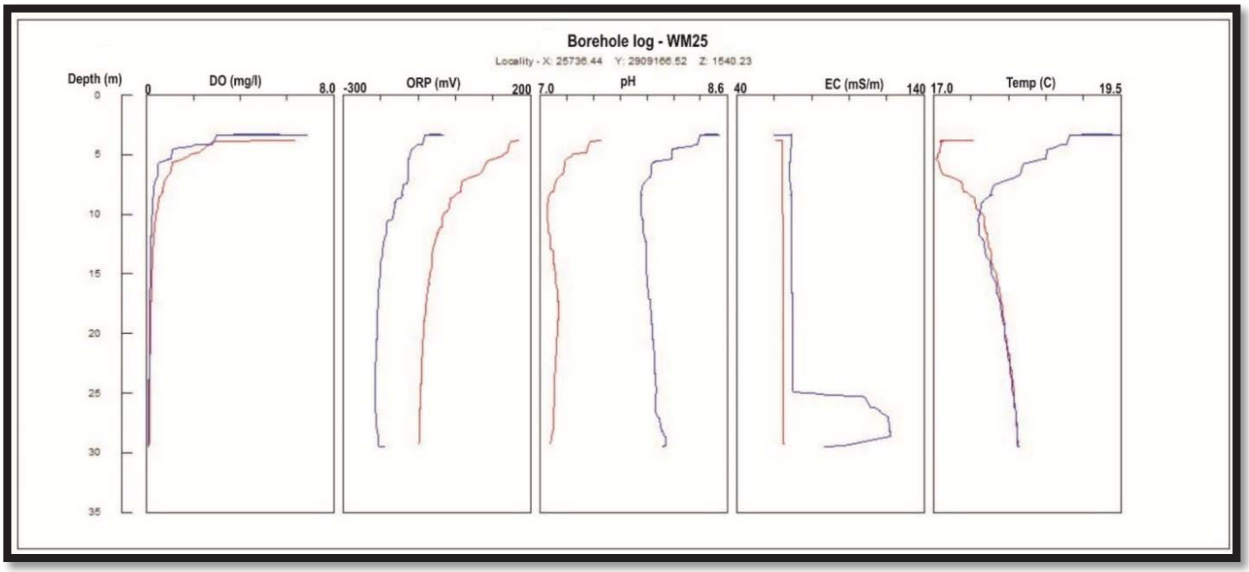


Figure 5-21: Kriel Borehole OBH WM25: Multiparameter profile.

The water quality in the boreholes in the natural aquifer surrounding the pitlakes at Pit 44 can be characterised as follows:

- The groundwater temperature ranged between 16°C and 20°C.
- The DO is oxidising for the first 1-2 m below water level but decreases with depletion levels at 7 mbgl. DO concentrations can reach maximum values of 8 mg/l in water under normal circumstances. However, as rain water infiltrates the ground, dissolved oxygen reacts as part of oxidation/ reduction processes and becomes depleted. The degree of depletion is a function of the influx rate and mineral reactivity (Usher, 2003). The depletion in the DO in the natural aquifer could therefore suggest restrictive recharge into the natural aquifer or extensive interaction with reactive material.
- The EC of the boreholes in the aquifer surrounding the pit varied between 50 and 300 mS/m which is indicative of relatively high mineralisation of the groundwater, suggesting that the aquifer is affected by mining activities. Lower EC at the top of the water column are typically ascribed to rainfall recharge whereas the higher EC water at the bottom is non-circulating water approaching equilibrium conditions (Usher, 2003). High relative EC values were recorded in boreholes WM21 and WM23 with values between 200 mS/m and 300 mS/m, suggestive that the pitlake water and recharge water seeping through the backfilled opencast is impacting on the aquifer in a northern direction towards the confluence of the Dwars-in-die-Weg Spruit and Steenkoolspruit.

The boreholes drilled into the backfilled material had as expected variable geological logs which showed a mixture of clay, sandstone, shale and coal. The logs show that weathered sandstone and shale form the bulk of the backfill volume as seen in Figure 5-22 to Figure 5-23. The backfilled material in the Pit 4 opencast was levelled and covered with 1 to 4 m topsoil and vegetated with grass.

The temperature in the backfill water was not significantly elevated, indicating that sulphide oxidation is mostly excluded by flooding the reactive material. Wetting and drying of the zone above the saturated water level in the spoils occurs. The water levels in the spoils drop during the dry season with a corresponding rise in water in the wet season has the effect of flushing secondary precipitates from the pore spaces. This high TDS water flows into the pitlakes.

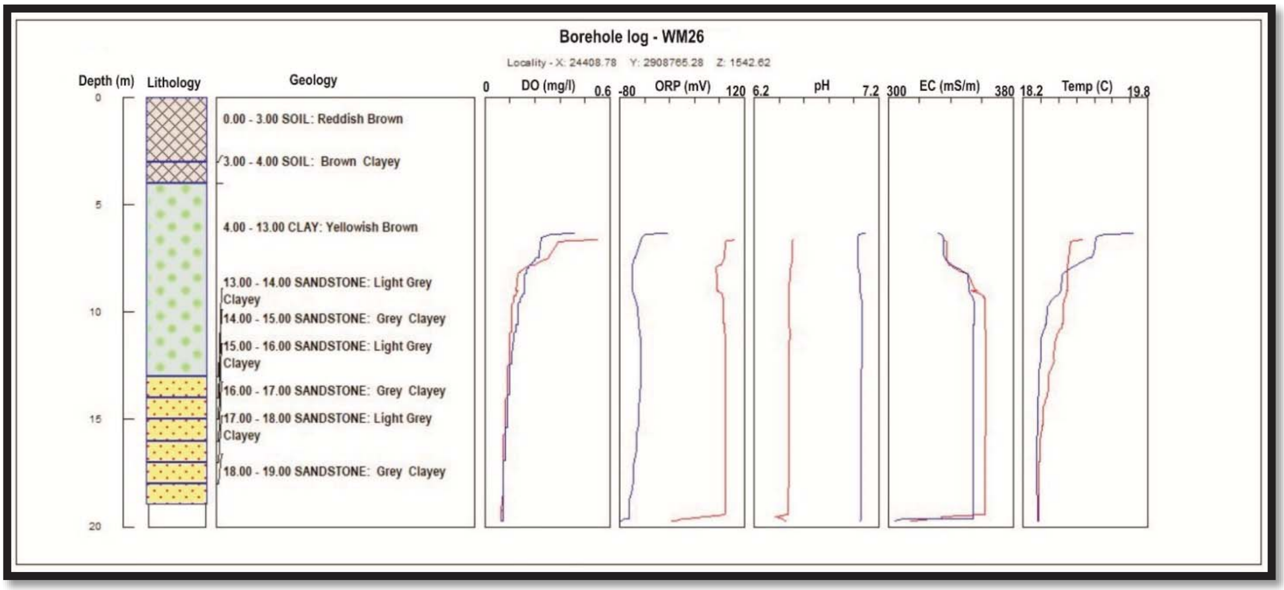


Figure 5-22: Kriel Borehole WM26: Multiparameter profiles.

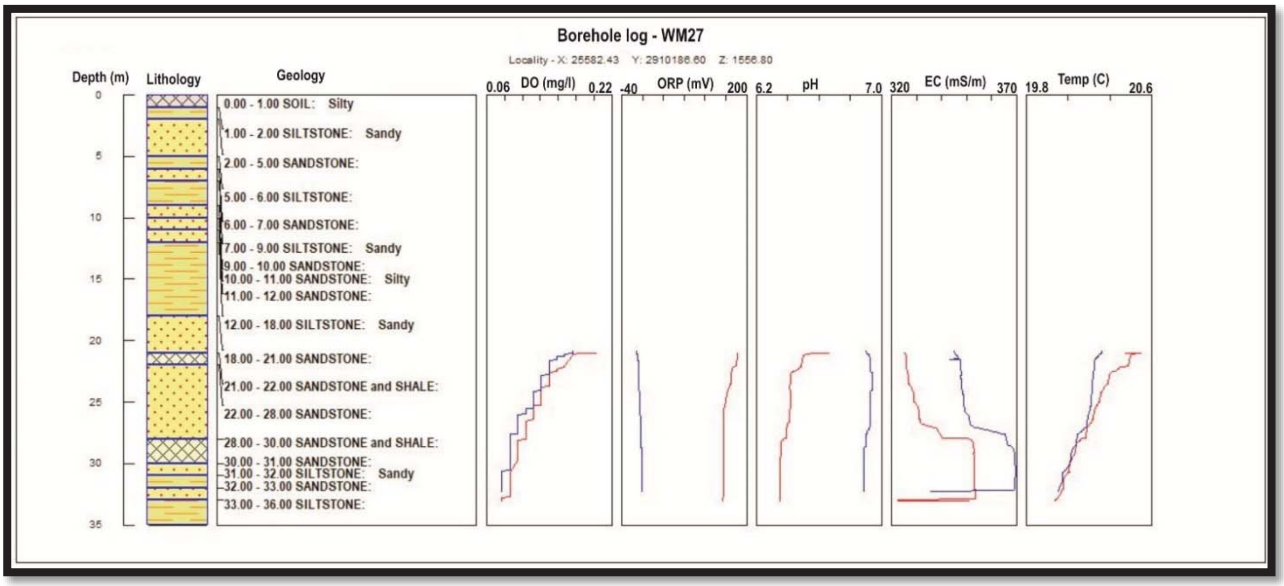


Figure 5-23: Kriel Borehole WM27: Multiparameter profiles.

The water quality in the backfilled material can be summarised as follows:

- EC of the water in the backfilled pit increases with depth and varied from 320 to 400 mS/m. The TDS ranged from 2600-3700 mg/l.
- The redox potential of the backfill water was oxidising in May 2017 and reducing in September 2017. The oxygen concentrations were low (0-0.6 mg/l) in both measurements. The oxidation is only expected in the backfill above the water level. The flooded backfill material will have limited oxidation to the extent that future sulphate generation should be very little to insignificant (Hodgson et al., 2007).
- pH ranged between 6.5 and 7, which is suggestive of buffering by Ca/Mg carbonates (pH range 6.5-8).
- The water level in the backfill will correspond to water levels in the pitlakes. The backfill is hydraulically linked to the pitlakes and makes up a significant contribution to the pitlake water balance and as a result will impact on pitlake water quality.

Pitlakes

Pitlake profiles were conducted in the Kriel Pit 4 pitlakes included Ramp 44 North, Ramp 44 South and Ramp 42 South. The results of the March 2017, September 2017 and November 2017 vertical water quality profiling are shown in Figure 5-24 to Figure 5-26.

Due to the elongated shape and shallow depth of the Kriel pitlakes wind action and wave fetch plays a large role in circulation patterns in the lakes. Ramp 44 pitlakes were covered in algal mats and had large amounts of rooted aquatic plants on the bottom of the lake. The littoral zone of the Ramp 44 pitlakes was also more extensive than that of Ramp 42, whereby Ramp 42 had steeper banks and a wider pelagic zone relative to littoral zone which limited growth of plants. Ramp 42 South also had a large influx of sediment from erosion channels on the banks during the rainy season.

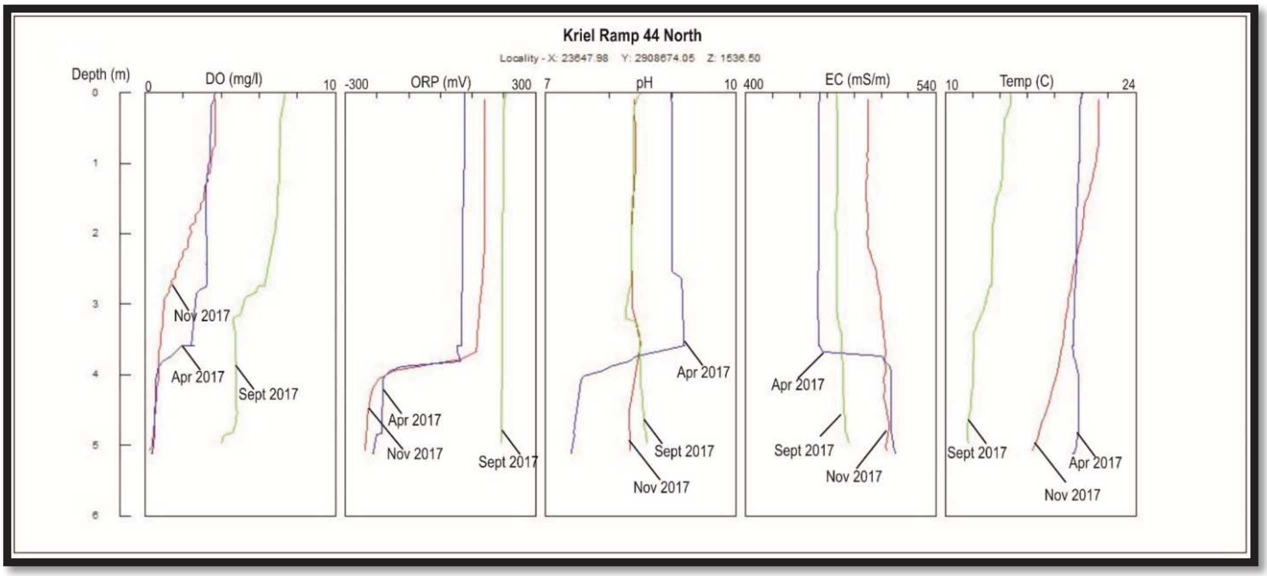


Figure 5-24: Kriel Pitlake Ramp 44 North: Multiparameter profile.

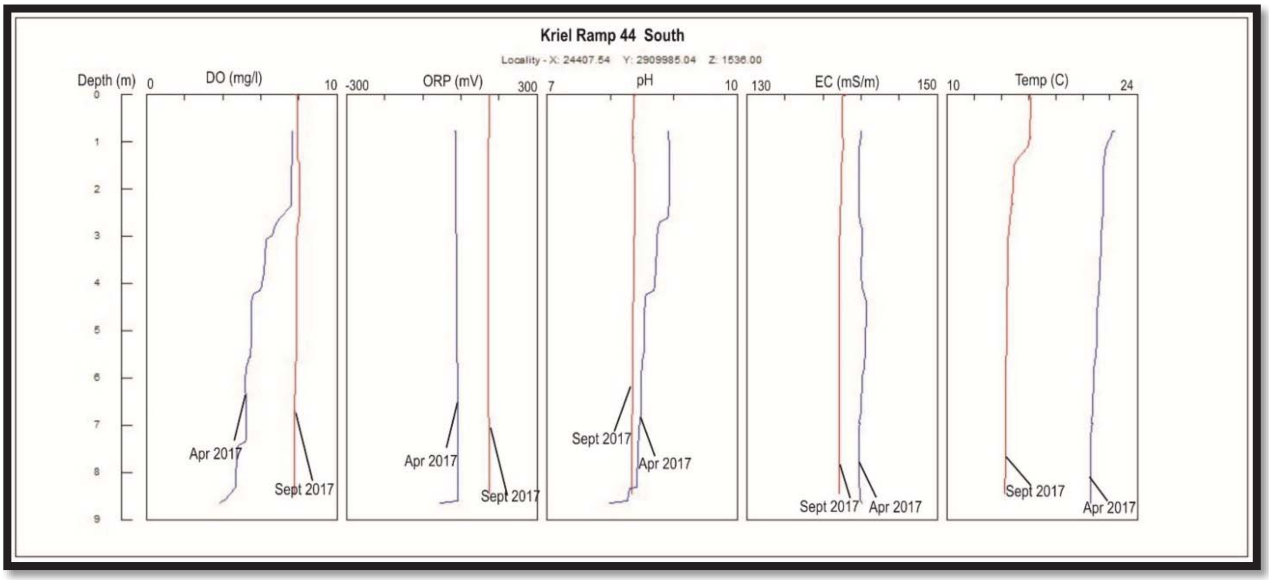


Figure 5-25: Kriel Pitlake Ramp 44 North: Multiparameter profile.

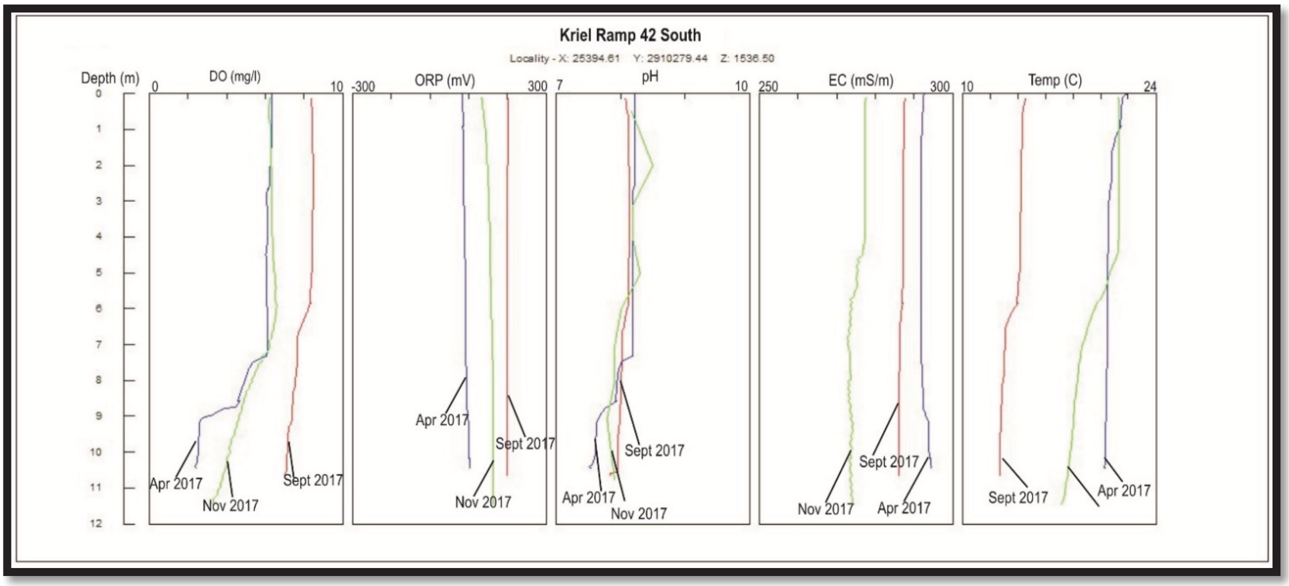


Figure 5-26: Kriel Pitlake Ramp 44 North: Multiparameter profile.

The following could be derived from the pitlake profiles:

- The T of all the pitlakes ranged between 20°C and 22°C in the summer and 12°C to 16°C in the late winter profiles. The water temperature was relatively constant throughout the depth of the pitlakes in the summer. In winter, the top of the pitlake had higher temperatures than the bottom. The homogeneity of temperature in the lakes in the summer months could be attributed to storm events which circulated the water due to wind and wave action.
- Ramp 44 North showed a higher EC 450 to 500 mS/m, with a layer of higher salinity at the base in the March profile. Ramp 42 South had lower EC of 280 to 300 mS/m. Ramp 44 South showed a low EC relative to the other lakes, which varied between 140 and 143 mS/m. The homogeneity of the EC with depth in each individual pitlake could be attributed to wind-induced mixing of these lakes.
- The concentration of DO is highly dependent on temperature, salinity, biological activity such as microbial and primary production and transfer of oxygen from the atmosphere. In all the pitlakes, DO was more saturated during the late winter profiles, than in the summer profiles, indicative of turnover events which mixed dissolved oxygen across whole water column.
- The pH of the lakes varied between 8 and 9 which classifies as alkaline water.
- The pitlakes showed positive redox potential in the top layers of the water column, indicating an oxidative chemical environment. Contrary to this, the negative redox potential observed at the base of Ramp 44N is suggestive of the activity of anaerobic sulphur bacteria and decomposition of organic material, such as algal mats that drop to the bottom and decomposition of the organic material, which consumes oxygen and produce H_2S.
- Overall, the pitlakes classified as holomictic, with monomictic circulation patterns. It is likely that the lakes do not form a monimolimnion (unless it is in the sediments) and the whole water column mixes at least once a year.
- The water quality after the turnover event seems to improve, especially in terms of oxygen, which is available at near-saturated to saturated concentrations for aquatic life in the winter. In the summer, there is a stratification in oxygen levels, with aquatic life will most likely situate themselves in the top water layers where oxygen is abundant.

Source of water for the pitlakes

The chemistry of pitlakes Ramp 44N, Ramp 44 and Ramp 42 S, out-pit boreholes WM21 to WM25, in-pit boreholes WM26 and WM27 and Dwars-in-die-Weg Spruit (sample points S28 and S29) are graphically shown in a Piper diagram Figure 5-27 for comparison. The median values for the study period of 2016-2017 were calculated and used in Figure 5-27.

Figure 5-27 shows that the groundwater quality can be divided into three types based on dominant water types:

- Natural Karoo aquifer (WM22, WM24, WM25) with Na-Cl/ Na-HCO3 type water;
- Natural Karoo aquifer, but affected by the opencast mine (WM21, WM23) with Na/Ca-SO_4 type water
- Backfill Water quality (WM26, WM27) where WM26 shows Na-SO4 type and WM27 Ca-SO_4 type water.

The natural Karoo aquifer water is mostly dominated by sodium-bicarbonate, especially for boreholes WM22 and WM24 which are situated in the floodplain wetland and banks of the Dwars-in-die-Weg and Steenkoolspruit, respectively. Borehole WM25 is positioned on the perimeter of the pit and shows higher concentrations of sulphate than WM22 and WM24.

Groundwater in out-pit boreholes WM21 and WM23 showed higher relative sulphate concentrations than the other surrounding boreholes, suggestive of interaction between the pitlakes and groundwater in the weathered zone. The geological log of borehole WM21 also indicated the presence of pyrite in the coal which may be the source of the sulphate as direct product of sulphide oxidation.

The stream water is strongly Ca/Mg bicarbonate type with equal amounts of calcium and magnesium (Ca 33-36%; Mg 32-38%). The sodium was another prominent specie in the stream with 20-25% of the cation composition. The stream samples show bicarbonate as the dominant anion (50-60%), followed by sulphate (25-30%) and chloride (12-15%) and nitrates (1% and less). An evolution of the stream water quality towards the SO_4 apex indicates that the opencast operations to the west and east of the Dwars-in-die-Weg Spruit is impacting on the stream water quality.

The water quality of the pitlake were plotted on Figure 5-27 (Piper diagram) is the calculated average of all the pitlake samples collected at all depths during March 2017, September 2017 and November 2017 for the respective pitlakes. It is evident that the water type in the pitlakes is similar and can be classified as Na-SO_4 type water, with sodium 55% and sulphate 85%. The ionic characteristics of the water in the backfill is very similar to the pitlakes and supports the water balance calculations regarding the interaction between the backfill water and the pitlakes. The backfill contributes sulphate, Ca and Mg-rich water to the pitlakes, especially during the dry season when the groundwater gradient is towards the pitlakes.

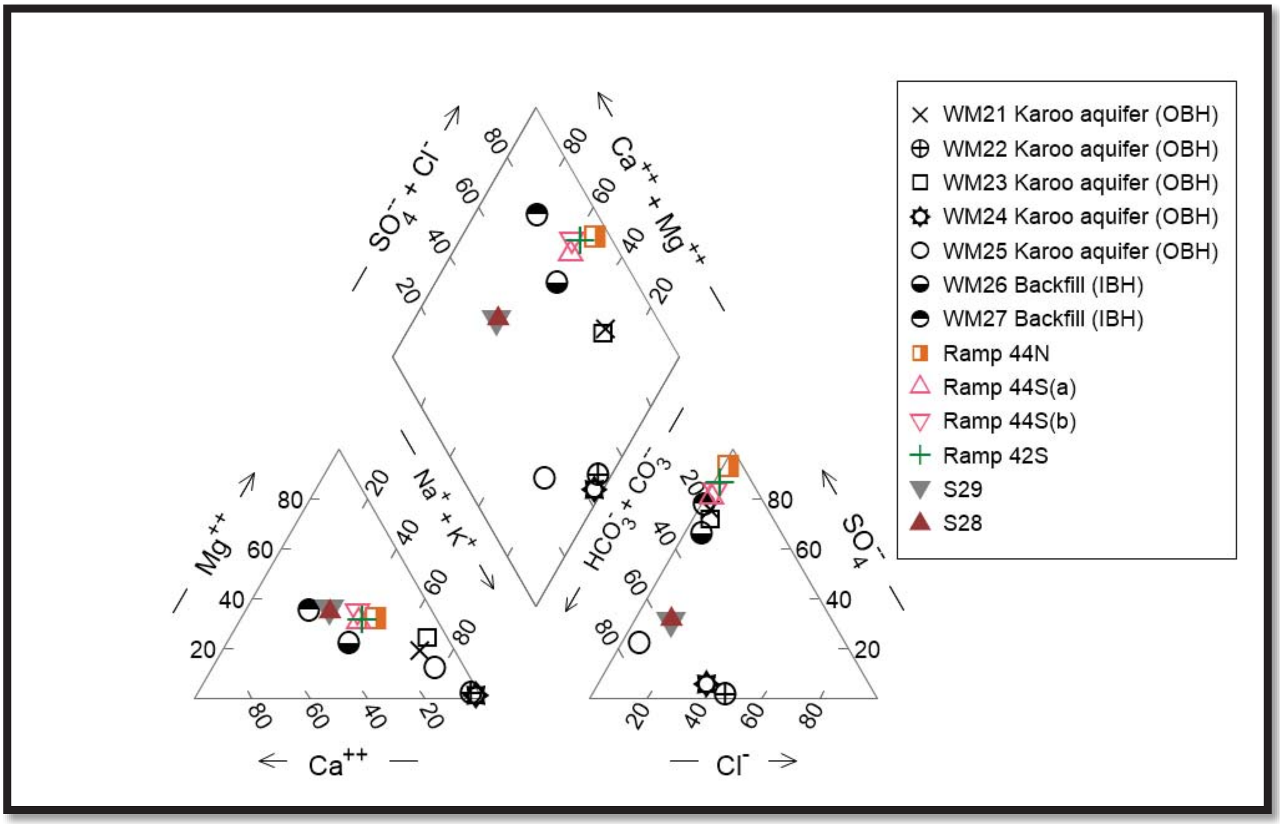


Figure 5-27: Kriel Water Quality: Piper Diagram

The groundwater hydro-chemistry indicates two prominent groups:

- High chloride, high HCO3, low sulphate
- Low chloride, high HCO3, high sulphate

Groundwater samples from the Karoo aquifer (OBH) with high chloride, low sulphate have not yet been affected by drainage from the mine. Boreholes that fall in this group WM22 and WM24 some distance from perimeter of Pit 4, in the floodplain wetland and stream bank, respectively. This group was identified as uncontaminated aquifer water with chloride and sodium as the respective dominant anion and cation. The water is not regarded as recently recharged, due to the high chloride contents. WM25 showed low sulphate content, although higher than WM22 and WM24, indicating that the aquifer in this area maybe impact on by mine water. However, the lower Cl content of WM25 is an indication of more recently recharged water than WM22 and WM25.

Water samples from the backfilled opencast with low chloride and high sulphate include boreholes WM26 and WM27. The high sulphate and TDS are a direct result of leaching salts from the disturbed overburden and discard material in the backfilled pit. The samples from the backfilled opencast also showed elevated bicarbonate concentrations. WM21 and WM23 have intermediate sulphate and low chloride with elevated EC values are impacted by the water from the pitlakes.

The pH of the groundwater ranged from 7 to 9.5, with the affected boreholes WM21 and WM23 showing evolution towards alkaline conditions. The backfill water has high TDS values of 2500 to 3500 mg/l. All samples have high bicarbonate and together with the alkaline pH, it is unlikely that acidification will take place in Pit 4 of Kriel Colliery. According to Hodgson et al. (2007) it is a common phenomenon for collieries to enter an alkaline phase while being flooded. The base potential of the overburden is usually sufficient to neutralise the acid mine water generated during the mining phase (Hodgson et al., 2007).

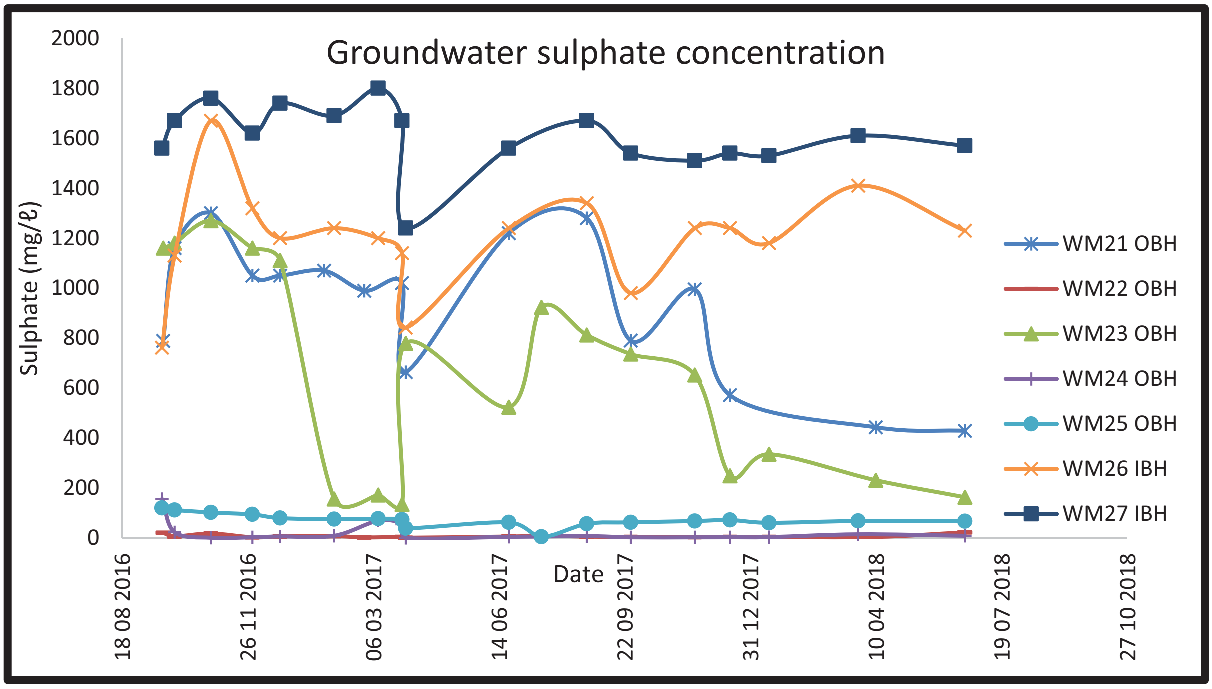


Figure 5-28: Kriel Pit 4: Karoo Aquifer and backfill sulphate concentrations.

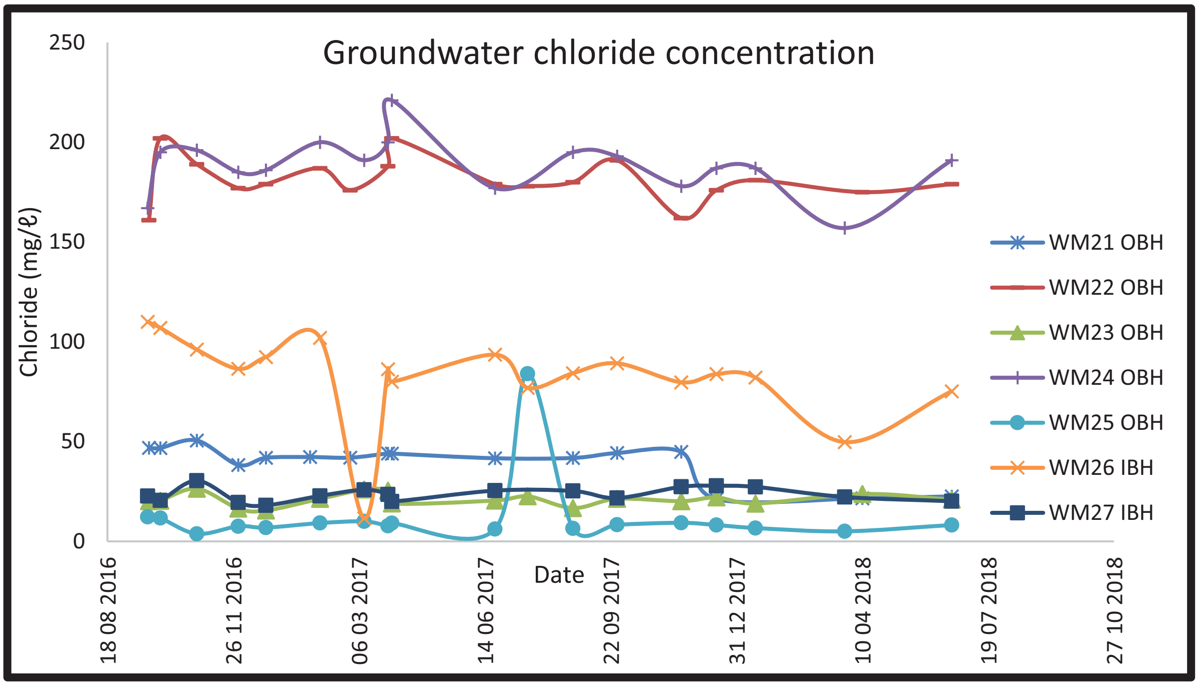


Figure 5-29: Kriel Pit 4: Karoo Aquifer and Backfill chloride concentrations.

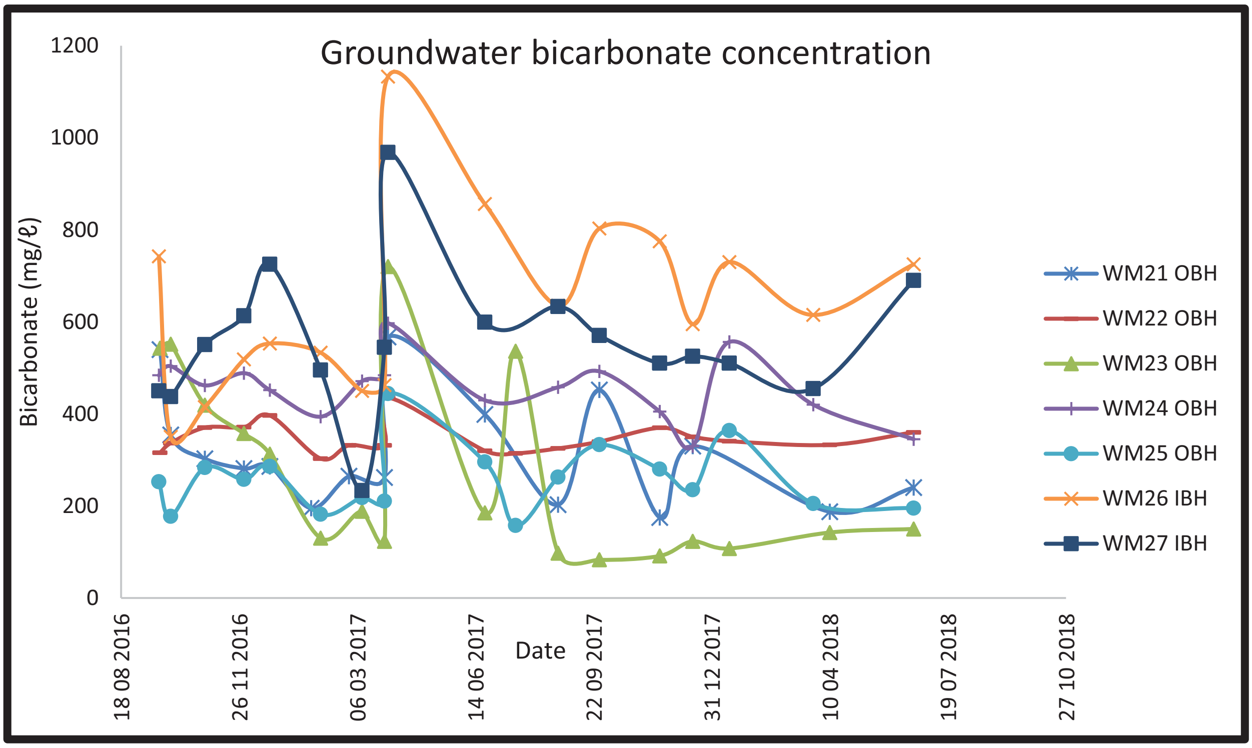


Figure 5-30: Kriel Pit 4: Karoo Aquifer and Backfill bicarbonate concentrations.

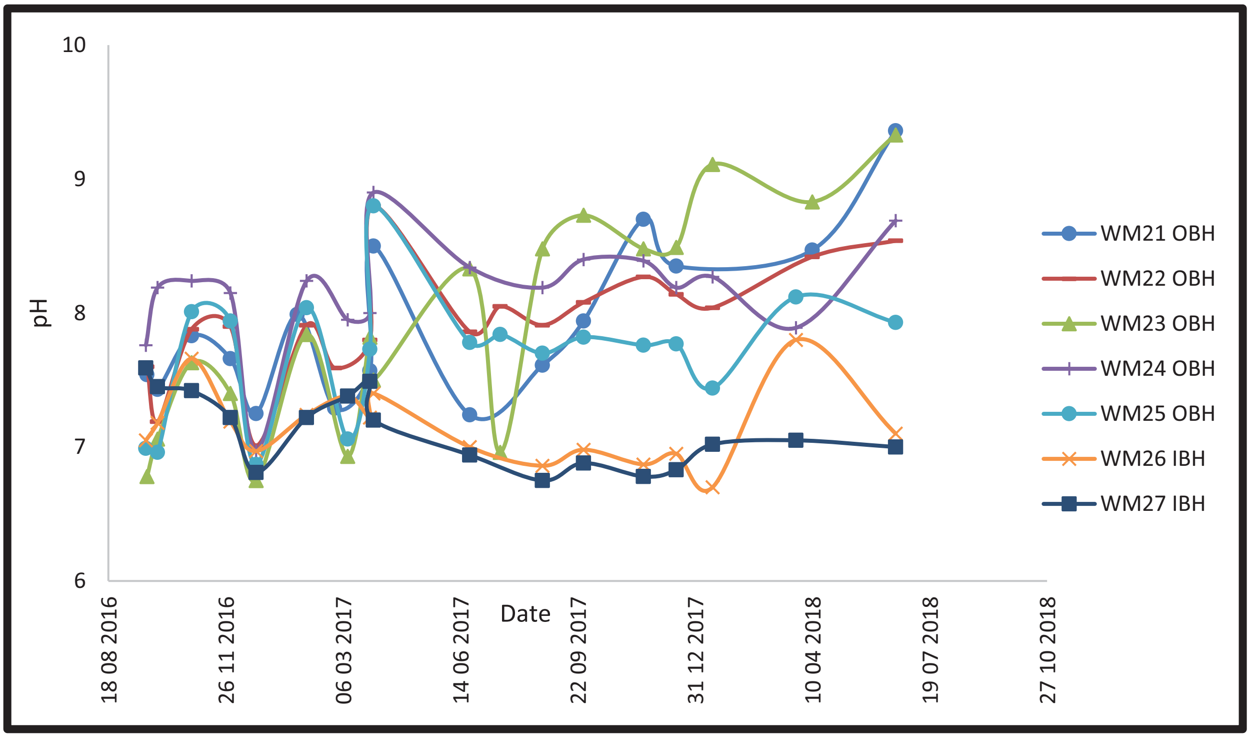


Figure 5-31: Kriel Pit 4: Karoo Aquifer and Backfill pH.

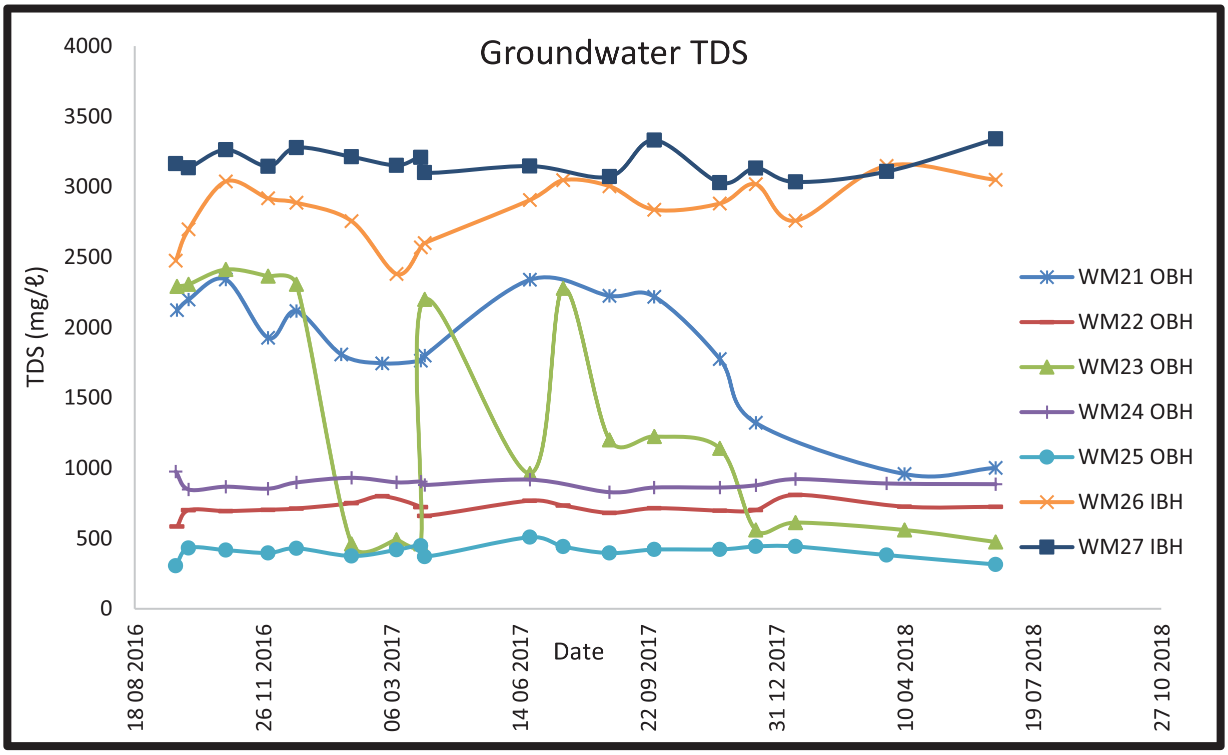


Figure 5-32: Kriel Pit 4: Karoo Aquifer and Backfill water TDS.

For the Karoo aquifer boreholes (WM22, 24 and 25), the main water type was Na-HCO_3. According to Jalali (2007), Na-HCO_3 water is usually an indication of cation exchange processes, especially in discharge zones, such as in lowland areas and streams, where boreholes WM22-25 are located. Ion exchange then occurs where Na existing in the clay fraction of the aquifer materials is exchanged for Ca and Mg in the groundwater (Jalali, 2007). Ca+Mg-HCO_3+SO_4 vs K+Na-Cl plots indicate whether or not the groundwater chemistry is highly influenced by ion exchange (Lufuno, 2017; Puntoriero et al., 2015). The Na + K-Cl show the quantity added or removed for Na+K in relation to the amount added by dissolved Cl salts, such as NaCl (halite), while Ca + Mg - SO_4 - HCO_3 show the quantity for Ca + Mg added or removed, relative to the amount added by dissolution of gypsum, calcite and dolomite. The slope of the plot is -0.8 which can be indicative of ion exchange processes as a cause for the high Na concentrations relative to other cations in the groundwater (Figure 5-33).

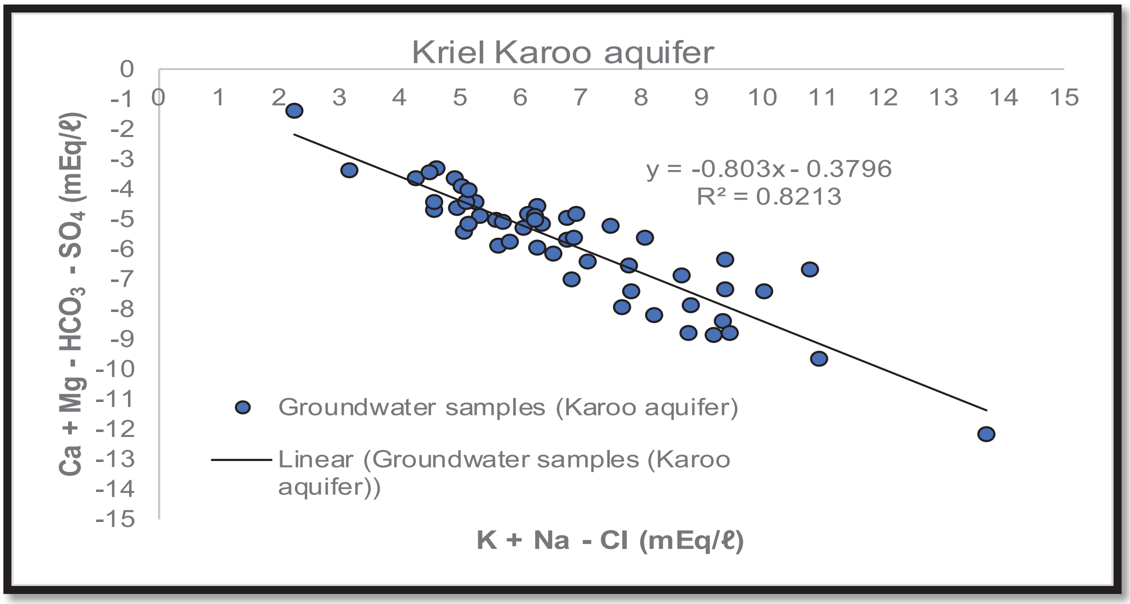


Figure 5-33: Kriel Pitlake: Groundwater scatter plots.

The backfill groundwater types were classified as $Na\text{-}SO_4$ for WM 26 and $Ca\text{-}SO_4$ for WM 27. For WM 26, sodium was the most prevalent of the cations present and could be attributed to cation exchange and anthropogenic processes (Jalali, 2007). The calcium dominance in WM 27 could be explained by various sources, such as gypsum dissolution, calcite dissolution or carbonate weathering and reverse ion exchange (Hounslow, 1995). The hydrochemical signature of the backfill water was important and could be seen as an indication of hydrogeochemical processes occurring in the backfilled spoils and most importantly be indicative of any AMD related reactions that could lead to further deterioration of the pitlake water quality. Overall, an increasing trend of sulphate concentration with TDS was observed. A strong linear correlation (r=0.95) between SO_4 and TDS, suggestive that SO_4 is responsible for the bulk of the TDS in the water (Figure 5-34).

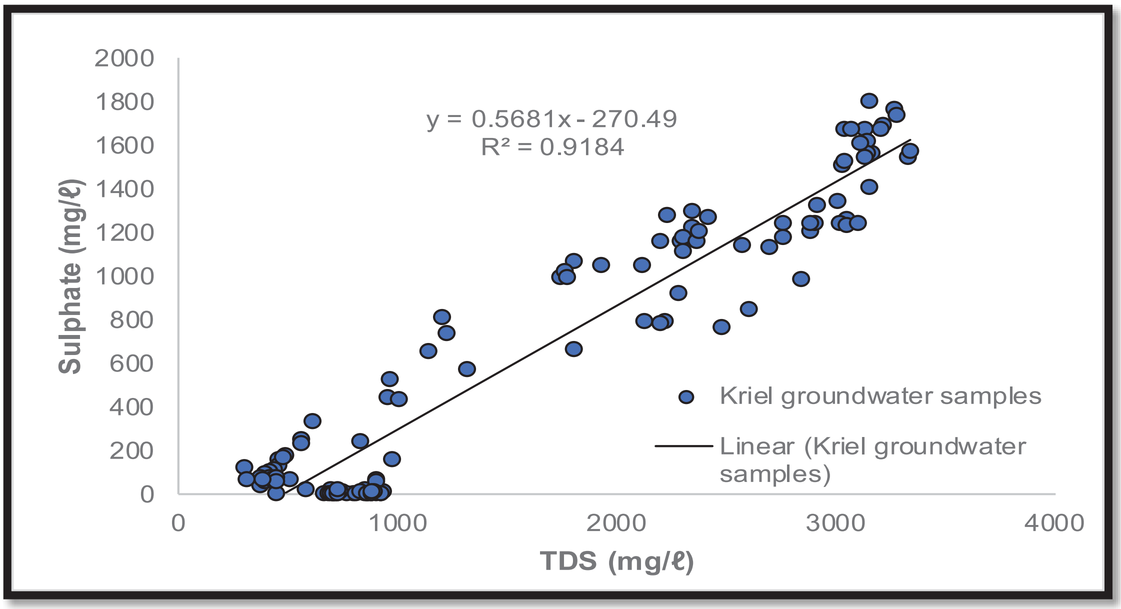


Figure 5-34: Kriel Water Quality: Scatter plot of sulphate versus TDS.

Additionally, a scatter plot of total hardness and sulphate for the backfill groundwater also indicated a strong positive linear relationship (r=0.86), suggesting that sulphate, Ca and Mg are increasing in the same relative amounts, which could be indicative of carbonate buffering with the release of Ca and Mg, as well as SO_4 into the water (Figure 5-35Figure 5-35:).

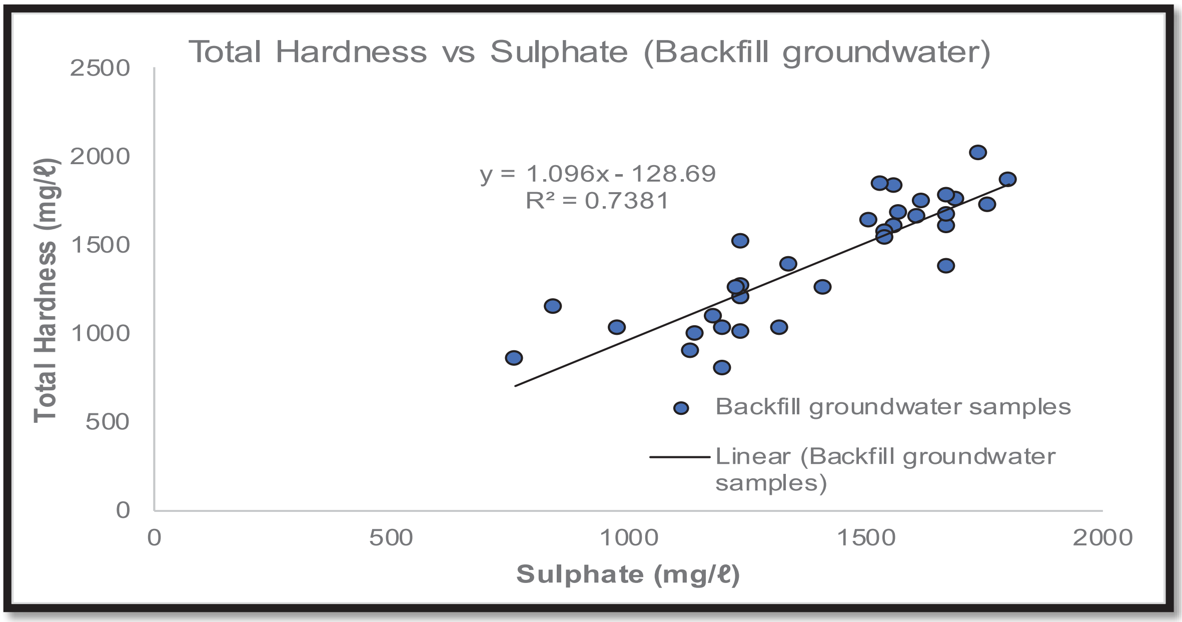


Figure 5-35: Kriel Water Quality: Scatter plot of hardness versus sulphate.

Groundwater chemistry data from all the boreholes was entered into the Geochemist Workbench (Student edition, Bethke et al., 2018) for further analysis. This included major ions, silica and metals (Fe, Al, Mn, Ba). Mineral saturation indices for gypsum were calculated for all the Karoo aquifer and backfill boreholes. Figure 5-36 shows a trend towards higher saturation states for gypsum was observed for the backfill groundwater, while some of the Karoo aquifer groundwater samples also showed relative enrichment in gypsum and hence higher saturation levels.

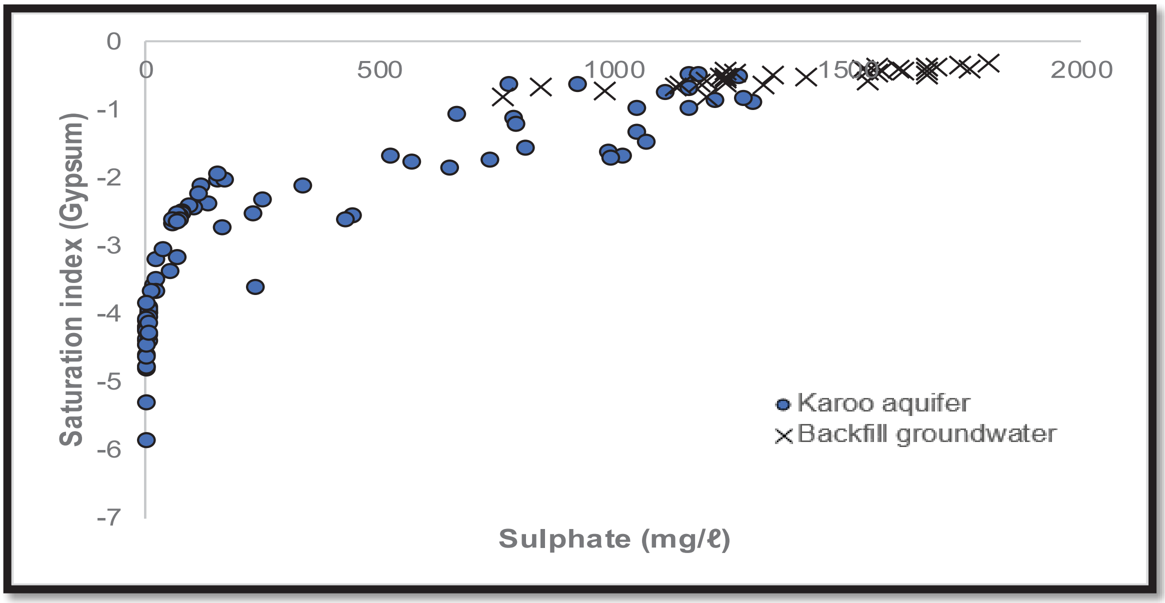


Figure 5-36: Kriel Water Quality: Gypsum saturation index.

The gypsum saturation index shows that gypsum oversaturation has not been reached. Although calcium and sulphate shows a strong linear correlation (r=0.88) in Figure 5-37, the calcium is limited relative to sulphate, and will be depleted with progressive gypsum saturation, after which sulphate concentrations will continue to increase. As a result it is expected that that sulphate will continue to increase in the aquifer as there is no mechanism to precipitate sulphate and remove excess sulphate from the groundwater system.

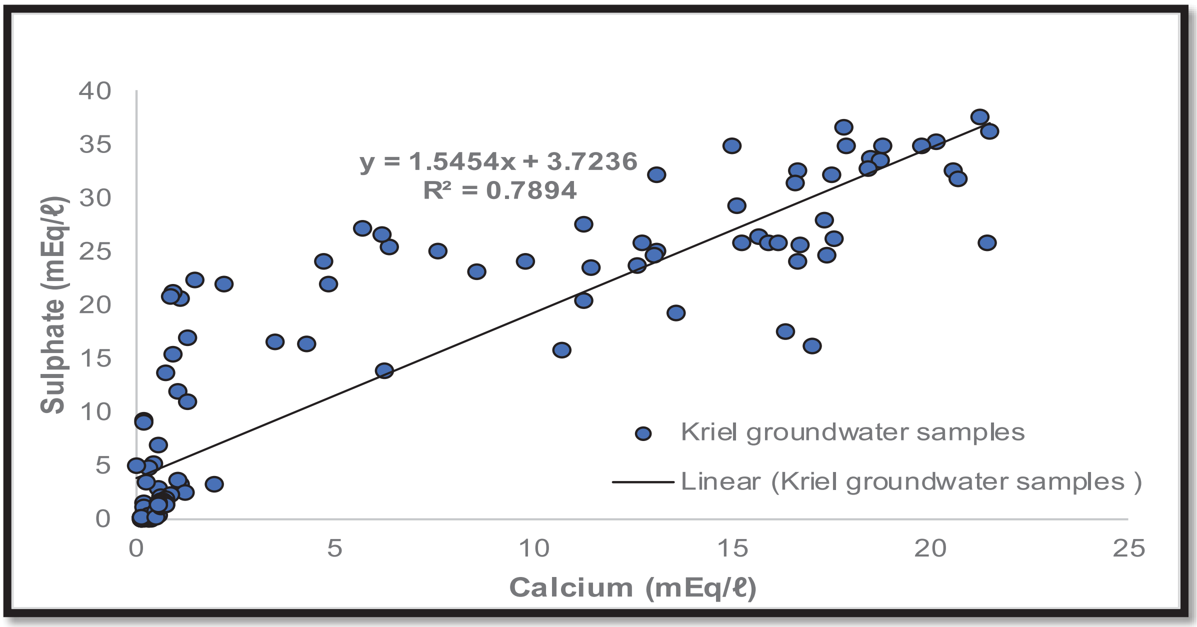


Figure 5-37: Kriel: Scatter plot of groundwater sulphate versus calcium

Calcite saturation index of Karoo aquifer and backfill groundwater indicated an increase with sulphate concentration. A plot of calcite versus sulphate concentration was chosen as sulphate indicates an increase in general salinity, as SO_4 are products of sulphide oxidative reactions and calcite alkalinity is usually a buffer and results in an increase the total dissolved solid content (Figure 5-38).

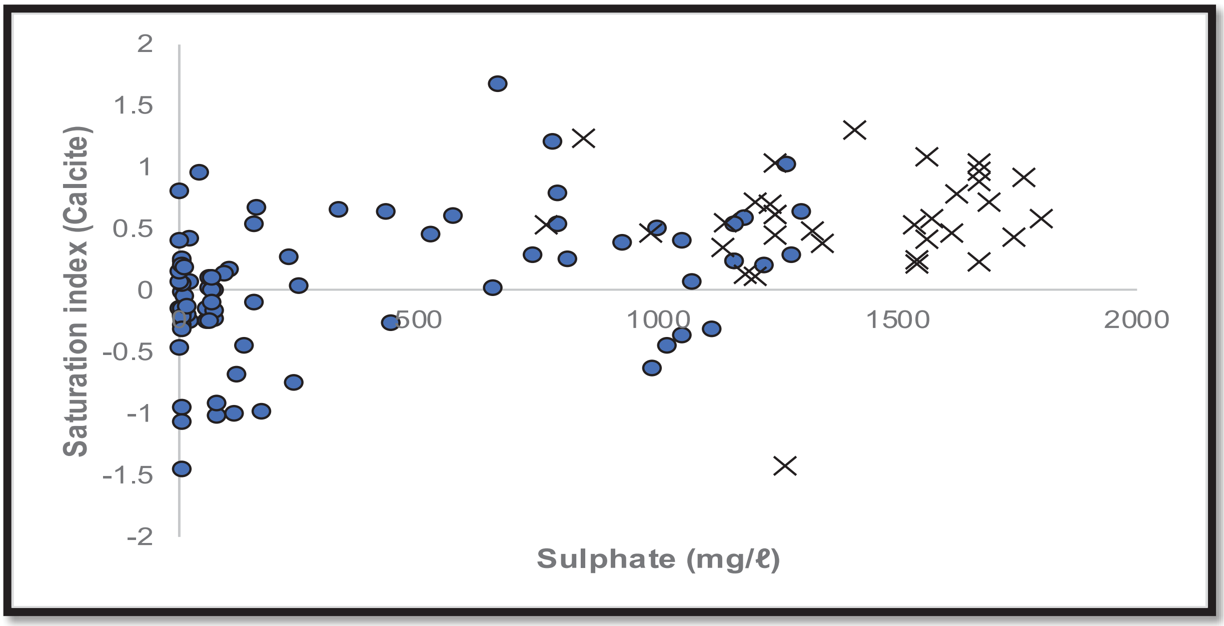


Figure 5-38: Kriel: Saturation state of sulphate in groundwater.

5.9.2 Pitlake Chemistry

Water samples were collected from Ramp 44 North, Ramp 44 South and Ramp 42 South pitlakes, at selected depths based on the profiling measurements of March 2017, September 2017 and November 2017. The chemistry data are displayed in Quality and indicate little variation with depth and over the specific sampling periods. A summary of the pitlakes and stream water qualities are provided in Table 5-8 to Table 5-10.

Table 5-8: Kriel Ramp 44 North Pitlake: Water quality statistics.

Parameter	Unit	n	Arithmetic Mean	SD	Minimum	Maximum
pH		16	8.0	0.5	7.3	8.7
EC	mS/m	16	512.5	36.9	453.0	556.0
TDS	mg/ℓ	16	4850.0	457.5	4200.0	5500.0
Ca	mg/ℓ	16	254.6	64.7	187.0	359.0
Mg	mg/ℓ	16	234.4	106.6	159.0	390.0
Na	mg/ℓ	16	618.6	95.1	486.0	763.0
K	mg/ℓ	16	36.3	3.4	31.0	40.0
HCO_3	mg/ℓ	16	201.5	41.5	154.0	262.0
Cl	mg/ℓ	16	49.5	5.0	45.0	57.0
SO_4	mg/ℓ	16	2928.8	462.9	1930.0	3350.0
SiO_2(aq)	mg/ℓ	16	4.8	3.5	2.4	14.3
NO_3-NO_3	mg/ℓ	10	0.5	0.1	0.4	0.6
N-ammonia	mg/ℓ	11	0.3	0.3	0.01	0.8
PO_4-P	mg/ℓ		<0.08	-	-	-
F	mg/ℓ		<0.05	-	-	-
Al	mg/ℓ		<0.003	-	-	-
Fe	mg/ℓ	5	0.61	0.061	0.56	0.7
Mn	mg/ℓ	12	0.21	0.45	0.004	1.4
Sr	mg/ℓ	16	1.28	0.21	1.10	1.60
Li	mg/ℓ	16	0.07	0.01	0.06	0.10
Ba	mg/ℓ	16	0.03	0.01	0.02	0.04
B	mg/ℓ	16	0.06	0.03	0.03	0.13
Cu	mg/ℓ	5	0.03	0.003	0.03	0.03
Cr	mg/ℓ	5	0.04	0.002	0.04	0.04

Table 5-9: Kriel Ramp 44 South Pitlake: Water quality statistics.

Parameter	Unit	n	Arithmetic Mean	SD	Minimum	Maximum
pH		11	8.2	0.2	7.8	8.5
EC	mS/m	11	151.6	16.4	139.0	175.0
TDS	mg/ℓ	11	1060.0	111.9	950.0	1200.0
Ca	mg/ℓ	11	85.4	11.4	77.0	100.0
Mg	mg/ℓ	11	63.9	7.8	57.0	83.0
Na	mg/ℓ	11	137.5	18.5	120.0	161.0
K	mg/ℓ	11	18.6	4.8	16.0	32.0
HCO_3	mg/ℓ	11	125.8	26.7	102.0	163.0
Cl	mg/ℓ	11	11.5	1.0	10.0	13.0
SO_4	mg/ℓ	11	530.5	62.4	459.0	620.0
SiO_2(aq)	mg/ℓ	3	2.3	0.1	2.1	2.4
NO_3-NO_3	mg/ℓ		<0.1			
F	mg/ℓ	6	1.655	0.324	1.200	2.200
Al	mg/ℓ	6	0.004	0.002	0.003	0.008
Fe	mg/ℓ	11	0.283	0.025	0.250	0.320
Mn	mg/ℓ	2	0.004	0.003	0.002	0.006
Sr	mg/ℓ	11	0.693	0.105	0.610	0.830
B	mg/ℓ	11	0.051	0.006	0.046	0.060

Table 5-10: Kriel Ramp 42 South Pitlake: Water quality statistics.

Parameter	Unit	n	Arithmetic Mean	SD	Minimum	Maximum
pH		31	8.0	0.3	7.4	8.5
EC	mS/m	31	299.3	17.7	268.0	320.0
TDS	mg/ℓ	31	2583.9	149.1	2361.3	2900.0
Ca	mg/ℓ	31	184.3	15.7	162.0	210.0
Mg	mg/ℓ	31	139.4	36.2	102.0	187.7
Na	mg/ℓ	31	312.4	45.1	262.0	397.0
K	mg/ℓ	31	22.6	4.2	15.0	28.0
HCO_3	mg/ℓ	31	230.0	28.4	192.0	268.0
Cl	mg/ℓ	31	26.1	2.1	24.0	35.4
SO_4	mg/ℓ	31	1445.4	163.9	1140.0	1589.8
SiO_2(aq)	mg/ℓ	31	5.9	0.4	5.4	6.7
NO_3-NO_3	mg/ℓ		<0.5	-	-	-
N-ammonia	mg/ℓ	7	0.04	0.05	0.01	0.16
PO_4-P	mg/ℓ		<0.08	-	-	-
F	mg/ℓ	9	0.5	0.2	0.1	0.7
Al	mg/ℓ	25	0.3	0.7	0.01	3.3
Fe	mg/ℓ	16	0.4	0.3	0.02	0.7
Mn	mg/ℓ	31	0.2	0.3	0.03	0.9
Sr	mg/ℓ	31	3.4	0.5	2.9	4.5
Li	mg/ℓ	31	0.04	0.01	0.02	0.1
Ba	mg/ℓ	31	0.1	0.1	0.1	0.2
B	mg/ℓ	31	0.3	0.1	0.2	0.5
Cu	mg/ℓ	16	0.01	0.01	0.01	0.02
Cr	mg/ℓ	10	0.03	0.00	0.03	0.03

A scatter plot of TDS and sulphate for the Kriel Pit 4 pitlakes (Figure 5-39) shows a strong linear relationship, which is suggestive that sulphate contributes contribute to a large proportion of the TDS.

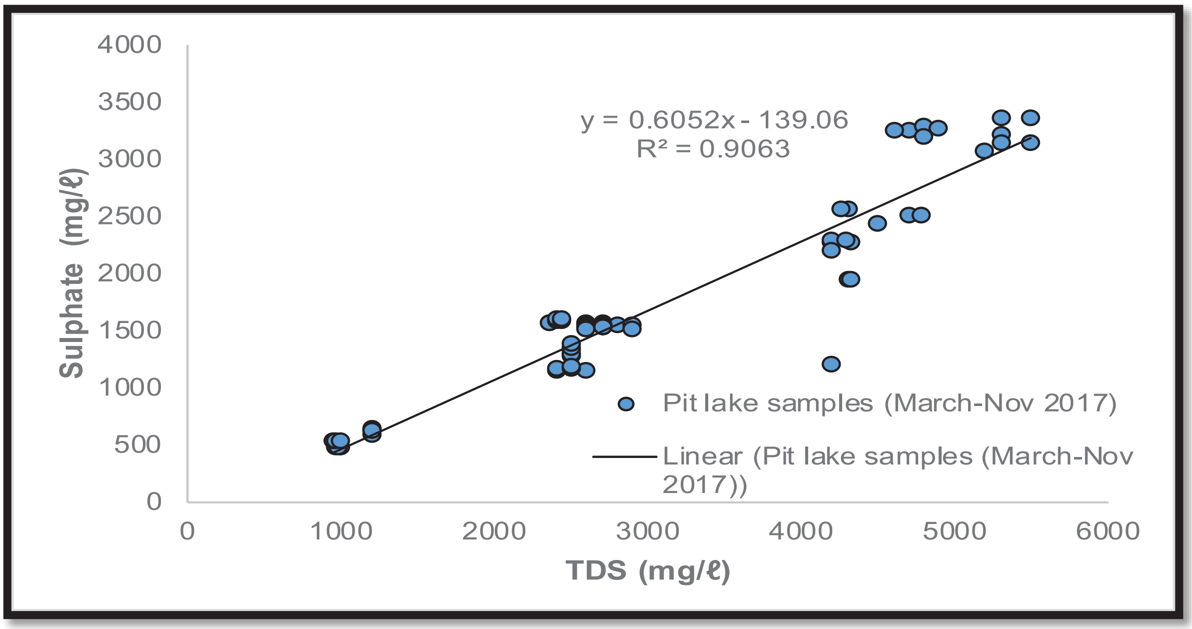


Figure 5-39: Kriel Ramp 44N, Ramp 44S and Ramp 42S: Scatter plot of TDS and sulphate

Furthermore, the strong positive correlation between total hardness and sulphate seen in Figure 5-40 suggested an affinity of sulphate to the major Mg and Ca divalent cations. The relative increase in Mg and Ca ions into the water, occurs in proportion to the increasing sulphate concentrations. Azzie (2002) found that alkaline mine water generally contains calcium and carbonate alkalinity as major solutes, where the Ca and carbonate alkalinity is affected by the solubility of calcite. The saturation index (SI) for calcite in Figure 5-41 shows an increase in calcite with an increasing pH from 7.2 to 8.8. Pitlakes with a pH>7 generally have calcite SI values > 0, indicating that oversaturation is typical. Additionally, the degree of calcite saturation is related to the solubility of CO_2(g) in solution (Eary, 1999). The scatter plot in Figure 5-42 show oversaturation of CO_2(g) in the pitlake water at lower pH.

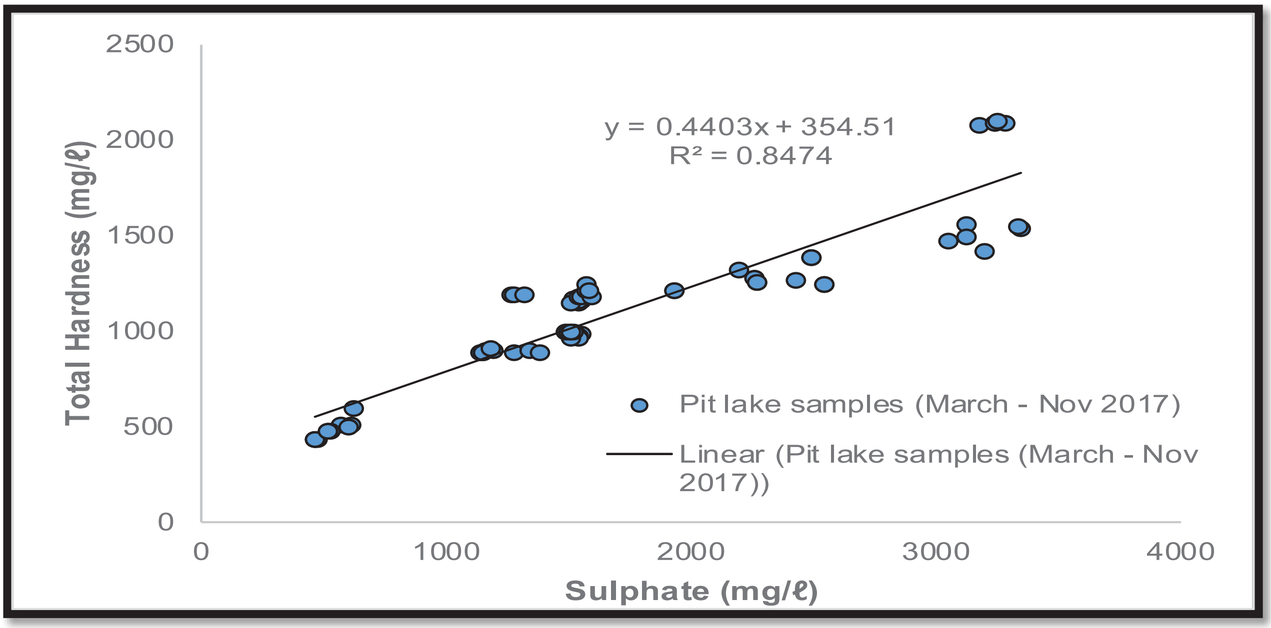


Figure 5-40: Kriel Ramp 44N, Ramp 44S and Ramp 42S: Scatter plot of total hardness versus TDS.

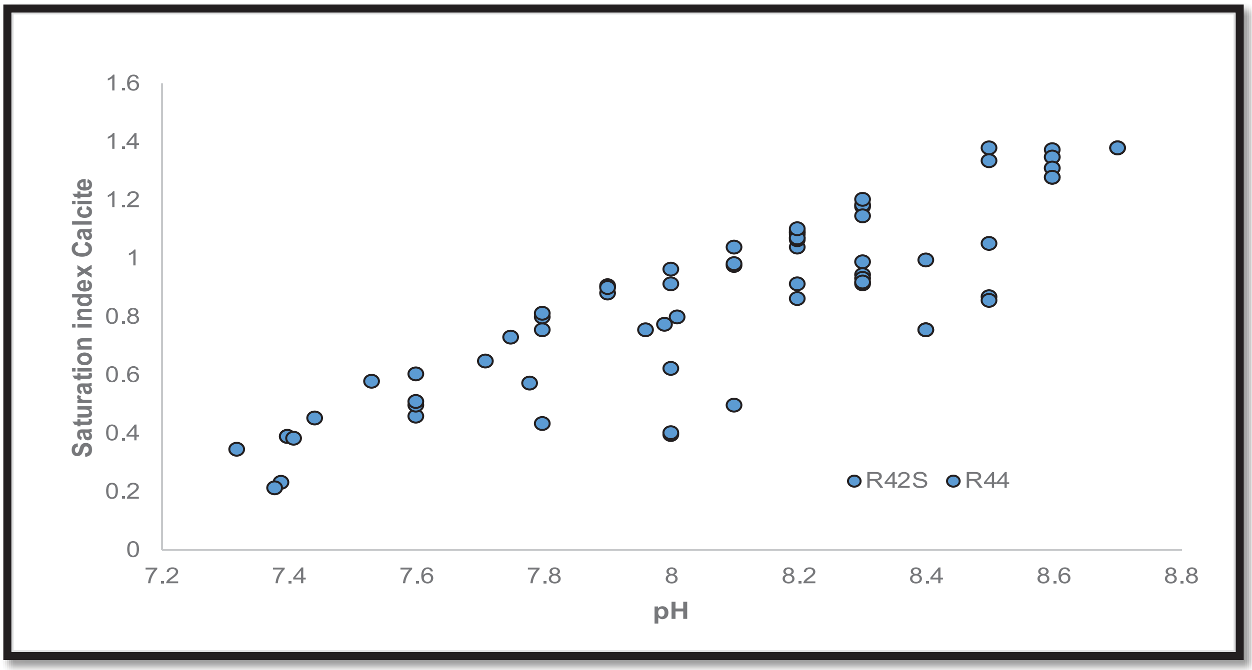


Figure 5-41: Kriel Pitlakes: Saturation index for calcite as a function of pH.

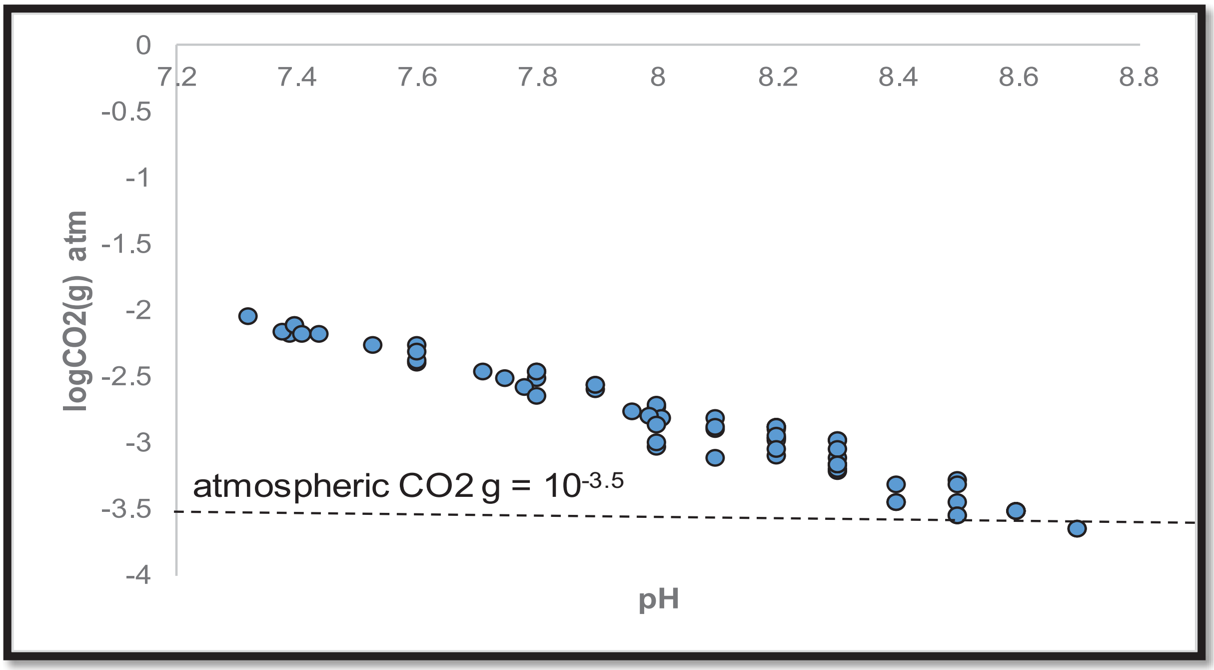


Figure 5-42: Kriel Pitlakes: Equilibrium partial pressure of CO2(g) as a function of pH.

Ramp 44 North Pitlake has very high sulphate concentrations and as a result was further investigated with scatter plots and saturation indices. In many aqueous systems, gypsum solubility has been shown to serve as a limiting factor for sulphate concentration and can be true for mine waters with SI values that increase from negative at low sulphate concentrations, towards SI=0 at higher sulphate concentrations. However, a plot of Ca versus sulphate (Figure 5-43Figure 5-43:) shows that calcium concentration is limited relative to sulphate, and SO_4 exceed Ca. As a result, it is concluded that gypsum saturation is probably the limiting control for Ca and not for SO_4. Hence, potential natural gypsum precipitation is not likely to manage SO_4 in the Pitlake and the addition of lime is required to increase Ca concentrations. The saturation index for sulphate in the pitlake water is shown in Figure 5-44.

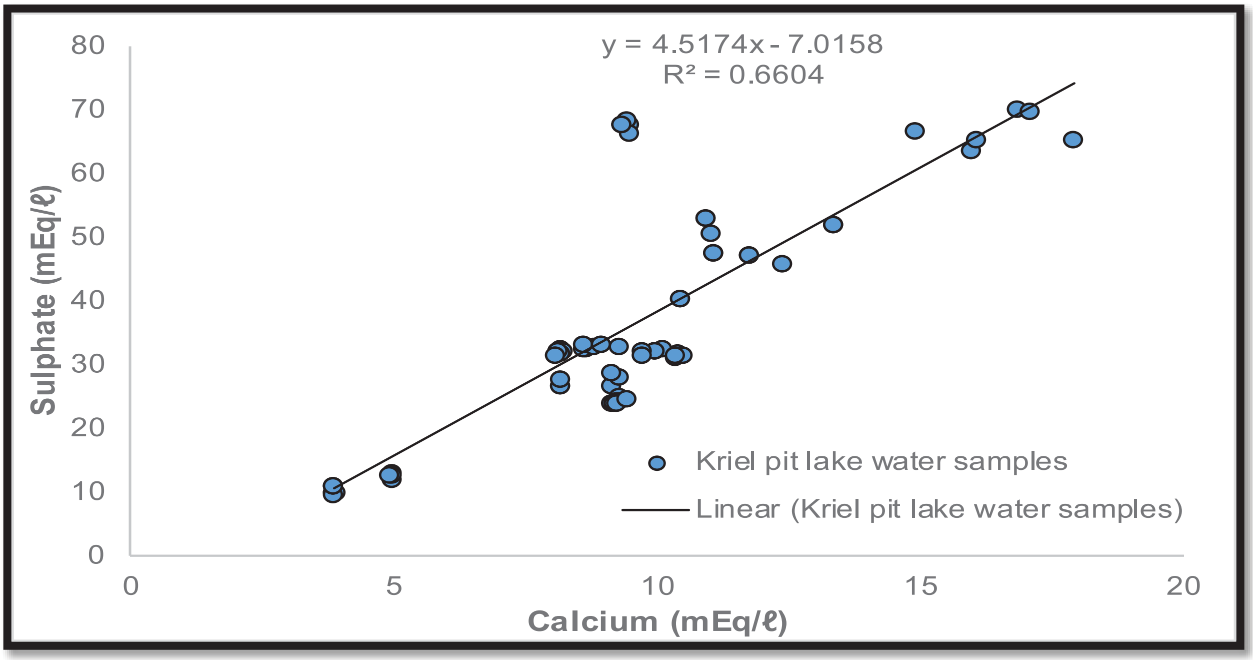


Figure 5-43: Kriel Pitlakes Ramp 44 North: Scatter plot of sulphate versus calcium.

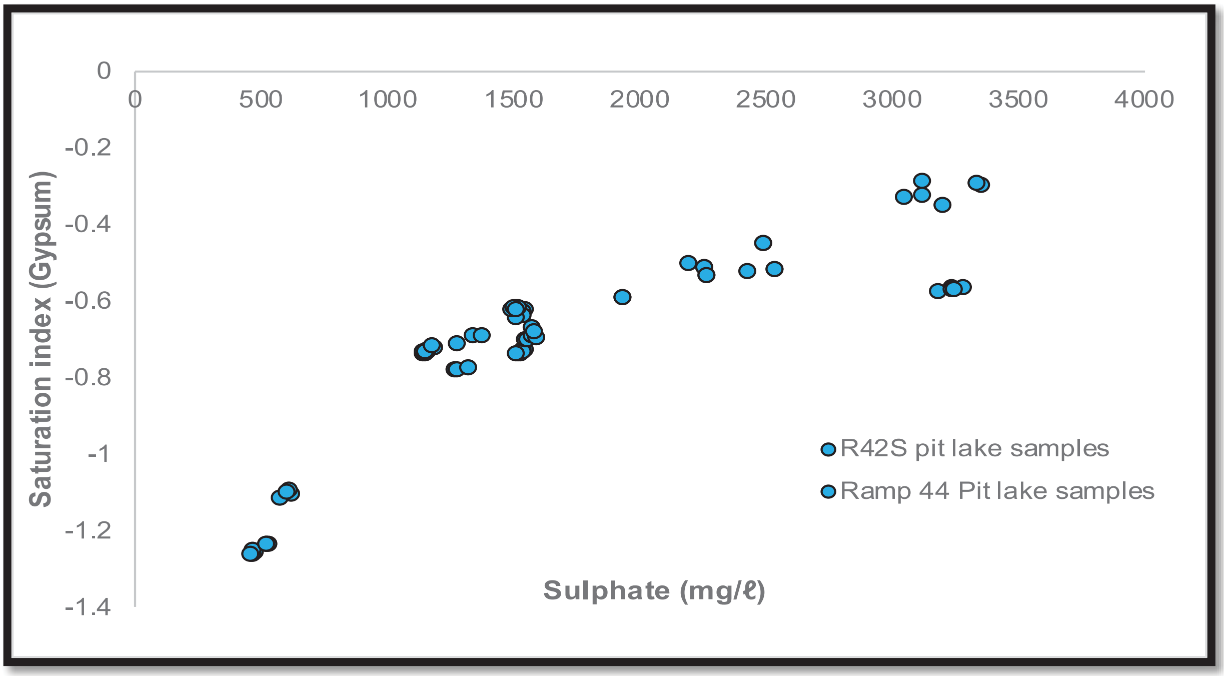


Figure 5-44: Kriel Ramp 44N Pitlake: Gypsum saturation index.

Trace Element Chemistry

According to Hodgson et al. (2007), heavy metals are present throughout the Mpumalanga Coal fields, even though they temporarily mobilise during oxidation, most precipitate under alkaline conditions. The Kriel Pit4 pitlakes are all alkaline. As a result very limited heavy metals where found in the Kriel pitlakes water it is thought the metals possibly resides in the bottom sediments as oxy-hydroxide minerals and captured in clays or organic material that has accumulated at the bottom of the pitlakes over the years. The trace elements and metals found in solution in the pitlakes are Al, Fe, Mn, Sr, Li, Ba, B, Cu and Cr. Descriptive statistics for the heavy metals measured in each of the pitlakes are provided in Table 5-11 to Table 5-13.

Table 5-11: Kriel Ramp 44 North Pitlake: Trace elements.

Parameter	Unit	n	Arithmetic Mean	SD	Minimum	Maximum
Al	mg/ℓ		<0.003	-	-	-
Fe	mg/ℓ	5	0.61	0.061	0.56	0.7
Mn	mg/ℓ	12	0.21	0.45	0.004	1.4
Sr	mg/ℓ	16	1.28	0.21	1.10	1.60
Li	mg/ℓ	16	0.07	0.01	0.06	0.10
Ba	mg/ℓ	16	0.03	0.01	0.02	0.04
B	mg/ℓ	16	0.06	0.03	0.03	0.13
Cu	mg/ℓ	5	0.03	0.003	0.03	0.03
Cr	mg/ℓ	5	0.04	0.002	0.04	0.04

Table 5-12: Kriel Ramp 44 South Pitlake: Trace elements.

Parameter	Unit	n	Arithmetic Mean	SD	Minimum	Maximum
Al	mg/ℓ	6	0.004	0.002	0.003	0.008
Fe	mg/ℓ	11	0.283	0.025	0.250	0.320
Mn	mg/ℓ	2	0.004	0.003	0.002	0.006
Sr	mg/ℓ	11	0.693	0.105	0.610	0.830
B	mg/ℓ	11	0.051	0.006	0.046	0.060

Table 5-13: Kriel Ramp 42 South Pitlake: Trace elements.

Parameter	Unit	n	Arithmetic Mean	SD	Minimum	Maximum
Al	mg/ℓ	25	0.3	0.7	0.01	3.3
Fe	mg/ℓ	16	0.4	0.3	0.02	0.7
Mn	mg/ℓ	31	0.2	0.3	0.03	0.9
Sr	mg/ℓ	31	3.4	0.5	2.9	4.5
Li	mg/ℓ	31	0.04	0.01	0.02	0.1
Ba	mg/ℓ	31	0.1	0.1	0.1	0.2
B	mg/ℓ	31	0.3	0.1	0.2	0.5
Cu	mg/ℓ	16	0.01	0.01	0.01	0.02
Cr	mg/ℓ	10	0.03	0.00	0.03	0.03

5.9.3 Surface water quality

The Kriel Pit 4 opencast workings are situated in the Dwars-in-die-Weg and Steenkoolspruit sub-catchment which are part of the larger Olifants River catchment area. The water quality of Dwars-in-die-Weg Spruit is monitored by Kriel Colliery on a monthly basis. The two water monitoring weirs (S28-upstream and S29-downstream) installed in the Dwars-in-die-Weg Spruit in 1994, are still monitored. The positions of the weirs are indicated in the site layout map Figure 5-2. Time series data in Figures 5-45, 5-46 and 5-47 show variable water quality with a general improvement since 2009. The cause of the impact on the water quality around 2008 is thought to be as a result of mining activities.

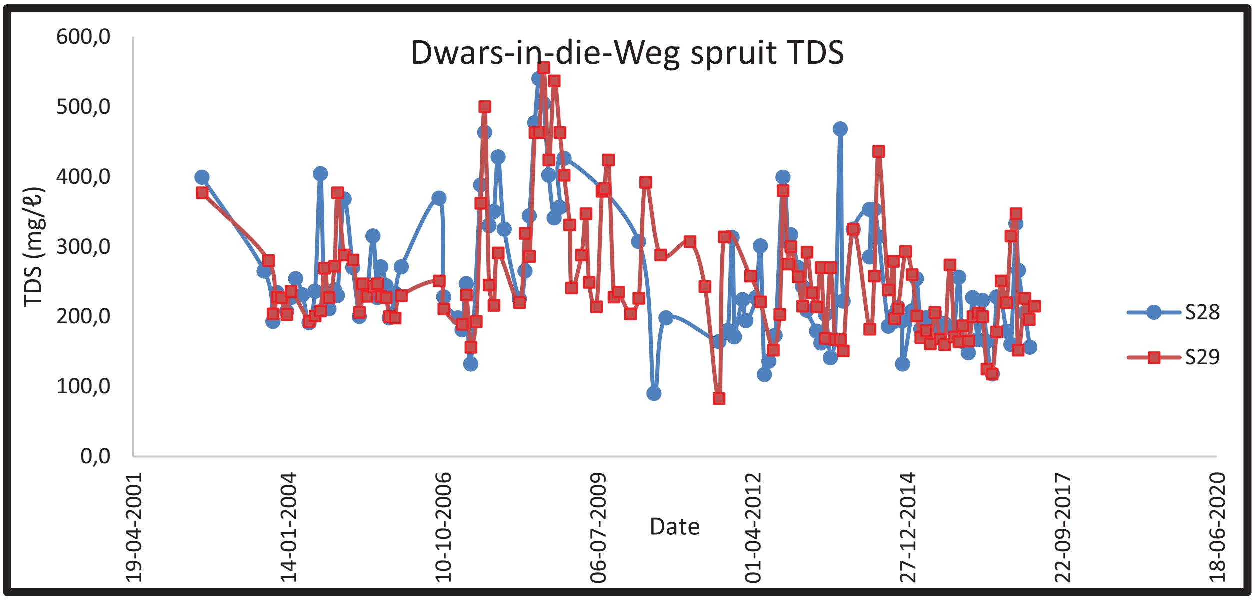


Figure 5-45: Kriel Dwars-in-die-Weg Spruit weirs S28 and S29 TDS.

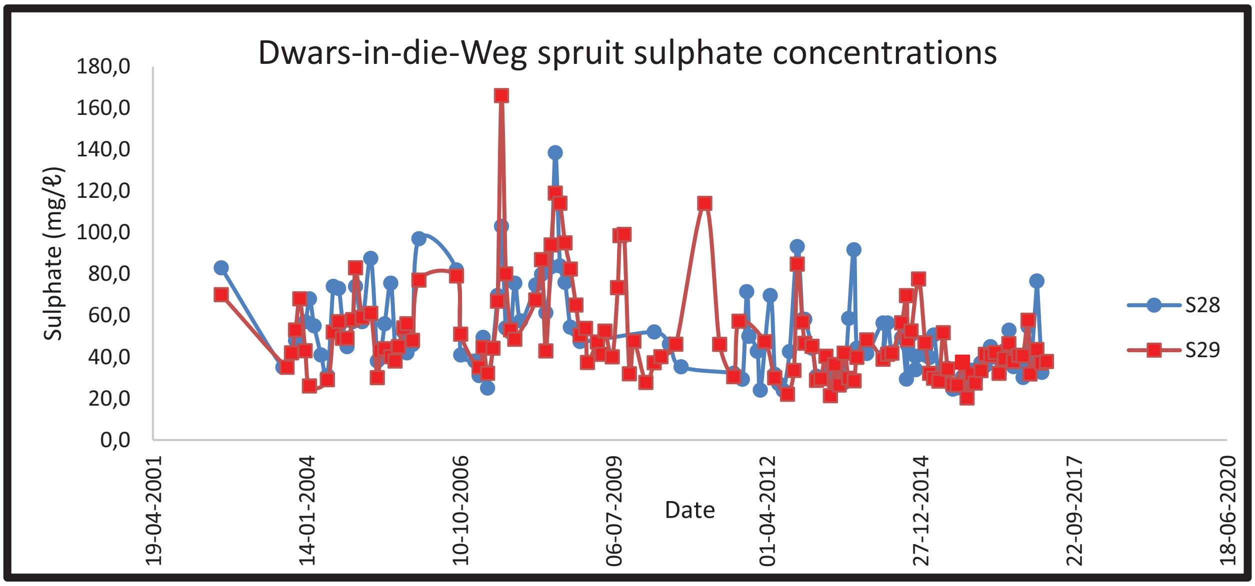


Figure 5-46: Kriel Dwars-in-die-Weg Spruit weirs S28 and S29 sulphate levels.

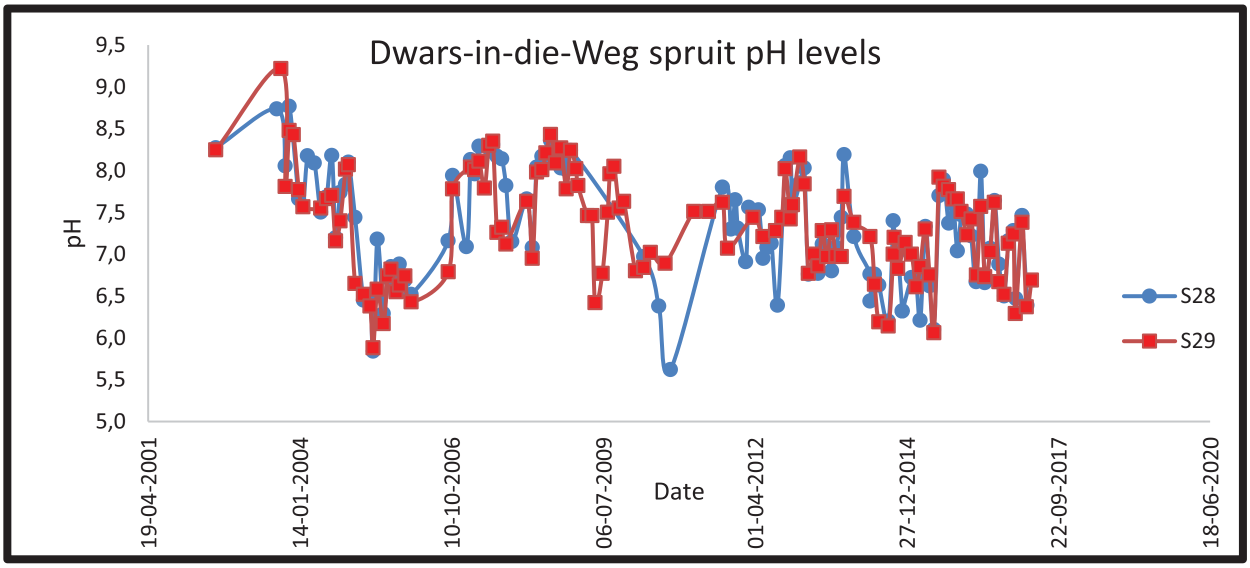


Figure 5-47: Kriel Dwars-in-die-Weg Spruit weirs S28 and S29 – pH.

5.10 Pitlake Biota

The pitlake biota monitored in the Kriel pitlakes includes Phytoplankton and microbiology. The samples were taken during the water quality sampling and preserved in dedicated bottles for analysis.

5.10.1 Phytoplankton

The Kriel pitlakes were classified as mesotrophic to hypereutrophic based on the chlorophyll-a concentrations, which ranged from 5 to 30 µg/l according to the classification system proposed by De Lange et al. (2018). It is interesting to note there are higher chlorophyll-a concentrations in the summer than (Table 5-14), suggesting a greater algal biomass in the summer than in the winter. The dominant algal groups in Ramp 44 North were Cyanobacteria, which was found the bottom samples and Cryptomonas (Cryptophyta group) in the upper samples. *Cryptomonas* was also found to be the dominant algae during the late winter sampling program (Figure 5-49 and Figure 5-50). In Ramp 42 South, the dominant algal group were Chlorophyta, with the *Ankistrodesmus* dominating the water column in the late winter (September) and early summer (November) (Figure 5-50 and Figure 5-51). As mentioned earlier, nutrients exert an important control on algae with phosphorous often being the limiting constituent (Vos, 2001). Detailed phytoplankton with cell volumes and chlorophyll-a concentrations are provided in Appendix J: Kriel Water Quality.

Table 5-14: Kriel Colliery's R44N and R42S: Average nutrient and chlorophyll a concentrations with secchi depths

Site	Date	Ammonia-N (mg/ℓ)	Nitrate-N (mg/ℓ)	Si (mg/ℓ)	Hardness (as CaCO3 (mg/ℓ)	Average chlorophyll-a (µg/ℓ)	Secchi depth (m)
Kriel Colliery R44N	Mar 2017	-	0.5	2.3	1264	25.5	3.5
	Sept 2017	0.03	0.1	0.62	2075	8	5
Kriel Colliery R42S	Sept 2017	0.04	0.05	2.7	1149	15.6	1.6
	Nov 2017	<0.08	0.05	2.7	977	14.8	1.5

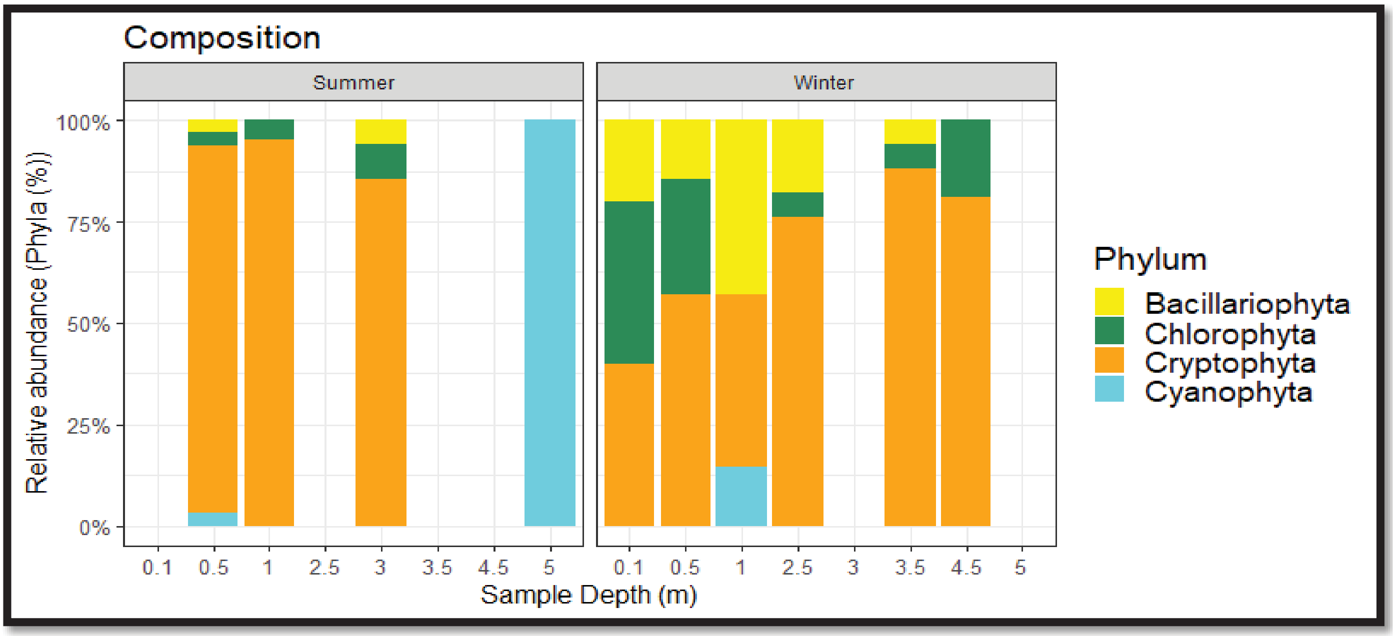


Figure 5-48: Kriel Ramp 44 North: Phytoplankton to phylum level for summer and winter.

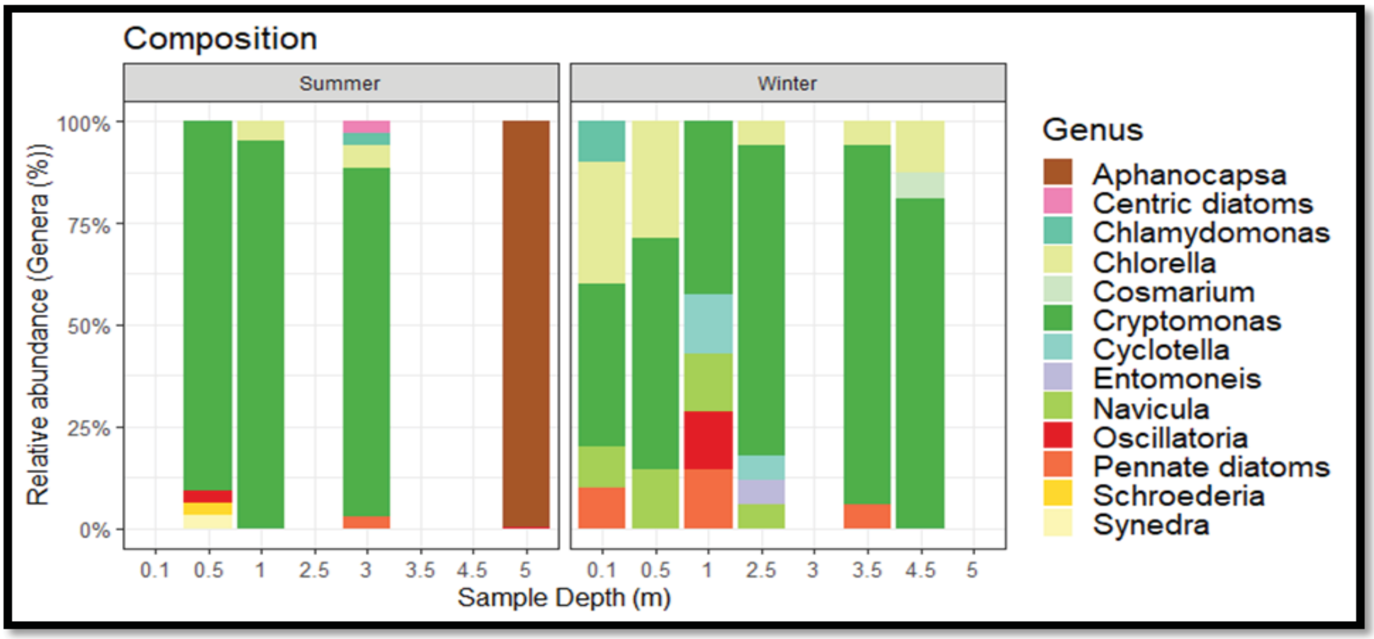


Figure 5-49: Kriel Ramp 44N: Microbiological stack diagrams of genera for summer and winter.

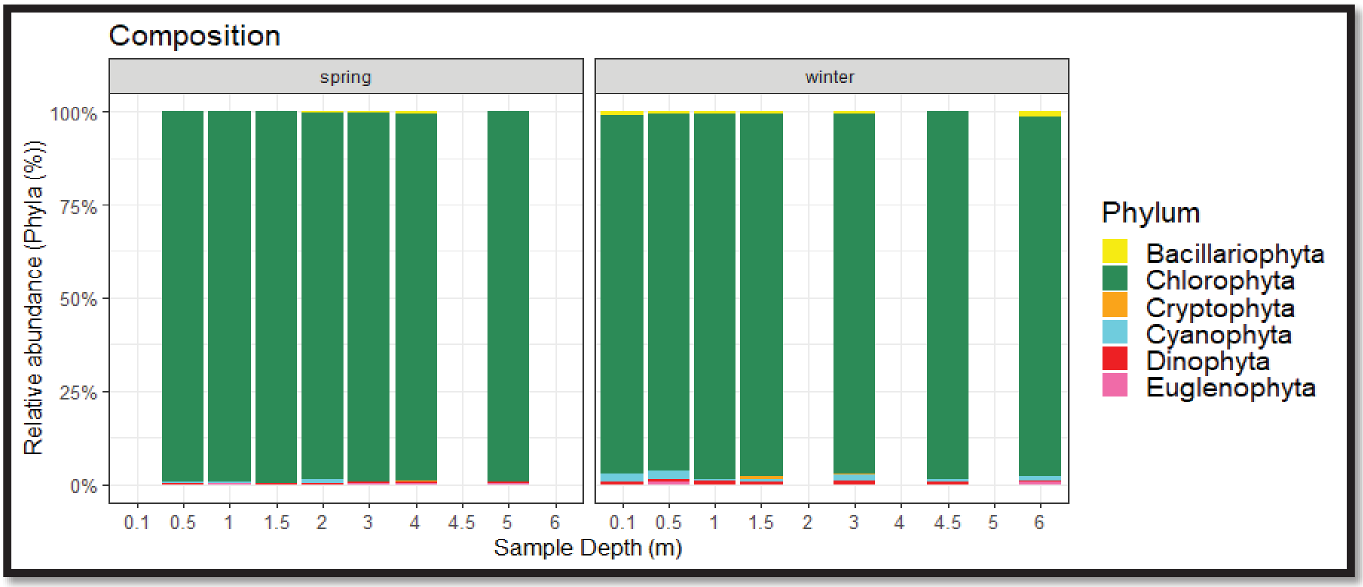


Figure 5-50: Kriel Ramp 42S: Stack diagrams of phytoplankton phyla.

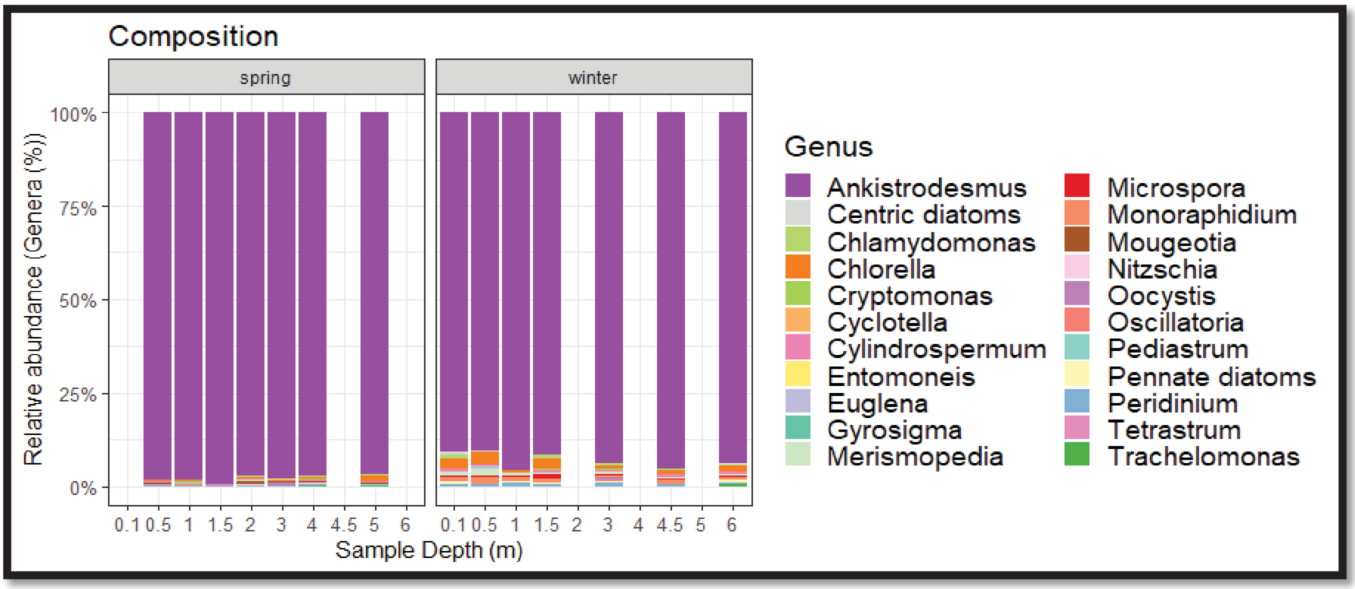


Figure 5-51: Kriel Ramp 42S: Stack diagrams of phytoplankton genera.

5.10.2 Microbiology

The microbiology of the Kriel pitlakes was dominated by Proteobacteria, Cyanobacteria, Planctomycete, Actinobacteria and Chlorobi and the bacteria had potential chemoheterotrophic metabolism. In the Ramp 42 Pitlakes communities was dominated by cyanobacteria. Ramp 44 North pitlake had no Cyanobacteria. A full microbial report drawn up by the Department of Biotechnology at the UFS and provided in Appendix M: Microbial Report Figure 5-52 shows the relative abundance of microbial phyla in the Kriel pitlakes.

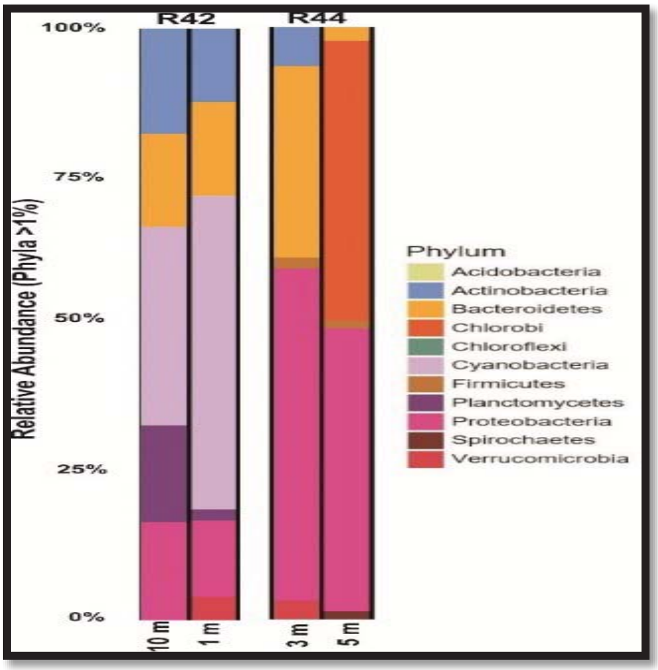


Figure 5-52: Kriel Ramp 42 South and Ramp 44 North Pitlakes: Bacterial communities.

5.11 Conclusions

The following conclusions could be drawn regarding the Kriel Pitlakes:

- All the pitlakes were hydrological sinks.
- Stratification did not play a role in the water chemistry of the pitlakes. It is though that due to the shallow depth of the pitlakes there is constant mixing which resulted in a homogenous water quality.
- The Kriel Colliery pitlakes were dominated by large concentrations of sodium and sulphate with major ion concentrations SO_4 > Na > Mg >Ca > HCO_3 >Cl >K >NO_3.
- The flooding of the backfilled spoils contribute large volumes of water and associated salts to the pitlakes. The groundwater in the spoils was alkaline with high TDS. The chemistry of the water in the backfilled opencast is similar to the chemistry of the pitlakes, with SO_4> HCO_3 > Na> Ca > Mg> Cl > K. The Backfill water has lower concentrations of SO_4, HCO_3 and Na than the pitlakes.
- Some dissolved metals have greater concentration in the backfill water than the lakes particularly Al, As, Co and Mn.
- The pitlakes were supersaturated with respect to carbonate minerals, in particular calcite and dolomite. Gypsum was found to be undersaturated the only viable control for sulphate concentrations would be the addition of calcium to enhance precipitation but would result in an overall increase in total dissolved solids.
- The dominant phytoplankton was chlorella, although large populations of cyanobacteria found at the bottom of Ramp 44 North in March 2017.
- The Kriel pitlakes are mesotrophic to eutrophic, but the algal groups are mostly dominated by one or two groups, and thus display limited diversity. The algae in the pitlakes has adapted to relatively saline conditions.
- The pitlake water balance for all four pitlakes demonstrates similar behaviour. Natural groundwater contribution from the surrounding aquifer into the pitlakes is minimal due to the low hydraulic gradient. Evaporation rate increases as the pitlakes fills due to increased surface areas. Water elevation fluctuations were observed due to seasonal rainfall and once the pitlakes reach equilibrium the majority of flow into the pitlakes is from the backfill material.

CHAPTER 6: ROOIKOP

6.1 Introduction

The Rooikop pitlake (30° 22' 16.0 " E; 26° 59' 03.8" S) is located on the farm Rooikop 18HT, 40 km to the west of Piet Retief and 10 km to the west of the Heyshope Dam in Mpumalanga (Figure 6-1). The pitlake is part of the Rooikop Section of the Taaiboschspruit Colliery. The coal deposit consists of the upper Alfred seam and lower Dundas seams of the Vryheid Formation of the Karoo Supergroup. The coal is a high-grade bituminous coal with relatively low in sulphur. In general, the eastern KwaZulu coalfields have undergone extensive thermal metamorphism which has reduced the majority of the coals to anthracite and low volatile bituminous coals (Azzie, 2002). The Rooikop pitlake is a complex system that hydraulically connected to both the underground and opencast mines.

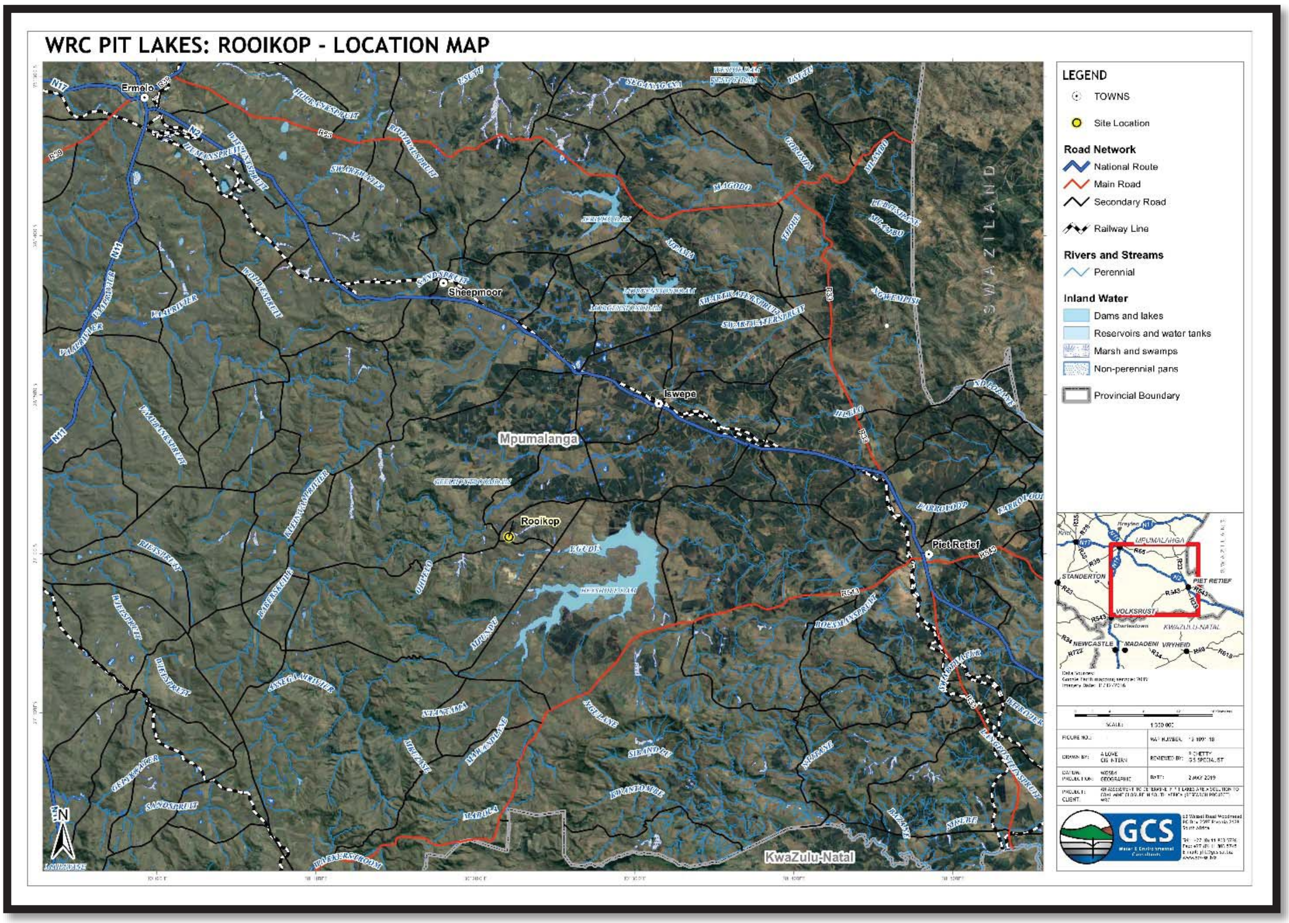


Figure 6-1: Rooikop Pitlake; Locality Plan.

6.2 Mining

The mining operations at Rooikop, which started on 1998, consisted of both opencast and underground operations. The sub-outcropped areas were mined by open cast contour stripping to a stripping ratio of 4:1 which lasted for three years, after which the areas with a higher stripping ratio were mined by conventional bord-and pillar methods, where coal was extracted by means of coal cutters, loaders and shuttle cars for another four years. The Alfred seam was the main target and yielded approximately 5 million tonnes Run-of-mine, where 60 000 tonnes/month were mined for seven years; 40 000 tonnes/month from underground conventional bord-and-pillar mining and 20 000 tonnes/month from open pit for the initial three years. In total, approximately 4 million tonnes of coal were removed by underground mining and approximately 1 million tonnes by open pit mining. The coal floor dips to the east with the difference between the highest and lowest coal floor is elevation being 50 m. The underground bord and pillar did not involve pillar extraction. Mining commenced in 1999 and ended in 2006 after which groundwater levels began to rebound.

The opencast area is 15 ha and the underground operation were approximately 100 ha. The opencast area was backfilled and rehabilitated during the operational phase leaving three final voids, the largest of which is 1.5 ha, and two other voids of 0.4 ha and 0.2 ha. Two pollution control dams (1.25 ha W and 1 ha E) was also constructed to contain contaminated water originating from the opencast workings. The mine layout, groundwater and surface water sampling locations are shown in Figure 6-2 and a photograph of the pitlake is provided in Plate 6. The underground workings where accessed from the open cast highwall and mining advance west and upgradient. On closure the accessed portals were not sealed leaving the highwall open void, the open cast and the underground to fill with water. The conceptual hydrogeological model is shown in Figure 6-10.

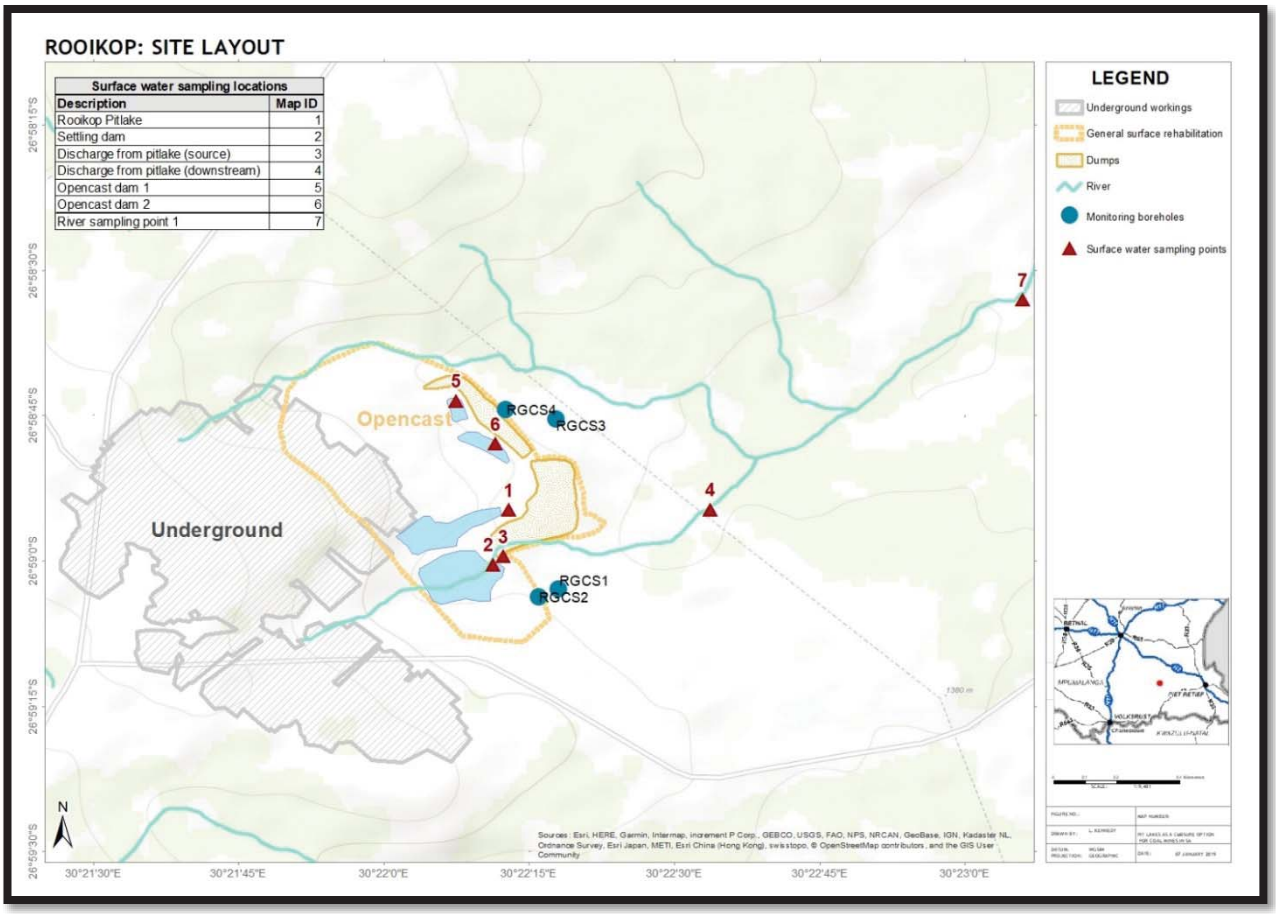


Figure 6-2: Rooikop: Mining operations and groundwater and surface water monitoring points.

Plate 6: Rooikop Pitlake looking east November 2016.

The Rooikop mine extends over a surface watershed with the majority of the coal seam being east of watershed. The coal floor however all dips to the east and discharges into the Rooikop pitlake. Consequently, the underground mine area is flooded to the pitlake surface elevation. Recharge to the underground workings' discharges into the pitlake. Only the lower portion of the underground workings is flooded. Consequently, portion of the mining area is not flooded. The composition of the air/gas in the unsaturated mine void not monitored. The geochemistry of the Alfred seam is discussed in Section 6.5.

6.3 Pitlake Morphology

The Rooikop pitlake hydraulically connected to the old opencast and underground operations. The depth of the pitlake is 15 m with the minimum elevation at 1376 mamsl and the maximum elevation at 1391 mamsl. The total volume and area of pitlake is 206 367 m^3. A bathymetric map of Rooikop pitlake is shown in Figure 6-3 and shows that the pitlake deepens towards the underground adits.

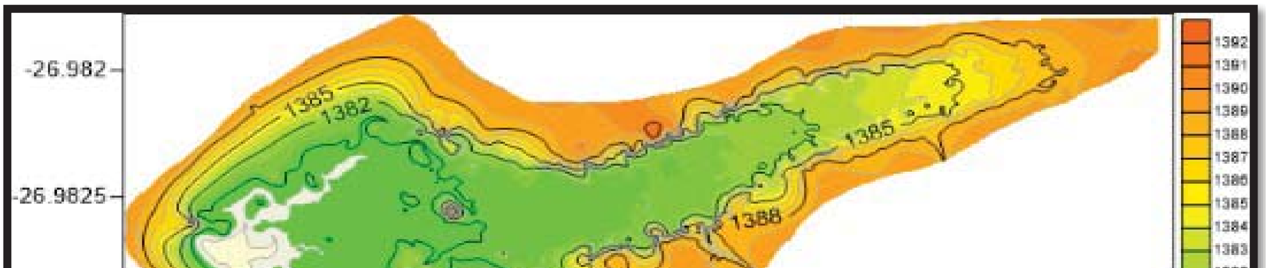


Figure 6-3: Rooikop Pitlake: Bathometry.

6.4 Geology and Structural Geology

Rooikop mine is situated in the Karoo Supergroup, Ecca Group; lower Pietermaritzburg and upper Volksrust Formations. The Dwyka Group is absent or thin below the coalfield and as a result Pietermaritzburg Formation directly overlies the basement in area. The Ecca sedimentation terminated with the deposition of the Volksrust mudstones. The Vryheid formation is characterised by thick beds of yellow-white cross-bedded sandstone and grit, which alternate with beds of soft, dark grey, sandy shale (Taaiboschspruit Colliery Rooikop Section EMPR, 1998). Most of the coalfield has been affected by transgressive dolerite sheets which are ubiquitous in the area. Dolerite intrusions in the Rooikop Section have been found to be either vertical dykes or near horizontal sheets, which have been shown, by previous geophysical traverses, to intrude the coal seams in the area (Taaiboschspruit Colliery Rooikop Section EMPR, 1998). A major northeast-southwest striking fault forms the western boundary of the coal seams. This fault coincides with a major sill contact. A 1:250 000 geological map with the Rooikop site indicated, is provided in Figure 6 4.

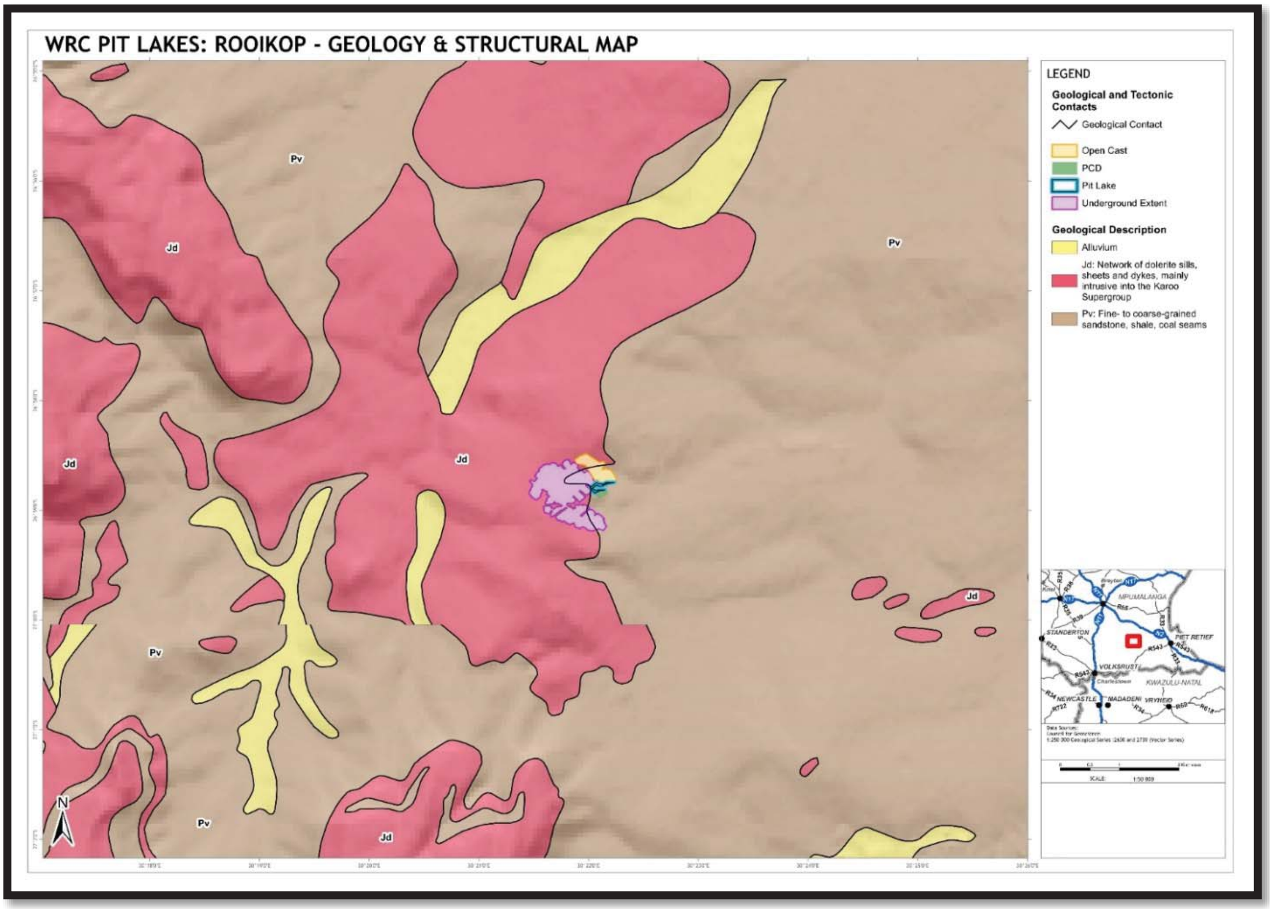


Figure 6-4: Rooikop Geological map.

Eleven coal seams were identified in the Natal coal fields of which only four can be economically mined which are the Alfred, Dundas, Gus and Coking seam (Spurr et al., 1986). The economic coal seams mined at the Rooikop section of Taaiboschspruit Colliery comprise the Alfred and Dundas seams. The Dundas seam attains thicknesses of 2 m and consists of an upper mixed dull and bright horizon, a central bright horizon and at the base a mixed shale and coal. The roof of the Dundas seam comprises competent, medium-grained sandstone, while the floor is usually an incompetent shale, which can cause issues during mining. The Alfred seam has been found to have generally high ash and sulphur content, with a thickness of 1.9 m to 3.8 m. The floor of the coal seam generally consists of medium to coarse grained sandstone (Hancox and Götz, 2014). A typical stratigraphic column of the coal field is provided in Figure 6 5, showing the position of the Alfred and Dundas seams in the Pietermaritzburg formation.

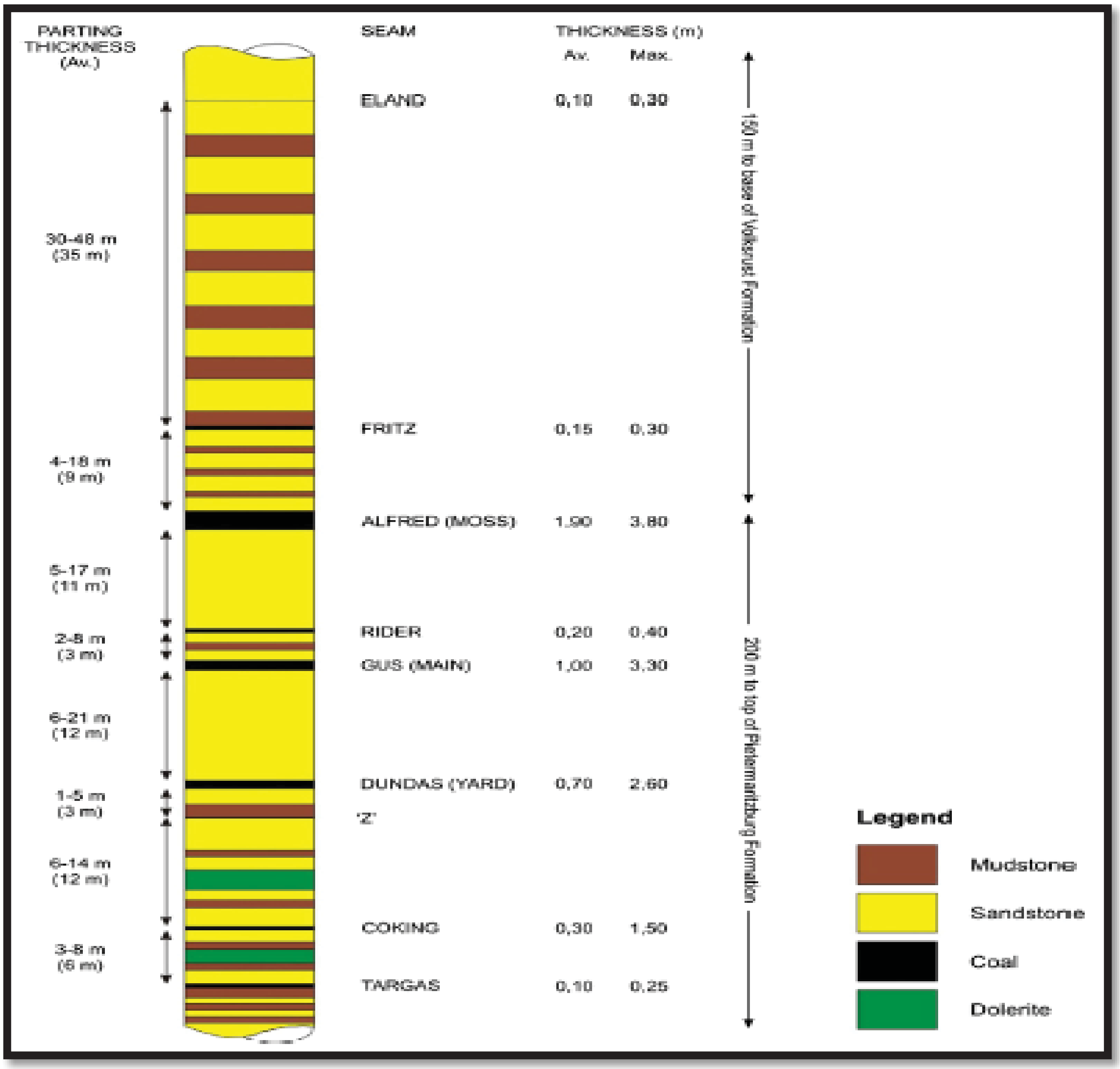


Figure 6-5: Stratigraphy of the Natal coal fields (From Hancox and Gotz, 2014).

6.5 Geochemistry

The impacts after closure were analysed and risks for acid mine drainage were evaluated by means of Acid Base Accounting (ABA) and Net Acid Generation (NAG) done on core samples from site exploration boreholes prior to mining (Taaiboschspruit Colliery Rooikop Section EMPR, 1998). The results showed that the contact zone above the Alfred coal seam released high concentrations of sulphates and total dissolved solids when weathered (Figure 6-6Figure 6-6:). The pH was expected to remain neutral as the most acid generating formation was found below the Alfred coal seam and would most likely be submerged in the underground workings.

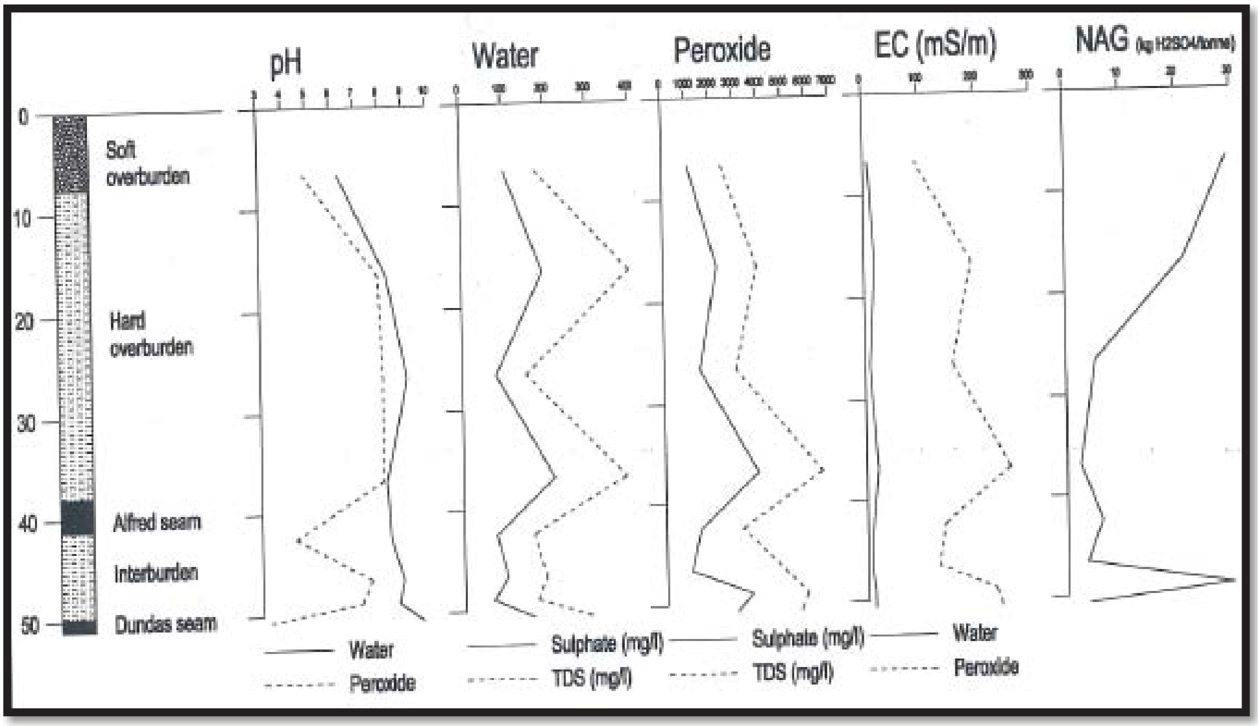


Figure 6-6: Water and Peroxide leach test results for a vertical lithological profile at Rooikop mine.

The ABA and NAG values for RK15 are reported in Table 6-1, where the Acid Potential (AP), neutralising potential (NP), Net Neutralising Potential (NNP) and Neutralisation Potential Ratio (NPR) are reported in kg $CaCO_3$/tonne. The Net Acid Potential is reported in kg H_2SO_4/ tonne. The more negative the NNP value and, the lower NPR (i.e. NPR values <1), the higher the acid potential of the rock unit. Both the Alfred and the Dundas seams are expected to produce acid according to their NPR; however the Dundas seam has higher AP values than the Alfred seam. The contact zone above the Alfred seam might have the potential to produce more acidity than the underlying lithologies, but also requires further testing according to the NNP values. As stated earlier, the Dundas seam and lower Alfred seam will most likely be submerged and therefore may remedy the possibility of acid generation.

Table 6-1: Rooikop Borehole RK15 ABA and NAG results (Rooikop EMPR 1998).

Depth (m)	Lithology	%S	AP	NP	NNP	NPR	NAG
6-7.35	Soft overburden	0.04	1.25	1.37	0.12	1.10	29.1
16.10-17	Hard overburden	0.11	3.44	7.76	4.32	2.26	21.41
26.2-27	Hard overburden	0.4	12.5	3.43	-9.07	0.27	5.12
36.5-37.2	Contact zone above Alfred seam	0.53	16.56	10.3	-6.26	0.62	2.38
42-43	Contact zone below Alfred seam	0.07	2.19	1.71	-0.48	0.78	6.25
46.2-47.0	Interburden	0.12	3.75	2.87	-0.88	0.77	3.54
48.4-49.4	Contact zone above Dundas seam	0.24	7.5	2.32	-5.18	0.31	29.7
50.5-50.7	Contact zone below Dundas seam	0.2	6.25	1.89	-4.36	0.30	3.85

Where NNP = NP-AP; NPR = NP/AP and AP = %S x 31.25 assuming all sulphur is pyritic.

6.6 Conceptual Hydrogeological Model

The information in this section is extracted from the Hydrogeological Investigation Report compiled for the proposed Discard Dump (GCS, 2016) (Annexure 2B).

Aquifer description
Based on a review of available data, it is evident that the key aquifers host media within the regional area can be generalised as follows:

- Unconsolidated aquifer – Alluvial material;
- Semi-confined aquifer – weathered rock; and
- Fractured rock aquifer.

Generally, the unconsolidated surface alluvium overlies the unconfined weathered aquifers and stores water resulting from precipitation infiltration and overland flow. Due to the spatial distribution in relation to the pitlake the unconsolidated alluvial aquifers are not considered in detail.

Unconfined aquifer – weathered rock / material
The weathered rock aquifer hosted within the Vryheid Formation Sediments is classified as the uppermost weathered rock/material, which possesses primary porosity associated with weathering. The depth of weathering is generally less than ~20 metres below ground level (mbgl), with borehole yields generally less than 2 l/s. Discrete and localised variations in hydraulic parameters may occur and are likely to be a result of characteristics of porosity. Groundwater quality indicates a bicarbonate groundwater type with elevated aluminium, manganese and iron values.

Fractured rock aquifer
The fractured rock aquifer hosted within the Vryheid Formation Sediments is classified as a thick sequence of sediments (i.e. sandstone, shale, siltstone, carbonaceous shale and coal). The matrix of the Vryheid Formation Sediments has a very low primary porosity and groundwater storage and movement is predominantly confined and is associated with geological structures, fracturing and bedding planes.

Water strikes in the discrete fracture zones, generally range between ~20 and ~50 metres below ground level (mbgl) with moderate yields (>2 L/s). Higher yields (~5 to >10 L/s) are largely associated with dolerite intrusion contact zones. Transmissivity values obtained from various aquifer testing programs, using a number of analytical methods, range from ~0.4 to ~30 m³/d.

Groundwater levels measured across the regional project area, when compared with available groundwater intersection data, indicates confined groundwater flow conditions within the fractured rock aquifer with an inferred groundwater flow towards the east (a subdued reflection of the surface topography). However, on a local scale, groundwater flow is likely to be significantly more complex due to geological and structural controls, resulting in potential flow of groundwater barriers and/or discrete conduits.

Recharge processes are by means of direct and indirect infiltration of precipitation. Based on the chloride-method, the localised recharge estimate for the weathered aquifer is between 10 and 25% of the mean annual precipitation; while 1 to 3% of the annual precipitation is estimated for the fractured rock aquifer unit.

Water Levels

Groundwater levels in the surrounding Karoo aquifer were used to determine the relationship between the topography and groundwater levels. Groundwater levels were obtained from a hydrocensus and aquifer tests conducted during the July to September 1998 period by GCS. The aquifer at Rooikop is low to moderate yielding with the potential to supply local domestic and stock watering purposes. Monitoring borehole information is given in Table 6-2, and the borehole locations and pitlake is shown in Figure 6-7. The Bayesian relationship between topography and groundwater levels prior to mining is shown in Figure 6-8.The groundwater levels measured after mining ceased ranged from 2.3 and 20.21 mbgl (Figure 6-9).

Table 6-2: Rooikop Borehole Information

BH ID	Longitude (m)	Latitude (m)	Elevation (mamsl)	Collar Height (m)
RGCS 1	30.37168	-26.98416	1382	0.32
RGCS 2	30.37111	-26.98439	1385	0.3
RGCS 3	30.37161	-26.97928	1376	0.41
RGCS 4	30.37018	-26.97901	1381	0.25

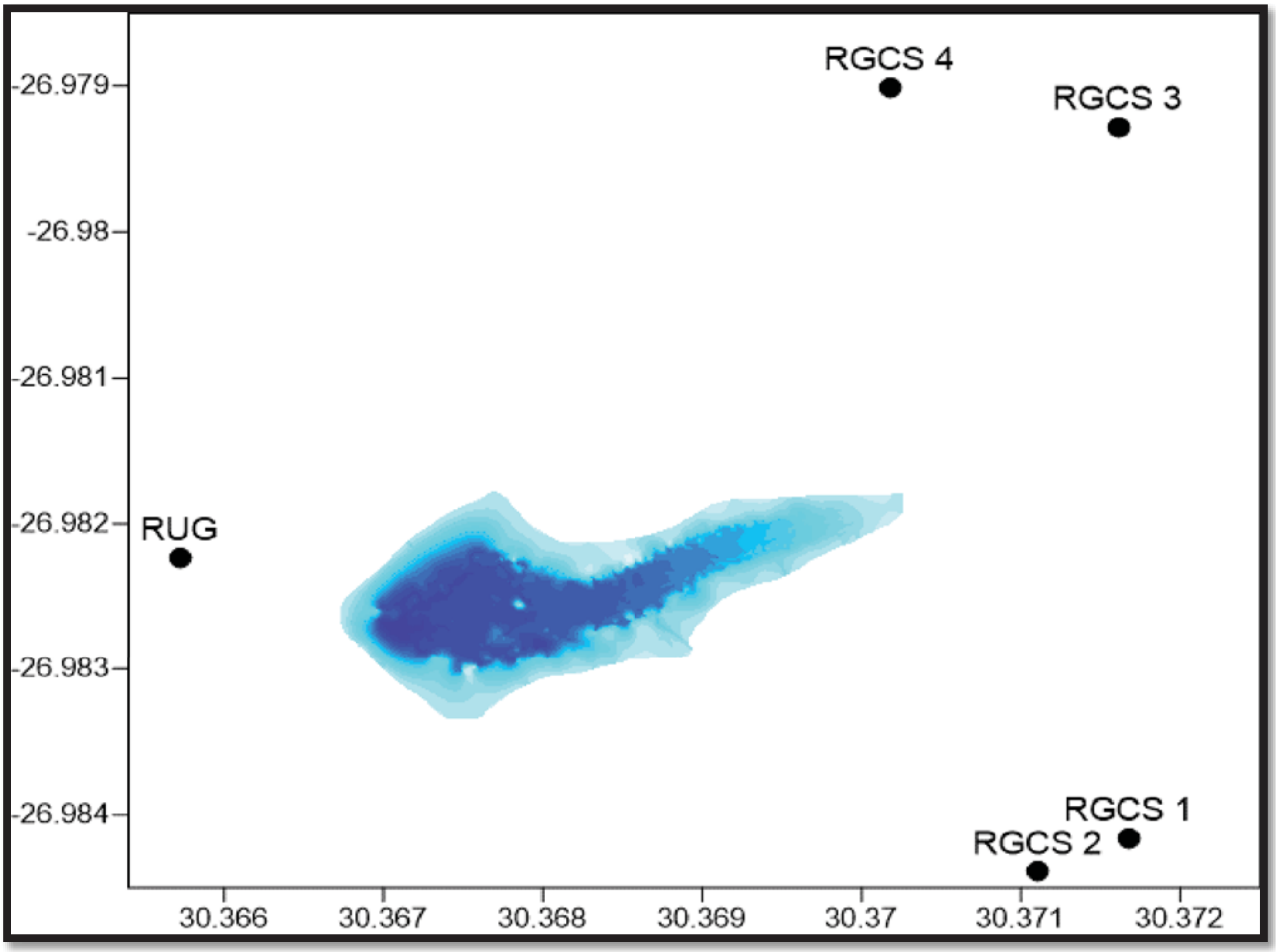


Figure 6-7: Rooikop Borehole Locality Map.

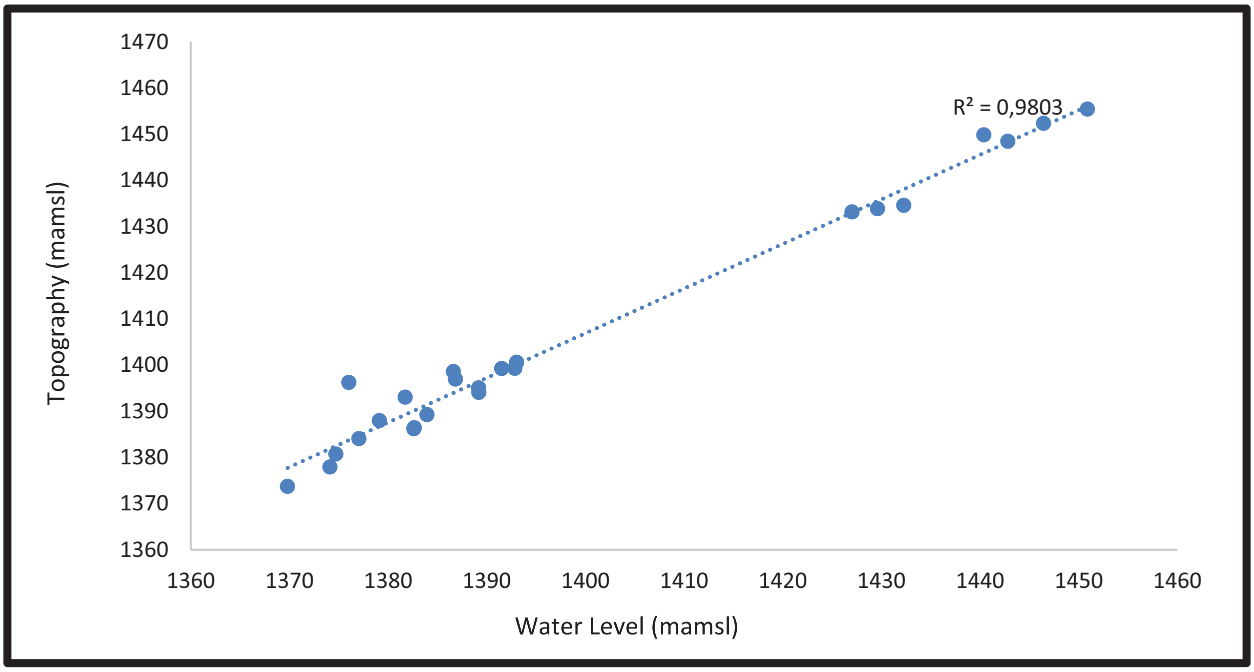


Figure 6-8: Rooikop Pitlake: Bayesian Plot

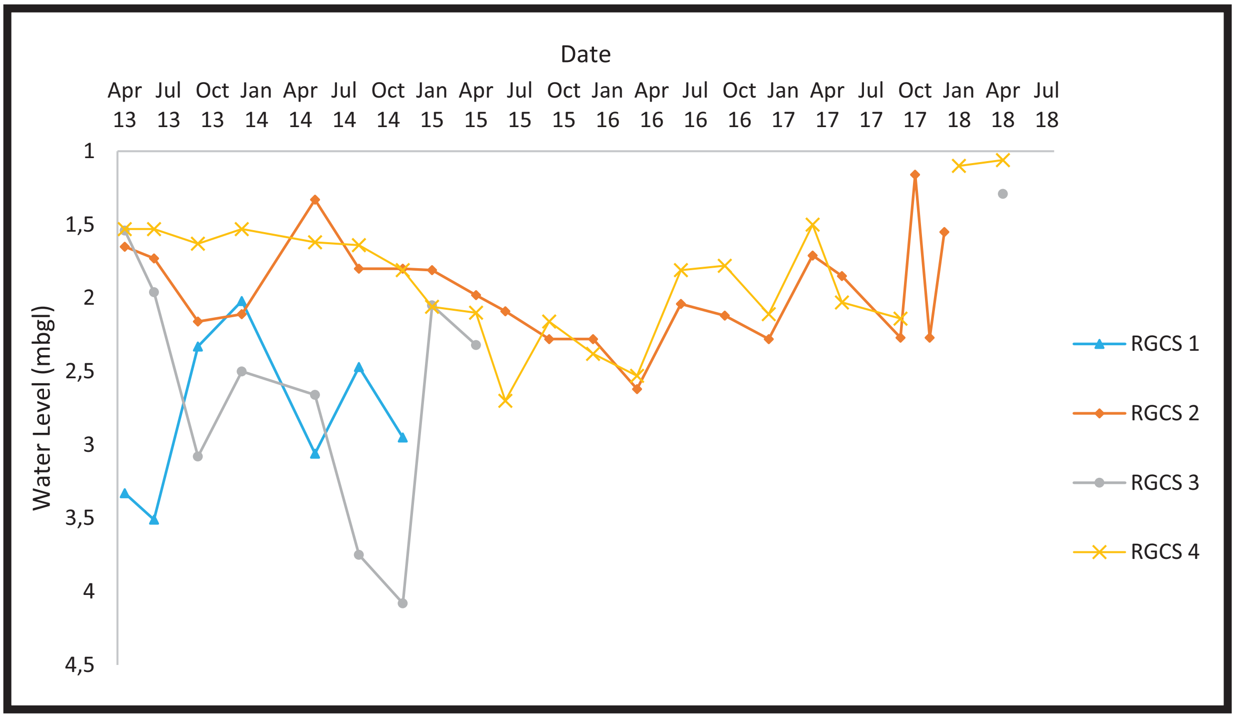


Figure 6-9: Rooikop Monitoring Boreholes Water Levels.

6.7 Conceptual Water Balance Model

The conceptual hydrogelogical model is based availble data. The conceptual model takes inot cognisanse that after underground and open pit mining ceased, the water levels rebounded in the Rooikp pit. The water levles in the open pit is similar to the water level in the underground operation due to the open adits in the pitlake highwall. The water inflow into thr pitlake comprises water from the open cast, undegrounf workings via the open adiits surfface runoff and direct rainfall. The losses of water from the pitlake is seepage and evaporation. The following parameters and equation was used to determine the of the Rooikop pitlake water balance:

$$\Delta S = P + GW_{u/g} + GW_{Backfill} + Ro_{Backfilled} + Ro_{Karoo} - E - D$$

Where:

ΔS is change in storage, P is precipitation, $GW_{u/g}$ is groundwater inflow from the underground workings, $GW_{Backfill}$ is groundwater inflow from the backfiled material, $Ro_{Backfilled}$ is runoff from the backfilled material, Ro_{Karoo} is the runoff from the Karoo aquifer, E is the evaporation and D is the surface discharge. Figure 6-10 is the conceptual hydrological model for Rooikop pitlake showing the water balance components.

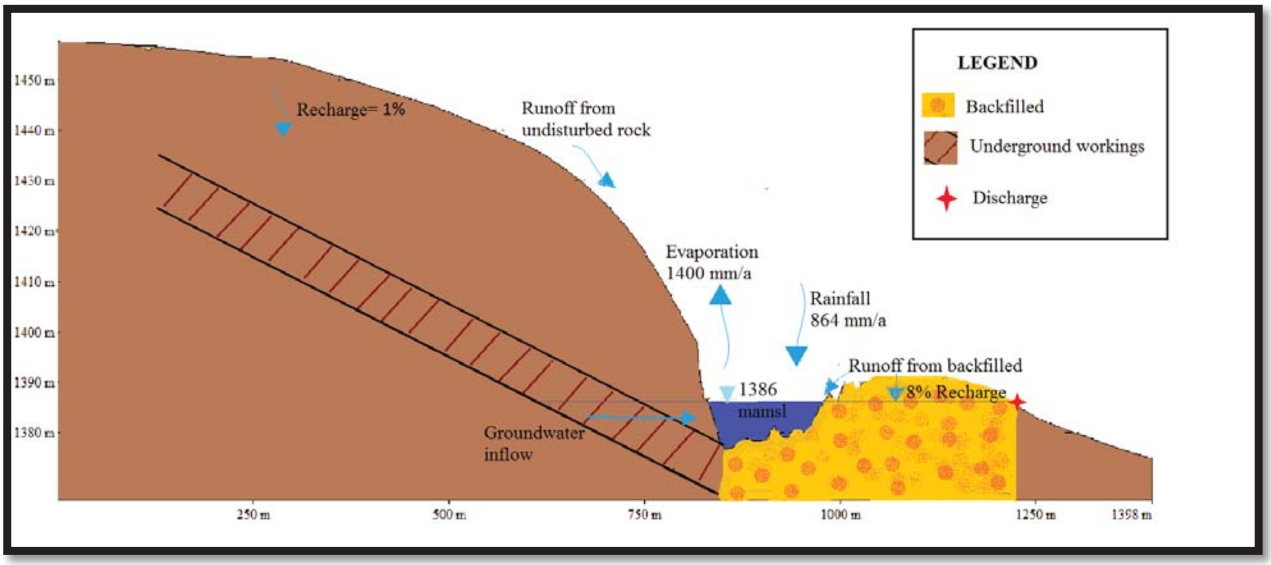


Figure 6-10: Rooikop Conceptual Water Balance.

Rainfall

The W51B quaternary catchment falls into rainfall zone W5A and has a catchment MAP value of 864 mm. Recharge to groundwater is approximately 1.74% of the MAP (15 mm).

Runoff

The topography of the area is undulating with a net slope towards the east. The lowest elevation is 1358 mamsl and the highest point is 1461 mamsl with an average elevation of 1420 mamsl. Rooikop falls within W51B quaternary catchment of the Usutu-Mhlathuze with an area of 496 km^2. Runoff was determined using the DEMs (Figure 6-11) with runoff area contributing to the pitlake estimated at 90 000 m^2 of which 40 000 m^2 is from the undisturbed/natural and 50 000 m^2 is from the backfilled area. Runoff from the natural topography was calculated to be 12% of the rainfall, whilst runoff from the backfill material is estimated at 10% of the rainfall.

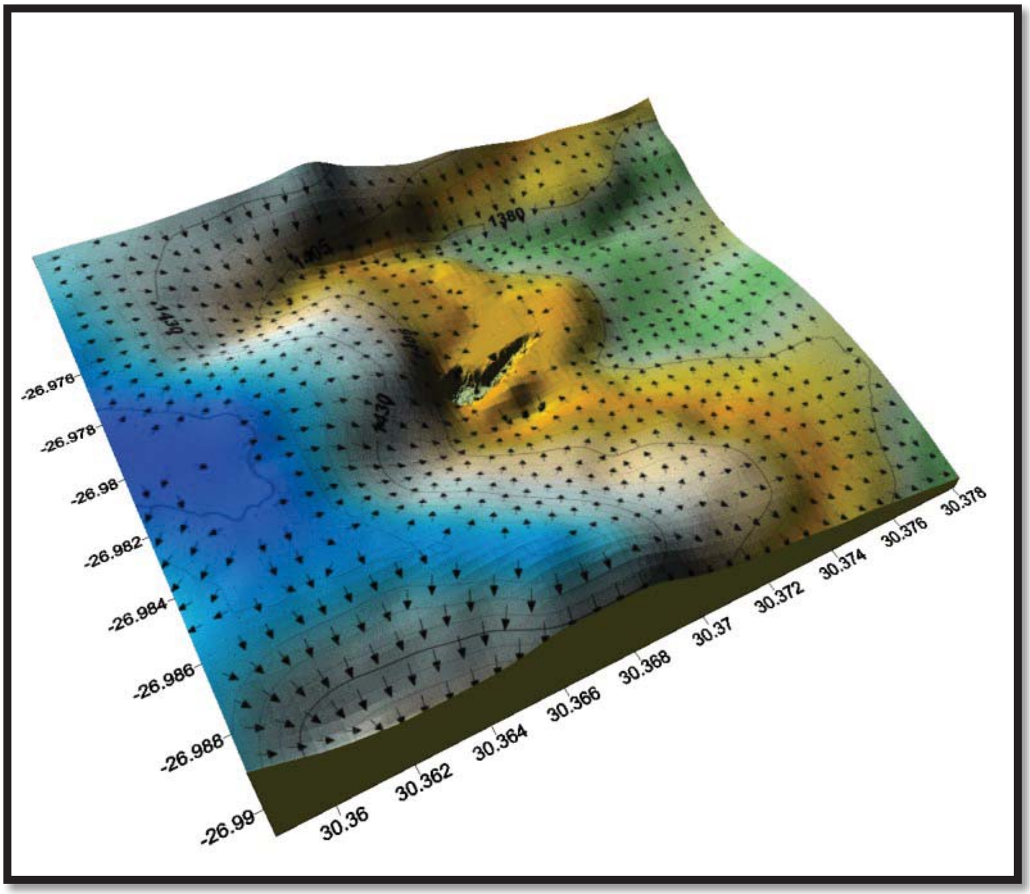


Figure 6-11: Rooikop Surface Elevation.

<u>Groundwater Inflow</u>
The underground mine void acts as preferrential flowpath for groundwater, which discharges inot the pitlake from the open high wall adits. The total mine void is approximately 100 ha and it is assumed that all groundwarr recharge above the mine void reports into the void and discharges into the pitlake. Recharge to the backfilled area recharges the backfill water which daylights in the pitlakes.

<u>Evaporation</u>
The yearly evaporation is 1400 mm, greater than the average rainfall. Evaporation zone 13A was used to determine the monthly evaporation distribution. The results of the monthly distribution for the S-Pan evaporation are shown in Table 6-3.

Table 6-3: Rooikop Monthly Evaporation

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Evaporation	137.1	142.7	152.7	153.7	131.5	127.3	99.0	82.3	69.2	77.6	100.1	127.0
Lake Evaporation	111.0	117.0	126.8	129.1	115.7	112.0	87.1	71.6	58.8	64.4	81.1	102.9

<u>Observations</u>
Contribution to the pitlake is largely runoff, direct rainfall and groundwater inflow from the underground mine workings, as shown in Table 6-4. Evaporation is not sufficient to prevent surface water discharge occurring at

Rooikop. This occurs as seepage into the stream. The Rooikop pitlake elevation is 1387 mamsl where the volume of the lake is 104 590 m^3. The net losses are from evaporation. After evaporation was accounted for, the model showed an excess volume of 17 523 m^3 /year, which an average seepage rate of 48 m^3/day. The full water balance is provided in Appendix F: Rooikop Water Balance.

Table 6-4: Rooikop Water Balance Summary

Parameter	%
Runoff from natural topography	11
Direct Precipitation	37
Underground workings contribution	58

6.8 Water Quality

6.8.1 Water Quality Profiles

Pitlake

The profiles conducted in the Rooikop pitlake (Figure 6-12Figure 6-12:) showed that stratification does not play a major role in this pitlake. The Rooikop pitlake has the lowest EC of all the pitlakes and is oxygenated throughout the entire depth of the lake indicating that the lake water is well mixed and homogenous. The elongated shape and long fetch of the pitlake together with the shallow indicate that the water column was influenced by wind-induced mixing.

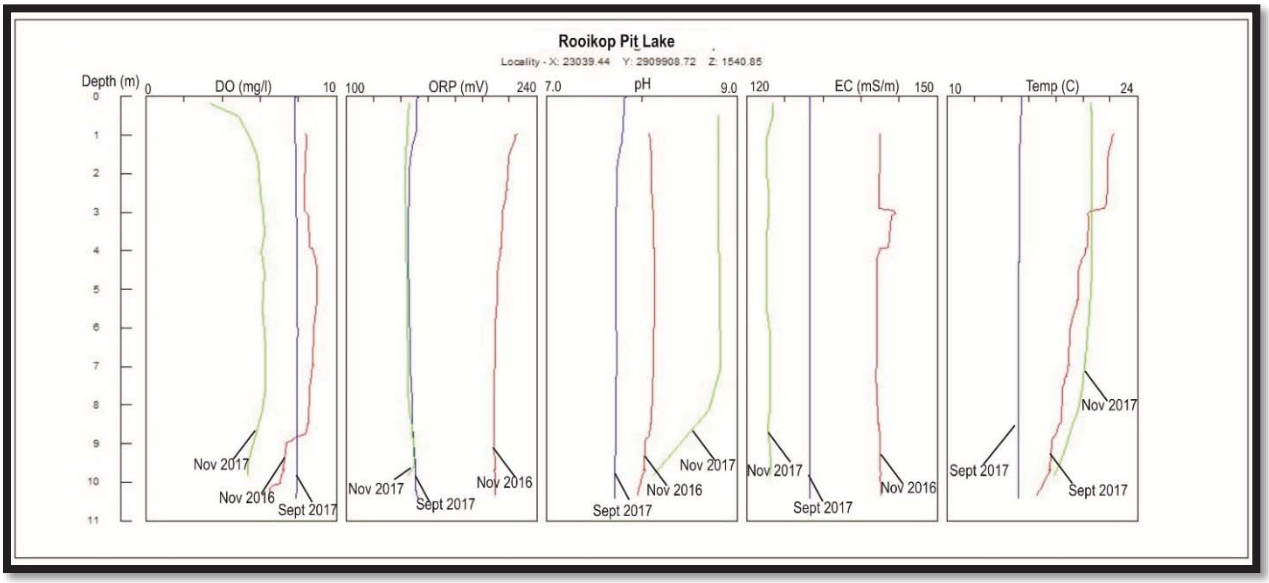


Figure 6-12: Rooikop Pitlake: Multiparameter profiles.

The following could be derived from the Rooikop profiles:

- Temperature ranged from 20°C to 22°C in the summer and dropped to 15°C in winter.
- EC ranged from 120 to 140 mS/m in the lake. The base shift in the EC profiles is due to the different make of probes used during the September 2017 and November 2017 profiling.
- The pitlake was overall well-oxygenated, with oxygen levels ranging between 5 and 9 mg/l.
- A circumneutral pH ranging from pH 8 to 8.5.
- The redox potential of the pitlake water was oxidising.

Source water for the pitlake

Figure 6-13 shows the ionic characteristics of groundwater, surface water and pitlake water sampled during the 2016-2017 sampling period. Contributions to the pitlake water quality included the underground workings, opencast and surface runoff. The Rooikop pitlake samples showed calcium as the dominant cation (70%) and sulphate as the dominant anion (84%).

The Ca-SO_4 signature is indicative that the pitlake water was influenced by a source where sulphide oxidation and subsequent neutralisation took place (such as the underground adits) and flushing of the products into the pitlake.

The general groundwater chemistry can be divided into three major water types: Mg-SO_4 for RGCS1 and RGCS2, Ca-SO_4 for RGCS4 and Ca-HCO_3 for RGCS3. RGCS3 is typical of ambient groundwater quality. The monitoring boreholes are located on the perimeter of the pitlake, in the natural Karoo aquifer.

The contribution from the Karoo aquifer to the pitlake is currently minimal with the pitlake chemistry indicating that the majority of the water originates in the flooded backfill and the partially flooded underground workings. The Opencast Dam 1 & 2 showed similar chemistry to that of the Rooikop pitlake, with contribution to the water inflow and quality from recharge through the rehabilitated opencast mining area with associated leaching of salts from disturbed overburden backfilled material that contributes to the high TDS and SO_4 concentrations in the water.

The Rooikop underground mine is currently discharging water into the pitlake which ultimately seeps into an unknown tributary of the Heyshope dam. The seepage water ("Discharge from pitlake") has average sulphate concentrations of 388 mg/ℓ. The water quality further downstream from the discharge ("Discharge from pitlake downstream") showed lower sulphate concentrations with an average of 291 mg/ℓ. The ionic characteristics of the river closely resembles that of the pitlake.

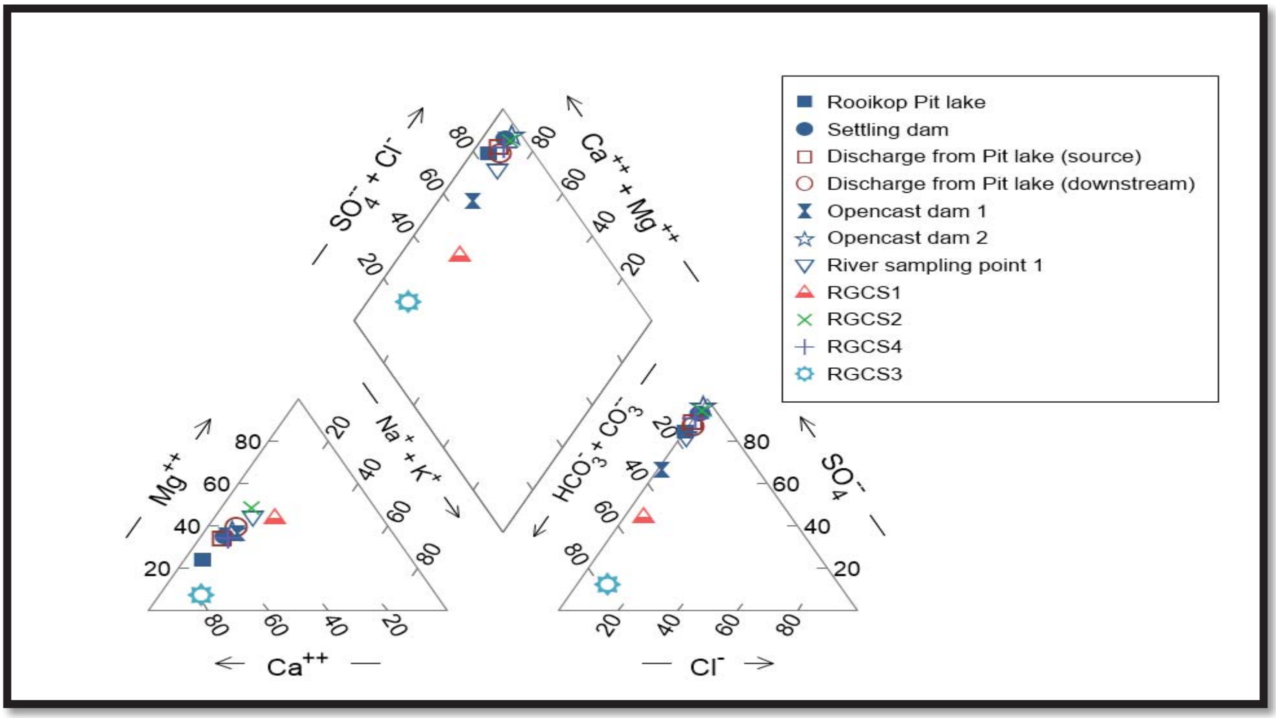


Figure 6-13: Rooikop Water Quality Piper diagram.

6.8.2 Pitlake water chemistry

The Rooikop pitlake was sampled during the November 2016, September 2017 and November 2017 sampling runs. The chemical results did not vary much with depth or with time. The complete data set is shown in Appendix K: Rooikop Water Quality. The Rooikop pitlake has higher equivalent calcium than sodium concentration with an average hardness measured at 702 mg/l. This high degree of hardness can be attributed to carbonate minerals that first dissolve and neutralise acidity and generate alkalinity in the mine water (Azzie, 2002). The seepage discharge water from the Rooikop pitlake is very similar to the pitlake water quality, indicating that the pitlake is discharging high sulphate and calcium concentrations onto surface. The pitlake and seepage have pH neutral conditions.

The descriptive statistics for the pitlake water quality from the different sampling events are shown in Table 6-5. The fundamental ionic characteristics of the pitlake have not changed in depth or season as can be expected from the homogenous EC.

Table 6-5: Rooikop Pitlake: Water quality.

Parameter	Unit	n	Average	SD	Minimum	Maximum
pH	units	17	7.8	0.1	7.5	8.0
EC	mS/m	17	137.2	4.5	132.5	143.0
TDS	mg/l	17	1111.0	191.3	795.0	1300.0
Ca	mg/l	17	219.6	13.6	200.0	244.2
Mg	mg/l	17	45.5	4.2	40.0	51.6
Na	mg/l	17	18.0	1.0	16.4	20.0
K	mg/l	17	5.5	0.3	5.2	6.0
HCO_3	mg/l	17	122.8	12.7	108.0	155.0
Cl	mg/l	17	2.6	0.3	2.3	3.0
SO_4	mg/l	17	607.7	25.9	577.0	653.0
NO_3	mg/l		<0.1	-	-	-
NH_3	mg/l	13	0.05	0.04	0.01	0.16
SiO_2 (aq)	mg/l	17	11.38	0.52	10.54	12.20
Hardness as $CaCO_3$	mg/l	17	735.43	47.37	688.00	822.02
F	mg/l		<0.5	-	-	-

The scatter plot (Figure 6-14) of sulphate (mEq/ℓ) versus Ca+Mg (mEq/ℓ) shows a strong linear correlation and proportional increase, indicated by a slope of 1. This can suggest that the acid generating processes are buffered by acid neutralising processes, releasing SO_4, Ca and Mg in equal proportions into the groundwater.

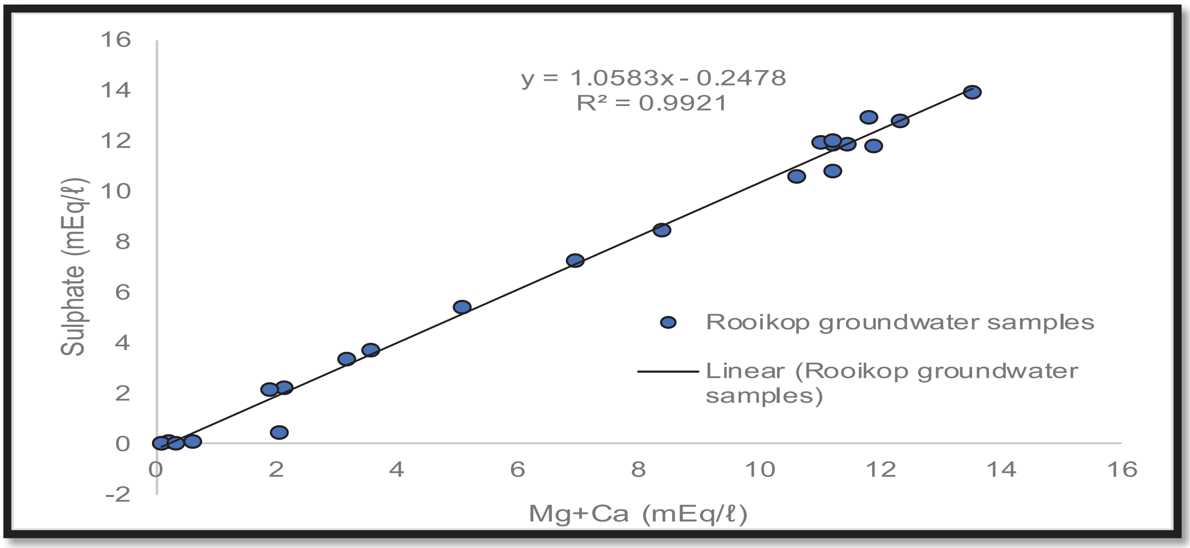


Figure 6-14: Rooikop: Scatter plot of sulphate vs Ca+Mg.

The saturation index of Rooikop pitlake samples were modelled using Geochemist Workbench (Bethke, 2018). Calcite and CO_2(g) were found to be oversaturated in the water (Figure 6-15 and Figure 6-16), with calcite the potential to precipitate. Gypsum showed SI values of high unsaturation (Figure 7-17) and cannot be considered a sink for SO_4.

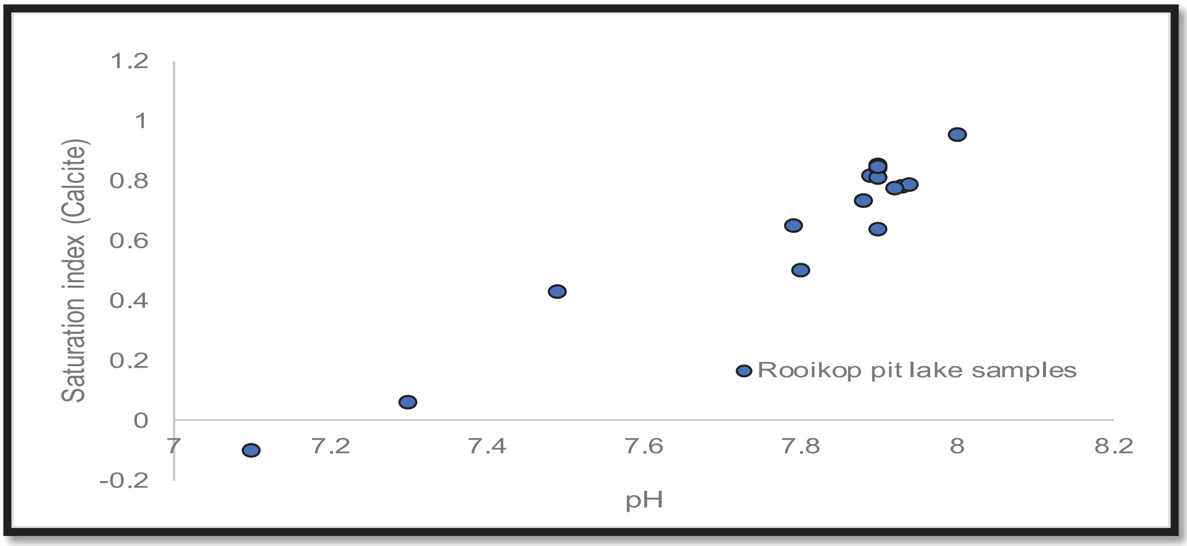


Figure 6-15: Rooikop Pitlake: Saturation state of calcite.

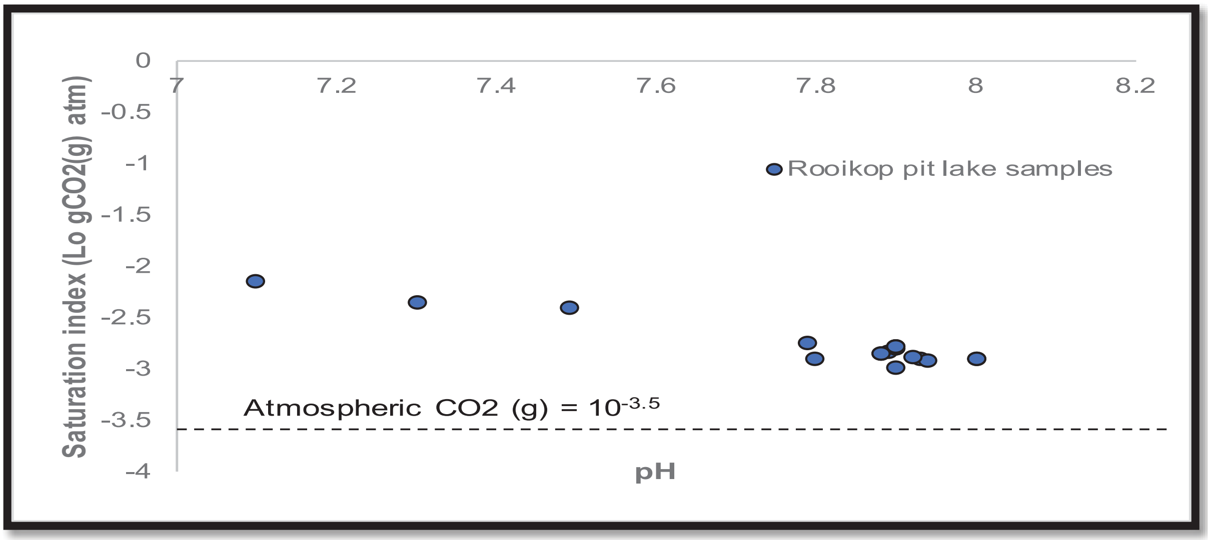


Figure 6-16: Rooikop Pitlake: Saturation state for CO2.

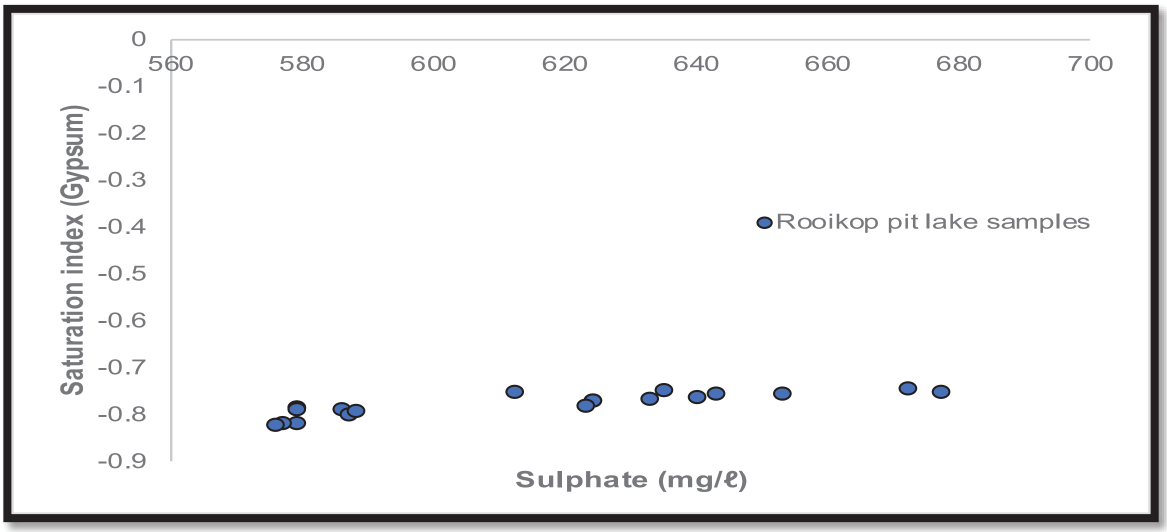


Figure 6-17: Rooikop Pitlake: Undersaturation of gypsum.

Trace Element Chemistry

The trace elements in Rooikop pitlake were generally below detection limits. Manganese was detected at maximum concentrations of 0.05 mg/l, aluminium 0.015 mg/l and boron 0.017 mg/l. All other heavy metals were below detection limits, as shown in Table 6-6.

Table 6-6: Rooikop Pitlake: Water quality.

Parameter	Unit	n	Average	SD	Minimum	Maximum
Al	mg/l	6	0.010	0.005	0.003	0.015
Fe	mg/l		<0.5	-	-	-
Mn	mg/l	10	0.026	0.010	0.016	0.050
B	mg/l	17	0.0103	0.0055	0.0030	0.0171
As	mg/l		<0.0005	-	-	-
Cd	mg/l		<0.0001	-	-	-
Zn	mg/l		<0.05	-	-	-
Pb	mg/l	17	<0.0005	-	-	-

6.8.3 Surface water quality

A small unknown tributary flows from the Rooikop mine towards the Heyshope dam, which is sampled at various places. The Rooikop pitlake discharge seeps into this stream with an average sulphate concentrations of 388 mg/ℓ.

6.9 Pitlake Biota

6.9.1 Phytoplankton

Phytoplankton was only sampled in September 2017 in the Rooikop pitlake. The pitlake water was very clear and the secchi disc was visible to the bottom of the pitlake (secchi depth of 10.5 m) (Table 6-7). Chlorophyll-a concentrations indicated oligotrophic to mesotrophic conditions, with average concentrations of 5 µg/l and concentrations ranging from a minimum of less than 1 µg/ℓ to a maximum of 7.74 µg/ℓ. This results in a higher diversity of phytoplankton genera with the dominant group being Chlorophyta with genera *Ankistrodesmus*, *Chlorella* and *Chlamydomonas* in almost equal volumes.(Figure 6-18 and Figure 6.23). The phytoplankton data is contained in Appendix K: Rooikop Water Quality.

Table 6-7: Rooikop Chlorophyll-a concentration and secchi depths.

Site	Date	Ammonia-N (mg/ℓ)	Nitrate-N (mg/ℓ)	Total phosphorous (µg/ℓ)	Si (mg/ℓ)	Hardness (as CaCO3 (mg/ℓ)	Average chlorophyll-a (µg/ℓ)	Secchi depth (m)
Rooikop	Sept 2017	0.03	0.02	<250	5.6	720	5	10.5

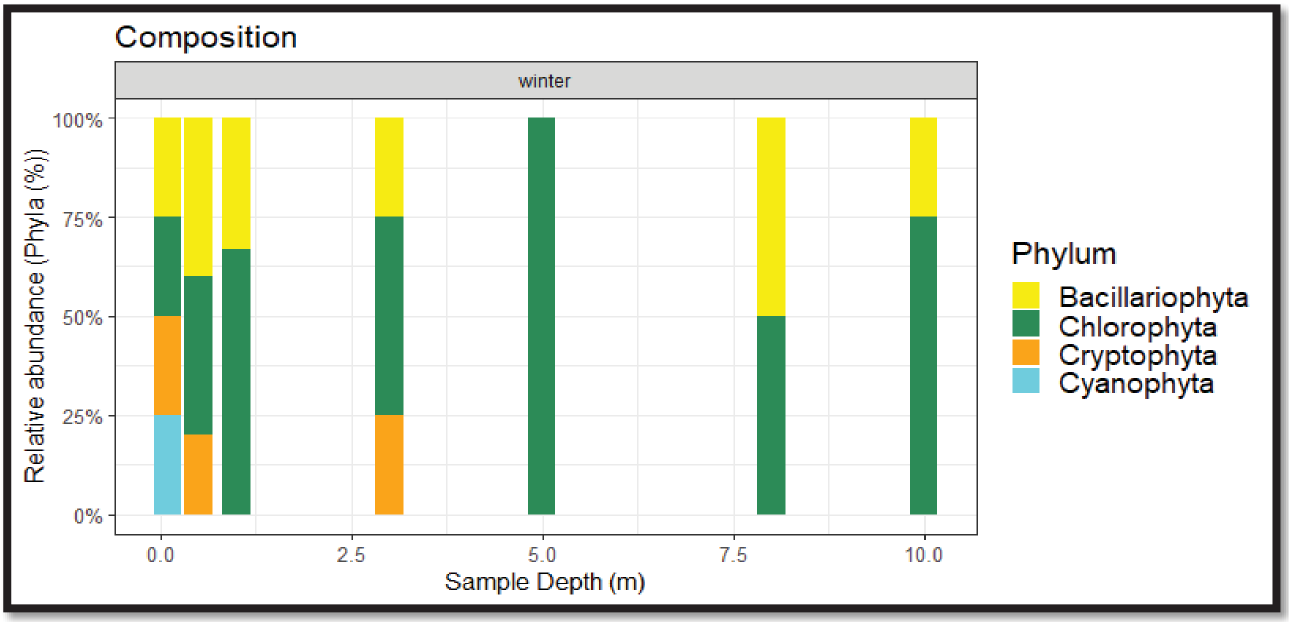


Figure 6-18: Rooikop: Phytoplankton phyla.

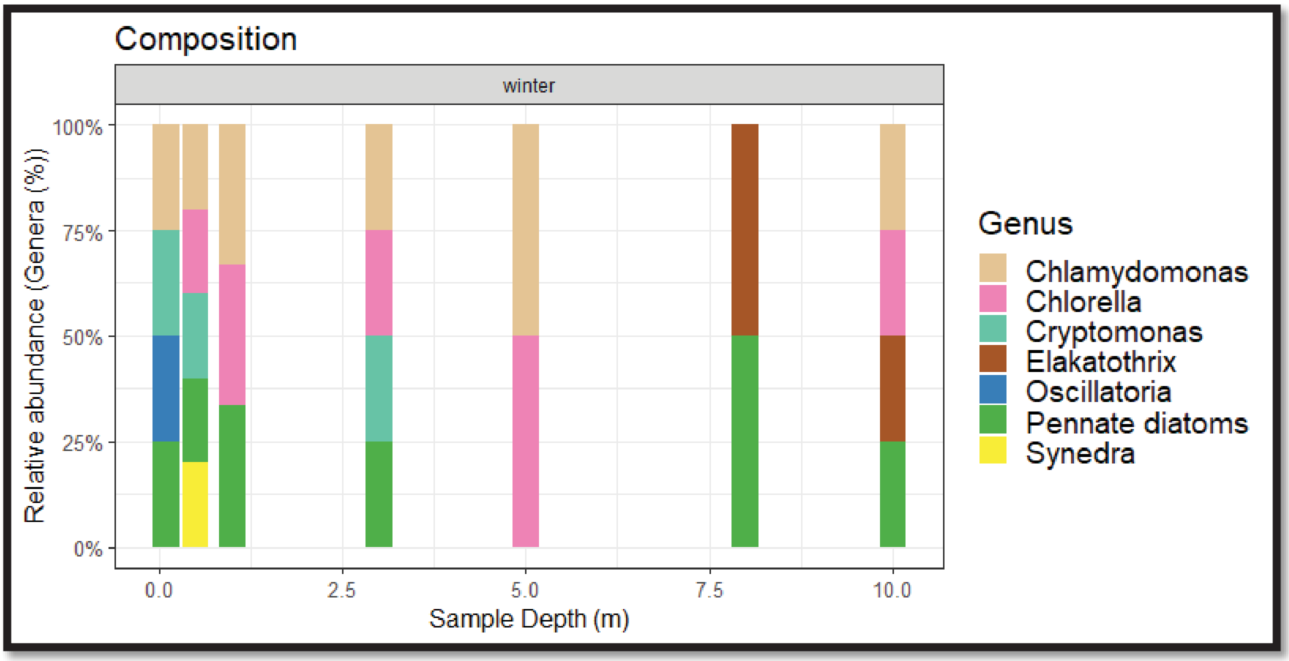


Figure 6-19: Rooikop Pitlake: Genera with depth.

6.9.2 Microbiology

In the Rooikop pitlake, the dominant phyla were Bacteroidetes and Verrucomicrobia, together with Proteobacteria and Actinobacteria (Figure 6-20). The function of these bacteria in the pitlake was not researched in this study. Literature indicated the phyla have symbiotic relationships with Spaghnum mosses in peat lands of South America (Oloo et al., 2016). A full microbial report drawn up by the Department of Biotechnology at the UFS is provided in Appendix M: Microbial Report.

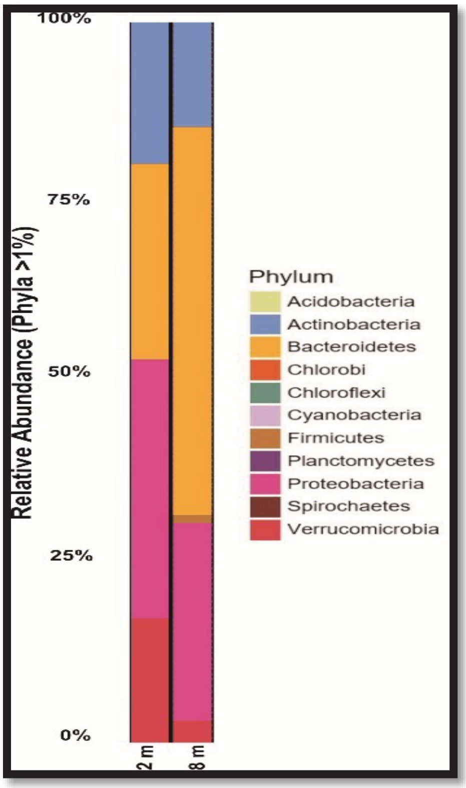


Figure 6-20: Rooikop Pitlake: Microbial Diversity to Phylum Level.

6.10 Conclusions

- The water balance of Rooikop is different to that of the other sites as both rainfall and groundwater are major contributions to the pitlake; Evaporation at Rooikop is not sufficient to prevent the occurrence of surface overflow. Rooikop pitlake may be considered a surface flow-through pitlake.
- The Rooikop pitlake is a complex system which receives contributions from the rainfall that recharges the underground mine with seepage onto surface.
- The Rooikop pitlake was dominated by calcium sulphate with major ion concentrations SO_4> Ca >Mg > HCO_3 > Na >K >Cl>NO_3.
- Although the pitlake displayed oligotrophic to mesotrophic status, a wide diversity of algae and bacteria was detected in the pitlake. The pitlake is unique in the sense that it receives water from the flooded underground mine runoff and rainfall. The Rooikop pitlake has lower EC than the pitlakes of Kriel and Kleinfontein.
- The pitlake chemistry indicates that the sulphate concentrations are in equilibrium with the underground mine, or that there is insufficient free oxygen in the mine to sustain further sulphide mineral oxidation.
- The water quality profiles of the pitlake show good water quality in terms of water clarity, dissolved oxygen saturation, circum-neutral pH, relatively low EC (compared to the other pitlakes) and oxidative redox potential which prevents the occurrence of the metals in the water. The pitlake discharge impact on the surface water quality.
- Regarding the pitlake primary productivity, the pitlake was classified as mesotrophic status, according to De Lange et al. (2018).
- The phytoplankton Chlorella and Chlamydomonas, are indicators of contamination (Vos, 2001). These algae are commonly used as waste-water-treatment pond algae are the most common genus found together with freshwater invertebrates*.*

CHAPTER 7: KLEINFONTEIN

7.1 Introduction

Kleinfontein pitlake is situated approximately 42 km south of Middelburg and 35 km north of Bethal, directly west of R35 (Figure 7-1). The mine falls within the Magisterial District of Bethal, under the jurisdiction of the eMalahleni Local Council, Mpumalanga Province. An opencast section to the south of the study site has recently resumed with active mining operations. The extent of the mining activities will involve the following properties: Kleinfontein 49 IS; Leeufontein 48 IS; and Middelkraal 50 IS. It is unlikely to impact on the existing Kleinfontein pitlake. The existing pitlakes are currently being used by recreation fisherman.

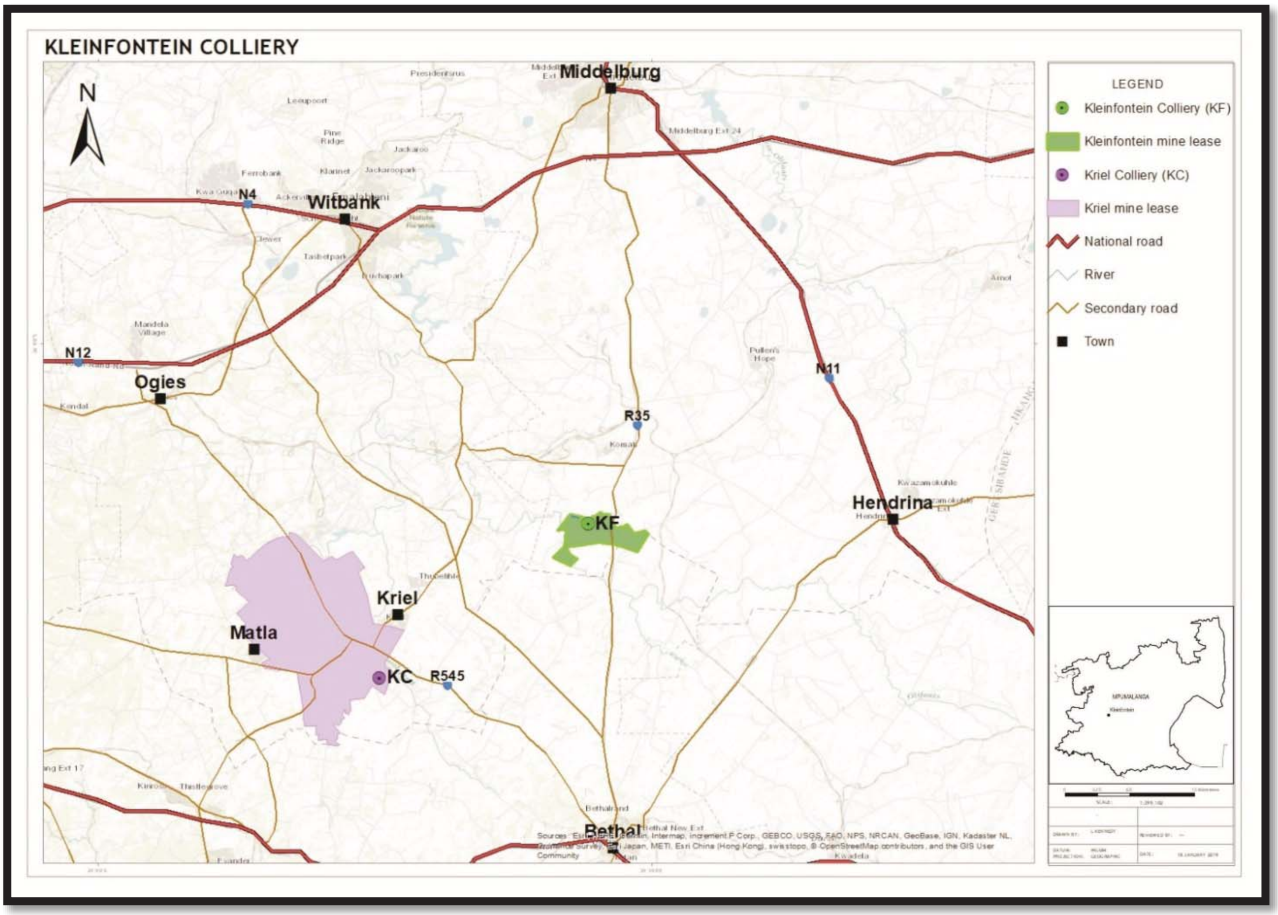


Figure 7-1: Location of Kleinfontein Colliery (KF).

7.2 Mining

The Kleinfontein mine is situated on the farm Kleinfontein 49 IS. The mining around the pitlakes ceased in 1991, after which the surface was rehabilitated. Mining involved box cuts, which exposed the coal seams and was mined by strip mining with the “roll over method”. Additional mining was undertaken at Kleinfontein by Jikama Mines from 2008. Figure 7-2 shows the site layout for the old Kleinfontein pitlakes and the new box cuts.

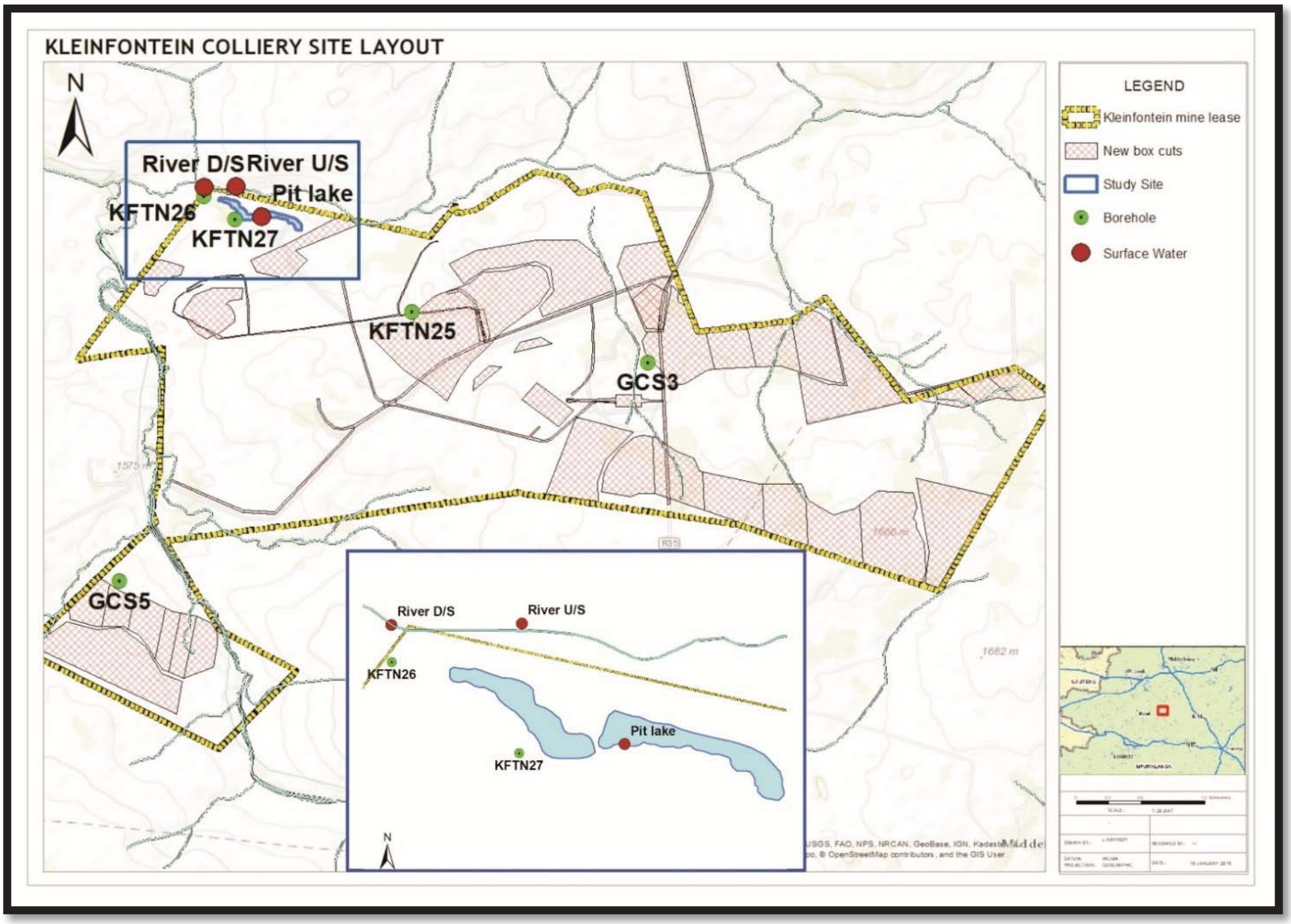


Figure 7-2: Kleinfontein Colliery Site Plan.

The pitlake, that formed in the final void of the rehabilitated opencast mine, has a thick reed growth which divides the pitlake into two parts. A berm to the north of the pitlakes separates the rehabilitated opencast workings and pitlake from the Kleinfontein Spruit. Plate 7 shows a photograph of the pitlake, with the berm in the foreground and discard dumps in the background.

Plate 7: Kleinfontein Pitlake, looking south, 6 March 2017.

7.3 Pitlake Morphology

The Kleinfontein site consists of two pitlakes which resulted from a lack of backfilling material. The maximum depth of pitlake A is 7.5 m, with the minimum elevation of 1538 mamsl and the maximum elevation of 1545.5 mamsl. The total volume and area of pitlake A is 109 003.93 m^3 and 321 720 m^2 respectively.

Pitlake B has a maximum depth of 1 m with the minimum elevation of the pitlake of 1537 mamsl and the maximum elevation of 1548 mamsl. The volume of pitlake B is 162 437.65 m^3 and area is 470 450 m^2. The bathymetric maps for the Kleinfontein pitlakes A and b are shown in Figure 7-3.

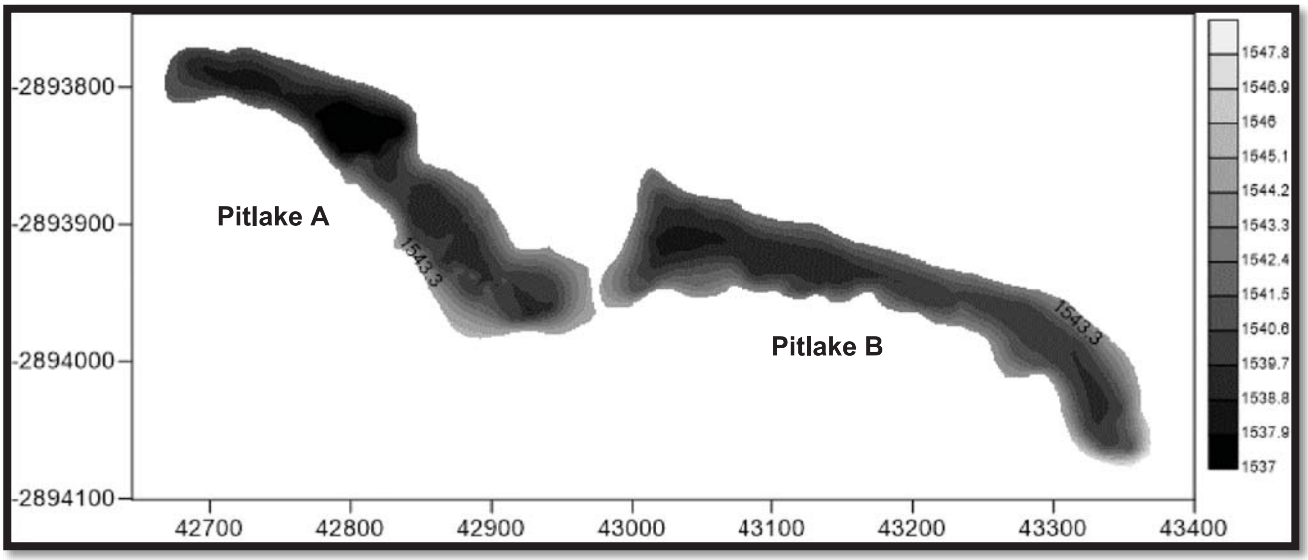


Figure 7-3: Kleinfontein Pitlakes.

7.4 Geology and Structural Geology

The Kleinfontein site is situated in the Witbank Coalfield which covers an area of 568 00 ha and is elongated over 180 km in a west to east direction (Hancox and Götz, 2014). The coalfield accounts for approximately one fifth of South Africa's coal reserves (Cairncross et al., 1990). Sedimentological investigations of the coal-bearing Vryheid Formation (Karoo Sequence) in the Witbank Coalfield have revealed that coal-peat deposition was associated with both marine and non-marine palaeodepositional events (Cairncross et al., 1990). The coalfield is roughly surrounded the towns of Witbank, Delmas, Springs, Devon, Hendrina and Belfast with the southern boundary formed by a pre-Karoo felsite ridge, which separates it from the Highveld Coalfield (Lurie, 2008).

Five (5) major seams are present and are numbered, according to Highveld Coalfield nomenclature from the base upwards, namely No's 1, 2, 3, 4 and 5. The thickness and distribution of the seams was controlled by pre-depositional paleotopography, and syndepositional events, with later destructive effects of dolerite intrusions.

The 1:250 000 East Rand Geological Map 2628 East Rand (Figure 7-4Figure 7-4:) shows three prominent lithostratigraphic units that are exposed within the immediate study area. These include:

- The northern parts of the study area including portions of the farm Kleinfontein, are the largest parts of Leeufontein and northern portions of Middelkraal. The lithological units that outcrop are the sedimentary rocks of the Vryheid Formation, located at the base of the Ecca Group of the Karoo sequence. Sediments associated with the Vryheid formation are sandstone, mudstones and shales. The Vryheid formation of the Ecca Group that contains the minable coal seam layers.

- Directly south, overlying the Ecca group in the central portion of the study area, are the volcanic rocks of the Vaalian Age (diabase), which intruded the Vryheid Formation.
- The southern portions of the study area are overlain by Vaalian sedimentary rocks of the Selons River Formation. The Selons River Formation is uppermost unit of the Rooiberg Group of the late Archean to Paleoproterozoic age. The lithology consists of porphyritic rhyolite with interbedded mudstone and sandstone.

During late Jurassic period, the Karoo strata were intruded by dolerite dykes and sills resulting in the devolatilization of coal proximal to the intrusions. The dolerite sills and dykes have resulted in coal seam displacement in certain areas.

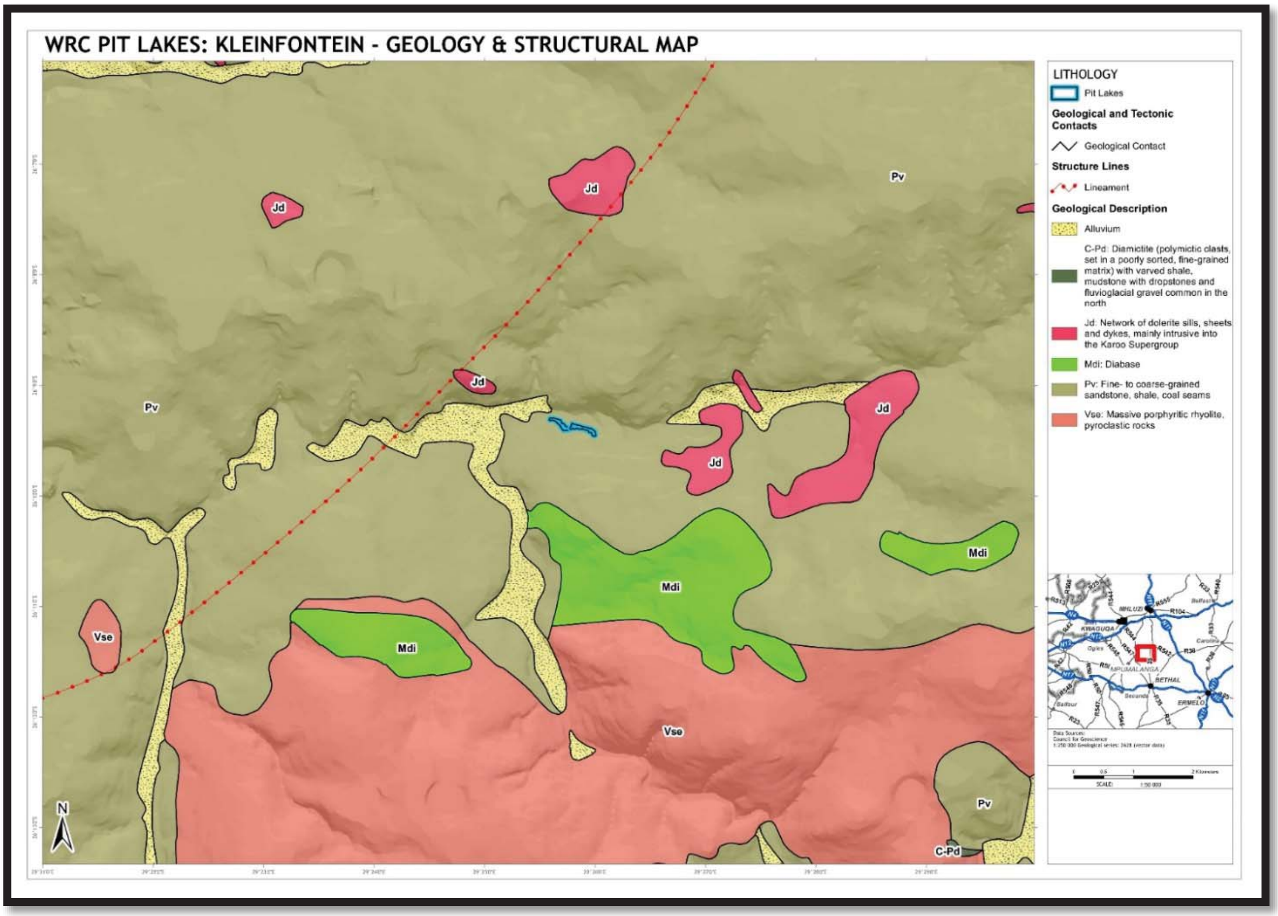


Figure 7-4: Geology of Kleinfontein pitlake.

A typical lithological profile of the geology of the Kleinfontein mine is shown in Figure 7-5. The coal seam dips in a south-westerly direction. The coal seam is 8 m below surface in south-western portion and 25 m below surface in the south-western sections. The coal seams were intruded by sills and dykes resulted in faulting and de-volatisation.

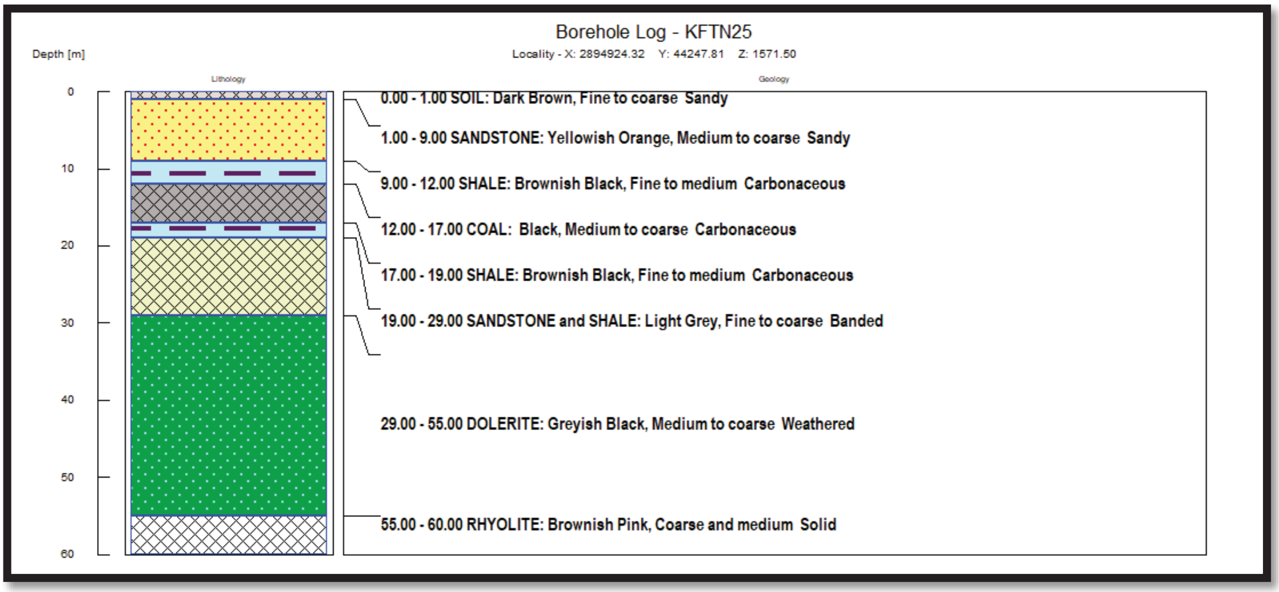


Figure 7-5: Kleinfontein Lithography.

7.5 Mineralogy and Geochemistry

The mineralogy and geochemistry for the Witbank coal field was extensively studied by Pinetown and Boer (2006). XRD analyses on coal showed a dominance of quartz and kaolinite, while pyrite, calcite and dolomite were also detected as dominant phases relative to other mineral phases, with the latter three minerals were almost ubiquitous in the coal. Further XRF analyses supported the findings of the XRD analyses, whereby the inorganic components consisted of major oxide dominance of SiO_2 (35 wt%), $Al2O_3$ (0.5 to 16 wt%), $Fe2O_3$ (0.5-10 wt%) and S (0.15 to 8 wt%). ABA results from the same study showed that the lithologies of the Witbank coal field acid generating potential and high TDS quality leachate generating acid and thereby the deterioration of water quality (Pinetown and Boer, 2006). ABA results obtained from a geohydrological study conducted on Kleinfontein mine in 2008 are presented in Figure 7-6.

Table 7-1: ABA results for exploration borehole GCS3 of Kleinfontein mine (Data from GCS, 2008).

Sample depth	Lithological unit	S%	AP	NP	NNP	NAG	NPR
11	Shale	<0.01	<0.3	1.71	1.71	<0.1	5.7
13-14	Shale and sandstone	1.2	37.5	9.43	-28.1	55.4	0.25
16	Sandstone	0.035	1.09	0.98	-0.11	1.6	0.89
22-23	Sandstone	0.18	5.91	1235	6.93	<0.1	2.11
25	Carbonaceous shale	0.087	2.72	20.4	17.7	<0.1	7.5
32	coal	1.08	33.8	34.6	0.8	0.1	1.02

7.6 Conceptual Model

Like the Kriel pitlakes, the Kleinfontein pitlakes also formed because of a shortage of backfill material. The elevation around the pitlakes is flat and as a result the surface runoff into the pitlakes is expected to minimal.

The pitlakes shores have extensive reed vegetation (see Plate 7) and there is a surface water divide between pitlake A & B. The pitlakes are however hydraulically linked via the backfill material.

The aquifer properties of the backfill materiel or the aquifer were not assessed. Assumptions that the hydraulic properties of the surrounding undisturbed Karoo aquifer and the backfill material is similar to the other sites studied. The backfill pit was assumed to be an unconfined aquifer of homogeneous properties to simplify the model due to data limitations. Figure 7-6 is the conceptual hydrogeological model of the two pitlakes. The following simplified equation was used to calculate the pitlake water balance

$$\Delta S = P + GW_{Backfill} - E$$

Where:
ΔS is change in storage, P is precipitation, $GW_{Backfill}$ is groundwater inflow from the backfiled material, E is the evaporation.

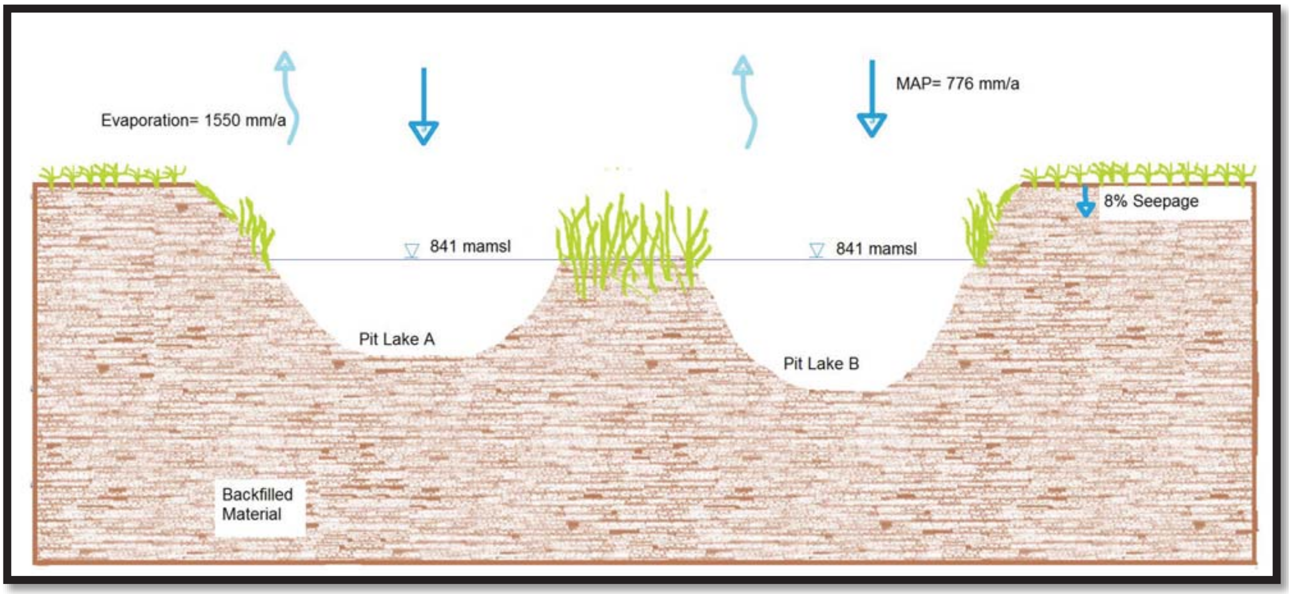


Figure 7-6: Kleinfontein Conceptual Hydrogeological Model

<u>*There were the following data limitations regarding the water balance*</u>
- No water level data were made available for the study
- No mine plan
- No pitlake recovery data
- Exact size of the original open pit and backfill.

<u>*Rainfall*</u>
The study area lies within the B11B quaternary catchment and rainfall zone B1A with mean annual precipitation of 687 mm. Additional rainfall data was available from a rain gauge 6.9 km and a mine rain gauge placed 8.8 km form the pitlakes. The average rainfall from both gauges is 776.4 mm/a over a 16 years record. The time series rainfall is shown in Figure 7-7. Recharge to natural aquifer is estimated to be 6% of MAP and to the backfill 10% of MAP based on data from the other pitlakes.

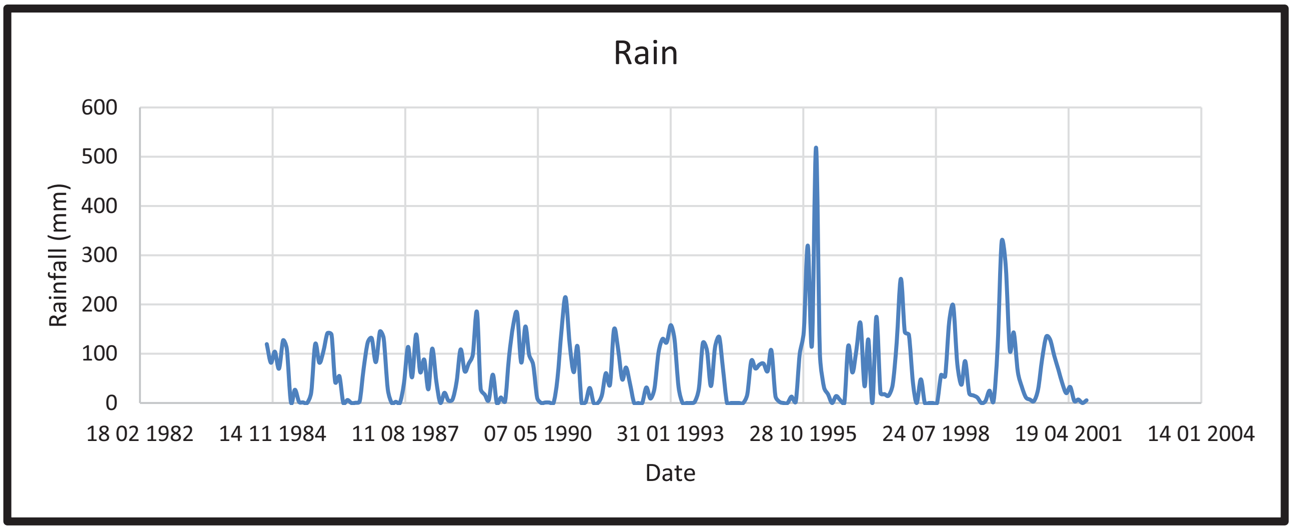


Figure 7-7: Kleinfontein Rainfall.

Runoff

Kleinfontein falls within B11B quaternary catchment of the Upper Olifants WMA, which has a MAP value of 687 mm and falls within rainfall zone B1A. The catchment area is 367.6 km^2. Surface drainage is towards the Olifants River. The calculated quaternary catchment runoff is 9% of the average annual rainfall, DEMs of the site illustrate that surface runoff does not contributes to the Kleinfontein pitlake water balance (Figure 7-8). The topography is generally flat at an elevation of 1560 mamsl.

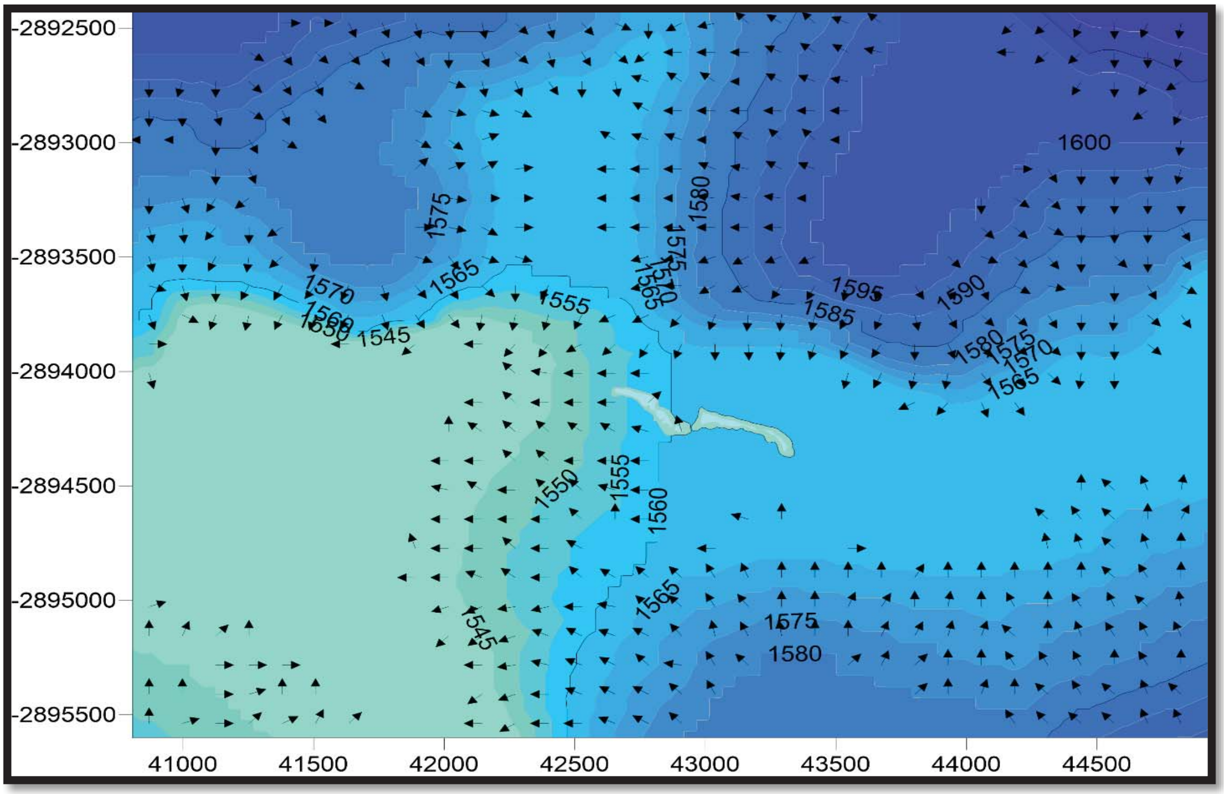


Figure 7-8: Kleinfontein Surface Elevation.

Groundwater Inflow

The groundwater balance as calculated using the Dupuit-Forchheimer equation and Darcy law.

Evaporation

The potential average annual evaporation is 1550 mm, which greater than the average rainfall. Table 7-2 shows the monthly distribution for the S-Pan evaporation obtained from evaporation zone 4A and shows that the lowest evaporation is experienced in the month of June.

Table 7-2: Kleinfontein Monthly Evaporation

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep
Evaporation Factor	10.78	10.17	11.2	11	9.17	9.05	6.96	5.86	4.76	5.21	6.9	8.94
Evaporation (mm)	167.1	157.6	173.6	170.5	142.1	140.3	107.9	90.1	73.8	80.8	107	138.6

Reeds surrounding the pitlakes were included as the total pitlake area and evapotranspiration from the reeds was include in the water balance calculations. According to Parsons (2014) the standard approach of setting transpiration losses from the reeds is 10% greater than the lake evaporation.

Observations

The net contributors to the Kleinfontein pitlakes water balance are direct rainfall and groundwater. The water balances calculations for the Kleinfontein pitlakes are provided in Appendix G: Kleinfontein a Water Balance and Appendix H: Kleinfontein b Water Balance. The result of water balance calculations are shown in Table 7-3.

Table 7-3: Kleinfontein Water Balance Summary.

	Pitlake A	**Pitlake B**
Rainfall (%)	26	26
Groundwater (%)	73	73
Runoff (%)	1	1

7.7 Water Quality

7.7.1 Water Quality Profiles

The ambient groundwater quality surrounding the Kleinfontein mine made available by the mine. The results of borehole EC profiles are shown in Figure 7-9 to Figure 7-11. The water quality show indication of contamination.

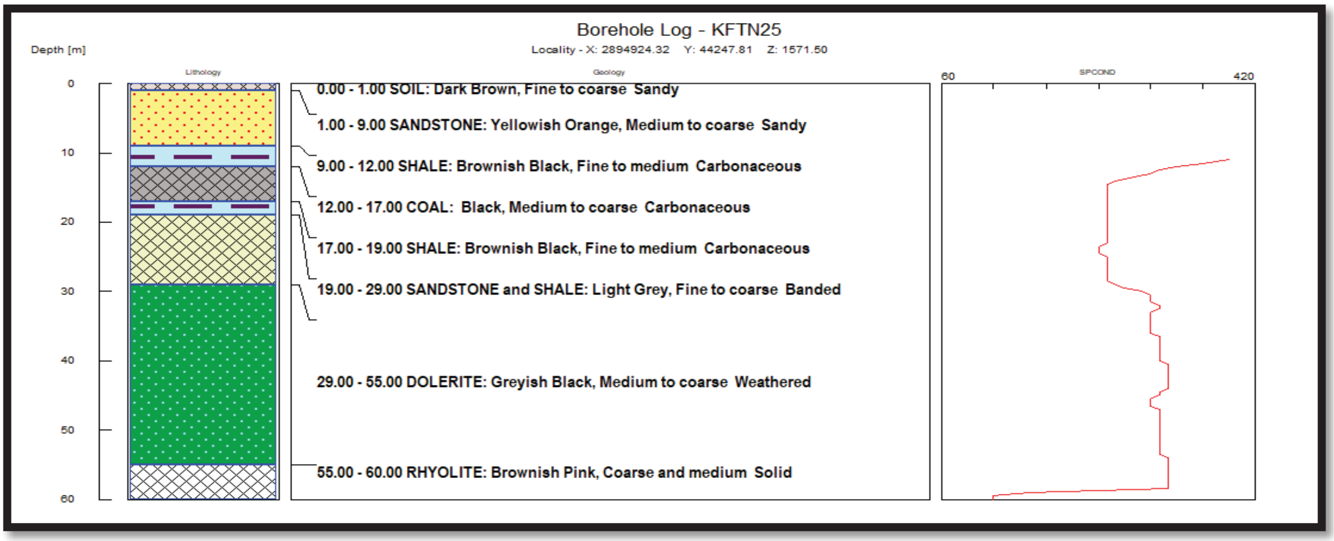


Figure 7-9: Kleinfontein Borehole KFTN25: Geology and EC profile

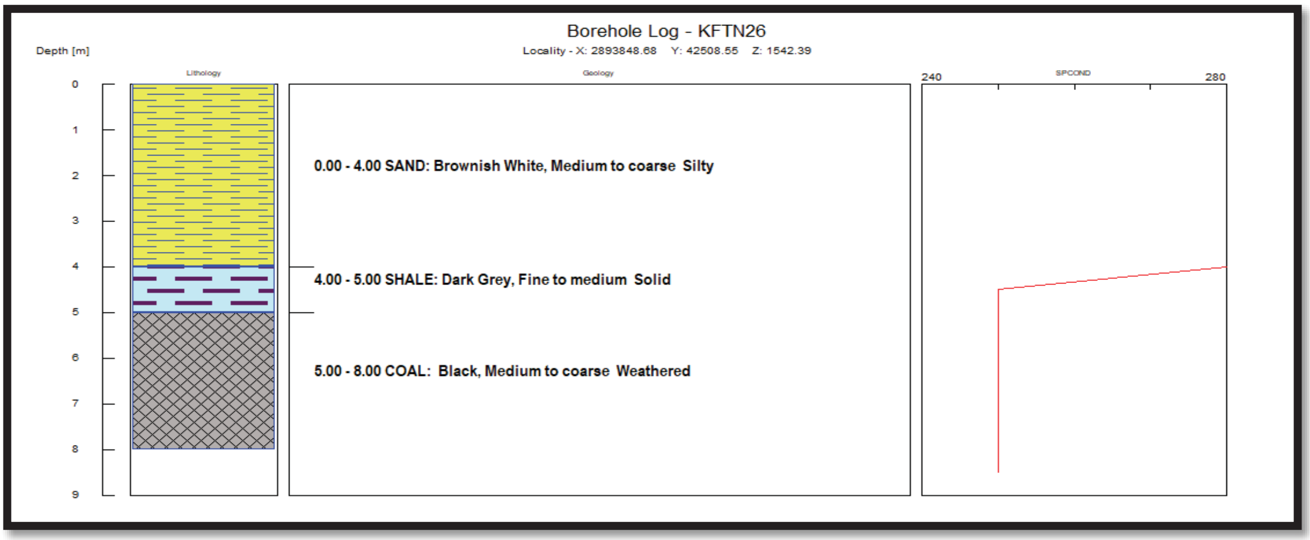


Figure 7-10: Kleinfontein Borehole KFTN 26 .Geology and EC profile

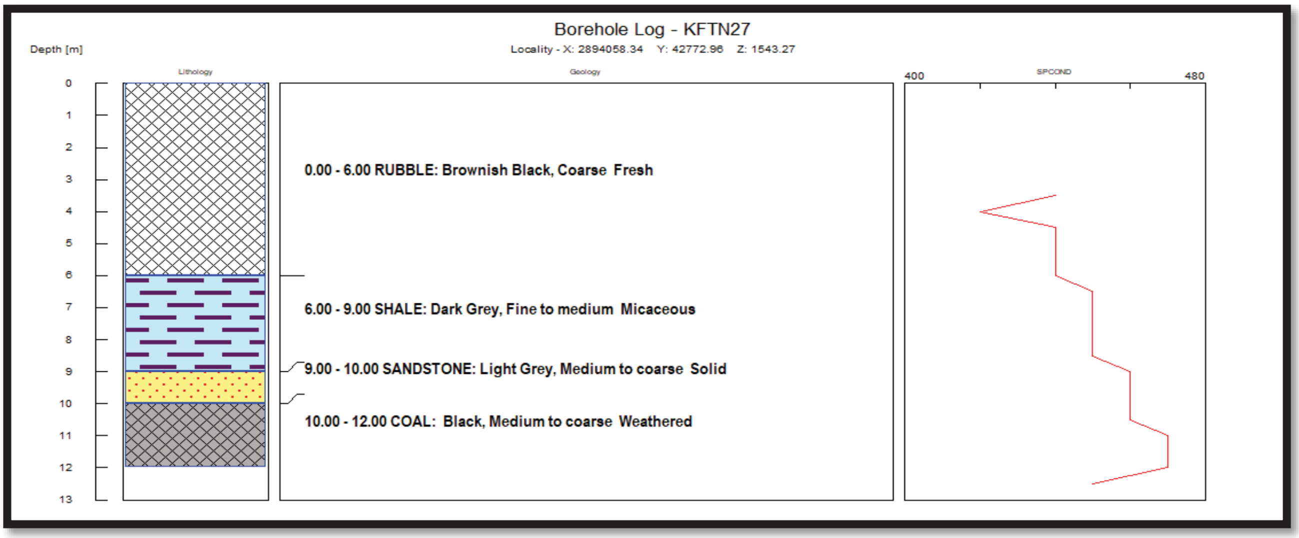


Figure 7-11: Kleinfontein Borehole KFTN27 Geology and EC profile.

Pitlake Profiles

The Kleinfontein pitlake is very shallow, with a maximum recorded depth was 3.5 m (Figure 7-12). Due to the shallow nature of the lake, and its elongated morphology, no thermal stratification was present. The water quality variables indicated a circum-neutral pH and EC of 180 to 200 mS/m. The dissolved oxygen showed a decrease towards the base where the probe was probably lowered into the layer unconsolidated sediments.

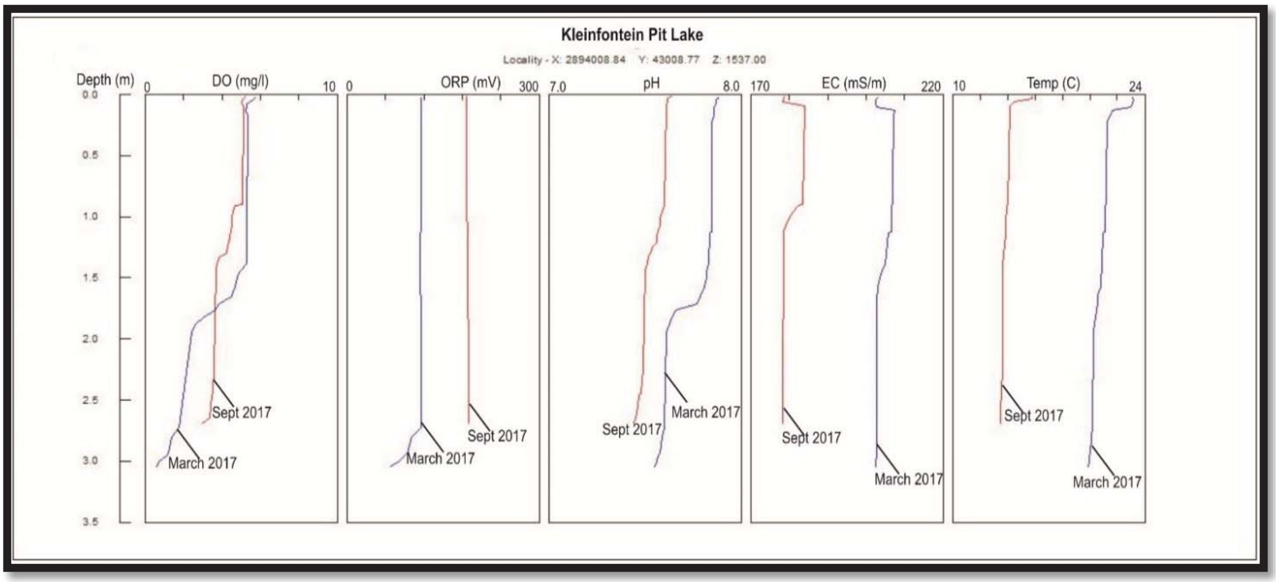


Figure 7-12: Kleinfontein Pitlakes Water Quality Profiles.

The observations can be made from the Kleinfontein pitlake profiles:

- The T ranged from 24°C to 22°C in the summer and dropped to 14°C in the winter.
- The measured EC varied between 200 mS/m in the summer and 180 mS/m in the winter. The same probe was used for these two profiling events, so this could possibly indicate a real change in the EC with the winter turnover.
- The DO was saturated in the top 1 to 1.5 m with values of 6 mg/l. The pitlake was very shallow and turbid with algae mats and submerged water plants depleting the oxygen, especially with decomposition of organic material.
- The ORP showed oxidative redox potential.
- pH showed a circum-neutral pH which ranged between 7.5 and 8.

Source of water for pitlake

Figure 7-13 shows the ionic characteristics of groundwater, surface stream water and pitlake water sampled at Kleinfontein. Water samples were collected from the Kleinfontein pitlake during March and September 2017. A total of 18 samples was analysed and all was classified as Mg-SO_4 type water, as shown in the Piper diagram in Figure 7-13. Samples from the pitlake show the dominant cation as magnesium (45-50%), calcium (37-41%) and sodium (10-14%). The dominant anion is sulphate (60-78%), followed by bicarbonate (20-40%) and very little chloride (1-3%). The water has low metal concentrations.

The groundwater in the study area (Borehole 26) is strongly bicarbonate and magnesium-calcium, while the surface stream water is strongly sulphate and primarily calcium-magnesium dominant. Both the upstream and downstream samples showed that the pitlakes are interacting with the stream.

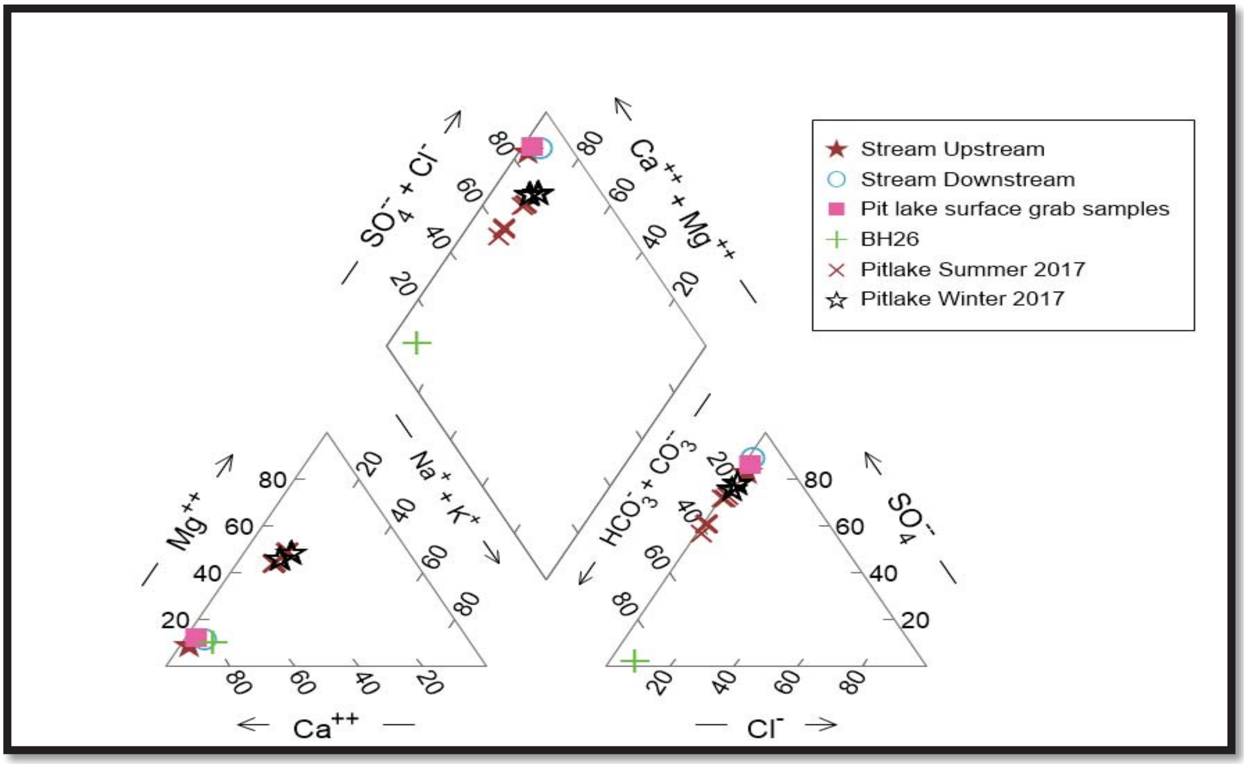


Figure 7-13: Kleinfontein Pitlakes: Piper Diagram of groundwater, surface water and pitlake.

7.7.2 Pitlake chemistry

Due to the shallow depth of the pitlake, the hydro-chemistry did not vary much with depth and time. Kleinfontein pitlake was sampled during March 2017 and September 2017. The full chemical analyses are provided in Appendix L: Kleinfontein Water Quality. A scatter plot of sulphate versus magnesium was used as the water type indicated dominance of Mg and SO_4. The plot shows relationship between Mg an SO_4 with a correlation coefficient (r = 0.93) and a slope of 1, indicating sulphate is in excess of Mg and Ca.

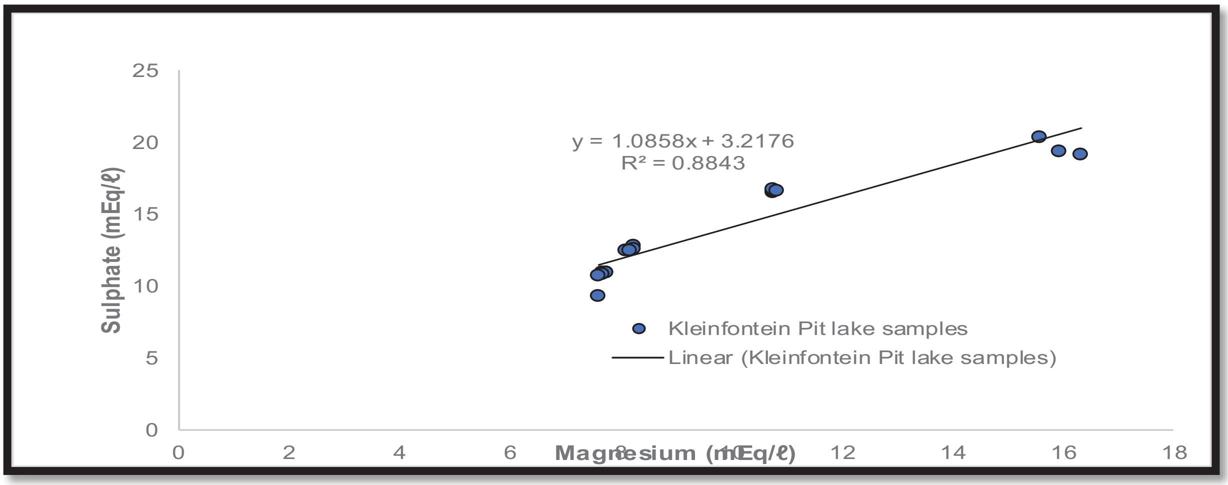


Figure 7-14: Kleinfontein Water Quality: Scatter plot of sulphate versus magnesium.

The saturation index for calcite and dolomite in shown in Figure 7-15, where dolomite showed greater oversaturation than calcite, even though they evolved along a similar pattern. Similarly, the Kleinfontein pitlake showed oversaturation of carbon dioxide partial pressure (Figure 7-16Figure 7-16:), but lower saturation levels than that for Kriel and Rooikop.

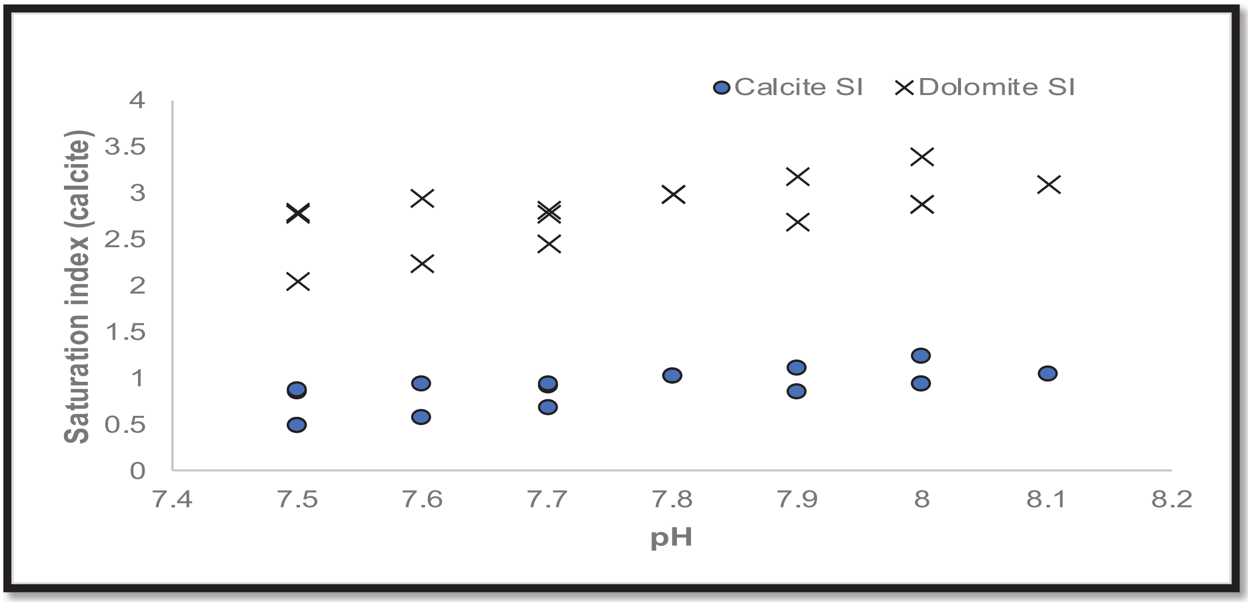


Figure 7-15: Kleinfontein Pitlakes: Saturation index for calcite and dolomite.

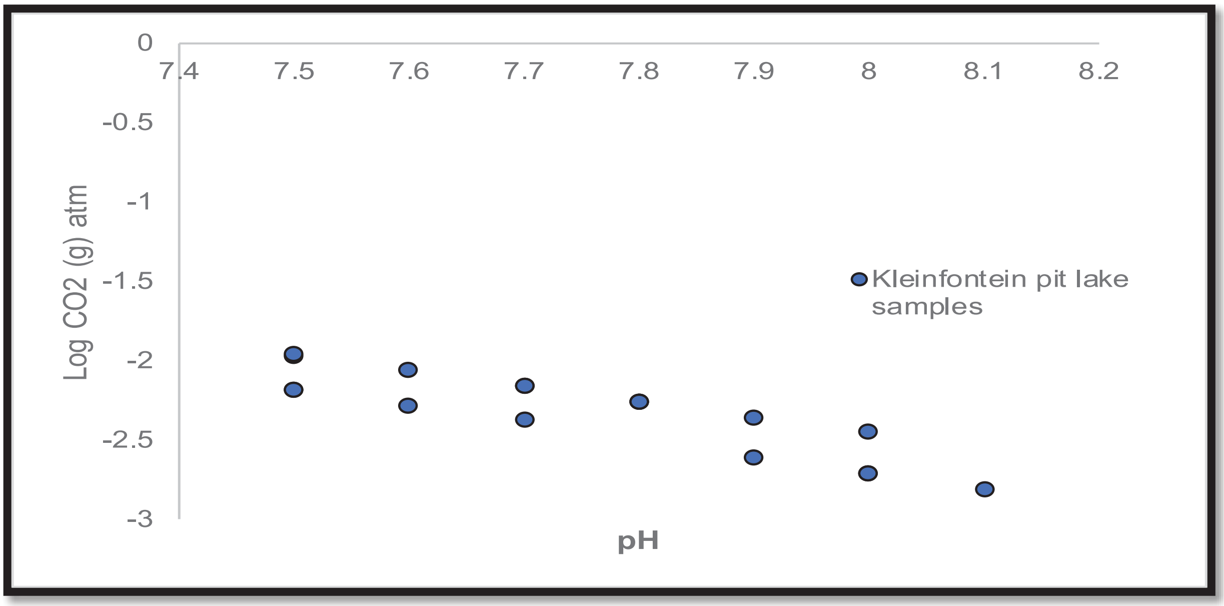


Figure 7-16: Kleinfontein pitlake. Saturation index for CO2(g).

7.7.3 Surface water quality

The Kleinfontein spruit to the north of the pitlakes is a tributary of the Olifants River. The pitlakes and associated rehabilitated opencast area is separated from the spruit by a man made berm. Water quality of the stream has been monitored by South 32 as part of BECSA Mine Closure requirements since 2000. The sulphate concentrations and TDS measured in the pitlakes (depicted as "Evaporation Dam" in the graphs) and stream far exceed the catchment Water Quality Objectives (RWQO). The data shows the Kleinfontein pitlake water chemistry to be stable with no major variations. Time series data from the monitored locations are provided in Figure 7-17 to Figure 7-19.

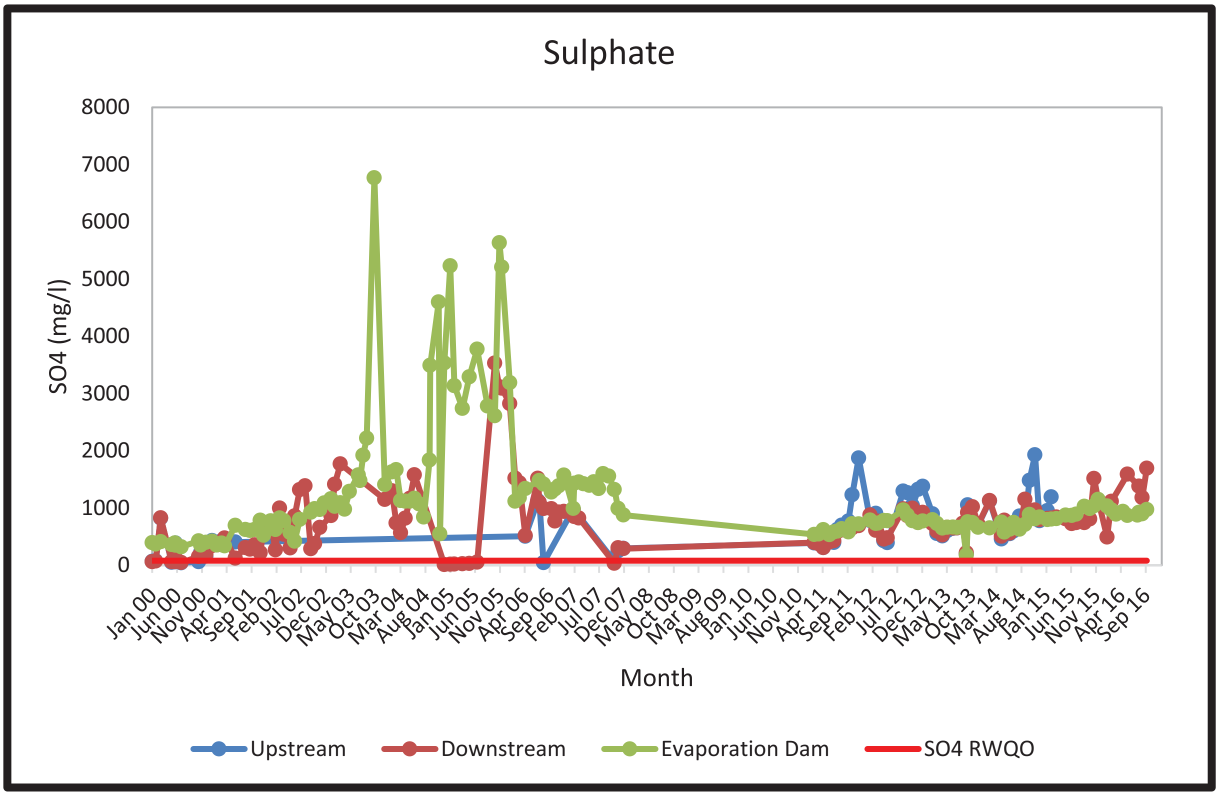


Figure 7-17: Kleinfontein Surface water Sulphate concentrations.

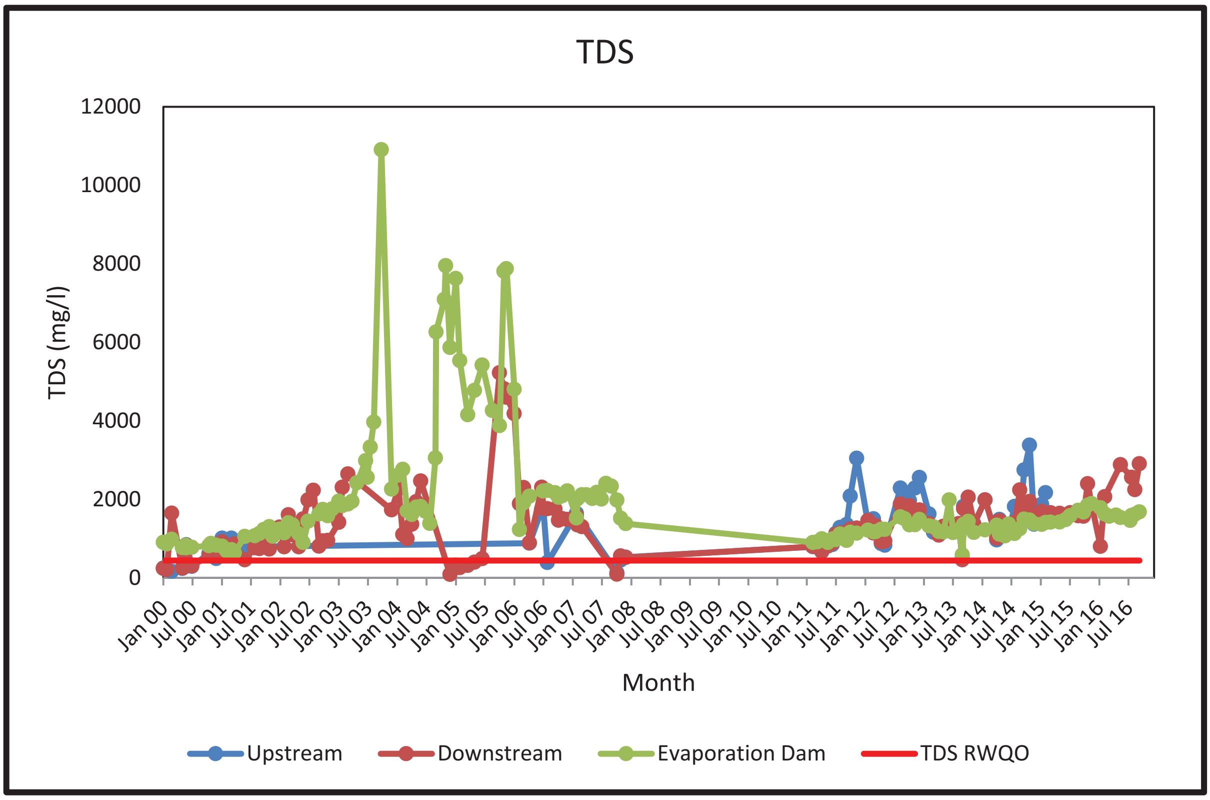


Figure 7-18: Kleinfontein Surface water TDS.

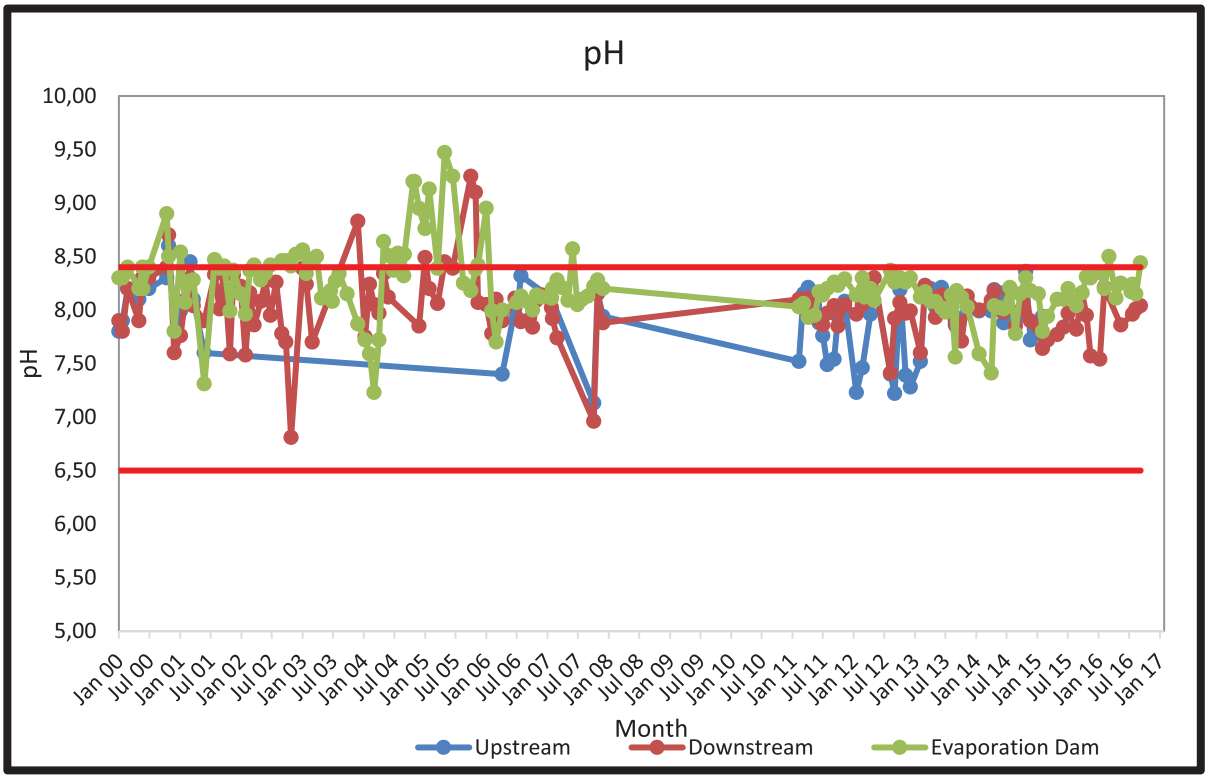


Figure 7-19: Kleinfontein Surface water pH.

7.8 Pitlake Biota

7.8.1 Phytoplankton

The chlorophyll-a concentrations measured in the Kleinfontein Pitlake B increased from the surface to the bottom, with concentrations of 6 µg/ℓ to 9.7 µg/ℓ to 18 µg/ℓ at 1,5 m and with an average of 12.5 in pitlake (Table 7-4). The dominant algae was *Cryptomonas* of the Cryptophyta group, as shown in the stack diagrams

Figure 7-20 and Figure 7-21. Details of the phytoplankton analysis are shown Appendix L: Kleinfontein Water Quality.

Table 7-4: Kleinfontein Pitlakes Average nutrients, chlorophyll-a concentrations and secchi depths.

Site	Date	Ammonia-N (mg/ℓ)	Nitrate-N (mg/ℓ)	Total phosphorous (µg/ℓ)	Si (mg/ℓ)	Hardness (as CaCO3 (mg/ℓ)	Average chlorophyll-a (µg/ℓ)	Secchi depth (m)
Kleinfontein (a)	Sept	0.075	0.01	<250	2.3	778	1	2.5
Kleinfontein (b)	Sept	0.23	0.01	<250	0.5	951	12.5	2

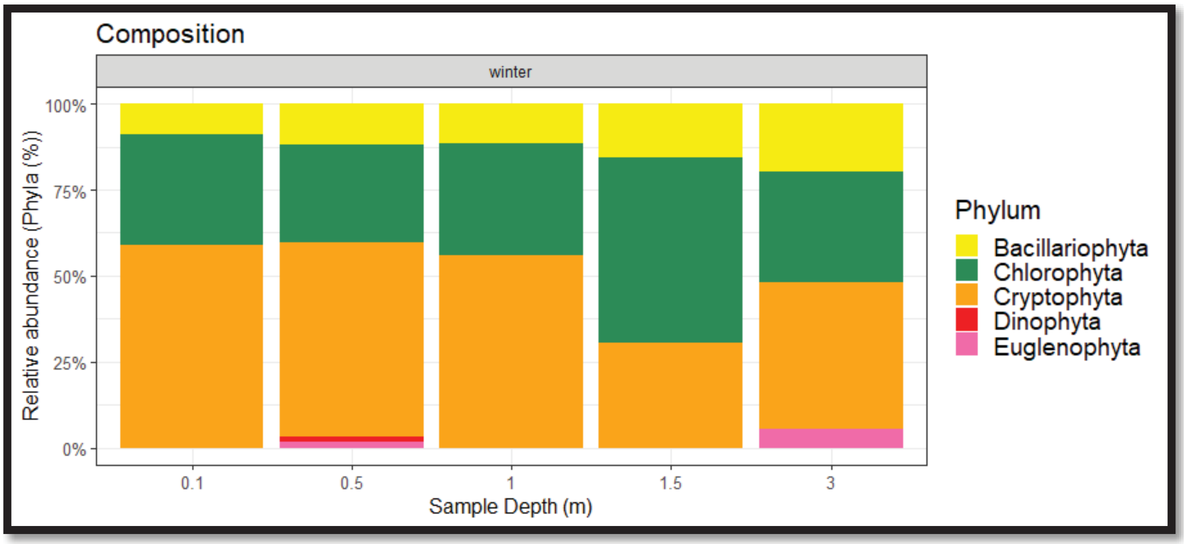


Figure 7-20: Kleinfontein Pitlakes Stack diagram of algal phyla.

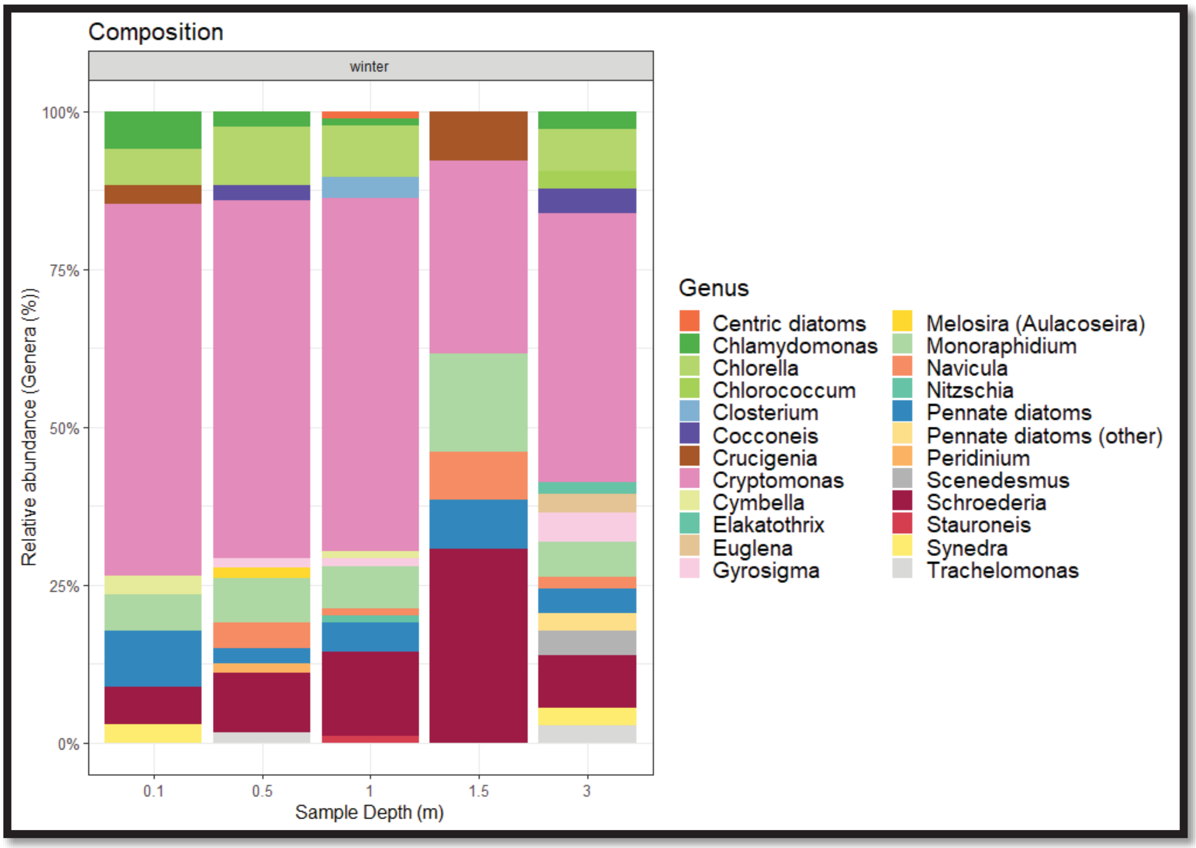


Figure 7-21: Kleinfontein Pitlakes Stack diagrams of algal genera.

7.8.2 Microbiology

The microbial population in the pitlakes was dominated by Proteobacteria with microbial assemblages similar to those of the Rooikop pitlake. Dominant microbes for Kleinfontein included Proteobacteria, Bacteroidetes, Chloroflexi, Actinobacteria and Verrucomicrobia. The full microbial report by the Department of Biotechnology at the UFS is provided in Appendix M: Microbial Report. The bacterial phyla for Kleinfontein pitlake are shown in Figure 7-22.

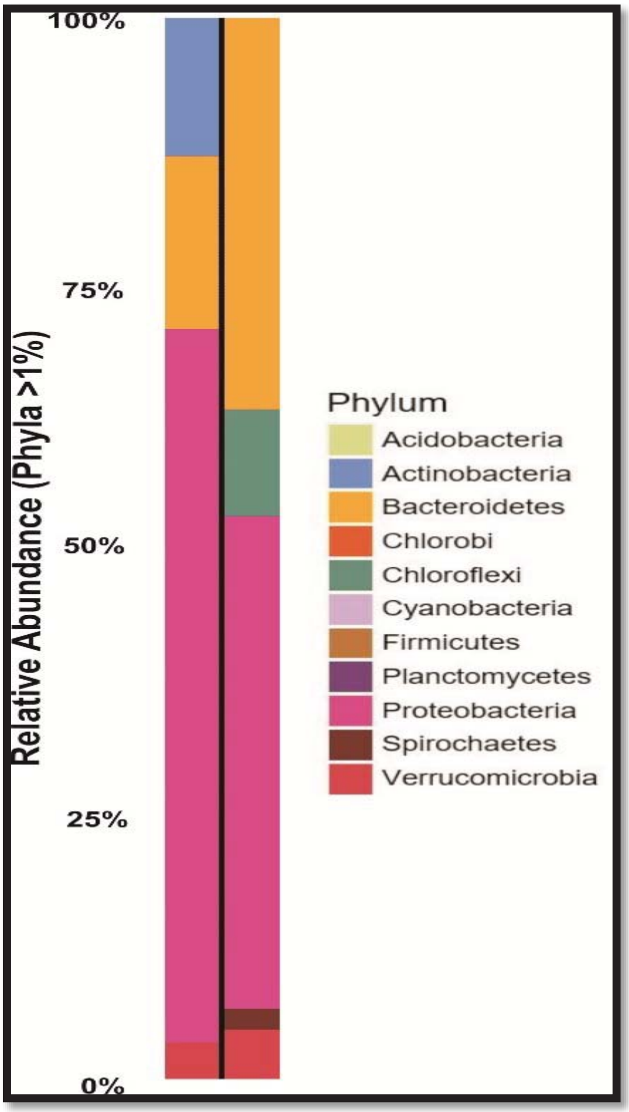


Figure 7-22: Kleinfontein Pitlakes Bacterial diversity to phylum level.

7.9 Conclusions

The following conclusions were drawn for the Kleinfontein pitlake investigation:

- The pitlake water balance and water quality are directly influenced were determined by the backfilled. The pitlake has relatively high sulphate concentrations with an average of 670 mg/l.
- Surface water quality sampled from the tributary shows that there is interaction between the pitlake and the Kleinfontein spruit.
- The pitlake was very shallow with homogenous EC. The DO decreased with depth, indicating possible biological and/or chemical oxygen demand.
- The overall chemistry of Kleinfontein pitlake showed Mg>Ca>Na>K for the major cations and SO_4>HCO_3>Cl>NO_3 for the major anions.
- The phytoplankton was dominated by Cryptomonas indicating a eutrophic trophic status, while the microbial communities of Proteobacteria and Bacteroidetes were the dominant phyla.
- The pitlake water is saturated with carbon dioxide and calcite with relatively high SO_4 and HCO_3 concentrations as measured in the water.

CHAPTER 8: CONCLUSIONS

South Africa has been mining coal since the early 1800s, initially by conventional underground method, but since 1950 coal production has been mainly from open cast mines. Coal is the major component of the South African Power supply network and this is predicted to continue into the latter half of the 21st century. Open cast coal mines generally leave a final void as a consequence of the mining method, this being the result of insufficient overburden to fill the voids created by removal of the coal and /or to manage water. Once mining operations cease, these voids fill with water forming a lake which is generally referred to as a “pitlake”. The authors have estimated that there are over 200 pitlakes in the three major South African coal fields namely the Mpumalanga/Witbank, KwaZulu-Natal and Waterberg areas.

The study evaluated the environmental sustainability of using pitlakes as a closure option for new and proposed coal mines in South Africa. The current South African mining and environmental legislation states that all pitlakes should be backfilled for the mine to achieve mine closure. This study evaluated the environmental sustainability of using pitlakes as a mine closure option for new and proposed coal mining projects in South Africa.

The major factor of determining environmental sustainability of pitlakes are the water balance and water quality. Positive water balances result in discharge onto surface. A further environmental sustainability consideration is the chemical and biological nature of the water in pitlakes. Pitlake water quality varies depending on the geology, mining method and catchment characteristics. In general, pitlake water quality may not comply with legislated catchment water quality standards resulting in potential threats to the overall catchment water quality.

8.1 Classification of Pitlakes

Pitlakes are classified according to their morphology, the interaction with regional hydrology and climatic conditions. Table 8-1 shows the classification of the pitlakes studied during this investigation.

Table 8-1: Pitlake Classifications

Parameters	Mafutha	Kriel	Rooikop	Kleinfontein
Volume of Lake (m^3)	505 819	44a: 255 713 44b: 67 379 44c: 162 060 R42: 311 919	86681.03	A: 20 171.7 B: 14 131.9
Area of Lake (ha)	2.6558	44a: 14.55 44b: 4.29 44c: 3.9 R42: 4.89	1.7	A: 1.09 B: 3.21
Classification of Size of Pitlake	Microscale	44a: Mesoscale 44b: Microscale 44c: Microscale R42: Microscale	Microscale	Microscale Microscale
Lake Depth (m)	70.6	44a: 6 44b: 5 44c: 9.5	10	A: 3.9 B: 3

Parameters	Mafutha	Kriel	Rooikop	Kleinfontein
		R42: 12		
Hydroperiod	Permanent	Permanent	Permanent	Permanent
Plan Shape	Round	Rectangular	Irregular	Irregular
Type of ore	Coal	Coal	Coal	Coal
Water resources in the vicinity	None	Dwars-in-die-Wegspruit and Steenkoolspruit	Tributaries of Egude River	Kleinfontein Spruit
Slope	26-45º	44a: 1-25º 44b: 1-25º 44c: 1-25º R42: 1-25º	26-45º	A: 1-25º B: 1-25º

8.2 Pitlake Water Balances

The study pitlake of the water balances were on based on a generalized mathematical expression, described by Gammons et al. (2009):

$$\Delta S = (P + SWin + GWin) - (E + (T) + SWout + GWout)$$

where
ΔS is change in storage, which is the volume of water in the lake,
P is the precipitation falling onto the pitlake,
SWin is the sum of any surface water inputs which includes runoff and diverted streams,
GWin is groundwater entering the lake,
E is the evaporation from the lake,
T is plant transpiration (which is often negligible),
SWout is surface water existing in the pitlake and includes pumpage,
GWout is the groundwater leaving the pitlake.

The most important contributors to all pitlake water balances was the net groundwater inflow. This could be either from the surrounding aquifer, groundwater in the backfilled material, discharge from flooded box cut adits and or a combination of all, depending on the historical mining methods

In some cases, surface runoff contributed to the positive water balance of the pitlakes. This was however less than groundwater due to the rehabilitation methods employed. Direct rainfall contributed periodically to the water balance, but this was largely negated by the high evaporation results.

The most important losses from the pitlakes was evaporation. There was little evidence of high volumes of surface discharge or net migration from the pitlake into the aquifers. In most cases the pitlakes were terminal sinks.

Pitlake Water Quality

One of the biggest concerns regarding pitlakes is their potential to turn acidic. Conceptual models of pitlake geochemistry are described by external and internal processes, of which many of the internal processes are mediated by algae and microbes (Gammons et al., 2009). External processes have been described as groundwater inflow and runoff. Figure 8-1 summarises the processes that drive the chemistry in pitlakes.

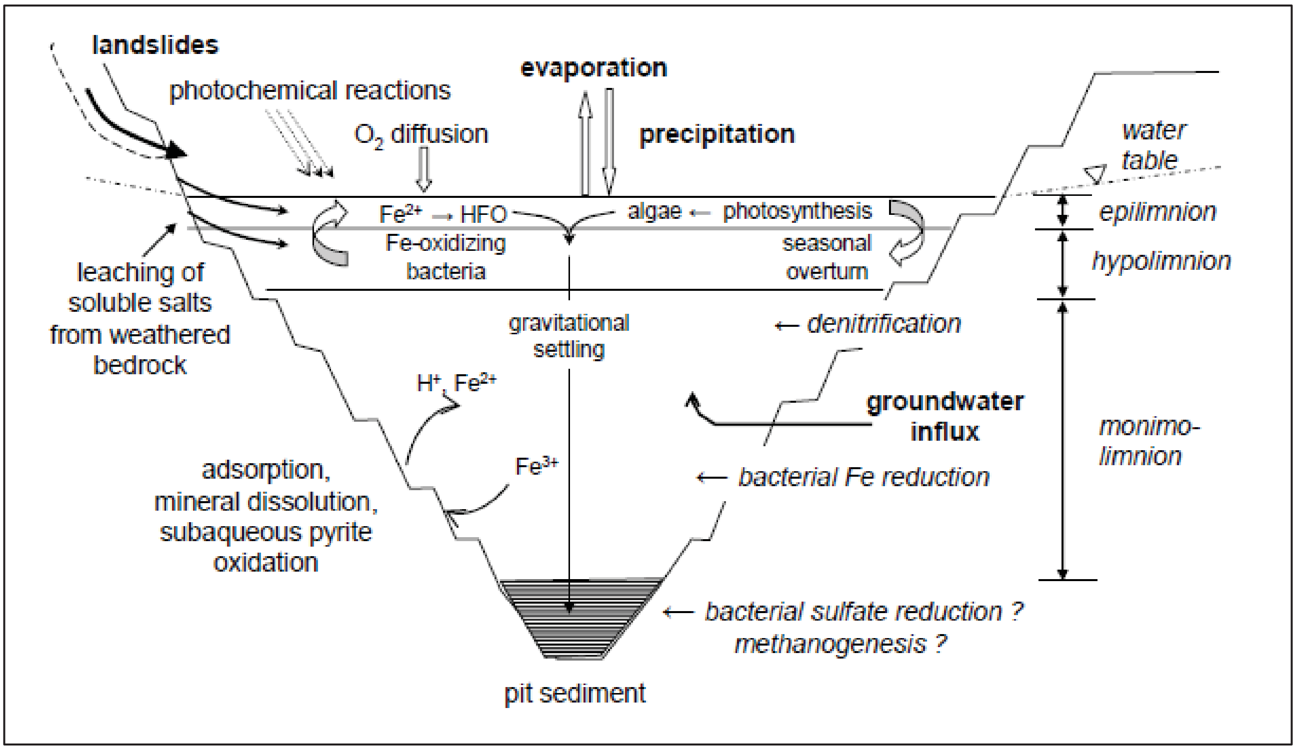


Figure 8-1: Chemical processes in pitlakes (Gammons et al., 2009).

After mining ceased, rebounding groundwater enters the pit by passing through the dewatered strata from where the groundwater transports the products of pyrite oxidation, mainly sulphate, iron, and acidity or dissolves secondary minerals that might have formed, in the backfill material. The hydrochemistry of coal mine pitlakes is thus influenced by the geology of the area, the groundwater and surface water hydrologic characteristics, the amount of sulphur within the strata, the extent of pyrite oxidation, and the mining technology used (Friese et al., 2013).

All pitlakes studies showed alkaline conditions. Geochemical assessments indicate there is sufficient buffering capacity to maintain neutral conditions pitlakes studied for a considerable period. In fact, indications are that there is sufficient buffering capacity to maintain an alkaline pH.

The total dissolved content of the pitlakes varied from 800 to 3500 mg/l. The major salts were sulphates and calcium /magnesium bicarbonates. Contrary to expectations there were surprisingly low sodium and chloride centrations.

Conclusion: Pitlake biota

Pitlakes provide a unique environment for biological communities, especially in terms of water quality and habitat. Communities of phytoplankton and microbes, together with other organisms are often used in conjunction with water quality parameters to determine the health of an aquatic ecosystem. The presence and diversity of algae and microbes were determined by sampling and analyses. Phytoplankton are suspended, free-floating organisms in the pelagic zone of the pitlakes are important indicators of the general food web. Bacteria are single celled organisms, which have been found to participate in the cycling of sulphur, iron, manganese, carbon and nitrogen, depending on the redox conditions in a pitlake. Initially, the aim of the biological investigation was to determine a relationship between hydrochemistry and the biota, as well as the possible role of the organisms in the pitlake water quality. However, this proved to be a statistically rigorous exercise, for which the data collected in the study were inadequate – due to a too small database, inconsistent sampling frequencies and data gaps. Therefore, discussions of the phytoplankton mainly focused on descriptions of the assemblages found in the pitlakes.

The aim of the phytoplankton investigation was to determine the presence and diversity in the pitlakes. Samples for phytoplankton analysis were collected at the deepest location in the pitlakes, along with an associated chlorophyll-a sample at each sample depth. The concentration of chlorophyll-a (a photosynthetic pigment dominant in algal cells) is a basic indicator of pitlake phytoplankton biomass and general phytoplanktonic composition. As a first estimate, a high chlorophyll-a concentration indicates the presence of a large biomass of phytoplankton, or at least suggests the presence of green and blue-green algae. The chlorophyll-a concentration is commonly used in conjunction with the Secchi depth (a measure of water transparency) and N and P concentrations, to determine the trophic state of an aquatic system. The Secchi depths measured in the pitlakes ranged from 0.4 m to 8 m, while the average chlorophyll-a concentrations ranged from 2 to 10.8 µg/ℓ, the NO_3-N from <0.1 mg/ℓ to 2.19 mg/ℓ, while PO_4-P were generally below detection concentrations.

The chlorophyll-a concentrations and the ranges of the pitlakes identified as oligotrophic Chl-a < 3.5 µg/ℓ; Mafutha, oligotrophic-mesotrophic 3.5 to 9 µg/ℓ; Rooikop, mesotrophic-eutrophic 9 to 25 µg/ℓ; Kriel and Kleinfontein according to De Lange et al. (2018). Oligotrophic lakes contain moderate species diversity, but are low productivity systems. Mesotrophic lakes on the other hand, contain the highest levels of species diversity and productivity, with the increased risk of blue-green algae that are seldom toxic. Eutrophic to hypertrophic systems (> 25 µg/ℓ) usually become problematic for aquatic systems as they tend to have low species diversity, high productivity with associated blue-green algal blooms that are toxic to human, animals and wildlife (Vos, 2001). Algae blooms reduce light penetration and diversity, and deplete oxygen levels when the die-off occurs.

The abundance of the phytoplankton was expressed as numbers of cells/mℓ. For all the pitlakes, the total phytoplanktonic algal assemblage comprised 45 different algal genera, from six divisions. Algal divisions identified in the pitlakes were Bacillariophyta (golden-brown, diatoms), Chlorophyta (green algae), Cryptophyta (various colours, cryptomonads), Euglenophyta (various colours, euglenoids), Dinophyta (red-brown, dinoflagellates) and Cyanophyta (blue-green, cyanobacteria). Of these, 50% of the unique genera belonged to the Chlorophyta group. Chlorophyta was found to be the dominant division in the pitlakes, followed by Cryptophyta and Bacillariophyta. Species from the Dinophyta and Eulgenophyta groups seldom occurred and were identified only in Mafutha and Kleinfontein pitlakes, with low cell numbers.

The most common genera identified in the pitlakes occur wide spread and in most of the natural water bodies in South Africa (Janse van Vuuren et al., 2006). Major genera identified from the Chlorophyta group in the pitlakes were *Ankistrodesmus*, *Mesotaenium, Monoraphidium*, *Chlorella Chlamydomonas* and *Schroederia spp*. The first three genera were prevalent in Mafutha pitlake, while *Chlorella sp.* were the dominant green algae in Kriel; *Chlamydomonas* and *Chlorella* spp. were equally dominant in Rooikop and *Schroederia sp.* was most dominant in Kleinfontein pitlake. Generally, no problems are associated with the green algae found in the pitlakes, except for the formation of dense blooms of *Chlamydomonas sp.* in summer months.

From the Bacillariophyta group, the Pennate diatoms (*Navicula* and *Nitzschia spp*) and *Synedra sp*. were ubiquitous in all the pitlakes. *Navicula* and *Synedra spp.* are known to clog filters at water treatment plants, while *Nitzschia sp.* are tolerant to organic pollutants and indicative of nutrient enrichment and high salinities (Janse van Vuuren et al., 2006). Filter clogging algae may become a problem if the pitlake water were to be used for domestic purposes.

In the Kriel and Kleinfontein pitlakes, the *Cryptomonas sp.* of the Cryptophyta group were dominant. *Cryptomonas sp*. are known to occur in organically enriched waters, in small to moderate numbers and pose no specific problems to water quality (Janse van Vuuren et al., 2006). The maximum cell count for *Cryptomonas sp*. was 4100 cells/mℓ.

The Cyanophyta were generally present in low cell numbers in the pitlakes, except in Ramp 44 North of Kriel. In Ramp 44 North, cyanophyta such as *Oscillatoria*, *Aphanocapsa* and *Cylindrospermum spp*. proliferated in the late summer samples, where cell counts of *Aphanocapsa sp*. reached 2300 to 3.7×10^6 cells/mℓ in the bottom samples. In Mafutha pitlake, *Oscillatoria* and *Cylindrospermum* spp. were the dominant species present in the summer, winter and spring, with *Anabaena sp.* occurring only in the summer. *Oscillatoria sp*. were also identified in Rooikop in the late winter samples. Cyanophyta were completely absent in Kleinfontein pitlake. Cyanophyta typically becomes problematic under circumstances where water bodies are warm and stagnant with excessive influx of phosphorous, or where phosphorous are released from bottom sediments. Cyanobacterial blooms of the abovementioned species cause degradation of the water quality by forming surface scums, odours, and release of toxins that are harmful to livestock and humans that come in contact with the water. Toxins produced by *Oscillatoria sp.* in particular, are known to cause skin irritations and irritations to the mucous membranes of humans and animals (Janse van Vuuren et al., 2006).

Phytoplankton have rapid reproduction rates and short life cycles, and quick responses to environmental changes. They are directly impacted by chemical factors (e.g. nutrients) and physical factors (e.g. temperature and rainfall), thereby having great potential as pitlake water quality monitoring tools. When monitoring is conducted for phytoplankton in pitlakes, clear objectives should be set in order to collect data statistically. Ecological data analysis benefit more from multivariate analysis, where environmental variables and chemistry can be related and correlated with phytoplankton assemblages, in order to better evaluate the changes in their community structures. Phytoplankton reflect the health and trophic status of an aquatic ecosystem through their biomass, diversity and density.

Samples for microbial analysis were collected during the summer sampling runs. The aim of the microbial investigation was to determine the presence and diversity of bacteria in the pitlakes. Pyrosequencing of bacterial communities from oxic and anoxic parts of the pitlakes, with combined chemical composition, were used to delineate possible biogeochemical functions (metabolic functions) performed by the bacteria. A total of 8600 bacterial and archaeal Operational Taxonomic Units (OTUs) (97% similarity cut-off) were found in all samples using identical sequencing depth (31086 sequences per sample). Rarefaction curves and Chao1 estimates (refer to Appendix for figures) suggest that this sequencing depth was adequate to capture most of the prokaryotic diversity in each sample.

The number of OTUs per sample ranged from 574 to 2037 and the samples were highly diverse as shown by Chao1, Pielou and Shannon index, which combines richness and evenness (Refer to Appendix for figures). Altogether, this indicates that these prokaryotic communities are highly diverse. Different prokaryotic communities (OTU level) were detected in the four locations.

Overall, Proteobacteria (47% mean relative abundance), Bacteroidetes (20%), Actinobacteria (11%) and Cyanobacteria (7%) were the most abundant phyla in the samples. Six other phyla, with average relative abundances higher than 0.4%, were also detected.

The most abundant genera were *Flavobacterium* (3.7% mean relative abundance), *Pseudomonas* (3%), *Fluviicola* (2.8%) and *Nodularia* (2.9%). Fourteen other genera, with average relative abundances higher than 0.5%, were also detected. These results indicate that pitlake microbial communities are taxonomically diverse and present biogeographic patterns.

Overall, microbial communities were dominated by chemoheterotrophs and phototrophs. Taxa involved in the sulphur, nitrogen and carbon cycles were also an important component of the microbial communities. The results indicated that pitlake microbial communities are functionally diverse and that the microbial communities of the different pitlakes harbour different functional profiles; that is, that there is little functional redundancy.

Recommendations for future biological sampling from pitlakes:

- Evaluation of pitlake biota can include other types of life forms such as periphyton, zooplankton, macro-invertebrates, crayfish, finfish, aquatic macrophytes and riparian vegetation, as suggested by studies conducted on Australian pitlakes. Clear objectives should be set to better sample and assess these organisms in order to extract information about the health of the ecosystem and water quality of the pitlakes.
- Appropriate methods should be used to analyse for nutrients. In this study, the levels of N and P were generally below the laboratory detection levels, but the values could actually be above accepted criteria for specific end-uses.
- Sample frequencies of the various biological factors should be constant between pitlake sites. Sampling of the phytoplankton and chlorophyll-a should occur at least seasonally, with even sample sizes if more than one habitat or site are sampled. The biggest issue associated with phytoplankton are blooms of unwanted algae, such as the blue-green algae, which should be detected and managed.
- The genetic potential of bacteria is often associated with beneficial uses of these organisms, especially in unusual/ extreme environmental problems. Additionally, the presence of certain bacteria might be suggestive of certain biogeochemical processes in the pitlake water. Further investigation into the bacterial communities can render some information about the function of these bacteria in the pitlakes and their impact on the hydrochemistry and vice versa.
- Ecological and environmental data are often better interpreted through multivariate statistics.

8.3 Uses of Pitlakes as a Closure Option

Mine pitlakes are usually associated with environmental problems and backfilling has been preferred as the best closure option. However, there is frequently unrecognised potential for pitlakes to provide benefit to companies, communities and the environment (McCullough and Lund, 2006). Pitlakes have value as resources for various purposes depending on topography, location water use and safety characteristics (Soni et al., 2014). A review was conducted by (Doupé and Lymbery, 2005) on alternative end-use options for mine pitlakes around the world and found that the following options have been either proposed or implemented:

- Recreation and tourism (development of swimming, boating, fishing or diving).
- Wildlife conservation (permanent wetland habitat).
- Aquaculture (extraction of pitlake water to grow aquaculture species in cages).
- Irrigation (pitlake water may be pumped to irrigate horticulture, agricultural crops, and urban landscapes).
- Livestock water resource (extraction of pitlake water for livestock production).
- Potable water source (extraction of water for human consumption).
- Industrial water source (extraction of pitlake water for industrial processes).
- Chemical extraction.

The physical parameters of pitlakes are taken into consideration for the design of end-use options. Suggestions that features such as geology, bathymetry and water balance be evaluated prior to closure option decision making was made by (Westcott and Watson, 2007), where the aim of sustainable pitlake management is to minimize short and long term pitlake liabilities and maximise opportunities pitlakes offer (McCullough and Lund, 2006).

A number of factors which influence the viability and choice of beneficial end uses for any pitlake are given by McCullough et al. (2009) as follows:

Table 8-2: Factors influencing the viability of pitlake end uses

Factors Requiring Consideration	Implication Factor
Lake area and Volume	Limits possible and desirable end uses
Water quality	Long-term liability and economic remediation
Geographic location	Climate and proximity to population centres
Proximity to natural water bodies	Pitlake water mixing with natural waters
Pitlake development and/or remediation costs	A cost-benefit analysis for different uses will be required, if costs are significant
Short-and long-term risks to mining companies and post closure managers	A formal risk assessment is required before any developments can take place. This has to be updated during remediation and post closure. Assessment, results must be incorporated into the decision-making process.
Stakeholder political pressure	May positively or negatively influence end use options
Regulatory requirements for rehabilitation and/or end use	Will generally exclude some end uses, support will increase viability of other end use choices
Support from stakeholders for end use options	Support will increase viability of other end use choices
Water resource needs at local, regional, and national levels	Water demand will influence regulatory and stakeholder decision making

8.4 Environmental Considerations

Although pitlakes are mining related legacies to communities, long term considerations of the health and safety of humans and animals should be evaluated. The most unfavourable situation of pitlakes is the contamination of clean waters by pitlake water. Groundwater contamination is probable in flow-through pitlake systems where the rainfall is higher than the evaporation (McCullough and Lund, 2006).

An alteration in the hydrologic system takes place due to the formation of a lake where there was initially no lake prior to mining (Castendyk and Eary, 2009). Collection of water in pitlakes rather than being discharged to surface rivers and natural lakes, can results in net losses of water, especially in arid regions (Castendyk and Eary, 2009)

Pit walls should be reinforced to promote stability and avoid pit wall failure and falls. If the pitlakes are not intended for use by humans or animals but are not protected, animals and humans will be at risk of falling into the pitlake and drowning. Severe illnesses from the ingestion of contaminated pitlake water can result in the death of wildlife (McCullough and Lund, 2006).

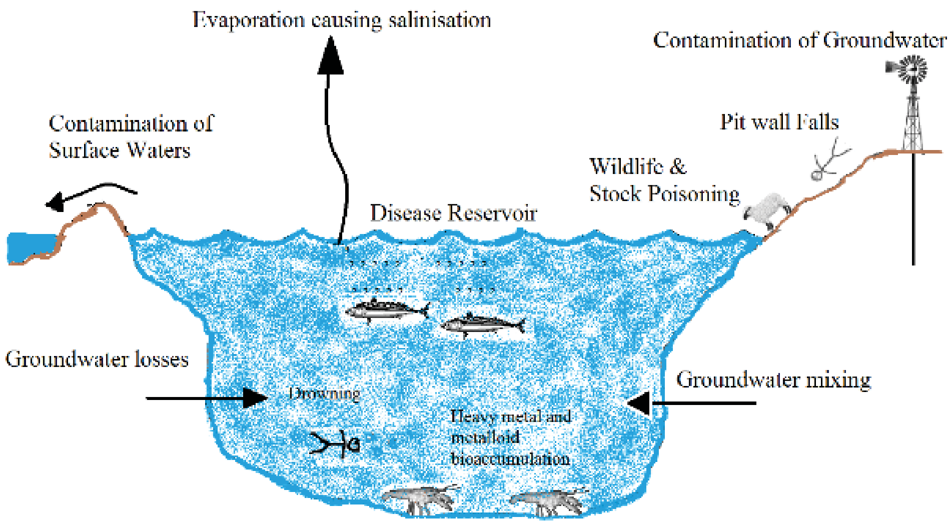


Figure 8-2: Potential liabilities of pitlakes to communities and the environment (after McCullough and Lund, 2006)

During their investigation, Doupé and Lymbery (2005) also assessed the potential environmental risks of the different beneficial end uses of mine pitlakes, using the risk management guidelines of the Standards Association of Australia to develop a semi-quantitative assessment of the likelihood of occurrence and the consequences of environmental impacts. A similar risk assessment to evaluate the potential impacts of South African Coal Mine pitlakes is conducted, based on the South African legislation.

8.5 Design Suggestions

The pitlake design should be such that it restricts the pitlake water from coming into contact with fresh clean water. Climate change stressors act on components of the water balance, which will vary with location, and therefore conceptually understanding how the behaviour of water balance components will influence design criteria is essential to ensure design criteria that can be manipulated by designers accommodate criteria for current and future climatic parameters (Andrew, 2016). In situations where surface discharge may be a threat, it is critical to maximize evaporation in order to keep a pitlake a terminal sink. This suggestion includes increasing pitlake surface area to ensure sufficient water is naturally removed from the pitlake without being in contact with fresh water. Increasing the surface areas is suggested for the Kriel pitlakes, as well as the Kleinfontein pitlakes.

From a water quality perspective, the following design options are suggested:

- To ensure acceptable water quality in the pitlake, it is recommended that the pitlake be flooded as rapidly as possible in order to exclude further sulphide oxidation from occurring.
- If reactive coal seams are submerged, the sulphide oxidative minerals remain in a reduced environment.
- For pitlakes where opencast strip mining was applied with concurrent rehabilitation, the reactive waste material should be backfilled at the bottom of the pit where it is flooded rapidly by groundwater and will remain in a reduced environment. In terms of the design options, in this case, elongated pitlakes which are attached to backfilled spoils with high transmissivities and hydraulic conductivities are beneficial so that the water level is the same in the pitlake and the backfilled opencast area. If the pitlake is cone shaped or deep, the possibility exists whereby a steep hydraulic gradient is created. A steep hydraulic gradient towards the pitlake will render some of the reactive spoils unsaturated during dry seasons, which leaves the material conducive to atmospheric conditions and oxidation. Subsequent wetting in the rainy season will then flush all of the secondary precipitates and oxidation products into the pitlake.

- In the pitlakes investigated in the study, the natural groundwater quality has a high alkalinity, which acts as an immediate buffer for any possible acid generation that may occur with the first flush of the groundwater through the spoils.
- Shallow and elongated pitlakes are more conducive to wind-induced mixing, which in the case of the pitlake in the study, is beneficial. Wind induced mixing on a regular or even daily basis, mixes dissolved oxygen through the whole water column, which reduces the solubility of some heavy metals.
- Oxygenated water is also beneficial for pitlake ecological systems, such as algae growth, fish and water plants.

8.6 Recommendations

Recommendations for future research include:

- Environmental isotopes to determine the degree of evaporation.
- Investigation of pitlake sediments.
- Detailed investigation of the biogeochemical functions of algae and bacteria in the pitlake water – some microbes are known to play important roles in the cycling of Fe, sulphur and nitrogen.
- Detailed investigation of pitlake wall rock geochemistry.
- The possible uses of these pitlakes, especially in terms of irrigation.

CHAPTER 9: REFERENCES

ANDREW, B.P.S., O'KANE, M. (2016) Climate Change and Mine Closure – A Practical Framework for Addressing Risk. *International Mine Water Association.* Germany: Technische Universität Bergakademie Freiberg

ARDEJANI, F. (2003) *Hydrogeological investigations of backfilled surface coal mine sites.* Doctor of Philosophy, University of Wollongong.

AZZIE, B.A. (2002) Coal mine waters in South Africa, their geochemistry , qality and classification. PhD thesis, University of Cape Town.

BELLINGER, E.G. and SIGEE, D.C. (2015) Fresh water algae: Identification, enumeration and use as bioindicators, 2nd Edition, Wiley Blackwell.

BENGTSSON, L. (2012) Water Balance of Lakes. *In:* BENGTSSON, L., HERSCHY, R. W. & FAIRBRIDGE, R. W (eds.) *Encyclopedia of Lakes and Reservoirs.* Dordrecht: Springer Netherlands.

BESTER, M. (2009) *Groundwater resource assessment of the Waterberg Coal reserves.* University of the Free State.

BESTER, M. and VERMEULEN, P.D. (2010) Investigation of potential water quality and quantity impacts associated with mining of the shallow Waterberg coal reserves, west of the Daarby Fault, Limpopo Province, South Africa. Water SA, 36,531-542.

BETHKE, C.M., FARREL, B. and YEAKEL, S. (2018) Geochemist Workbench Release 12, Aqueous Solutions LLC, Champaign, Illinois. Student Edition.

BLOCK, L.V., BURNETT, R.P., CUNNINGHAM, A.J., DIDRICKSEN, K.D., HAMILTON, J.L., LACEY, J.E., MATUSKA, P.E., PRINCE, N.W., PRUITT, T.D., RAPPMUND, R.A., REEVES, C.R., SANDERS, G.D., SHADIX, S.J., BIANCHI, R., TALBOT, W.R. and WATT, A.D.E. (1995) Groundwater Manual. *In:* CENTER, B. O. R. E. A. T. S. (ed.) *A Water esources Technical Publication.* Washington: U.S Government.

BOEHRER, D. and SCHULTZE, M. (2006) On the relevance of Meromixes in mine pitlakes. In: *The 7th International Conference on Acid Rock Drainage (ICARD)*. St Louis, Missouri, USA, 200-213.

BOUWER, H. and RICE, R. (1976) A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. *Water resources research,* 12**,** 423-428.

CADLE, A. (1990) *The Permo-Triassic coal-bearing deposits of the Karoo basin, southern Africa*, Economic Geology Research Unit, University of the Witwatersrand.

CAIRNCROSS, B. (2004) *Field Guide to Rocks and Minerals of Southern Africa,* Cape Town, Struik Nature.

CAIRNCROSS, B., HART, R. and WILLIS, J. (1990) Geochemistry and sedimentology of coal seams from the Permian Witbank Coalfield, South Africa; a means of identification. *International Journal of Coal Geology,* 16**,** 309-325.

CASTENDYK, D. (2009) Predictive Modeling of the Physical Limnology of Future Pitlakes. *In:* CASTENDYK D, Eary L E (ed.) *Mine Pitlakes Characteristics, Predictive Modeling and Sustainability.* Society for Mining, Metallurgy and Exploration.

CASTENDYK, D.N. and EARY, L.E. (2009) The Nature and Global Distribution of Pitlakes. *In:* CASTENDYK D., E. L. E. (ed.) *Mine Pitlakes Characteristics, Predictive Modelling and Sustainability.* Society for Mining, Mettalurgy and Exploration.

CASTENDYK, D.N., EARY, L.E. and BALISTRIERI, L.S. (2015) Modelling and management of pitlake water chemistry 1. Theory Applied Geochemistry 57 267-288.

CASTRO, J.M. and MOORE, J.N. (2000) Pitlakes: their characteristics and the potential for their remediation. Environ. Geol. 39, 1254-1260.

CHIANG, W-H. and KINZELBACH, W. (1998) Processing Modflow. *A simulation program for modelling groundwater flow and pollution. User manual*.

COAL VALLEY ROBB TREND PROJECT (2011) *An Evaluation of Water Quality in Existing End Pitlakes in the Coal Valley area*. Hatfield consultants, North Vancouver. URL: https://www.ceaa.gc.ca/050/documents_staticpost/61436/100422/21_Appendix_8-End_Pit_Lake_Report_Redacted.pdf

COOPER, H. and JACOB, C. (1946) A graphical method of evaluating formation constants and summarizing wellfield history: Am. Geophys. *Union Trans,* 27**,** 526-534.

DAVIS, A. AND ASHENBERG, D. (1989) The aqueous geochemistry of the Berkeley Pit, Butte, Montana, USA. Applied Geochemistry, 4, 23-36.

DEYSEL, L.M., MACDONALD, N., APHANE, V. AND VERMEULEN, P.D. (2014) A Detailed Acid-Base Accounting Study of the Coal-Bearing Karoo Formations in the Waterberg Coal Field. Report to the Water Research Commission, WRC Report No. 2142/1/14, ISBN 978-1-4312-0599-8.

DEYSEL, L-M. (2015) *Environmental Geochemistry Of The Waterberg Coalfields.* Doctor of Philosophy, Institute for Groundwater studies, University of the Free State.

DE LANGE, W.J., GENTHE, B., HILL, L. and OBERHOLSER, P.J. (2018) Towards a rapid assessment protocol for identifying pitlakes worthy of restoration. Journal of Environmental Management, 206, 949-961.

DENIMAL, S., BERTRAND, C., MUDRY, J-N., PAQUETTE, Y., HOCHART, M. AND STEINMANN, M. (2005). Evolution of the aqueous geochemistry of mine pitlakes – Blanzy-Montceau-les-Mines coal basin (Massif Central, France): Origin of sulfate contents; effects of stratification on water quality. Applied Geochemistry. 20. 825-839. 10.1016/j.apgeochem.2004.11.015.

DOYLE, G.A. and RUNNELLS, D.D. (1997) Physical limnology of existing mine pitlakes. Mining Engineering,

DONOVAN, J.G. (1999) *The Effects of Backfilling on Ground Control and Reovery in Thin-Seam Coal Mining.* Master of Science Virginia Tech.

DOUPÉ, R.G. and LYMBERY, A.J. (2005) Environmental risks associated with beneficial end uses of mine lakes in southwestern Australia. *Mine Water and the Environment,* 24**,** 134-138.

DRUSCHEL, G.K. and KAPPLER, A. (2015). Geomicrobiology and Microbial Geochemistry. Elements, 11(6), 389-394. http://doi.org/10.2113/gselements.11.6.389.

DU PLESSIS, J.L. (2010) *Decant calculations and groundwater: surface water interaction in an opencast coal mining environment.* University of the Free State.

DU PLESSIS, G.P. (2008) *The relationship between geological structures and dolerite intrusions in the Witbank-Highveld Coalfield, South Africa.* Magister Scientiae, University of Bloemfontein.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF). 1996b. South African Water Quality Guidelines. Volume 7. Aquatic environment (1st ed; 1st issue). 159pp.

EARY, L.E. (1999) Review: Geochemical and equilibrium trends in mine pitlakes. Applied Geochemistry, 14, 963-987.

EBRAHIM, G. (2013) *Modelling Groundwater Systems.* Master of Science in Hydroinformatics, UNESCO-IHE

FINCH, J. and CALVER, A. (2008) Methods for the quantification of evaporation from lakes.

FOURIE, P.J. (2007) The Description of Physico-chemical Processes in Coal Mine Spoils and Associated Production of Acid Mine Drainage. MSc Dissertation, University of the Free State.

FRIESE, K., HERZSPRUNG, P. and SCHULTZE, M. (2013) Chapter 3: Limnochemistry of water and sediments of acidic pitlakes. In: Geller et al. (eds.), Acidic Pitlakes, Environmental Science and Engineering, DOI: 10.1007/978-3-642-29384-9_5, Springer-Verlag Berlin Heidelberg, pp. 42-51.

GAMMONS, C.H., HARRIS, L.N., CASTRO, J.M., COTT, P.A. and HANNA, B.W. (2009) Creating Lakes from Open Pit Mines: Processes and Considerations, Emphasis on Northern Environments.

GCS (2008) Jikama Mines Hydrogeological Study on Kleinfontein Mine. Confidential report.

GENTHE, B., OBERHOLSTER, P.J., DE LANGE, W.J. (2017) Evaluation of the Post Coal Mining Landscapes in Mpumalanga for Realistic Mitigation Options to Regain Wetland Losses and Reduce Human Health Impacts. CSIR report number: CSIR/NRE/WR/IR/2017/0038/B, Pretoria.

GOMO, M. and MASEMOLA, E. (2016) Groundwater hydrogeochemical characteristics in rehabilitated coal mine spoils. Journal of African Earth Sciences, 116, 114-126.

GOMO, M. AND VERMEULEN, D. (2014) Hydrogeochemical characteristics of a flooded underground coal mine groundwater system. Journal of African Earth Sciences 92 68-75, doi: http://dx.doi.org/10.1016/j.jafrearsci.2014.01.014.

HAARHOFF, J. and CASSA, A.M. (2009) *Introduction to flood hydrology*, Juta and Company Ltd.

HANCOX, P.J. and GÖTZ, A.E. (2014) South Africa's coalfields—A 2014 perspective. *International Journal of Coal Geology,* 132**,** 170-254.

HEM, J.D. (1985) *Study and Interpretation of the Characteristics of Natural Water*. 3rd Edition, US Geological Survey Water-Supply Paper 2254, University of Virginia, Charlottesville, 263 p.

HOBBS, P., OELOFSE, S.H.H. and RASCHER, J. (2008) Management of Environmental Impacts from Coal Mining in the Upper Olifants River Catchment as a Function of Age and Scale, International Journal of Water Resources Development, 24:3, 417-431, DOI: 10.1080/07900620802127366

HODGSON, F.D.I., VERMEULEN, P.D., CRUYWAGEN, L.M. and DE NECKER, E. (2007) Investigation Of Water Decant From The Underground Collieries In Mpumalanga, With Special Emphasis On Predictive Tools And Long-Term Water Quality Management. Report to the Water Research Commission No 1263/1/107, ISBN 1-77005-416-2.

HODGSON, F.D.I. (2009) Mine Water Balance for Dorsfontein Colliery and Water Supply from TNC.

HODGSON, F.D.I. and KRANTZ, R. (1998) *Investigation into groundwater quality deterioration in the Olifants River catchment above the Loskop Dam with specialised investigation in the Witbank Dam sub-catchment*, Water Research Commission.

HODGSON, F.D.I. and KRANTZ, R.M. (1995) Groundwater quality deterioration in the Olifants River Catchment above the Loskop Dam with Specialised Investigations in the Witbank Dam Sub-Catchment. *In:* COMMISSION, W. R. (ed.).

HOUNSLOW, A.W. (1995) Water quality data: Analysis and interpretation. New York: Lewis Publishers.

HUISAMEN, A. (2017) Quantification methods and management of hydrogeochemistry in decommissioned collieries of the Mpumalanga coal field. PhD Thesis, University of Pretoria.

HUISAMEN, A. and WOLKERSDORFER, C. (2015) Modeling the hydrogeochemical evolution of mine water in a decommissioned opencast coal mine. International Journal of Coal Geology, p 1-10. DOI: http://dx.doi.org/10.1016/j.coal.2016.05.006

HUTCHINSON, G.E. and LÖFFLER, H. (1956) The thermal classification of lakes. Proc. Natl. Acad. Sci. U. S. A. 42 (2), 84-86.

JALALI, M. (2007) Assessment of chemical components of Famenin Groundwater, Western Iran. Environmental Geochemistry and Health, 29, 357-374. DOI 10.1007/s10653-006-9080-y

JEFFREY, L. (2005) Characterization of the coal resources of South Africa. *Journal of the Southern African Institute of Mining and Metallurgy,* 105**,** 95-102.

JOHNSON, B. and CARROLL, K. (2015) Waste Rock Backfill of Open Pits: Design, Optimisation, and Modelling Considerations.

KIRILLIN, G. and SHATWELL, T. (2016) Generalized scaling of seasonal thermal stratification in lakes. Earth Science Reviews, 161, 179-190.

KRUSEMAN, G.P. and RIDDER, N.A. (1990) Analysis and evaluation of pumping test data. *Analysis and evaluation of pumping test data.*

KUMAR, C. (2002) Groundwater flow models. *Scientist 'E1'National Institute of Hydrology Roorkee – 247667 (Uttaranchal) publication*.

LIMPITLAW, D., AKEN, M., LODEWIJKS, H. and VILJOEN, J. (2005) Post-mining rehabilitation, land use and pollution at collieries in South Africa. The South African Institute for Mining and Metallurgy.

LUFUNO, L.M. (2017) Investigation of the groundwater hydrogeochemistry characteristics in Beaufort West, South Africa. MSc dissertation, University of the Free State.

LUKAS, E. (2012) *WISH as a water management tool in opencast and underground collieries.* University of the Free State.

LURIE, J. (2008) *South African Geology*, Lupon Publishing CC.

MARINELLI, F. and NICCOLI, W.L. (2000) Simple analytical equations for estimating ground water inflow to a mine pit. *Groundwater,* 38**,** 311-314.

MCCULLOUGH, C., HUNT, D. and EVANS, L. (2009) Sustainable Development of Open Pit Mines: Creating End Uses for Pitlakes. *In:* CASTENDYK D, Eary LE (ed.) *Mine Pitlakes Characteristics, Predictive Modeling, and Sustainability.* Colorado: Society for Mining, Metallurgy, and Exploration, Inc.

MCCULLOUGH, C.D. and LUND, M.A. (2006) Opportunities for sustainable mining pitlakes in Australia. *Mine Water and the Environment,* 25**,** 220-226.

MCCULLOUGH, C., LUND, M. and LU, Y.L.Z. (2010). Mine Voids Management Strategy (III): A Monitoring Strategy for Pitlakes and Connected Waters. 90.

MCCULLOUGH, C.D., MARCHAND, G. and UNSELD, J. (2013) Mine closure of pitlakes as terminal sinks: best available practice when options are limited? *Mine Water and the Environment,* 32**,** 302-313.

MCGOWAN, W. (2000) Water Processing: Residential, Commercial, Light-Industrial, 3rd ed. Water Quality Association, Lisle, Illinois, USA.

MIDGLEY, D.C., PITMAN, W.V. and BAJ, M. (1994) Surface Water Resources of South Africa. Pretoria.

MOREIRA, S., BOEHRER, B., SCHULTZE, M., DIETZ and SAMPER, J. (2011) Modeling Geochemically Caused Permanent Stratification in Lake Waldsee (Germany). Aquatic Geochemistry, DOI 10.1007/s10498-011-9133-4.

MÜLLER, M., EULITZ, K., MCCULLOUGH, C.D. and LUND, M.A. (2010). Mine Voids Management Strategy (III): Water Quality Modelling of Collie Basin Pitlakes. Department of Water Project Report MiWER/Centre for Ecosystem Management Report 2010-10, Edith Cowan University, Perth, Australia. 173pp. Unpublished report to Department of Water.

NEFF, B.P. and KILLIAN, J.R. (2003) The Great Lakes Water Balance.

PARSONS, R.P. (2014) *Quantifying the role of groundwater in sustaining Groenvlei, a shallow lake in the southern Cape region of South Africa.* University of the Free State.

PINETOWN, K.L. (2003) Quantitative evaluation of minerals in coal deposits in the Witbank and Highveld coalfields and the potential impact on acid mine drainage. MSc thesis, University of the Free State.

PINETOWN, K.L. and BOER, R.H. (2006) a Quantitative evaluation of the modal distribution of minerals in coal deposits in the Highveld area and the associated impact on the generation of acid and neutral mine drainage.WRC Report No. 1264/1/06.

PUNTORIERO, M.L., CIRELLI, A.F. and VOLPEDO, A.V. (2015) Geochemical mechanisms controlling the chemical composition of groundwater and surface water in the southwest of the Pampean plain (Argentina). Journal of Geochemical Exploration 150 64-72, doi: http://dx.doi.org/10.1016/j.gexplo.2014.12.011.

OHIO EPA (2010) Inland lake sampling procedure manual. URL:https://epa.ohio.gov/Portals/35/documents/Inland_Lake_Sampling_Manual.pdf

OLOO, F., VALVERDE, A., QUIROGA, M.V., VIKRAM, S., COWAN, D. AND MATALONI, G. (2016) Habitat heterogeneity and connectivity shape microbial communities in South American peatlands. Scientific Reports, www.nature.com/Scientificreports/DOI: 10.1038/srep25712.

RALPH MORRIS AND ASSOCIATES (1998) EMPR: Taaiboschspruit Colliery. Confidential Report.

SANCHEZ ESPANA, J., LOPEZ PAMO, E., SANTOFIMIA PASTOR, E., DIEZ ERCILLA, M. (2008) The acidic mine pitlakes of the Iberian Pyrite Belt: An approach to their physical limnology and hydrogeochemistry. Applied Geochemistry, 23, 1260-1287.

SARTORY, D.P. AND GROBBELAAR, J.U. (1984) Extraction of chlorophyll-*a* from freshwater phytoplankton for spectrophotometric analysis. Hydrobiologia, 114, 3, 177-187. doi: 10.1007/BF00031869.

SCHULTZE, M. (2012) The filling and remediation of pitlakes in former open cast lignite mines. PhD Thesis, Technical University of Carolo Wilhemina, Braunschweig.

SCHULTZE, M., CASTENDYK, D., WENDT-POTTHOFF, K., SÁNCHEZ-ESPAÑA, J. and BOEHRER, B. (2016) On the relevance of meromixis in pitlakes – an update. Proceedings IMWA 2016: Mining meets Water – Conflicts and Solutions, 227-235, Drebenstedt, Carsten, Paul, Michael (eds.), Freiberg, Germany.

SHAFER, W.M. and EARY, L.E. (2009) Approaches for Developing Predictive Models of Pitlake Geochemistry and Water Quality. In: Castendyk, D.N., Eary, L.E. (Eds.), Mine Pitlakes: Characteristics, Predictive Modeling, and Sustainability. Society for Mining, Metallurgy, and Exploration Inc, Littelton, Colorado, pp 115-116.

SINGH, R. and ATKINS, A. (1985) Application of idealised analytical techniques for prediction of mine water inflow. *Mining science and technology,* 2**,** 131-138.

SLABBERT, N. (2007) The potential impact of an interbasin water transfer on the Modder and Caledon river systems. PhD Thesis, University of the Free State.

SMITH, L.A., LÓPEZ, D.L., BECKIE, R., MORIN, K., DAWSON, R. and PRICE, W. (1995) *Hydrogeology of waste rock dumps*, British Columbia Ministry of Energy, Mines and Petroleum Resources and CANMET.

SNYMAN, C.P. (1998) Coal. In: Wilson MGC and Anhaeusser CR (Eds), The Mineral Resources of South Africa, sixth ed, Handbook 16, Council for Geoscience, Pretoria.

SØNDERGAARD, M., LAURIDSEN, T.L., JOHANSSON, L.S. and JEPPESEN, A. (2018) Science of the total Environment, 612, 9-17.

SONI A, MISHRA B and SINGH S (2014) Pitlakes as an end use of mining: A review. *Journal of Mining and Environment,* 5**,** 99-111.

SPURR, M.R., GILLARD, T.D., BELL, K. (1986) The Utrecht Coalfield of Northern Natal. In: Anhaeusser, CR, Maske, S. (Eds.), Mineral Deposits of Southern Africa, II. Geological Society of South Africa, pp. 2011-2022.

SRK (2013) Sasol mining: *Proposed Limpopo West Mine-Environmental Management Programme*.

SWART, E. (2003) The South African legislative framework for mine closure, *Proceedings of the Colloquium on Mine Closure for Sustainable Development*, South African Institute of Mining and Metallurgy, Johannesburg.

USHER, B. (2003) The evaluation and development of hydrochemical prediction techniques for long-term water chemistry in South African Coalmines. 10-4 Unpublished PhD Thesis, Dept. of Geohydrology, Faculty of Natural Science and Agriculture, University of the Free State, S.A.

USHER, B., CRUYWAGEN, L-M., DE NECKER, E. and HODGSON, F.D.I. (2003) *On-Site And Laboratory Investigations Of Spoil In Opencast Collieries And The Development Of Acid Base Accounting Procedures.* Report ot the Water Research Commission, No. 1055/1/03.

VANDERBERG, J., MCCULLOUGH, C. and CASTENDYK, D. (2015) Key issues in Mine Closure Planning Related to Pitlakes. Proceedings of 10th International Conference on Acid Rock Drainage and IMWA Annual Conference, 1-10.

VAN TONDER, G., BARDENHAGEN, I., RIEMANN, K., VAN BOSCH, J., DZANGA, P. and XU, Y. (2002) Manual on pumping test analysis in fractured-rock aquifers. *Water Research Commission (WRC) of South Africa, Report***,** 02.

VERMEULEN, P.D. (2003) Investigation of water decant from underground collieries in Mpumalanga. MSc thesis. Institute for Groundwater studies, University of the Free State, South Africa.

VERMEULEN, P.D. and USHER, B.H. (2006) Sulphate generation in South Africa underground and opencast collieries. Environmental Geology, 49, 552-569.

VOS, T.A. (2001) Limnological aspects of Loch Logan: an urban impoundment. MSc thesis, University of the Free State.

WAGENER, T., WHEATER, S. and GUPTA, H.V. (2004) *Rainfall-Runoff Modelling in Gauged and Ungauged Catchments,* London, Imperial College Press.

WALMSLEY, R.D. (1984) A chlorophyll-a trophic status classification system for South African impoundments. Journal of Environmental Quality 13(1):97-104.

WALMSLEY, R.D., BRUWER, C.A. (1980) Water transparency characteristics of South African impoundments. Journal of Limnological Society of Southern Africa 6 (2): 69-76.

WATES, MEIRING and BARNARD (1993) EMPR: Kriel Colliery. Confidential Report.

WESTCOTT, F. and WATSON, L. (2007) *End Pitlakes Technical Guidance Document.* Clearwater Environmental Consultants Inc.

WETZEL, R.G. (2001) Limnology: Lake and River Ecosystems, third ed. Academic Press, San Diego, California, 1006 pp.

WILLIAMS, R.D. (2009) Backfilling. *In:* CASTENDYK D, Eary LE (ed.). Society for Mining, Metallurgy and Exploration.

WR 2012. Water Resources of South Africa. Pretoria: Water Research Commission.

ZHU, C. and SCHWARTZ, F.W. (2011) Hydrogeochemical processes and controls on water quality and water management. Elements, 7, 169-174.

ZHAO, B., USHER, B.H., YIBAS, B. and PULLES, W. (2010) *Evaluation and Validation of Geochemical Prediction Techniques for Underground Coal Mines in the Witbank/Vryheid Regions*. Report to the Water Research Commission, WRC Report No. 1249/1/10.

Appendix A: Mafutha Water Balance

Result:	Precipitation	Groundwater Inflow	Runoff	Evaporation	Volume of Water	Water Elevation	Change in Storage
Unit:	**m^3/mon**	**m^3/mon**	**m^3/mon**	**m^3/mon**	**m^3**	**mamsl**	**m^3**
01/06/2010	84.54	37710	461.8	114.9	8985	778.2	8985
01/07/2010	0	28681	0	418.8	42552	793.9	33567
01/08/2010	0	26632	0	678.2	70210	800.3	27658
01/09/2010	0	24356	0	1056	95322	805.5	25112
01/10/2010	7.081	22609	0.07632	1307	117468	808.2	22146
01/11/2010	242.4	21349	74.51	1413	138530	810.8	21062
01/12/2010	502.3	20300	272	1639	158159	813.3	19629
01/01/2011	2053	20670	1896	1759	179667	815.9	21508
01/02/2011	0	18172	0	1700	199545	818.4	19878
01/03/2011	0	17083	0	1730	214184	820.2	14639
01/04/2011	0	16158	0	1353	229261	822.1	15077
01/05/2011	0	15228	0	1220	243440	823.8	14179
01/06/2011	1.099	14347	0.0006193	952.4	257252	825.5	13812
01/07/2011	32.88	13514	0.5067	1072	270061	826.9	12809
01/08/2011	0	12651	0	1388	282294	827.6	12233
01/09/2011	0	11938	0	1874	293389	828.3	11095
01/10/2011	5.911	11390	0.01296	2182	303026	828.9	9637
01/11/2011	202.6	10933	14.27	2239	312256	829.5	9230
01/12/2011	712	10659	165.6	2484	321162	830.1	8906
01/01/2012	2069	10865	784.6	2553	331501	830.7	10339
01/02/2012	1032	9903	293.2	2380	341577	831.3	10076
01/03/2012	402.1	9232	43.39	2364	349245	831.8	7668
01/04/2012	336.8	8859	28.95	1804	356462	832.3	7217
01/05/2012	0	8399	0	1591	363358	832.7	6896
01/06/2012	0	8111	0	1217	370140	833.1	6782
01/07/2012	0	7887	0	1345	376827	833.5	6687
01/08/2012	0	7587	0	1714	383348	834	6521
01/09/2012	0	7344	0	2280	389211	834.3	5863
01/10/2012	9.235	7105	0.0167	2622	394063	834.6	4852
01/11/2012	286.5	7008	15.55	2659	398744	834.9	4681
01/12/2012	218.1	6670	8.735	2918	403135	835.2	4391
01/01/2013	54.54	6299	0.5316	2954	406874	835.4	3739
01/02/2013	341.1	6182	20.27	2715	410431	835.6	3557
01/03/2013	355.6	6014	21.5	2672	413881	835.9	3450
01/04/2013	100.3	5709	1.667	2021	417338	836.1	3457
01/05/2013	985.4	5895	156	1772	421682	836.3	4344
01/06/2013	0	5268	0	1348	426105	836.6	4423
01/07/2013	0	5089	0	1481	429871	836.9	3766
01/08/2013	0	4861	0	1875	433435	837.1	3564
01/09/2013	0	4760	0	2481	436436	837.3	3001
01/10/2013	6.149	4547	0.005363	2837	438593	837.4	2157
01/11/2013	210.7	4551	6.213	2862	440426	837.5	1833
01/12/2013	915.7	4727	115.3	3127	442688	837.7	2262
01/01/2014	4905	6198	1371	3177	448841	838	6153
01/02/2014	768.2	4230	74.29	2929	454430	838.4	5589
01/03/2014	1160	4256	166.6	2874	456535	838.5	2105
01/04/2014	4911	5520	1255	2182	462400	838.9	5865
01/05/2014	630.4	3468	45.05	1916	468002	839.2	5602

Result: Unit:	Precipitation m^3/mon	Groundwater Inflow m^3/mon	Runoff m^3/mon	Evaporation m^3/mon	Volume of Water m^3	Water Elevation mamsl	Change in Storage m^3
01/06/2014	24.26	3056	0.0658	1450	469724	839.3	1722
01/07/2014	0	2914	0	1587	471264	839.4	1540
01/08/2014	0	2809	0	2001	472552	839.5	1288
01/09/2014	0	2720	0	2637	473324	839.6	772
01/10/2014	17.91	2719	0.03486	3006	473397	839.6	73
01/11/2014	566.4	2888	34.82	3023	473505	839.6	108
01/12/2014	972.6	2964	102.1	3293	474166	839.6	661
01/01/2015	3538	3906	685.5	3327	477068	839.8	2902
01/02/2015	787	2637	64.08	3051	479532	840	2464
01/03/2015	2031	3127	304.6	2990	480891	840	1359
01/04/2015	503.9	2434	25.73	2253	482137	840.1	1246
01/05/2015	550.7	2435	30.54	1962	482891	840.2	754
01/06/2015	4.96	2161	0.002464	1483	483517	840.2	626
01/07/2015	0.497	2123	2.46E-05	1620	484171	840.2	654
01/08/2015	14.92	2094	0.0221	2040	484677	840.3	506
01/09/2015	17.31	2097	0.02971	2686	484739	840.3	62
01/10/2015	528	2313	27.7	3059	484521	840.3	-218
01/11/2015	837.6	2430	69.72	3076	484518	840.3	-3
01/12/2015	1976	2857	283.8	3354	485719	840.3	1201
01/01/2016	273.9	2142	7.358	3375	486108	840.4	389
01/02/2016	1251	2539	153.8	3082	485891	840.4	-217
01/03/2016	1935	2806	273	3020	487257	840.4	1366
01/04/2016	1129	2489	122.6	2276	488671	840.5	1414
01/05/2016	130.3	2067	1.622	1982	489326	840.6	655
01/06/2016	4.661	1973	0.002074	1497	489418	840.6	92
01/07/2016	136.1	2039	1.76	1635	489987	840.6	569
01/08/2016	20.08	1978	0.03817	2059	490435	840.6	448
01/09/2016	3.112	1947	0.0009175	2709	490334	840.6	-101
01/10/2016	109	2033	1.131	3084	489667	840.6	-667
01/11/2016	615	2242	36.23	3098	489058	840.6	-609
01/12/2016	1662	2629	219.7	3375	489634	840.6	576
01/01/2017	2224	2780	319.9	3403	491256	840.7	1622
01/02/2017	1134	2301	120.1	3112	492224	840.7	968
01/03/2017	4545	3580	875	3058	495247	840.9	3023
01/04/2017	418.3	1876	15.58	2309	497822	841.1	2575
01/05/2017	513.1	1889	23.43	2009	497902	841.1	80
01/06/2017	5.073	1693	0.002289	1517	497967	841.1	65
01/07/2017	5.08	1701	0.002292	1656	498153	841.1	186
01/08/2017	152.4	1745	2.061	2084	498310	841.1	157
01/09/2017	0	1737	0	2742	498046	841.1	-264
01/10/2017	24.68	1743	0.0546	3120	497057	841	-989
01/11/2017	771	2198	53.62	3133	496308	841	-749
01/12/2017	990.2	2407	88.34	3411	496420	841	112
01/01/2018	1597	2620	197.9	3433	497023	841	603
01/02/2018	433.1	2168	16.81	3136	497025	841	2
01/03/2018	3782	3523	644.1	3076	498982	841.2	1957
01/04/2018	3489	3423	551	2330	503764	841.5	4782
17/04/2018	1874	2791	228.3	2337	505819	841.6	2055

Appendix B: 44a Water Balance

Result:	Evaporation	Precipitation	Groundwater	Runoff	Volume of water in pit	Change in Storage	Surface Elevation
Unit:	m^3/mon	m^3/mon	m^3/mon	m^3/mon	m^3	m^3	mamsl
31/12/2005	0	0	8058	4399	0		1530
01/01/2006	360.4	282.4	8058	4715	409.2	409.2	1531
01/02/2006	2343	1745	8055	3763	12949	12539.8	1532
01/03/2006	3153	1837	8052	2856	23144	10195	1533
01/04/2006	3033	1200	8048	1468	32723	9579	1533
01/05/2006	2805	579.2	8044	631.8	40177	7454	1533
01/06/2006	2385	285.7	8040	289	46663	6486	1533
01/07/2006	2709	220	8035	208.2	52737	6074	1533
01/08/2006	3697	300.1	8030	267.3	58527	5790	1534
01/09/2006	5005	1095	8025	928.3	63439	4912	1534
01/10/2006	6294	3057	8019	2473	68324	4885	1534
01/11/2006	6412	5198	8013	3910	75602	7278	1534
01/12/2006	8150	5885	8007	3810	86039	10437	1534
01/01/2007	9014	7062	8000	4037	95604	9565	1534
01/02/2007	8717	6491	7993	3288	105732	10128	1534
01/03/2007	9280	5405	7987	2499	113958	8226	1535
01/04/2007	7554	2989	7979	1289	120559	6601	1535
01/05/2007	6527	1348	7971	555	125102	4543	1535
01/06/2007	5320	637.2	7962	253.9	128435	3333	1535
01/07/2007	5838	474.3	7954	182.8	131852	3417	1535
01/08/2007	7705	625.4	7945	234.7	134615	2763	1535
01/09/2007	10065	2201	7935	817.7	135702	1087	1535
01/10/2007	12213	5932	7926	2186	136549	847	1535
01/11/2007	11991	9721	7916	3458	140350	3801	1535
01/12/2007	14022	10125	7905	3386	149240	8890	1535
01/01/2008	14467	11333	7894	3610	156673	7433	1535
01/02/2008	13158	9460	7883	2856	165106	8433	1535
01/03/2008	13393	7800	7872	2259	171742	6636	1535
01/04/2008	10515	4161	7860	1172	176293	4551	1535
01/05/2008	8854	1828	7849	507	178890	2597	1535
01/06/2008	7068	846.6	7836	232.9	180217	1327	1535
01/07/2008	7614	618.5	7823	168.3	182008	1791	1535
01/08/2008	9884	802.2	7810	217.1	183001	993	1535
01/09/2008	12747	2788	7797	759	181941	-1060	1535
01/10/2008	15279	7421	7783	2037	180581	-1360	1535
01/11/2008	14718	11931	7769	3237	182536	1955	1535
01/12/2008	16981	12261	7754	3172	190563	8027	1535
01/01/2009	17322	13571	7739	3387	196800	6237	1535
01/02/2009	15589	11608	7724	2777	204226	7426	1536
01/03/2009	15750	9173	7710	2122	210163	5937	1536
01/04/2009	12266	4854	7694	1103	213424	3261	1536

Result: Unit:	Evaporation m³/mon	Precipitation m³/mon	Groundwater m³/mon	Runoff m³/mon	Volume of water in pit m³	Change in Storage m³	Surface Elevation mamsl
01/05/2009	10263	2119	7678	477.9	214761	1337	1536
01/06/2009	8145	975.5	7661	220	214765	4	1536
01/07/2009	8728	709	7645	159.3	215450	685	1536
01/08/2009	11271	914.8	7627	205.8	215226	-224	1536
01/09/2009	14462	3163	7609	721.5	212697	-2529	1536
01/10/2009	17245	8376	7592	1942	209825	-2872	1536
01/11/2009	16512	13386	7573	3092	210480	655	1536
01/12/2009	18933	13671	7555	3031	217841	7361	1536
01/01/2010	19200	15042	7536	3239	223187	5346	1536
01/02/2010	17182	12794	7516	2658	229848	6661	1536
01/03/2010	17280	10064	7498	2033	235115	5267	1536
01/04/2010	13399	5302	7478	1058	237430	2315	1536
01/05/2010	11169	2306	7458	459.2	237848	418	1536
01/06/2010	8834	1058	7438	211.8	236890	-958	1536
01/07/2010	9437	766.6	7417	153.5	236757	-133	1536
01/08/2010	12150	986.2	7395	198.7	235643	-1114	1536
01/09/2010	15542	3399	7373	697.9	232068	-3575	1536
01/10/2010	18476	8974	7352	1882	228129	-3939	1536
01/11/2010	17628	14290	7329	3001	227849	-280	1536
01/12/2010	20139	14541	7307	2944	234675	6826	1536
01/01/2011	20350	15942	7284	3149	239345	4670	1536
01/02/2011	18149	13514	7260	2586	245408	6063	1536
01/03/2011	18202	10601	7238	1979	250149	4741	1536
01/04/2011	14075	5570	7214	1031	251761	1612	1536
01/05/2011	11705	2417	7190	448.1	251497	-264	1536
01/06/2011	9237	1106	7165	206.9	249831	-1666	1536
01/07/2011	9848	800	7141	150.2	249081	-750	1536
01/08/2011	12652	1027	7115	194.6	247306	-1775	1536
01/09/2011	16151	3532	7089	684.6	242984	-4322	1536
01/10/2011	19160	9306	7063	1849	238297	-4687	1536
01/11/2011	18238	14785	7037	2952	237342	-955	1536
01/12/2011	20786	15009	7010	2898	243718	6376	1536
01/01/2012	20956	16417	6983	3102	247861	4143	1536
01/02/2012	18648	13407	6955	2461	253438	5577	1536
01/03/2012	18602	10834	6929	1956	257366	3928	1536
01/04/2012	14329	5670	6900	1021	258483	1117	1536
01/05/2012	11915	2460	6872	443.8	257747	-736	1536
01/06/2012	9416	1128	6843	204.8	255571	-2176	1536
01/07/2012	10023	814.2	6815	148.8	254351	-1220	1536
01/08/2012	12857	1044	6785	192.9	252084	-2267	1536
01/09/2012	16388	3584	6755	679.4	247240	-4844	1536
01/10/2012	19412	9428	6725	1836	242044	-5196	1536
01/11/2012	18447	14955	6694	2935	240608	-1436	1536

Result: Unit:	Evaporation m^3/mon	Precipitation m^3/mon	Groundwater m^3/mon	Runoff m^3/mon	Volume of water in pit m^3	Change in Storage m^3	Surface Elevation mamsl
01/12/2012	20992	15157	6664	2883	246592	5984	1536
01/01/2013	21130	16554	6632	3088	250311	3719	1536
01/02/2013	18775	13980	6600	2540	255481	5170	1536
01/03/2013	18657	10866	6571	1953	259443	3962	1536
01/04/2013	14363	5684	6539	1020	260169	726	1536
01/05/2013	11937	2465	6507	443.3	259056	-1113	1536
01/06/2013	9439	1131	6473	204.5	256489	-2567	1536
01/07/2013	10041	815.7	6441	148.6	254883	-1606	1536
01/08/2013	12863	1044	6407	192.9	252222	-2661	1536
01/09/2013	16375	3581	6373	679.7	246993	-5229	1536
01/10/2013	19371	9409	6342	1838	241439	-5554	1536
01/11/2013	18385	14904	6310	2940	239642	-1797	1536
01/12/2013	20897	15089	6279	2890	245266	5624	1536
01/01/2014	21010	16460	6246	3098	248631	3365	1536
01/02/2014	18648	13886	6213	2549	253447	4816	1536
01/03/2014	18594	10830	6183	1957	257081	3634	1536
01/04/2014	14308	5662	6150	1022	257444	363	1536
01/05/2014	11881	2453	6117	444.5	255986	-1458	1536
01/06/2014	9339	1119	6084	205.7	253095	-2891	1536
01/07/2014	9918	805.7	6053	149.6	251201	-1894	1536
01/08/2014	12694	1030	6087	194.2	248298	-2903	1536
01/09/2014	16148	3532	6121	684.6	242939	-5359	1536
01/10/2014	19096	9275	6153	1852	237347	-5592	1536
01/11/2014	18122	14691	6186	2961	235547	-1800	1536
01/12/2014	20602	14876	6218	2911	241150	5603	1536
01/01/2015	20723	16235	6251	3120	244589	3439	1536
01/02/2015	18405	13705	6283	2567	249527	4938	1536
01/03/2015	18397	10714	6312	1968	253323	3796	1536
01/04/2015	14177	5610	6344	1027	253939	616	1536
01/05/2015	11756	2427	6374	447.1	252792	-1147	1536
01/06/2015	9251	1108	6374	206.8	250277	-2515	1536
01/07/2015	9837	799.1	6374	150.3	248757	-1520	1536
01/08/2015	12605	1023	6374	195	246235	-2522	1536
01/09/2015	16053	3511	6374	686.7	241228	-5007	1536
01/10/2015	19001	9229	6374	1856	235939	-5289	1536
01/11/2015	18048	14631	6374	2967	234397	-1542	1536
01/12/2015	20533	14826	6374	2916	240187	5790	1536
01/01/2016	20666	16190	6374	3125	243791	3604	1536
01/02/2016	18363	13202	6374	2482	248854	5063	1536
01/03/2016	18336	10679	6374	1972	252338	3484	1536
01/04/2016	14134	5593	6374	1029	253029	691	1536
01/05/2016	11722	2420	6374	447.8	251923	-1106	1536
01/06/2016	9225	1105	6374	207.1	249436	-2487	1536

Result: Unit:	Evaporation m^3/mon	Precipitation m^3/mon	Groundwater m^3/mon	Runoff m^3/mon	Volume of water in pit m^3	Change in Storage m^3	Surface Elevation mamsl
01/07/2016	9810	796.9	6374	150.5	247939	-1497	1536
01/08/2016	12571	1020	6374	195.2	245443	-2496	1536
01/09/2016	16011	3502	6374	687.7	240467	-4976	1536
01/10/2016	18952	9205	6374	1859	235210	-5257	1536
01/11/2016	18003	14595	6374	2971	233696	-1514	1536
01/12/2016	20484	14791	6374	2919	239498	5802	1536
01/01/2017	20618	16153	6374	3128	243120	3622	1536
01/02/2017	18322	13643	6374	2573	248197	5077	1536
01/03/2017	18321	10670	6379	1972	252087	3890	1536
01/04/2017	14127	5590	6531	1029	252866	779	1536
01/05/2017	11724	2421	6668	447.7	251985	-881	1536
01/06/2017	9236	1106	6668	206.9	249791	-2194	1536
01/07/2017	9831	798.6	6668	150.3	248570	-1221	1536
01/08/2017	12610	1024	6668	194.9	246349	-2221	1536
01/09/2017	16076	3516	6668	686.2	241631	-4718	1536
01/10/2017	19046	9251	6668	1854	236608	-5023	1536
01/11/2017	18109	14680	6668	2962	235335	-1273	1536
01/12/2017	20620	14889	6668	2910	241397	6062	1536
01/01/2018	20771	16272	6668	3116	245267	3870	1536
01/02/2018	18471	13754	6668	2562	250595	5328	1536
01/03/2018	18482	10764	6668	1963	254709	4114	1536
01/04/2018	14257	5642	6668	1024	255625	916	1536
01/05/2018	11832	2443	6668	445.5	254728	-897	1536
01/06/2018	9319	1116	6668	206	252447	-2281	1536
01/07/2018	9917	805.6	6668	149.6	251154	-1293	1536
01/08/2018	12718	1032	6668	194	248853	-2301	1536
01/09/2018	16210	3545	6668	683.3	244035	-4818	1536
01/10/2018	19201	9326	6668	1847	238908	-5127	1536
01/11/2018	18251	14795	6668	2951	237548	-1360	1536
01/12/2018	20776	15001	6668	2898	243573	6025	1536
31/12/2018	21040	15192	6668	2879	247266	3693	1536

Appendix C: 44b Water Balance

Result: Unit:	Evaporation m^3/mon	Precipitation m^3/mon	Groundwater m^3/mon	Runoff M^3/mon	Volume of Water in pit m^3	Change in Storage m^3	Surface Elevation mamsl
31/12/2005	0	0	1949	2322	0		1531
01/01/2006	97.53	76.41	1949	2504	140.3	140.3	1531
01/02/2006	685.8	510.7	1948	2079	4563	4422.7	1533
01/03/2006	951.4	554.1	1946	1605	8073	3510	1534
01/04/2006	941.6	372.6	1944	838.5	11231	3158	1534
01/05/2006	924.5	190.9	1942	364.1	13363	2132	1534
01/06/2006	815.4	97.66	1940	167.6	14922	1559	1534
01/07/2006	946.4	76.88	1937	121.5	16261	1339	1534
01/08/2006	1309	106.2	1934	156.9	17440	1179	1535
01/09/2006	1778	388.8	1931	547.9	18315	875	1535
01/10/2006	2261	1098	1928	1467	19352	1037	1535
01/11/2006	2398	1944	1925	2339	21560	2208	1535
01/12/2006	3053	2205	1922	2322	25281	3721	1535
01/01/2007	3346	2622	1918	2504	28694	3413	1535
01/02/2007	3220	2398	1914	2079	32421	3727	1535
01/03/2007	3405	1983	1910	1605	35310	2889	1535
01/04/2007	2745	1086	1906	838.5	37406	2096	1535
01/05/2007	2338	482.8	1902	364.1	38455	1049	1536
01/06/2007	1872	224.2	1897	167.6	38863	408	1536
01/07/2007	2018	163.9	1893	121.5	39265	402	1536
01/08/2007	2617	212.4	1888	156.9	39423	158	1536
01/09/2007	3365	735.8	1883	547.9	39063	-360	1536
01/10/2007	4040	1962	1877	1467	38871	-192	1536
01/11/2007	3963	3212	1872	2339	40130	1259	1536
01/12/2007	4728	3414	1866	2322	43513	3383	1536
01/01/2008	4963	3888	1860	2504	46400	2887	1536
01/02/2008	4599	3306	1854	2007	49715	3315	1536
01/03/2008	4726	2753	1848	1605	52135	2420	1536
01/04/2008	3691	1460	1842	838.5	53623	1488	1536
01/05/2008	3086	637.1	1835	364.1	54059	436	1536
01/06/2008	2442	292.6	1828	167.6	53805	-254	1536
01/07/2008	2606	211.7	1822	121.5	53652	-153	1536
01/08/2008	3353	272.2	1814	156.9	53194	-458	1536
01/09/2008	4295	939.3	1807	547.9	52077	-1117	1536
01/10/2008	5097	2476	1799	1467	51112	-965	1536
01/11/2008	4920	3989	1792	2339	51752	640	1536
01/12/2008	5673	4096	1784	2322	54885	3133	1536
01/01/2009	5784	4531	1776	2504	57437	2552	1536
01/02/2009	5202	3874	1767	2079	60497	3060	1536
01/03/2009	5247	3056	1760	1605	62797	2300	1536
01/04/2009	4079	1614	1751	838.5	63976	1179	1536
01/05/2009	3399	701.8	1742	364.1	64093	117	1536
01/06/2009	2683	321.3	1733	167.6	63494	-599	1536
01/07/2009	2855	231.9	1724	121.5	63040	-454	1536
01/08/2009	3663	297.3	1715	156.9	62253	-787	1536
01/09/2009	4680	1023	1705	547.9	60749	-1504	1536
01/10/2009	5570	2705	1695	1467	59384	-1365	1536
01/11/2009	5334	4325	1685	2339	59678	294	1536
01/12/2009	6115	4415	1675	2322	62631	2953	1536

Result: Unit:	Evaporation m^3/mon	Precipitation m^3/mon	Groundwater m^3/mon	Runoff M^3/mon	Volume of Water in pit m^3	Change in Storage m^3	Surface Elevation mamsl
01/01/2010	6209	4864	1665	2504	64948	2317	1536
01/02/2010	5564	4143	1654	2079	67802	2854	1536
01/03/2010	5594	3258	1644	1605	69912	2110	1536
01/04/2010	4336	1716	1633	838.5	70828	916	1536
01/05/2010	3605	744.3	1623	364.1	70678	-150	1536
01/06/2010	2839	340	1611	167.6	69793	-885	1536
01/07/2010	3015	245	1600	121.5	69085	-708	1536
01/08/2010	3861	313.4	1588	156.9	68024	-1061	1536
01/09/2010	4922	1076	1576	547.9	66210	-1814	1536
01/10/2010	5845	2839	1564	1467	64536	-1674	1536
01/11/2010	5584	4527	1552	2339	64555	19	1536
01/12/2010	6382	4608	1540	2322	67330	2775	1536
01/01/2011	6463	5063	1527	2504	69434	2104	1536
01/02/2011	5776	4301	1514	2079	72092	2658	1536
01/03/2011	5794	3375	1503	1605	74024	1932	1536
01/04/2011	4482	1774	1489	838.5	74711	687	1537
01/05/2011	3719	767.8	1476	364.1	74334	-377	1536
01/06/2011	2924	350.2	1463	167.6	73209	-1125	1536
01/07/2011	3100	251.8	1449	121.5	72283	-926	1536
01/08/2011	3963	321.6	1435	156.9	70991	-1292	1536
01/09/2011	5043	1103	1421	547.9	68929	-2062	1536
01/10/2011	5978	2903	1407	1467	67012	-1917	1536
01/11/2011	5699	4620	1393	2339	66804	-208	1536
01/12/2011	6500	4693	1378	2322	69399	2595	1536
01/01/2012	6569	5146	1363	2504	71305	1906	1536
01/02/2012	5859	4212	1348	2007	73773	2468	1536
01/03/2012	5861	3413	1334	1605	75384	1611	1537
01/04/2012	4526	1791	1318	838.5	75871	487	1537
01/05/2012	3749	774.1	1303	364.1	75300	-571	1537
01/06/2012	2943	352.5	1287	167.6	73977	-1323	1536
01/07/2012	3115	253.1	1272	121.5	72862	-1115	1536
01/08/2012	3976	322.7	1255	156.9	71375	-1487	1536
01/09/2012	5051	1105	1239	547.9	69120	-2255	1536
01/10/2012	5978	2904	1223	1467	67018	-2102	1536
01/11/2012	5689	4612	1206	2339	66624	-394	1536
01/12/2012	6479	4679	1189	2322	69037	2413	1536
01/01/2013	6538	5122	1172	2504	70757	1720	1536
01/02/2013	5822	4336	1155	2079	73036	2279	1536
01/03/2013	5824	3392	1139	1605	74627	1591	1537
01/04/2013	4490	1777	1121	838.5	74932	305	1537
01/05/2013	3715	766.9	1104	364.1	74189	-743	1536
01/06/2013	2911	348.6	1085	167.6	72691	-1498	1536
01/07/2013	3077	249.9	1068	121.5	71406	-1285	1536
01/08/2013	3920	318.2	1049	156.9	69749	-1657	1536
01/09/2013	4972	1087	1031	547.9	67337	-2412	1536
01/10/2013	5875	2854	1014	1467	65093	-2244	1536
01/11/2013	5583	4526	996.4	2339	64542	-551	1536
01/12/2013	6350	4585	979.3	2322	66769	2227	1536
01/01/2014	6399	5013	961.6	2504	68312	1543	1536
01/02/2014	5693	4239	943.7	2079	70409	2097	1536

Result: Unit:	Evaporation m^3/mon	Precipitation m^3/mon	Groundwater m^3/mon	Runoff M^3/mon	Volume of Water in pit m^3	Change in Storage m^3	Surface Elevation mamsl
01/03/2014	5688	3313	927.4	1605	71837	1428	1536
01/04/2014	4380	1733	909.2	838.5	71986	149	1536
01/05/2014	3618	747	891.4	364.1	71101	-885	1536
01/06/2014	2831	339.1	872.9	167.6	69467	-1634	1536
01/07/2014	2988	242.7	856	121.5	68043	-1424	1536
01/08/2014	3801	308.5	874.6	156.9	66273	-1770	1536
01/09/2014	4816	1053	893.1	547.9	63814	-2459	1536
01/10/2014	5687	2762	910.8	1467	61572	-2242	1536
01/11/2014	5404	4381	928.9	2339	61031	-541	1536
01/12/2014	6149	4440	946.3	2322	63242	2211	1536
01/01/2015	6202	4859	964.1	2504	64826	1584	1536
01/02/2015	5523	4113	981.8	2079	66986	2160	1536
01/03/2015	5525	3218	997.6	1605	68502	1516	1536
01/04/2015	4261	1686	1015	838.5	68808	306	1536
01/05/2015	3525	727.7	1031	364.1	68113	-695	1536
01/06/2015	2762	330.9	1031	167.6	66703	-1410	1536
01/07/2015	2920	237.2	1031	121.5	65500	-1203	1536
01/08/2015	3722	302.1	1031	156.9	63960	-1540	1536
01/09/2015	4723	1033	1031	547.9	61722	-2238	1536
01/10/2015	5585	2713	1031	1467	59675	-2047	1536
01/11/2015	5315	4309	1031	2339	59299	-376	1536
01/12/2015	6057	4373	1031	2322	61618	2319	1536
01/01/2016	6116	4791	1031	2504	63305	1687	1536
01/02/2016	5452	3920	1031	2007	65543	2238	1536
01/03/2016	5450	3174	1031	1605	66969	1426	1536
01/04/2016	4205	1664	1031	838.5	67332	363	1536
01/05/2016	3480	718.5	1031	364.1	66677	-655	1536
01/06/2016	2728	326.7	1031	167.6	65302	-1375	1536
01/07/2016	2884	234.3	1031	121.5	64130	-1172	1536
01/08/2016	3676	298.4	1031	156.9	62623	-1507	1536
01/09/2016	4665	1020	1031	547.9	60427	-2196	1536
01/10/2016	5518	2680	1031	1467	58424	-2003	1536
01/11/2016	5253	4258	1031	2339	58083	-341	1536
01/12/2016	5988	4324	1031	2322	60413	2330	1536
01/01/2017	6049	4739	1031	2504	62120	1707	1536
01/02/2017	5394	4016	1031	2079	64372	2252	1536
01/03/2017	5401	3145	1034	1605	65957	1585	1536
01/04/2017	4170	1650	1117	838.5	66384	427	1536
01/05/2017	3455	713.3	1191	364.1	65871	-513	1536
01/06/2017	2712	324.8	1191	167.6	64678	-1193	1536
01/07/2017	2872	233.3	1191	121.5	63675	-1003	1536
01/08/2017	3666	297.6	1191	156.9	62341	-1334	1536
01/09/2017	4660	1019	1191	547.9	60315	-2026	1536
01/10/2017	5521	2681	1191	1467	58471	-1844	1536
01/11/2017	5263	4267	1191	2339	58289	-182	1536
01/12/2017	6009	4339	1191	2322	60775	2486	1536
01/01/2018	6078	4762	1191	2504	62638	1863	1536
01/02/2018	5427	4041	1191	2079	65047	2409	1536
01/03/2018	5440	3169	1191	1605	66770	1723	1536
01/04/2018	4204	1664	1191	838.5	67299	529	1536

Result: Unit:	Evaporation m^3/mon	Precipitation m^3/mon	Groundwater m^3/mon	Runoff M^3/mon	Volume of Water in pit m^3	Change in Storage m^3	Surface Elevation mamsl
01/05/2018	3484	719.3	1191	364.1	66801	-498	1536
01/06/2018	2735	327.5	1191	167.6	65585	-1216	1536
01/07/2018	2896	235.2	1191	121.5	64563	-1022	1536
01/08/2018	3696	300	1191	156.9	63207	-1356	1536
01/09/2018	4698	1027	1191	547.9	61153	-2054	1536
01/10/2018	5564	2703	1191	1467	59281	-1872	1536
01/11/2018	5304	4300	1191	2339	59077	-204	1536
01/12/2018	6053	4371	1191	2322	61556	2479	1536
31/12/2018	6155	4445	1191	2322	63347	1791	1536

Appendix D: 44c Water Balance

Result:	Evaporation	Groundwater	Runoff	Precipitation	Volume of water in pit	Change in Storage	Surface Elevation
Unit:	**m^3/mon**	**m^3/mon**	**m^3/mon**	**m^3/mon**	**m^3**	**m^3**	**mamsl**
31/12/2005	0	1697	1811	0	0		1527
01/01/2006	184	1697	1953	144.2	115.3	115.3	1527
01/02/2006	687.9	1697	1621	512.2	3723	3607.7	1528
01/03/2006	840.8	1697	1251	489.7	6591	2868	1528
01/04/2006	730.6	1696	653.8	289.1	9213	2622	1529
01/05/2006	657.8	1696	284	135.8	11077	1864	1529
01/06/2006	544.6	1696	130.7	65.23	12550	1473	1529
01/07/2006	601.6	1695	94.76	48.87	13870	1320	1529
01/08/2006	801.5	1695	122.4	65.06	15121	1251	1529
01/09/2006	1066	1694	427.2	233	16212	1091	1530
01/10/2006	1322	1694	1144	642.3	17470	1258	1530
01/11/2006	1325	1693	1824	1074	19651	2181	1530
01/12/2006	1621	1693	1811	1170	22859	3208	1530
01/01/2007	1762	1692	1953	1380	25947	3088	1530
01/02/2007	1679	1691	1621	1251	29253	3306	1531
01/03/2007	1769	1691	1251	1030	31893	2640	1531
01/04/2007	1420	1690	653.8	562	34118	2225	1531
01/05/2007	1203	1689	284	248.4	35575	1457	1531
01/06/2007	966.7	1688	130.7	115.8	36606	1031	1531
01/07/2007	1045	1688	94.76	84.88	37555	949	1531
01/08/2007	1364	1687	122.4	110.7	38387	832	1531
01/09/2007	1778	1686	427.2	388.9	38949	562	1531
01/10/2007	2162	1685	1144	1050	39657	708	1531
01/11/2007	2106	1684	1824	1707	41394	1737	1531
01/12/2007	2428	1683	1811	1753	44451	3057	1532
01/01/2008	2489	1682	1953	1950	47312	2861	1532
01/02/2008	2245	1681	1565	1614	50455	3143	1532
01/03/2008	2263	1680	1251	1318	52940	2485	1532
01/04/2008	1769	1679	653.8	700	54955	2015	1532
01/05/2008	1487	1678	284	307	56195	1240	1532
01/06/2008	1188	1677	130.7	142.3	56987	792	1532
01/07/2008	1277	1675	94.76	103.7	57734	747	1532
01/08/2008	1658	1674	122.4	134.6	58339	605	1532
01/09/2008	2153	1673	427.2	470.9	58614	275	1532
01/10/2008	2605	1672	1144	1265	59023	409	1532
01/11/2008	2517	1670	1824	2040	60518	1495	1532
01/12/2008	2869	1669	1811	2072	63486	2968	1533
01/01/2009	2911	1668	1953	2280	66209	2723	1533
01/02/2009	2599	1666	1621	1935	69247	3038	1533
01/03/2009	2611	1665	1251	1520	71654	2407	1533
01/04/2009	2040	1663	653.8	807.1	73505	1851	1533
01/05/2009	1713	1662	284	353.7	74568	1063	1533
01/06/2009	1366	1660	130.7	163.6	75161	593	1533
01/07/2009	1467	1659	94.76	119.2	75737	576	1533
01/08/2009	1903	1657	122.4	154.4	76147	410	1533
01/09/2009	2466	1655	427.2	539.3	76178	31	1533
01/10/2009	2977	1654	1144	1446	76330	152	1533
01/11/2009	2873	1652	1824	2329	77611	1281	1533
01/12/2009	3278	1650	1811	2367	80494	2883	1533

Result:	Evaporation	Groundwater	Runoff	Precipitation	Volume of water in pit	Change in Storage	Surface Elevation
Unit:	m^3/mon	m^3/mon	m^3/mon	m^3/mon	m^3	m^3	mamsl
01/01/2010	3326	1648	1953	2605	83081	2587	1533
01/02/2010	2971	1647	1621	2212	86006	2925	1534
01/03/2010	2984	1645	1251	1738	88307	2301	1534
01/04/2010	2323	1643	653.8	919.4	89979	1672	1534
01/05/2010	1946	1641	284	401.9	90854	875	1534
01/06/2010	1549	1639	130.7	185.5	91239	385	1534
01/07/2010	1660	1637	94.76	134.9	91637	398	1534
01/08/2010	2149	1635	122.4	174.5	91845	208	1534
01/09/2010	2780	1633	427.2	608.1	91624	-221	1534
01/10/2010	3350	1631	1144	1627	91514	-110	1534
01/11/2010	3224	1629	1824	2614	92578	1064	1534
01/12/2010	3667	1627	1811	2648	95373	2795	1534
01/01/2011	3717	1625	1953	2912	97825	2452	1534
01/02/2011	3321	1623	1621	2473	100639	2814	1534
01/03/2011	3335	1621	1251	1942	102835	2196	1534
01/04/2011	2595	1618	653.8	1027	104332	1497	1534
01/05/2011	2172	1616	284	448.4	105021	689	1534
01/06/2011	1726	1614	130.7	206.7	105199	178	1534
01/07/2011	1848	1612	94.76	150.1	105418	219	1534
01/08/2011	2388	1609	122.4	193.9	105426	8	1534
01/09/2011	3083	1607	427.2	674.3	104957	-469	1534
01/10/2011	3707	1604	1144	1801	104589	-368	1534
01/11/2011	3564	1602	1824	2889	105439	850	1534
01/12/2011	4056	1599	1811	2929	108142	2703	1534
01/01/2012	4102	1597	1953	3214	110456	2314	1534
01/02/2012	3655	1594	1565	2627	113156	2700	1535
01/03/2012	3660	1592	1251	2132	115180	2024	1535
01/04/2012	2842	1589	653.8	1124	116510	1330	1535
01/05/2012	2374	1586	284	490.1	117024	514	1535
01/06/2012	1884	1584	130.7	225.6	117009	-15	1535
01/07/2012	2014	1581	94.76	163.6	117063	54	1535
01/08/2012	2600	1578	122.4	211	116885	-178	1535
01/09/2012	3352	1575	427.2	733.1	116188	-697	1535
01/10/2012	4024	1573	1144	1955	115585	-603	1535
01/11/2012	3862	1570	1824	3130	116238	653	1535
01/12/2012	4385	1567	1811	3166	118854	2616	1535
01/01/2013	4425	1564	1953	3467	121042	2188	1535
01/02/2013	3934	1561	1621	2929	123638	2596	1535
01/03/2013	3935	1558	1251	2292	125634	1996	1535
01/04/2013	3053	1555	653.8	1208	126813	1179	1535
01/05/2013	2547	1552	284	526	127168	355	1535
01/06/2013	2019	1549	130.7	241.8	126979	-189	1535
01/07/2013	2156	1546	94.76	175.2	126883	-96	1535
01/08/2013	2780	1543	122.4	225.6	126537	-346	1535
01/09/2013	3578	1540	427.2	782.6	125638	-899	1535
01/10/2013	4291	1537	1144	2084	124827	-811	1535
01/11/2013	4111	1534	1824	3333	125305	478	1535
01/12/2013	4667	1531	1811	3370	127839	2534	1535
01/01/2014	4708	1528	1953	3689	129910	2071	1535
01/02/2014	4185	1525	1621	3116	132406	2496	1535

Result:	Evaporation	Groundwater	Runoff	Precipitation	Volume of water in pit	Change in Storage	Surface Elevation
Unit:	m^3/mon	m^3/mon	m^3/mon	m^3/mon	m^3	m^3	mamsl
01/03/2014	4185	1522	1251	2437	134309	1903	1535
01/04/2014	3241	1519	653.8	1283	135346	1037	1535
01/05/2014	2702	1516	284	557.8	135554	208	1535
01/06/2014	2139	1513	130.7	256.2	135205	-349	1535
01/07/2014	2283	1510	94.76	185.4	134969	-236	1535
01/08/2014	2940	1513	122.4	238.6	134472	-497	1535
01/09/2014	3781	1516	427.2	827	133398	-1074	1535
01/10/2014	4528	1519	1144	2199	132412	-986	1535
01/11/2014	4335	1522	1824	3514	132751	339	1535
01/12/2014	4916	1525	1811	3549	135235	2484	1535
01/01/2015	4953	1528	1953	3880	137233	1998	1535
01/02/2015	4397	1531	1621	3274	139679	2446	1535
01/03/2015	4393	1534	1251	2558	141541	1862	1535
01/04/2015	3400	1537	653.8	1345	142505	964	1535
01/05/2015	2832	1540	284	584.8	142640	135	1535
01/06/2015	2242	1540	130.7	268.5	142212	-428	1535
01/07/2015	2391	1540	94.76	194.2	141915	-297	1535
01/08/2015	3079	1540	122.4	249.9	141347	-568	1535
01/09/2015	3958	1540	427.2	865.7	140169	-1178	1535
01/10/2015	4738	1540	1144	2301	139070	-1099	1535
01/11/2015	4533	1540	1824	3675	139320	250	1535
01/12/2015	5136	1540	1811	3708	141782	2462	1535
01/01/2016	5170	1540	1953	4050	143732	1950	1536
01/02/2016	4585	1540	1565	3296	146140	2408	1536
01/03/2016	4575	1540	1251	2664	147864	1724	1536
01/04/2016	3538	1540	653.8	1400	148756	892	1536
01/05/2016	2946	1540	284	608.2	148810	54	1536
01/06/2016	2330	1540	130.7	279.1	148290	-520	1536
01/07/2016	2485	1540	94.76	201.8	147917	-373	1536
01/08/2016	3198	1540	122.4	259.6	147262	-655	1536
01/09/2016	4110	1540	427.2	898.9	145973	-1289	1536
01/10/2016	4918	1540	1144	2389	144759	-1214	1536
01/11/2016	4702	1540	1824	3811	144915	156	1536
01/12/2016	5322	1540	1811	3843	147346	2431	1536
01/01/2017	5354	1540	1953	4194	149243	1897	1536
01/02/2017	4745	1540	1621	3533	151611	2368	1536
01/03/2017	4734	1540	1251	2757	153398	1787	1536
01/04/2017	3659	1555	653.8	1448	154230	832	1536
01/05/2017	3046	1567	284	628.9	154234	4	1536
01/06/2017	2409	1567	130.7	288.5	153661	-573	1536
01/07/2017	2568	1567	94.76	208.6	153248	-413	1536
01/08/2017	3305	1567	122.4	268.3	152542	-706	1536
01/09/2017	4246	1567	427.2	928.7	151183	-1359	1536
01/10/2017	5080	1567	1144	2467	149891	-1292	1536
01/11/2017	4854	1567	1824	3935	149991	100	1536
01/12/2017	5493	1567	1811	3966	152421	2430	1536
01/01/2018	5522	1567	1953	4326	154298	1877	1536
01/02/2018	4892	1567	1621	3642	156657	2359	1536
01/03/2018	4879	1567	1251	2841	158435	1778	1536
01/04/2018	3770	1567	653.8	1492	159225	790	1536

Result: Unit:	Evaporation m^3/mon	Groundwater m^3/mon	Runoff m^3/mon	Precipitation m^3/mon	Volume of water in pit m^3	Change in Storage m^3	Surface Elevation mamsl
01/05/2018	3137	1567	284	647.6	159170	-55	1536
01/06/2018	2480	1567	130.7	297	158525	-645	1536
01/07/2018	2643	1567	94.76	214.7	158050	-475	1536
01/08/2018	3400	1567	122.4	276	157275	-775	1536
01/09/2018	4368	1567	427.2	955.3	155827	-1448	1536
01/10/2018	5223	1567	1144	2537	154443	-1384	1536
01/11/2018	4989	1567	1824	4045	154468	25	1536
01/12/2018	5642	1567	1811	4074	156873	2405	1536
31/12/2018	5702	1567	1811	4117	158649	1776	1536

Appendix E: R42 Water Balance

Result:	Evaporation	Ground water	Runoff	Precipitation	Volume of water in pit	Change in Storage	Surface Elevation
Unit:	m^3/mon	m^3/mon	m^3/mon	m^3/mon	m^3	m^3	mamsl
31/12/2005	63.09	4650	945.4	45.55	0		1524
01/01/2006	110.1	4650	1020	86.25	183.3	183.3	1524
01/02/2006	985.6	4647	846.3	733.9	5794	5610.7	1525
01/03/2006	1244	4644	653.3	724.5	10583	4789	1526
01/04/2006	1121	4640	341.4	443.5	15399	4816	1526
01/05/2006	1034	4636	148.2	213.4	19604	4205	1527
01/06/2006	896.5	4631	68.25	107.4	23601	3997	1527
01/07/2006	1023	4626	49.47	83.14	27426	3825	1527
01/08/2006	1400	4621	63.89	113.7	31200	3774	1527
01/09/2006	1906	4615	223.1	416.7	34627	3427	1528
01/10/2006	2402	4609	597.3	1167	37893	3266	1528
01/11/2006	2422	4603	952.2	1963	41901	4008	1528
01/12/2006	2894	4596	945.4	2089	46905	5004	1528
01/01/2007	3061	4589	1020	2398	51701	4796	1529
01/02/2007	2842	4581	846.3	2116	56714	5013	1529
01/03/2007	2948	4574	653.3	1717	61019	4305	1529
01/04/2007	2332	4566	341.4	922.9	65067	4048	1529
01/05/2007	1983	4557	148.2	409.3	68496	3429	1529
01/06/2007	1604	4548	68.25	192.1	71667	3171	1529
01/07/2007	1746	4539	49.47	141.8	74809	3142	1530
01/08/2007	2296	4530	63.89	186.4	77830	3021	1530
01/09/2007	3018	4519	223.1	660.1	80339	2509	1530
01/10/2007	3687	4509	597.3	1791	82670	2331	1530
01/11/2007	3585	4498	952.2	2907	85917	3247	1530
01/12/2007	4076	4487	945.4	2943	90608	4691	1530
01/01/2008	4119	4476	1020	3227	94972	4364	1530
01/02/2008	3660	4464	817.1	2631	99647	4675	1530
01/03/2008	3666	4452	653.3	2135	103686	4039	1531
01/04/2008	2857	4439	341.4	1130	107310	3624	1531
01/05/2008	2403	4427	148.2	496.2	110306	2996	1531
01/06/2008	1926	4413	68.25	230.6	113007	2701	1531
01/07/2008	2077	4400	49.47	168.8	115739	2732	1531
01/08/2008	2706	4385	63.89	219.6	118312	2573	1531
01/09/2008	3526	4371	223.1	771.2	120297	1985	1531
01/10/2008	4274	4356	597.3	2076	122096	1799	1531
01/11/2008	4115	4341	952.2	3336	124886	2790	1531
01/12/2008	4646	4326	945.4	3355	129323	4437	1531
01/01/2009	4672	4310	1020	3660	133361	4038	1532
01/02/2009	4130	4293	846.3	3076	137744	4383	1532
01/03/2009	4119	4278	653.3	2399	141490	3746	1532
01/04/2009	3196	4261	341.4	1265	144745	3255	1532

Result: Unit:	Evaporation m^3/mon	Ground water m^3/mon	Runoff m^3/mon	Precipitation m^3/mon	Volume of water in pit m^3	Change in Storage m^3	Surface Elevation mamsl
01/05/2009	2679	4244	148.2	553.2	147362	2617	1532
01/06/2009	2139	4226	68.25	256.2	149655	2293	1532
01/07/2009	2300	4208	49.47	186.9	152018	2363	1532
01/08/2009	2990	4190	63.89	242.7	154186	2168	1532
01/09/2009	3889	4170	223.1	850.6	155706	1520	1532
01/10/2009	4706	4152	597.3	2286	157027	1321	1532
01/11/2009	4521	4132	952.2	3665	159382	2355	1532
01/12/2009	5093	4112	945.4	3678	163536	4154	1532
01/01/2010	5110	4092	1020	4003	167229	3693	1533
01/02/2010	4508	4071	846.3	3357	171292	4063	1533
01/03/2010	4487	4052	653.3	2613	174743	3451	1533
01/04/2010	3475	4030	341.4	1375	177610	2867	1533
01/05/2010	2908	4009	148.2	600.4	179834	2224	1533
01/06/2010	2318	3987	68.25	277.6	181701	1867	1533
01/07/2010	2489	3965	49.47	202.2	183672	1971	1533
01/08/2010	3229	3941	63.89	262.1	185416	1744	1533
01/09/2010	4193	3918	223.1	917.1	186458	1042	1533
01/10/2010	5066	3895	597.3	2461	187297	839	1533
01/11/2010	4859	3871	952.2	3939	189201	1904	1533
01/12/2010	5463	3847	945.4	3944	193033	3832	1533
01/01/2011	5469	3822	1020	4285	196350	3317	1533
01/02/2011	4815	3797	846.3	3586	200057	3707	1534
01/03/2011	4785	3773	653.3	2787	203183	3126	1534
01/04/2011	3699	3747	341.4	1464	205638	2455	1534
01/05/2011	3091	3722	148.2	638.2	207449	1811	1534
01/06/2011	2461	3695	68.25	294.7	208875	1426	1534
01/07/2011	2639	3669	49.47	214.3	210434	1559	1534
01/08/2011	3420	3641	63.89	277.6	211735	1301	1534
01/09/2011	4436	3613	223.1	970.2	212293	558	1534
01/10/2011	5353	3586	597.3	2600	212644	351	1534
01/11/2011	5128	3557	952.2	4157	214082	1438	1534
01/12/2011	5758	3529	945.4	4158	217554	3472	1534
01/01/2012	5762	3500	1020	4514	220461	2907	1534
01/02/2012	5072	3470	817.1	3647	223774	3313	1534
01/03/2012	5038	3442	653.3	2934	226483	2709	1534
01/04/2012	3893	3412	341.4	1540	228492	2009	1534
01/05/2012	3250	3382	148.2	671.1	229855	1363	1534
01/06/2012	2585	3351	68.25	309.7	230805	950	1534
01/07/2012	2770	3320	49.47	225	231914	1109	1534
01/08/2012	3587	3288	63.89	291.2	232735	821	1534
01/09/2012	4648	3256	223.1	1017	232776	41	1534
01/10/2012	5603	3224	597.3	2721	232611	-165	1534

Result:	Evaporation	Ground water	Runoff	Precipitation	Volume of water in pit	Change in Storage	Surface Elevation
Unit:	**m^3/mon**	**m^3/mon**	**m^3/mon**	**m^3/mon**	**m^3**	**m^3**	**mamsl**
01/11/2012	5363	3191	952.2	4347	233549	938	1534
01/12/2012	6020	3159	945.4	4347	236613	3064	1534
01/01/2013	6018	3125	1020	4714	239067	2454	1535
01/02/2013	5290	3091	846.3	3939	241939	2872	1535
01/03/2013	5249	3059	653.3	3057	244301	2362	1535
01/04/2013	4050	3024	341.4	1603	245829	1528	1535
01/05/2013	3378	2990	148.2	697.5	246716	887	1535
01/06/2013	2684	2955	68.25	321.4	247163	447	1535
01/07/2013	2872	2920	49.47	233.3	247796	633	1535
01/08/2013	3715	2883	63.89	301.5	248114	318	1535
01/09/2013	4808	2848	223.1	1052	247623	-491	1535
01/10/2013	5789	2848	597.3	2812	246950	-673	1535
01/11/2013	5535	2848	952.2	4487	247425	475	1535
01/12/2013	6207	2848	945.4	4482	250134	2709	1535
01/01/2014	6198	2848	1020	4856	252237	2103	1535
01/02/2014	5444	2848	846.3	4054	254805	2568	1535
01/03/2014	5398	2848	653.3	3144	256921	2116	1535
01/04/2014	4163	2848	341.4	1647	258188	1267	1535
01/05/2014	3470	2848	148.2	716.5	258850	662	1535
01/06/2014	2756	2848	68.25	330.1	259097	247	1535
01/07/2014	2949	2848	49.47	239.6	259578	481	1535
01/08/2014	3813	2862	63.89	309.5	259777	199	1535
01/09/2014	4933	2876	223.1	1079	259198	-579	1535
01/10/2014	5938	2890	597.3	2884	258464	-734	1535
01/11/2014	5677	2904	952.2	4602	258910	446	1535
01/12/2014	6374	2917	945.4	4602	261654	2744	1535
01/01/2015	6370	2931	1020	4991	263786	2132	1535
01/02/2015	5601	2945	846.3	4171	266407	2621	1535
01/03/2015	5558	2957	653.3	3237	268581	2174	1535
01/04/2015	4289	2971	341.4	1697	269897	1316	1535
01/05/2015	3577	2979	148.2	738.5	270611	714	1535
01/06/2015	2840	2842	68.25	340.2	270838	227	1535
01/07/2015	3038	2704	49.47	246.8	271176	338	1535
01/08/2015	3926	2557	63.89	318.6	271066	-110	1535
01/09/2015	5072	2410	223.1	1109	269991	-1075	1535
01/10/2015	6096	2443	597.3	2961	268702	-1289	1535
01/11/2015	5821	2478	952.2	4719	268623	-79	1535
01/12/2015	6527	2511	945.4	4713	270931	2308	1535
01/01/2016	6515	2545	1020	5104	272617	1686	1535
01/02/2016	5722	2579	817.1	4114	274823	2206	1535
01/03/2016	5671	2610	653.3	3303	276538	1715	1535
01/04/2016	4371	2644	341.4	1730	277464	926	1535

Result:	Evaporation	Ground water	Runoff	Precipitation	Volume of water in pit	Change in Storage	Surface Elevation
Unit:	**m^3/mon**	**m^3/mon**	**m^3/mon**	**m^3/mon**	**m^3**	**m^3**	**mamsl**
01/05/2016	3642	2676	148.2	751.9	277816	352	1535
01/06/2016	2890	2708	68.25	346.1	277765	-51	1535
01/07/2016	3091	2740	49.47	251.1	278009	244	1535
01/08/2016	3994	2772	63.89	324.2	277974	-35	1535
01/09/2016	5164	2804	223.1	1129	277144	-830	1535
01/10/2016	6212	2834	597.3	3017	276170	-974	1535
01/11/2016	5937	2866	952.2	4813	276425	255	1535
01/12/2016	6662	2896	945.4	4810	279091	2666	1535
01/01/2017	6655	2927	1020	5214	281128	2037	1535
01/02/2017	5849	2957	846.3	4355	283690	2562	1536
01/03/2017	5802	2984	653.3	3379	285824	2134	1536
01/04/2017	4476	2984	341.4	1771	287057	1233	1536
01/05/2017	3731	2984	148.2	770.4	287666	609	1536
01/06/2017	2962	2984	68.25	354.8	287840	174	1536
01/07/2017	3169	2984	49.47	257.5	288276	436	1536
01/08/2017	4098	2984	63.89	332.6	288399	123	1536
01/09/2017	5300	2984	223.1	1159	287672	-727	1536
01/10/2017	6376	2984	597.3	3097	286756	-916	1536
01/11/2017	6094	2984	952.2	4941	287062	306	1536
01/12/2017	6839	2984	945.4	4938	289800	2738	1536
01/01/2018	6831	2984	1020	5352	291861	2061	1536
01/02/2018	6003	2984	846.3	4470	294427	2566	1536
01/03/2018	5954	2984	653.3	3468	296537	2110	1536
01/04/2018	4592	2984	341.4	1817	297705	1168	1536
01/05/2018	3827	2984	148.2	790.1	298246	541	1536
01/06/2018	3038	2984	68.25	363.9	298342	96	1536
01/07/2018	3250	2984	49.47	264	298714	372	1536
01/08/2018	4201	2984	63.89	341	298762	48	1536
01/09/2018	5432	2984	223.1	1188	297939	-823	1536
01/10/2018	6534	2984	597.3	3174	296921	-1018	1536
01/11/2018	6244	2984	952.2	5062	297145	224	1536
01/12/2018	7005	2984	945.4	5058	299855	2710	1536
31/12/2018	7037	2984	945.4	5081	301805	1950	1536

Appendix F: Rooikop Water Balance

Result:	Evaporation	Runoff from Backfill	Natural runoff	Ground water Inflow	Rainfall	Volume of Water in Pit	Change in Volume	Surface Elevation
Unit:	m^3/yr	m^3/yr	m^3/yr	m^3/yr	m^3/yr	m^3	m^3	mamsl
31/12/2006	0	0	0	0	0	0	0	1377
01/01/2007	203.2	4796	4727	8950	156.9	50.45	50.45	1377
01/01/2008	6378	3193	3147	5958	3370	9309	9258.55	1380
01/01/2009	7715	2538	2501	4735	3156	10451	1142	1380
01/01/2010	8670	3114	3069	5811	4798	24393	13942	1382
01/01/2011	9911	3385	3336	6315	6063	36775	12382	1383
01/01/2012	10983	3547	3496	6619	7057	48697	11922	1384
01/01/2013	11925	3654	3601	6818	7877	60189	11492	1384
01/01/2014	12777	3731	3678	6963	8597	71381	11192	1385
01/01/2015	13564	3790	3735	7071	9244	82239	10858	1386
01/01/2016	14301	3835	3780	7156	9837	92786	10547	1386
01/01/2017	15016	3870	3815	7221	10397	102918	10132	1387
01/01/2018	15713	3900	3844	7277	10941	112774	9856	1387
31/12/2018	16411	3924	3867	7321	11475	122113	9339	1388

Appendix G: Kleinfontein a Water Balance

Result:	Evaporation	Groundwater	Rainfall	Volume of water in pit	Change in Storage	Surface Elevation
Unit:	m^3/yr	m^3/yr	m^3/yr	m^3	m3	mamsl
1992	0	0	0	0		1537
1993	4877	8831	2145	6111	6111	1539
1994	8070	9088	3863	9770	3659	1540
1995	9752	9147	4252	10942	1172	1540
1996	10757	9309	5332	15534	4592	1541
1997	12290	9565	7042	21593	6059	1541
1998	13465	9762	8355	27924	6331	1542
1999	14397	9785	8506	27259	-665	1541
2000	15080	9840	8871	29044	1785	1542
2001	15792	9925	9444	32199	3155	1542
2002	16322	9904	9300	28819	-3380	1542
2003	16678	9882	9151	25904	-2915	1541
2004	16941	9871	9084	24171	-1733	1541
2005	17115	9868	9063	23617	-554	1541
2006	17312	9894	9237	25469	1852	1541
2007	17429	9871	9079	22810	-2659	1541
2008	17548	9901	9283	26176	3366	1541
2009	17683	9898	9264	25150	-1026	1541
2010	17792	9903	9292	25259	109	1541
2011	17895	9904	9299	24849	-410	1541
2012	17983	9904	9303	24487	-362	1541
2013	18058	9904	9303	24133	-354	1541
2014	18122	9904	9302	23856	-277	1541
2015	18177	9904	9300	23610	-246	1541
2016	18225	9903	9296	23394	-216	1541
2017	18267	9903	9291	23169	-225	1541
2018	18303	9902	9286	23005	-164	1541

Appendix H: Kleinfontein b Water Balance

Result:	Evaporation	Groundwater	Rainfall	Volume of water in pit	Change in Storage	Surface Elevation
Unit:	m^3/yr	m^3/yr	m^3/yr	m^3	m^3	mamsl
1992	0	0	0	0		1539
1993	6919	8957	2987	5035	5035	1540
1994	9719	9204	4633	8241	3206	1540
1995	11101	9238	4862	8999	758	1540
1996	11956	9398	5929	13484	4485	1541
1997	13547	9672	7757	19424	5940	1541
1998	14775	9883	9160	25613	6189	1542
1999	15757	9905	9305	24166	-1447	1542
2000	16438	9959	9667	25504	1338	1542
2001	17217	10053	10292	28163	2659	1542
2002	17751	10027	10118	23937	-4226	1542
2003	18054	9997	9924	20538	-3399	1541
2004	18247	9980	9811	18536	-2002	1541
2005	18333	9970	9740	17899	-637	1541
2006	18475	9991	9883	19594	1695	1541
2007	18515	9961	9681	16902	-2692	1541
2008	18576	9987	9855	20257	3355	1541
2009	18670	9980	9811	19072	-1185	1541
2010	18734	9981	9814	19101	29	1541
2011	18799	9979	9799	18593	-508	1541
2012	18848	9976	9781	18169	-424	1541
2013	18885	9973	9759	17781	-388	1541
2014	18913	9970	9738	17491	-290	1541
2015	18933	9966	9716	17249	-242	1541
2016	18948	9963	9695	17046	-203	1541
2017	18958	9960	9672	16845	-201	1541
2018	18965	9957	9651	16710	-135	1541

Appendix I: Mafutha Water Quality

	Mafutha				
Date	Jan-17	Jan-17	Jan-17	Jan-17	Jan-17
Sample ID	M059-4	M059-5	M059-6	M059-7	M059-8
Sampling depth (m)	5	15	20	45	60
Parameter (mg/l)					
pH	8.45	8.37	8.25	7.61	8.01
EC (ms/m)	173	173	172	171	172
TDS	1126.1	1105.7	1104.0	1100.0	1099.7
Total Hardness as CaCO3	230.0	223.4	231.2	232.4	232.6
Turbidity (NTU)	-	-	-	-	-
TSS	-	-	-	-	-
Ca	26.1	25.5	28.9	29.6	29.9
Mg	40.2	38.9	38.8	38.6	38.5
Na	291.1	274.7	266.0	266.9	267.9
K	15.2	15.0	14.8	14.9	14.9
HCO3	340.94	344.84	345.48	349.99	347.95
MAlk	287.0	289.0	288.0	288.0	288.0
Cl	346.7	342.1	339.5	336.5	340.3
NO2(N)	<0.1	<0.1	<0.1	<0.1	<0.1
NO3(N)	3.7	3.3	3.7	3.8	3.6
SO4	102.6	104.8	109.8	107.2	103.8
F	1.4	1.5	1.7	1.7	1.3
Al	<0.010	<0.010	<0.010	<0.010	<0.010
As	0.012	0.017	<0.010	<0.010	<0.010
B	0.312	0.311	0.299	0.296	0.297
Ba	0.079	0.079	0.076	0.075	0.074
Br	1.1297	1.0877	1.421	0.9716	0.8355
Cd	<0.010	<0.010	<0.010	<0.010	<0.010
Co	<0.010	<0.010	<0.010	<0.010	<0.010
Cr	<0.010	<0.010	<0.010	<0.010	<0.010
Cu	<0.010	<0.010	<0.010	<0.010	<0.010
Fe	0.04	0.021	0.021	0.017	0.018
Li	-	-	-	-	-
Mn	<0.010	<0.010	<0.010	<0.010	<0.010
Mo	<0.010	<0.010	<0.010	<0.010	<0.010
Ni	0.013	0.014	0.012	0.013	0.014
P	-	-	-	-	-
Pb	<0.010	<0.010	<0.010	<0.010	<0.010
S	-	-	-	-	-
Sb	<0.010	<0.010	<0.010	<0.010	<0.010
Se	<0.010	<0.010	<0.010	<0.010	<0.010
Si	21.376	21.246	20.554	21.597	21.562
Sr	-	-	-	-	-
U	<0.010	<0.010	<0.010	<0.010	<0.010
V	<0.010	<0.010	<0.010	<0.010	<0.010
Zn	0.011	<0.010	<0.010	<0.010	<0.010
NH3-N	-	-	-	-	-
PO4	<1	<1	<1	<1	<1
TP	-	-	-	-	-
ΣAnion (meq)	15.2	15.2	15.2	15.1	15.1
ΣCation (meq)	17.7	16.8	16.6	16.7	16.7
Anion-Cation Balance (%)	7.4	5.3	4.4	5.0	5.2

	Mafutha									
Date	Aug-17	Aug-17	Aug-17	Aug-17	Aug-17	Aug-17	Aug-17	Aug-17	Aug-17	Aug-17
Sample ID	M684.001	M684.002	M684.003	M684.004	M684.005	M684.006	M684.007	M684.008	M684.009	M684.10
Sampling depth (m)	1	5	10	15	20	30	40	50	60	70
Parameter (mg/l)										
pH	8.5	8.5	8.6	8.5	8.5	8.5	8.5	8.5	8.5	8.5
EC mS/m	187	187	187	188	188	188	187	187	188	188
TDS	1000	1100	1000	1000	1000	990	960	970	980	1000
Turbidity (NTU)	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	0.5	<0.4
TSS	<21	<21	<21	<21	<21	<21	<21	<21	<21	<21
Total hardness as CaCO3	188.5	186.0	186.0	190.1	186.0	190.1	186.0	186.0	186.0	186.0
Ca	26	25	25	25	25	25	25	25	25	25
Mg	30	30	30	31	30	31	30	30	30	30
Na	365	363	351	336	334	334	319	301	342	340
K	23	23	23	23	23	23	23	23	23	23
Bicarbonate Alk as HCO3	400	397	400	397	394	391	397	400	400	400
Total Alk as CaCO3	328	326	328	326	323	321	326	328	328	328
Cl	318	301	308	301	305	302	322	303	308	319
NO3	9.7	9.8	9.6	9.7	9.6	9.6	9.5	9.4	9.5	9.7
NO3-N	2.19	2.21	2.17	2.19	2.17	2.17	2.15	2.12	2.15	2.19
SO4	93	94	93	93	93	93	93	90	92	94
Al	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
As	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
B	0.27	0.27	0.26	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Ba	0.072	0.072	0.071	0.071	0.071	0.073	0.071	0.072	0.071	0.071
Cd	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Co	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Cr	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Fe	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Li	0.046	0.046	0.045	0.045	0.045	0.047	0.046	0.046	0.045	0.045
Mn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mo	0.012	0.009	0.01	0.008	0.008	0.008	0.008	0.008	0.008	0.007
Ni	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
P	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
S	35	34	34	34	34	34	34	35	34	33
Sb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Se	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Si	23	23	22	23	22	23	23	23	23	22
Sr	0.33	0.33	0.33	0.33	0.33	0.33	0.32	0.33	0.32	0.32
U	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
V	0.01	0.01	0.01	0.01	0.01	0.01	0.009	0.01	0.01	0.01
W	0.41	0.2	0.17	0.12	0.09	0.09	0.07	0.06	0.06	0.05
Zn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NH3	0.051	0.041	0.034	3.2	0.26	0.057	0.046	0.095	0.04	0.064
NH3-N	0.04	0.03	0.03	2.6	0.21	0.05	0.04	0.08	0.03	0.05
TP	<0.25	<0.25	<0.25	0.32	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
PO4-P	<0.080	<0.080	<0.080	0.11	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080
ΣAnion (meq)	17.6	17.1	17.3	17.1	17.1	17	17.7	17.1	17.3	17.7
ΣCation (meq)	20.3	20.1	19.6	19	18.8	18.9	18.2	17.5	19.2	19.1
Anion-Cation Balance (%)	6.94	8.17	6.1	5.23	4.73	5.26	1.47	0.99	5.2	3.88

	Mafutha								
Date	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17
Sample ID	M0979.001	M0979.002	M0979.003	M0979.004	M0979.005	M0979.006	M0979.007	M0979.008	M0979.009
Sampling depth (m)	1	5	10	15	20	30	45	60	69
Parameter (mg/l)									
pH	8.4	8.6	8.4	8.4	8.2	8.2	8.1	8.1	8.1
EC (mS/m)	190	190	187	186	183	187	188	186	186
TDS	1100	1100	1100	1000	1100	1000	1100	1000	1000
Total hardness as CaCO3	166	170	168	169	167	165	168	164	166
Turbidity (NTU)	<0.4	0.4	0.6	0.6	0.5	<0.4	<0.4	<0.4	60
TSS	<21	<21	<21	<21	<21	<21	<21	<21	94
Ca	22	22	23	23	23	23	23	23	23
Mg	27	28	27	27	27	26	27	26	26
Na	286	288	295	292	289	290	295	288	291
K	20	20	21	20	19	20	19	19	19
Bicarbonate Alk as HCO3	311	306	275	331	302	357	375	372	375
Total Alk as CaCO3	335	331	325	329	323	318	323	325	323
Cl	332	316	331	314	315	312	314	316	319
NO2	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
NO3	11	11	11	8.2	10	10	9.8	9.6	9.5
NO3-N	2.48	2.48	2.48	1.85	2.26	2.26	2.21	2.17	2.15
SO4	108	107	107	104	107	103	108	106	104
Al	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	0.11
As	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
B	0.099	0.099	0.1	0.098	0.1	0.1	0.11	0.11	0.12
Ba	0.15	0.15	0.15	0.15	0.14	0.15	0.14	0.15	0.14
Cd	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Co	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
Cr	0.046	0.047	0.046	0.045	0.047	0.047	0.046	0.048	0.047
Cu	<0.0009	<0.0009	<0.0009	<0.0009	<0.0009	<0.0009	<0.0009	<0.0009	<0.0009
Fe	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.08
Li	0.015	0.015	0.015	0.015	0.014	0.015	0.015	0.015	0.017
Mn	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.002	0.003	0.004
Mo	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Ni	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.004	0.004
P	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Pb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
S	38	39	40	39	38	37	38	39	39
Sb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Se	0.014	0.015	0.014	0.014	0.014	0.012	0.014	0.013	0.014
Si	23	24	24	22	23	22	23	23	24
Sr	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Ti	0.005	0.005	0.005	0.004	0.005	0.005	0.005	0.005	0.012
U	0.012	0.012	0.011	0.011	0.011	0.011	0.011	0.011	0.011
V	0.018	0.018	0.018	0.017	0.017	0.017	0.017	0.017	0.018
Zn	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
NH3	0.016	0.11	<0.012	0.032	0.029	0.55	0.11	<0.012	0.012
NH3-N	0.01	0.09	0.01	0.03	0.02	0.45	0.09	0.01	0.01
TP	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
PO4-P	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080
ΣAnion (meq)	18.5	17.9	18.2	17.7	17.7	17.5	17.7	17.8	17.8
ΣCation (meq)	16.3	16.4	16.7	16.6	16.4	16.4	16.7	16.3	16.5
Anion-Cation Balance (%)	-6.4	-4.32	-4.46	-3.38	-3.89	-3.07	-2.91	-4.38	-3.74

Mafutha physicochemical and chlorophyll-a data collected during phytoplankton and bacterial sampling.

Mafutha Pit lake field measurements for bacteria and phytoplankton samples. (Grey = bacteria; white = phytoplankton)												
Physical Parameter	**Date**	**0.1**	**0.5**	**1**	**3**	**5**	**7**	**8**	**15**	**20**	**24**	**45**
pH	Jan-17	8.54	8.54	8.55	8.56	8.58	8.6	8.6	8.63	8.64	8.59	8.31
	Sep-17	8.5	8.5	8.5	8.47	8.47	8.46	8.46	8.42	8.39	8.37	8.34
	Nov-17			8.4	8.6	8.4	8.4	8.2	8.2	8.1	8.1	8.1
Temperature (°C)	Jan-17	27.73	27.72	27.5	27.3	27.25	27.21	27.2	25.37	20.52	19.06	18.11
	Sep-17	19.14	19.14	19.13	19.05	19.02	18.95	18.89	18.63	18.53	18.50	18.48
	Nov-17	24.99	24.98	24.97	24.8	24.75	24.71	24.67	22.19	19.82	19.12	18.61
EC (mS/m)	Jan-17	177.4	177.2	177	176.9	176.9	176.8	176.7	176.7	172.2	172.4	172.6
	Sep-17	174.82	174.82	174.3	174.2	174.16	174.13	174.08	173.94	173.96	173.96	174
	Nov-17	172.5	172.5	172.4	172.2	172.2	172.2	172.1	167.9	167.9	168	168.2
ORP (mV)	Jan-17	307.1	305.4	303.2	301.3	301.1	301.7	301.9	304.7	310.4	313.6	305.7
	Sep-17	243.2	243.2	239.3	235.8	233	231.5	230.9	228.9	227.9	227.9	226.6
	Nov-17	98.6	98.6	98.6	98.5	98.3	98.3	98.4	102.1	103.3	103.7	107.8
DO (mg/l)	Jan-17	-	-	-	-	-	-	-	-	-	-	-
	Sep-17	7.81	7.81	7.81	7.8	7.78	7.78	7.78	7.6	7.28	7.18	6.59
	Nov-17	8.19	8.19	8.1	8.47	8.56	8.56	8.67	13.81	10.39	7.91	3.02
Chlorophyll-a (ug/l)	Jan-17	-	-	2.8	-	5.73	<1.00	-	-	3.15	-	-
	Sep-17	8.31	2.87	-	6.02	-	10.03	-	2.87	11.75	-	-
	Nov-17	-	<1.00	5.16	5.45	18.63	-	-	5.45	15.48	6.59	-

Phytoplankton collected for Mafutha pitlake during January sampling.

27 January 2017 Mafutha Analyses:								
SAMPLE --->	**1 m**		**5 m**		**7 m**		**20 m**	
GENERA:	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%
1. CYANOPHYTA	*74*	3	*148*	8	*74*	2	*148*	7
Anabaena (F)	74	3	74	4	74	2	74	4
Oscillatoria (F)		0	74	4		0	74	4
2. BACILLARIOPHYTA	*148*	5	*148*	8	*222*	7	*148*	7
Achnanthes		0		0	74	2		0
Cymbella		0	74	4		0		0
Nitzschia		0		0	74	2		0
Pennate diatoms (other)	74	3	74	4	74	2	74	4
Centric diatoms (other)	74	3		0		0	74	4
3. CHLOROPHYTA	*2,564*	87	*1,321*	72	*2,565*	83	*1,686*	82
Ankistrodesmus	1,611	55	952	52	1,977	64	1,245	61
Chlamydomonas	74	3	74	4	74	2	74	4
Chlorella		0	74	4	74	2	74	4
Monoraphidium	879	30	147	8	440	14	293	14
Oocystis (C)		0	74	4		0		0
4. CRYPTOPHYTA	*0*	0	*0*	0	*0*	0	*0*	0
5. DINOPHYTA	*74*	3	*147*	8	*74*	2	*74*	4
Peridinium	74	3	147	8	74	2	74	4
6. EUGLENOPHYTA	*74*	3	*74*	4	*147*	5	*0*	0
Trachelomonas	74	3	74	4	147	5		0
7. CHRYSOPHYTA	*0*	0	*0*	0	*0*	0	*0*	0
Total:	**2,934**	100	**1,838**	100	**3,082**	100	**2,056**	100
Chlorophyll-*a* (µg/l)	2.58		5.73		<1.00		3.15	

Phytoplankton collected for Mafutha during the September sampling programme.

01 September 2017 Mafutha Phytoplankton and Chlorophyll-a Analyses:														
SAMPLE --->	**MF 0.1**		**MF 0.5**		**MF3**		**MF7**		**MF10**		**MF15**		**MF20**	
GENERA:	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%
1. CYANOPHYTA	*220*	8	*74*	6	*147*	20	*74*	7	*74*	9	*147*	14	*74*	14
Oscillatoria (F)	220	8	74	6	147	20	74	7	74	9	147	14	74	14
2. BACILLARIOPHYTA	*222*	8	*146*	12	*0*	0	*222*	20	*74*	9	*148*	14	*74*	14
Navicula	74	3		0		0		0		0		0		0
Pennate diatoms (other)	74	3	74	6		0	74	7		0	74	7		0
Centric diatoms (other)	74	3	74	6		0	74	7	74	9	74	7	74	14
Synedra		0		0		0	74	7		0		0		0
3. CHLOROPHYTA	***1,983***	**75**	***735***	**59**	***516***	**70**	***663***	**60**	***518***	**64**	***664***	**64**	***369***	**71**
Ankistrodesmus	74	3	74	6	74	10	220	20	74	9	74	7		0
Chlamydomonas	74	3		0		0	74	7		0	74	7		0
Chlorella	367	14	147	12	147	20	147	13	74	9	220	21	147	28
Coelastrum (C)	74	3	147	12	147	20	74	7	74	9	74	7	74	14
Cosmarium		0	220	18	74	10	74	7		0		0		0
Mesotaenium	1,172	44	147	12		0		0	74	9	74	7	74	14
Microspora	74	3		0		0		0	74	9	74	7		0
Monoraphidium	74	3		0		0		0		0		0		0
Oocystis (C)	74	3		0	74	10		0	74	9	74	7	74	14
Tetraedron		0		0		0	74	7	74	9		0		0
4. CRYPTOPHYTA	*0*	0	*147*	12	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0
Cryptomonas		0	147	12		0		0		0		0		0
5. DINOPHYTA	*220*	8	*147*	12	*74*	10	*74*	7	*74*	9	*0*	0	*0*	0
Peridinium	220	8	147	12	74	10	74	7	74	9		0		0
6. EUGLENOPHYTA	*0*	0	*0*	0	*0*	0	*74*	7	*74*	9	*74*	7	*0*	0
Trachelomonas		0		0		0	74	7	74	9	74	7		0
7. CHRYSOPHYTA	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0
Total:	**2,645**	100	**1,251**	100	**737**	100	**1,107**	100	**814**	100	**1,033**	100	**517**	100
Chlorophyll-*a* (µg/l)	8.31		2.87		6.02		10.03		<1.00		2.87		11.75	

Genera of phytoplankton analysed for Mafutha pitlake with associated [chlorophyll-a], for November 2017.

22 November 2017 Analyses:														
SAMPLE --->	**MFN/0.5**		**MFN/1**		**MFN/3**		**MFN/5**		**MFN/15.5**		**MFN/20**		**MFN/24**	
GENERA:	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%
1. CYANOPHYTA	***74***	6	***0***	0	***74***	8	***147***	14	***0***	0	***74***	7	***74***	7
Cylindrospermum (F)	74	6		0	74	8	147	14		0		0		0
Oscillatoria (F)		0		0		0		0		0	74	7	74	7
2. BACILLARIOPHYTA	***441***	37	***222***	20	***295***	33	***221***	21	***147***	20	***295***	27	***74***	7
Cymbella	74	6		0	74	8		0		0		0		0
Nitzschia	74	6	74	7		0		0		0	74	7		0
Pennate diatoms (other)	293	25	74	7	147	17	74	7	147	20	147	13	74	7
Centric diatoms (other)		0	74	7	74	8	147	14		0	74	7		0
3. CHLOROPHYTA	***588***	50	***736***	67	***296***	33	***589***	57	***515***	70	***662***	60	***881***	80
Ankistrodesmus	74	6	74	7	74	8	74	7	74	10	74	7	74	7
Carteria		0		0		0		0		0		0	74	7
Chlamydomonas	74	6	74	7	74	8	74	7	74	10	147	13		0
Chlorella	293	25	147	13	74	8	293	28	220	30	367	33	293	27
Chlorococcum		0	74	7		0		0		0		0		0
Chodatella	147	12	293	27	74	8	74	7	147	20	74	7	293	27
Cladophora (F)		0		0		0		0		0		0		0
Closterium		0	74	7		0	74	7		0		0		0
Tetraedron		0		0		0		0		0		0	147	13
4. CRYPTOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0
5. DINOPHYTA	***74***	6	***147***	13	***220***	25	***74***	7	***74***	10	***74***	7	***74***	7
Peridinium	74	6	147	13	220	25	74	7	74	10	74	7	74	7
6. EUGLENOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0
7. CHRYSOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0
Total:	**1,177**	100	**1,105**	100	**885**	100	**1,031**	100	**736**	100	**1,105**	100	**1,103**	100
Chlorophyll-*a* (µg/l)	<1.00		5.16		5.45		18.63		5.45		15.48		6.59	

Appendix J: Kriel Water Quality

	R44N				
Date	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17
Sample ID	44N287-1	44N287-2	44N287-3	44N287-4	44N287-5
Sampling depth (m)	1	2	3	3.5	5
Parameter (mg/l)					
pH	8.30	8.34	8.33	8.44	7.67
EC (mS/m)	426	429	429	430	476
TDS	4316	4327	4266	4291	4784
Total Hardness as CaCO3	2467	2469	2430	2457	2751
Turbidity (NTU)	-	-	-	-	-
TSS	-	-	-	-	-
Ca	223.3	224.2	221.8	224.9	247.5
Mg	165	166	166	167	173
Na	450.3	450.5	443.7	450.4	484.4
K	25.9	26.2	25.6	25.6	29.7
Bicarbonate Alk as HCO3	130	130	131	122	277
Total Alk as CaCO3	109	109	110	103	228
Cl	47.4	49.3	49.0	50.5	56.8
NO2(N)	<0.2	<0.2	<0.2	<0.2	<0.2
NO3(N)	<1	<1	<1	<1	<1
SO4	3003	3011	2965	2983	3225
F	<0.2	0.20	<0.2	<0.2	0.23
Al	<0.020	<0.020	<0.020	<0.020	<0.020
As	<0.020	<0.020	<0.020	<0.020	<0.020
B	0.057	0.057	0.052	0.046	0.130
Ba	0.032	0.032	0.032	0.033	0.058
Br	<0.8	<0.8	1.1131	<0.8	<0.8
Cd	<0.003	<0.003	<0.003	<0.003	<0.003
Co	<0.020	<0.020	<0.020	<0.020	<0.020
Cr	<0.020	<0.020	<0.020	<0.020	<0.020
Cu	0.028	0.034	0.026	0.028	0.027
Fe	<0.020	<0.020	<0.020	<0.020	<0.020
Li	0.055	0.058	0.058	0.057	0.063
Mn	0.073	0.156	0.171	0.447	5.966
Mo	<0.020	<0.020	<0.020	<0.020	<0.020
Ni	<0.020	<0.020	<0.020	<0.020	<0.020
P	<0.03	0.03	0.03	0.03	0.67
Pb	<0.020	<0.020	<0.020	<0.020	<0.020
S	804	804	809	814	859
Sb	<0.020	<0.020	<0.020	<0.020	<0.020
Se	<0.020	<0.020	<0.020	<0.020	<0.020
Si	1.247	1.379	1.340	1.383	5.893
Sr	1.1	1.1	1.1	1.1	1.3
U	<0.015	<0.015	<0.015	<0.015	<0.015
V	<0.010	<0.010	<0.010	<0.010	<0.010
Zn	<0.020	0.021	<0.020	<0.020	0.021
NH3-N	-	-	-	-	-
PO4-P	-	-	-	-	-
TP	<2	<2	<2	<2	<2
ΣAnion (meq)	65.0	65.2	64.3	64.6	71.1
ΣCation (meq)	70.2	70.3	69.2	70.0	77.5
Anion-Cation Balance (%)	3.84	3.72	3.67	4.00	4.33

	R44N				
Date	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17
Sample ID	44N0714.008	4N0714.00	4N0714.01	4N0714.01	44N0714.012
Sampling Depth (m)	1	2	3	4	5
Parameter (mg/l)					
pH	8.3	8.3	8.2	8.4	8.5
EC (mS/m)	512	511	512	512	518
TDS	4700	4800	4800	4600	4900
Total hardness as CaCO3	2070	2070	2060	2070	2080
Turbidity (NTU)	1.3	1.2	1.3	0.9	1.9
TSS	<21	<21	<21	<21	40
Ca	190	189	190	187	187
Mg	386	388	384	389	390
Na	513	486	693	506	504
K	36	37	36	36	36
Bicarbonate Alk as HCO3	171	186	189	168	156
Total Alk as CaCO3	165	163	165	153	153
Cl	45	46	46	46	47
NO3	0.4	0.4	0.4	0.4	0.4
NO3-N	0.09	0.09	0.09	0.09	0.09
SO4	3240	3280	3180	3240	3250
Al	<0.02	<0.02	<0.02	<0.02	<0.02
As	<0.01	<0.01	<0.01	<0.01	<0.01
B	0.045	0.038	0.035	0.035	0.029
Ba	0.019	0.019	0.018	0.017	0.016
Cd	<0.001	<0.001	<0.001	<0.001	<0.001
Co	<0.005	<0.005	<0.005	<0.005	<0.005
Cr	<0.002	<0.002	<0.002	<0.002	<0.002
Cu	<0.02	<0.02	<0.02	<0.02	<0.02
Fe	<0.05	<0.05	<0.05	<0.05	<0.05
Li	0.072	0.073	0.072	0.072	0.072
Mn	<0.01	0.02	0.04	0.03	0.03
Mo	<0.005	<0.005	<0.005	<0.005	<0.005
Ni	<0.005	<0.005	<0.005	<0.005	<0.005
P	<0.03	<0.03	<0.03	<0.03	<0.03
Pb	<0.01	<0.01	<0.01	<0.01	<0.01
S	1050	987	1390	1040	1030
Sb	<0.01	<0.01	<0.01	<0.01	<0.01
Se	<0.01	<0.01	<0.01	<0.01	<0.01
Si	<1.0	<1.0	<1.0	<1.0	1.1
Sr	1.1	1.1	1.1	1.1	1.1
U	<0.01	<0.01	<0.01	<0.01	<0.01
V	<0.001	<0.001	<0.001	<0.001	<0.001
W	<0.01	<0.01	<0.01	<0.01	<0.01
Zn	<0.01	<0.01	<0.01	<0.01	<0.01
NH3	0.013	0.08	0.063	0.021	<0.012
NH3-N	0.01	0.07	0.05	0.02	<0.01
TP	<0.25	<0.25	<0.25	<0.25	<0.25
PO4-P	<0.080	<0.080	<0.080	<0.080	<0.080
ΣAnion (meq)	72.1	72.9	70.8	71.9	72
ΣCation (meq)	64.5	63.5	72.1	64.3	64.3
Anion-Cation Balance (%)	-5.54	-6.92	0.95	-5.58	-5.66

	R44N					
Date	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17
Sample ID	44-1004.021	44-1004.022	X17-1004.0	X17-1004.0	X17-1004.0	X17-1004.0
Sampling depth (m)	1	2	3	3.5	4.5	5
Parameter (mg/l)						
pH	7.71	7.75	7.53	7.44	7.41	7.32
EC (mS/m)	545	549	541	552	550	556
TDS	5300	5200	5500	5500	5300	5300
Total hardness as CaCO3	1410	1460	1550	1520	1480	1540
Turbidity (NTU)	4.4	3.6	20	11	8	7.1
TSS	28	26	40	42	26	34
Ca	298	320	359	337	322	342
Mg	162	160	159	165	165	166
Na	696	620	763	721	695	740
K	39	40	40	40	40	39
Bicarbonate Alk as HCO3	230	230	248	251	233	260
Total Alk as CaCO3	208	203	203	206	206	213
Cl	55	53	57	57	56	55
NO2	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
NO3	0.5	0.5	0.5	0.5	0.5	0.6
NO3-N	0.11295	0.11295	0.11295	0.11295	0.11295	0.13554
SO4	3200	3050	3120	3350	3120	3340
Al	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
As	<0.0005	<0.0005	<0.0005	<0.0005	0.012	<0.0005
B	0.072	0.063	0.075	0.087	0.04	0.05
Ba	0.029	0.03	0.028	0.029	0.038	0.037
Cd	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Co	0.001	0.001	0.001	0.001	0.001	0.001
Cr	0.027	0.028	0.026	0.024	0.024	0.026
Cu	0.005	0.005	0.005	0.005	0.004	0.005
Fe	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Li	0.069	0.062	0.077	0.096	0.06	0.067
Mn	0.083	0.013	0.015	0.009	0.91	1.4
Mo	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ni	0.008	0.009	0.007	0.007	0.008	0.009
P	0.04	<0.03	0.05	0.06	0.14	0.19
Pb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
S	1160	1260	1340	1470	1340	1370
Sb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Se	0.007	0.007	0.006	0.005	0.006	0.007
Si	<1.0	<1.0	1.5	1.8	2.5	2.9
Sr	1.5	1.5	1.5	1.6	1.5	1.6
Ti	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
U	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
V	0.007	0.015	0.008	0.009	0.041	0.02
Zn	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
NH3	0.34	0.33	0.38	0.4	0.76	0.96
NH3-N	0.28	0.28	0.31	0.33	0.62	0.79
TP	<0.25	<0.25	<0.25	<0.25	0.45	0.64
PO4-P	<0.080	<0.080	<0.080	<0.080	0.15	0.21
ΣAnion (meq)	72.3	69	70.6	75.4	70.6	75.4
ΣCation (meq)	59.4	57.2	65.2	62.8	60.8	64
Anion-Cation Balance (%)	-9.75	-9.39	-3.92	-9.15	-7.39	-8.22

Kriel pitlake physicochemical variables collected for biological samples of Ramp 44 N

Kriel Ramp 44North pit lake field measurements for bacteria and phytoplankton samples (Grey = Bacteria; White = phytoplankton)								
Physical Parameter	**Date**	**0.1 m**	**0.5 m**	**1 m**	**2.5 m**	**3 m**	**3.5 m**	**5 m**
pH	Apr-17	8.99	8.99	8.99	9	9.17	9.19	7.45
	Sep-17	7.3	7.07	7.05	6.26	5.11	4.75	4.82
Temperature (°C)	Apr-17	19.92	19.87	19.80	19.62	19.51	19.37	19.76
	Sep-17	14.783	14.2305	14.151	13.405	12.856	12.073	11.758
EC (mS/m)	Apr-17	454.38	454.225	454.14	453.73	454.18	455.11	507.44
	Sep-17	467.14	467.6	468.06	466.76	467.03	470.72	472.79
ORP (mV)	Apr-17	77.5	77.15	75.8	70.8	68.7	53.8	-185.5
	Sep-17	203.2	199.35	199.2	197		194.8	193.6
DO (mg/l)	Apr-17	3.54	3.45	3.31	3.24	2.65	1.91	0.51
	Sep-17	7.3	7.07	7.05	6.26		4.75	4.82
Chlorophyll-a (µg/l)	Apr-17	-	30.45	27.94	-	17.91	-	194.17
	Sep-17	7.45	7.74	11.18	5.16	-	10.32	5.73

07 April 2017 Kriel Ramp 44N Analyses:								
SAMPLE --->	**R44/0.5**		**R44/1**		**R44/3**		**R44/5**	
GENERA:	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%
1. CYANOPHYTA	***74***	3	***0***	0	***0***	0	***3,698,713***	100
Aphanocapsa (C)		0		0		0	23,721	1
Aphanocapsa (sc)		0		0		0	3,672,356	99
Oscillatoria (F)	74	3		0		0	2,636	0
2. BACILLARIOPHYTA	***74***	3	***0***	0	***148***	6	***0***	0
Pennate diatoms (other)		0		0	74	3		0
Centric diatoms (other)		0		0	74	3		0
Synedra	74	3		0		0		0
3. CHLOROPHYTA	***74***	3	***74***	5	***221***	9	***0***	0
Chlamydomonas		0		0	74	3		0
Chlorella		0	74	5	147	6		0
Schroederia	74	3		0		0		0
4. CRYPTOPHYTA	***2,197***	91	***1,465***	95	***2,197***	86	***879***	0
Cryptomonas	2,197	91	1,465	95	2,197	86	879	0
5. DINOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0
6. EUGLENOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0
7. CHRYSOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0
Total:	**2,419**	100	**1,539**	100	**2,566**	100	**3,699,592**	100
Chlorophyll-*a* (µg/l)	30.45		27.94		17.91		194.17	
R44/surface	*Microspora* = dominant							
	Oscillatoria = very few							
	Diatoms = free floating and epiphytic							

Kriel pitlake phytoplankton samples of Ramp 44 N during September 2017.

06 September 2017 Kriel R44N Analyses:												
SAMPLE --->	**R44N/0.1**		**R44N/0.5**		**R44N/1**		**R44N/2.5**		**R44N/3.5**		**R44N/4.5**	
GENERA:	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%
1. CYANOPHYTA	***0***	0	***0***	0	***74***	14	***0***	0	***0***	0	***0***	0
Oscillatoria (F)		0		0	74	14		0		0		0
2. BACILLARIOPHYTA	***148***	20	***74***	14	***222***	43	***222***	18	***74***	6	***0***	0
Cyclotella		0		0	74	14	74	6		0		0
Entomoneis		0		0		0	74	6		0		0
Navicula	74	10	74	14	74	14	74	6		0		0
Pennate diatoms (other)	74	10		0	74	14		0	74	6		0
3. CHLOROPHYTA	***294***	40	***147***	29	***0***	0	***74***	6	***74***	6	***221***	19
Chlamydomonas	74	10		0		0		0		0		0
Chlorella	220	30	147	29		0	74	6	74	6	147	13
Cosmarium		0		0		0		0		0	74	6
4. CRYPTOPHYTA	***293***	40	***293***	57	***220***	43	***952***	76	***1,099***	88	***952***	81
Cryptomonas	293	40	293	57	220	43	952	76	1,099	88	952	81
5. DINOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0
6. EUGLENOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0
7. CHRYSOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0
Total:	**735**	100	**514**	100	**516**	100	**1,248**	100	**1,247**	100	**1,173**	100
Chlorophyll-*a* (µg/l)	7.45		7.74		11.18		5.16		10.32		5.73	

	R42					
Date	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17
Sample ID	42-307-1	42-307-2	42-307-3	42-307-4	42-307-5	42-307-6
Sampling depth (m)	1	3	4	5	8	10
Parameter (mg/l)						
pH	8.01	7.99	7.96	7.78	7.39	7.38
EC (mS/m)	268	269	270	273	274	275
TDS	2361	2362	2402	2407	2436	2433
Total Hardness as CaCO3	1168	1165	1200	1170	1233	1196
Turbidity (NTU)	-	-	-	-	-	-
TSS	-	-	-	-	-	-
Ca	173.0	172.0	176.3	172.7	185.4	179.5
Mg	179.4	179.4	185.1	180.0	187.7	182.3
Na	264.9	262.1	270.5	264.5	274.1	263.0
K	15.0	15.4	16.1	15.9	16.6	16.1
HCO3	195	194	194	197	213	217
MAlk	161	160	160	162	175	178
Cl	25.7	24.7	26.1	26.7	26.1	35.4
NO2(N)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
NO3(N)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
SO4	1546	1552	1571	1590	1576	1582
F	0.10	<0.1	<0.1	<0.1	<0.1	<0.1
Al	0.030	0.029	0.024	0.020	0.015	0.037
As	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
B	0.444	0.446	0.458	0.446	0.463	0.449
Ba	0.116	0.114	0.117	0.117	0.138	0.130
Br	<0.4	0.45	0.42	<0.4	<0.4	0.55
Cd	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Co	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Cr	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Cu	0.018	0.021	0.018	0.018	0.017	0.023
Fe	0.026	0.025	0.023	0.020	0.020	0.027
Li	0.04	0.039	0.039	0.048	0.049	0.049
Mn	0.047	0.048	0.055	0.137	0.739	0.948
Mo	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Ni	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
P	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Pb	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
S	478	480	477	724	662	696
Sb	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Se	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Si	2.626	2.633	2.698	2.680	3.128	3.115
Sr	3.1	3.1	3.1	3.1	3.1	3.1
U	<0.015	<0.015	<0.015	<0.015	<0.015	<0.015
V	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Zn	<0.020	<0.020	<0.020	<0.020	<0.020	0.020
NH3-N	-	-	-	-	-	-
PO4-P	-	-	-	-	-	-
TP	<1	<1	<1	<1	<1	<1
ΣAnion (meq)	34.6	34.6	35.1	35.5	35.3	35.8
ΣCation (meq)	35.5	35.3	36.4	35.5	37.3	36.0
Anion-Cation Balance (%)	1.35	1.00	1.87	0.05	2.67	0.36

	R42S						
Date	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17
Sample ID	42-0714.001	42-0714.002	42-0714.003	42-0714.004	42-0714.005	42-0714.006	42-0714.007
Sampling Depth (m)	1	3	5	6	7	9	10
Parameter (mg/l)							
pH	8.3	8.3	8.2	8.2	8.2	8.2	8.2
EC (mS/m)	316	315	315	315	314	314	316
TDS	2600	2600	2700	2600	2700	2700	2600
Turbidity (NTU)	2.1	2.5	2	2.3	3	2.1	2.6
TSS	<21	<21	<21	54	32	58	82
Total hardness as CaCO3	1140	1150	1160	1140	1160	1150	1140
Ca	163	164	165	163	164	163	162
Mg	177	179	182	179	182	180	179
Na	262	270	269	299	293	281	272
K	21	22	22	22	22	22	22
Bicarbonate Alk as HCO3	257	260	263	260	263	254	263
Total Alk as CaCO3	225	223	225	223	225	223	225
Cl	25	25	25	25	25	25	25
NO3	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
NO3-N	-	-	-	-	-	-	-
SO4	1540	1550	1540	1530	1520	1540	1510
Al	0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
As	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
B	0.38	0.39	0.39	0.39	0.39	0.39	0.39
Ba	0.055	0.055	0.055	0.055	0.056	0.056	0.056
Cd	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Co	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Cr	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Fe	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Li	0.049	0.052	0.051	0.051	0.053	0.053	0.05
Mn	0.04	0.04	0.04	0.04	0.03	0.03	0.03
Mo	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Ni	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
P	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
S	469	489	482	526	528	502	511
Sb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Se	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Si	2.7	2.8	2.8	2.7	2.8	2.8	2.8
Sr	2.9	3	3	3	3	3	3
U	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
V	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
W	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NH3	<0.012	0.068	0.019	0.033	0.018	0.2	0.013
NH3-N	<0.01	0.06	0.02	0.03	0.02	0.16	0.01
TP	0.46	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
PO4-P	0.15	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080
ΣAnion (meq)	37.3	37.3	37.3	37.1	36.9	37.1	36.6
ΣCation (meq)	34.6	35.2	35.5	36.4	36.4	35.7	35.3
Anion-Cation Balance (%)	-3.75	-2.95	-2.43	-0.95	-0.64	-1.93	-1.92

	R42									
Date	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17
Sample ID	42-0966.001	42-0966.002	42-0966.003	42-0966.004	42-0966.005	42-0966.006	42-0966.007	42-0966.008	42-0966.009	42-0966.010
Sampling depth (m)	1	2	3	4	5	6	7	8	9	10.5
Parameter (mg/l)										
pH	8.3	8.5	8.2	8.2	8.3	8	7.9	7.9	7.8	7.9
EC (mS/m)	311	318	316	312	320	312	311	311	314	309
TDS	2700	2800	2700	2900	2700	2600	2700	2600	2900	2700
Total hardness as CaCO3	978	973	971	960	960	987	984	986	989	984
Turbidity (NTU)	2.6	1.9	1.9	2.5	2.9	4.2	1.7	2.7	3	2.9
TSS	<21	26	<21	22	<21	<21	<21	<21	<21	<21
Ca	202	199	199	195	195	208	208	207	210	207
Mg	115	116	115	114	115	114	113	114	113	114
Na	311	310	308	302	300	316	309	309	315	307
K	28	28	28	27	28	27	27	27	27	28
Bicarbonate Alk as HCO3	192	195	204	225	226	241	253	268	265	265
Total Alk as CaCO3	178	180	193	205	205	213	213	220	218	218
Cl	27	27	27	27	27	27	27	27	27	28
NO2	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
NO3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SO4	1550	1530	1540	1540	1510	1510	1520	1490	1500	1510
Al	0.007	0.016	0.023	0.013	0.015	0.015	0.014	0.012	0.005	0.01
As	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
B	0.24	0.21	0.21	0.21	0.2	0.19	0.19	0.18	0.17	0.16
Ba	0.15	0.15	0.15	0.15	0.14	0.19	0.22	0.23	0.23	0.22
Cd	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Co	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.003	0.003	0.002
Cr	0.034	0.032	0.031	0.031	0.031	0.033	0.032	0.033	0.032	0.032
Cu	0.007	0.006	0.006	0.006	0.005	0.005	0.005	0.005	0.005	0.005
Fe	<0.05	0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.08
Li	0.031	0.024	0.024	0.025	0.024	0.025	0.023	0.023	0.022	0.02
Mn	0.034	0.037	0.038	0.047	0.033	0.28	0.48	0.56	0.5	0.54
Mo	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Ni	0.014	0.015	0.015	0.016	0.015	0.015	0.017	0.017	0.016	0.017
P	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Pb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
S	388	385	401	399	383	390	413	418	400	371
Sb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Se	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Si	2.5	2.5	2.5	2.5	2.5	2.7	2.8	2.9	2.8	3.1
Sr	4.2	4.1	4	4.1	4.1	4	4.5	4.2	3.9	3.9
Ti	0.002	0.002	0.003	0.002	0.002	0.002	0.002	0.002	0.001	0.001
U	0.009	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.011
V	0.006	0.004	0.003	0.003	0.003	0.003	0.003	0.002	0.002	0.002
Zn	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
NH3	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
NH3-N	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08
TP	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
PO4-P	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080
ΣAnion (meq)	36.6	36.3	36.7	37	36.3	36.4	36.6	36.2	36.4	36.6
ΣCation (meq)	33.8	33.6	33.5	33	33	34.1	33.8	33.8	34.1	33.7
Anion-Cation Balance (%)	-4.08	-3.74	-4.52	-5.66	-4.78	-3.14	-3.96	-3.38	-3.15	-4.12

Table J13 Kriel pitlake physiochemical variables collected for biological samples of Ramp 42S

Kriel Ramp 42 (R42) pit lake field measurements for bacteria and phytoplankton samples (Grey = Bacteria; White = phytoplankton)

Physical Parameter	Date	0.1 m	0.5 m	1 m	1.5 m	2 m	3 m	4.5 m	5 m	6 m	10 m
pH	Apr-17	8.22	8.22	8.22	8.22	8.22	8.19	8.19	8.19	8.2	7.6
	Sep-17	8.08	8.11	8.12	8.13	8.13	8.14	8.14	8.13	8.11	7.96
	Nov-17	8.18	8.3	8.5	8.2	8.2	8.3	8	7.9	7.9	7.9
Temperature (°C)	Apr-17	21.6	21.54	21.29	20.89	20.8	20.59	20.51	20.5	20.48	20.4
	Sep-17	14.57	14.35	14.32	14.28	14.22	14.21	14.18	14	13.7	12.7
	Nov-17	21.28	21.35	21.36	21.36	21.35	21.34	21.19	20.66	19.53	17.8
EC (mS/m)	Apr-17	293.3	293.3	292.1	291.91	291.87	291.8	291.78	291.79	291.79	294
	Sep-17	287.65	287.4	287.37	287.32	287.3	287.2	287.2	287.19	286.78	286.08
	Nov-17	277.7	277.3	277.2	277.2	277.3	277.3	276.6	275.4	274	273.4
ORP (mV)	Apr-17	42.1	42.15	42.4	43.5	44	45.3	46.9	49.4	50.5	61.3
	Sep-17	184.2	183.2	182.75	182.3	181.1	180.1	179.5	179	179	178
	Nov-17	101	105.4	112.5	115.4	117.9	122.9	126.3	127.7	130	136.4
DO (mg/l)	Apr-17	6.32	6.32	6.33	6.34	6.25	6.08	6.03	6.06	6.11	2.5
	Sep-17	8.38	8.44	8.45	8.46	8.48	8.47	8.44	8.4	8.23	7.11
	Nov-17	6.3	6.19	6.3	6.3	6.31	6.35	6.41	6.47	6.54	4.17
Chlorophyll-a (µg/l)	Apr-17	23	13	23	11	-	-	-	-	-	-
	Sep-17	19.49	19.49	14.04	10.89	-	15.76	3.44	-	14.33	-
	Nov-17		29.5	18.63	17.77	4.59	21.78	7.45	5.16	-	-

Kriel pitlake phytoplankton samples of Ramp 42S during September 2017 sampling.

06 September 2017, Kriel R42S Analyses:														
SAMPLE --->	R42/0.1		R42/0.5		R42/1		R42/1.5		R42/3		R42/4.5		R42/6	
GENERA:	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%
1. CYANOPHYTA	*295*	2	*294*	2	*74*	1	*148*	1	*222*	1	*148*	1	*148*	1
Cylindrospermum (F)	74	1	74	1		0	74	1	74	0	74	1	74	0
Merismopedia (C)	147	1	220	2	74	1	74	1	74	0	74	1	74	0
Oscillatoria (F)	74	1		0		0		0	74	0		0		0
2. BACILLARIOPHYTA	*148*	1	*74*	1	*74*	1	*74*	1	*74*	0	*0*	0	*221*	1
Pennate diatoms (other)	74	1		0	74	1	74	1	74	0		0	147	1
Centric diatoms (other)	74	1	74	1		0		0		0		0	74	0
3. CHLOROPHYTA	*12,377*	96	*11,424*	96	*14,206*	98	*13,255*	97	*15,159*	97	*13,694*	98	*15,451*	97
Ankistrodesmus	11,715	91	10,763	90	13,838	95	12,447	91	14,716	94	13,252	95	15,009	94
Chlamydomonas	147	1		0		0	147	1	147	1	74	1	74	0
Chlorella	367	3	367	3	147	1	367	3	74	0	147	1	220	1
Microspora	74	1	74	1	74	1	147	1	74	0	74	1	74	0
Monoraphidium	74	1	220	2	147	1	147	1	74	0	147	1	74	0
Oocystis (C)		0		0		0		0	74	0		0		0
4. CRYPTOPHYTA	*0*	0	*0*	0	*0*	0	*74*	1	*74*	0	*0*	0	*0*	0
Cryptomonas		0		0		0	74	1	74	0		0		0
5. DINOPHYTA	*74*	1	*74*	1	*147*	1	*74*	1	*147*	1	*74*	1	*74*	0
Peridinium	74	1	74	1	147	1	74	1	147	1	74	1	74	0
6. EUGLENOPHYTA	*0*	0	*74*	1	*0*	0	*0*	0	*0*	0	*0*	0	*74*	0
Euglena		0	74	1		0		0		0		0		0
Trachelomonas		0		0		0		0		0		0	74	0
7. CHRYSOPHYTA	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0
Total:	**12,894**	100	**11,940**	100	**14,501**	100	**13,625**	100	**15,676**	100	**13,916**	100	**15,968**	100
Chlorophyll-*a* (µg/l)	19.49		19.49		14.04		10.89		15.76		3.44		14.33	

Kriel pitlake phytoplankton samples of Ramp 42S during November 2017 sampling.

17 November 2017, Kriel R42N, Analyses:														
SAMPLE --->	R42/0.5		R42/1		R42/1.5		R42/2		R42/3		R42/4		R42/5	
GENERA:	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%
1. CYANOPHYTA	*74*	0	*221*	0	*74*	0	*148*	1	*0*	0	*74*	0	*74*	0
Cylindrospermum (F)	74	0	147	0	74	0	74	0		0	74	0	74	0
Merismopedia (C)		0	74	0		0	74	0		0		0		0
2. BACILLARIOPHYTA	*0*	0	*74*	0	*74*	0	*74*	0	*74*	0	*222*	1	*0*	0
Cyclotella		0		0		0		0		0	74	0		0
Entomoneis		0		0		0		0	74	0		0		0
Gyrosigma		0	74	0		0		0		0		0		0
Nitzschia		0		0	74	0	74	0		0	74	0		0
Pennate diatoms (other)		0		0		0		0		0	74	0		0
3. CHLOROPHYTA	*23,651*	99	*60,916*	99	*59,890*	100	*18,672*	98	*24,016*	99	*30,532*	98	*44,590*	99
Ankistrodesmus	23,429	98	60,328	98	59,742	99	18,450	97	23,721	98	30,164	97	43,489	97
Chlamydomonas		0		0		0	74	0		0	74	0	74	0
Chlorella	74	0	367	1	74	0	74	0		0	147	0	806	2
Monoraphidium		0	147	0		0		0	74	0		0		0
Mougeotia (F)	74	0	74	0	74	0	74	0	74	0	147	0	147	0
Oocystis (C)		0		0		0		0	147	1		0		0
Pediastrum (C)		0		0		0		0		0		0	74	0
Tetrastrum (C)	74	0		0		0		0		0		0		0
4. CRYPTOPHYTA	*0*	0	*74*	0	*0*	0	*0*	0	*0*	0	*74*	0	*0*	0
Cryptomonas		0	74	0		0		0		0	74	0		0
5. DINOPHYTA	*74*	0	*74*	0	*74*	0	*74*	0	*74*	0	*74*	0	*74*	0
Peridinium	74	0	74	0	74	0	74	0	74	0	74	0	74	0
6. EUGLENOPHYTA	*0*	0	*74*	0	*0*	0	*0*	0	*74*	0	*74*	0	*148*	0
Euglena		0	74	0		0		0	74	0		0	74	0
Trachelomonas		0		0		0		0		0	74	0	74	0
7. CHRYSOPHYTA	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0
Total:	**23,799**	100	**61,433**	100	**60,112**	100	**18,968**	100	**24,238**	100	**31,050**	100	**44,886**	100
Chlorophyll-*a* (µg/l)	29.52		18.63		17.77		4.59		21.78		7.45		5.16	

Date	R44S	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17
Sample ID		44b	44b	44b	44b	44c	44c	44c	44c	44c	44c	44c
Depth sampled (m)		1	2	3	4	1	3	5	8	1	3	6
Parameter (mg/)												
Bicarbonate Alkalinity as HCO3	mg/l	157	160	157	163	105	102	108	108	105	105	114
Total Alkalinity as CaCO3	mg/l	129	131	129	134	86	83	88	88	86	86	93
Conductivity in mS/m @ 25ºC	mS/m	175	171	169	174	140	139	140	139	141	140	140
TDS (0.7µm) @ 105ºC	mg/l	1200	1200	1200	1200	1000	970	1000	980	950	970	990
Silver	mg/l	0.003	0.002	<0.002	<0.002	<0.002	<0.002	0.002	0.002	<0.002	0.002	0.003
Arsenic	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Boron	mg/l	0.059	0.058	0.058	0.06	0.047	0.047	0.047	0.046	0.047	0.047	0.046
Barium	mg/l	0.063	0.063	0.063	0.063	0.13	0.13	0.12	0.13	0.13	0.13	0.12
Beryllium	mg/l	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Bismuth	mg/l	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Calcium	mg/l	100	100	100	99	77	77	78	77	77	77	77
Cadmium	mg/l	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cobalt	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Chromium	mg/l	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Copper	mg/l	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Potassium	mg/l	20	20	20	32	17	16	16	16	16	16	16
Lithium	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Magnesium	mg/l	83	63	63	61	57	57	57	58	68	68	68
Molybdenum	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Sodium	mg/l	161	161	161	158	120	121	120	120	131	130	130
Nickel	mg/l	<0.005	<0.005	<0.005	0.007	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Phosphorus	mg/l	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Lead	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sulphur	mg/l	289	289	290	283	234	234	234	234	236	236	234
Antimony	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Selenium	mg/l	<0.01	<0.01	0.01	<0.01	<0.01	0.01	0.01	0.01	<0.01	<0.01	0.02
Silicon	mg/l	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	1	1.1	<1.0	<1.0	1.1
Tin	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Strontium	mg/l	0.83	0.82	0.83	0.82	0.61	0.61	0.62	0.61	0.62	0.62	0.63
Tellurium	mg/l	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17
Thorium	mg/l	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Titanium	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Thallium	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total hardness as CaCO3	mg/l	590	507	509	500	426	428	430	429	472	473	NA
Uranium	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Vanadium	mg/l	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Tungsten	mg/l	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Zinc	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zirconium	mg/l	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18
Aluminium	mg/l	<0.003	<0.003	<0.003	<0.003	<0.003	0.003	0.003	0.008	0.003	0.004	0.003
Iron	mg/l	0.29	0.32	0.32	0.31	0.25	0.25	0.26	0.28	0.27	0.28	0.28
Manganese	mg/l	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.002	0.006	<0.002	<0.002	<0.002
Chloride	mg/l	12	13	13	13	11	11	11	10	11	11	11
Fluoride	mg/l	1.2	1.3	1.3	1.3	1.8	1.8	1.8	1.8	1.8	2.2	1.9
Nitrite	mg/l	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Nitrate	mg/l	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sulphate	mg/l	620	575	608	605	472	464	466	459	526	522	518
pH in water at 25ºC	-	8	8.3	8.3	7.8	8.5	8.5	8.1	8	8.4	8.4	8
Sum of Anion Milliequivalents		15.8	15	15.6	15.6	11.8	11.6	11.8	11.6	13	12.9	13
Sum of Cation Milliequivalents		19.3	17.7	17.7	17.7	14.2	14.2	14.2	14.2	15.6	15.5	15.5
Anion-Cation Balance		9.86	8.29	6.29	6.09	9.02	9.99	9.49	10.1	9.11	9.33	8.99

Date	R44S		Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17
Lab ID			JBX17-071	JBX17-071	JBX17-071	JBX17-071	JBX17-071	JBX17-071	JBX17-071	JBX17-071	JBX17-071	JBX17-0714.022
Sample ID			44c	44c	44c	44c	44c	44c	44b	44b	44b	44b
Sampling Depth (m)			1	2	3	5	7	8	1	2	3	4
Parameter (mg/l)												
Turbidity	NTU	0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	0.5	<0.4	<0.4	<0.4
Bicarbonate Alkalinity as HCO3	mg/l	12	107	107	110	110	113	116	144	147	144	144
Methyl Orange (M) Alkalinity as CaCO3	mg/l	12	93	93	95	95	98	98	125	128	125	125
Phenolphthalein (P) Alkalinity as CaCO3	mg/l	12	<12	<12	<12	<12	<12	<12	<12	<12	<12	<12
Total Alkalinity as CaCO3	mg/l	12	98	98	100	100	103	100	133	135	133	133
Conductivity in mS/m @ 25ºC	mS/m	2	153	152	152	152	153	152	188	188	188	188
TDS (0.7µm) @ 105ºC	mg/l	21	1100	1100	1100	1100	1000	1100	1400	1400	1400	1400
TSS (0.7µm) @ 105ºC	mg/l	21	<21	<21	<21	<21	<21	<21	<21	<21	<21	24
Silver	mg/l	0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Aluminium	mg/l	0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Arsenic	mg/l	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Boron	mg/l	0.005	0.034	0.034	0.034	0.034	0.034	0.031	0.034	0.034	0.034	0.035
Barium	mg/l	0.002	0.093	0.092	0.094	0.092	0.092	0.092	0.046	0.045	0.046	0.046
Beryllium	mg/l	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Bismuth	mg/l	0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Calcium	mg/l	0.5	71	70	70	69	69	70	88	88	89	88
Cadmium	mg/l	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cobalt	mg/l	0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Chromium	mg/l	0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002		<0.002	<0.002	<0.002
Copper	mg/l	0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Iron	mg/l	0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Potassium	mg/l	0.2	17	17	17	17	17	17	21	21	21	21
Lithium	mg/l	0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Magnesium	mg/l	0.01	83	81	83	81	82	82	107	106	107	107
Manganese	mg/l	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Molybdenum	mg/l	0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Sodium	mg/l	0.5	115	114	118	120	117	103	142	139	140	140
Nickel	mg/l	0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Phosphorus	mg/l	0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.03	<0.03	<0.03	<0.03
Lead	mg/l	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sulphur	mg/l	0.07	220	221	220	222	215	187	219	244	272	240
Antimony	mg/l	0.008	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
Selenium	mg/l	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Silicon	mg/l	1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Tin	mg/l	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Strontium	mg/l	0.001	0.6	0.6	0.61	0.61	0.59	0.6	0.82	0.82	0.85	0.83
Tellurium	mg/l	0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17
Thorium	mg/l	0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Titanium	mg/l	0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Thallium	mg/l	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total hardness as CaCO3	mg/l	1.5	519	510	515	508	510	514	658	657	662	659
Uranium	mg/l	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Vanadium	mg/l	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Tungsten	mg/l	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc	mg/l	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zirconium	mg/l	0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18
Chloride	mg/l	0.05	10	10	9.9	9.9	9.9	9.9	12	12	12	12
Nitrate	mg/l	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sulphate	mg/l	0.05	585	581	579	578	570	582	770	757	771	758
Orthophosphate (Total Reactive Phosphorous or PO4)	mg/l	0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
Orthophosphate as P	mg/l	0.08	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080
pH in water at 25ºC	-	1	8.4	8.4	8.3	8.4	8.6	8.3	8.5	8.5	8.5	8.5
Ammonia	mg/l	0.012	0.033	0.015	<0.012	0.022	<0.012	0.019	0.018	0.026	<0.012	<0.012
Ammonia as N	mg/l	0.01	0.03	0.01	<0.01	0.02	<0.01	0.02	0.02	0.02	<0.01	<0.01
Sum of Anion Milliequivalents	meq/l	-	14.4	14.3	14.3	14.3	14.2	14.4	19	18.8	19	18.8
Sum of Cation Milliequivalents	meq/l	-	15.8	15.6	15.9	15.8	15.7	15.2	19.9	19.7	19.9	19.8
Anion-Cation Balance	%	-100	4.55	4.22	5.07	4.89	5.02	2.74	2.16	2.38	2.13	2.67

Kriel pitlake physiochemical variables collected for biological samples of Ramp 6.

Kriel Ramp 6 (R6) pit lake field measurements for bacteria and phytoplankton samples (Grey = Bacteria; White = phytoplankton)								
Physical Parameter	**Date**	**0.1 m**	**0.5 m**	**1 m**	**2.5 m**	**3 m**	**3.5 m**	**4.5 m**
pH	Apr-17	9.38	9.37	9.35	9.3	9.28	9.26	8.94
	Sep-17	8.32	8.32	8.32	8.3	8.25	8.47	8.5
Temperature (°C)	Apr-17	20.6	19.82	19.59	19	18.89	18.82	18.72
	Sep-17	14.47	14.16	13.96	13.24	12.71	11.83	11.58
EC (mS/m)	Apr-17	453.1	457	460	464.6	464.8	464.7	466.2
	Sep-17	466.81	467.31	467.24	466.89	467.62	471.48	472.44
ORP (mV)	Apr-17	-12.7	-12.65	-12.4	-51.6	-116.9	-140.65	-220.3
	Sep-17	146.9	146.9	146.9	147.2	147.7	147.2	146.6
DO (mg/l)	Apr-17	5.05	4.41	3.4	1.22	1.22	0.6	0.39
	Sep-17	7	6.9	6.86	5.84	4.44	3.68	3.28
Chlorophyll-a (µg/l)	Apr-17	-	-	-	-	-	-	-
	Sep-17	15.48	5.73	16.62	-	<20	-	10.61

Kriel pitlake phytoplankton samples collected at Ramp 6 (additional pitlake).

08 September 2017, Kriel R6 Analyses:										
SAMPLE --->	**R6w/0.1**		**R6w/0.5**		**R6w/1**		**R6w/3**		**R6w/4.5**	
GENERA:	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%
1. CYANOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0
2. BACILLARIOPHYTA	***442***	43	***734***	77	***441***	50	***368***	50	***296***	45
Cyclotella	74	7		0		0	74	10	74	11
Nitzschia	147	14	586	61	220	25	220	30	74	11
Pennate diatoms (other)	147	14	74	8	74	8		0	74	11
Centric diatoms (other)	74	7	74	8	147	17	74	10	74	11
3. CHLOROPHYTA	***74***	7	***148***	15	***74***	8	***0***	0	***220***	33
Chlamydomonas	74	7	74	8	74	8		0		0
Chlorella		0		0		0		0	220	33
Monoraphidium		0	74	8		0		0		0
4. CRYPTOPHYTA	***513***	50	***74***	8	***293***	33	***293***	40	***147***	22
Cryptomonas	513	50	74	8	293	33	293	40	147	22
5. DINOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0
6. EUGLENOPHYTA	***0***	0	***0***	0	***74***	8	***74***	10	***0***	0
Lepocinclis		0		0		0	74	10		0
Trachelomonas		0		0	74	8		0		0
7. CHRYSOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0	***0***	0
Total:	**1,029**	100	**956**	100	**882**	100	**735**	100	**663**	100
Chlorophyll-*a* (µg/l)	15.48		5.73		16.62		###		10.61	

Kriel pitlake physiochemical variables collected for biological samples of Ramp11.

Kriel Ramp 11 (R11) pit lake field measurements for bacteria and phytoplankton samples (Grey = Bacteria; White = phytoplankton)						
Physical Parameter	**Date**	**0.1 m**	**0.5 m**	**1 m**	**5 m**	**22 m**
pH	May-17	8.44	8.425	8.42	8.38	7.61
	Sep-17	8.24	8.24	8.23	8.18	8.07
Temperature (°C)	May-17	20.218	20.1095	20.078	19.364	15.314
	Sep-17	14.5	14.5	14.5	14.107	12.2
EC (mS/m)	May-17	289.13	288.995	288.98	288.44	330.86
	Sep-17	279.1	279.1	279	278.9	278.62
ORP (mV)	May-17	41.9	42.75	42.9	48.7	-125.2
	Sep-17	173.6	173.5	173.6	173.1	177.3
DO (mg/l)	May-17	6.74	6.685	6.67	6.44	0.2
	Sep-17	8.16	8.19	8.23	8.29	7.07
Chlorophyll-a (µg/l)	May-17	-	32.24	13.97	-	-
	Sep-17	23.21	30.38	10.32	-	-

Kriel pitlake phytoplankton samples of Ramp11 during September 2017 sampling. (Additional pitlake)

07 September 2017, Kriel R11, Analyses:						
SAMPLE --->	R11/0.1 m		R11/0.5 m		R11/1 m	
GENERA:	cells/ml	%	cells/ml	%	cells/ml	%
1. CYANOPHYTA	0	0	0	0	74	8
Oscillatoria (F)		0		0	74	8
2. BACILLARIOPHYTA	221	19	295	29	74	8
Entomoneis		0	74	7		0
Melosira (F)	74	6		0		0
Navicula		0	74	7		0
Pennate diatoms (other)	147	12	147	14	74	8
3. CHLOROPHYTA	808	69	662	64	591	61
Chlamydomonas	74	6	147	14	74	8
Chlorella		0		0	74	8
Crucigenia (C)		0		0	74	8
Microspora	440	37	293	28	147	15
Oocystis (C)	147	12	74	7	74	8
Oocystis (sc)		0	74	7	74	8
Scenedesmus (C)	147	12	74	7	74	8
4. CRYPTOPHYTA	0	0	0	0	0	0
5. DINOPHYTA	74	6	0	0	74	8
Peridinium	74	6		0	74	8
6. EUGLENOPHYTA	74	6	74	7	148	15
Euglena	74	6	74	7	74	8
Trachelomonas		0		0	74	8
7. CHRYSOPHYTA	0	0	0	0	0	0
Total:	1,177	100	1,031	100	961	100
Chlorophyll-*a* (µg/l)	23.21		30.38		10.32	

Kriel pitlake phytoplankton of Ramp11 during May 2017 sampling (Additional pitlake).

05 May 2017, Kriel R11 Analyses:				
SAMPLE --->	R11/0.5		R11/1	
GENERA:	cells/ml	%	cells/ml	%
1. CYANOPHYTA	0	0	0	0
2. BACILLARIOPHYTA	148	11	74	7
Pennate diatoms (other)	74	5	74	7
Centric diatoms (other)	74	5		0
3. CHLOROPHYTA	735	53	735	71
Carteria		0	74	7
Chlamydomonas	147	11	74	7
Chlorella	74	5		0
Crucigenia (C)	293	21	147	14
Monoraphidium	147	11	440	43
Oocystis (C)	74	5		0
4. CRYPTOPHYTA	367	26	147	14
Cryptomonas	367	26	147	14
5. DINOPHYTA	74	5	74	7
Peridinium	74	5	74	7
6. EUGLENOPHYTA	74	5	0	0
Euglena	74	5		0
7. CHRYSOPHYTA	0	0	0	0
Total:	1,398	100	1,030	100
Chlorophyll-*a* (µg/l)	32.24		13.97	

Physicochemical variable for biological data collected for Ramp 7.

Kriel Ramp 7 (R7) pit lake field measurements for bacteria.			
Physical Parameter	Date	1 m	20 m
pH	May-17	8.64	7.71
Temperature (°C)	May-17	18.348	16.352
EC (mS/m)	May-17	294.2	305.29
ORP (mV)	May-17	124.4	-253.2
DO (mg/l)	May-17	6.63	0.54

Appendix K: Rooikop Water Quality

	Rooikop			
Date	11/1/2016	11/1/2016	11/1/2016	11/1/2016
Sample ID	R0019.036	R0019.037	R0019.038	R0019.039
Sampling depth (m)	2	3.5	5	8
Parameter (mg/l)				
pH	7.89	7.77	7.59	7.84
EC (mS/m)	132.5	132.9	132.8	133
TDS	795	797.4	796.8	798
Total hardness as CaCO3	798.5	809.9	822.0	817.8
Turbidity	-	-	-	-
TSS	-	-	-	-
Ca	234.4	240.7	244.2	242.1
Mg	51.6	50.6	51.4	51.6
Na	17.1	16.4	16.9	17.4
K	6.0	5.7	5.9	5.9
Malk	112.0	124.0	103.0	116.0
Alkalinity as HCO3	135.0	155.0	125.0	140.0
Cl	3.0	2.9	2.9	2.9
NO2	<0.5	<0.5	<0.5	<0.5
NO3(N)	0.1	0.1	0.1	0.1
SO4	612.4	605.4	604.7	605.3
F	<0.05	<0.05	<0.05	<0.05
Al	<0.003	<0.003	<0.003	<0.003
As	<0.0005	<0.0005	<0.0005	<0.0005
B	0.017	0.015	0.015	0.015
Ba	0.029	0.028	0.029	0.029
Br	<0.1	<0.1	<0.1	<0.1
Cd	<0.0001	<0.0001	<0.0001	<0.0001
Co	<0.0004	<0.0004	<0.0004	<0.0004
Cr	<0.002	<0.002	<0.002	<0.002
Cu	<0.0009	<0.0009	<0.0009	<0.0009
Fe	<0.05	<0.05	<0.05	<0.05
Li	0.027	0.026	0.026	0.026
Mn	0.031	0.029	0.025	0.030
Mo	<0.001	<0.001	<0.001	<0.001
Ni	<0.001	<0.001	<0.001	<0.001
P	<0.03	<0.03	<0.03	<0.03
Pb	<0.0005	<0.0005	<0.0005	<0.0005
S	223.53	215.37	205.00	222.31
Sb	<0.008	<0.008	<0.008	<0.008
Se	<0.002	<0.002	<0.002	<0.002
Si	5.025	4.923	5.084	5.240
Sr	4.006	3.898	4.014	4.089
U	<0.0005	<0.0005	<0.0005	<0.0005
V	<0.0005	<0.0005	<0.0005	<0.0005
Zn	<0.05	<0.05	<0.05	<0.05
NH3-N	-	-	-	-
PO4-P	-	-	-	-
TP	-	-	-	-
ΣAnion (meq)	15.8	16.2	15.6	15.9
ΣCation (meq)	16.8	17.0	17.3	17.2
Anion-Cation Balance (%)	3.3	2.4	5.2	4.0

	Rooikop						
Date	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17
Sample ID	RK0714.039	RK0714.040	RK0714.041	RK0714.042	RK0714.043	RK0714.044	RK0714.045
Sampling depth (m)	1	3	5	7	8	10	10.5
Parameter (mg/l)							
pH	8	7.9	7.9	7.9	7.9	7.9	7.9
EC mS/m	142	142	142	142	143	142	143
TDS	1300	1300	1200	1300	1200	1300	1200
Turbidity (NTU)	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
TSS	<21	<21	<21	<21	<21	<21	32
Total hardness as CaCO3	740	740	688	688	736	717	731
Ca	222	220	200	200	217	210	215
Mg	45	47	46	46	47	47	47
Na	17	18	17	17	18	18	18
K	5.2	5.4	5.2	5.3	5.3	5.3	5.4
Bicarbonate Alk as HCO3	150	147	150	150	153	156	153
Total Alk as CaCO3	123	120	123	123	125	128	125
Cl	2.4	2.3	2.3	2.3	2.3	2.3	2.3
NO3	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1
NO3-N	-	-	-	-	-	-	-
SO4	579	579	579	577	586	587	588
Al	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
As	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
B	0.013	0.013	0.013	0.014	0.013	0.014	0.014
Ba	0.028	0.028	0.028	0.028	0.028	0.028	0.028
Cd	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Co	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Cr	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Fe	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Li	0.019	0.021	0.019	0.021	0.021	0.02	0.018
Mn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mo	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Ni	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
P	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
S	199	200	202	193	193	208	184
Sb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Se	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Si	5.7	5.7	5.3	5.6	5.5	5.4	5.5
Sr	4	4	4	4	4.1	4.1	4.1
U	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
V	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
W	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NH3	0.017	<0.012	0.038	0.069	0.027	0.019	0.032
NH3-N	0.01	<0.01	0.03	0.06	0.02	0.02	0.03
TP	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
PO4-P	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080
ΣAnion (meq)	14.6	14.5	14.6	14.5	14.8	14.8	14.8
ΣCation (meq)	15.7	15.7	14.6	14.6	15.6	15.2	15.5
Anion-Cation Balance (%)	3.64	3.83	0.19	0.39	2.84	1.36	2.32

	Rooikop					
Date	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17	Nov-17
Sample ID	RK1004.001	RK1004.002	RK1004.003	RK1004.004	RK1004.005	RK1004.006
Sampling depth (m)	1	3	5	7	8	10
Parameter (mg/l)						
pH	7.88	7.93	7.94	7.92	7.79	7.49
EC (mS/m)	133	134	134	134	134	137
TDS	1100	1100	1200	1200	1100	1200
Total hardness as CaCO3	696	698	697	704	695	724
Turbidity (NTU)	1.3	1.7	1.6	0.8	0.9	1.4
TSS	<21	<21	<21	<21	<21	<21
Ca	212	213	212	215	211	224
Mg	41	40	41	41	41	40
Na	19	19	19	19	20	19
K	5.4	5.4	5.5	5.7	5.8	5.8
Bicarbonate Alk as HCO3	126	126	126	126	129	150
Total Alk as CaCO3	108	108	108	108	110	123
Cl	2.6	2.5	2.5	2.8	3	2.6
NO2	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
NO3	<0.1	<0.1	<0.1	<0.1	<0.1	0.1
SO4	624	653	640	643	633	635
Al	0.014	0.015	0.013	0.006	0.006	<0.003
As	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
B	0.003	0.003	0.003	0.003	0.003	0.004
Ba	0.046	0.046	0.046	0.046	0.046	0.051
Cd	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Co	0.001	0.001	0.001	0.001	0.001	0.001
Cr	0.011	0.011	0.011	0.011	0.012	0.014
Cu	<0.0009	<0.0009	<0.0009	<0.0009	<0.0009	<0.0009
Fe	<0.05	<0.05	<0.05	<0.05	<0.05	0.06
Li	0.006	0.006	0.006	0.005	0.006	0.007
Mn	0.016	0.018	0.019	0.02	0.022	0.05
Mo	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ni	0.02	0.021	0.021	0.021	0.02	0.021
P	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Pb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
S	237	245	263	266	273	270
Sb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Se	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Si	5	5.3	5.2	5.1	5.3	5.5
Sr	5.3	4.9	5.1	4.9	5.1	5
Ti	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
U	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
V	0.001	0.001	0.001	0.001	0.001	0.001
Zn	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
NH3	0.027	0.12	0.062	0.027	0.04	0.16
NH3-N	0.02	0.1	0.05	0.02	0.03	0.13
TP	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
PO4-P	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080
ΣAnion (meq)	15.2	15.8	15.5	15.6	15.5	15.8
ΣCation (meq)	14.9	14.9	14.9	15.1	14.9	15.5
Anion-Cation Balance (%)	-1.12	-2.98	-2.14	-1.78	-1.88	-0.95

Physicochemical variables collected for Rooikop biological data.

Rooikop pit lake field measurements for bacteria and phytoplankton samples (Grey = Bacteria; White = phytoplankton)									
Physical Parameter	**Date**	**0.1 m**	**0.5 m**	**1 m**	**2 m**	**3 m**	**5 m**	**8 m**	**10 m**
pH	Nov-16			8.1	8.10	8.1	8.1	8.1	8
	Sep-17	7.82	7.815	7.79	7.74	7.73	7.73	7.73	7.72
T	Nov-16			22.17	21.82	20.36	19.63	18.41	17.10
	Sep-17	15.45	15.44	15.38	15.31	15.30	15.28	15.24	15.22
EC (mS/m)	Nov-16			140.92	140.885	143.44	140.43	140.57	141.08
	Sep-17	129.97	129.96	129.92	129.88	129.9	129.9	129.9	129.92
ORP (mV)	Nov-16			224.40	219.15	215.00	211.10	208.50	209.40
	Sep-17	152	151.8	150.2	146.2	145.6	146.1	148.7	151
DO (mg/l)	Nov-16			8.42	8.36	8.49	8.97	8.55	7.03
	Sep-17	7.83	7.83	7.84	7.86	7.89	7.94	7.95	7.93
Chlorophyll-a (µg/l)	Sep-17	6.31	7.17	5.16	-	<1	1.15	7.17	7.74

Phytoplankton collected for Rooikop pitlake during September sampling.

08 September 2017, Rooikop pit lake, Analyses:														
SAMPLE --->	**RKw/0.1**		**RKw/0.5**		**RKw/1**		**RKw/3**		**RKw/5**		**RKw/8**		**RKw/10**	
GENERA:	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%
1. CYANOPHYTA	*74*	25	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0
Oscillatoria (F)	74	25		0		0		0		0		0		0
2. BACILLARIOPHYTA	*74*	25	*148*	40	*74*	33	*74*	25	*0*	0	*74*	50	*74*	25
Pennate diatoms (other)	74	25	74	20	74	33	74	25		0	74	50	74	25
Synedra		0	74	20		0		0		0		0		0
3. CHLOROPHYTA	*74*	25	*148*	40	*148*	67	*148*	50	*148*	100	*74*	50	*222*	75
Ankistrodesmus		0		0		0		0		0		0		0
Chlamydomonas	74	25	74	20	74	33	74	25	74	50		0	74	25
Chlorella		0	74	20	74	33	74	25	74	50		0	74	25
Elakatothrix		0		0		0		0		0	74	50	74	25
4. CRYPTOPHYTA	*74*	25	*74*	20	*0*	0	*74*	25	*0*	0	*0*	0	*0*	0
Cryptomonas	74	25	74	20		0	74	25		0		0		0
5. DINOPHYTA	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0
6. EUGLENOPHYTA	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0
7. CHRYSOPHYTA	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*	0
Total:	**296**	100	**370**	100	**222**	100	**296**	100	**148**	100	**148**	100	**296**	100
Chlorophyll-*a* (µg/l)	6.31		7.17		5.16		<1.00		1.15		7.17		7.74	

Appendix L: Kleinfontein Water Quality

Date	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17	Mar-17
Sample ID	S32/1M	S32/2M	S32/2.5M	S32/B/1M	S32/B/2M	S32/B/3M	S32/B2/1M	S32/B2/2M	S32/B2/3M	S32/B3/1.5
Sampling depth (m)	1	2	2.5	1	2	3	1	2	3	1.5
Parameter (mg/l)										
pH	7.6	7.5	7.5	7.8	7.9	8	7.8	7.8	7.7	7.7
EC (mS/m)	201	200	201	131	133	131	131	131	132	133
TDS	1600	1600	1500	940	960	940	930	900	980	790
Total hardness as CaCO3	1376.667	1431.667	1418.333	777.5	768.3333	777.5	768.3333	765.8333	756.6667	764.1667
Turbidity (NTU)	-	-	-	-	-	-	-	-	-	-
TSS	-	-	-	-	-	-	-	-	-	-
Ca	239	246	249	156	154	156	154	153	151	154
Mg	187	196	191	93	92	93	92	92	91	91
Na	89	91	86	43	42	43	42	42	42	42
K	19	20	22	11	11	11	11	10	10	10
Bicarbonate Alk as HCO3	441	439	452	416	412	421	418	416	417	417
Total Alk as CaCO3	362	360	371	341	338	345	343	341	342	342
Cl	21	19	9.2	9.5	9.5	9.4	9.4	9.3	9.2	10
NO2										
NO3	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	0.3
F	0.85	2.2	0.86	1.3	1.1	1.1	1.1	1.1	1.1	0.95
SO4	979	921	930	526	527	523	521	520	517	447
Al	<0.02	<0.02	<0.02	<0.02	0.07	0.15	0.05	0.09	0.16	0.08
As	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
B	0.036	0.036	0.035	0.029	0.028	0.029	0.028	0.028	0.027	0.027
Ba	0.032	0.034	0.034	0.053	0.055	0.057	0.054	0.056	0.056	0.056
Cd	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Co	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Cr	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Fe	<0.05	<0.05	<0.05	<0.05	<0.05	0.06	<0.05	<0.05	0.07	<0.05
Li	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Mn	0.03	0.03	0.15	0.14	0.15	0.15	0.16	0.14	0.17	0.14
Mo	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Ni	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
P	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
S	407	427	481	216	212	215	213	212	209	213
Sb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Se	<0.01	0.02	<0.01	<0.01	<0.01	0.02	0.01	<0.01	<0.01	<0.01
Si	1.9	2	2.2	4.8	4.8	5.1	4.8	4.9	5	5
Sr	1.5	1.5	1.5	1	1	1	1	1	1	1
Ti	<0.005	<0.005	<0.005	<0.005	<0.005	0.008	<0.005	<0.005	0.009	<0.005
U	<0.01	0.03	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01
V	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Zn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NH3	-	-	-	-	-	-	-	-	-	-
NH3-N	-	-	-	-	-	-	-	-	-	-
TP	-	-	-	-	-	-	-	-	-	-
PO4-P	-	-	-	-	-	-	-	-	-	-
ΣAnion (meq)	28.2	26.9	27	18	18	18	18	17.9	17.9	16.4
ΣCation (meq)	31.7	32.8	32.5	17.6	17.4	17.6	17.3	17.3	17.1	17.3
Anion-Cation Balance (%)	5.84	9.92	9.23	-1.22	-1.76	-1.34	-1.75	-1.55	-2.23	2.45

Date	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17	Sep-17
Sample ID	S32wa-1m	S32wa-2m	S32wa-2.5	S32wa-3m	S32wB-1m	S32wB-2m	S32wB-2.5	S32wB-3m
Sampling depth (m)	1	2	2.5	3	1	2	2.5	3
Parameter (mg/l)								
pH	8.1	8	8	7.9	7.7	7.6	7.5	7.5
EC (mS/m)	159	159	159	158	194	191	196	197
TDS	1300	1200	1200	1200	1600	1600	1700	1700
Total hardness as CaCO3	776	767	775	775	940	943	940	947
Turbidity (NTU)	4.5	5.8	5.9	6.4	9.7	9.3	9.7	13
TSS	<21	<21	<21	<21	<21	<21	<21	<21
Ca	148	147	148	148	163	164	164	164
Mg	99	97	99	98	129	129	129	130
Na	46	45	46	46	66	68	67	70
K	12	12	12	12	19	19	19	19
Bicarbonate Alk as HCO3	235	232	229	232	260	257	260	257
Total Alk as CaCO3	193	190	188	190	213	210	213	210
Cl	11	11	11	11	18	17	18	18
NO2								
NO3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
F								
SO4	613	599	605	600	793	800	801	800
Al	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
As	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
B	0.029	0.024	0.024	0.024	0.019	0.018	0.018	0.018
Ba	0.044	0.044	0.044	0.044	0.018	0.018	0.018	0.018
Cd	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Co	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Cr	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Fe	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Li	<0.005	0.005	0.005	0.006	0.006	0.006	0.005	0.006
Mn	0.04	0.02	0.02	0.01	0.03	0.02	0.02	0.01
Mo	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Ni	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
P	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.06
Pb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
S	202	205	193	248	248	242	228	259
Sb	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Se	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Si	2.3	2.3	2.3	2.3	<1.0	<1.0	<1.0	<1.0
Sr	1.1	1.1	1.1	1.1	1.3	1.3	1.3	1.3
Ti	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
U	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
V	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Zn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NH3	0.077	0.11	0.1	0.084	0.25	0.32	0.29	0.27
NH3-N	0.06	0.09	0.08	0.07	0.2	0.26	0.24	0.22
TP	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
PO4-P	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080
ΣAnion (meq)	16.9	16.6	16.6	16.6	21.3	21.3	21.4	21.3
ΣCation (meq)	17.8	17.6	17.8	17.8	22.2	22.3	22.2	22.5
Anion-Cation Balance (%)	2.55	2.95	3.3	3.44	2.05	2.24	1.74	2.53

Kleinfontein pit lake field measurements for bacteria and phytoplankton samples (Grey = Bacteria; White = phytoplankton)					
Physical Parameter	**Date**	**0.1 m**	**0.5 m**	**1 m**	**3 m**
pH	Mar-17	7.86	7.85	7.85	7.55
	Sep-17	7.61	7.6	7.58	7.44
T	Mar-17	22.933	21.245	21.091	19.902
	Sep-17	14.144	13.973	13.853	13.475
EC (mS/m)	Mar-17	202.72	207.13	206.5	202.62
	Sep-17	183.9	183.5	179.07	178.41
ORP (mV)	Mar-17	115.5	115.1	115	68.1
	Sep-17	187.1	187.2	187.8	191
DO (mg/l)	Mar-17	5.26	5.34	5.31	0.58
	Sep-17	5.10	5.06	4.49	2.99
Chlorophyll-a (ug/l)					
	Sep-17	Jan-00	9.74	15.48	18.06

Phytoplankton data collected at Kleinfontein pitlake during September 2017.

08 September 2017, Kleinfontein, Analyses:								
SAMPLE --->	**0.1 m**		**0.5 m**		**1 m**		**3 m**	
Site --->								
GENERA:	cells/ml	%	cells/ml	%	cells/ml	%	cells/ml	%
1. CYANOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0
2. BACILLARIOPHYTA	***294***	12	***441***	9	***1,029***	16	***880***	23
Cocconeis		0		0		0	293	8
Cymbella		0		0	147	2		0
Gyrosigma		0	147	3	147	2	147	4
Melosira (Aulacoseira) (F)		0	147	3		0		0
Navicula		0	147	3	147	2	147	4
Nitzschia		0		0	147	2		0
Pennate diatoms (other)	147	6		0	147	2	293	8
Stauroneis		0		0	147	2		0
Centric diatoms (other)		0		0	147	2		0
Synedra	147	6		0		0		0
3. CHLOROPHYTA	***733***	29	***879***	19	***1,172***	19	***733***	19
Chlamydomonas	293	12		0	147	2		0
Chlorella	293	12	879	19	1,025	16	293	8
Crucigenia (C)	147	6		0		0		0
Elakatothrix		0		0		0	147	4
Scenedesmus (C)		0		0		0	293	8
4. CRYPTOPHYTA	***1,465***	59	***3,075***	66	***4,100***	65	***2,197***	58
Cryptomonas	1,465	59	3,075	66	4,100	65	2,197	58
5. DINOPHYTA	***0***	0	***147***	3	***0***	0	***0***	0
Peridinium		0	147	3		0		0
6. EUGLENOPHYTA	***0***	0	***147***	3	***0***	0	***0***	0
Trachelomonas		0	147	3		0		0
7. CHRYSOPHYTA	***0***	0	***0***	0	***0***	0	***0***	0
Total:	**2,492**	100	**4,689**	100	**6,301**	100	**3,810**	100
Chlorophyll-*a* (µg/l)	6.88		9.74		15.48		18.06	

Appendix M: Microbial Report

Microbial Diversity
A total of 8600 bacterial and archaeal OTUs (97% similarity cut-off) was found in all samples using identical sequencing depth (31086 sequences per sample). Rarefaction curves and Chao1 estimates suggest that this sequencing depth was adequate to capture most of the prokaryotic diversity in each sample (Figure 1).

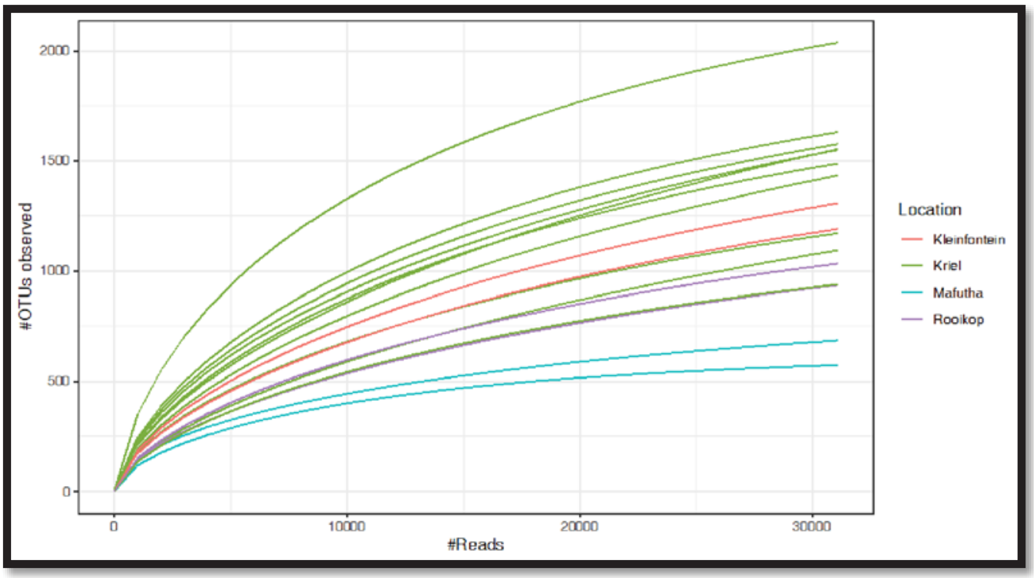


Figure 1. Rarefaction curves.

The number of OTUs per sample ranged from 574 to 2037 (Figure 2, Observed) and the samples were highly diverse (Figure 2, Chao1, Pielou and Shannon).

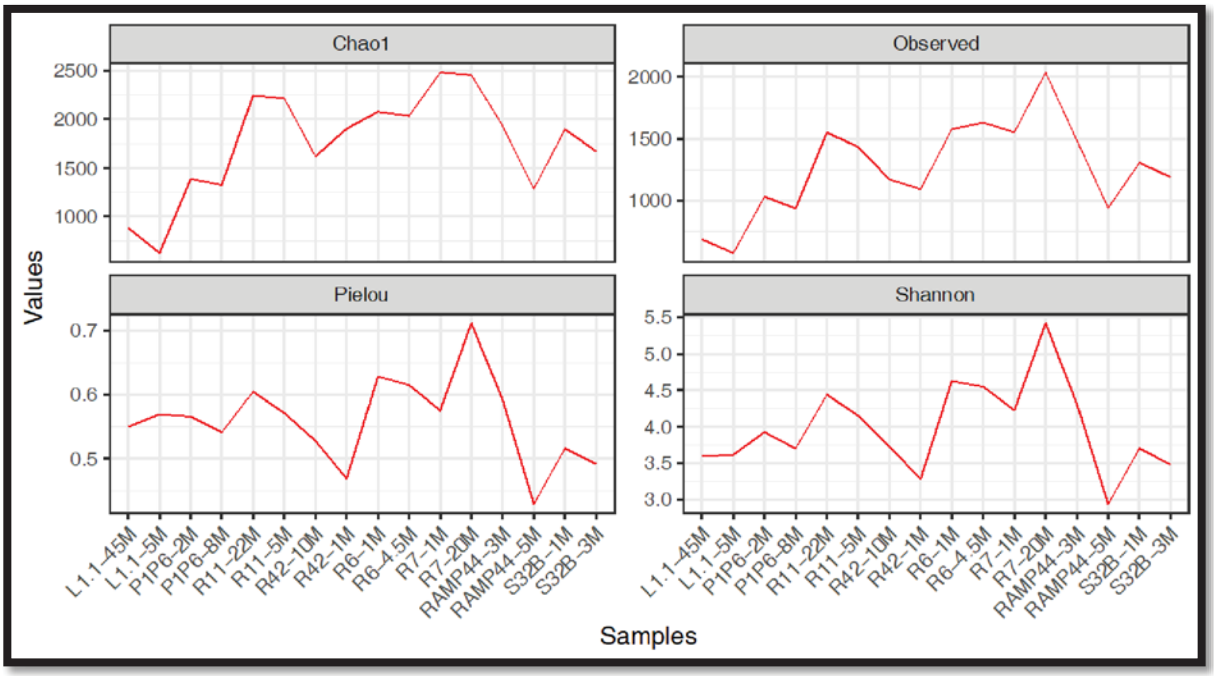


Figure 2. Microbial diversity

Most OTUs were found only in one sample (Figure 3).

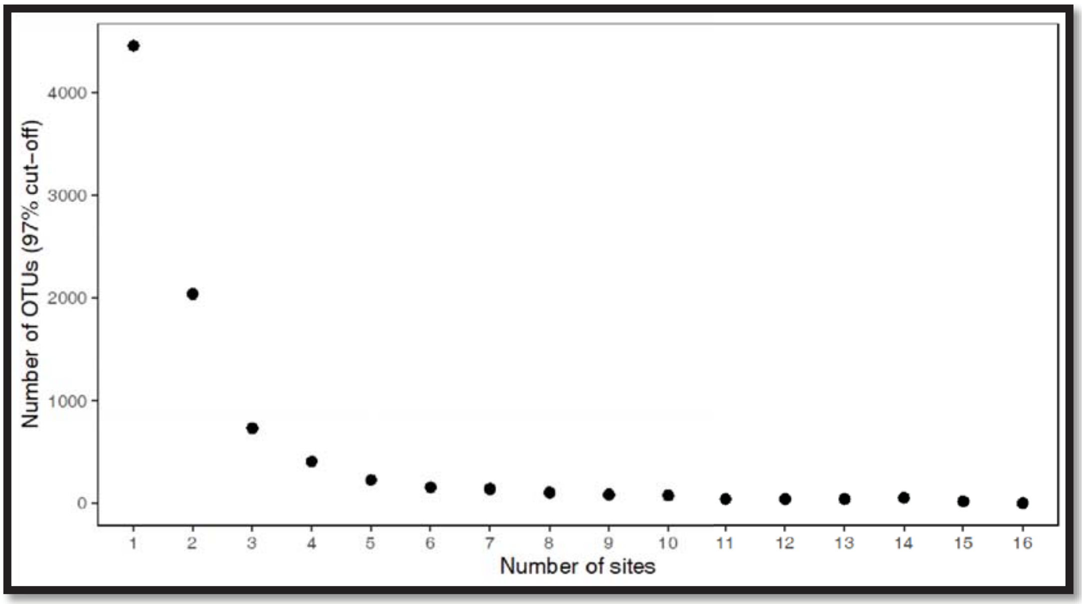


Figure 3. Distribution of the OTUs

Altogether, this indicates that these prokaryotic communities are highly diverse.

Microbial community composition
Different prokaryotic communities (OTU level) were detected in the four locations (Figure 4).

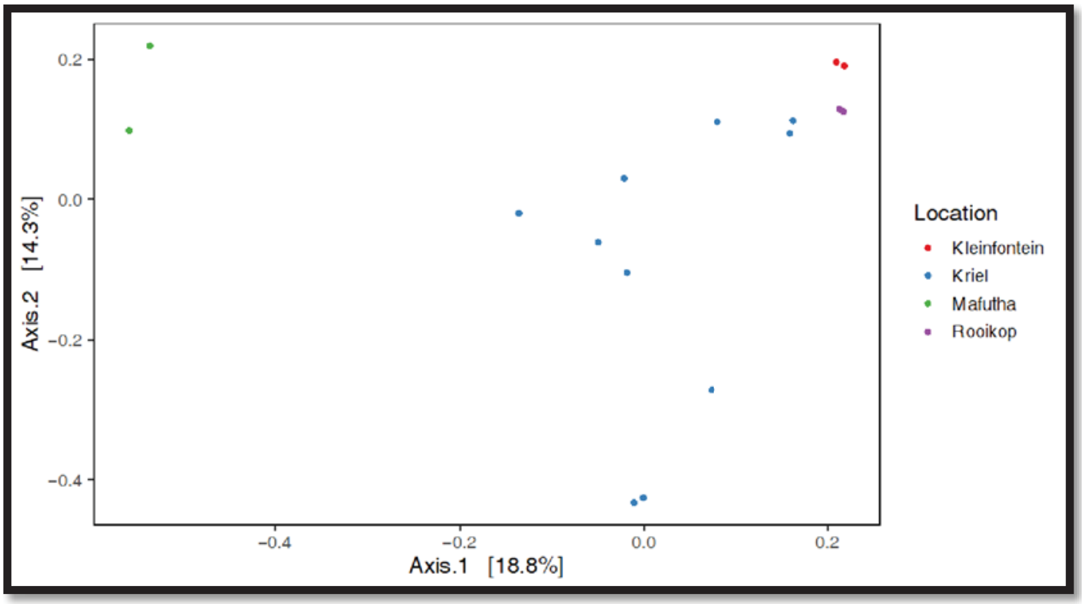


Figure 4. PCoA ordination plot.

Samples that are closer are more similar in microbial community composition.
Overall, Proteobacteria (47% mean relative abundance), Bacteroidetes (20%), Actinobacteria (11%) and Cyanobacteria (7%) were the most abundant phyla in the samples. Six other phyla, with average relative abundances higher than 0.4%, were also detected (Figure 5).

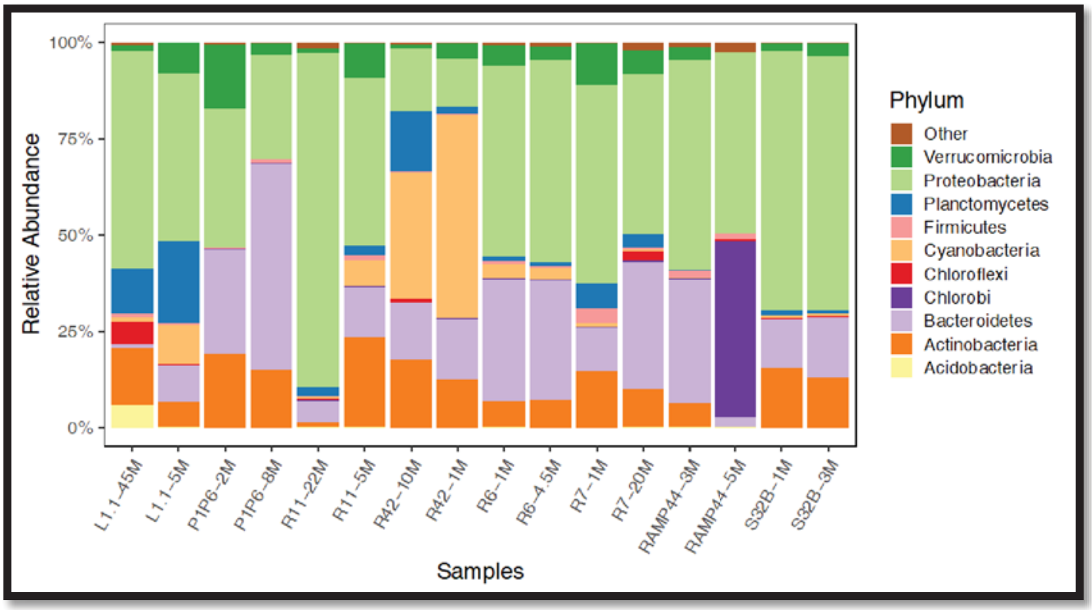


Figure 5. Major phyla present in the samples

The most abundant genera were Flavobacterium (3.7% mean relative abundance), *Pseudomonas* (3%), *Fluviicola* (2.8%) and *Nodularia* (2.9%). Fourteen other genera, with average relative abundances higher than 0.5%, were also detected (Figure 6).

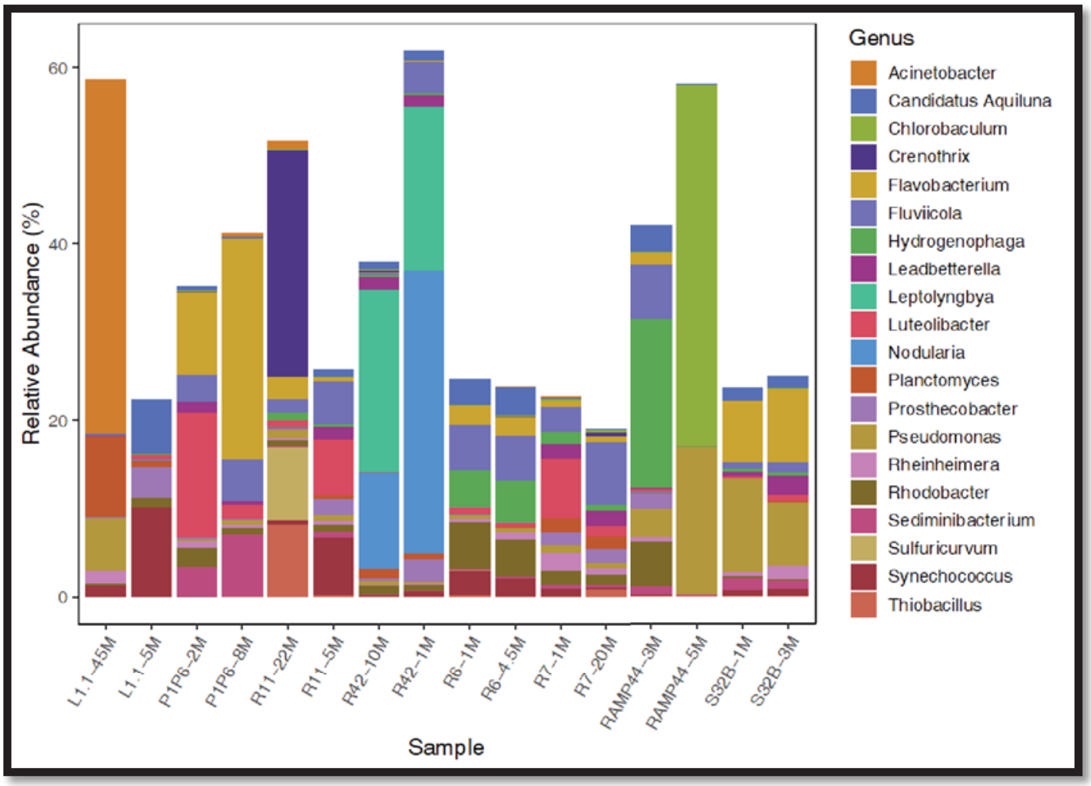


Figure 6. Major genera present in the samples

These results indicate that pitlake microbial communities are taxonomically diverse and present biogeographic patterns.

Microbial Functional groups
Functional groups were predicted using FAPROTAX, which extrapolates taxonomic microbial community profiles into putative functional profiles based on a database of cultured microorganisms. Functional annotation of the OTUs revealed a total of 90 metabolic functional groups in the samples. The numbers of functions per sample ranged between 35 and 56 (Figure 7).

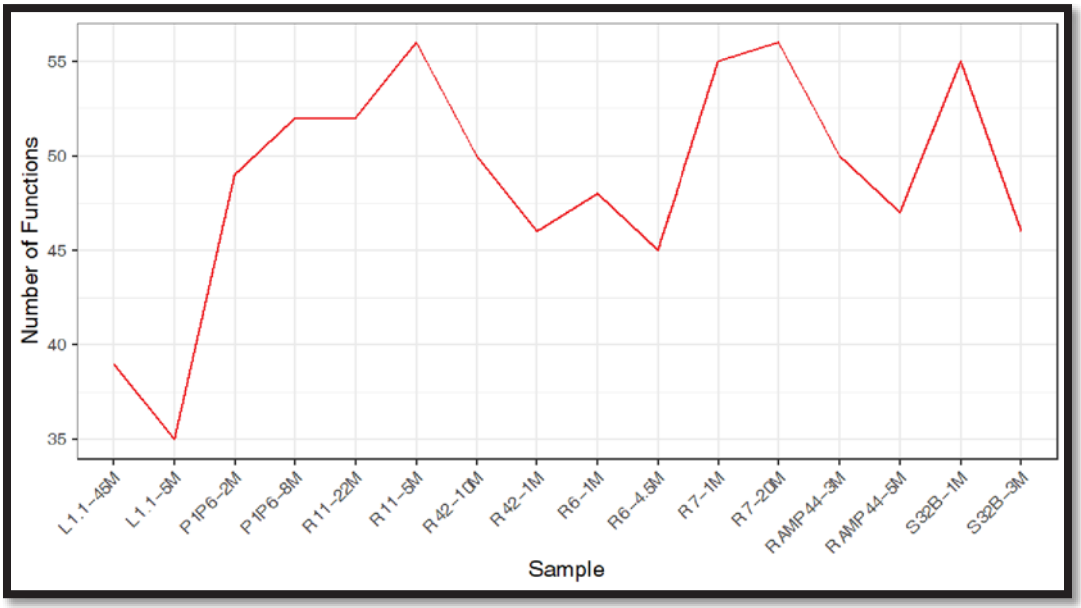


Figure 7. Functional diversity

It was found that the richness of the functional profiles was significantly correlated (R^2 = 0.69, $P < 0.05$) with the richness of bacterial communities across the samples). This observation suggests that microbial communities that are taxonomically richer also have a richer array of functional genes
Noteworthy, a different set of functions was found in the different locations (Figure 8).

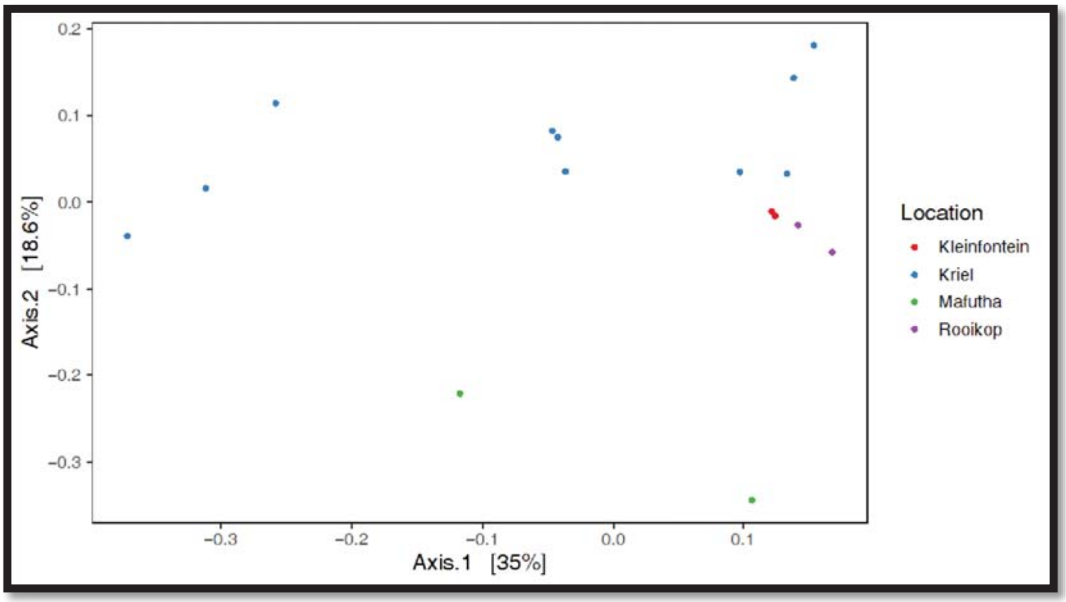


Figure 8. PCoA ordination plot. Samples that are closer are more similar in function.

Overall, microbial communities were dominated by chemoheterotrophs (Figure 9) and phototrophs. Taxa involved in the sulphur, nitrogen and carbon cycles were also an important component of the microbial communities.

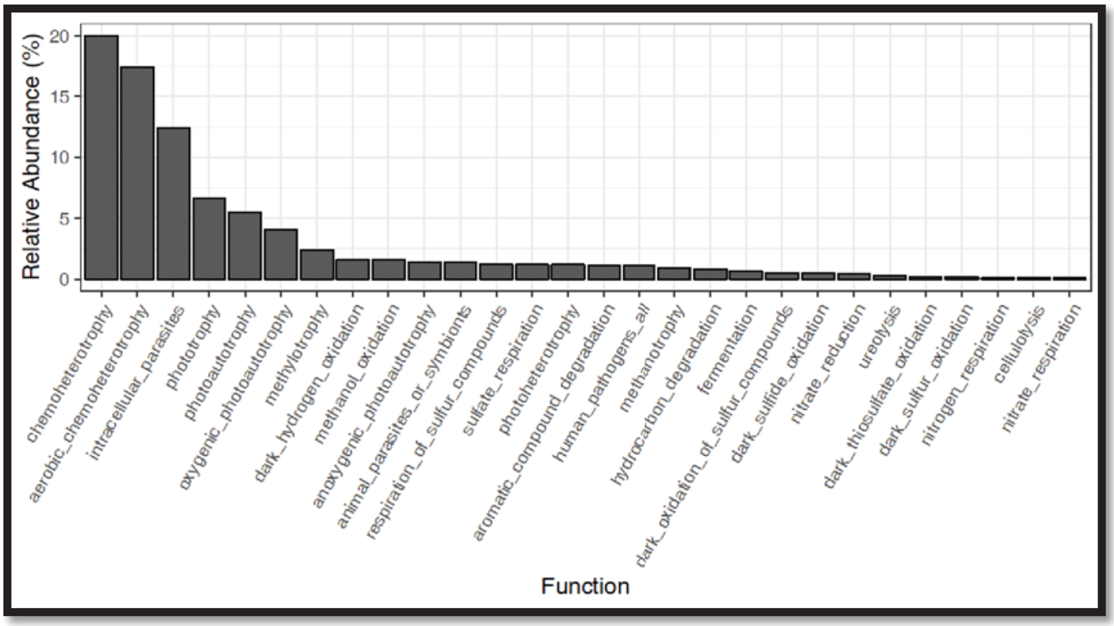
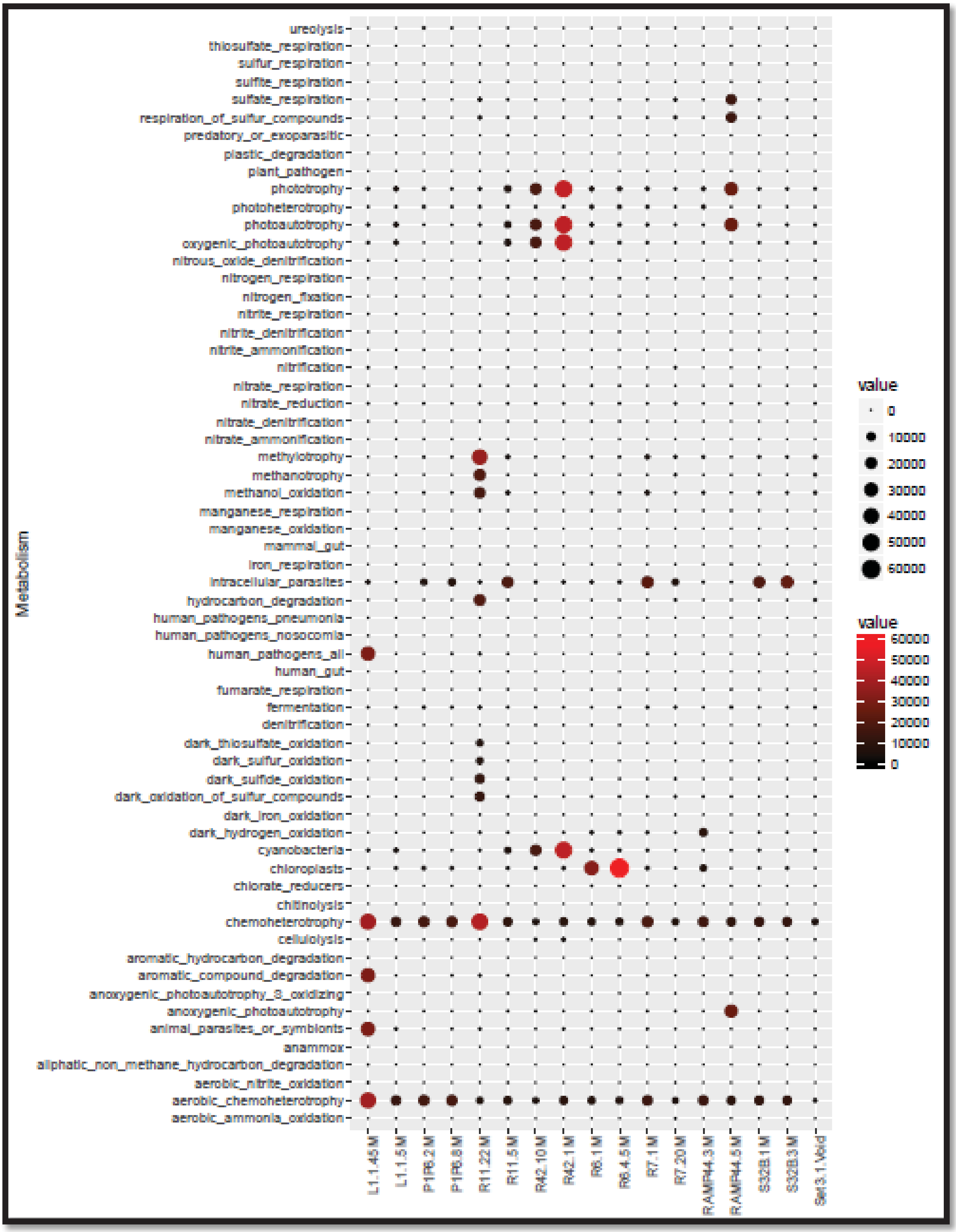


Figure 9. Relative abundance of the major functional groups

These results indicate that pitlake microbial communities are functionally diverse and that the microbial communities of the different pitlakes harbour different functional profiles; that is, that there is little functional redundancy.

Overall, our preliminary findings demonstrate that pitlakes' microbial diversity reflects a tremendous diversity of microbial metabolism and highlights the genetic potential yet to be discovered.


Metabolism
ureolysis
thiosulfate_respiration
sulfur_respiration
sulfite_respiration
sulfate_respiration
respiration_of_sulfur_compounds
predatory_or_exoparasitic
plastic_degradation
plant_pathogen
phototrophy
photoheterotrophy
photoautotrophy
oxygenic_photoautotrophy
nitrous_oxide_denitrification
nitrogen_respiration
nitrogen_fixation
nitrite_respiration
nitrite_denitrification
nitrite_ammonification
nitrification
nitrate_respiration
nitrate_reduction
nitrate_denitrification
nitrate_ammonification
methylotrophy
methanotrophy
methanol_oxidation
manganese_respiration
manganese_oxidation
mammal_gut
iron_respiration
intracellular_parasites
hydrocarbon_degradation
human_pathogens_pneumonia
human_pathogens_nosocomia
human_pathogens_all
human_gut
fumarate_respiration
fermentation
denitrification
dark_thiosulfate_oxidation
dark_sulfur_oxidation
dark_sulfide_oxidation
dark_oxidation_of_sulfur_compounds
dark_iron_oxidation
dark_hydrogen_oxidation
cyanobacteria
chloroplasts
chlorate_reducers
chitinolysis
chemoheterotrophy
cellulolysis
aromatic_hydrocarbon_degradation
aromatic_compound_degradation
anoxygenic_photoautotrophy_S_oxidizing
anoxygenic_photoautotrophy
animal_parasites_or_symbionts
anammox
aliphatic_non_methane_hydrocarbon_degradation
aerobic_nitrite_oxidation
aerobic_chemoheterotrophy
aerobic_ammonia_oxidation
L1.1.45 M
L1.1.5 M
P1P6.2 M
P1P6.8 M
R11.22 M
R11.5 M
R42.10 M
R42.1 M
R6.1 M
R6.4.5 M
R7.1 M
R7.20 M
RAMP44.3 M
RAMP44.5 M
S32B.1 M
S32B.3 M
Set3.1 Void
value
0
10000
20000
30000
40000
50000
60000
value
60000
50000
40000
30000
20000
10000
0

Appendix N: Preliminary Manual

A PRELIMINARY MANUAL FOR THE DESIGN OF COAL MINE PITLAKES AS AN ENVIRONMENTALLY STABLE CLOSURE OPTION IN SOUTH AFRICAN MINES

Preliminary Manual
to the Water Research Commission

by

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Project No. K5/2577//3

April 2019

INTRODUCTION

South Africa has been mining coal since the early 1800s, initially by conventional underground methods, but since 1950 the majority of the coal production has been from open cast mines. Coal is the major component of the South African Power supply network and this is predicted to continue into the latter half of the 21st century. Open cast coal mines generally leave a final void because of the mining method, insufficient overburden to fill the voids created by removal of the coal and /or to manage water. Once mining operations cease, these voids fill with water forming a lake which is generally referred to as a “pitlake”. The author has estimated that there are over 200 pitlakes in the three major South African coal fields namely the Mpumalanga/Witbank/Highveld, KwaZulu-Natal and Waterberg. The research study evaluates the environmental sustainability of using pitlakes as a closure option for old and proposed coal mines in South Africa. The current South African mining and environmental legislation states that all pitlakes should be backfilled for the mine to achieve mine closure.

The major factors which determining environmental sustainability of pitlakes are the water balance and water quality. Positive water balances result in discharge onto surface. The water quality of a pitlake determines the future use and the environmental risk. Pitlake water quality varies depending on the geology, mining method and catchment characteristics. In general, pitlake water quality may not comply with legislated catchment water quality standards.

This investigation concentrated on the two major drivers of pitlake sustainability (quantity and quality), whilst investigating four different pitlakes; the pitlakes were selected on the basis that they are representative of the major South African coal fields considering variances in geology, climatic conditions and mining methods.

Sufficient data was collected in the study to allow for the development of a guideline for the design of coal mine pitlakes in the South African coal fields. This preliminary design manual considered the water balances of the pitlakes and the biological and chemical process that drive the water quality of pitlakes.
The aim of this manual is to provide guidelines for the design of coal mine pitlakes for the pitlake to be a sustainable closure option.

Summary of the key findings

Detailed below is a summary of the major finding of the study and the reader is referred to WRC report 2577/1/19 for more details.

The factors affecting pitlake water balances (and as a result the variation in water levels) are groundwater, direct rainfall, runoff; while the losses from the pitlakes are evaporation, surface discharge and flow into the surrounding aquifer. The water balances of each of the pitlakes were evaluated to determine the major inputs and losses. The major input was groundwater, either from the aquifer or backfilled material, and the major loss was evaporation. Pitlake morphology, volumes and surface area are the major design considerations to prevent discharge of pitlake water into catchment.

The water quality in a pitlake determines the long-term ecological sustainability of pitlakes. The inorganic chemistry study concentrated on the water quality and vertical stratification. The in-situ parameters that were measured were pH, temperature, dissolves oxygen and the redox potential of each of the pitlakes. The organic study determined the phytoplankton, chlorophyll-a and the microbiology of the pitlakes. Additional research is required into the ecology to fully understand the evolution of the pitlake (Blanchette and Lund, 2016).

The conclusion of this study is that pitlakes can be environmentally sustainable if designed correctly. The organic and inorganic water quality in the pitlakes studied showed that the pitlakes are alkaline and have elevated total dissolved solid contents (mainly calcium sulphate) when compared to the natural surface and groundwater in the catchment. Pitlakes can support life in terms of chlorophyll-a, phytoplankton and microbiology (bacteria). The study did not investigate the biota or vegetation that the pitlake supported.

The surface area of a pitlake is vitally important to maximise evaporation which directly affects the water balance. In addition, surface runoff should be controlled to avoid excess runoff into the pitlake that may lead to a temporary positive water balance and uncontrolled discharge into the catchment. Should the pitlake be suitably designed, it forms a *"terminal pitlake"* which is a water sink and prevents uncontrolled discharge.

A fundamental change in the thinking and the South African legislative requirement is required to view pitlakes as an environmentally sustainable solution, to prevent uncontrolled discharge from open cast mining operations and to avoid the expense of ongoing water treatment. Correctly designed pitlakes offer an environmentally sustainable option for open cast coal mine closure in South Africa.

Design Considerations

This manual only deals with "terminal sink "and does not consider "flow through" pitlakes.

There are several fundamental considerations in the design of a terminal sink pitlake. These design concepts should be incorporated into mine plan and then developed into the mine closure plan and implemented during the last stages of mining while the earth moving equipment is still active on site.

The theory of pitlakes is based on research completed by Castendyk et al. (2009) and is shown in Figure 1: Conceptual relationship between the principal factors that affect pitlake water quality, where different elements ultimately contribute to the pitlake evolutions and their sustainability.

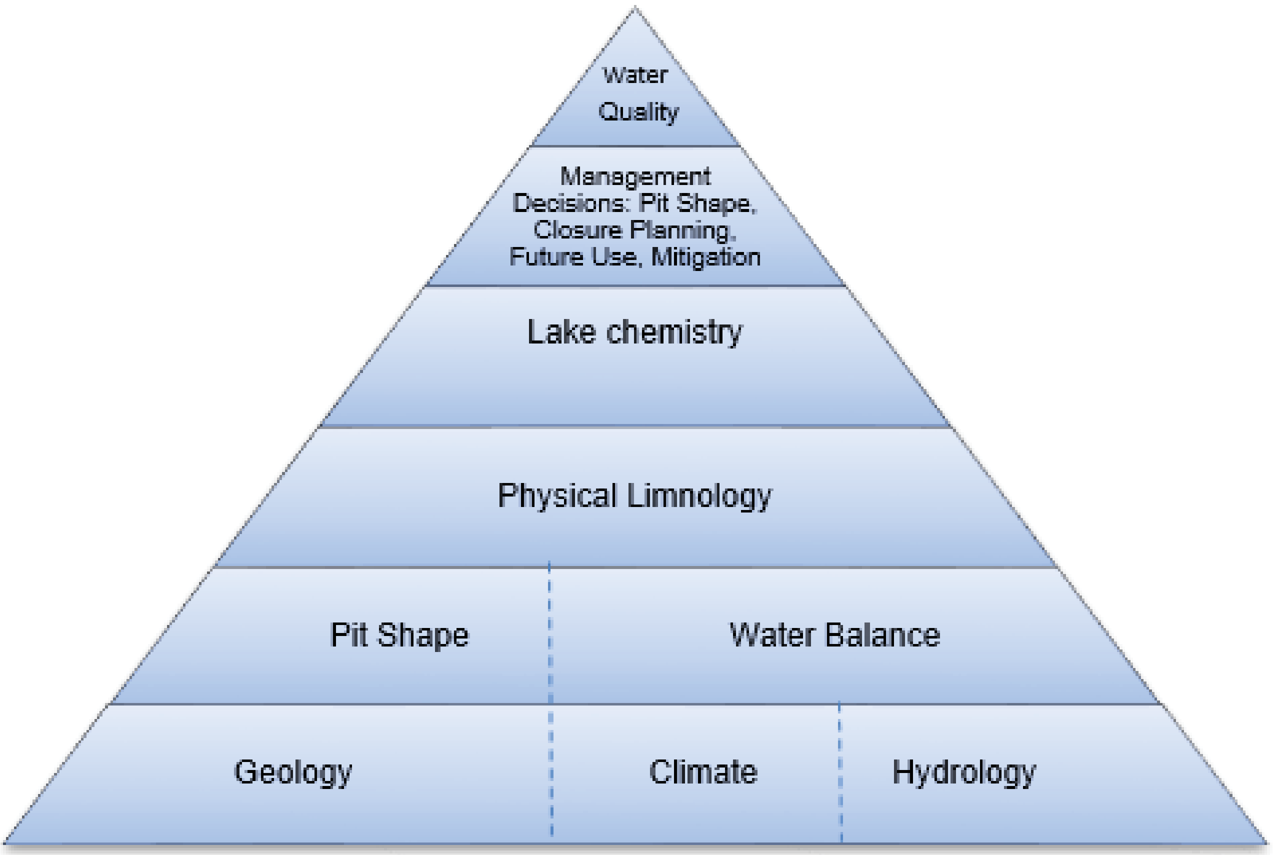

Figure 1: Conceptual relationship between the principal factors that affect pitlake water quality (after Castendyk and Eary, 2009)

The classification of pitlakes is primarily based on their interaction with the hydrology of the pitlake as described by Niccoli (2009):

- Flow-through pitlakes – groundwater and/or surface water flows into and out of the pitlake due to rainfall rates that exceed evaporation rates, and where the net water balance surrounding the pit is positive.
- Terminal sinks – Groundwater flows into the pit and the only outflow is evaporation. Accordingly, the net water balance surrounding the pit is negative.

The aim of the design of South African Pitlakes is that the pitlake is a terminal sink and prevents discharge onto surface under normal climatic condition. This manual does not consider flow through pitlakes as no flow through pitlakes were investigated as part of the study. In addition, the aim of the design manual is to ensure that the water quality in the pitlake is able to support an ecosystem no matter if it does not comply with catchment water quality standards. This maybe a licensing issue in terms of the National Water Act 1998.

Factors to consider in Pitlake water balances

The water balances are calculated based on a generalized mathematical expression, described by Gammons et al. (2009):

$$\Delta S = (P + SWin + GWin) - (E + (T) + SWout + GWout)$$

where

ΔS is change in storage, which is the volume of water in the lake,

P is the precipitation falling onto the pitlake,

SWin is the sum of any surface water inputs which includes runoff and diverted streams,

GWin is groundwater entering the lake,

E is the evaporation from the lake,

T is plant transpiration (which is often negligible),

SWout is surface water existing in the pitlake and includes pumpage,

GWout is the groundwater leaving the pitlake.

Discussion on the water balance components

ΔS; the aim is to maintain the pitlake level below the point of discharge on surface. In addition, the freeboard in the pitlake must be sufficient to allow for seasonal fluctuations in pitlake levels. As a tool a dynamic pitlake model should be used to determine the pitlake water balance and the potential variations in pitlake water levels.

P; Precipitation. In South Africa evaporation exceeds precipitation by a factor of 2-5 depending on the geographical location. Precipitation intensity and annual variations are critical in calculating pitlake water balances.

SWin; is the runoff into the pitlake from the catchment. This can be from natural catchment runoff or from the sidewalls of the pitlake. The aim is to keep runoff from the catchment into the pitlake to an absolute minimum to prevent a net positive water balance and discharge on surface. Another principal that should be incorporated into the surface water balance is the separation of clean and dirty water, where dirty water can be diverted into the pitlake (should the water balance still be negative) and the clean water into the catchment.

GWin; Groundwater inflow into the pitlake is usually greatest when mining ceased and the groundwater gradients into the pitlake are steep. As the pitlake levels rebound the net contribution to the pitlake water balance decreases. Where there is hydraulic connection between the pitlake, backfilled spoils and underground operation the net contribution of the historical mine areas should be assessed both in terms of volumes and quality (salt load contribution to the pitlake). In open cast operation the contribution to the pitlake water balance from recharge to the open cast spoils is a major consideration in terms of net inflow into the pitlake and the impact on the pitlake water quality.

E; Evaporation is the fundamental parameter that enables pitlake in South Africa to be sustainable. As a result, the area of the pitlake and the corresponding evaporation must exceed the sum of all the potential inflow. In other words, the greater the sum of the inflows the greater the surface area of the pitlake to allow for enough evaporation. Another consideration is that an excessive negative water balance will lead to an increase in salinity of the pitlake.

T; transpiration in South African pitlake is generally very low due to the limited vegetation in the pitlake. However potential transpiration must be included into the calculation of the pitlake water balance. This is more applicable to shallow pitlake that can support vegetated fringes.

SWout; Discharge from the pitlake must be avoided as the discharge water will not comply with catchment water quality standards. As a result the aim of the pitlake design is to eliminate SWout under natural climatic conditions and for return periods of less than 1:20 years.

GWout; Groundwater out is generally limited in South African pitlakes as pitlake tend to rebound to the near pre-mining groundwater levels. Groundwater gradients tend to be towards the pitlake if the lake is a terminal sink. Outflow into the aquifer usually only occurs during periods of excess inflow into the pitlake and an associated rise in the pitlake level above regional groundwater level. This may occur for limited periods.

The water balance of pitlakes is important, as it determines if the pitlake will discharge water into the environment and impact on communities and downstream water courses. Water balances in mines comprise an important role in mine planning and management, where calculations and decisions on best practice are made based on the prevailing climatic and hydrological/ hydrogeological conditions of the mine. If it is decided that a terminal pitlake is the best option for a mine closure, it should be incorporated into the initial mine plan.

Factors Impacting on Pitlake water quality

One of the most important factors to consider in the design of a pitlake is the water quality and if it will be a sustainable ecosystem. A major task is to predict the final pitlake water quality and how this water quality may evolve over time. The water quality must be assessed in determining the environmental sustainability of the pitlake.

During this study we did not find any final pitlakes that had really poor water quality. The research did not study any acid coal pitlakes. The pitlakes studied had a neutral to slightly alkaline pH and a total dissolve solid content varying from 1000 to 4000 mg/l mostly sodium bicarbonate in nature. Research by Annandale et al. (2007) has shown that the water is acceptable for agricultural irrigation.

One of the biggest impacts on water quality and the water balance of the pitlake is the level of rehabilitation on previously opencast material. The surface of opencast spoils should be rehabilitated to allow vegetation growth and normal soil forming process. The establishment of soil and vegetation reduces recharge to the spoils and as a result the salt load into the pitlake (Coleman et al., 2011).

Sulphide rich overburden above the coal seam has the potential to generate poor quality leachate. Also discard from washing plants and slimes also has the potential of generating low pH and poor-quality leachate. As a result, any potentially contaminating material must be place below the rebound water level. Climate change factors should be incorporated into the water balance calculations.

In general, shallow pitlake are more subject to wind which leads to aeration and introduction of oxygen into the pitlake. This has the added advantage of oxidising and the precipitation of metals. An additional advantage of shallow pitlakes is the increase in surface area and the corresponding evaporation.

Conclusions

Correctly designed terminal sink pitlakes are a sustainable mine closure option in South Africa Backfilling of pitlakes removes one of the major benefits of a pitlake, which is evaporation and creates the potential of uncontrolled surface discharge and the associated treatment.

This brief manual is aimed at highlighting some critical factors that have to be taken into consideration in designing environmentally sustainable pitlakes. The correct scientific data must be collected and applied to achieve the desired results which is an environmentally sustainable pitlake.

REFERENCES

ANNANDALE, J.G., BELETSE, Y.G., DE JAGER, P.C., JOVANOVIC, N.C., STEYN, J.M., BENADE, N., LORENTZ, S.A., HODGSON, F.D.I., USHER, B., VERMEULEN, P.D. and AKEN, M.E. (2007) “Predicting the environmental impact and sustainability of irrigation with coal-mine water.” Water Research Commission Report No. 1149/01/07, Pretoria, South Africa

BLANCHETTE, M.L., LUND, M.A. (2016) “Pitlakes are a global legacy of mining: an integrated approach to achieving sustainable ecosystems and value for communities.” Current Opinion in Enviromental Sustainability, 23:28-34

GAMMONS, C.H., HARRIS, L.N., CASTRO, J.M., COTT, P.A. and HANNA, B.W. (2009) Creating Lakes from Open Pit Mines: Processes and Considerations, Emphasis on Northern Environments.

COLEMAN, T.J., USHER, B., VERMEULEN, D., SCHOLTZ, N. and LORENTZ, S. (2011) “Prediction of how different management options will affect drainage water quality and quantity in the Mpumalanga Coal Mines up to 2080.” Water Research Commission Report No. 1628/1/11, Pretoria, South Africa.

NICCOLI, W.L. (2009) Hydrologic characteristics and classifications of pitlakes. In: Castendyk D, Eary T (eds) Mine pitlakes: characteristics, predictive modelling, and sustainability. SME, Littleton, pp 33-43.