GROUNDWATER MONITORING GUIDE-LINES FOR THE COAL INDUSTRY

by

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Declaration

I hereby declare that this dissertation submitted for the degree Masters in the Faculty of Natural and Agricultural Sciences, Department of Geohydrology, University of the Free State, Bloemfontein, South Africa, is my own work and have not been submitted to any other institution of higher education. I further declare that all sources cited or quoted are indicated and acknowledged by means of a list of references.

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Signed————————   Date 17/10/2011

M. R. Barnes

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This Study is dedicated to my late Grandfather.

I wish to give great thanks to;

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SECTION 1: APPROACH AND BACKGROUND

CHAPTER 1: INTRODUCTION

Coal was first discovered in South Africa, according to Roux (1998), in 1838 and 1859 in the provinces of Mpumalanga, Kwa-Zulu Natal, and the Eastern Cape. Since then, coal has played a vital role in South Africa's economy, satisfying the majority of the country's primary energy requirements, as well as bringing foreign investment into the country.

It is well established in literature (Hodgson *et al.*, 1998, Grobbelaar, 2001, and Lloyd, 2002) that the environmental impacts associated with the Coal Industry are severe, with one of the major impacts resulting in the deterioration of South Africa's scarce water resources. Due to the scope of the Coal Industry in South Africa and the associated impacts, it is vital that the industry's role players take a preventative, rather than a reactive approach, to manage these impacts on the environment. Groundwater monitoring is a management tool that, if properly utilised, can identify potential impacts before they result in irreversible levels of water degradation.

Groundwater monitoring is defined by the DWA (2008) as "the regular or routine collection of groundwater data (e.g. water levels, water quality and water use) to provide a record of the aquifer response over time". This 'response' over time refers to both the quality and quantity of the groundwater system. The main aims of a monitoring programme are to assist in the management of the water resource, help enforce compliance to environmental legislation and standards, and to facilitate in the protection of the country's groundwater. Monitoring, as a tool, can further assist in determining the effectiveness of various management measures and pollution control facilities that are used to contain contaminated water. For example if pollution control dams are lined with a clay and or plastic liner, there will be no contaminated groundwater identified during monitoring.

However if contamination is detected, this may point to design faults or breaches within the pollution control dams liners.

In order to have an effective groundwater monitoring programme, one has to conduct a number of investigations, ranging from desktop studies, to fieldwork investigations, to complex data interpretations. These investigations must be conducted methodically and combined to result in a realist conceptual model and useful groundwater monitoring programme.

1.1   SCOPE AND OBJECTIVES

The scope of this Study is to provide a comprehensive guide to the establishment of a groundwater monitoring programme in the Coal Industry. The specific aim of this Study is to present an inclusive methodology describing the different stages of establishing a groundwater monitoring programme. This methodology will focus on the 'why' and the 'how' of monitoring, with specific focus on the Coal Industry. This Study further aims to support role-players, in the management of the groundwater resources in and around their operations and to empower them to have clear guidance on the processes to follow for the establishment of a groundwater monitoring programme.

The objectives of the Study are to;
- Discuss the Coal Industry in South Africa,
- Describe the impacts of the Coal Industry on the groundwater resource,
- Develop a methodology comprising sequential stages required for the establishment of a groundwater monitoring programme for the Coal Industry, and
- Discuss each of these stages as laid out by the methodology as to provide insight into the requirements and process's needed for each stage.

1.2   STRUCTURE OF STUDY

This Study consists of three main Sections, each having a number of chapters specific to each relevant Section.

The first Section consists of three Chapters and forms the introduction to the Study.
- Chapter 1: Describes the goals of the Study and why it is important.
- Chapter 2: Is a discussion about the reserves of coal found in South Africa, whilst describing the utilisation of coal, and an overview of the impact of this utilisation in South Africa.
- Chapter 3: Is a brief overview of the relevant environmental and mining legislation regarding groundwater in South Africa.

The second Section consists of 11 Chapters and describes the different stages in the establishment of a groundwater monitoring programme.
- Chapter 1: Describes how a monitoring programme is established and focuses on the objectives of a monitoring programme. Chapter one therefore forms the initial step in the development of a monitoring programme.
- Chapter 2: Describes what a conceptual model is and explains the different site investigation methods used to conceptualise the model.
- Chapter 3: Discusses how risk assessments can be undertaken in terms of the Source-Pathway-Receptor Principal and how they are used to refine the conceptual model.
- Chapter 4: Discusses the different borehole drilling methods by focusing on the benefits and disadvantages of each method.
- Chapter 5: Discusses how monitoring boreholes are installed, with particular focus to the construction of monitoring boreholes.
- Chapter 6: Briefly discusses how sampling must be conducted during groundwater monitoring.
- Chapter 7: This chapter highlights the interpretation of key chemical parameters for groundwater monitoring with respect to the Coal Industry.

- Chapter 8: Discusses how and why groundwater programmes are reviewed and updated.
- Chapter 9: Highlights the main safety concerns that need to be identified at the different stages of a monitoring programme.
- Chapter 10: Contains the conclusions of the Study.
- Chapter 11: Provides a summary of all the necessary stages.

The third Section serves as a case study for the establishment of a groundwater monitoring programme following the methodology as set out in the Study. The case study will be carried out on a green fields Coal Mine in the Province of Mpumalanga, South Africa.

CHAPTER 2: THE COAL INDUSTRY IN SOUTH AFRICA

2.1   INTRODUCTION

Coal, according to Roux, (1998) is a "readily combustible sedimentary rock containing more then 50 percent by weight and 70 percent by volume of carbonaceous material, and is formed by the accumulation, compaction, and induration of variously altered plant remains". Coal in South Africa was first discovered in the mid 1800's in Mpumalanga, the Eastern Cape, and KwaZulu-Natal provinces. South Africa has extensive coal reserves ranging in grade, type, and rank. Even though South Africa has the benefits of widespread reserves, it is highly dependent on its coal reserves. Coal is South Africa's primary source of electricity production, contributing over 75 percent of the country's power supply (Fourie *et al.*, 2006). South African coal can be divided into three broad categories, each decreasing in quality. The first is export coal South Africa is the fourth largest coal exporter in the world (GCIS, 2007) where coal is exported to foreign markets. The total export revenue in 2002 amounted to R20 billion (Hobbs *et al.*, 2008). The second category is steam coal it can be regarded as a lower grade of coal, however steam coal is widely utilised for the generation of electricity through coal fired power stations. The last category is discard coal it was estimated that 500 million tons of discard, in 2003, was lying in coal discard stockpiles around the country. There has been extensive research into the reworking of these dumps in order to generate electricity (WEC, 2003).

2.2   SOUTH AFRICAN COAL RESERVES

Coal is found in South Africa in 19 coalfields, as can be seen in Figure 1. Of these coalfields, the majority of the coal reserves are located in KwaZulu-Natal, Mpumalanga, Limpopo (previously the Northern Province), and the Free State, with lesser reserves in Gauteng, the North West Province and the Eastern Cape (Jeffery, 2005). The geological unit associated with the coalfields in South Africa belongs to the Karoo Supergroup and is estimated to have been deposited during the Devonian and Cretaceous period, around 330 ma ago. In 2007, the extent of the coal reserves in South Africa was estimated at 34 billion tons (EIA, 2010). The coal in South Africa consists of bituminous and anthracite coal, with bituminous coal making up the majority of South Africa's coal reserves.

Name of Coalfields
1. Limpopo (Tuli)
2. Waterberg (Ellisras)
3. Soutpansberg West (Mopane)
4. Soutpansberg Central (Tshipise)
5. Soutpansberg East (Venda-Pafuri)
6. Springbok Flats
7. Witbank
8. Kangwane
9. Free State
10. Vereeniging-Sasolburg
11. South Rand
12. Highveld
13. Ermelo
14. Klip River
15. Utrecht
16. Vryheid
17. Nongoma
18. Somkhele
19. Molteno-Indwe
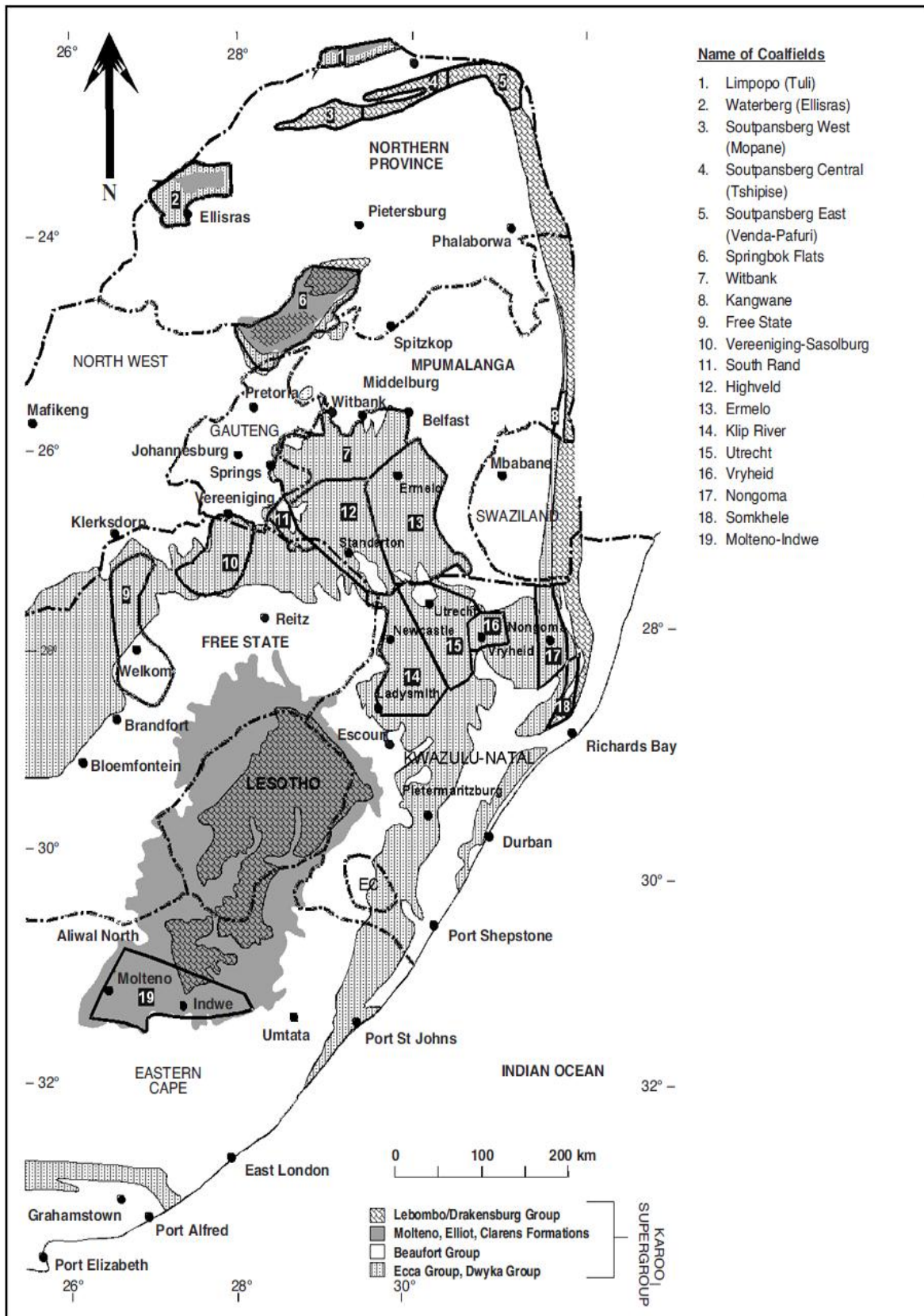
Figure 1: Coal reserves in South Africa.   (Jeffery, 2005)

2.3   CURRENT MINING IN SOUTH AFRICA

Five Mining houses dominated the mining industry in 2006 and made up nearly 90 percent of the saleable coal in South Africa. Figure 2 represents these mining houses, as well as their stake in South Africa's total saleable coal production.
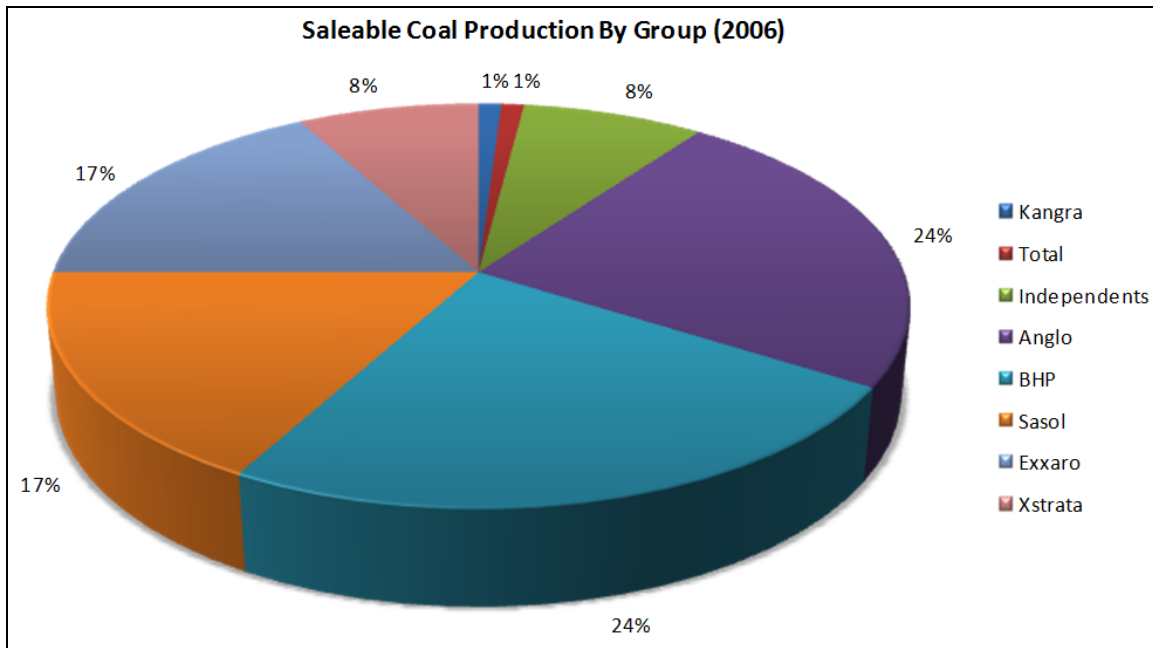
Figure 2: Dominant Mining houses.   (EPA, 2008)

Both underground and opencast mining take place within South Africa**.** About 37 percent of South Africa's coal production comes from underground mines and about 63 percent comes from surface mines (GCIS, 2007). The most common form of underground mining, especially in the Mpumalanga coal fields, is the bord-and-pillar method of coal extraction. According to Grobbelaar, (2001) bord-and-pillar mining consists of removing the coal deposits that are mined, by cutting and blasting a system of "bords" into the coal seam, which are represented by the portion of coal seam removed, and the "pillars" of coal are left behind to support the roof. The pillars can also be removed during a practice called stooping. The two most common opencast (surface) mining methods are open pit mining and strip mining. For open pit mining, a large pit is excavated and the coal body is mined in whichever direction the coal seam is located. For strip mining, the mining is conducted in long narrow strips. The stripping of overburden is conducted in alternating sequences until the coal is removed (Roux, 1998).

2.4   COAL UTILISATION

The use of coal is dependent on its type, rank, and grade. Roux (1998) adapted Alperns' Classification of Coal to indicate how the different types of coal can be utilised. The classification diagram according to utilisation of coal can be seen in Figure 3 below.
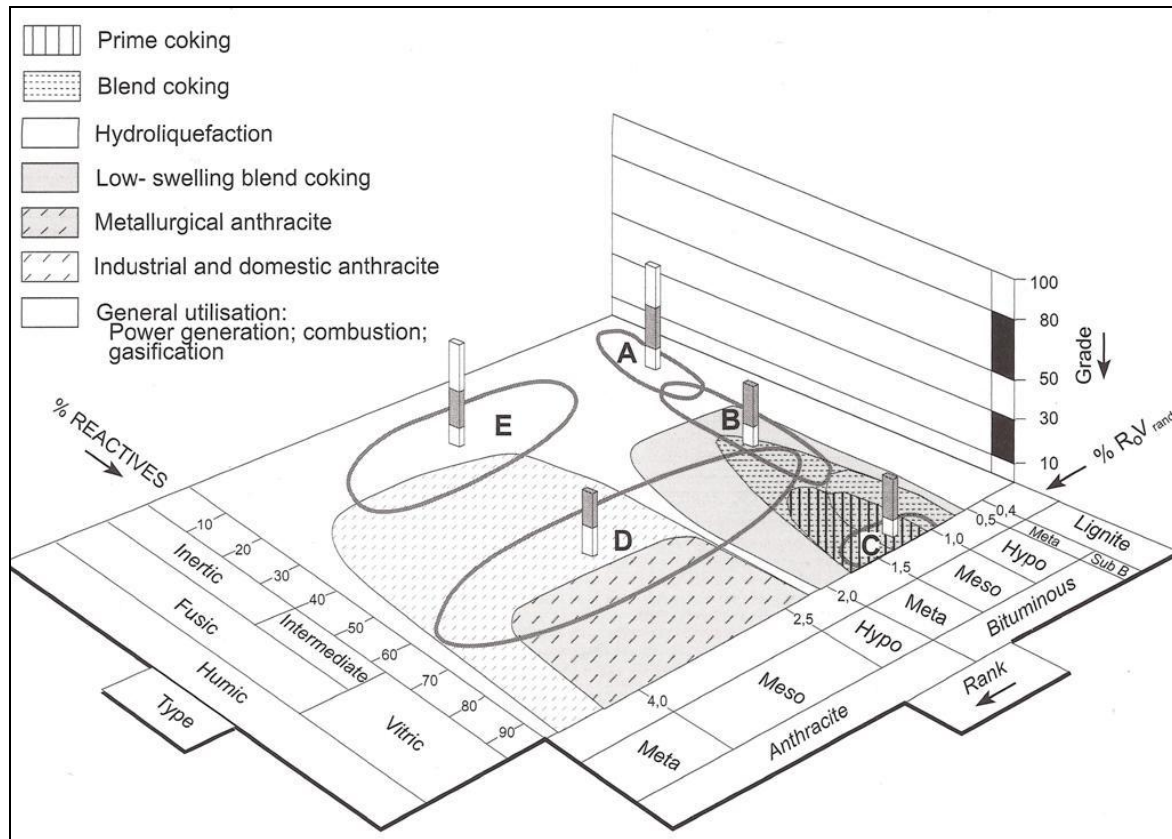
Figure 3: Coal utilisation classification.   (Roux, 1998)

By studying the Alpern diagram, one can see for example, that a low-medium grade bituminous coal, with low reactives can be used by Sasol, which produces synthetic fuels from low-grade coal. Coal is chiefly utilised in South Africa by the energy sector, with the principal energy producer for the country being Eskom. There are a number of coal fired power stations in South Africa as shown in Figure 4. Due to the increasing electricity demands in the country, Eskom is planning on increasing the country's electrical capacity. The expansion project, according to Eskom (2010), will cost R385 billion up to the year of 2013. In association with the expansion project, construction of new coal fired power stations as well as the re-commissioning of previously mothballed power stations will be put into operation.

Legend

- Coal-fired
- Coal-fired (RTS)
- Nuclear
- Hydroelectric
- Pumped storage
- Open cycle gas turbine
- National grid
- Windfarm

ZIMBABWE

MOZAMBIQUE

LIMPOPO
- Musina
- Lephalale
- Tzaneen
- Phalaborwa
- Polokwane
- Thabazimbi
- Bela Bela

BOTSWANA

MPUMALANGA
- Pretoria
- Johannesburg
- Nelspruit

NORTH WEST

GAUTENG

SWAZI LAND

NAMIBIA

- Oranjemund
- Newcastle
- Ladysmith
- Bergville
- Richards Bay
- Welkom

FREE STATE

- Kleinsee
- Springbok
- Kenhardt
- De Aar

NORTHERN CAPE

- Bloemfontein
- Pietermaritzburg
- Durban

LESOTHO

KWAZULU-NATAL

- Port Shepstone

- Beaufort West

- Mthatha

EASTERN CAPE

- Vredendal

- Saldanha

WESTERN CAPE

- Grabouw
- Agulhas
- George
- Mossel Bay
- Cape Town

- East London

- Port Elizabeth

Base load stations

1	Arnot	2 100 MW
2	Duvha	3 600 MW
3	Hendrina	2 000 MW
4	Kendal	4 116 MW
5	Koeberg	1 930 MW
6	Kriel	3 000 MW
7	Lethabo	3 708 MW
8	Majuba	4 110 MW
9	Matimba	3 990 MW
10	Matla	3 600 MW
11	Tutuka	3 654 MW

Return-to-service

12	Camden	1 600 MW
13	Grootvlei	1 200 MW
14	Komati	1 000 MW

The return-to-service (RTS) stations were mothballed in 1990 and are in the process of being recommissioned to meet the growing demand for electricity.

Peak demand stations

Hydroelectric:

15	Gariep	360 MW
16	Vanderkloof	240 MW

Pumped storage:

17	Drakensberg	1 000 MW
18	Palmiet	400 MW

Peak demand stations

Open cycle gas turbine:

19	Acacia	171 MW
20	Port Rex	171 MW
21	Ankerlig	592 MW
22	Gourikwa	444 MW

The peaking stations can generate electricity within a few minutes of start-up, making them ideally suited to supply power during peak periods. They also assist in regulating the system voltage and frequency to ensure stability of the national transmission network.

Renewable energy

Windfarm:

23	Klipheuwel Windfarm	3.2 MW

New build

Base load:

24	Medupi	4 788 MW

Pumped storage:

25	Ingula	1 332 MW

Open cycle gas turbine:

26	Gas 1	1 036 MW

Distribution

27	First Falls	6.4 MW
28	Second Falls	11 MW
29	Colley Wobbles	42 MW
30	Ncora	2.4 MW

These hydroelectric power stations fall within the Distribution Division's Southern Region and are used to stabilise the distribution network in that area.

Figure 4: Eskoms Power Stations.   (GCD, 2008)

2.5   IMPACTS OF COAL MINING

Coal has the most waste implications of all energy sources. Several wastes result from the utilisation of coal namely sulphur and nitrogen oxides, heavy metals, greenhouse gases and large ash waste dumps (Eskom, 2010). For the purpose of this Study, the impacts relating to groundwater will be discussed.

2.5.1   Water Quality Deterioration

There are a number of chemical reactions that result in groundwater contamination during opencast and underground mining. Once uncovered rock is exposed to water and air, the dissolution of sodium, potassium and chloride-bearing minerals occurs. The amount of minerals dissolving into the hydrosphere systems is dependent on a number of factors, for example, the pH and oxygen content of the solution. When water and oxygen come into contact with sulphide-bearing mineral species during coal mining, a reaction called acid mine drainage (AMD) occurs (Hodgson and Krantz, 1998). In some geological sulfide bearing rocks, sulfides constitute a major proportion, for instance, metallic ore deposits, coal seams, oil shales, and mineral sands (Lattermoser, 2010). Pyrite is a typical mineral that undergoes acid mine drainage. Tiwary (2001) states that "Acid mine drainage occurs in those mines in which sulphur content is found in the range of 1–5 percent in the form of pyrite (FeS_2). The reaction of pyrite oxidation and mine drainage is simplified into three steps below

Step 1: Pyrite reacts with water and oxygen, forming dissolved ferrous iron, acidity and sulfate.

$$4FeS_{2(s)} + 14O_{2(g)} + 4H_2O_{(l)} \longrightarrow 4Fe^{2+}_{(aq)} + 8SO4^{2-}_{(aq)} + 8H^+_{(aq)}$$
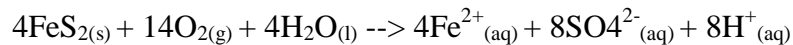
The reaction initiates once pyrite has come into contact with oxygen and water.

Step 2: Ferrous iron is oxidized to ferric iron.

$$4Fe^{2+}_{(aq)} + O_{2(g)} + 4H^+_{(aq)} \longrightarrow 4Fe^{3+}_{(aq)} + 2H_2O_{(l)}$$
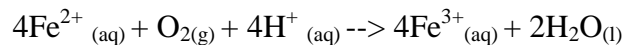
Constructed silt traps/ponds and aerobic wetlands promote this reaction.

Step 3: Ferric iron is hydrolyzed into insoluble iron hydroxide (yellow boy).

$$4Fe^{3+}_{(aq)} + 12\ H_2O_{(l)} \dashrightarrow 4Fe(OH)^{3}_{(s)} + 12H^{+}_{(aq)}$$
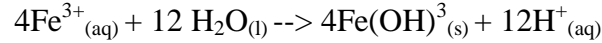
Yellow boy is an insoluble precipitate which coats stream beds and forms thick yellowy-orange sludges in water bodies.

With each step, more and more hydroxides are released into the systems, further adding to the acidity of the solution. Once at the third step, the hydrolysis of iron hydroxide from ferric iron can be self sustaining as long as ferric iron is present within the system. This means that once the third step has initiated, oxygen is no longer a driving force for acid generation. The typical consequences of mine drainage are water with very low pH values as well as highly elevated amounts of dissolved metals and salts, such as iron, and aluminium and sulfate. Groundwater then becomes toxic for domestic and livestock consumption. Table 1 further summarises the environmental impacts associated with AMD waters.

Table 1: Impacts associated with AMD waters.   (Ritchie, 1994)

Property	Chemical species	Concentration range in solution	Environmental impact
Acidity	H^+	pH<4.5	Loss of bicarbonate to photosynthetic organisms; degradation and death to animals and plants; reduction in drinking water quality; mobilisation of metals ions; corrosion of man made structures.
Iron precipitates	Fe^{3+}, Fe^{2+}, $Fe(OH)_{3(S)}$	100 to $1-9x10^3$mg l^{-1}	Discoloration and turbidity in receiving water as pH increases and ferric salts precipitate; smothering of benthic organisms and clogging up of fish gills; reduction on light penetrating the water column; encrustation of man-made structures
Dissolved heavy metals and metalloids	Cu, Pd, Zn, Co ,Ni ,Hg, As, S	0.01 to $1-9x10^3$mg l^{-1}	Degradation and death to plants and animals; bioaccumulation; reduction in drinking water quality; soil and sediment contamination
TDS	Ca, Mg, K, Na, Fe, Al, Si, Mn, SO_4	100 to more than $1-9x10^4$mg l^{-1}	Reduction in drinking water quality; reduction in stockwater quality; encrustation of man made structures as TDS precipitates as salts; soil and sediment contamination

2.5.2 Water Quantity Deterioration

The Coal Industry does not just have an impact on the groundwater quality, but also impacts on the quantity of the water available (Choubey, 1991). Once the mine workings intercept aquifer systems, water from these systems enters the open pit or underground workings. Mines workings, therefore have to be continuously pumped to remove excess water from the workings (Robb, 1994). The main aims of dewatering the underground and opencast workings are to ensure the safety of the miners as well as to gain accessibility to the coal seams. The act of removing this water from mine workings however, results in a cone of depression surrounding the mine. A cone of depression is a decrease in hydraulic head and results in the lowering of the water table. Mining further alters the natural underground hydrological conditions by deviating the natural flow of groundwater, thus creating paths of less resistance which results in water entering the mining area.

The dewatering of aquifers can have a number of implications on the surrounding water uses, such as, the lowering of the static water levels in boreholes, directly impacting on borehole yields, and the drying out of rivers and wetlands as the result of subsiding water levels feeding these systems.

CHAPTER 3: SOUTH AFRICAN ENVIRONMENTAL LEGISLATION

3.1   INTRODUCTION

Below is a brief summary of the various environmental legislation relating to groundwater use and protection. South Africa's environmental legislation is driven through Section 24 of the Constitution which states:

> *Everyone has the right-*
>
> *(a) to an environment that is not harmful to their health or well-being and*
>
> *(b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that-*
>
> *(i) prevent pollution and ecological degradation*
>
> *(ii) promote conservation and*
>
> *(iii) secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development.*

The constitution ensures that the groundwater system in South Africa is protected and is properly used. The constitution makes it every South Africans responsibility to protect the groundwater resource for present and future generations.

3.2   MINERAL AND PETROLEUM RESOURCES DEVELOPMENT ACT

The Mineral and Petroleum Resources Developments Act, No. 49 of 2008 (MPRDA) governs all activities regarding the minerals of South Africa. The MPRDA oversees mineral rights, prospecting permits, and mining authorisations. The MPRDA has a number of objectives, one of which is to ensure the mining of resources in an environmentally conscious and sustainable manner (Implates, 2007). Under the MPRDA it is therefore illegal to contaminate the groundwater resource either intentionally or accidentally. The MPRDA enforces stakeholders to ensure their operations are not impacting of this resource by being proactive and implementing management tools to prevent pollution.

3.3   NATIONAL ENVIRONMENTAL MANAGEMENT ACT

The National Environmental Management Act, No. 107 of 1998 (NEMA) came into operation in January 1999. It forms the base of the environmental statute of South Africa. NEMA sets out a number of national environmental management principles that assist with the management of all activities that impact on the environment.

One of the foundations from NEMA is the 'polluter pays' principle that states that the person whom is responsible for the degradation of the environment covers the costs of remedying the pollution and/or degradation. NEMA imposes a duty of care on every person who causes, has caused or may cause significant pollution or degradation of the environment and to take reasonable measures to prevent the pollution or degradation of the environment from occurring. The remediation of groundwater contamination is a long and expensive process. By implementing financial and legal penalties, NEMA therefore again ensures that stakeholders take reasonable measures to prevent the pollution of the groundwater resource.

3.4   THE NATIONAL WATER ACT, 1998 (ACT 36 OF 1998)

The Department of Water Affairs (DWA), through the National Water Act, No. 36 of 1998 (NWA) recognises that the protection of the quality and quantity of the water resources is necessary to ensure sustainability of the nation's water resources in the interests of all water users and recognises the need for the integrated management of all aspects of water resources. Failure to manage the impacts of the Coal Industry on South Africa's groundwater in a sustainable manner throughout the life of the mine will result in the mining industry finding it progressively more difficult to obtain community and government support for existing and future projects (DWA, 2006). Therefore, monitoring programmes, especially in the Coal Industry, play a vital role in the sound management and protection of South Africa's groundwater resource. Section 21 of the NWA also discuses the different water uses that must be either registered or licensed before water can be utilised.

Under the NWA is the Government Notice 704 which specifically focuses on the use and protection of water in the mining industry. Since 1999, DWA and Private Stakeholders have been developing a series of Best Practice Guidelines for Water Resource Protection for the South African Mining Industry, one of these is the Best Practice Guideline G3, which specifically deals with the development of a monitoring programme. Both the Government Notice 704 and Best Practice Guidelines are discussed briefly below.

3.4.1 Government Notice 704

Government Notice 704 was promulgated on the 4th of June 1999 with the intention of regulating the use of water for mining and related activities. Its main goal is the protection of the water resource, by setting restrictions on the locality for mining activities and the use of materials utilised for mining activities. The Government Notice also sets out the procedure that must be followed for any incident involving a water resource.

3.4.2 Best Practice Guidelines

The Best Practice Guidelines for Water Resource Protection in the South African Mining industry, with the above mentioned legal documentation, all strive for a proactive management style instead of reactive management.

By being proactive, especially in the commissioning stages of mining activities, one can identify a potential problem and put in place a management system in order to prevent the incident or pollution source from occurring. DWA (2006) states that "monitoring programmes are very site-specific and need to be tailored to meet a specific set of needs or expectations focusing on the procedures that need to be addressed when designing a monitoring system". Best Practice Guidelines provide guidance for the construction of various pollution control activities for instance the construction of pollution control dams and mine residue dumps. The Guidelines further assist stakeholders by providing many tools, such as, predictive modelling and the development of water and salt balances.

SECTION 2: MONITORING PROGRAMME DEVELOPMENT

CHAPTER 1: INTRODUCTION

Fresh water is used, as described by Jackson *et al.,* (2001) to satisfy an endless amount of needs such as domestic use, industrial production, irrigation, waste processing, and to sustain habitat for aquatic life. According to the EPA (2000) between 1990 and 1995 there was a six fold increase in global water use. This increase is twice that of global population growth. The continual population growth in South Africa will result in a continual growing demand on South Africa's freshwater resources. In addition to this the mining, processing and transportation of coal, however critical to the country's economy, also has a number of harmful implications on the South African fresh groundwater resources. This therefore creates an urgent need to proactively prevent or minimise these potential groundwater impacts through long term protection and improved water management practices. One of these initiatives is to implement monitoring programmes in the various sectors in the Coal Industry. Monitoring is "the collection and analysis of repeated observations or measurements to evaluate changes in condition and progress toward meeting a management objective" (Elzinga *et al.,* 1998). Groundwater monitoring requires sophisticated interlinked stages which are often overlooked or not fully understood. This results in ineffective monitoring systems that do not represent the true nature of the groundwater system. Consequently a methodical approach must be undertaken in order to have an effective and economical groundwater monitoring systems.

1.1   ESTABLISHING A MONITORING PROGRAMME

Before one commissions a monitoring programme clear management objectives must be established. Objectives act as the 'ruler' to measure the effectives of a monitoring programme and to set out what exactly needs to be achieved. The management objectives must be set out with a practical and efficient mind set.

There is no need to have complex and drawn out objectives as these will only result in extra expenditure and confusion. By revolving the monitoring programme the objectives around three questions as prescribed by Steele (1987) one can set obtainable objectives that are meaningful and achievable. The first question that must be considered is 'why'. Why do you want to monitor the groundwater? Why is it important for your company to monitor the groundwater? When setting the objectives for a monitoring programme one must ensure that the objectives satisfy all the 'why' questions. Some of these objectives can be to maintain company policy and to promote an environmentally sustainable enterprise, to be a responsible stakeholder, or simply to be legally compliant and to comply with the requirements set out in the company's Environmental Management Plan Report (EMPR) and Water Use Licence.

The second question that the management objectives must answer is 'how'. How will the monitoring programme be implemented?, how many monitoring boreholes will be installed?, how often will sampling take place?, etc. The 'how' questions involve the company's commitment to effectively monitoring the groundwater. Economical factors will also have to be addressed during this phase of setting the objectives. Unfortunately one must revolve around the financial restraints of the company undertaking the monitoring programme. There is no point to setting objectives describing elaborate monitoring borehole designs with state of the art electronic devices when there are no monies for these idealised expenditures. One would rather set realistic objectives that fall within the company's budget and if need be implement a programme over a specified period. Oakley *et al.*, (2003) casually stresses this point by stating, "Designing a monitoring project is like getting a tattoo: you want to get it right the first time because making major changes later can be messy and painful".

Lastly the objectives must answer the question of 'how do we evaluate' the monitoring programmes? Objectives must also encompass time in order to effectively monitor trends in quality or quantity in the surrounding groundwater systems. The objectives must be developed with future plans and proposed activities in mind.

Like the management objectives, a monitoring programme too must evolve in order to represent the current and future operations.

The main aim of a successful monitoring programme as stated by Nielsen (2006) is one that consists of an adequate number of wells that are installed at targeted locations and depths. Monitoring programmes must also yield sufficient groundwater samples from the aquifer that represents the quality of up gradient groundwater that has not been affected by a facility and to represent the quality of groundwater down gradient of the facility.

Figure 5, shows the eight stages necessary for achieving a holistic and representative monitoring programme. A methodological approach must be followed as a monitoring programme where boreholes are installed at random locations, where boreholes are poorly constructed and maintained, and where improper sampling techniques are practiced is far too common. This can result in the company facing potential costly impacts that they themselves are not aware of due to the inadequate monitoring. The recommended eight stages for a groundwater monitoring programme are listed below:

- Stage 1: Develop monitoring objectives (Chapter 1, pg 16;
- Stage 2: Conceptual model and site investigations (Chapter 2, pg 20);
- Stage 3: Risk assessment (Chapter 3, pg 34);
- Stage 4: Drilling of targeted monitoring boreholes (Chapter 4, pg 46);
- Stage 5: Borehole installation (Chapter 5, pg 50);
- Stage 6: Sampling of monitoring boreholes (Chapter 6, pg 58);
- Stage 7: Water quality analyses and interpretation (Chapter 7, pg 74); and
- Stage 8: Review and updating (Chapter 8, pg 86).

With each stage an atmosphere of good health and safety must be present.

Figure 5: Groundwater Monitoring Programme Stages.

2.1   INTRODUCTION

The conceptual model is the most important step in developing a monitoring programme. It serves as a mental model of site conditions. In order to achieve an accurate conceptual module, numerous forms of data and information must be gathered and assessed. The Triangulation method is best used to develop a conceptual model and incorporates various forms of data and information as shown in Figure 6.
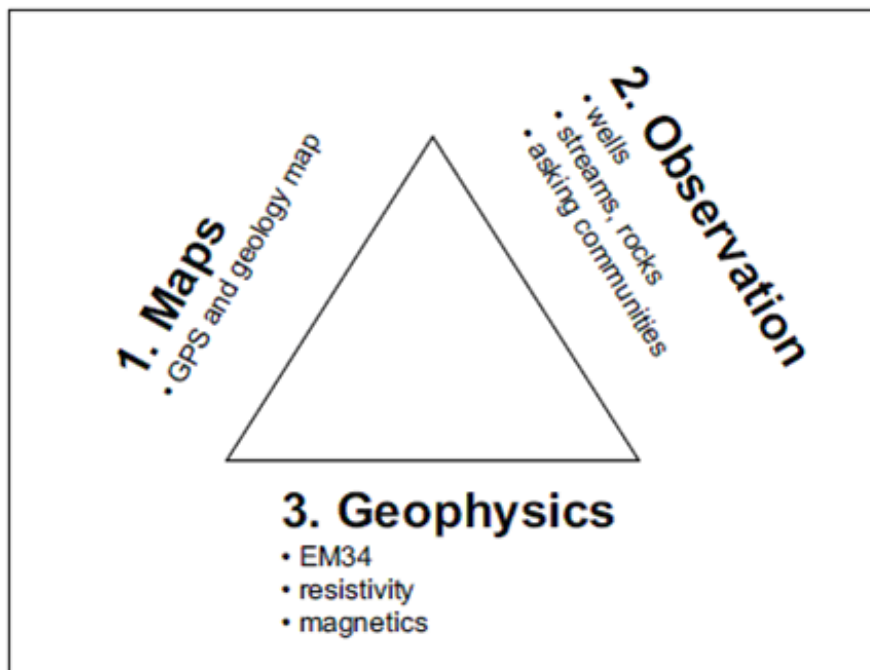
Figure 6: Triangulation method.   (EPA, 1999)

The fist step in the Triangular method is to obtain and study the sites specific cartographical source. The second step involves a site visit and observing the sites characteristics. The last step involves the utilisation of different geophysical methods to gain an understanding of the subsurface.

2.2   CARTOGRAPHICAL SOURCES

Cartographical sources are the starting point when siting monitoring boreholes. These sources provide background data for the investigation and aim to minimise extensive study areas, by highlighting focal points for surveys and traverses, which are later conducted during the geophysical investigations. Cartographical sources include photographs, images, maps, and background literature. These types of source are readily available and allow one to assess the site holistically (Nielsen, 2006).

2.2.1   Aerial Photographs

Aerial photographs can provide highly detailed images of the site and are helpful for identifying local geological structures, such as fractures and dykes, as they can appear as linear features on the photograph. Once these linear features have been identified, further site geophysical investigations can be carried out (EPA, 1999).

2.2.2   Satellite Imagery

Satellite imagery resources, such as Google Earth, unlike aerial photographs can be available for use at no cost. These sources however can be outdated and are of a lower quality depending on the source of the imagery. Satellite imagery is also often used to identify linear features around the site, which can then be targeted as potential pathways.

2.2.3   Site Specific Maps

Geological, hydrogeological, and topological maps all can either provide conformation of features identified in the aerial and satellite imagery or point to features that have not yet been identified. Maps too can be overlapped and the relationships between the maps can be assessed. If no linear features have been identified in the imagery sources, geological maps in particular can be used to site preferential flow paths such as contact zones and intrusions. The coordinates of the geological structures can then be used to identify target areas that can be further investigated by geophysical methods.

2.3 SITE VISIT

Site reconnaissance must commence as soon as possible after the review of the cartographical information states Nielsen (2006). This is important as all the information is fresh in ones mind and a clear conceptual model is conceptualised. During the site visit, the site itself as well as the immediate areas surrounding the site are investigated. It is highly recommended that one cannot simply look at cartographical source and sight-monitoring boreholes from the office, rather a site walk must be conducted before installing a borehole. There are benefits of going to site and taking a site walkover. By physically visiting the site there are a number of advantages such as: confirming the accuracy of existing information, identification of the presence of local geological anomalies, providing more insight to local geology, identifying gaps in information, and determining site suitability concerning access etc. Surrounding water users and communities can also be visited during site investigations. These communities also add valuable information to seasonal changes, daily water practices and usages (Nielsen, 2006).

2.3.1 Hydrocensus

During a hydrocensus, information is collected from areas surrounding the site under investigation, such information includes: water usage, the identification of springs and other boreholes, potential sources of contamination, static water levels, surrounding peoples experiences and opinions etc. The involvement in the community can provide valuable information. Usually the community has been there before the mine or dumps were established. They can therefore provide the Assessor/s with an insight to long-term changes in water levels, water quality, and local climate variations. It also gives a chance for one to educate the community about your site and operations, addressing their concerns and rectifying any negative myths connected to your operations (DWA, 2004).

2.3.2 Using One's Senses

When conducting site investigations it is important for the Assessor/s to utilise all their senses. Usually one simply observes the site and does not use all their senses such as touch and smell and as a result misses potentially useful information.

For example, Sewage and oil spillages maybe out of sight or concealed, however they can be identified through the sense of smell. During site investigations, if the soil is hard and feels crusty this is a sign of contaminated water flowing though the soil. When the soil dries and the water evaporates, the salts precipitate into the soil, resulting in a hard and crusty surface.

Therefore during field investigation, one must take in as much information as possible through all the senses, as this will help identify potential contaminates and other information that may be missed.

2.4   GEOPHYSICAL METHODS

In this Chapter, some common geophysical techniques used in the groundwater industry will be examined with the aim of describing when a particular method should be used and the advantages and disadvantages of each method. Geophysics, according to Anderson and Croxton (2008) **"**is the application of physics principles to the study of the Earth". Geophysics is a tool used to assist with solving geotechnical and hydrogeological problems by obtaining information regarding the subsurface. With respect to groundwater, geophysics is used to identify anomalies such as faults, intrusions, and zones of weathering by identifying contrasts within the subsurface. By utilising geophysical techniques these potentially water bearing anomalies can be identified and can then be targeted as potential pathways to groundwater flow.

There are two categories of geophysical methods namely passive and active systems. Active systems measure the subsurface responses to electric, electromagnetic or seismic energy. Passive systems measure the subsurface ambient magnetic, electric or gravitational characteristics (EPA, 1999). Geophysical methods have a number of advantages over other investigative techniques as they are: cost effective, rapid in obtaining subsurface data, non-invasive, portable, and safe (Anderson and Croxton, 2008).

The two more commonly utilised methods for groundwater investigations are the Magnetic and Electromagnetic methods. There are however numerous other geophysical methods available as is summarised in Table 2.

Each method measures a different characteristic of the subsurface and therefore they are often used in co-operation with each other. By utilising more than one method, a number of physical parameters can be measured and a clearer indication of the subsurface conditions can be realised, further adding the chance of siting a successful monitoring borehole. It must also be realised that no single method is successful for all environments. The choice of which geophysical method is to be used is based on what you aim to achieve with the method and what local conditions are present at site, such as local geology, depth, accessibility etc.

Table 2: Different geophysical methods and their applicability. (EPA, 1999; Nielsen, 2006; and Anderson and Croxton, 2008)

Geophysical Method	Uses	Penetration Depth
Gravitational	Identifies spatial variations in the density of the subsurface. Used to identify location of karsted features and variable depth to bedrock.	30m
Magnetic	Can locate magnetic bodies such as dykes or sills and provide a geologic profile or map (location of faults, variable depth to bedrock, etc.)	30m
Seismic	Can determine sediment thickness and identify fractures or faults present in bedrock.	100m
Electrical	Can locate changes in the weathered zone as well as the distribution of sands and clays, bedrock, fractures, faults, and the differences in geology. Can be used to calibrate electromagnetic surveys.	50m
Electromagnetic	Distribution of sand and clays, bedrock, fracture zones, faults, groundwater. Quick and easy method for determining changes in thickness of weathered zones or alluvium.	50m

2.4.1 Magnetic Methods

Magnetic methods work by measuring contrasts in the Earth's magnetic field due to the presence of magnetically susceptible materials (Anderson and Croxton, 2008). Susceptibility of a specific geological feature usually depends on its magnetite, pyrrhotite and ilmenite content. Usually sedimentary rock and acidic igneous rocks have small to no magnetite content where as gabbro, basalts etc are strongly magnetic.

Magnetic fields are measured in nanoTesla (nT) and are measured with a magnetometer. A G5 Magnetometer is and example of a magnetometer used to measure the magnetic fields in the underlying geology. A Magnetometer is used by one person whom carries a sensor on the supplied pole. The pole is kept in front of the carrier, so that the direction of the traverse has no influence on the measurements. However, if the emitter is carried on ones back, the direction of the traverse must be noted as this will have an impact on the magnetometer outputs. In this case the traverses are either conducted from north to south or east to west. At every station a reading is then taken and recorded. The entire site is usually gridded by numerous traverses, with each station spacing being five meters apart.

Magnetometers are very sensitive to noise from any metallic objects, power lines, fences, vehicles, cables etc (EPA, 1999). During field investigation it is recommended that all metallic objects and cell phones be removed from the person conducting the survey as these objects may potentially create noise within the data set.

2.4.2 Electromagnetic Methods

Electromagnetic methods (EM) measure the contrasts in the electrical conductivity of subsurface conditions. The unit of electrical conductivity is millisiemens per meter (mS/m). EM methods utilise a transmitter coil, which radiates an electromagnetic field, which induces eddy currents into the subsurface, as shown in Figure 7.

These eddy currents then induce secondary electromagnetic fields, which are intercepted by the receiver coil. The subsurface conditions can then be related to the voltage measured in the receiver coil. The coils can be orientated either vertically or horizontally. The different orientations change the direction of the inducing field. When the coils are orientated vertically, the instrument is sensitive to the electrical conductivity of horizontal conductors, such as weathering zones. When the coils are orientated horizontally the coils are sensitive to vertical conductors, such as vertical fractures (EPA, 1999).
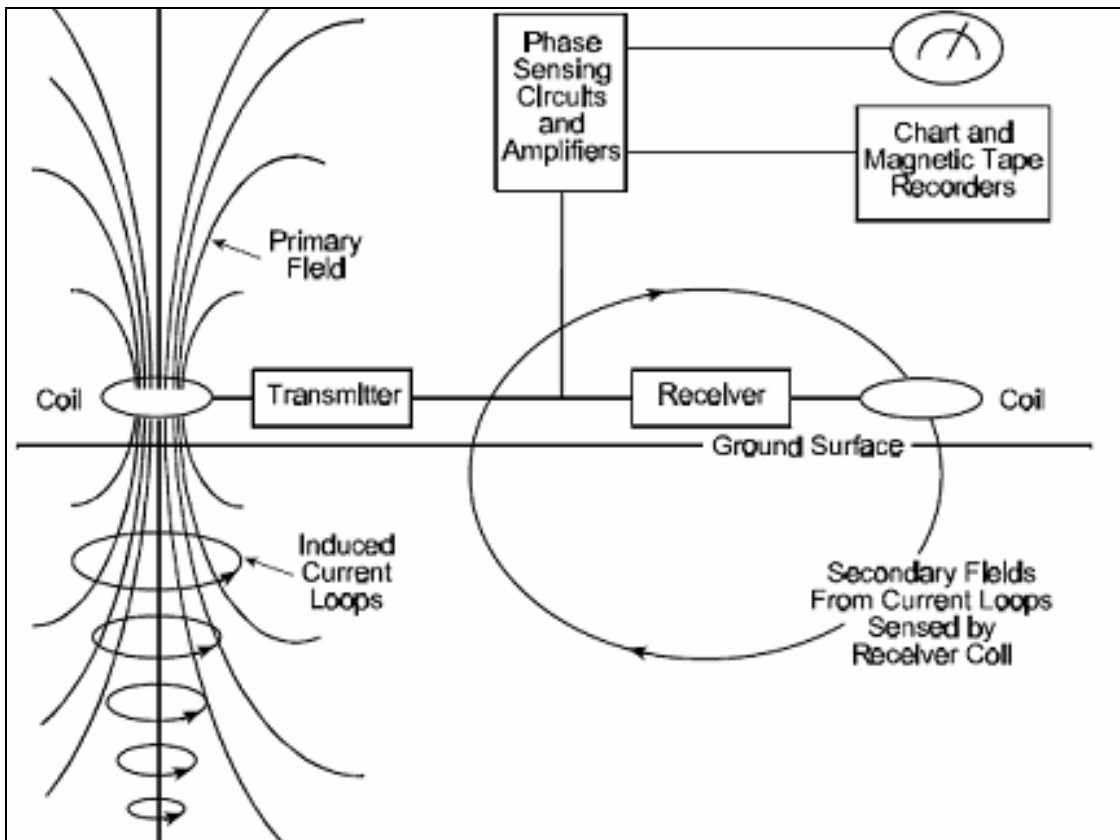
Figure 7: EM methods.   (EPA, 1999)

EM methods are used to detect changes in the weathered zone, the distribution of sand and clays, bedrock, fractures, faults, and mapping contamination plumes. EM methods are useful for surveying large areas as surveys can be done speedily and a large amount of anomalies can be identified.

When interpreting EM results it is important to keep in mind that a number of factors can influence the conductivity of the subsurface as listed below

- Recent rainfall resulting in saturated soils, artificially increasing the conductivity of the soil
- The electrical conductivity of the rock minerals – generally very low
- The volume of water in the rock (porosity and saturation)
- The salt content of groundwater and
- The amount of clay in the ground – clay is highly conductive.

Commonly an EM34 system (frequency-domain system) is used in groundwater investigations. The transmitter and receiver are connected to one another by a cable.

Depending on the depth of the groundwater investigations various cable lengths can be used. The EM34 system requires two people, one that holds the transmitter and the other whom holds the receiver. Similar to the Magnetometer, the site can be set up to form a grid consisting of a number of traverses. The system makes use of two loop orientations (vertical and horizontal) and measures the contrasts of the apparent conductivity of the subsurface. Readings are taken for both the horizontal and vertical dipoles at each station to ensure that the vertical and horizontal features are identified. By using coil separators of different lengths, ranging from 10 to 40 meters, different depths and targets can be either highlighted or dimmed, as shown in Figure 8. The EM34 system must be set to represent the specific cable spacing which is to be used for the investigations. This is done by simply changing the switch on the transmitter and receiver to the cable spacing to be used.

In the example portrayed in Figure 8, the targeting of deep weathering zones with the 10m coil separation, results in a sharper image of the lower lying weather zones, whilst the deeper weathered zones are more flattened and dimmed. For the 40 meter coil separation, the deep weathering zones are more highlighted whilst the shallow features are poorly differentiated. The 20 meter cable separation finds a more common ground between the 10 and 40 meter shallower and deeper areas.

Therefore it is recommended that the 20 meter coil separation be used for initial surveys. If time allows, the survey can also be repeated with the 40 and 10 meter coil separation to further enhance the interpretation of the deeper and shallower anomalies (EPA, 1999).
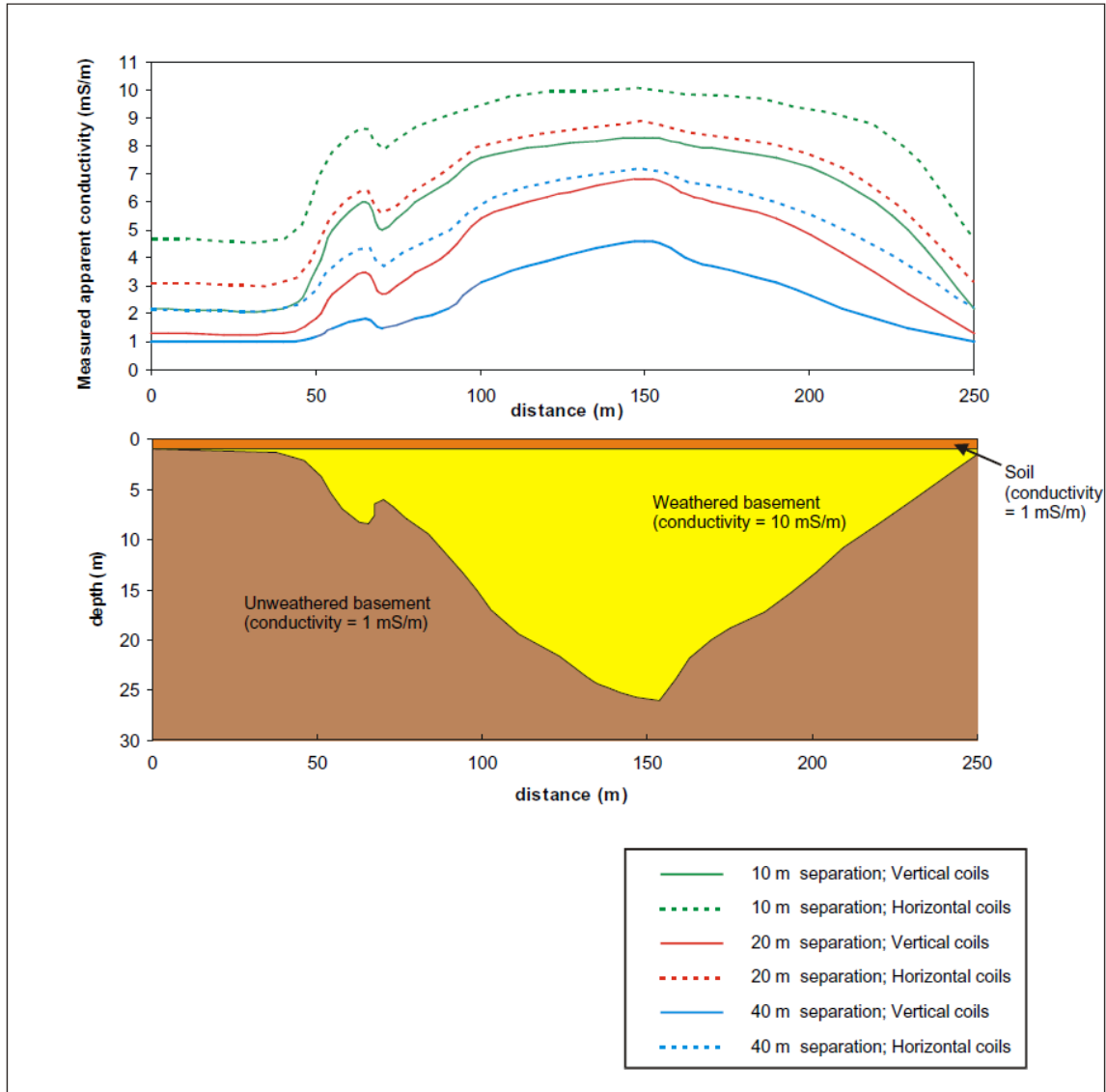
Figure 8: EM survey.   (EPA, 1999)

2.4.3 Electrical Resistivity Methods

Electrical Resistivity methods are used to determine the distribution of sands and clays, bedrock, karst formation, fractures, and faults. Ahmed *et al.,* (2008) defines resistivity as "the resistance offered by a unit cube of material for the flow of current through its normal surface". Resistance can be defined by the equation below where *L* is the length of the conductor, and *A* is its cross-sectional area, and where ρ is a constant of proportionality or resistivity:

$$R = \rho \frac{L}{A}$$

The unit of resistivity is ohm-metre (Ωm). Electrical resistivity is based on the electrical contrasts in the ability of the subsurface to conduct electrical current. This is done by passing an electrical current through a number of electrodes (metal stakes) placed into the surface. The electrical current is then measured by the adjacent electrodes. In order to survey at greater depths the electrodes are simply moved further away from each other (Nielsen, 2006).

Electrical resistivity methods are often used to calibrate EM surveys. These methods however are slow and require careful interpretation. As different materials have different electrical resistivity the variation in resistivity during a survey can be interpreted to represent a number of different anomalies. EPA (1999) states that electrical resistivity methods can produce a number of useful results depending on the required output including: 1-dimensional vertical geoelectric sections more complex equipment gives 2-dimensional or even 3-dimensional geoelectric sections. An example of a 2-dimensional geoelectric section can be seen in Figure 9.
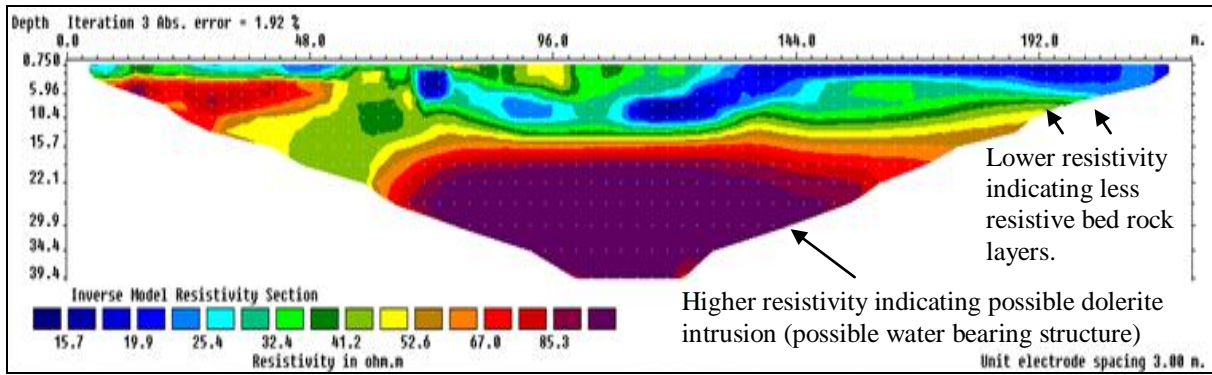
Figure 9: 2D resistivity imaging.   (IGS, 2011)

The images represent a geological cross-section where the darker regions are areas of a higher resistivity and, in this case, a possible dolerite intrusion is represented as the break in the layered bed rock (yellow and green).

2.4.4   Gravitational Methods

Gravitational methods work on the principle that difference in rock densities produce small changes to the Earths surface gravitational field. Instruments called gravity meters then measure these changes (Milsom, 2003).

The unit of acceleration used in gravitational methods is called a gallon. The Earths normal gravity is 980 gallons. During gravitational surveys, changes in the sub surface's density results in minute changes to the gravitational field of the earth surface and these subtle changes are recorded by the gravity meter. Gravity meters are very sensitive to these changes and are capable of detecting a change in the Earth's surface gravitational field of up to 10^{-8} (Nielson, 2006). These changes in the Earth's surface gravitational field can be interpreted in a number of ways, for example a lower gravitational value (gallon) indicates a low density subsurface mass such as karstic conditions, a thickening of the soil layer overlying bedrock, or a variation of groundwater volume (Hinze, 1988).

There are two types of gravitational methods used, the first is called gravitational survey, which employs numerous stations that are widely spread and are used to cover large areas. These are carried out to assess changes in the regional geological conditions.

The second is for a local scale and is called microgravity surveys, were stations are placed in close proximity to each other. These surveys result in the identification of localised anomalies such as cavities, bedrock channelling and fracturing. Gravity meters are commonly used to generate 1 or 2-dimensional density-depth models of the subsurface (Anderson and Croxton, 2008). However, the USEPA (1992) states that "Gravity measurements alone are not sufficient to uniquely determine the cause of a gravity anomaly".

In conjunction with gravitational data, a skilled interpreter with local knowledge of site conditions can result in the explanation of the source of the anomaly. Other limitations to gravitational methods are that they are slow to set up and can be tedious to perform. They require extensive data reduction and regular corrections for the constant changes in elevation and earth tides. Gravity meters are very expensive and are highly delicate pieces of equipment. During surveys, gravity meters are also sensitive to ground vibrations and wind (Nielson, 2006).

2.4.5 Seismic Methods

Seismic methods consist of seismic reflection and refraction measures. Seismic methods are based on the propagation of elastic waves inside the earth (Kirsch, 2006). Seismic methods can be used to;

- Determine depth and thickness of geologic strata,
- Determine depth to groundwater,
- Estimate soil and rock composition, and
- Help resolve fracture location and orientation.

The difference between seismic refraction and reflection states (EPA, 1999) is that "seismic refraction measures the travel times of multiple sound (*i.e.*, acoustic) waves as they travel along the interface of two layers having different acoustic velocities. Seismic reflection, on the other hand, measures the travel time of acoustic waves in the subsurface as they reflect off of these interfaces".

This difference results in seismic reflection is commonly used to investigate deep geological features, whereas seismic refraction is used to measure shallow areas of the subsurface. Seismic refraction uses an energy source such as small explosions or a hammer to create acoustic waves that, when they travel from one geological layer to the next, they are refracted. These refracted waves are then measured using geophone sensors (EPA, 1999).

The limitations to seismic methods are that they are fairly slow and difficult to interpret. They require considerable energy for deeper surveys and are sensitive to ground vibrations, urban noise, and buried concrete (Nielsen, 2006).

2.5   PRELIMINARY CONCEPTUAL MODEL

The conceptual model is the most important step in developing a monitoring programme. It serves as a mental model of where possible target sites locations are relative to proposed monitoring boreholes, groundwater flow, aquifer systems etc. One example of a conceptual model is shown by Nielsen (2006) in Figure 10, showing the groundwater flow direction, target area, and potential borehole positions.
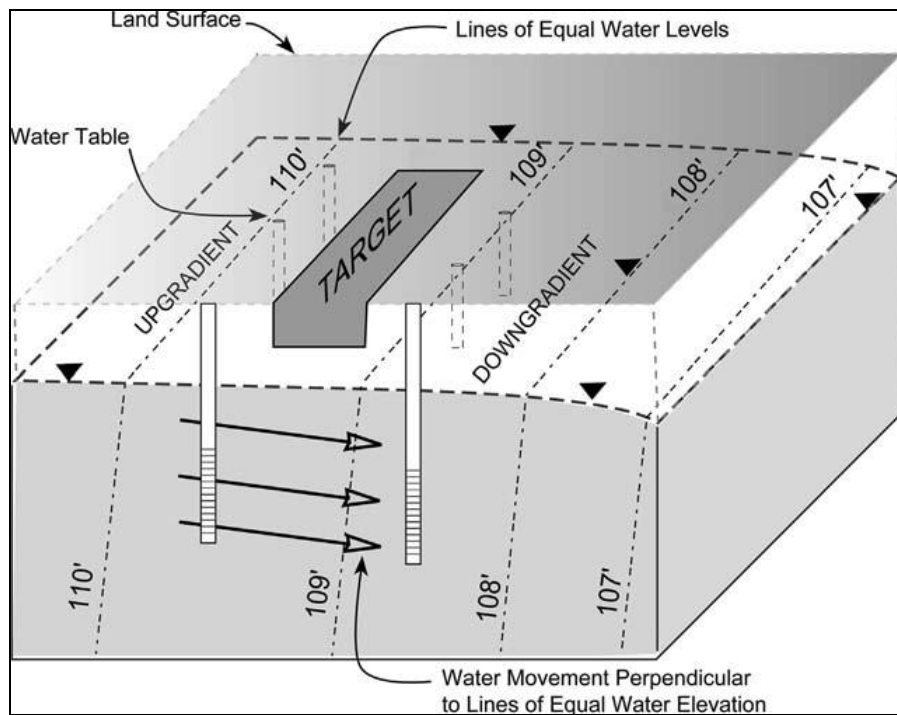
Figure 10: Conceptual model.   (Nielsen, 2006)

By assessing the documentation and studying the local geology and geohydrological conditions, aided by visiting the site and having a site walk over, one begins to conceptualise the site. Once the geophysics has been completed, this preliminary conceptual model provides one with a greater insight into the nature of the subsurface conditions. One can then start to conceptualise the number and position of boreholes that need to be installed. The development of the conceptual model is an ongoing process and after each stage in the establishment of the monitoring programme the model will be further refined.

CHAPTER 3: RISK ASSESSMENT

3.1   INTRODUCTION

Conducting a risk assessment is the third stage when setting up a groundwater monitoring programme. The risk assessment forms the basis for a monitoring programme and according to Hodgson and Krantz (1998) the main aim of a risk assessment is to assist the preliminary design of the monitoring facilities that can be prescribed according to the results of the risk assessment. The results of the risk assessments will also provide a guideline to identifying target areas and to determine the density and location of monitoring points. Risk assessment therefore facilitates a clear decision-making process.

When conducting a risk assessment, the risk approach of the company must be assessed, this will determine if the company favours a more risk adverse approach or a more risky approach. Based on the NWA and NEMA principles and due to the complex nature of groundwater systems, a precautionary and preventive approach must be applied to the risk assessment. DWA (2008) describes these approaches as, recognising that the water resource is susceptible to pollution and recognises that there are certain constraints in terms of the current knowledge base. By having a preventative approach there are proactive measures that are actively investigated to minimise the potential risk of polluting the groundwater resource.

3.2   SOURCE-PATHWAY-RECEPTOR PRINCIPAL

With respect to risk the Source-Pathway-Receptor Principal is commonly used. This Principal is based on three components, namely a Source, Pathway, and Receptor. Under this Principal for a risk to occur, all three components must be present on site. For example, if a source (discard dump) is present and receptors (down gradient water users) are also present, but there is no pathway (geological intrusion) for the pollutant to travel along, it can be assumed that there is no risk (Institute of Petroleum, 2002). Figure 11 shows the linkages between the different sources, pathways, and receptors. Figure 11 further highlights how the groundwater is connected to all spheres of the environment.
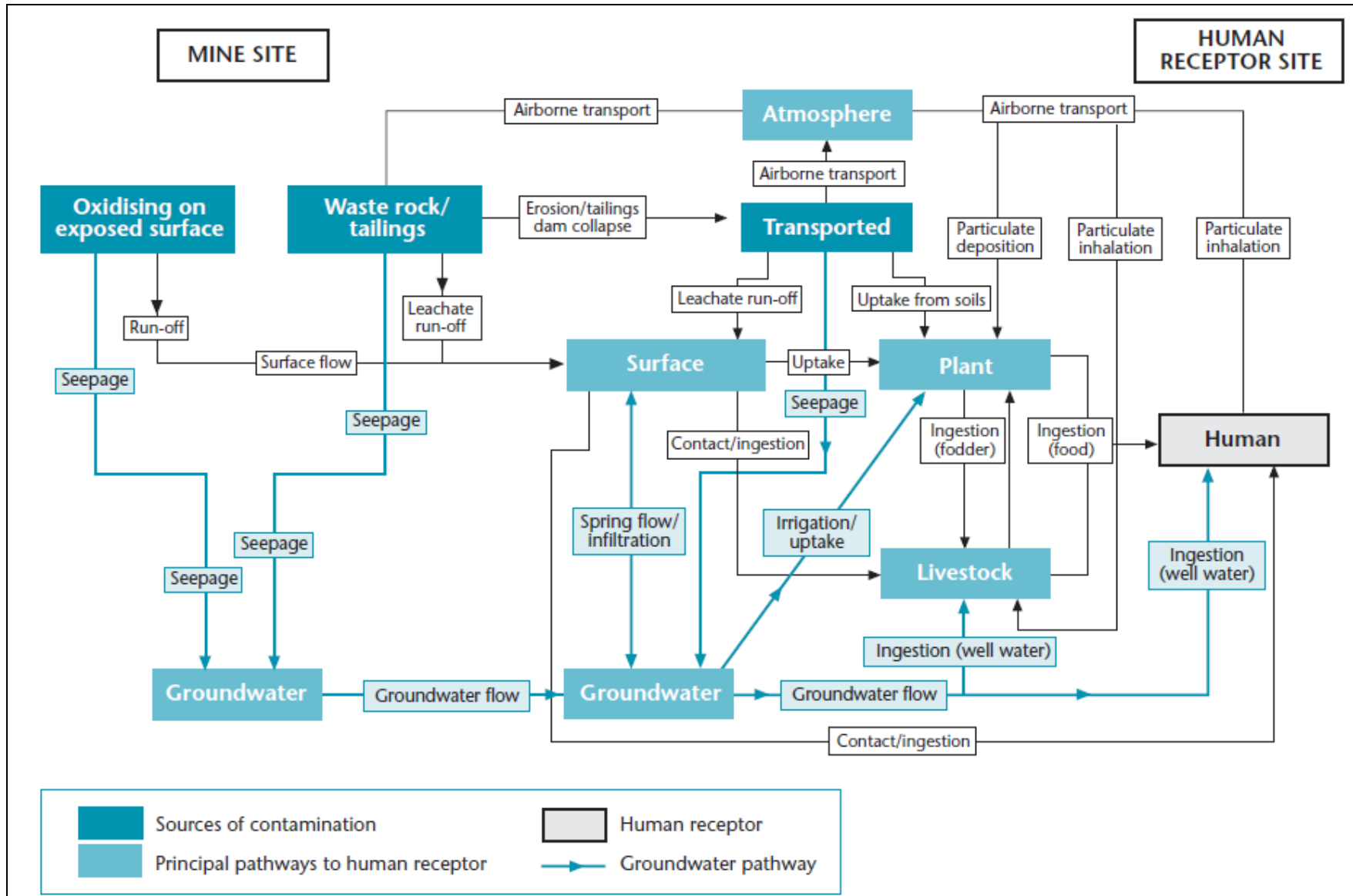
Figure 11: Main pathways of mining contamination to a human receptor. (Klinck *et al.*, 2002)

3.2.1   Potential Sources

Numerous phases of the Coal Industry produce sources of pollution, whether it is the physical mining or extraction of the coal, the processing of the coal, the transportation, or the final utilisation of the coal. Throughout the utilisation of coal, numerous waste dumps are also created, further adding to the impact on the groundwater resource. Of particular importance to the Coal Industry is that of sulphide containing waste products, such as pyrite, as this waste stream is a major role player to the process of AMD. Therefore sulphide containing wastes will be the main focus of this research in terms of the identification of a potential 'source'.

There are two main types of sources that exist, as described by DWA (2006) in the Best Practice Guideline G3, as point and diffuse pollution sources. A point source is a single identifiable source of pollution, such as a pipeline, culvert, channel, or other container from which pollutants may be discharged. Diffusive Sources are much more difficult to identify and are associated with runoff, leachate, seepage, and atmospheric deposition (Pankratz, 2000; Hill, 2004).

There are numerous sources of pollution in the Coal Industry such as:
- Underground mining;
- Opencast mining;
- Unlined pollution control dams;
- Slurry dams;
- Haul roads;
- Beneficiation plants;
- Sewage plants;
- Product stockpiles;
- Discard dumps; and
- Ash disposal dumps.

Of particular importance to the Coal Industry are sulphide containing wastes, as stated by Lottermoser (2010) "In particular, metallic ore deposits (Cu, Pb, Zn, Au, Ni, U, Fe), phosphate ores, coal seams, oil shales, and mineral sands may contain abundant sulphides". During the extraction of coal, these sulphide wastes are exposed to oxygen through the mining process and the storage of these wastes in dumps. When sulphide wastes such as pyrite (FeS_2) react with oxygenated groundwater, the result is highly acidic water loaded with sulphate, metalloids and heavy metals such as iron, lead, aluminium, manganese, etc.

Sulphide oxidation is an autocatalytic reaction and therefore, once AMD generation has started, it can be very difficult to halt, as described in Section 1, Chapter 2. AMD is the most serve in the initial decades and over time the levels of pollution become lower, however it has been noted that AMD may continue for decades resulting in long term acidic water which is toxic to humans, livestock and aquatic systems (Lambert *et al.*, 2004; Demchak *et al.,* 2004).

Lottermoser (2010) lists several field indicators which can assist with the identification of sources of AMD on a coal mine or other associated facility. These are listed below;

- "*pH values less than 5.5.* Many natural surface waters are slightly acidic (pH ~5.6) due to the dissolution of atmospheric carbon dioxide to produce weak carbonic acid. Waters with a pH of less than 5.5 may have obtained their acidity through the oxidation of sulphide minerals,
- *Disturbed or lacking riparian fauna and flora.* AMD waters have low pH values and can carry high levels of sulphate, heavy metals, metalloids, and salts. This results in the degradation or even death of aquatic and terrestrial ecosystems,
- *Precipitated mineral covering stream beds and banks.* The observation of colourful yellow-red-brown precipitates, which discolour seepage points and stream beds, is typical for the AMD process. The sight of such secondary iron-rich precipitates (i.e. yellow boy) is a signal that AMD generation is well underway,

- *Discoloured, turbid or exceptionally clear waters.* AMD water can have a distinct yellow-red-brown colouration, caused by an abundance of suspended iron hydroxides particles. The turbidity of the AMD water generally decreases downstream as the iron and aluminium flocculate and salts precipitate with increasing pH. As a result, acid waters can also be crystal clear and result in the wrong impression of being of good quality, and

- *Abundant algae and bacterial slimes.* Elevated sulphate levels in AMD waters favour the growth of specific algae, and acid waters may contain abundant slimy streamers of green, brown, and white algae.

Identifying the pollution sources can be a time consuming process but is the first critical step during a risk assessment. If any potential sources are missed the potential pathways and final impact will not be identified, which will result in having to 'back track', consuming both time and money.

3.2.2   Potential Pathways

A pathway is the link between the source and the receptor and is described by Leeson *et al.,* (2003) as "The route along which an article of water, substance or contaminant moves through the environment (for example, the route contaminants are transported between the source of landfill leachate and a water receptor)". It must be remembered that the groundwater resource itself can be considered a receptor in its own right. When assessing potential pathways one would require an assessment of the sites geological, hydrogeological information, and any available surface and groundwater monitoring data (Labuschagne and Human, 2009). These sources of information will help highlight possible intrusion, faults, contact zones or other geological structures that may result in potential pathways.

By understanding the hydrological conditions for the site one can further identify other potential pathways such as shallow groundwater levels, fractures, karstic cavities etc.

When studying potential groundwater pathways one must also determine the groundwater flow and aquifer vulnerability. Aquifer vulnerability is the intrinsic characteristics of the aquifer which determine how the aquifer will be affected and how the potential contaminants will be transported. When considering the vulnerability of an aquifer, one must take into account a number of considerations, as discussed by Hodgson and Krantz, (1998);

- Climate, precipitation and surface water run-off,
- Nature and composition of the unsaturated zone, and
- Aquifer characteristics, such as hydraulic conductivity and water quality.

Aquifer vulnerability is based on the potential pollution attenuation from the source to the groundwater (Morris *et al.*, 2003).The different aquifer vulnerabilities are summarised in Table 3. Aquifers with extreme vulnerability will allow pollution to flow through it at a more rapid velocity when compared to that of an aquifer with a low vulnerability.

Table 3: Different aquifer vulnerability classes.   (Morris *et al.*, 2003)

Vulnerability Class	Description
Extreme	Vulnerable to most water pollutants with relatively rapid impact in many pollution scenarios
High	Vulnerable to many pollutants except those highly adsorbed or readily transformed
Low	Only vulnerable to the most persistent pollutants in the very long term
Negligible	Confining bed present with no significant groundwater flow across them

Examples of aquifers with extreme vulnerability are, fractured rock aquifers, primary aquifers, karstic aquifers, and aquifers associated with shallow water levels.

Therefore when assessing the vulnerability of the groundwater system, the type of aquifer system must be known. The most common aquifer system types in South Africa are shown in Table 4.

Determining the groundwater flow is a necessary step in determining areas that are hydraulically up gradient and down gradient of the target area, as this will determine the direction of the pollution plume and will assist in identifying possible receptors. By understanding and visualising the gradients and flows of groundwater, one starts to conceptualise the groundwater system and can begin visualising where to install monitoring boreholes.

Table 4: Aquifer types.   (DWA, 2008)

Aquifer type	Basic information
Intergranular Aquifers	Generally unconsolidated but occasionally consolidated
	Groundwater within interstices in porous medium and in basal conglomerate. Moderate areal extent.
	Examples include Tertiary-Quaternary coastal deposits and alluvial deposits along river terraces.
Fractured Aquifers	Fissured and fractured bedrock resulting from decompression and/or tectonic action. Groundwater occurs predominantly within fissures and fractures.
	Extensive in area.
	Examples include sedimentary and metamorphic rocks within limited overlying unsaturated residual weathered products.
Karstic Aquifers	Water-bearing properties depend on fractures, joints and cavities in Namibian ages calcareous rocks.
	Very limited in areal extent.
	Examples included limestone and interbedded shale is particularly groundwater bearing in valleys where sizable alluvial deposits occur.
Intergranular and Fractured Aquifers	Largely medium to coarse grained granite, weathered to varying thicknesses, with groundwater contained in intergranular interstices in the saturated zone and in jointed and occasional fractured bedrock.
	Occurs extensively throughout South Africa but its characteristics varies in space and time.

The general assumption made by hydrogeologists regarding groundwater flow is, that groundwater flow mimics the surface topography, meaning as the topography dips and raises so does the water level. Please note that this is not always the case and can be a dangerous assumption. One can determine this relationship by using regression analyses. Regression analysis is a statistical tool used to determine the degree of relationship between variables.

By using regression analysis on the surface topography and borehole water level data, one can determine whether or not a significant relationship exists between water levels and the surface topography. If there exists a 90 percent or more relationship then one can assume that surface water follows topography. Bayesian interpretation can also be used to determine the degree of relationship between topography and water levels, as shown in Section 3, Chapter 4,

The more precise method for determining groundwater flow and to calculate the hydraulic gradient of the water level simultaneously is one that utilises the water level of three neighbouring boreholes and the methodology as described by Heath (2004). This method of determining groundwater flow and hydraulic gradient is shown in Figure 12.
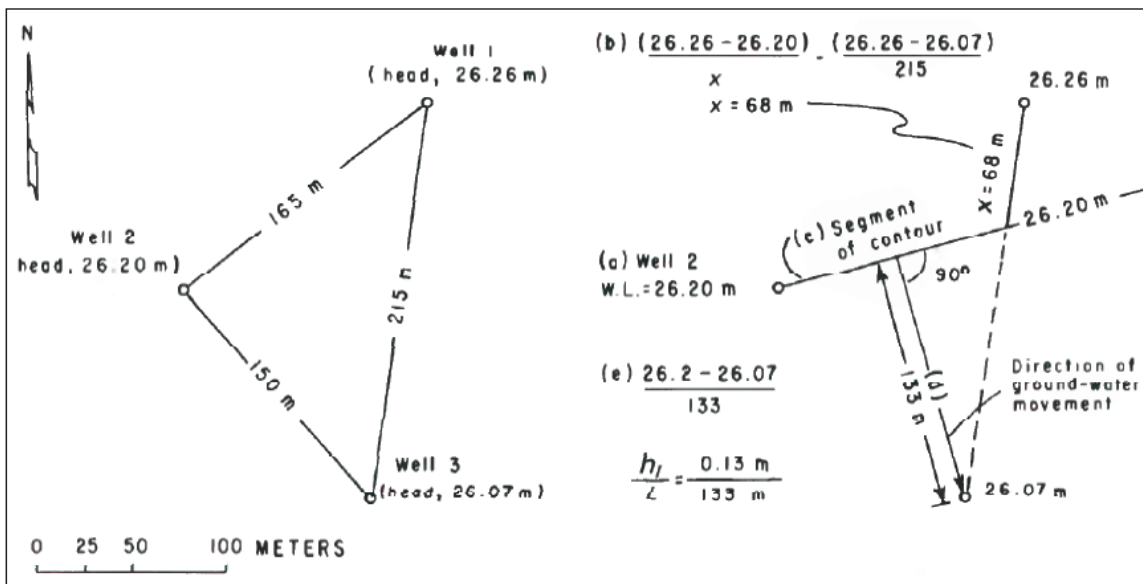
Figure 12: Steps in calculating the hydraulic gradient.   (Heath, 2004)

Figure 12 illustrates the five steps in determining groundwater flow. The triangle to the left of the figure represents three wells or boreholes, with the upper most having the highest head (water level), the lowest well on the triangle having the deepest head, and the well to the far left having the intermediate head. The distance between the wells make up the sides of the triangle.

1. Firstly identify the well with the intermediate head i.e. Well 2

2. Then calculate the position from the well with the highest head and the well with the lowest head at which the head is the same as the intermediate well

3. Draw a straight line from the intermediate well to the point (x) identified in step 'b' (being between the well with the highest head and the well with the lowest head). This line represents a segment of the water level contour along which the total head is the same as the intermediate well.

4. Draw a line perpendicular to the water level contour and through the well with the lowest or heights head. This line is then parallel to the direction of groundwater flow.

5. As shown below the groundwater gradient (I) is the difference between two hydraulic heads (h) over the distance between the two boreholes (L) and is represented by the following formula:

$$I = \frac{h1 - h2}{L}$$

Numerous aquifer systems and pathways may exist for the site and a common oversight during the monitoring process is that of cross-contamination between these pathways. Cross-contamination results in clean groundwater resources becoming contaminated by already impacted aquifer systems. During the drilling of a monitoring borehole numerous aquifers may be intersected. If the different aquifers are not clearly identified and isolated, polluted water may travel from the upper contaminated aquifer and into the lower uncontaminated aquifer systems. One can prevent this type of cross-contamination by installing packers and piezometers which can be used to isolate different aquifer systems from each other. Borehole construction is further discussed in Section 2, Chapter 5.

With the understating of site geological and hydrogeological conditions, the potential pathways to sensitive receptors can be identified. These pathways must be targeted during the installation of monitoring boreholes so that in the event of pollution emanating from the potential sources, it can be detected and mitigation measures implemented.

3.2.3   Potential Receptors

The receptor is the receiver of the pollution that has migrated along the pathway from the source. When one thinks of a receptor, one often does not think of water, however if water becomes polluted it has a direct impact on the surrounding flora and fauna.

Leeson *et al.,* (2003) defines a receptor as "An entity/organism or a controlled water that is being or could be harmed by a potential pollutant, such as groundwater or surface water resources". The most commonly referred receptor is that of human beings. Humans are identified through their presence, so when one is identifying potential receptors, the aim is to identify down gradient receptors such as towns, settlements, agricultural, recreational areas, farm boreholes etc. One must also take into account the potential health risks associated with the source and how it would impact on the human population (EPA, 2007). Contaminants also enter the human food system by livestock or vegetation ingesting the contaminated water these aspects too must not be over looked. Sensitive receptors like wetlands and nature and conservation parks must also be delineated.

3.3   FINAL DESIGN OF MONITORING NETWORK

Based on the Source-Receptor-Pathway Principle the preliminary conceptual model of the site can be refined. Once the conceptual model is fully visualised and all the sources, receptors, and pathways are identified, the number and location of the monitoring boreholes can be confirmed or adjusted.

In order to effectively monitor any potential contamination emanating from a source or targeted area, there must be a sufficient number of monitoring boreholes situated around the target area. It is recommended that at least two or three monitoring boreholes (depending on budgeting constraints) must be installed down gradient of the target area. This must be done within preferential groundwater flow pathways, such as geological intrusions, or located in close proximity to sensitive receptors. At least one of the down gradient monitoring boreholes must be installed as close to the source as possible. This is because groundwater moves at very slow rates, so the closer the monitoring borehole is to the source the sooner contamination can be detected.

When conceptualising the monitoring network, various monitoring boreholes of various depths can also be utilised to ensure that targeted pathways are monitored.

The aquifer to be intersected by the monitoring boreholes must be the uppermost aquifer system. By targeting the upper aquifer, the monitoring borehole will penetrate the groundwater most likely to be contaminated first. The key in identifying the uppermost layer is, by firstly identifying a confining layer. For example, if the source of contamination is at the surface, such as a discard dump, the uppermost aquifer will be the weather aquifer system. This is identified by the weathered material resting on least permeable bedrock. Contaminated water from the surface will first percolate into this weather aquifer, before entering the lower fractured rock aquifer systems. With respect to opencast operations, the uppermost aquifer system will be the lowest coal seam layer. Once the opencast pit has been rehabilitated, water will percolate to the bottom of the pit and rest on the least permeable layer at the bottom. Water will then rise in the pit and enter all the exposed aquifers that were previously intersected by mining activities.

One borehole must also be installed up gradient of the target area, as this will provide information on water entering the system and give insight into the regional or background water qualities of the area. Background groundwater qualities are useful as they give the assessor/s water quality data which can be compared against the down gradient and potentially impacted water quality.

Depending on the type of facility and the type of waste present, the number of monitoring boreholes required for the monitoring programme may vary. DWA (2008) in Table 5 sets out the minimum requirement for a monitoring network, based on the minimum amount of boreholes required and distances between each of the monitoring boreholes.

Table 5: Minimum requirement for a monitoring network.   (DWA, 1998)

Environment	No. Holes	Distance From Waste	Monitoring Frequency
Mines – Reactive Environment			
Slimes (Slurry)	1-3.	50-25- m downstream	Samples from boreholes every 3 months. Sample monthly from streams above and below mine. If pollution from mine occurs, install recorders in streams above and below mine measure daily flow, EC and pH. Sample farmers' boreholes initially and when problems are expected
Ore discards	2-5.	50-500 m downstream and above	
Rock discards (opencast)	1/250	to water accumulations	
Rock discards (other)	1-3.	50-200 m downstream	
Mine water (impoundment)	2-6.	50-1000 m downstream	
Framers' boreholes		Within 1-5 km from mine workings	
Mines – Inert Environment			
Slimes (Slurry)	0-1.		Monthly from streams above and below mine. If pollution from mine occurs, install recorders in streams above and below mine measure daily Sample farmers' boreholes flow, EC and pH. Sample farmers' boreholes initially and when problems are expected
Ore discards	0-1.		
Rock discards (opencast)	0-1.		
Rock discards (other)	0-1.		
Mine water (impoundment)	0-1.		
Framers' boreholes		Within 1-2 km from mine workings	
Coal Fired Power Stations			
Coal stockpiling	2-3.	50-500 m downstream	Samples from boreholes every 3 months. Monthly from streams above and below power station. If pollution occurs in streams, install recorders in streams above and below power station measure daily flow, EC and pH. Sample farmers' initially and when expected
Ash disposal (wet)	2-3.	50-500 m downstream	
Ash disposal (dry)	2-3.	50-500 m downstream	
Dirty water systems	2-3.	50-500 m downstream	
Private boreholes	2-3.	Within 1-5 km from mine workings	
General Waste			
Large (>500 t/d)	3-6.	20-200 m surrounding	Samples from boreholes every 6 months or as specified in permit. Sample water-supply initially and when problems are expected. Sample surface water as specified in permit. Sample monthly for Leachate, if any
Medium (150 – 500 t/d)	2-3.	20-200 m downstream	
Small (25 – 149 t/d)	1-2.	20-200 m downstream	
Communal (<25 t/d)	0-1.	20 m downstream	
Hazardous waste	5-10.	10-200 m surrounding	Site-specific constituents at frequencies recommended by impact study
Sewage			
Unlined maturation ponds	1	20-50 m downstream	Samples from boreholes every 3 months. Samples monthly from streams above and below sewage works
Sludge	1	20-50 m downstream	
Septic tanks and pit latrines	0		Samples from existing water-supply boreholes when problems are expected

CHAPTER 4: DRILLING

4.1 INTRODUCTION

Once target zones and the number of boreholes have been selected, the next stage in the monitoring programme is the drilling of the monitoring boreholes. Before drilling a borehole on site the EPA (1999) states that there are a number of factors that must be taken into account. These factors can be logistical, economical, and drilling considerations and are summarised in Table 6. There are numerous drilling rigs and methods used in the Coal Industry, however four main types of drilling methods for the drilling of monitoring boreholes are commonly used, namely auger drilling, rotary-percussion air drilling, mud rotary drilling and percussion drilling. Each method is briefly described below with a focus on each methods advantages and limitations. This chapter also focuses on the importance of taking records during the drilling of the monitoring boreholes and which information must be recorded. The chapter ends with borehole development and why it is necessary to develop the borehole after drilling.

Table 6: Drilling considerations.   (Lapham *et al.*, 1995)

Logistical considerations:
- Accessibility of the drilling site - Ability to obtain permits and approval to drill at the site - Availability of necessary equipment - Time available to complete drilling program - Ease of equipment decontamination at and between sites - Experience of the driller
Drilling considerations:
- Types and competency of water-bearing units to be drilled and sampled - Types and quality of lithologic and other borehole logs required - Types and quality of aquifer samples required - The importance of minimizing contamination of aquifers by a drilling fluid - The importance of minimizing cross contamination between aquifers - The importance of minimizing disturbance of aquifers during drilling - Total depth of drilling anticipated - Casing diameter and casing material selected for the monitoring well - Ease of completing the monitoring well as designed, for example ease of installation of filter pack, grouting, and instrumentation
Economic considerations:
- Cost of drilling and sampling to meet data needs.

4.2   DRILLING METHODS

There are a number of drilling methods where each different drilling method may be more applicable to overcome specific geological conditions than the others, however the most commonly used drilling method in the Coal Industry is Rotary-Percussion Air Drilling. Table 7 summarises the four main drilling methods and their geological settings to which they are most suited for. When selecting the drilling method to use for the specific monitoring programme it is vital that the selected method will not introduce pollutants into the aquifer system, such as air percussion drilling. Some methods require lubricants and chemicals that are not biodegradable and will pollute the water quality in the monitoring borehole. The diameter of the monitoring borehole is also a vital component, as the diameter must allow for easy access for sampling equipment, this however is discussed further in the chapter (Hodgson and Krantz, 1998).

Table 7: Common drilling methods.   (Aller *et al.*, 1991; EPA, 1999)

Drilling Method	Formation	Depth	Diameter
Auger Drilling	Unconsolidated material: Gravel, sand, silt and clay. Casing my be required in collapsible substrates	2-15m	5-200mm
Rotary-Percussion Air Drilling	Semi-consolidated and consolidated rock. Can drill rapidly into soft to very hard rocks	600m	110-500mm
Mud Rotary Drilling	Unconsolidated material: Sands, silts, and clays	120m	400-1200mm
Percussion Drilling	Unconsolidated to consolidated: Medium hard to hard rock	450m	100-610mm

4.2.1   Auger Drilling

Mastropietro (2005) states that, there are a number of advantages when drilling monitoring boreholes with augers. Some of these include fast penetration rates, low operating cost, conserves material samples and they do not require any potentially contaminating drilling fluids or lubricants. Auger drilling however can only be used for soft to medium unconsolidated materials with relatively low hydraulic conductivities and can only drill to shallow depths. Auger drilling is often used when the unconfined aquifer is the upper aquifer, and where the aquifer is underlain by a confining layer.

It must be noted that the borehole cannot be advanced far below the water table because the borehole may collapse, this however can be overcome with mud additives that stabilise the side of the borehole (Aller *et al.,* 1991). These shallower monitoring boreholes are useful for identifying any possible contaminated seepage emanating through the subsurface. They are also useful in workshop areas where hydrocarbons are present. By monitoring the surface of the water table, hydrocarbons that have moved through the subsurface can be detected on the surface of the water within the borehole.

There are a number of different augering methods available, from hand augers for shallow boreholes, to bucket augers for larger diameter and deeper boreholes. Auger drilling methods all consist of a spiral drill (large screw) that conveys the drilled material to the surface (Nielson, 2006).

4.2.2   Mud Rotary Drilling

Mud rotary drilling utilises various drilling fluids, muds, and or water. There are a number of benefits to introducing these fluids during drilling, states Aller *et al.,* (1991), of which includes the cooling and lubricating of the drill bit, and the stabilisation of the borehole wall. Mud drilling is best suited for unconsolidated material and is usually not be used for the drilling in hard geological layers or in cavernous formations (DWA, 2008).

Once a lubricant has been introduced into the borehole it can often be difficult to remove from the outer perimeter of the borehole. If the borehole is not effectively developed, the lubricants may affect the groundwater quality in the borehole and therefore lead to misinterpretations during sampling and monitoring. The introduction of lubricants also makes the identification of different aquifers difficult (USEPA, 1992).

4.2.3   Rotary-Percussion Air Drilling

Woodford and Chevallier (2002) state that Rotary-Percussion Air Drilling is the most economical method of drilling boreholes in hard rock and semi-consolidated formations.

A major advantage with Rotary-Percussion Air Drilling is that when different aquifers are intercepted during drilling, water immediately flows to the surface as consecutive aquifers are intercepted and the discharge rate increases (blow yield). This allows the hydrogeologist to identify different aquifers and as well as to monitor any changes to the volume or quality of the different aquifers. Rotary-Percussion Air Drilling further allows for easy recovery of the rock material resulting in accurate geological logging and sampling. Boreholes can be drilled quickly and several can be installed in a single day.

4.3   DRILLING RECORDS

During the drilling of the boreholes it is important to note numerous pieces of vital information. The main aim for this data collection is the identification of water bearing zones (aquifers) during drilling. The data that needs to be recorded consists of the penetration rate, water strikes and samples.

The penetration rate is one such data collection. At every meter of drilling, the time it took the rig to drill one meter is recorded (m/s). This is important to distinguish between the weathered and non-weathered zones, where weathered zones could represent a potential water bearing zone. The recording of water strikes represents when a fracture has been intersected during drilling. Once water is hit, a column of water sprays out of the borehole, indicating a strike. The depth of the water strike must be recorded as this will represent the position of the aquifer system. After every water strike, the blow yield must be measured so that the yield of the particular aquifer can be estimated. By recording each aquifer's contribution to the overall discharge, minor and major aquifers can be identified. Each water strike results in an additional volume of water flowing into the borehole increasing the cumulative yield of the borehole.

After every meter of drilling, a geological sample be taken out and stored next to the rig for logging. After rock samples have been cleaned, the geological logs can also be recorded. The recording of chip samples can provide a number of valuable pieces of information, such as assisting in identifying different contact zones, weathering zones, and intrusions in the surrounding geology. The geological log further serves to enhance ones conceptual model for the site.

CHAPTER 5: BOREHOLE INSTALLATION

5.1 INTRODUCTION

There are two main types of boreholes, namely production and monitoring boreholes, each having different design and installation requirements. For the rationale of this research only the later will be discussed. Delleur (1999), states that "the purpose of a groundwater monitoring well is to provide access to the target monitoring zone for collection of a representative sample of groundwater". The 'target monitoring zone' as mentioned by Delluer (1999) refers to the upper or target aquifer system that will be affected by a given activity, as this aquifer will be impacted on, it must be monitored. When taking a sample of this target zone, the representatives of the sample can be altered by how the borehole is constructed. Therefore the primary consideration when selecting material for borehole construction is to select appropriate material that minimises any alteration, in either, the chemical or physical characteristics of the groundwater sample (Lapham *et al.*, 1995). The water type to be sampled, alkaline or acidic, can play a role when selecting construction materials.

5.2 BOREHOLE SPECIFICATIONS

Before the borehole construction is addressed the physical nature of the borehole, i.e. diameter and depth, must be decided.

5.2.1 Borehole Diameter

When determining the borehole diameters there are two factors to take into consideration, namely the desired yield and depth of the borehole. With respect to the yield of the borehole, by increasing the diameter of the borehole, the yield will only increase slightly, however the size of the pump is restricted by the borehole diameter. Therefore, the larger the pump, the larger the diameter and the larger the yield.

Deeper target aquifers may require larger drill bits in order to successfully reach the required depths. This affects the choice of borehole diameters, as the size of the drill bit must be considered (Heath, 2004). Hodgson and Krantz (1998) state that the borehole diameters must take into account the lowering of sampling and other testing equipment. The most common diameter for monitoring boreholes in the Coal Industry is 165mm. This diameter provides sufficient space for smaller diameter pumps, casings, gravel packs etc.

5.2.2   Borehole Depth

DWA (1998) states that "A monitoring hole must be such that the section of the groundwater most likely to be polluted first is suitably penetrated, to ensure the most realistic monitoring result". If the potential pollution source is located on the surface (discard dump), the depth of the monitoring borehole, for example, must intersect the uppermost or target aquifer. In the case of a discard dump, the weathered aquifer system (5-15m), will be the first aquifer to become polluted and hence must be the target for monitoring. A second example is that of opencast mining, where the target monitoring depth is the depth of the lowest mined coal seam. Preferably piezometers can be installed in the monitoring boreholes where a number of aquifer systems can be simultaneously monitored for pollution.

5.3   BOREHOLE CONSTRUCTION

It is vital that the purpose and use of the borehole be decided before borehole construction is finalised. The design of the borehole is determined by the site location, on consolidated or unconsolidated geology. In the Coal Industry, monitoring wells will be installed in partially consolidated and consolidated geology. The design of a monitoring borehole in unconsolidated, as stated by the Lapham *et al.,* (1995), commonly consists of a well screen and casing installed in a borehole with the annular space filled with a primary and secondary gravel pack (filter pack) and with annular and surface seals.

For partially consolidated and consolidated geology three main types of designs for monitoring boreholes can be considered and can be seen in Figure 13. These are the open borehole to the depth of interest with the casing installed up to the point of interest.
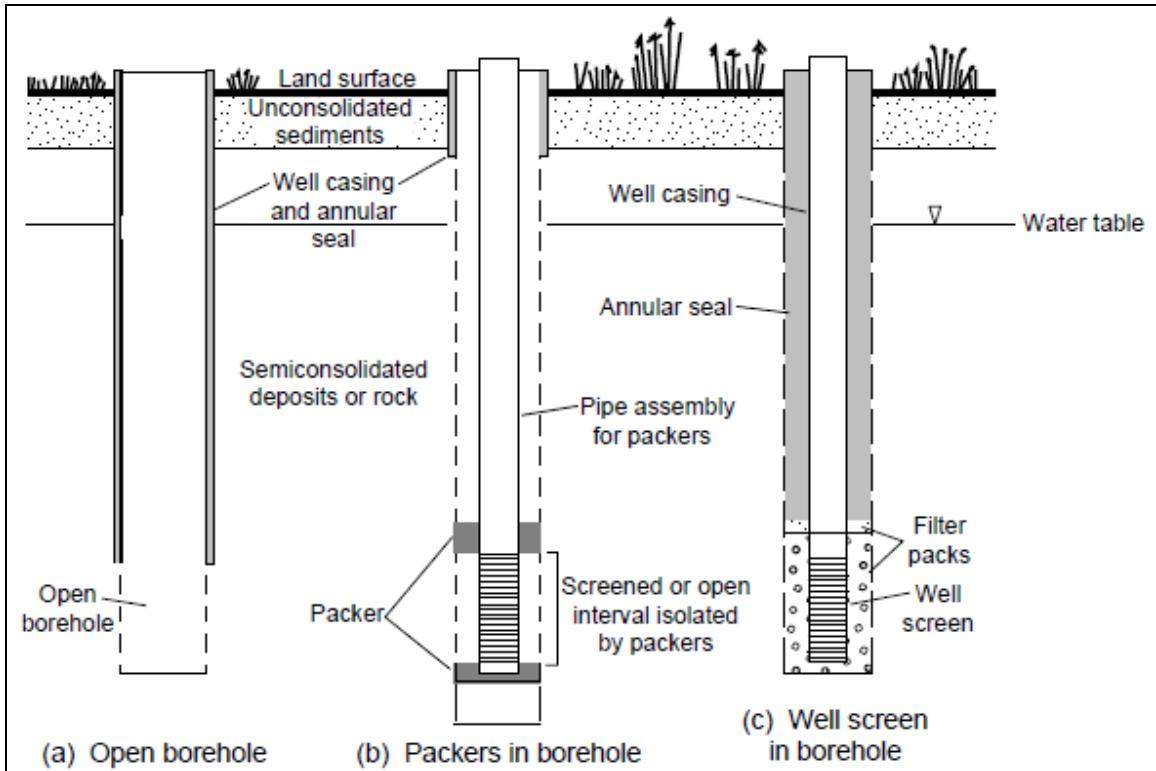
Figure 13: Different borehole designs.   (Lapham *et al.*, 199)

The second design is one with a packer system installed to isolate the targeted aquifer. Lastly is a borehole design where a well screen with gravel packs is installed at the targeted aquifer. An annular seal is then installed above this interval to the surface.

A single borehole can also house a number of piezometers where different aquifer systems can be monitored without the threat of cross contamination. Piezometers are further discussed under Section 2, Chapter 5. This multi-aquifer monitoring design can be seen in Figure 14. Figure 14 shows a sandstone layer which is underlain by a shale layer, followed by an additional sandstone layer. The shale layer acts as an aquitard, which is a saturated low permeability unit that can restrict the movement of groundwater, and as a result, creates an aquifer system above and below it.

To save costs, a single borehole can be drilled and two piezometers or packer systems can be inserted at different depths to measure the two different aquifers created by the contact between the shale and the sandstone layers.
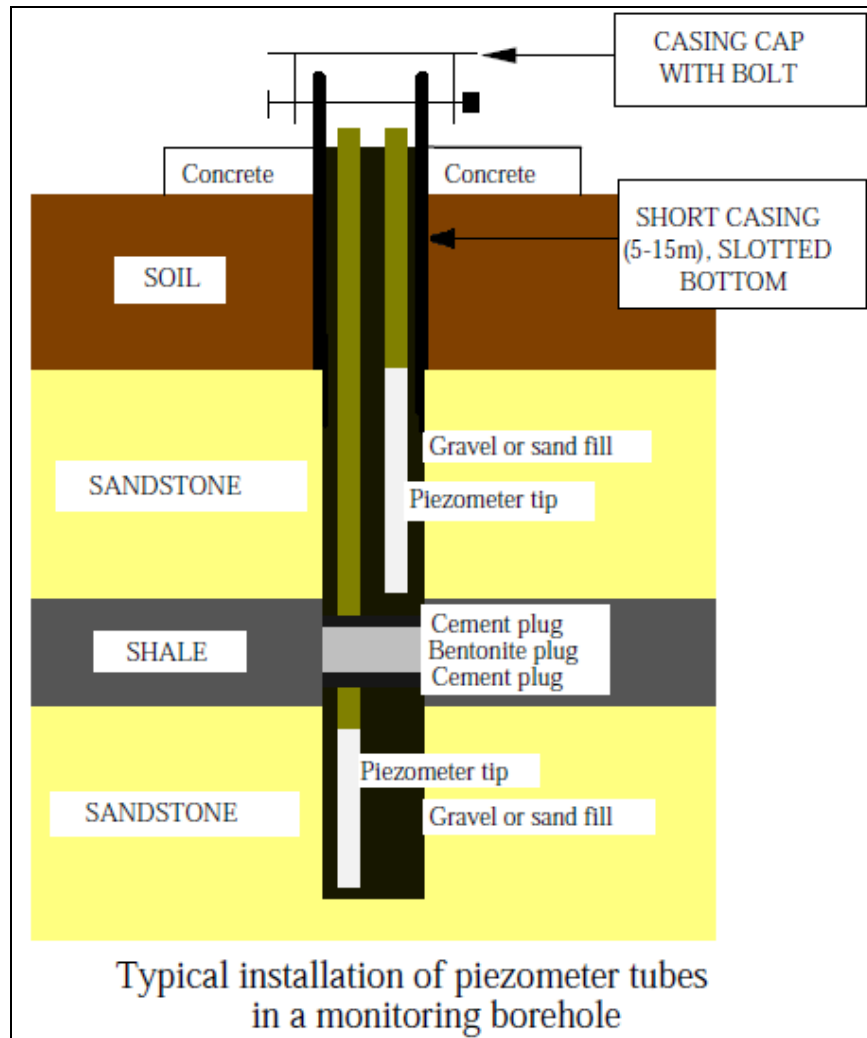
Figure 14: Multi-aquifer monitoring design.   (DWA, 1998)

The two aquifer systems are separated by an impermeable layer such a bentonite and/or cement plug. This plug therefore serves as protection to separate the aquifers to prevent any cross contamination between the two systems.

5.3.1   Piezometers

Piezometers are utilised for isolating specific aquifer systems whilst preventing cross contamination, as seen in Figure 14. Hodgson and Krantz (1998) state that piezometers are access tubes that are installed within a monitoring borehole at different horizons (sample points), such as at the weathered zone and at a fracture intersected in the fractured rock aquifer. Different piezometers are then separated from one another by an impermeable layer such as bentonite or concrete. The diameter of the piezometers must be considered so as to keep in mind the diameter of the sampling equipment.

5.3.2   Casing and Screens

The main aim of using a casing is to prevent the borehole from collapsing and therefore allowing access to the groundwater present in the borehole. For the majority of the boreholes solid casings can be used. Solid casing is less expensive then perforated casings, so for cost savings, perforated casings can only be installed at the water bearing zones identified during drilling. Screen diameters for perforated casings vary, however it is recommended that the size of the screen be between 2-4 mm, alternatively a size screen that is smaller then the gravel to be used for the gravel pack (DWA, 2008).

For the Coal Industry the water that may be monitored may be of highly acidic conditions amongst others, so as stated by DWA, (1998), "The materials used for casing, screens and filters in contact with water must be compatible with and resistant to chemical attack by the water being monitored". Steel casing can be used to provide extra support in unconsolidated materials (reaming), but must not be installed below the water level present in the borehole. If the steel casing is installed below the water level, the steel will eventually oxidise (especially under acidic environments) and heavy metals will be released into the borehole. This results in water quality results with exceeding concentrations of iron, magnesium, etc which do not represent the characteristics of the aquifer being monitored. PVC (Polyvinyl chloride) casing are commonly utilised in the monitoring industry as they have a number of advantages as listed by USEPA (1992):

- Completely resistant to galvanic and electrochemical corrosion;

- Lightweight for ease of installation;

- High abrasion resistance;

- Requires low maintenance;

- Flexible and workable for ease of cutting and joining;

- High strength and low weight per unit length;

- Easily available; and

- Cost effective when compared to steel or other casing materials.

When joining the different casings, the thrush threaded (screw in) casing variety is best suited as no glues are required. When using glues, there exists the possibility of leaching of volatile organic compounds from the PVC glues and/or primers (Lapham *et al.*, 1997).

5.3.3   Gravel Pack

The gravel pack, or filter pack, must consist of an inherit material to prevent the gravel pack altering the water quality entering the borehole. Quartzitic gravel is commonly used in monitoring boreholes. The gravel must be well rounded and must have a diameter of between 6-10 mm (DWA, 2008). The diameter of the gravel is vital, as the diameter must not be smaller then the screen diameter, as the gravel will enter the borehole or block the screens. Gravel packs help to stabilise the borehole casing by creating a tight fit between the casing and borehole wall. Gravel packs further assist water to flow towards the screen as the gravel is permeable and uniform in grain size.

5.4   BOREHOLE PROTECTION

Borehole protection comprises two main components, namely, the protection of the actual borehole from physical harm and the protection necessary to prevent contaminated water entering the borehole.

5.4.1   Sanitary Seal

In any casing or borehole system, states Nielsen (2006), "there are several potential pathways for water and contamination to flow". Therefore a sanitary or surface seal is installed after the borehole has been constructed. Surface seals can either be a concrete slab (100 cm x 100 cm x 30 cm) surrounding the surface of the borehole casing. The concrete slab is sunk into the ground at a depth of 30 cm. The slabs main aim is to prevent any surface contamination from flowing into the borehole and contaminating the aquifer. The concrete slab further provides protection to the actual casing and borehole. In addition to the concrete slab, a bentonite Sanitary Seal can be installed. Instead of filling the annular space (space between the casing and borehole) completely with gravel, bentonite can be placed for the last three meters on top of the gravel pack. The bentonite layer creates an impenetrable layer, further adding to the protection of the borehole from potentially polluted surface waters. The addition of a bentonite seal is commonly used around sewage systems, feedlots, workshops, and any workspace were contamination is present on the surface.

Lastly it is vital that the top of a casing in a monitoring borehole be minimally 30 – 40 cm above the ground surface as this will prevent surface water flowing into the borehole (Hodgson and Krantz, 1998).

5.4.2   Cap and Borehole Identification

By placing a steel cap and lock on the top of the borehole, no foreign material can be placed in the borehole. Next to the borehole or on the cap surface the boreholes information such as name, depth, date of installation, construction etc. must be shown. This can provide valuable information at a later stage as well as providing an easy method of obtaining the information. By having a steel stand with name plaque next to the borehole, this also makes the borehole more visible in the field.

5.4.3   Fencing

In order to protect the borehole against accidental damage by vehicles or by vandalism, it is suggested that a fence be placed around the borehole. It must be kept in mind that the fencing must still allow sufficient access for sampling equipment. Alternatively to fencing, steel poles can be erected on the corners of the concrete slab. For monitoring boreholes outside the mining area it is recommended that the fences be securely installed with deep concrete bases as the fences themselves may be targeted by criminals.

5.5   WELL DEVELOPMENT

After the borehole has been drilled and constructed the borehole must be developed. Borehole development aims at restoring the aquifers characteristics in terms of both yield and water quality. Delleur (1999) states that the "principal purpose of well development is to remove the fine materials adjacent to the well bore, to increase porosity and hydraulic conductivity of the aquifer and gravel pack, to remove any mud cake or compacted zone that results from the actual drilling, and to minimise or eliminate sand pumping". Greases, glues and other chemicals used during borehole construction can also be flushed out of the borehole during well development. Sampling of the borehole should only be done after the well has been sufficiently developed as possible contamination from drilling and borehole construction will result in water chemistry that is not a reflection of aquifer conditions.

There are a number of different methods to develop a borehole such as air lift pumping, jetting and block surging. The most common method is air lifting or air surging this is where the drilling string is lowered three meters from the bottom of the borehole. Air is then injected into the borehole and water is then lifted to the surface. Periodically the borehole is allowed to recover which is then followed by the introduction of air into the borehole. This cycle is then continued with each period becoming longer for a period of approximately 30 minutes or until the water is clear and there are minimal suspended materials remaining in the water (DWA, 2008).

CHAPTER 6: SAMPLING TECHNIQUES

6.1   INTRODUCTION

The two main impacts of the Coal Industry on the groundwater, as discussed under Section 2, Chapter 2, is the decrease in groundwater quality and quantity. Both these impacts can be monitored by field measurements and sampling. The Coal Industry, with special mention to coal mining, can result in groundwater quality that can be highly acidic, furthermore water quality can be degraded by elevated concentrations of sulfate, iron, manganese, and aluminium (Cravotta, 1994). Groundwater quantity can be monitored by regularly measuring the water levels in the monitoring boreholes to identify any decreasing trends in water levels.

In order not to waste time and money it is essential that the sampling techniques and parameters monitored meet the monitoring objectives set out on the establishment of the monitoring programme. This leads to the question of 'what' to monitor. During monitoring, the key indicator parameters must be monitored. Key indicator parameters represent the certain parameters that are associated with the particular industry. Once these key indicators start to increase and show significant change, it would then be required to analyse water in more detail by monitoring more parameters (DWA, 2006). Key indicators for the Coal Industry are discussed in more detail under Section 2, Chapter 7.

There are a number of steps during a sampling programme including field inspection, borehole purging, sample collection, sample storage and sample handling. Laboratory results can often contain errors, where these errors often lead to misinterpretations. A common source of errors in chemistry results in facts is not from the laboratory, but is as a result of poor quality control during the sampling run. Therefore strict quality control and verification procedures must be put in place.

During the sampling of groundwater in the Coal Industry a number of hazards can be encountered where one's safety and health may be at risk.

This includes the handling of acids during the preservation of samples, bees often build nest in boreholes, heavy machinery can be in close proximity, etc. These hazards and risks are dealt with under Chapter 9 and must be kept in mind before and during a sampling run.

6.2   FIELD INSPECTION

During field inspection one firstly has to check the site for any hazardous conditions surrounding the borehole. Secondly when arriving at each monitoring borehole one has to inspect the physical condition and construction of the borehole, identify damages to or tampering with the borehole, missing locks or caps, and any other changes to the borehole or the surrounding area. Once the borehole and immediate area has been inspected, various field measurements can be taken, including the measuring of the water level, pH, and Total Dissolved Solids etc. as discussed below:

6.2.1   Water Level

Water levels in the borehole represent the upper surface of the saturated zone. By taking regular measurements of the water levels, trends can be identified and any possible dewatering of the aquifer can be identified. Additionally by measuring the water level one can determine the direction, gradient, and rate of ground-water flow across the site (Nielsen, 2006). Sometimes the top of the casing is cut skew, so ensure a consistent measurement a reference point must be established for each borehole, where the water level is measured at the same place on the casing every time. Water level can be measured with a number of instruments such as an Electrical contact meter.

6.2.2   Temperature

Changes in temperature will result in changes in a number of parameter such as oxygen concentration and Electric Conductivity (EC). Therefore, only once the temperature measurement on the electrode has stabilized, the temperature can be taken. Some species are temperature dependent and for most species, the higher the temperature, the more soluble they become. Therefore the temperature must always be taken into account when interpreting the chemistry results.

Groundwater temperature is far more stable than that of surface water, however it does vary with change in depth. Groundwater temperature gradients in Southern Africa change between 1 and 3°C per 100 meters increase in depth (Weaver *et al.*, 2007). Water samples however can be exposed to high temperatures during transport and therefore must be kept cold as discussed later in this Chapter.

6.2.3   Alkalinity and Acidity

According to Kleinmann (2001) the pH of a solution is "a measure of the effective hydrogen-ion (H^+) concentration or, more accurately, is the negative logarithm of the H^+ activity in moles per liter (pH = -log aH^+)". Therefore the pH of groundwater is controlled by reactions that create or consume H^+ ions. Alkalinity is the capacity of groundwater to consume H^+ ions or neutralise acidity. Carbonate dissolution is the main source of alkalinity present in groundwater (Hodgson and Krantz, 1998). The pH in a solution increases with the dissolution of carbonates (such as calcium carbonate). Acidity is the capacity of groundwater to create H^+ ions. Hodgson and Krantz (1998) further state that both, alkalinity and acidity values may change rapidly after the groundwater sample has be taken from the borehole (especially with confined aquifers). Therefore in order to obtain accurate measurements of pH, they must be measured immediately after the water sample has been withdrawn from the borehole.

6.2.4   Electrical Conductivity

EC as described by Radtke *et al.,* (2005) is the "capacity of water (or other media) to conduct an electrical current". The EC of groundwater is dependent on the presence of ions, their total concentration, mobility, etc. EC readings are further dependent on temperature, as discussed in Section 6.2.2. The standard temperature for reporting EC is 25°C. Fortunately today's conductivity probes have inbuilt temperature compensators which adjust the EC readings automatically. EC readings can be seen as one of the key indicators to groundwater contamination with EC readings over 70 millisiemen per metre (mS/m) seen as signs of contamination.

6.2.5 EC Profiling

In order to confirm the presence of a possible aquifer that may have been intersected during drilling EC profiling can be used. EC profiling is based on the fact that different groundwater sources could have different water qualities. Therefore water entering a borehole at a point will have a different EC reading as the rest of the water within the borehole column. With this in mind EC profiling is a critical tool that can be used to establish the sampling depth in a particular borehole.

For EC profiling an EC Profiler can be used. It is a small instrument that is lowered into the borehole and constantly reads the different EC concentrations of the groundwater within the borehole. The EC Profiler is lowered into the borehole and at every meter (depending on level of accuracy) an EC measurement is taken. At the point of a fracture, the EC concentration will either start to increase or decrease when compared to the EC concentration of the background water concentration within the borehole. Once the data is plotted the different sources of water in the borehole can be identified.

6.2.6 Redox Potential

Redox reactions (Eh) as described by Merkel and Planer-Friedrich (2002) "consist of two partial reactions, oxidation and reduction, as graphically shown in Figure 15.

Eh reactions influence the distribution of species like Iron, Magnesium, and Sulphate. It must be noted that Eh measuring can lead to misinterpretation if the electrochemical theory behind the measurement and the practical limitations of the measurement are not clearly understood. In redox reactions, every loss in an electron by oxidation is joined to an electron gain by other molecules through reduction (Hodgson and Krantz, 1998). With this in mind Eh does not measure the concentration of electrons in solution, but rather the "intensity" of electron transfer. Therefore more positive values of Eh indicate more oxidised environments whilst more negative values indicate more reducing conditions (Weaver *et al.*, 2007).
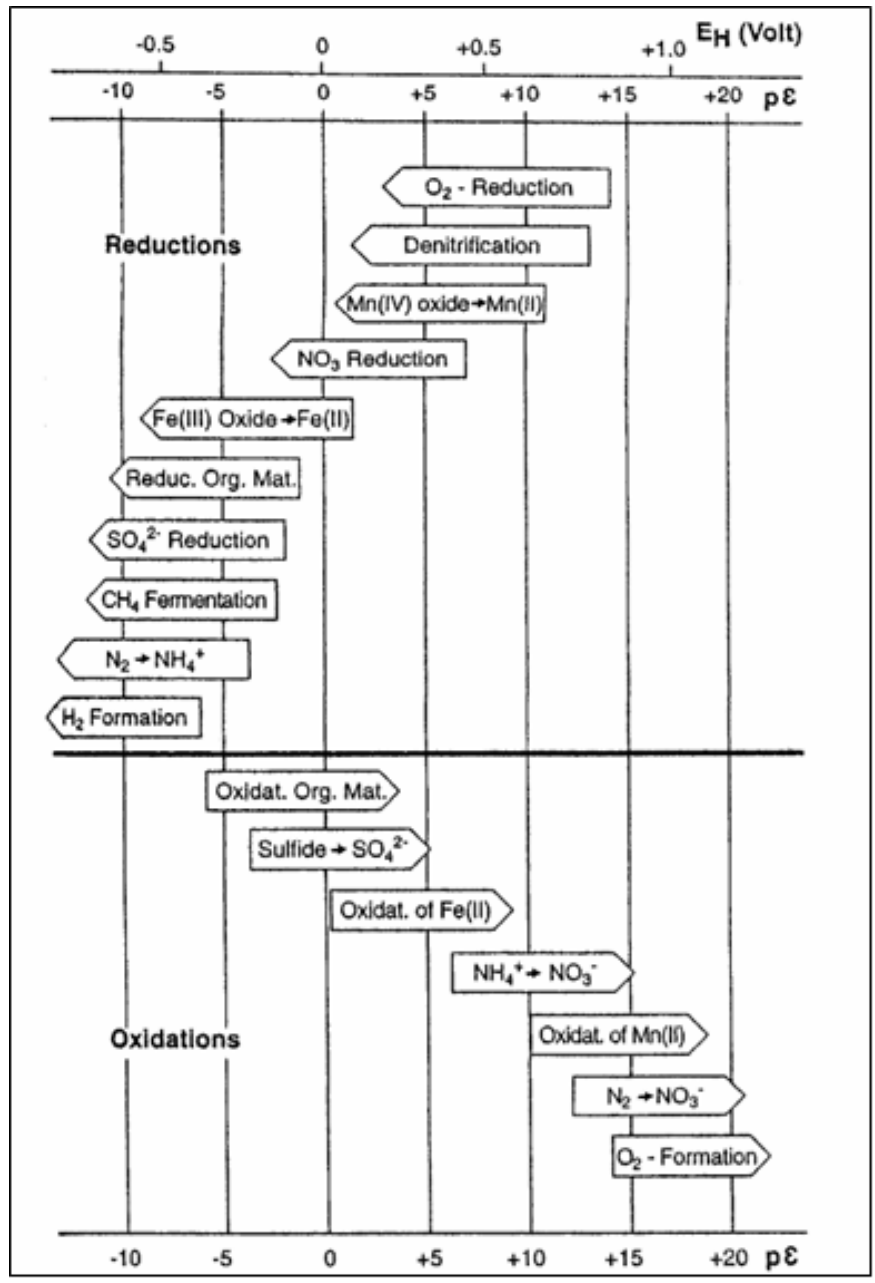
Figure 15: Redox reactions. (Merkel and Planer-Friedrich, 2002)

6.2.7 Dissolved Oxygen

Dissolved Oxygen is the relative measure of the amount of oxygen dissolved in water. Weaver *et al.,* (2007) states that "Oxygen, in large part, influences the solubility of many naturally occurring, polyvalent trace elements in groundwater". This means that minerals such as iron, sulphur, and magnesium have multiple oxidation states and are therefore sensitive to DO concentration.

In terms of the Coal Industry, DO is a vital component in AMD and pyrite oxidation, as discussed in Section 1 Chapter 2. If large amounts of DO are present in the groundwater there is a higher potential of possible AMD occurring. DO is easily measured in the field with a DO electrode. DO like pH must be measured immediately after withdrawing the groundwater from the borehole, as when the groundwater is exposed to atmospheric oxygen, atmospheric oxygen rapidly starts reacting with the groundwater sample, which can lead to elevated DO readings and misinterpretation of results.

6.3   BOREHOLE PURGING

Numerous authors and literature (USEPA, 1992; Wilde, 2006; Weaver *et al.,* 2007) state that borehole purging is necessary, as water in the borehole becomes stagnant and may not represent in-situ groundwater quality. This is based on the assumption that water in the borehole does not interact with water in the aquifer. Historically to overcome this, large amounts of water (removal of a fixed number of borehole volumes) would be removed from the borehole.

However, purging too much water at high rates may result in the mixing of water from zones of different quality, therefore resulting in potential contamination of non contaminated zones (Wilson and Rouse, 1983). Nielsen (2006) further states that "using traditional purging methods has been in accessing the water within the well screen (which, as discussed earlier, is representative of water in the formation screened by the well) without disturbing or mixing the water column in the well". By using bailers and high rate pumps to purge the borehole, other additional problems can be encountered, namely the mobilisation of fine-grained solids from the material surrounding the well, possible dewatering of part of the screen, causing agitation, aeration, and oxidation of formation water, and possibly creating potential for damage to the monitoring well filter pack (Nielsen, 2006).

Contrary to the above mentioned technique, Nielsen (2006), Puls and Powell (1992) and Puls *et al.,* (1992) states that water moving through the formation also moves through the well screen.

Thus, the water in the screen is representative of the formation water surrounding the screen, which can then be sampled using low-flow purging as indicated in Figure 16. Ideally boreholes should be purged at rates below those used to develop the well as to prevent further development of the well. During sampling boreholes should be purged using low-flow pumps at a rate of 0.2 to 0.3 L/min at the selected sampling depth (Puls and Powell, 1992).
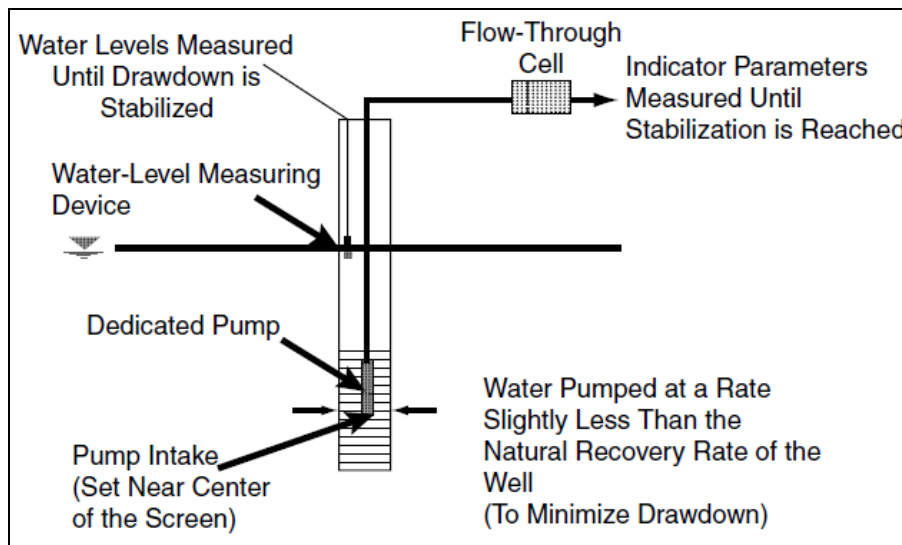
Figure 16: The key components of low-flow purging and sampling.   (Nielsen, 2006)

The USEPA (1993b) and Nielsen (2006) list several benefits to using low-flow pumps:

- *More Representative Samples* - Minimal disturbance of the sampling point and reduced stress on the formation results in low turbidity samples
- *Waste minimization* - The volume of purged water required to access formation water is much less than for more traditional purging methods (often less than one third of a boreholes volume) and
- *Preventing the mixing of water* - Low-flow purging involves removing water directly from the screened interval without physically or hydraulically disturbing the stagnant water column above the screen
- *Spatial Resolution in Sampling* - A fundamental benefit of the decreased purge volume is that a smaller volume of the aquifer is sampled.

This represents a significant improvement in our ability to detect and resolve contaminant distributions, which may vary greatly over small distances in three dimensional space.

However the abstraction rates in low-flow purging can even be too high for the majority of the boreholes drilled into fractured rock aquifers, where the common yield of a borehole is around 0.001l/s. In these cases, no type of purging is possible and as a result, the borehole must be sampled without the borehole being purged.

6.4   SAMPLE COLLECTION

The act of sample collection itself can seem to be a simple act however in reality can be a complicated stage in the groundwater investigations. Sample collection must be done correctly as it forms the crux of the entire groundwater investigations. The taking of a groundwater sample is not simply placing a bailer down a borehole and depositing the sample into a container. Depending on what analyses you require there can be a number of different sample preparations that need to be applied to the sample as a result one can be faced with a number of questions, including, what type of container to use, whether or not to filter the sample, and should the sample be preserved?

6.4.1   Sampling Techniques

The first step to sample collection would be to determine what technique must be used when taking the sample. DWA (1998) discusses two main sampling techniques, stratified sampling and composite sampling. Stratified sampling is conducted by taking small quantities of water at desired depths in the borehole. The main concern with this type of sampling is that, during sampling there must be no mixing of the water column. The aim of this sampling technique is to determine the vertical distribution of different water qualities and as a result one can identify various contaminated aquifer systems that contaminate the boreholes water quality.

This can be a tedious process as the aquifers that were intersected during drilling may not be known. In order to overcome this it is recommend that EC profiling (Refer to Section 2, Chapter 6) be conducted before sample collection takes place. This will ensure that all contaminated sources and possible sampling horizons within the borehole are identified. In order to conduct a stratified sample collection a pneumatic sampler (small diameter pumps) can be used.

Whilst stratified sample collection can provide valuable information, it does require a relatively strong yielding borehole, and as discussed in Section 6.3 above, the far majority of the boreholes drilled for groundwater monitoring will be into fractured rock aquifers, with limited yield potential. In these cases where the borehole is a low yielding borehole composite sampling can be used. With composite sampling, a sample is collected whilst the borehole is being pumped or purged by a submersible pump. It must be remembered that boreholes that are continuously pumped, such as borehole used for irrigation and for domestic water, do not need to be purged before sampling can take place as these boreholes are continuously 'purged'.

For very low yielding boreholes, a composite sample can simply be taken by bailing water out of the borehole. Note for composite sampling the sample collected represent the entire water column and water qualities are not representative of specific aquifers feeding the borehole (DWA, 1998; Hodgson and Krantz, 1998). Composite sampling can therefore be seen as taking the 'average' water quality of the borehole. Further by bailing the water out of the borehole the water sample comes into contact with air and the casings which may alter the water chemistry of the sample.

6.4.2   Sample Frequency

Sample frequency can be influence by a number of factors such as: the stage in mining, budget constraints, and even the type of pollution source can influence the frequency rates. As a general rule all monitoring boreholes should be sampled on a monthly basis at least for the first year of monitoring (Jones, 1983).

After the first year of monitoring the monitoring frequencies can then be reassessed. For long term monitoring, through out the general life span of a mine, after the first year, sampling can then be conducted on a quarterly basis. Table 8 shows the different types of waste environments to be expected within the Coal Industry and the associated sampling frequencies.

6.4.3   Sample Containers

There are two commonly used sample containers, these being glass and plastic containers (Weaver *et al.*, 2007). Glass containers are usually used for biological sampling whilst polyethylene or polyvinylchloride (PVC) plastic bottles are used for inorganic sampling. It is recommended that the sample containers be requested from a certified Water Analyses Laboratory. This will ensure that the correct sample containers are used. The laboratory will also sterilise and seal the containers to prevent any contamination. Before sampling each container one must be marked with its own unique identification number, date of sample, whether the sample has or not been filtered, and the sites name. To prevent any mishaps, such as the identification number being rubbed off, the sample details must written on adhesive tape with a permanent marker and then placed on the container. One should always fill the container to the top to reduce the possibility of volatilisation of organic constituents within the sample (USEPA, 1992).

Table 8: Groundwater monitoring frequency.   (DWA, 1998)

Waste Environment / Monitoring requirements	Within waste or unsat. zone						Groundwater monitoring							
	Pressure vacuum lysimeters	Gas samplers	Electrical conductivity probes	Leachate collectors	Temperature within waste	Special detectors	Special monitoring holes	Other holes	Groundwater levels	Groundwater chemistry	Borehole yield	Groundwater usage	Fountain seepage	Water balance
Mines – Reactive environment														m
Slimes (Slurry)				m			yes	yes	m	3m	y	y	m	m
Ore discards				m			yes	yes	m	3m	y	y	m	m
Rock Discards (opencast)							yes	yes	m	3m	y	y	m	m
Rock discards (other)							yes	yes	y	y	y	y	y	y
Mine water (impoundment)							yes	yes	3m	3m	y	y	m	m
Mine water (discharged)														w
Mines – Inert environment							no	yes	y	y	y	y	y	m
Slimes (slurry)							no	yes	y	y	y	y	y	m
Rock discards							no	yes	y	y	y	y	y	y
Ore discards							no	yes	y	y	y	y	y	y
Mine water (discharged)							no	yes	y	y	y	y	y	d
Coal fired power stations														
Coal stockpiling				m			yes	yes	3m	3m	y	y	m	m
Ash disposal (slurry)							yes	yes	3m	3m	y	y	m	m
Ash disposal (dry)							yes	yes	3m	3m	y	y	m	m
Dirty water systems							yes	yes	3m	3m	y	y	m	m
Water discharged							yes	yes	3m	3m	y	y	m	m
General waste														
Large (>500 t/d)		m		m			yes	yes	3m	3m	y	y	m	m
Medium (26 – 500 t/d)		m					yes	yes	y	3m	y	y	m	m
Small (1 – 25 t/d)							yes	yes	y	3m	y	y	m	
Informal (<1 t/d)							no	yes	y	3m	y	y	m	
Sewage														
Unlined maturation ponds							yes	yes	y	3m	y	y	m	
Hazardous waste	m	m		m		m	yes	yes	m	y	y	m	m	y
Septic tanks and pit latrines							no	yes	y	y	y	y		
Underground storage tanks							yes	yes	m	m	m	m	m	
Explanation of codes: d = daily monitoring; w = weekly monitoring; m = monthly monitoring; 3m = 3-monthly monitoring; y = yearly monitoring														

6.4.4 Filtering

Filtration of the water sample can be regarding as a pre-treatment to the sample. According to Nielsen (2006) the benefit of filtering the water sample is determine if a constituent is truly dissolved in water. Filtration is conducted by passing the raw water sample through a filter medium, of selected pore size. This is usually done by injecting a syringe filled with water and discharging the sample through the filter medium. The most commonly filter pore size used in 0.45 micron pore size (Triplett, 2006). The larger particles are then filtered out of the water and the particles smaller than the filter pore size can pass through.

The main reason for filtering is that it makes it possible to determine actual concentrations of dissolved metals in groundwater. If a water sample is not filtered and persevered with acid, the acid will leach metals from the surfaces of colloids and suspended particles, resulting in an artificially elevated dissolved metal concentration with in the sample. It is recommend that two water samples be taken, one for the analyses of dissolved metals and the second sample for the other inorganic constituents. Furthermore, it must be noted that one should not filter a water sample intended for bacteriological analyses, as some of the bacteria within the sample will be removed.

6.4.5 Preservation

It is very unlikely that a water sample is taken and analysed by a laboratory immediately. In order to retain the water samples original properties, samples are preserved. Weaver *et al.* (2007) states that "Preservation methods are intended to: retard biological activity retard chemical reaction and reduce volatility". Sample preservation can either be done chemically or physically as shown in Table 9. Physical preservation is done by storing all the water samples within a cooler box. It is recommend that the cooler box be filled with wet ice as it is inexpensive, usually close at hand, and will not get samples so cold that they will freeze. Numerous publications state that recommended temperature for storing of water samples is 4°C (Weaver *et al.*, 2007; Hodgson and Krantz, 1998; Nielsen, 2006; DWA, 2006).

Chemical preservation is the options of adding chemicals into the water sample during collection. As can be seen in Table 9 there are several chemicals used to preserve various chemical constituents.

Table 9: Water sample preservation. (Hodgson and Krantz, 1998)

VARIABLE	ACTION
Carbon dioxide Chloride – residual Dissolved oxygen pH	Analyze immediately
Elect. Conductivity Acidity Alkalinity BOD Colour Chromium (VI) Nitrite Silica Sulphate	No additives. Refrigerate. Analyze as soon as can reasonably be achieved
Boron Bromide Chloride Fluoride Potassium Sodium	Analyze when convenient
Hardness Metals (general)	Filter in field. Add NHO_3 to pH<2
COD Grease and oil Nitrogen – NH4 Nitrogen – NO3 Nitrogen – Organic Phenols TOC	Add H_2SO_4 to pH>2
Cyanide	Add NaOH to pH>12
Sulphide	Add 4 drops 2N zinc acetate/100 ml

Refer to Appendix A for a complete list of water sample sizes, preservation and residence times for various chemical determinants.

Nitric acid (NHO_3) is used to keep metal in solution, whilst sulphuric acid (H_2SO_4) is used to preserve nitrogen. It must be kept in mind that even though samples can be preserved each constituent has a specific residence time where once this has surpassed the chemical results will be questionable. Therefore it can be regarded as best practice to deliver the samples to the laboratory for analyses as soon as is practically possible.

6.5   SAMPLE HANDLING

It is very seldom where a sample can be collected and delivered and analysed at the laboratory within the same day. Each chemical constituent has a specific residence or holding time. Aluminium for example, if it is correctly preserved and stored it may have a residence time for a period up to six months, whilst pH only has a residence time of 15 minutes.

Before leaving the field and taking the water samples to the laboratory one must check that all the samples labelling is correct and that there is sufficient ice for the trip to the laboratory. All sample bottles are to be stored standing up and not on their sides as to prevent and water entering or leaking from the container. Once at the laboratory it is vital that a chain of custody form be completed by the laboratory personal. A copy of the chain of custody must then be filed as it serves as proof that all the samples were delivered to the laboratory on time.

6.6   QUALITY CONTROL

Errors in laboratory results do occur, where results seem to be too high or low or where there is a poor cation/anion balance. These errors may be from the laboratory themselves but the far majority of errors are as a direct result of poor quality control in the field. Groundwater sampling can be an expensive exercise so it pays to have a good quality control system in place. Kleinmann (2001) states that quality control "refers to a set of measurements that assures that the analytical results are accurate and precise". These measures can be in the form of equipment calibration, the use of blank or spiked samples, and equipment decontamination.

Quality control must be implemented throughout the 'life cycle' of monitoring, from the preparation stages all the way to the delivering of the sample to the laboratory.

6.6.1 Equipment Calibration

Calibration ensures continual quality performance of any equipment. Before calibrating, one must have a list of all equipment that needs to be calibrated. Once a list of equipment is in place, each instrument must be calibrated according to its own specifications (EPA, 2002). For sensitive equipment, and where a number of field measurements are to be made, recalibration and periodic checks in appropriate standards should be conducted during the sampling run. In the Coal Mining industry one can come across clean and contaminated waters. When going between such extremes it is advisable to recalibrate ones instruments before each use. After each measurement the instrument must also be rinsed with deionised water to prevent cross contamination.

Calibration is done in a number of ways but the most common is placing an instrument in a solution of know concentration. For other instruments that are expected to measure parameters over large ranges multipoint calibration can be preformed, where the instrument is systematically placed in a number of solutions of different concentrations. Equipment calibration can be a tedious and repetitive exercise but is a vital part of quality control.

6.6.2 Blank or Spiked Samples

It is always advisable to submit either blank or spiked samples to the laboratory with ones water quality samples. This is a way of testing the laboratory and to ensure quality control from their side is in place. A blank sample is simply deionised water that is submitted to the laboratory in a regular sample container. The spiked sample on the other hand is submitting a prepared sample using certified reagent grade chemicals of known concentrations. Additionally to these, are duplicate samples, where two samples from the same water source are taken (Kleinmann, 2001).

6.6.3 Decontamination

When sampling numerous boreholes being both contaminated and non-contaminated it is vital that all equipment that has come into contact with water from a borehole be decontaminated to prevent cross contamination of the next boreholes water sample. By following the basic decontamination procedure below one can significantly reduce the chance of any possible cross contamination (Weaver *et al.*, 2007);

(1) Use sampling equipment that is easy to clean and pumps that can easily be disassembled,

(2) If possible start sampling the borehole with the lowest chemical concentration and finish with the borehole with the highest chemical concentration,

(3) Place the water sample into a clean unused container, and

(4) After the borehole has been sampled rinse each piece of equipment thoroughly with a cleaning solution (such as a phosphate free detergent solution) and finally rinse with deionised water before sampling at a new location.

Ideally Nielsen (2006) suggests that at each sampling location a small decontamination area be created to facilitate cleaning of all equipment immediately prior to use or movement to the next sampling location. These decontamination areas usually involve series of buckets on heavy-gage plastic sheeting. Decontamination of equipment does take up large amounts of time which often is not ideal due to budget constrains. Therefore a decontamination protocol that is quick but yet effective needs to be developed and adhered to.

CHAPTER 7: WATER QUALITY ANALYSES

7.1 INTRODUCTION

There are a wide range of possible chemical constituents to analyse for. In order to have an efficient monitoring programme and to prevent unnecessary analysis and costs it is critical that one is aware of what parameters need to be analysed.

7.1.1 Comprehensive Analysis

For the first year of sampling it is recommended that a more comprehensive list of parameters is assessed. Hodgson and Krantz (1998) state that for new monitoring boreholes, a more comprehensive analysis must be conducted in order to ensure that a wide range of background parameters are monitored. These usually include a complete macro analysis as well as an analysis for trace elements (DWA, 1998). In areas where hydrocarbons are stored parameters such as Volatile Organic Compounds must be analysed for.

By having a comprehensive set of parameters one can possibly identify other unexpected sources of contamination to monitor for from the on set of investigations. Background parameters too will always serve as the water quality standard, where throughout the life of the operation the water samples will be compared to. The background water quality in the area of the operation may be contaminated from the outset and this will have to be kept in mind with respect to water resource quality objectives and commitments set out in various legal documentation. Appendix B contains the SANS Drinking Water Quality Standards.

7.1.2 Indicator Analysis

After the first year, one can hold discussions with interested and affected parties and the local authorities to discuss the narrowing of the focus of analyses to water quality indicators such a pH, Eh, electrical conductivity, sulphate and iron.

This will then keep laboratory cost to a minimum whilst still providing adequate information to identify possible sources of contamination as a result of the operation. The key to using indicator analysis is knowing what you are monitoring. Below is a brief discussion of chemical indicators specifically for the Coal Industry.

7.1.2.1 pH and Eh

pH is defined as the negative logarithm of the H^+ and is discussed in more detail in Section 2, Chapter 6. But how can it be regarded as an indicator in the Coal Industry? The more contaminated water becomes the lower the pH will become and the greater amount of minerals will dissolve (Wang *et al.*, 1998). Langmuir *et al.,* (2003) "The solubility of most metals that occur as cations is strongly pH dependent". This is why acidic water has elevated EC, dissolved metals, and TDS concentrations.

Figure 17 is a graphical representation of the effects both pH and Eh have on iron. Under oxidising conditions the ferric oxyhydroxides are dominant. In this state the ferric oxyhydroxides are stable and insoluble. However under reducing conditions the ferric oxyhydroxides become unstable (Langmuir *et al.*, 2003).

As discussed under Section 1, when water comes into contact with pyrite and other sulphur bearing minerals, sulphuric acid is generated. The lowering of the pH values is followed by ferrous iron being oxidised to ferric iron as seen in Figure 17. pH therefore can indicate that the process of AMD is commencing. pH cannot be used in isolation but can be regarded as the first 'stepping stone'.
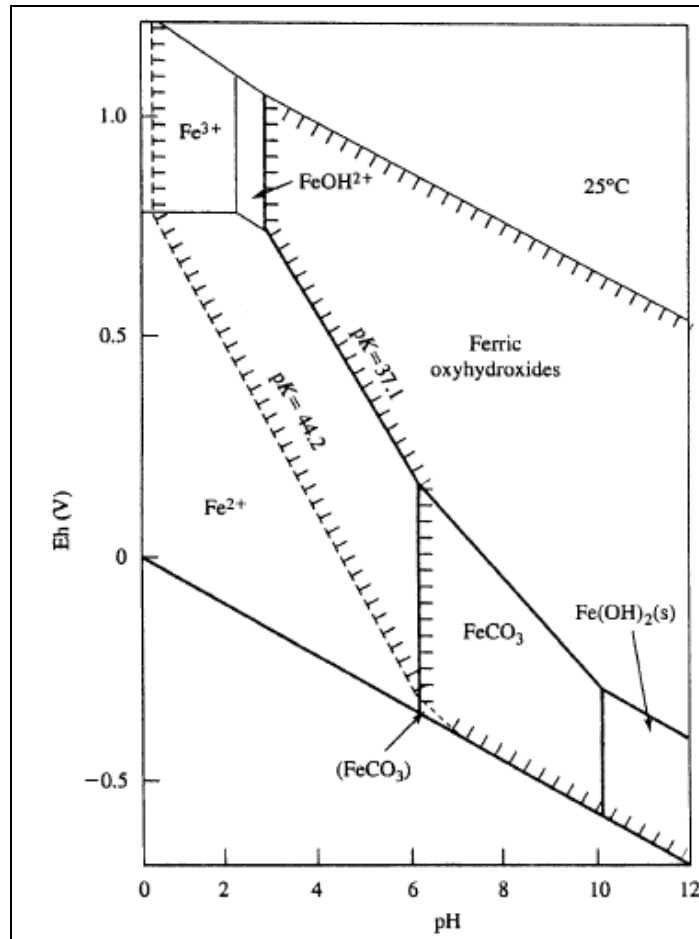
Figure 17: Solubility of amorphous Fe(OH)₃ and the fields of dominance of Fe³⁺ ion and Fe³⁺-OH complexes.   (Langmuir, 1997)

Typically with contaminated water the heavy metal concentration rises rapidly. Eh can be used as an indicator in identify this rise as it is the other main reasons for the solubility of metals. Eh is directly related to pH as discussed earlier in the Chapter. This relationship is shown in Figure 18, where lower pH ranges have higher redox potentials.
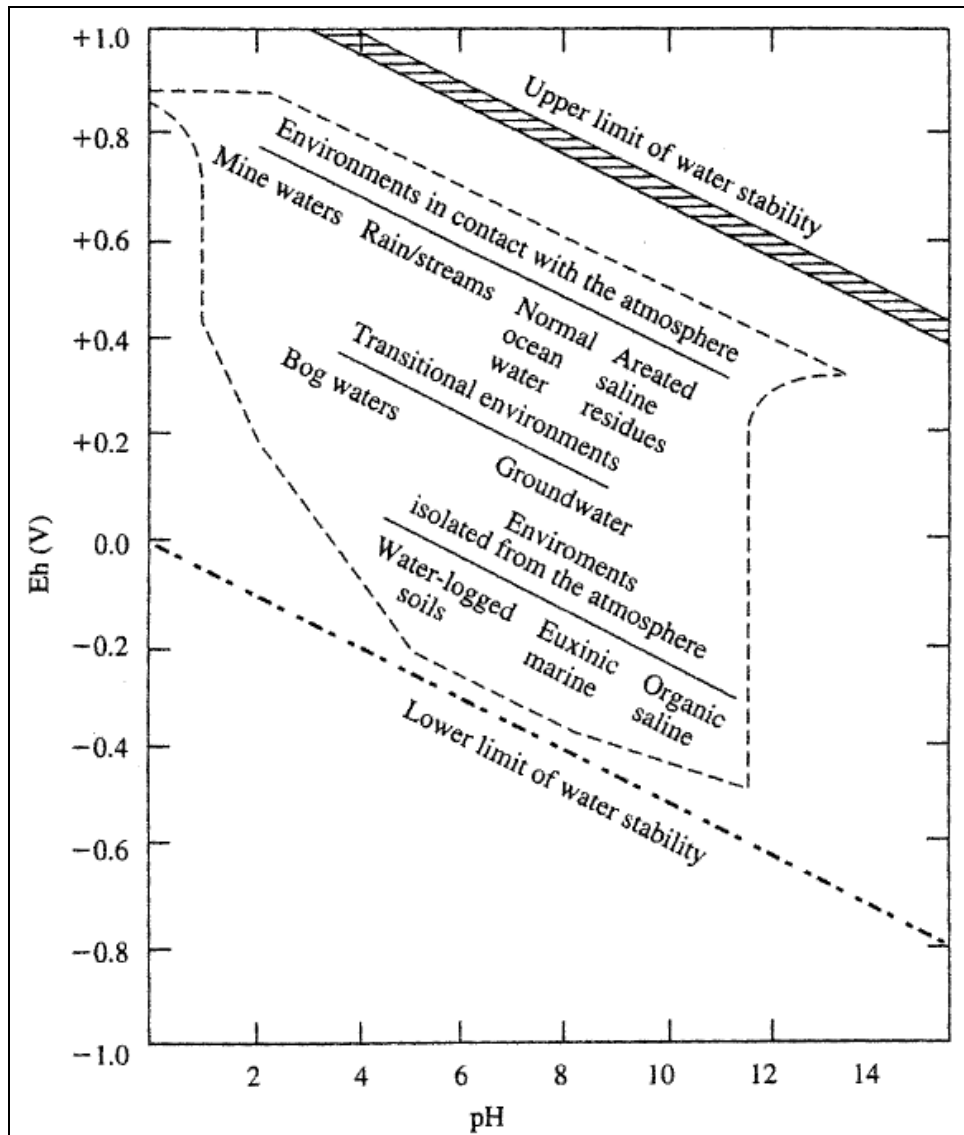
Figure 18: Eh and pH reactions.   (Wedepohl, 1978)

Therefore by knowing the Eh and pH one can estimate the expected water types of the solution and determine if the water is becoming polluted as a result of metals and other constituents becoming more soluble. Both pH and Eh can be easily measured by hand held device and must be measured in the field at the time when the water samples are taken.

7.1.2.2   Electrical Conductivity

Conductivity can readily be used as an indictor for contamination as it represent the ion concentrations, in particular the salt concentration. As water becomes more contaminated, as a result of chemical constituents becoming more soluble, the EC concentrations will rise. Major chemical constituents that affect EC are sodium and chloride, which under acidic conditions are more aggressively leached out of the surrounding rocks and soils. Therefore by monitoring the EC concentration one can determine whether or not water is contaminated. According to DWA (2005) once the EC concentration surpasses 150mS/m it exceeds the SANS Class 1 Drinking Water Quality Standards and is therefore no longer fit for long term ingestion.

7.1.2.3   Heavy Metals

Once the pH levels have declined and the Eh levels have raised sufficiently heavy metals (Iron, Magnesium, Manganese and Aluminium) become increasing soluble, as discussed in Section 7.1.2.1 above. Iron, in particularly, can be used as a contamination indicator as Iron is one of the chemical main constituents of pyrite, magnesium, manganese and aluminium at low pH levels, too become more soluble and are leached out of the surrounding rocks and soils. Under highly acidic conditions heavy metal concentrations can become toxic to both humans and animals.

7.1.2.4   Sulphide Bearing Minerals

Similar to that of iron, sulphur too is a main chemical constituent of pyrite and therefore can be regarded as a key indicator of polluted water in the Coal Industry. Lloyd (2002) states that sulphur compounds in coal are slowly oxidised when they are exposed to air.

Once these compounds oxidise, they generate acid, and the acid then leaches out and gives rise to AMD. This sulphuric acid is the main cause for low pH and high Eh levels in mine polluted groundwater. For water quality analyses one can regularly test for sulphate (SO_4) to indicate potential AMD.

7.1.2.5   Carbonate Minerals

When water starts to become acidic bicarbonates are leached from the soils and rocks to buffer the water. By identifying which carbonate (CO_2, HCO_3^-, CO_3^{2-}) is the dominant species one can estimate the pH range and the extent of pollution in the groundwater as shown in Figure 19. The y axis shows the relative concentration of carbonates in mmol/L and meq/L for alkalinity.
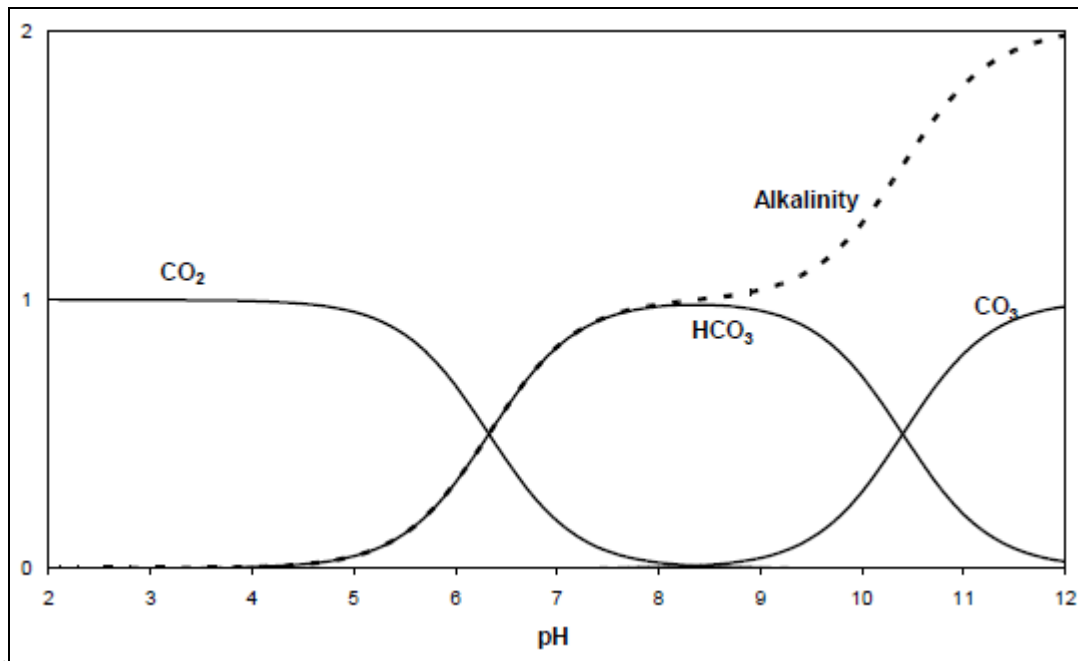
Figure 19: Distribution of CO_2, HCO_3^-, CO_3^{2-} and alkalinity as a function of pH.
 (Loewenthal *et al.,* 1986).

The equation for the reactions that relate these species to pH in uncontaminated waters is represented by the following equation:

$$CO_2 + H_2O <=> H_2CO_3 <=> HCO_3^- + H^+ <=> CO_3^{2-} + 2H^+$$
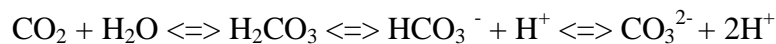
Weaver *et al.,* (2007) states that for uncontaminated groundwater the normal pH ranges between 6-8 where the dominant carbonate species is represented by the bicarbonate concentrations, whilst the carbonates species dominate towards the more acidic and alkaline ends of the pH scale.

7.2   DATA REVIEW AND VERIFICATION

Errors in laboratory results do occur as described under Section 2, Chapter 6.6. It is therefore vital to never assume data or its analyses are correct. One must always review and validate the data set. Data verification is a vital component of what field and laboratory staff and managers routinely do to ensure that they are producing appropriate outputs (EPA, 2002b). As seen in Figure 20 the process of data verification is conducted though out the life span of the monitoring programme from the asking 'why' the data must be collect, to the development of the Field and Laboratory SOPs, all the way to peer review. DWA (2006) states that the common methods of verifying data integrity are conducting consistency checks, ionic balances, and the identification, confirmation and rejection of outliers.
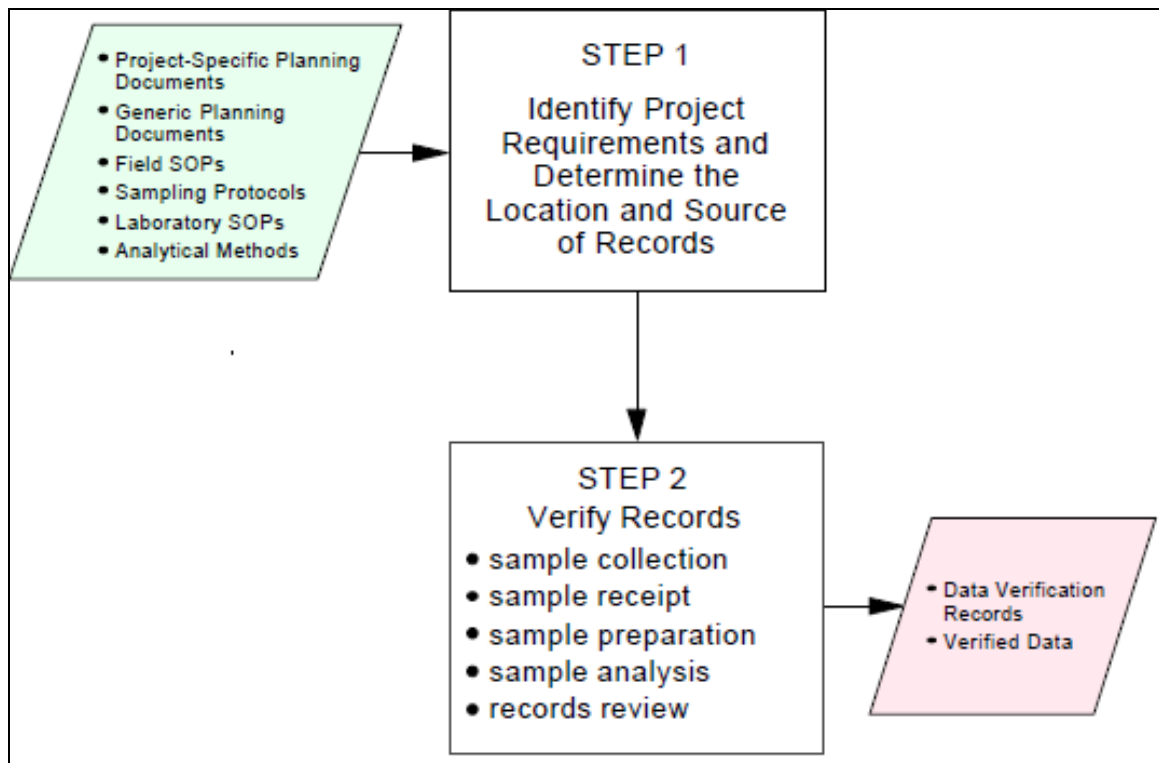
Figure 20: Data verification steps.   (EPA, 2002b)

The simplest version of data verification can simply be by regularly reviewing entered data as to highlight any absence, duplication, or transcription errors within the data set.

This is ideally done by the data entry personal or through a peer review conducted by a person of greater experience. All data must be entered into a specified data base timeously and this data base too must be reviewed for errors and maintained. Ideally a back up of all data bases should be in place.

Once the water analysis has been conducted by the laboratory, the laboratory must conduct a chemical ionic balance, or charge balance. The ionic balance requires that the positively charged ions (cations) and the negatively charge ions (anions) balance. Acceptable ionic balances are those within of less than five percent, where a significant difference might indicate a possible error in the laboratory analyses. All water quality analyses reports must contain the samples ionic balances and if large errors are observed one must contact the laboratory to explain the possible source of the errors. A more detailed discussion of calculating an ionic balance together with an example are presented in a Water Research Commission Report No 527/1/96 entitled "A manual on mine water treatment and management practices in South Africa: Appendix - Volume 1" by Pulles *et al.*, (1996).

If a groundwater sampling point one month shows unusually high concentrations of contamination, and the next month returns to normal without any feasible explanation, this may be as a result of field or laboratory errors. In these cases when an outlier sampling point is found either the point must be resample, noted, or rejected out of the data set.

7.3   SOUTH AFRICA COAL RESERVES CHEMICAL ANALYSES

As stated in Section 1, Chapter 2, South Africa has extensive coal reserves ranging in grade, type, and rank. The majority of the coal reserves are located in KwaZulu-Natal, Mpumalanga, Limpopo (Northern Province), and the Free State. In groundwater monitoring we are interested in the potential environmental impacts of coal due to its properties, such as the sulphur content and ash content of a specific coal field. Therefore the Table 10 is a summary of the different sulphur and ash contents of air dried coal from some of the main coal fields found in South Africa.

Table 10: Coal field analyses.   (Summarised from Wilson and Anhaeusser, 1998)

Coal Analyses				
Province	**Coal Field**	**Coal Form**	**Sulphur Range %**	**Ash Range %**
Mpumalanga	Witbank	Product	0.3 - 6	7 - 22.6
	Highveld	Product	0.7 - 1.2	19.4 - 27.3
	Ermelo	Product	0.4 - 1.6	12.4 - 28.5
Free State	Free Strate	Raw	0.3 - 1.5	24.6 - 43.5
Kwazulu-Natal	Utrecht	Product	0.6 - 7.5	11.3 - 18.4
	Vryheid	Product	0.9 - 1.2	16.5 - 18.6
	Klip River	Product	0.4 - 0.9	10.9 - 18.6
Limpopo	Ellisras	Product	0.7 - 1	9.6 - 34.6

Sulphur is present in coal in three forms, namely sulphate sulphur, sulphide sulphur and lastly organic sulphur. During coal analyses each type of sulphur is determined by its own unique method.

Sulphate sulphur is determined by subjecting the coal to hydrochloric acid and as a result the sulphates are dissolved. Sulphide sulphur is determined by decomposing pyrite in nitric acid. The organic sulphur is determined by subtracting the sulphate sulphur and the sulphide sulphur from the total sulphur content. This total sulphur content is obtained by using infrared techniques. As discussed throughout the chapters, sulphur is an undesirable product of coal as it contributes to acid formation and is the main driver of AMD (Roux, 1998).

The amount of ash produced from the combustion of coal is of environmental concern. Once coal has been combusted in the power stations most of the organic coal components are oxidised, whilst on the other hand, the majority of the inorganic components (trace elements) stay behind in the coal ash. The way and amount of these trace elements appear in the coal ash is determined by a number of parameters the most important of which is the coal characteristics (Djinovic and Popovic, 2006). In terms of groundwater, the type and concentration of these trace elements that leach into the ground from the large ash dumps is of main concern. Some of the heavy metals that can leach into the surrounding groundwater and result in contamination are iron, arsenic, lead, manganese, and aluminium.

Furthermore sulphur is present within the ash, which when it comes into contact with water forms sulphuric acid. As discussed in Section 2, Chapter 6, the leaching intensity of heavy metals increases with decreasing pH ranges. This further enhances the potential of leaching heavy metals into the groundwater.

The content of sulphur and ash varies from coal field to coal field and coal seam to coal seam. However a general rule can be assumed, that the rank of coal usually increases with depth. This can be accounted to the higher temperatures and pressure gradients the coal seams are exposed to during formation at these greater depths. This rule can be correlated to the Rank of coal, which is the degree of metamorphism that coal has under gone (refer to Figure 3). This means that the deeper coal seams consisting of higher Rank of coal has lower ash and sulphur content when compared to the shallower coal seams.

7.4   WATER ANALYSIS INTERPRETATION

Water chemistry and its evolution is one of the most complex natural systems to predict (DWA, 1998). Therefore the aim of this section is to assist with the identification of whether or not the groundwater samples show signs of contamination. It must be kept in mind that if the groundwater sample shows signs of contamination, a geohydrologist must be consulted. The geohydrologist can then conduct a detailed interpretation of the water quality data and initiate further investigations into the source of the contamination. The Piper and Expanded Durov diagrams below are simple chemical interpretation diagrams that assist in evaluating 'families' of different groundwater chemistry with the Coal Industry in mind (EPA, 2004).

There are numerous diagrams that can be utilised to interpret water quality including Piper diagrams, Expanded Durov diagrams, Stiff Diagrams, Line and Bar Diagrams, Box and Whisker Plots etc. To assist with groundwater quality interpretation the SANS Water Quality Guidelines, as shown in Appendix B, must also be taken into account when determining whether or not a groundwater sample is contaminated. Below is a brief discussion of the Piper diagrams, and Expanded Durov diagrams

7.4.1 Piper Diagram

The Piper or Triliner Diagrams are one of the simple and valuable methods that may be used to evaluate groundwater quality data. This method consists of two triangles each representing either a particular group of cations or anions bracketing a diamond-shaped plotting field, as seen in Figure 21. The coordinates of each corner equals to 100 percent (Nielsen, 2006).
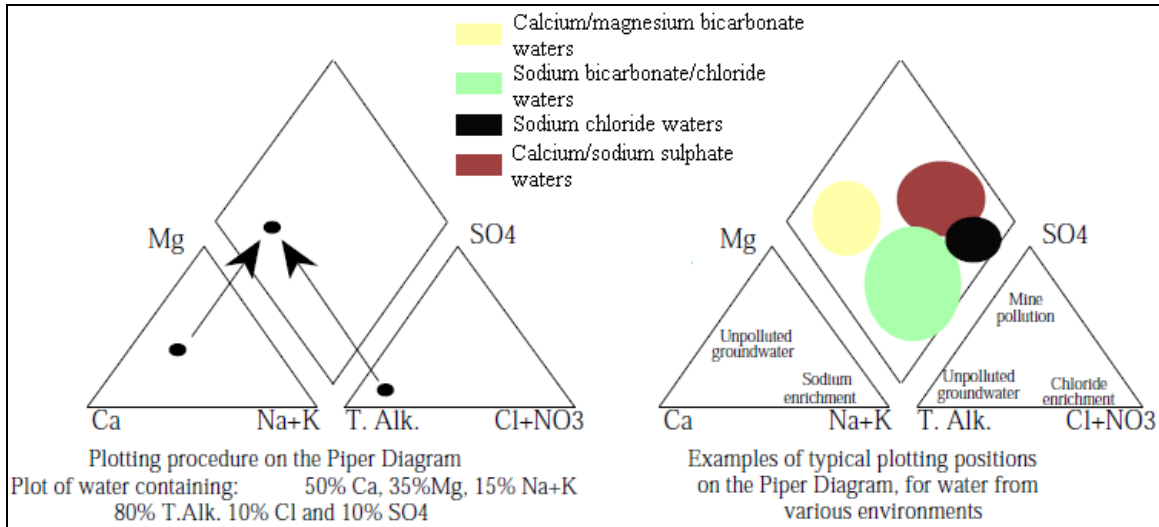
Figure 21: Piper Diagram interpretation.   (DWA, 1998)

Whilst Piper Diagrams are useful in the interpretation of water quality of a single sampling run, their most important feature is showing the evolution of a specific water sampling point over time. In the Coal Industry one of these evolutionary trends to identify is the sulphate enrichment. The water sample may evolve towards the sulphate region of the cation triangle as the water become more contaminated over time..

7.4.2 Expanded Durov Diagram

The Expanded Durov Diagram as shown in Figure 22 represents the different water types that can be expected to be found within the Coal Industry. Like the Piper Diagrams the Expanded Durov Diagram can also be used to indicate trends in water quality and water type. With the Expanded Durov Diagram the water type can be determined by looking at the various blocks the water sampling points lie in.

For example if the water sampling points falls with in the upper left two blocks, the water can be considered to be unpolluted, but if the water sampling points fall with in the middle block the water will have the chemical constituents of the of water that has been contaminated by opencast mining.

Unpolluted water	Unpolluted water	Waste water discharge High extraction underground coal mine
Lime treatment of acidic water	Opencast coal mine water	Gold mine water Power staions
Seldom found	Seldom found	Domestic waste dumps Deep mine water
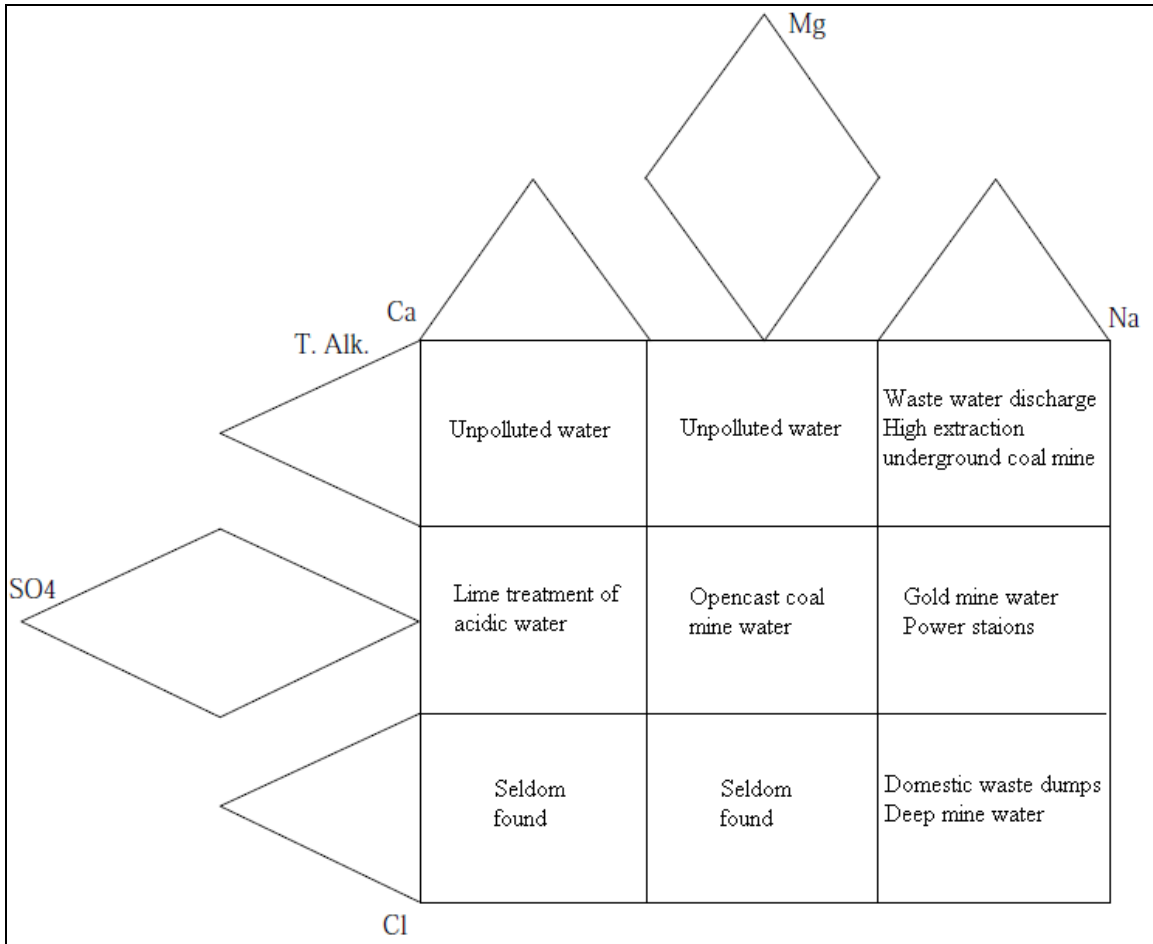
Figure 22: Expanded Durov Diagram interpretation.   (DWA, 1998)

CHAPTER 8: MONITORING PROGRAMME REVIEW

The last stage in the development of a groundwater monitoring programme is the reviewing of the monitoring programme itself. Once a groundwater monitoring programme has been established it must be reviewed and updated on a regular basis to keep a breath of new development. The reviewing process must be undertaken to ensure the monitoring programme is both cost effective and is representative of site conditions. It is recommended that the monitoring programme be reviewed on a yearly basis if site conditions remain constant.

When reviewing a groundwater monitoring programme one must review the sampling locations, the sampling frequency, and the water quality parameters that need to be analysed. Sampling locations must be reviewed and updates as per a site specific needs. The site that the monitoring programme was developed for is not stationary but changes on a daily basis. Some of these changes can include the construction of new opencast pits, new discard dumps, expansion of existing ash dumps, etc. With the development of new activities, new sources will be created, followed by new pathways being identified, followed by potential receptors being affected. To avoid this one must be proactive and have a groundwater monitoring programme that is diverse and continually growing to ensure that it will always be one step ahead of any new activates that are constructed on site.

Sampling frequency too must be assessed on regular bases as per site conditions. For example if a sampling point abruptly shows signs of contamination as a result of pollution control spillage, sampling can be conducted on a weekly period instead of monthly until such time that the source is known and mitigation measures are implemented. It is also recommended to maintain more frequent monitoring after mitigation measures are implemented to show how effective the mitigation measures are working. At the start of a monitoring programme one may have decided that sampling must be conducted on a biweekly basis and a comprehensive analysis must be undertaken. Over the first year if no signs of impact have been identified the indicator parameters can be analysed on a monthly basis or until such a time that contamination is detected.

CHAPTER 9: HEALTH AND SAFETY

When one is in the field either conducting geophysics, drilling monitoring boreholes, or taking retune sampling, personal safety must always be the first priority. People onsite must be made aware of the potential hazards and risks that they will be exposed to onsite. The degree of hazard refers to the inherent characteristics of a substance, such characteristics as it being toxic or flammable. The degree of risk on the other hand is the potential harm that a person may be exposed to (Nielsen, 2006). People establishing a groundwater monitoring programme are posed to a wide range of risk from the equipment and chemicals they use as well as onsite risks from nearby heavy machinery. In Table 11 the possible hazards and risk that can be expected during the development and operation of the groundwater monitoring programme are highlighted and the necessary mitigation measures are mentioned. Before any work is carried out on site it is always advisable to contact the sites Safety Practitioner to inform them of what work is to be carried out and do they have any safety concerns or advice on how to conduct the planned work safely.

When one is on site every effort must be made to anticipate the unexpected. A risk assessment must be conducted before any planned work is carried out on site, especially when working with or near heavy machinery. It is recommended that this risk assessment not be conducted in isolation but that the entire team (drilling personal, hydrogeologists, mine safety offers, etc) have input into the assessment. The risk assessment does not need to be a lengthy report but must just draw attention to all personal working on site of the possible hazards and risks to be aware of.

A major part of personal safety is Personal Protective Equipment or PPE. The typical PPE consists of overalls, reflective vest, hard hat, gloves, goggles, safety shoes, and a dust mask. Depending on the nature of the site and work to be carried out either additional or less PPE may be required. Weaver *et al.,* (2007) states that the "degree of protection required depends upon the nature of the site being sampled and the physical, chemical and biological properties of the water that will be handled". Each person must have sufficient training with respect to the when and how to wear their PPE.

Table 11: Hazard identification.   (Summarised from Nielsen, 2006)

Hazard Identification and Classification			
Type of Hazard	**Source of Hazard**	**Risk**	**Safety Measures**
Electrical	Electrical wires, buried cables, generators, electrical pumps, capacitors, lightning, power lines.	Shock or electrocution.	Always be aware of surroundings. Keep safe distance from drill rig and power lines. Contact Site Personal. Wear the necessary PPE. Utilise low-voltage equipment with ground-fault interrupters.
Physical	Uneven terrain, holes and ditches, steep grades, and slippery surfaces, sharp debris, such as broken glass and jagged metal, surrounding equipment.	Lacerations, broken bones, loss of fingers.	Always be aware of surroundings. Wear the necessary PPE. Keep safe distance from heavy equipment. Ensure good housekeeping. Ensure good maintenance of equipment.
Noise	Any noise over 85dB. Running of equipment, drilling rig, compressor, pump, and generators.	Short term hearing impairment and permanent hearing loss.	Wear the necessary PPE (plugs and earmuffs). Test equipment for noise levels. Ensure good maintenance of equipment. Send employees for annual hearing tests.
Temperature	Weather, overheating of the body and loss of fluids through sweating, wearing chemical protective clothing (prevents evaporation of moisture). Poorly insulated clothing.	Heat stress, frostbite and hypothermia.	Wear appropriate protective clothing. Rest periods should be based on anticipated workload and ambient temperatures.
Chemical	Preservation acids, calibration chemicals, gasoline, diesel, grease.	Fire, burns, and poisoning.	Be aware of the physical and chemical properties of the anticipated chemicals to be used. Wear the necessary PPE. Contact Site Personal.
Biological	Sewage, septic tanks, french drains, pit latrines, animals.	Infection, illness or disease.	Always be aware of surroundings. Wear the necessary PPE (gloves, safety shoes, goggles, coveralls, and a dust mask that covers the nose and mouth).

Safety measures must be conducted each time an activity commences and as a result can be time consuming and repetitive. One must however ensure these do not become routine and simply goes into the one ear of your colleges and out the other. Ensure safety measures are informative, 'get to the point' and encourage participation from the team. The goal of safety is to ensure that every body leaves the site as they arrived.

CHAPTER 10: CONCLUSION

The Coal Industry, with its associated coal powered power stations supply the majority of South African electricity, without it the country would not develop. The Coal Industry to provides millions of employment opportunities, whilst promoting training and the improvements of the lives of previously disadvantaged people. Coal mining generates tens of billions of Rands each year, boosting the South Africans Gross Domestic Product, further adding to the country's economy.

However, the countries fresh drinking water is rare and needs to be protected in this water scare country for the sake of all terrestrial and freshwater ecosystems. The Coal Industry impacts on this vital resource both in quantity and quality. Fresh groundwater can become acidic with highly elevated amounts of dissolved metals and salts. The result of this is groundwater becoming toxic for both domestic and livestock consumption.

Furthermore mining excavations result in the deviating of the natural flow systems of groundwater and the dewatering of aquifer systems. The Coal Industry therefore has direct positive and negative impacts, both environmental and social, the industry must therefore take accountability of its actions. Once groundwater becomes contaminated it requires long term and expensive mitigation measures. Therefore with respect to groundwater it is better to implement the philosophy of 'prevention is better then the cure' (Institute of Petroleum, 2002).

A groundwater monitoring programme therefore serves as a measuring tool and informs the particular industry on how well its pollution control structures are working. Furthermore the development and implementation of a groundwater monitoring programme becomes the first line of prevention and enables the industry to readily identify and mitigate any potential sources of contamination.

CHAPTER 11: MONITORING PROGRAMME SUMMARY

Groundwater monitoring requires a number of sophisticated interlinked stages. To ensure that these stages are remembered and utilised in everyday activities a summary of the different stages for developing a successful Monitoring Programme is shown in both Figures 23 and 24. Figure 23 provides a brief overview for all the stages discussed in this study, where as Figure 24 provides a more detailed summary of each of the eight required stages. By providing a summary of how to develop a Groundwater Monitoring Programme it is hoped that the summary itself acts a daily tool to remind the developer of the different spheres in developing their site specific Monitoring Programme.

Stage 1 is the development of monitoring objectives. These objectives act as the 'ruler' to measure the effectives of a monitoring programme and to set out what exactly needs to be achieved. This is accomplished by revolving the objectives around three questions as prescribed by Steele (1987).

Stages 2 is concerned with conducting of a risk assessment which aims to provide the preliminary design of the monitoring facilities that can be prescribed according to the results of the risk assessment. With respect to risk the Source-Pathway-Receptor Principal is used.

Stage 3 focuses on the Triangulation method which discusses: Cartographical sources, Site reconnaissance, and Geophysical methods to site the location of monitoring boreholes.

Stage 4 describes the factures that must be taken into account before the drilling of the monitoring boreholes can commence. These factors can be logistical, economical, and drilling constraints. The method of drilling for the monitoring boreholes in light of each drilling methods advantages and limitations must be assessed.

During Stage 5 one has to decide the use of the borehole followed by the required borehole construction. The main aim of this Stage is to prevent cross contamination of the different aquifer systems.

Stage 6 includes all the necessary steps for conducting groundwater sampling from the selection of the correct sampling container to quality control and verification.

Stage 7 is concerned with the groundwater samples quality results and its interpretation. The last stage, Stage 8 shows how and why a monitoring programme is regularly reviewed and updated.

Figure 23: Overview of Monitoring Programme Stages.

1. Set Monitoring Objectives

Before one commissions a monitoring programme clear management objectives must be established

Objectives must not be complecated but simple and achievalbe

The objectives must be developed with future plans and proposed activates in mind

Objectives act as the 'ruler' to measure the effectives of a monitoring programme

Set out what exactly needs to be achieved

Revolve the monitoring programme objectives around four questions

Why?

How?

Who?

How do we evaluate?

Objectives must also encompass time in order to effectively monitor trends in quality or quantity in the surrounding groundwater systems

2. Conceptual Model and Site Investigations

Triangulation method

Cartographical sources

Staring point when siting monitoring boreholes

Include photographs, images, maps, and background literature

Site reconnaissance

Confirming the accuracy of existing information

Identification of the presence of local geological anomalies

Geophysical methods

Measure contrasts in the physical properties of the subsurface that are indicators of potential water bearing structures rather the water itself

Numerous methods available. Each method measuring a different characteristic of the subsurface

Develop a preliminary conceptual model

3. Risk Assessment

Risk assessment forms the basis for a monitoring programme

Main aim of a risk assessment is to provide the preliminary design of the monitoring facilities

Provide a guideline to identifying target areas and to determine the density and location of monitoring points

Source-Pathway-Receptor Principal:

Source: point and diffuse source

Pathway: is the link between the source and the receptor

Receptor: is the receiver of the pollution that has migrated along the pathway from the source

Refined conceptual site model

Number and location of the monitoring boreholes can be established

Groundwater flow direction

Potentail targets areas

4. Drilling

Numer of factrs to conside

Logistical considerations

Accessablitiy to site

Time availabe for drilling

Economical considerations

Cost of drilling and sampling

Drilling considerations

Geological structures to be drilled

Total depth of drilling

Many different drilling methods each suitable to overcome specific geological conditions

Rotary-Percussion Air Drilling

Easily to dentify different aquifers

Accurate geological logging and sampling

Data collection

Main aim for this data collection is the identification of water bearing zones

Penetration rate, water strikes and samples

Atmosphere of safety

Atmosphere of safety

8. Review and Update

Must be reviewed and updated on a regular basis

Ensure the monitoring programme is both cost effective and is representative of site conditions

Reviewed on a yearly basis if site conditions remain constant

Review the sampling locations, the sampling frequency and the water quality parameters

Monitoring Programme must always be one step before new activates are constructed

7. Geochemistry and Results

Comprehensive analysis

New monitoring boreholes

Wide range of background parameters

Identify other unexpected sources

Water quality 'bar'

First year - Consult DWA

Indicator analysis

Narrowing of the focus of analyses

pH, Eh, EC, Sulphate, Iron and hydrocarbons

Data review and verification

Ensure that programme is producing appropriate outputs

Consistency checks, ionic balances, identification, confirmation and rejection of outliers

Water analysis interpretation

Show signs of contamination

Piper, Expanded Durov, Stiff diagrams

6. Sampling

Aim to monitor both decrease in groundwater quality and quantity

Field inspection and measurements

pH, Eh, water level, EC, Tempreture

Sample collection

Quaterly vs monthly

Use EC Profiling to identify sampling points

Low-flow purging and grap sampling

Glass and plastic

Filtration

Pre-treatment to the sample

Sample preservation

Chemical vs Physical

Addition of chemicals into the sample

Storing of water samples at 4°C

Quality control

Equipment calibration and decontamination

5. Borehole Construction

Use of the borehole must be decided first

Physical nature of the borehole

Depth - intercept upper aquifer

Diameter - 165mm. Take into account sampling equipment

Varoius designs for monitoring boreholes

Open borehole, Packer/piezometers etc

Be aware of cross contamination

Casing and screens

PVC (Polyvinyl chloride)

Prevent the borehole from collapsing

Gravel pack

Inherit material (Quartzitic gravel)

6-10mm must be larger then screen size

Borehole protection

From physical harm and contamination

Borehole Development

Restoring the aquifers characteristics

Figure 24: Summary of the Monitoring Programme Stages.

SECTION 3: GROUNDWATER INVESTIGATIONS AT AN MPUMALANGA COAL MINE: A CASE STUDY

CHAPTER 1: SETTING MONITORING OBJECTIVES

For the first stage of establishing the groundwater monitoring programme, the monitoring objectives had to be established. The monitoring objectives were developed with the input of the client and the hydrogeologist. The objectives for the investigation were to;

- Establish a monitoring network for the operation,
- Develop a conceptual model for the site,
- Identify potential sources, pathways, and sensitive receptors,
- Install monitoring boreholes around the possible contamination sources,
- Obtain background water qualities for future monitoring, and
- Provide advice on how the monitoring programme will be implemented and maintained.

Once the objectives were established, the second stage of gathering the different sources of data and information was initiated.

CHAPTER 2: CONCEPTUAL MODEL AND SITE INVESTIGATIONS

In order to develop the conceptual model, various forms of information had to be assessed. The Triangulation method was used in assisting with background knowledge and the development of the conceptual model. Firstly information regarding the mining operation was obtained from the client and other cartographical sources, as discussed below.

The Coal Mine is a green fields operation and a groundwater investigation was required to install monitoring boreholes. The Mine is located in the Mpumalanga Province, with bituminous coal from the Ermelo Coalfield making up the coal reserves. The coal reserves will be mined by opencast mining methods (truck and shovel). There will be four planned opencast areas to be mined adjacent to one another. The surrounding area is characterised by existing coal mining, farming and tourism activities. Farming activities include maize, fruit and cattle farming and tourism includes a number of guest houses as well as some nearby historical sites. Minimal infrastructure will be constructed for the Mining operation due to the relatively short time frame in which opencast mining will be conducted (4 years). The infrastructures that will be constructed include a workshop, offices, crusher plant and bunded fuel bay, and a pollution control dam. The plant area is located in the south eastern areas, of the site as can be seen in Figure 25.

The mining area falls under the central Mpumalanga climatic zone characterised by warm summers with rainfall and warm (during the day) to cold (at night) dry winters with sharp frosts. The average daily maximum temperature in January (the hottest month) is 23.9°C and in July (the coldest month) is 16.6°C. The mean daily minimum temperature in January is 13.4°C and in July it is 3.1°C but extremes of -14.7°C have occurred for the two months respectively. Precipitation occurs as showers and thunderstorms, mainly from October to March with the maximum rainfall occurring in November. The annual average rainfall for the data period is 737 mm/a.

The general landscape is typical of the highveld grasslands and has a gently undulating topography, with dispersed perennial and non perennial pans.

The project site covers a total area of 513 ha. A large perennial pan is located in the western portion of the site, adjoining this pan is a hill slope seepage wetland. The central portion of the site has two non perennial streams flowing in an easterly direction. Elevation on site is highest in the south eastern corner at 1735 metres above mean sea level (mamsl) and lowest along the perennial stream at 1630 m above sea level.
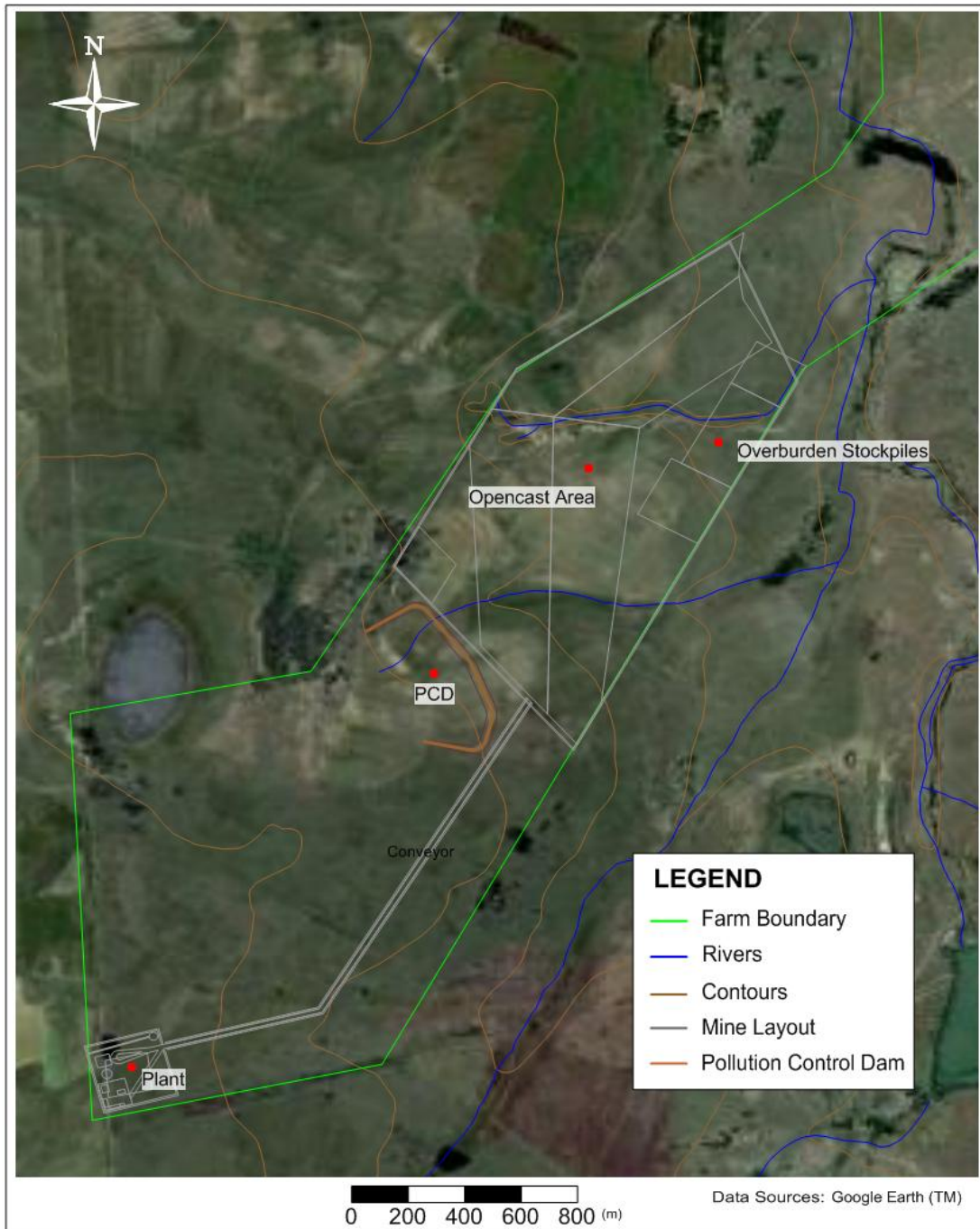

Figure 25: Surface layout.

From the geological map (1:250 000, 2628, East Rand, 1986) it was found that the geology of the site consists mainly of sediments of the Karoo Supergroup succession, with shale and sandstone being the dominant lithology types, as shown in Figure 26.
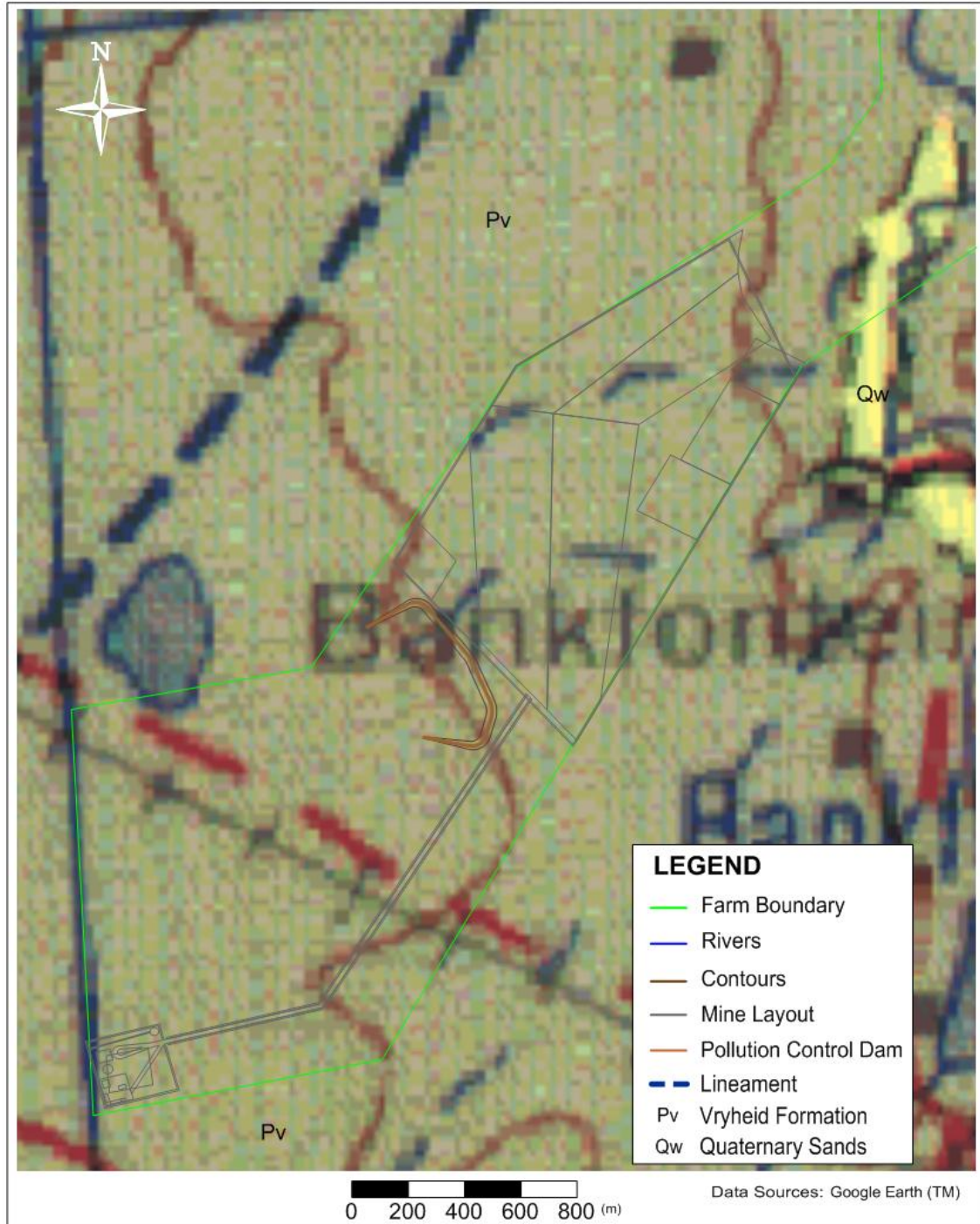

Figure 26: Site geology.

The Karoo Supergroup, which rests on a glaciated pre-Karoo basement, consists of the Dwyka Group, overlain by the Ecca Group (Pietermaritzberg, Vryheid and Volksrust Formations) with localised occurrences of the Beaufort Group in topographically high areas in the south of the coal field. The coal seams are all found within the Vryheid Formation, within the Ermelo Coal Field. Five coal seams are identified that are named from the base upwards: E, D, C, B and A. The C seam is usually the most economically attractive however the B, E and occasionally the D seams may attain mineable thicknesses over limited areas.

The Karoo geology has been extensively intruded by Jurassic era dolerite in the form of dykes and sills. These dolerite intrusions are typically investigated as potential pathways for water. However as indicated in the geological map, no dolerite intrusions were found within the mining area. Furthermore the geological map also shows a number of north east-south west trending regional scale faults throughout the area. However, these larger regional features again do not appear to intersect the mining area.

The D, C and B coal seams have been identified within the Mining area. The client did indicate contrary to the geological map that and stated that the coal deposit is divided into northern and southern portions by a dolerite sill striking east -west. Both the B and C seams are relatively flat-lying in the northern and southern parts of the property however, seam elevations contoured from the geological data exhibit an abrupt change in elevation of about 25 m in the central area. This appears to indicate that the seam has been displaced with the southern area being about 25 m higher. This is a result of a major dolerite sill transgressing from a stratigraphic position above the B Seam in the northern half of the property to a position below the C Seam in the southern portion. This sill divides the coal seams in two. The sill has resulted in small scale, localised devolatilisation of the coal seams. The lower E seam elevations were contoured and compared to elevation contour data as shown in Figure 27. By comparing the seam and elevation data a possible decanting point was identified towards the north-eastern portion of the opencast near the stream.
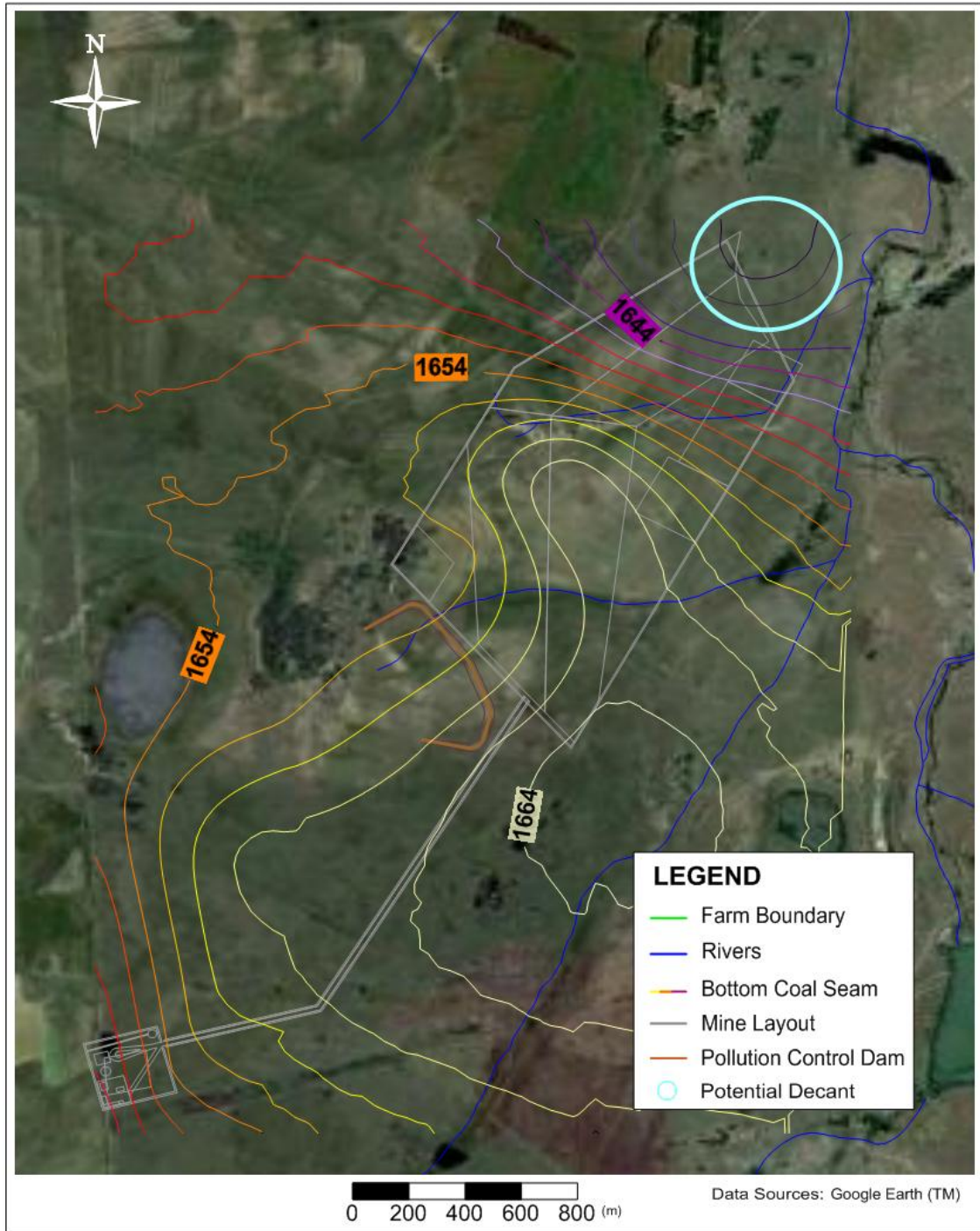
Figure 27: E seam contours and decant position.

Once all the cartographical sources and client information was studied, geophysical methods were then used to enhance the understanding of the sites subsurface conditions. Magnetic and electromagnetic (EM) ground geophysical methods were applied to locate possible water bearing geological structures (dolerite dykes and fault zones) for the drilling of monitoring boreholes. These geological structures can serve as possible pathways for contamination flow and therefore are of vital importance to identify and monitor. These structures were investigated in terms of their water bearing capabilities, serving either as preferential flow paths for groundwater or as groundwater flow barriers, forming groundwater compartments. Magnetic and electromagnetic (EM) ground geophysical methods are discussed in more detail in Section 2, Chapter 2.

Ground magnetic surveys were selected to detect local changes in the earth's magnetic field that could be used to locate these small-scale dyke intrusive bodies. The magnetic surveys were conducted using the G5 proton magnetometer manufactured by Geotron Systems (Pty) Ltd and can be seen in Figure 28.

Figure 28: G5 Magnetometer.

In conjunction with the G5, an EM ground survey at the study area was also conducted using the Geonics EM34-3 instrument as can be seen in Figure 29. This instrument is an active, frequency domain system that calculates an apparent conductivity of the earth by measuring the quadrature (out-of-phase) component of the secondary magnetic field at low induction numbers. Measurements were taken with two dipole orientations. Horizontal dipole (HD) orientations investigated at shallower depths gave good coupling with vertical structures while vertical dipole (VD) orientations investigated at deeper depths gave good coupling with horizontal structures. An inter-coil spacing of 40 m was used during the survey.

Figure 29: EM34-3 Instrument.

Traverses were walked across geological features identified on the geological map, satellite imagery, and geological data given by the client. These traverses can be seen in Figure 30. It must be noted that magnetometer readings were highly erratic or flat and few magnetic bodies were identified, therefore the majority of the borehole sittings were as a result of the EM method.

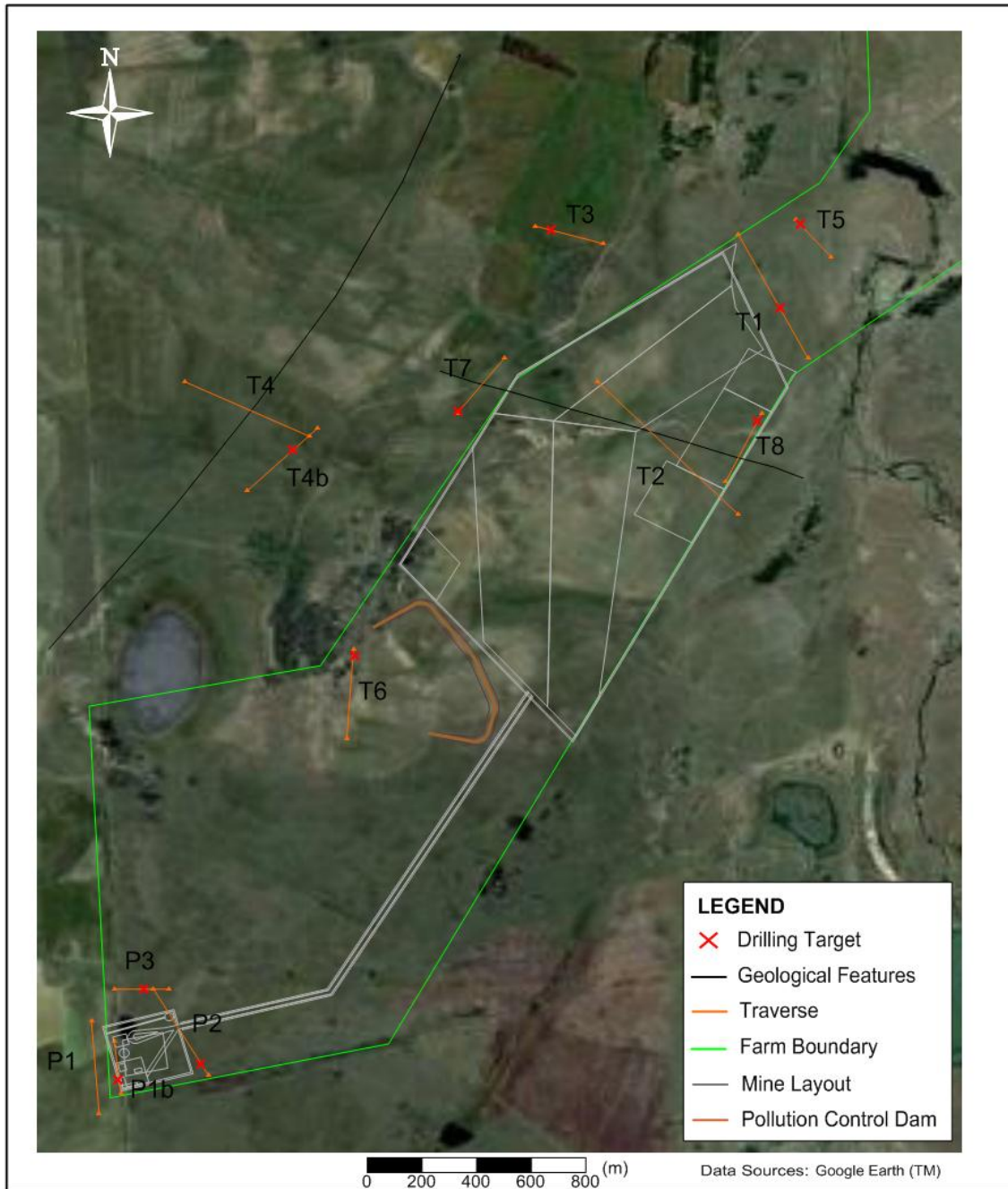**Figure 30: Geophysical traverses.**

The electrometric and magnetic data can be seen in Appendix C. The following interpretations were made from geophysics results:

- P1b: Was traversed from south to north. The traverse was 190 m long. The magnetometer detected an anomaly (possible fault) between station 60 and 70, where the initial readings were low but steadily increased and remained stable.

The EM was relatively stable however there was a sharp decrease in the vertical dipole indicating horizontal structures.

- P2: Was traversed from south to north. The traverse was 315 m long. No clear anomalies were detected with the magnetometer. The EM was relatively stable however there was a sharp increase followed by a decrease in the vertical dipole in the initial stages of the traverse, indicating horizontal structures or a zone of deeper weathering.

- P3: Was traversed from east to west. The traverse was 160 m long. The magnetometer readings were highly erratic and no clear anomalies could be identified, there was a sharp decrease in readings towards the end of the traverse. Towards the end of the traverse the two EM dipoles started to separate showing a possible zone of weathering.

- T1: Was traversed from south to north. The traverse was 540 m long. The magnetometer readings were stable and from 425 m the readings decreased sharply. The vertical dipole showed a sharp decrease from 200 m indicating horizontal structures or deep zone of weathering, at the same point the horizontal dipole stared to increase. A fence was also encountered towards the end of the traverse.

- T3: Was traversed from east to west. The traverse was 235 m long. The magnetometer revealed a convex anomaly. The EM readings were stable throughout the traverse however towards the end of the traverse the two dipoles started to separate indicating there was a minor anomaly in the subsurface.

- T4b: Was traversed from south-east to north-west. The traverse was 280 m long. The magnetometer readings showed a sharp decrease followed by a sharp increase around 150 m indicating a possible magnetic anomaly. The EM also showed an anomaly at this location by a rapidly decreasing vertical dipole.

- T5: Was traversed from south to north. The traverse was 200 m long. The magnetometer readings were highly erratic and no clear anomalies could be identified. The EM was relatively stable however as the traverse progressed there was an increase in the horizontal dipole, indicating possible vertical features.

- T6: Was traversed from south to north. The traverse was 450 m long. The magnetometer readings were highly erratic and no clear anomalies could be identified. The EM revealed that the horizontal dipole showed no clear anomalies, however the vertical dipole showed a sharp decrease from 350 m indicating horizontal structures or zones of weathering.

- T7: Was traversed from south-west to north-east. The traverse was 290 m long. During the traverse a fence was crossed. The magnetometer readings were stable with a minor anomaly detected during the start of the traverse. A potential anomaly was also detected with the EM during the start of the traverse.

- T8: Was traversed from south-west to north-east. The traverse was 280 m long. The magnetometer readings revealed a sharp decrease followed by a sharp increase around 250 m indicating a possible magnetic anomaly. The EM data was stable throughout the traverse.

After collaborating and studying all the information obtained in Stage 2, a preliminary conceptual model of the site was established. From the investigations it can be attained that the topography from the site is higher in the west and dips off toward the river along the eastern side of the site. The E seam reaches a high in the south eastern portion of the site and dips towards the north and western areas. There is limited dolerite intrusions located in the project area which results in limited pathways for possible contaminant to move along. However some possible areas with higher conductivity were identified pointing to possible areas of weathering. These zones of weathering may result in possible water bearing structures and potential pathways. For the preliminary model we can therefore visualise the possible ground water flow (still to be proved with Bayesian Interpretation), we know the local geology is sandstone, shale and coal seams, the potential decant point was established, and lastly with geophysical methods, potential pathways and drilling sites were determined.

CHAPTER 3: RISK ASSESSMENT

With a greater understanding of the surface and subsurface conditions a risk assessment based on the Source-Pathway-Receptor Principal was then carried out. The first step with the risk assessment was identifying the potential contamination sources located onsite. From information gathered from the client the following sources were identified;

- Plant area,
- Overburden stockpiles,
- Opencast area, and the
- Pollution control dam.

With data as given by the client, the geological map and the geophysics conducted onsite the following pathways were identified;

- Dolerite intrusion (through the opencast),
- The geological lineament (north-west of site),
- Future decant point, and
- Weathered zones.

With the satellite imagery and observation collected during the site walk over a number of sensitive receptors were identified;

- Large pan,
- The smaller pan north of the plant area,
- Informal residence (north of site),
- Local farmer borehole (south of site), and the
- The down gradient river (east of site).

When all these identified sources, pathways, and receptors were plotted over the site, as can be seen in Figure 31. The proposed drilling position and number of boreholes were then confirmed and the conceptual model was strengthened.
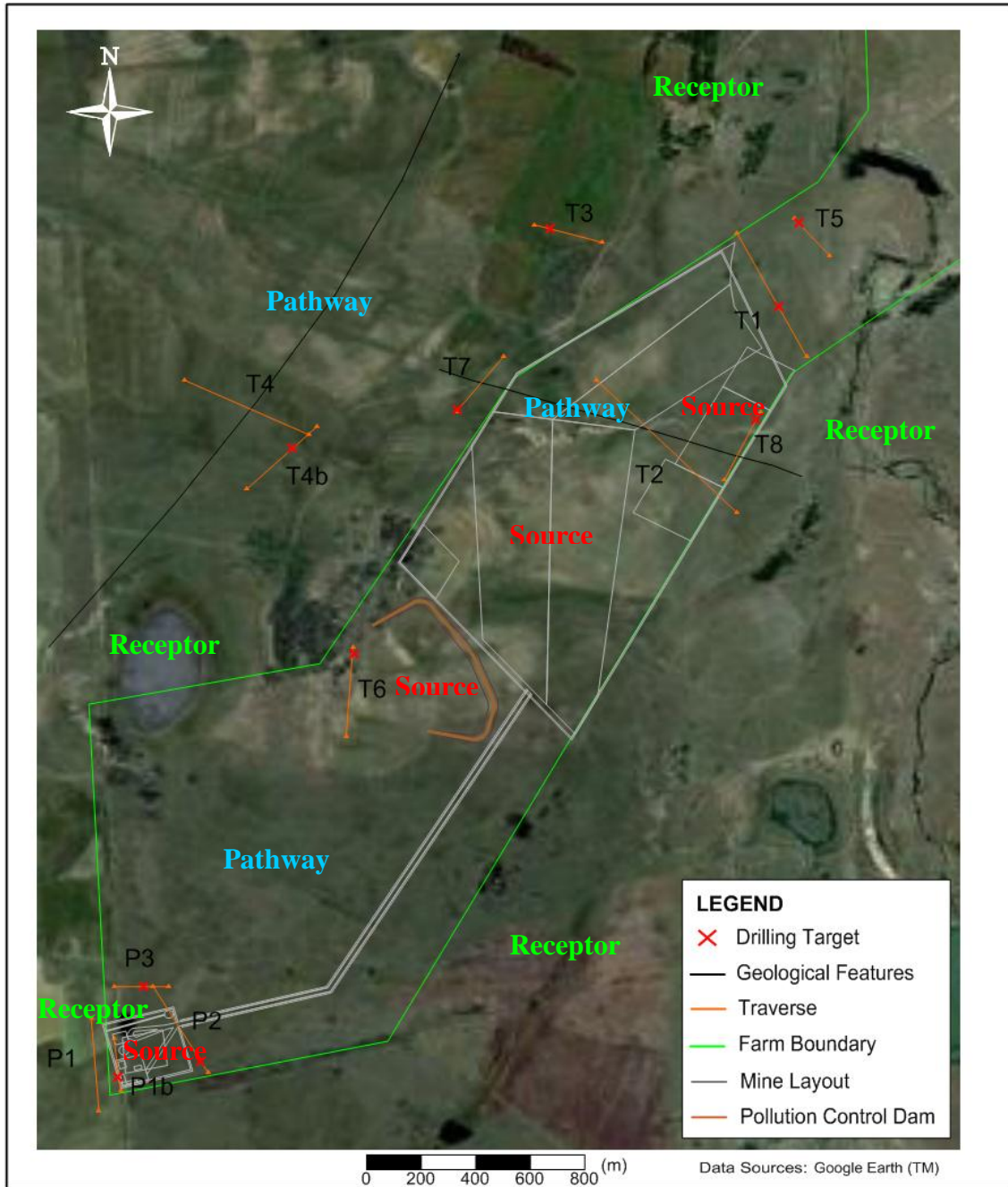
Figure 31: Potential risks.

In Figure 31, it must be noted that a number of up gradient boreholes were selected, boreholes were sited in the different pathways, and a number of down gradient boreholes were selected.

CHAPTER 4: DRILLING OF MONITORING BOREHOLES

The geophysical results were used to site 10 monitoring boreholes, 7 in the opencast area and 3 near the crusher plant. The boreholes were drilled by Rotary-Percussion Air Drilling Rig as can be seen in Figure 32.

Figure 32: Rotary-Percussion Air Drilling Rig.

Geological samples were taken at one meter intervals. To assist with the identification of the different geological strata, the chip samples were rinsed and sieved. The boreholes geological logs were then recorded and are presented in Appendix D. Every meter drilled during drilling was also timed so penetration rates to could be recorded. Overall the sandstone and shale present onsite were highly weathered.

Blow yields were determined by measuring the amount of water that is 'blown' out of the borehole.

First a small reservoir is created out of the drilled material and a discharge pipe, as seen in Figure 33, is installed. The flow of water leaving the discharge pipe is then measured and timed and the rate per minute is then established.

Figure 33: Blow yield estimation.

Most of the boreholes that were drilled had relatively low blow yields of which are typical for that of Karoo aquifers, with the majority of the boreholes only intercepting minor water strikes. However three boreholes namely P2, P3 and T6 had moderate to high blow yields for the region.

P2 had a blow yield of 6 l/s, P3 had a blow yield of 2 l/s, and T6 had a blow yield of 1.5 l/s. Boreholes T5 and T8 intersected no water during drilling, however over time seepage water from the weathered zone had flowed into the borehole resulting in a rest water level.

Water levels were obtained from the newly drilled monitoring boreholes as well as surrounding farm boreholes. A linear relationship often exists between the groundwater table and the topography. A plot showing groundwater elevations versus topography is shown in Figure 34, and confirms a linear relationship for most of the data.
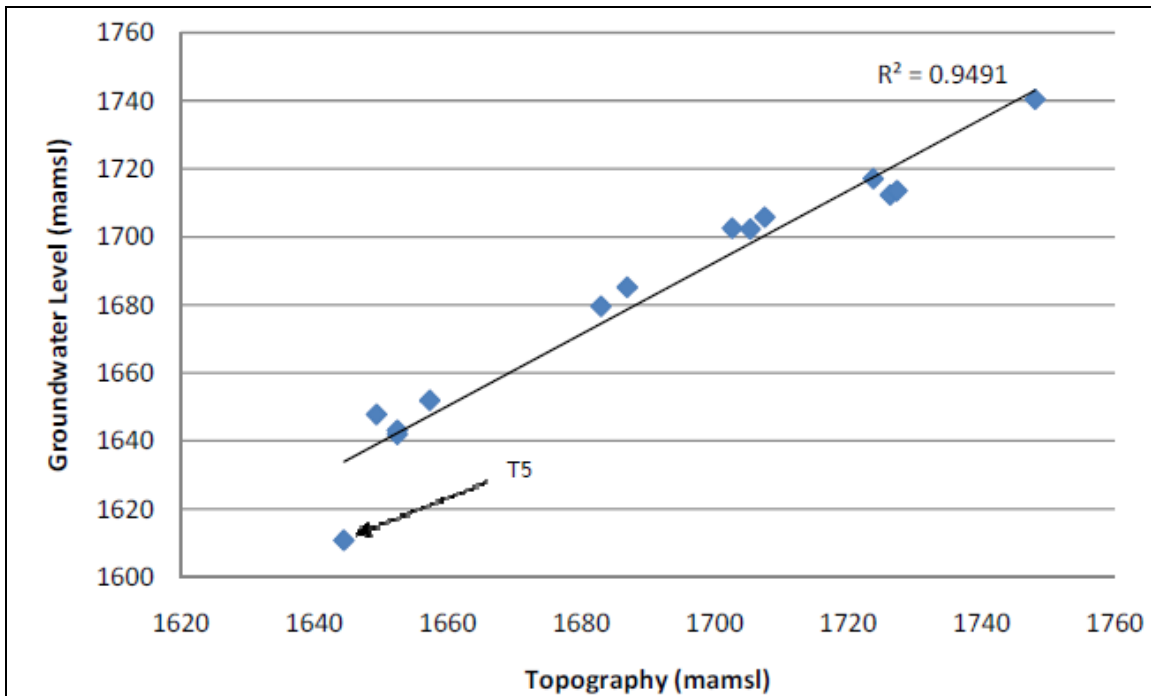
Figure 34: Bayesian interpretation.

Point T5 has poor linear relationship when compared to the other boreholes. During drilling of T5 no water strikes were intersected and as a result the water level in the borehole is seepage water from the weathered aquifer. Once all the water levels were obtained and a significant correlation between groundwater table and the topography was established the flow of groundwater could be obtained i.e. groundwater follows the surface topography.

Groundwater levels and flow directions across the mining area is shown in Figure 35. The groundwater flow is from west to east across the site towards the stream. It can therefore be assumed that all potential contaminates too will migrate towards the stream.
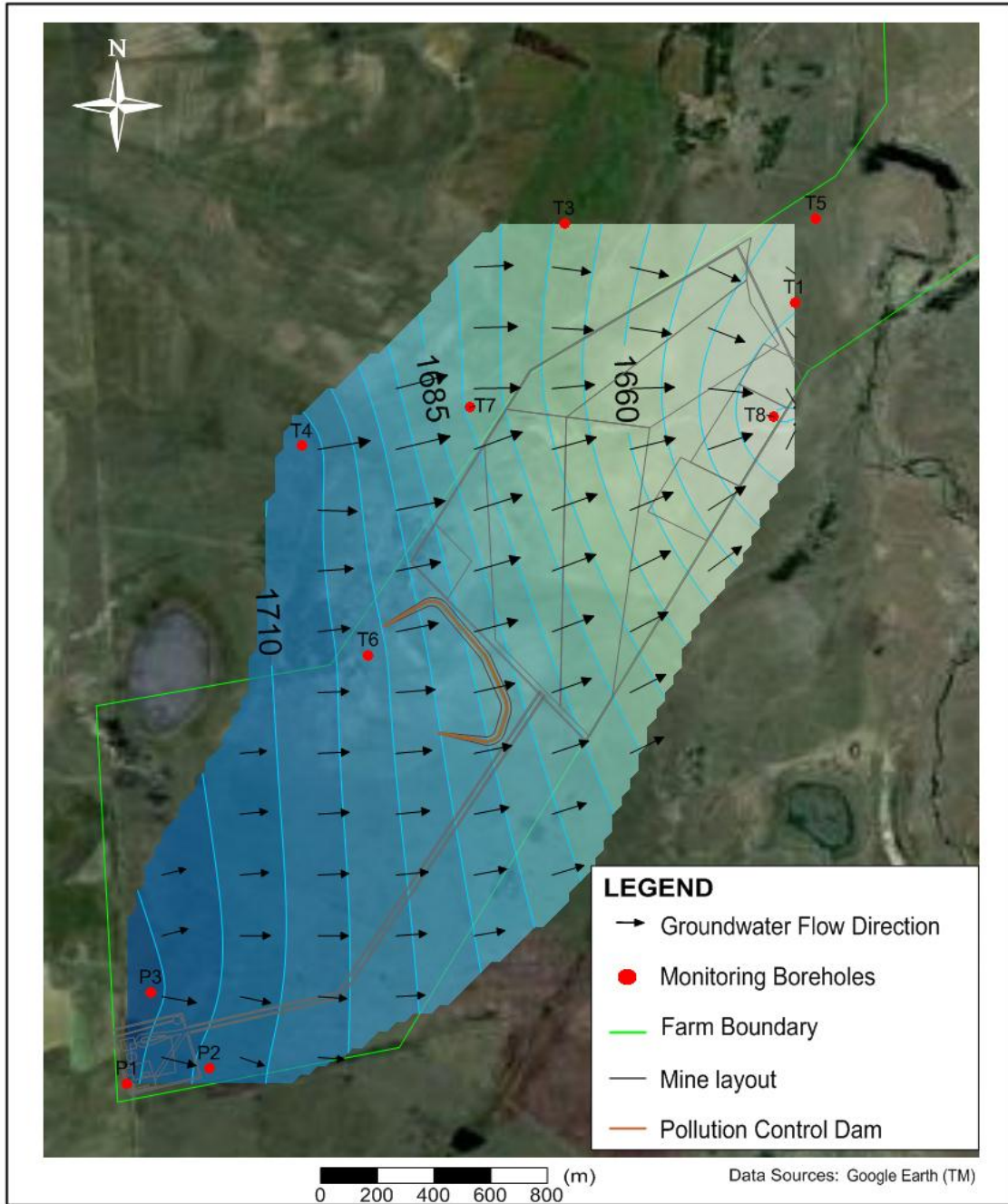
Figure 35: Groundwater flow direction.

Now that the groundwater flow has been confirmed and the geological logs studied, a greater insight to the subsurface conditions has been achieved and the conceptual model further strengthened.

CHAPTER 5: BOREHOLE CONSTRUCTION

The weathered zone was unstable and collapsing during drilling, in order to prevent this, all the boreholes were reamed to install a 170mm steel casing for the first six meters of drilling. The boreholes were then cased with 140mm solid PVC casing throughout the entire borehole. Where water was intersected, perforated PVC casing was installed as can be seen in Figure 36.

Figure 36: Slotted PVC casing.

Nominal size (4mm) gravel was then inserted in the annual space between the casing and the hole to form the gravel pack of each borehole.

CHAPTER 6: WATER SAMPLING

Water samples were collected depending on the borehole yields. The stronger yielding boreholes were sampled after purging of the borehole whilst samples were taken from the low yielding boreholes by utilising a bailer. For each low yielding borehole a new bailer was used to prevent cross contamination. For the high yielding boreholes the pump and pipeline was rinsed with deionised water and the pipes were sufficiently flushed with water within the borehole before the water sample was taken.

Two water samples were taken from each borehole, a 500 ml sample and a 100 ml sample. The 500 ml water sample was used for the major anions and cations analysis, whilst the smaller bottle was used for heavy metal analyses. Both sample containers were plastic bottles obtained from the laboratory. The water samples were filtered directly into the 100 ml bottle. Nitric acid was then added to the 100 ml water samples to ensure that the heavy metals within the water sample stay in solution. Field measurements were also taken from each sampling point this included the pH, EC, and temperature of the sample. Each sample bottle was marked with a permanent marker and included the samples unique name, site name, and the sample date. All samples were stored in a cooler box filled with ice.

The Chain of Custody sheet (COC) was then filled in listing each samples details including the amount of bottles per sample taken. Included in the COC were all the chemical parameters to be analysed for. The COC was then given to the laboratory with the water samples, where it was signed. The signed copy was then kept as proof of delivery.

CHAPTER 7: GEOCHEMISTRY AND RESULTS

The newly drilled monitoring boreholes (named after their geophysical traverse) were sampled and a comprehensive analysis was conducted on all samples. The groundwater quality results from the new monitoring boreholes water quality are shown in Table 12. The results were compared to both: the SANS 241 Class 1 and Class 2 Drinking Water Quality Guidelines.

Constituents that exceeded the Class 1, water quality objective were highlighted in green. Constituents exceeding the Class 2-Maximum allowable limit were highlighted in red. Most of the water samples taken represent good water quality and are in compliance with both the SANS 241 Drinking Water Standards. For some of the water samples the heavy metal concentration exceeded either the Class 1 or Class 2 Drinking Water Quality Guidelines. This could be as a result of the water rock interactions with the rocks of the Vryheid Formation within the boreholes. Both T4b and T7 have elevated aluminium, manganese and iron concentrations. These heavy metals can be seen as indicators of coal mining in the area. However this could not be confirmed as no surrounding mine plans was obtained. Borehole T5 is the only borehole that has a fluoride concentration that exceeds the Class 2 Drinking Water Quality Guidelines. Fluoride is a constituent commonly associated with the geology of basement rocks. T5 was only drilled to a depth of 43 m and no basement rocks were intersected during drilling. However sedimentary rocks such a sandstone and shale are secondary in their origin, and such the materials of which they are composed are similar to that of the previously existing rock mass (basement rock) and in this case the sedimentary rocks may have fluoride minerals present.

Table 12: Water Analyses.

Parameters:	Class 1	Class 11	P1b	P2	P3	T1	T3	T4b	T5	T6	T7	T8
pH Value @ 23°C	5.0 – 9.5	4.0 – 10.0	6.50	6.90	7.40	7.40	7.70	6.60	8.00	6.80	7.00	7.10
Conductivity mS/m @ 25°C			12.50	21.70	25.30	35.60	34.70	8.44	64.20	15.30	23.00	44.20
Total Dissolved Solids			126.00	202.00	208.00	322.00	234.00	54.00	538.00	176.00	182.00	430.00
Calcium,Ca	<150	150 - 300	5.50	15.50	21.00	24.00	21.00	5.00	6.90	10.90	18.20	19.20
Calcium Hardness as CaCO3			14.00	39.00	52.00	60.00	52.00	12.00	17.00	27.00	45.00	48.00
Magnesium, Mg	<70	70 - 100	2.30	4.20	6.20	15.30	9.50	1.40	3.60	4.60	8.00	8.30
Magnesium Hardness as CaCO3			9.00	17.00	26.00	63.00	39.00	6.00	15.00	19.00	33.00	34.00
Total Hardness as CaCO3			23.00	56.00	78.00	123.00	92.00	18.00	32.00	46.00	78.00	82.00
Sodium,Na	<200	200 - 400	11.90	11.70	18.30	24.00	25.00	6.60	127.00	8.10	10.40	62.00
Potassium,K	<50	50 - 100	3.00	6.30	4.60	2.20	3.60	2.30	3.40	3.30	2.50	3.60
Total Alkalinity as CaCO3			29.00	91.00	109.00	153.00	154.00	33.00	254.00	68.00	96.00	188.00
P Alk as CaCO3			Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Bicarbonate,HCO3			35.00	111.00	133.00	187.00	188.00	40.00	310.00	83.00	117.00	229.00
Carbonate, CO3			Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Chloride,Cl	<200	200 - 600	9.40	3.70	8.30	7.20	5.40	2.40	29.00	1.90	3.20	14.40
Sulfate,SO4	<400	400 - 600	1.80	2.60	1.40	9.40	5.60	<0.2	11.50	0.80	3.50	6.40
Nitrate,NO3			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Nitrate as N			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Fluoride,F	<1.0	1 – 1.5	<0.1	0.10	0.10	0.20	0.10	0.10	4.90	0.10	0.10	0.30
Aluminium, Al	<0.3	0.3 – 0.5	0.04	0.11	0.36	0.02	0.13	1.10	0.06	0.85	0.31	0.22
Manganese, Mn	<0.1	0.1 – 1.0	<0.001	<0.001	0.02	0.31	0.01	0.04	<0.001	0.07	0.24	0.08
Iron, Fe	<0.2	0.2 – 2.0	<0.001	0.10	0.32	1.20	0.38	1.60	<0.001	2.90	0.26	0.18
Zinc, Zn	<5.0	5.0 – 10.0	0.02	<0.005	<0.005	<0.005	<0.005	<0.005	0.01	0.10	<0.005	<0.005
Lead, Pb	<0.02	0.02 – 0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

*Constituents exceeding the more stringent compliance objective highlighted in red
*Constituents exceeding the less stringent compliance objective highlighted in green

Water quality data is plotted on a tri-linear diagram to aid in the characterisation of different water types. According to the Piper Diagram in Figure 37, the majority of the groundwater samples taken during the investigation are representative of calcium/magnesium - bicarbonate to sodium/calcium/magnesium - bicarbonate waters, typical of the region's Karoo aquifers, as expected from the conceptual mode.
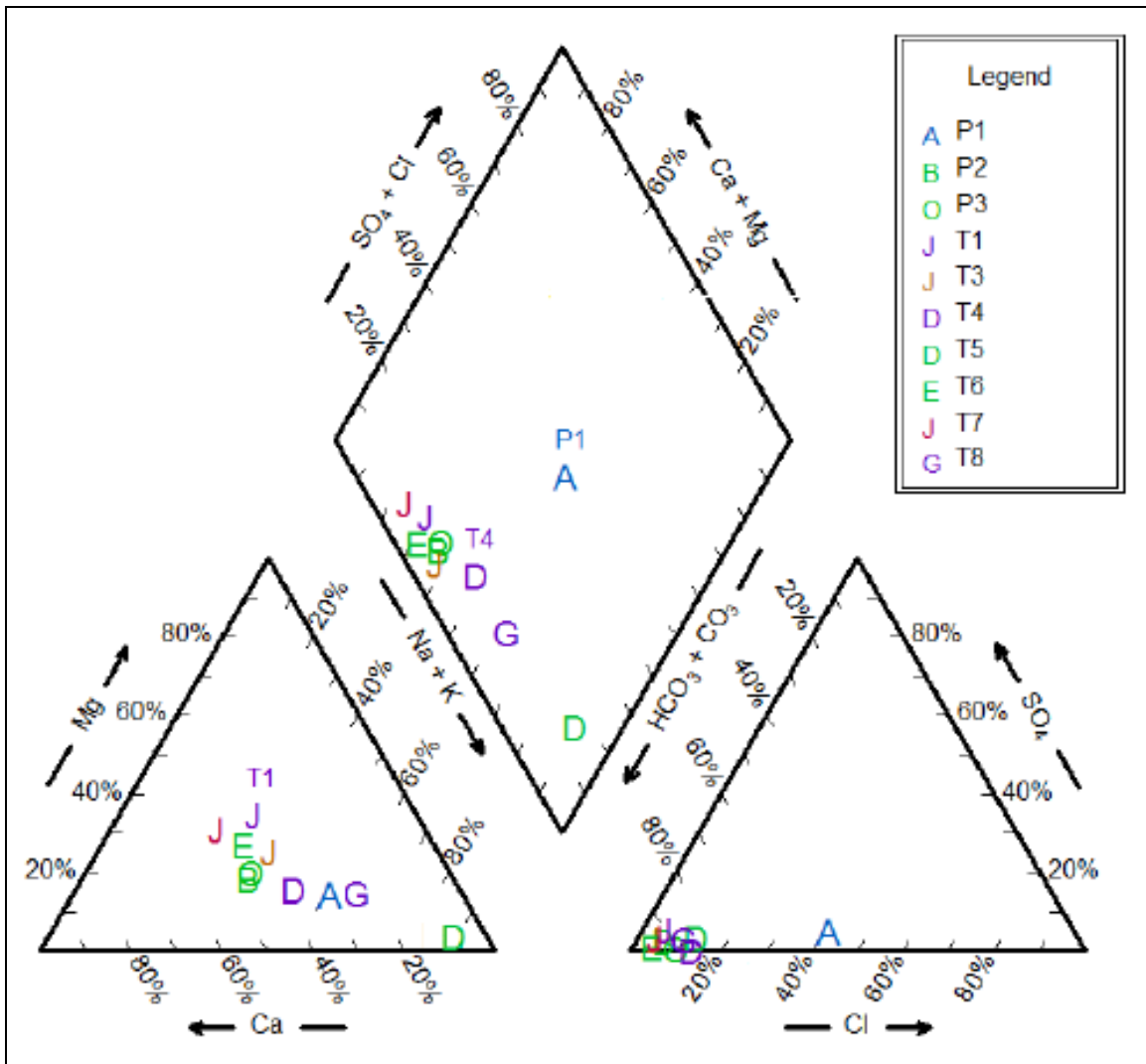
Figure 37: Piper Diagram.

CHAPTER 8: REVIEW AND UPDATE MONITORING PROGRAMME

It was recommended to the client that groundwater monitoring be conducted on a monthly basis for the first year and then to reduce the sampling frequency to quarterly. It was further recommended that the comprehensive analyses continue for the first year so a wide range of background water qualities can be obtained. After the first year the client can then speak to the governmental authorities and affected parties on reducing their monitoring constituents to only monitor selected indicator constituents.

The client must appoint an external water specialist company to take the groundwater samples as per the set time basis. This company must further analyse and interpret the groundwater monitoring data and write quarterly monitoring reports for the client. In these reports the water specialist company must highlight any decreasing trends in water quality or quantity. Lastly, the water specialist company must keep all the water monitoring data in a database and ensure there is a up to date back up of the database.

CHAPTER 9: FINDINGS AND RECOMMENDATIONS

When applying the methodology, as per Section 2, to the practical nature of the methodology was successfully applied to the case study. The step by step nature of the methodology made it easier to plan and initiate the groundwater investigations. The main area of concern identified through the case study was that of economical constraints and a s a result the different aquifer systems, namely the weathered upper aquifer and the fractured rock aquifer, could not be isolated with a packer system as described in Section 2, Chapter 5.3. This resulted in water qualities being 'averaged out' over the entire water column. Ideally a packer system or piezometers should have been installed so the water qualities of the different aquifer systems could be monitored and possible cross contamination avoided.

For the case study the decontamination of equipment as discussed under Section 2, Chapter 6.6, was too an area of concern. For the case study the pump and pipeline was rinsed with deionised water and the pipes were flushed with water within the borehole before the water sample was taken. Unfortunately there was not enough time and deionised water to sufficiently decontaminate and rinse each piece of equipment thoroughly with a cleaning solution. The 50 meters of piping was difficult and tedious to clean. Furthermore, creating a small decontamination area to facilitate cleaning of all equipment immediately prior to use or movement to the next sampling location, as discussed in the Study, too took large periods of time and eventually had to be overlooked. If the equipment used can not be cleaned easily one spends hours decontaminating equipment which places the project in jeopardy as time schedules and budgets can be exceeded.

It is recommended that the borehole construction options be discussed with the client on the outset of the project and the benefits and costs must be highlighted. The budget and timeframes of the project must include extra time and funding if equipment is to be effectively decontaminated.

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APPENDIX A: WATER SAMPLE SIZES, PRESERVATION AND RESIDENCE TIME FOR VARIOUS DETERMINANTS

(Weaver *et al.,* 2007)

Measurement	Volume required (ml)	Container plastic (P) or glass (G)	Preservation	Maximum holding time
Acidity	100	P/G	Cool, 4°C	24 hrs
Alkalinity	200	P/G	Cool, 4°C	24 hrs
Aluminium	50	P(A)/G(A)	Membrane filter on site, HNO_3 to pH<2	6 months
Ammonium	500	P/G	Cool, 4°C H_2SO_4 to pH<2	24 hours 7 days
Arsenic	100	P(A)/G(A)	Filter on site, HNO_3 to pH<2	6 months
Boron	1000	P(PTFE) or quartz	HNO_3 to pH<2	28 days
Bromide	100	P/G	Cool, 4°C	28 days
BTEX			See VOCs	
Calcium	100	P(A)/G(A)	Filter on site, HNO_3 to pH<2	6 months
$\delta^{13}C$	100	P/G	NaN_2	3 months
^{14}C	20-100 litre	P/G	Extract carbonate on site	1 year
^{14}C	200	G		6 months
CFCs	100	Special containers		3 months
COD	100	G preferred	H_2SO_4 to pH<2 Cool, 4°C	7 days
Chloride	50	P/G	Cool, 4°C	28 days
Colour	500	P/G	Cool, 4°C	48 hours
Chromium total hexavalent	100 1000	P(A)/G(A) P(A)/G(A)	Filter on site, HNO_3 to pH<2 Unfiltered, Cool, 4°C	6 months 24 hours
Cyanide total	1000	P/G	NaOH to pH>12 Cool, 4°C, Dark	14 days 24 h if S^{2-} present
Deuterium	20	P/G	-	1 year

Diesel Range Organics (DRO)	1000	G, TC	Cool, 4°C	7 days (40 days extracted)
DO: Winkler	300	G	Fix on site	8 hours
DOC	100	G preferred	Cool, 4°C, Dark	7 days
EC	500	P/G	None	28 days
Fluoride	100	P/G	None	28 days
Gasoline Range Organics	40 x 2	G, TC	Cool, 4°C	14 days
Hardness	100	P/G	Cool, 4°C HNO_3 to pH<2	7 days 6 months
Iodine	500	P/G	Unfiltered, Cool, 4°C	24 hours
Iron: total Iron: ferrous	50 50	P(A)/G(A) P(A)/G(A)	Filter on site HNO_3 to pH<2 Analyse on site	6 months 15 min
Manganese	50	P(A)/G(A)	Filter on site, HNO_3 to pH<2	6 months
Major cations & anions	500	P/G	Cool, 4°C	7 days
Metals (not Hg or Cr (VI)	1000	P(A)/G(A)	Filter on site HNO_3 to pH<2	6 months
Mercury	500	G(A)/P(A)	Filter on site HNO_3 to pH<2 Cool, 4°C	28 days (G) 14 days (P)
Microbiology Coliforms Plate count	1000 100	G(B)/P, sterilized	Cool, <10°C during transit	24 hours 24 hours
MTBE			see VOCs	
Nitrate	100	P/G	Cool, 4°C, dark H_2SO_4 to pH<2	1-2 days
Nitrite	100	P/G	Cool, 4°C, dark	ASAP
$\delta^{15}N$	500	P/G	Cool, Chloroform or H_2SO_4	2 months
Organic N (Kjeldahl)	500	P/G	Cool, 4°C H_2SO_4 to pH<2	7 days
Oil & grease	1000	G, wide mouth calibrated	Cool, 4°C H_2SO_4 to pH<2	24 hours 28 days
$\delta^{18}O$	20	P/G	-	1 year
Pesticides &	1000	G(S), Amber, TC	Cool, 4°C, Dark	7 days

PCBs				(40 days extracted)
Ph	50	P/G	Analyse on site	15 min
Phenolics	500	G/P, TC	Cool, 4°C H_2SO_4 to pH<2	28 days
PAHs	1000	G(S), Amber, TC	Cool, 4°C, Dark	7 days (40 days extracted)
Parasites	Filtered on site, 100 to 1000 L	Filter stored in plastic	Cool, 4°C	4 days
Phosphorus Total	100	P/G	Cool, 4°C H_2SO_4 to pH<2	28 days
Orthophosphate	100	G(A)	Filter on site Cool, 4°C	48 hours
Radioactivity Gross alpha Gross beta Radium 226 Radium 228 Radon 222 Uranium Caesium Strontium Iodine Photon-emitters	 >1000 >1000 >1000 >1000 2 x 25 >1000 >1000 >1000 >2000 >1000	 P/G P/G P/G P/G Special containers P/G P/G P/G P/G P/G	 HNO_3 to pH<2 HNO_3 to pH<2 HNO_3 to pH<2 HNO_3 to pH<2 Cool, 4°C HNO_3 to pH<2 HCl to pH<2 HNO_3 to pH<2 None HNO_3 to pH<2	 1 year 1 year 1 year 1 year 4 days 1 year 1 year 1 year 14 days 1 year
Potassium	100	P/G(B)	Filter on site, HNO_3 to pH<2	6 months
Semi VOCs	1000	G(S), Amber, TC	Cool, 4°C	7 days (40 days extracted)
Selenium	100	P(A)/G(A)	Filter on site, HNO_3 to pH<2	6 months
SF_6	200	Special containers	-	2 months
Silica	200	P (PTFE) or quartz	Cool, 4°C. Do not freeze	28 days
Sodium	100	P	Cool, 4°C	6 months
Sulphate	100	P/G	Cool, 4°C	28 days
Sulphide	100	P/G	Cool, 4°C, 4 drops Zn acetate/100 mL + NaOH to pH>9	28 days
Surfactants	250	P/G	Cool, 4°C	48 hours

| (MBAS)				
Temperature	50	P/G	Analyse on site	15 min
Tritium	500	G	None	1 year
Turbidity	100	P/G	Cool, 4°C, Dark	24 hours
THM	1000 2 x 25	G, TC G, TC	Cool, 4 C Cool, 4 C	24 hours 14 days
TPH	1000	G, TC	Cool, 4°C, Add 5 ml 50% HCl	28 days
Viruses	100 to 1000 L	Filtered on site Filter stored in plastic	Cool, 4°C	4 days
VOC	2 x 40	G, TC	Cool, 4°C HCl to pH<2	14 days

(A)   acid rinsed with 1+1 HNO_3 (B)   borosilicate glass
(S)   organic solvent rinsed (reagent grade acetone or methylene chloride) or baked
TC   Teflon lined cap

# APPENDIX B: 2005 SANS DRINKING WATER QUALITY STANDARDS

(DWA, 2005)

1	2	3	4	5
Determinand	Unit	Class I (recommended operational limit)	Class II (max. allowable for limited duration)	Class II water consumption period,[a] max.
Physical and organoleptic requirements				
Colour (aesthetic)	mg/L Pt	< 20	20 - 50	No limit[b]
Conductivity at 25 °C (aesthetic)	mS/m	< 150	150 - 370	7 years
Dissolved solids (aesthetic)	mg/L	< 1 000	1 000 - 2 400	7 years
Odour (aesthetic)	TON	< 5	5 - 10	No limit[b]
pH value at 25 °C (aesthetic/ operational)	pH units	5,0 - 9,5	4,0 - 10,0	No limit[c]
Taste (aesthetic)	FTN	< 5	5 - 10	No limit
Turbidity (aesthetic/operational/ indirect health)	NTU	< 1	1 - 5	No limit[d]
Chemical requirements — macro-determinand				
Ammonia as N (operational)	mg/L	< 1,0	1,0 - 2,0	No limit[d]
Calcium as Ca (aesthetic/operational)	mg/L	< 150	150 - 300	7 years
Chloride as Cl⁻ (aesthetic)	mg/L	< 200	200 - 600	7 years
Fluoride as F⁻ (health)	mg/L	< 1,0	1,0 - 1,5	1 year
Magnesium as Mg (aesthetic/ health)	mg/L	< 70	70 - 100	7 years
(Nitrate and nitrite) as N (health)	mg/L	< 10	10 - 20	7 years
Potassium as K (operational/health)	mg/L	< 50	50 - 100	7 years
Sodium as Na (aesthetic/health)	mg/L	< 200	200 - 400	7 years
Sulfate as SO₄ (health)	mg/L	< 400	400 - 600	7 years
Zinc as Zn (aesthetic/health)	mg/L	< 5,0	5,0 - 10	1 year
Chemical requirements — micro-determinand				
Aluminium as Al (health)	µg/L	< 300	300 - 500	1 year
Antimony as Sb (health)	µg/L	< 10	10 - 50	1 year
Arsenic as As (health)	µg/L	< 10	10 - 50	1 year
Cadmium as Cd (health)	µg/L	< 5	5 - 10	6 months
Total Chromium as Cr (health)	µg/L	< 100	100 - 500	3 months
Cobalt as Co (health)	µg/L	< 500	500 - 1 000	1 year
Copper as Cu (health)	µg/L	< 1 000	1 000 - 2 000	1 year
Cyanide (recoverable) as CN⁻ (health)	µg/L	< 50	50 - 70	1 week
Iron as Fe (aesthetic/ operational)	µg/L	< 200	200 - 2 000	7 years[b]
Lead as Pb (health)	µg/L	< 20	20 - 50	3 months
Manganese as Mn (aesthetic)	µg/L	< 100	100 - 1 000	7 years
Mercury as Hg (health)	µg/L	< 1	1 - 5	3 months
Nickel as Ni (health)	µg/L	< 150	150 - 350	1 year
Selenium as Se (health)	µg/L	< 20	20 - 50	1 year
Vanadium as V (health)	µg/L	< 200	200 - 500	1 year
Chemical requirements — organic determinand				
Dissolved organic carbon as C (aesthetic/health)	mg/L	< 10	10 - 20	3 months[e]
Total trihalomethanes (health)	µg/L	< 200	200 - 300	10 years[f]
Phenols (aesthetic/health)	µg/L	< 10	10 - 70	No limit[b]

[a] The limits for the consumption of class II water are based on the consumption of 2 L of water per day by a person of mass 70 kg over a period of 70 years. Columns 4 and 5 shall be applied together.

[b] The limits given are based on aesthetic aspects.

[c] No primary health effect - low pH values can result in structural problems in the distribution system.

[d] These values can indicate process efficiency and risks associated with pathogens.

[e] When dissolved organic carbon is deemed of natural origin, the consumption period can be extended.

[f] This is a suggested value because trihalomethanes have not been proven to have any effect on human health.

APPENDIX C: GEOPHYSICS RESULTS

P2 Geophysics

P3 Geophysics

T8 Geophysics
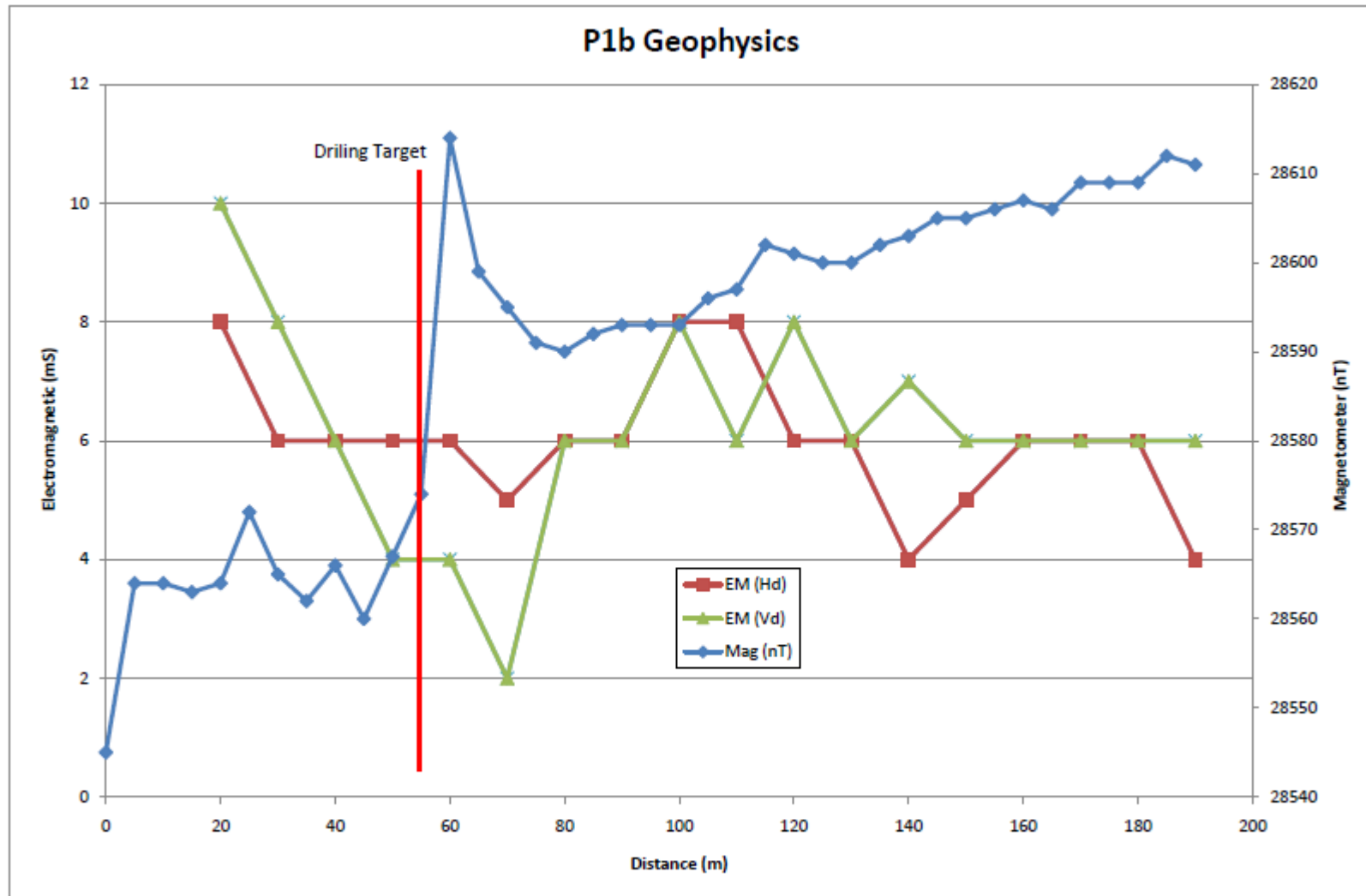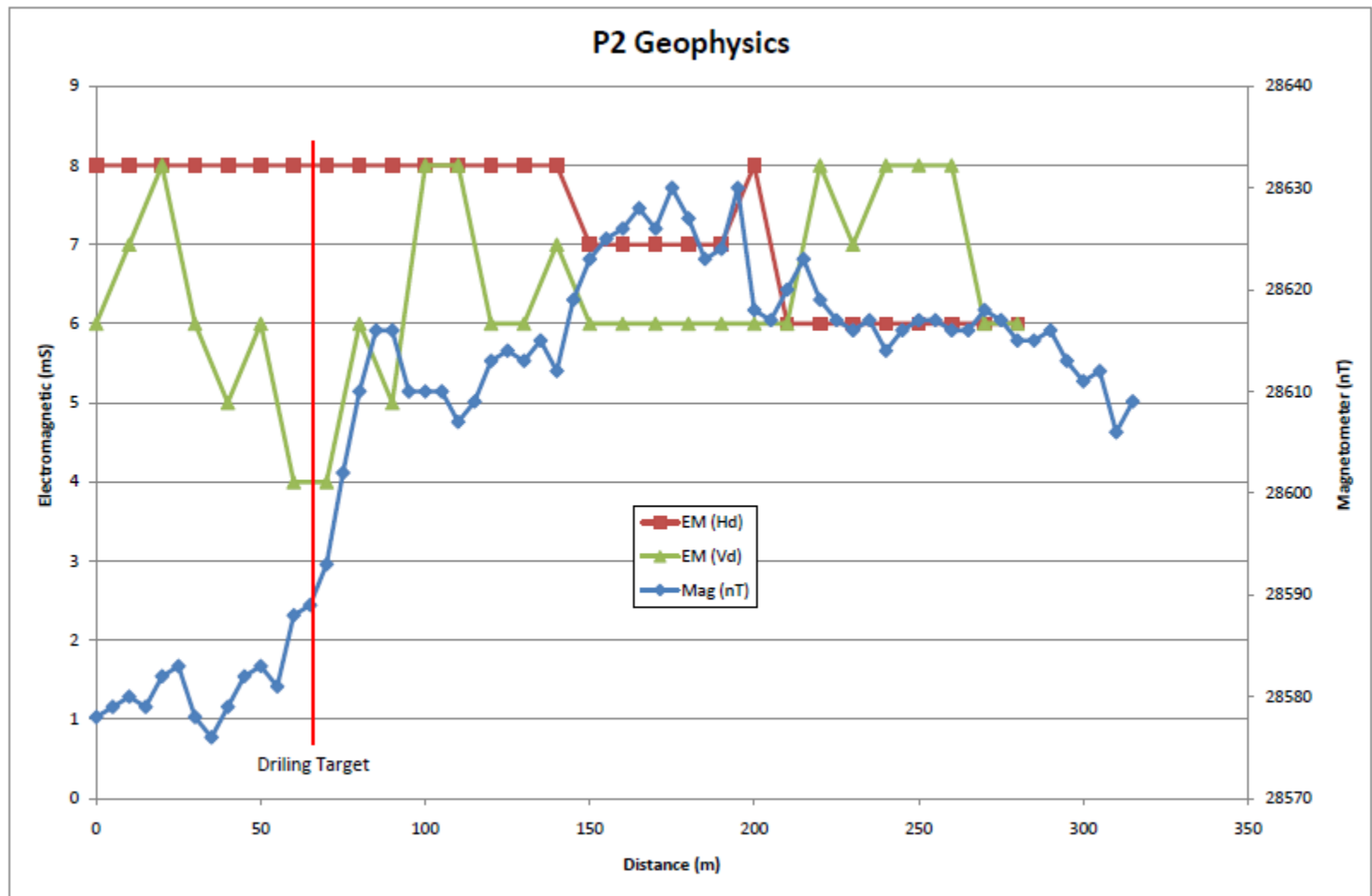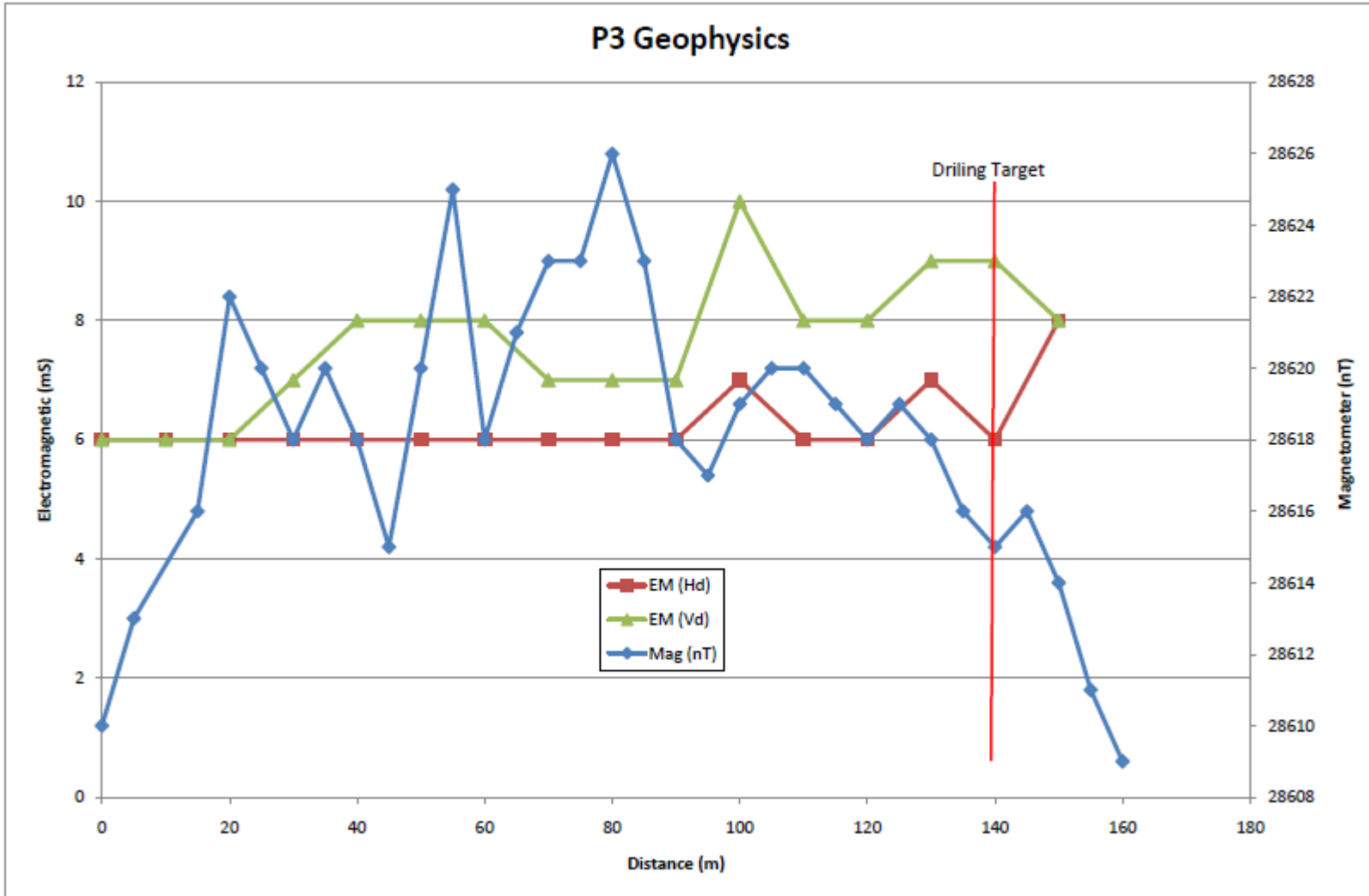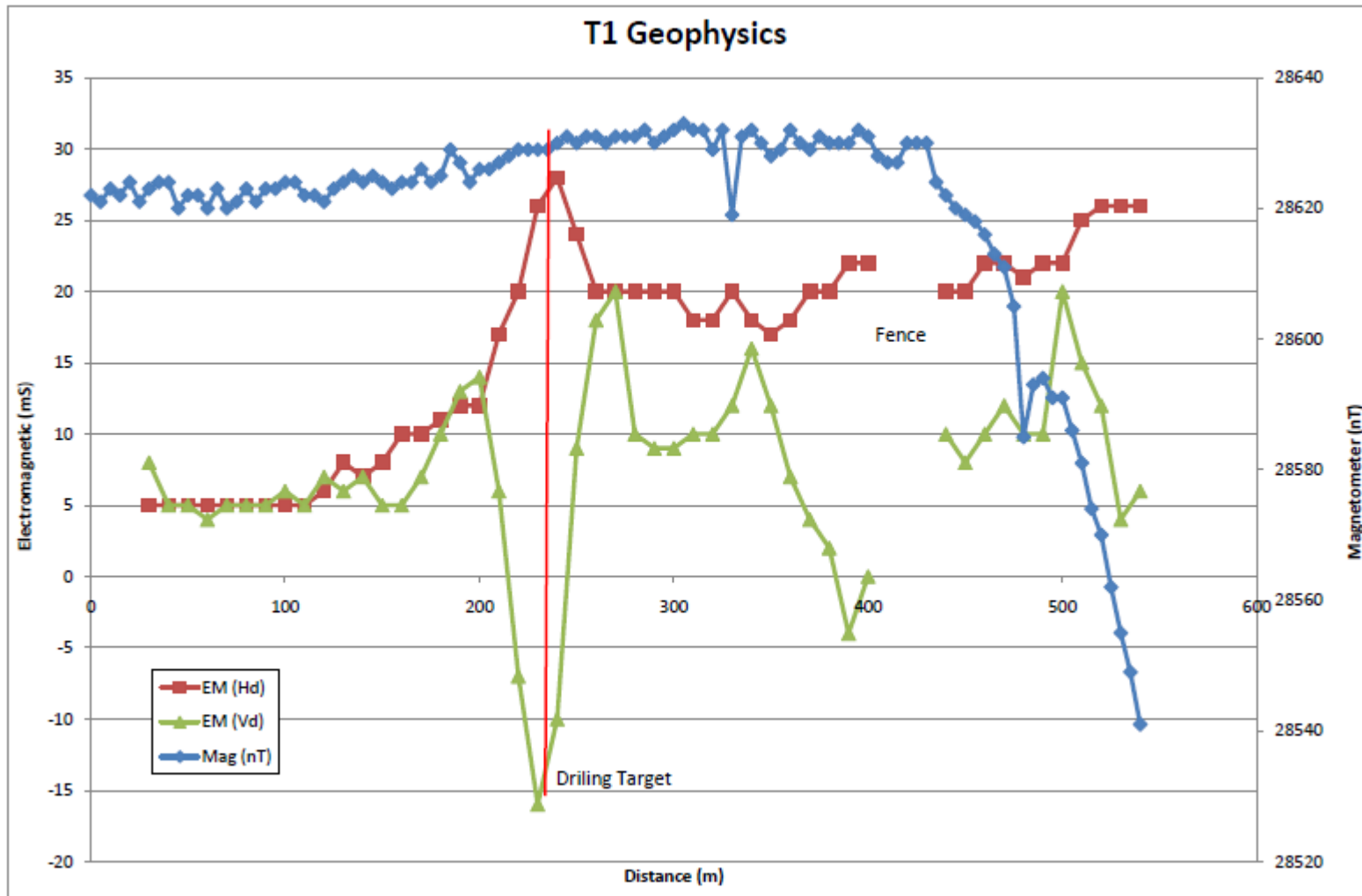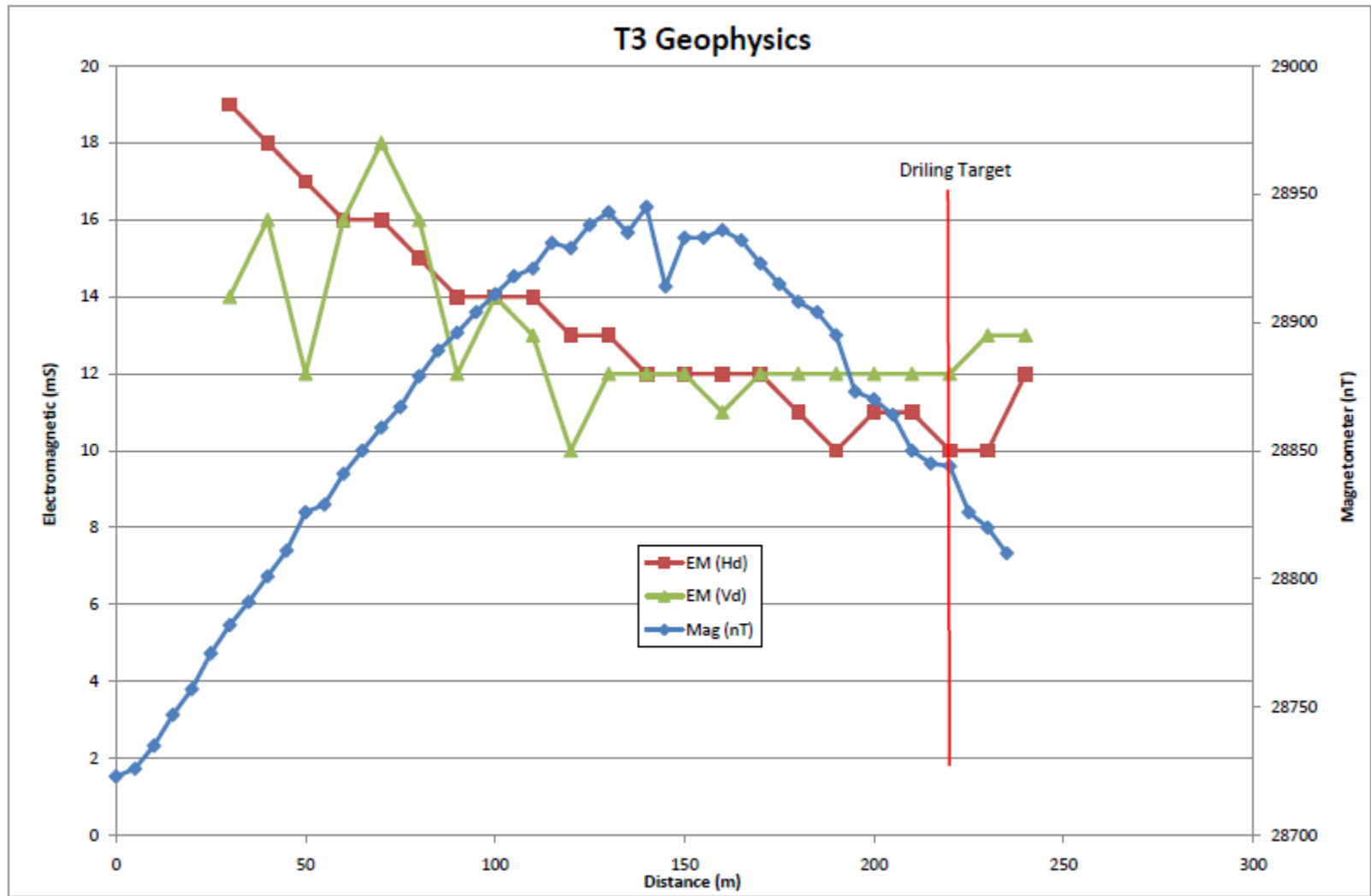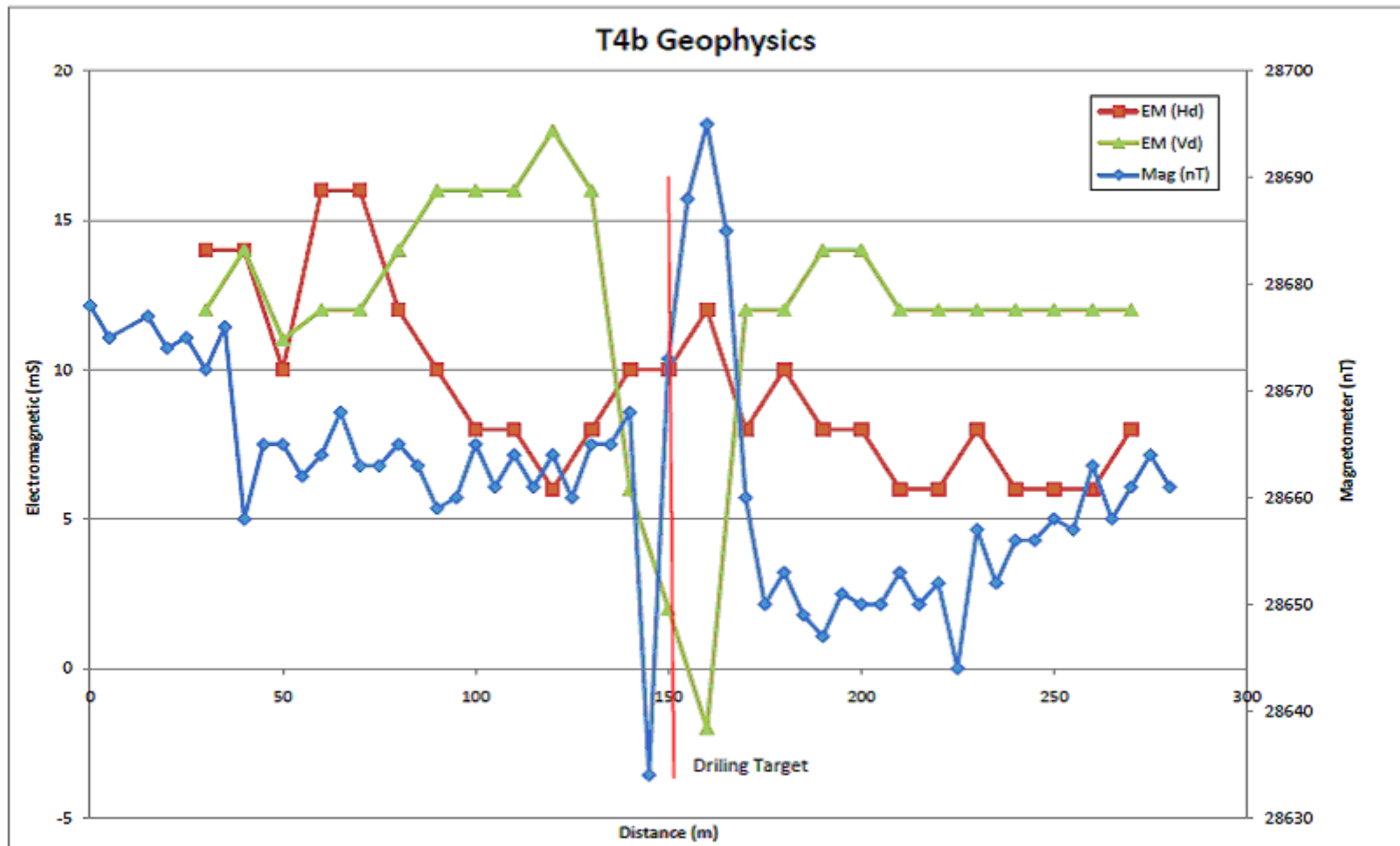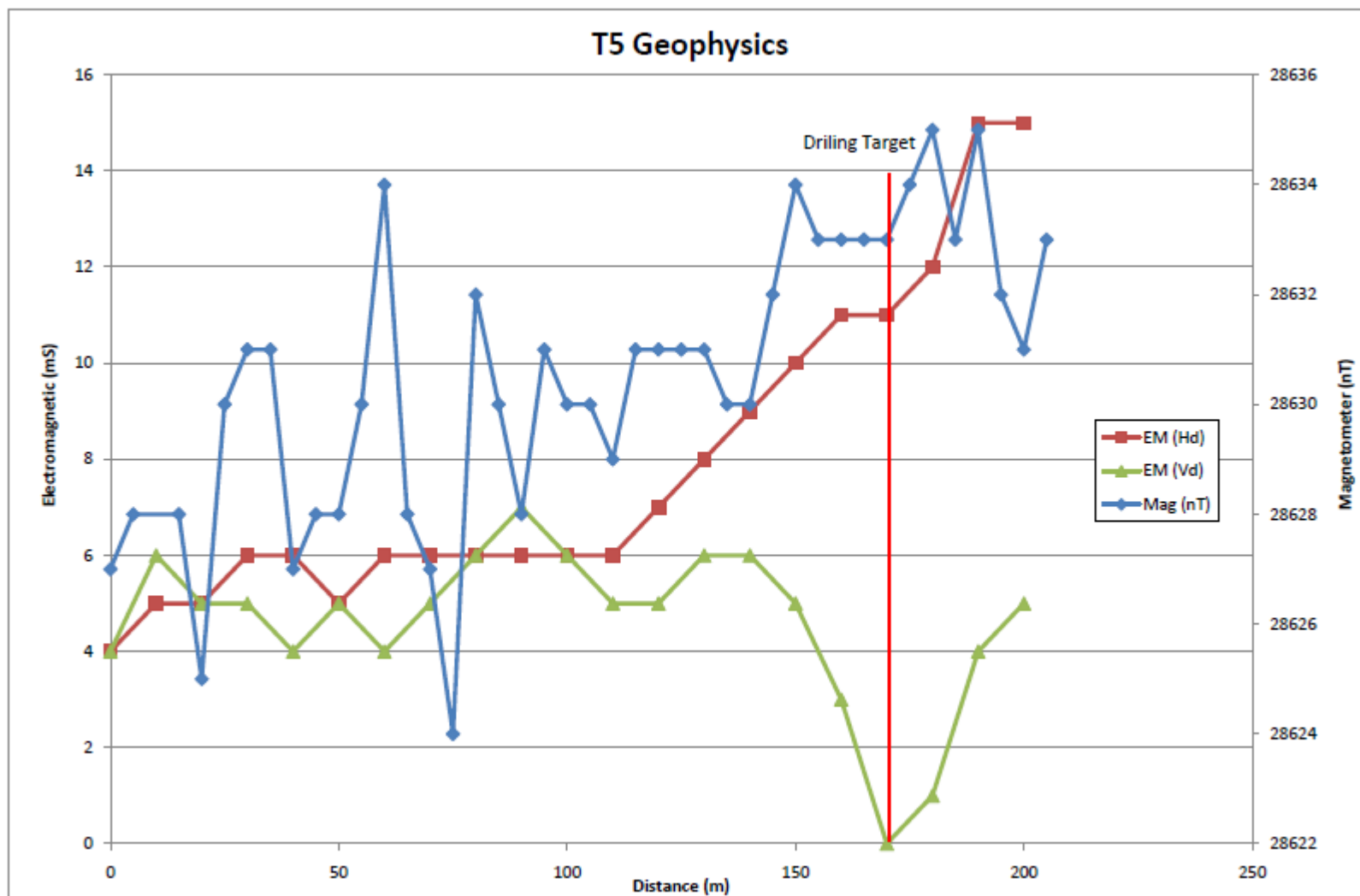
APPENDIX D: GEOLOGICAL LOGS

Borehole Construction and Geological Log (P1)

BASIC SITE INFORMATION: *Site Identifier:*   *Number:* P1   *Site type:* Borehole

Distr./Farm No.:   *Site Name/Des.:*

Region Type: *Region Descr.:*

Longitude [°]:	*Reg./BB.:* 11-041	*Topo-set.:* Flat surface, plain	*Depth [m]:* 45.00
Latitude [°]:	*G-Nr.:*	*Site status:* Unused	*Col. ht. [m]:* 0.31
Altitude [m]:		*Site purp.:* Observation	*Diam. [mm]:* 175
Coord. acc.: Accurate to within 1 unit		*Use applic.:* Industrial - mining	*Drain. reg.:*
Coord. meth.: Global Positioning System		*Equipment:* No equipment	*Rep. inst.:*

Coordinate System: Geographic Decimal Degrees (Longitude/Latitude), WGS 1984

Construction and Geohydrological Legend

——	Hole	165 →	Hole diameter [mm]
- - -	Casing (plain / perforated, sloted)	← 152	Casing diameter [mm]
——	Screen / Mesh Screen	▼	Waterlevel measured: 18/03/11
——	Piezometer	0:50 →	Piezometer (Nr. & Diameter [mm])
		▨	Gravel (> 2mm)

Construction   **Penetr. rate**   **Lithology**

[Min./m] 0.021 0.041

Lithology descriptions:
- SAND: Reddish brown, fine;
- SAND: Yellowish cream, fine; SLIGHTLY MOIST;
- SAND: White, fine weathered;
- SAND: Light brown, fine;
- SAND: Brown, fine to medium weathered;
- SAND: Cream, fine weathered;
- SAND: Grey, fine;
- SANDSTONE: Dark grey, fine laminated;
- SHALE: Dark grey, fine carbonaceous;
- SHALE: Grey, fine;
- SHALE: Dark grey, fine;

COMMENT:

Borehole logged by Mike Barnes

User name and adress

Page 1

BASIC SITE INFORMATION: *Site Identifier:*   *Number:* P2   *Site type:* Borehole

Distr./Farm No.:   *Site Name/Des.:*

Region Type: *Region Descr.:* MPUMALANGA

Longitude [°]:	*Reg./BB.:* 11-041	*Topo-set.:* Flat surface, plain
Latitude [°]:	*G-Nr.:*	*Site status:* Unused
Altitude [m]:		*Site purp.:* Observation

Coord. acc.: Accurate to within 1 unit	*Use applic.:* Industrial - mining
Coord. meth.: Global Positioning System	*Equipment:* No equipment

Depth [m]: 43.00
Col. ht. [m]: 0.10
Diam. [mm]: 165
Drain. reg.:
Rep. inst.:

Coordinate System: Geographic Decimal Degrees (Longitude/Latitude), WGS 1984

Construction and Geohydrological Legend

Hole	Hole diameter [mm]
Casing (plain / perforated, sloted)	Casing diameter [mm]
Screen / Mesh Screen	Waterlevel measured: 18/03/11
Piezometer	Piezometer (Nr. & Diameter [mm])

Gravel (> 2mm)

165 — Hole diameter [mm]
152 — Casing diameter [mm]
0:50 — Piezometer (Nr. & Diameter [mm])

Construction   Penetr. rate   Lithology

[Min./m] 0.011 0.022

SOIL: Brown, fine; SLIGHTLY MOIST;

SAND: Brown, fine; SLIGHTLY MOIST;

SAND: Dark brown, fine; SLIGHTLY MOIST;

SAND: Light brown, fine; SLIGHTLY MOIST;

SAND: Cream, fine weathered;

SAND: Brown, fine laminated;

COAL: ;

SHALE: Dark brown, fine fresh carbonaceous;

COMMENT:

Borehole logged by Mike Barnes

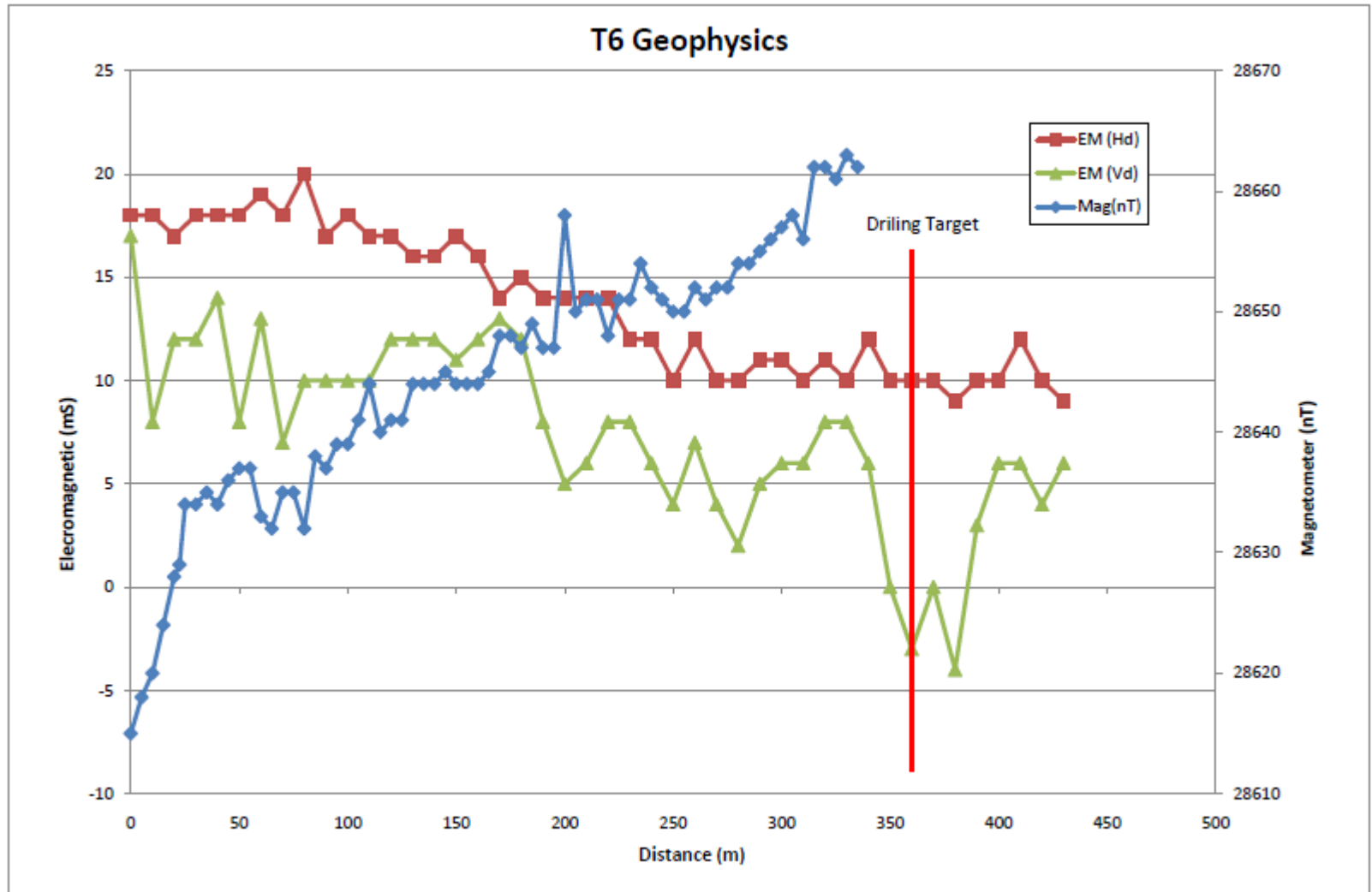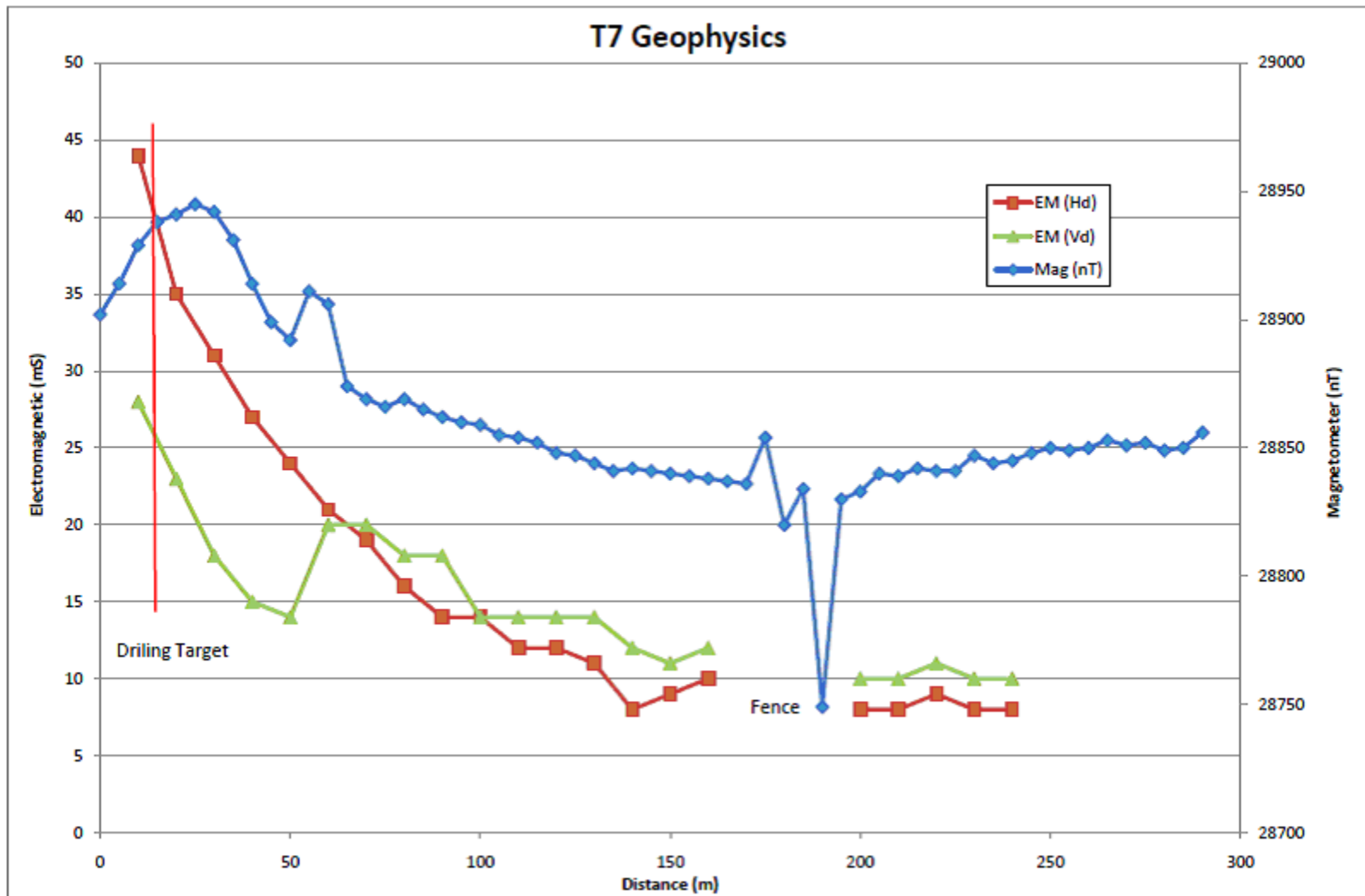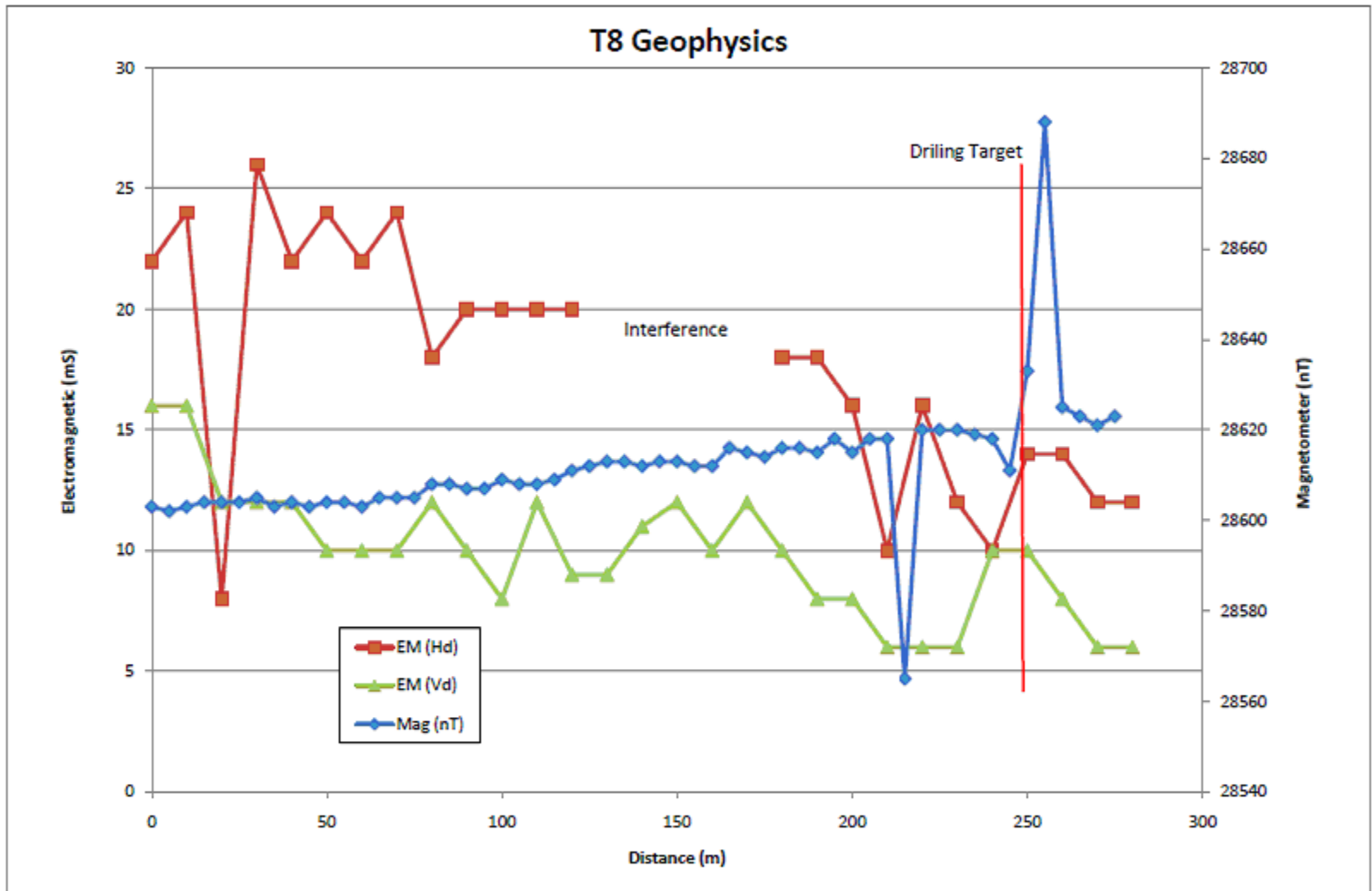User name and adress

Borehole Construction and Geological Log (P3)

BASIC SITE INFORMATION: Site Identifier: Number: P3   Site type: Borehole

Distr./Farm No.:   Site Name/Des.:

Region Type: Region Descr.: MPUMALANGA

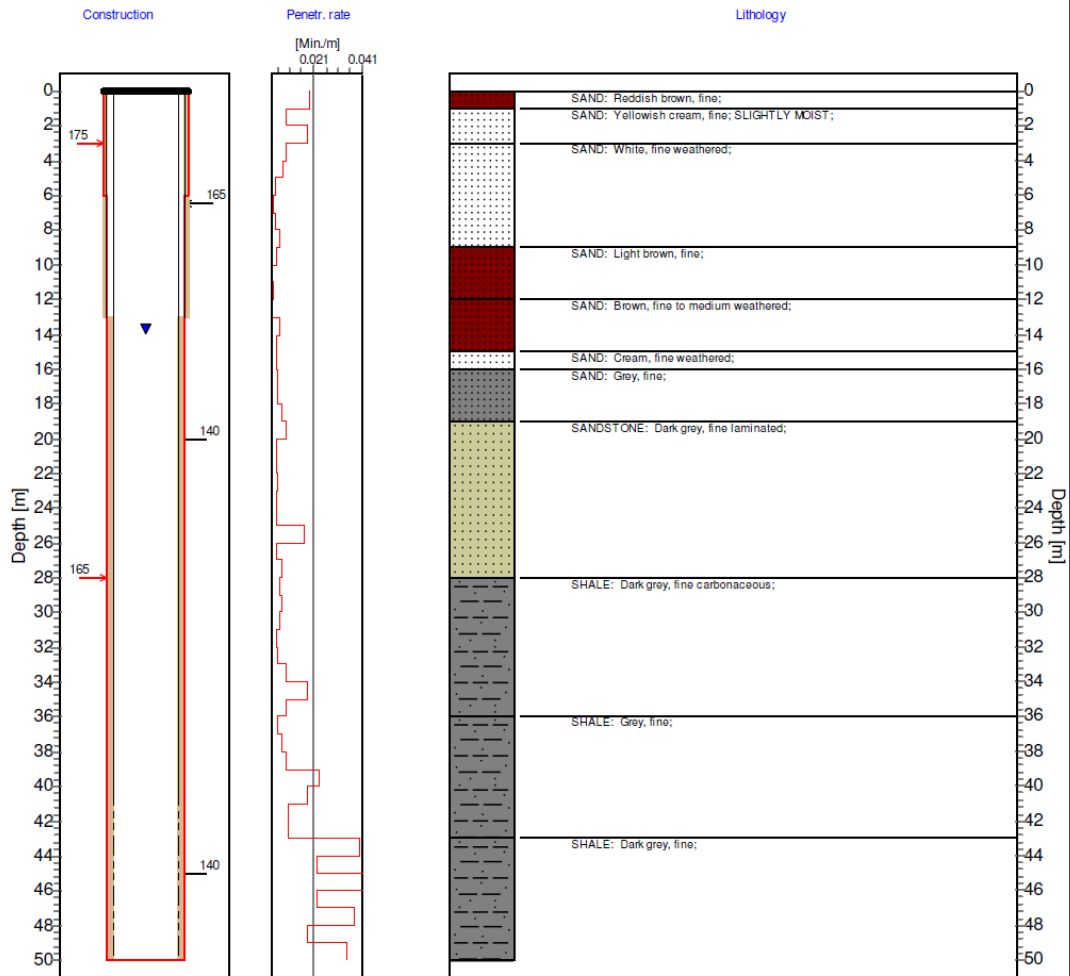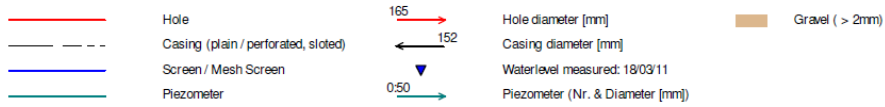|			
Longitude [°]:	Reg./BB.: 11-041	Topo-set.: Flat surface, plain	Depth [m]: 45.00
Latitude [°]:	G-Nr.:	Site status: Unused	Col. ht. [m]: 0.20
Altitude [m]:		Site purp.: Observation	Diam. [mm]: 175
Coord. acc.: Accurate to within 1 unit		Use applic.: Industrial - mining	Drain. reg.:
Coord. meth.: Global Positioning System		Equipment: No equipment	Rep. inst.:

Coordinate System: Geographic Decimal Degrees (Longitude/Latitude), WGS 1984

Construction and Geohydrological Legend

Hole	165 →	Hole diameter [mm]	Gravel (> 2mm)
Casing (plain / perforated, sloted)	← 152	Casing diameter [mm]
Screen / Mesh Screen	▼	Waterlevel measured: 18/03/11
Piezometer	0:50 →	Piezometer (Nr. & Diameter [mm])

Construction   Penetr. rate   Lithology

[Min./m]
0.01   0.019

Lithology descriptions:
- SOIL: Dark brown, fine; MOIST;
- SAND: Light brown, fine;
- SAND: Light brown, fine;
- SHALE: Dark grey, fine weathered carbonaceous;
- SANDSTONE: Cream, fine weathered;
- SANDSTONE: Greyish cream, fine to medium laminated;
- SANDSTONE: Grey, fine laminated; WITH COAL;
- SANDSTONE: Dark grey, fine carbonaceous;
- COAL; ;
- SANDSTONE: Cream, fine;

Construction values: 175, 165, 140, 140, 165, 140

COMMENT:

Borehole logged by Mike Barnes

User name and adress

Page 1

Borehole Construction and Geological Log (T1)

BASIC SITE INFORMATION:

Site Identifier:	**Number:** T1	**Site type:** Borehole
Distr./Farm No.:	**Site Name/Des.:**	
Region Type:	**Region Descr.:** MPUMALANGA	

	Reg./BB.: 11-041	**Topo-set.:** Flat surface, plain	**Depth [m]:** 45.00
Longitude [°]:	**G-Nr.:**	**Site status:** Unused	**Col. ht. [m]:** 0.40
Latitude [°]:		**Site purp.:** Observation	**Diam. [mm]:** 175
Altitude [m]:		**Use applic.:** Industrial - mining	**Drain. reg.:**
Coord. acc.: Accurate to within 1 unit		**Equipment:** No equipment	**Rep. inst.:**
Coord. meth.: Global Positioning System			

Coordinate System: Geographic Decimal Degrees (Longitude/Latitude), WGS 1984

Construction and Geohydrological Legend

—	Hole	165 →	Hole diameter [mm]	Gravel (> 2mm)
— – - –	Casing (plain / perforated, sloted)	← 152	Casing diameter [mm]	
—	Screen / Mesh Screen	▼	Waterlevel measured: 18/03/11	
—	Piezometer	0:50 →	Piezometer (Nr. & Diameter [mm])	

Construction   **Penetr. rate**   **Lithology**

[Min./m]
0.018   0.036

Lithology descriptions (by depth):
- SOIL: Light brown, fine; SLIGHTLY MOIST;
- SILTSTONE: Light grey, fine; (~6 m)
- SANDSTONE: Light grey, fine; (~8 m)
- COAL: Black soft;
- SANDSTONE: Light grey, medium fresh;
- SHALE: Light grey, medium fresh; (~18 m)
- SHALE: Grey, fine fresh carbonaceous; (~24 m)
- COAL: Black; (~40 m)
- SANDSTONE: White, fine fresh; (~44 m)

Construction annotations: 140, 175, 165, 140, 140 (casing/hole diameters)

COMMENT:
Borehole logged by Mike Barnes

User name and adress

Page 1

Borehole Construction and Geological Log (T3)

BASIC SITE INFORMATION:

Site Identifier:	*Number:* T3	*Site type:* Borehole
Distr./Farm No.:	*Site Name/Des.:*	
Region Type:	*Region Descr.:* MPUMALANGA	

Longitude [°]:	*Reg./BB.:* 11-041	*Topo-set.:* Flat surface, plain	*Depth [m]:* 45.00
Latitude [°]:	*G-Nr.:*	*Site status:* Unused	*Col. ht. [m]:* 0.49
Altitude [m]:		*Site purp.:* Observation	*Diam. [mm]:* 175
Coord. acc.: Accurate to within 1 unit		*Use applic.:* Industrial - mining	*Drain. reg.:*
Coord. meth.: Global Positioning System		*Equipment:* No equipment	*Rep. inst.:*

Coordinate System: Geographic Decimal Degrees (Longitude/Latitude), WGS 1984

Construction and Geohydrological Legend

Hole	165 →	Hole diameter [mm]	Gravel (> 2mm)
Casing (plain / perforated, sloted)	← 152	Casing diameter [mm]	
Screen / Mesh Screen	▼	Waterlevel measured: 18/03/11	
Piezometer	0:50 →	Piezometer (Nr. & Diameter [mm])	

Construction   Penetr. rate   Lithology

Lithology descriptions:

- CLAY: Yellowish brown, fine;
- CLAY: Black, fine;
- CLAY: Light brown, fine;
- CLAY: Dark brown, fine; WITH SILTSTONE;
- COAL: Dark grey, fine; WITH SHLE;
- SANDSTONE: Light white, fine;
- SHALE: Dark grey, fine carbonaceous;
- SHALE: Dark grey, fine carbonaceous;
- COAL: Black, fine carbonaceous; WITH SHLE;
- SHALE: Dark grey, fine carbonaceous;
- SHALE: Dark grey;

COMMENT:

Borehole logged by Mike Barnes

User name and adress

Page 1

BASIC SITE INFORMATION: *Site Identifier:*   *Number:* T4   *Site type:* Borehole

Distr./Farm No.:   *Site Name/Des.:*

Region Type: *Region Descr.:* MPUMALANGA

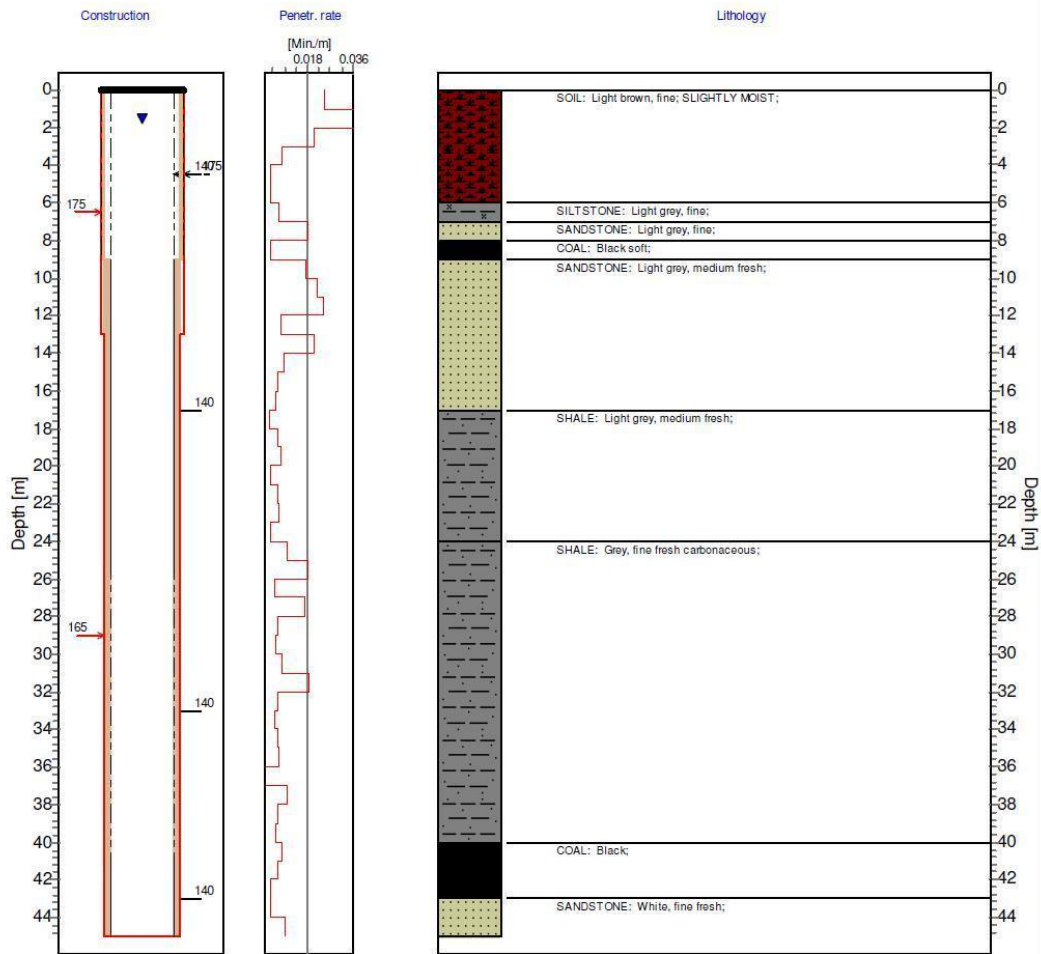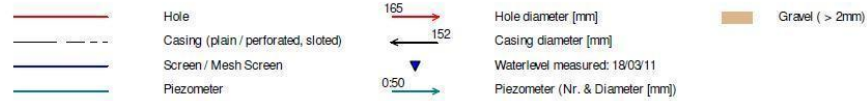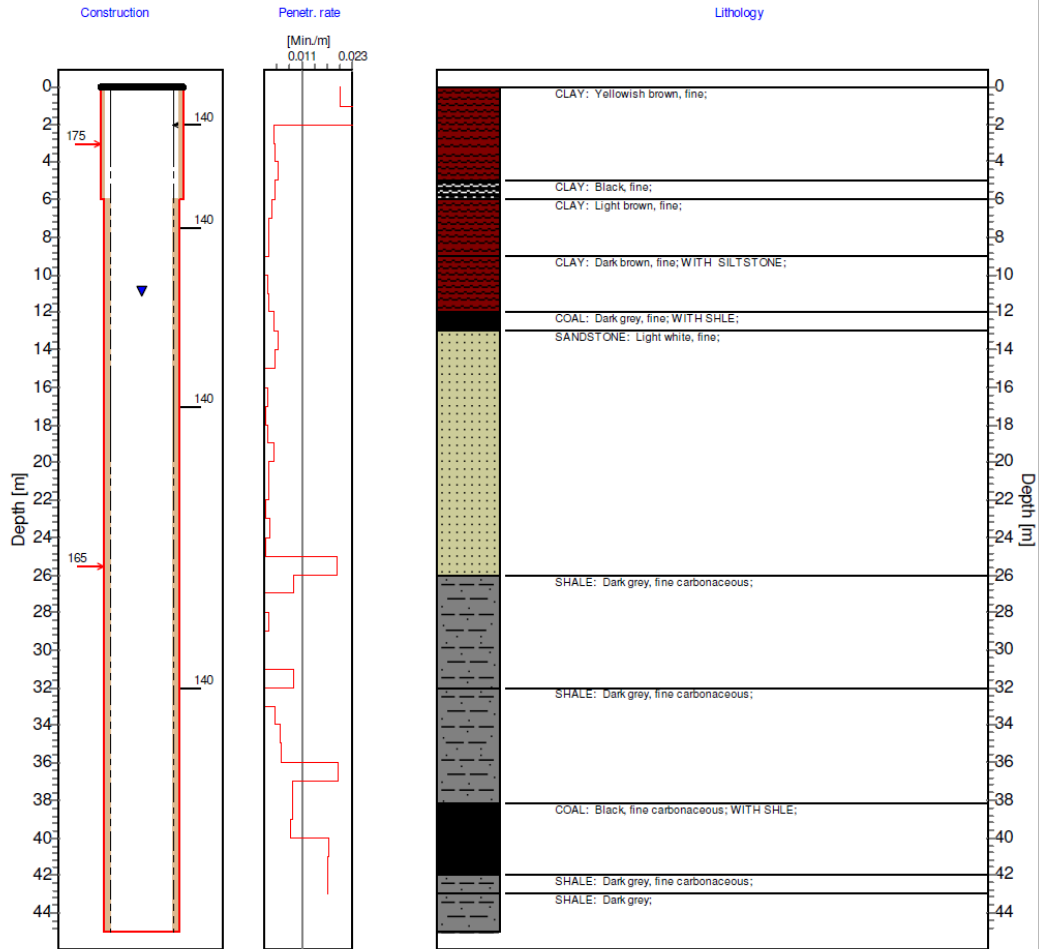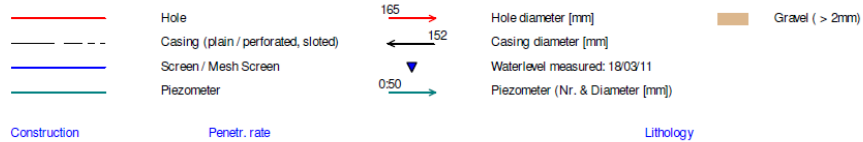|		
Longitude [°]:	*Topo-set.:* Flat surface, plain	*Depth [m]:* 49.00
Latitude [°]:	*Site status:* Unused	*Col. ht. [m]:* 0.30
Altitude [m]:	*Site purp.:* Observation	*Diam. [mm]:* 165
Coord. acc.: Accurate to within 1 unit	*Use applic.:* Industrial - mining	*Drain. reg.:*
Coord. meth.: Global Positioning System	*Equipment:* No equipment	*Rep. inst.:*

Reg./BB.: 11-041
G-Nr.:

Coordinate System: Geographic Decimal Degrees (Longitude/Latitude), WGS 1984

Construction and Geohydrological Legend

Hole	165 → Hole diameter [mm]	Gravel (> 2mm)
Casing (plain / perforated, sloted)	← 152 Casing diameter [mm]	
Screen / Mesh Screen	▼ Waterlevel measured: 18/03/11	
Piezometer	0:50 → Piezometer (Nr. & Diameter [mm])	

Construction   Penetr. rate   Lithology

[Min./m]
0.01   0.021

Construction column markings: 203, 175, 140, 140, 165, 140, 140

Lithology (Depth [m]):

Depth	Description
0	SAND: Brown, medium and fine;
	SAND: Yellow, medium and fine;
8	CLAY: Brown, fine;
	CLAY: Grey, fine; WAETHERED SHALE;
	SANDSTONE: White, fine weathered;
22	SANDSTONE: Grey, fine laminated;
24	COAL: Black;
	SHALE: Grey, fine; SLIGHTLY MOIST;
32	SHALE: Dark grey, fine carbonaceous;
	SHALE: Dark grey, fine carbonaceous; MOIST;
	SILTSTONE: White, fine weathered; MOIST;
40	SANDSTONE: Grey, fine laminated;
	SHALE: Dark grey, fine mineralised;

COMMENT:

Borehole logged by Mike Barnes

User name and adress

Page 1

Borehole Construction and Geological Log (T5)

Date compiled: 2011/03/18

BASIC SITE INFORMATION:

Site Identifier:	*Number:* T5	*Site type:* Borehole

Distr./Farm No.: *Site Name/Des.:*

Region Type: *Region Descr.:* MPUMALANGA

Longitude [°]:	*Reg./BB.:* 11-041	*Topo-set.:* Flat surface, plain	*Depth [m]:* 43.00
Latitude [°]:		*Site status:* Unused	*Col. ht. [m]:* 0.35
Altitude [m]:	*G-Nr.:*	*Site purp.:* Observation	*Diam. [mm]:* 175
Coord. acc.: Accurate to within 1 unit		*Use applic.:* Industrial - mining	*Drain. reg.:*
Coord. meth.: Global Positioning System		*Equipment:* No equipment	*Rep. inst.:*

Coordinate System: Geographic Decimal Degrees (Longitude/Latitude), WGS 1984

Construction and Geohydrological Legend

Hole	Hole diameter [mm]		Gravel (> 2mm)
Casing (plain / perforated, sloted)	Casing diameter [mm]		
Screen / Mesh Screen	Waterlevel measured: 18/03/11		
Piezometer	Piezometer (Nr. & Diameter [mm])		

Construction   Penetr. rate   Lithology

[Min./m]
0.012   0.025

Lithology descriptions:
- CLAY: Brown, fine; SLIGHTLY MOIST;
- COAL: Black;
- SHALE: Dark grey, fine carbonaceous;
- SANDSTONE: White, medium weathered;
- COAL: ; SHINY;
- SHALE: Light grey, fine to medium fresh;
- SHALE: Greyish brown, fine to medium fresh;
- SHALE: Light grey, fine to medium fresh;
- SHALE: Dark grey, fine fresh;
- SHALE: Light grey, medium fresh;
- SHALE: Dark grey, fine; WITH COAL;

COMMENT:

Borehole logged by Mike Barnes

User name and adress

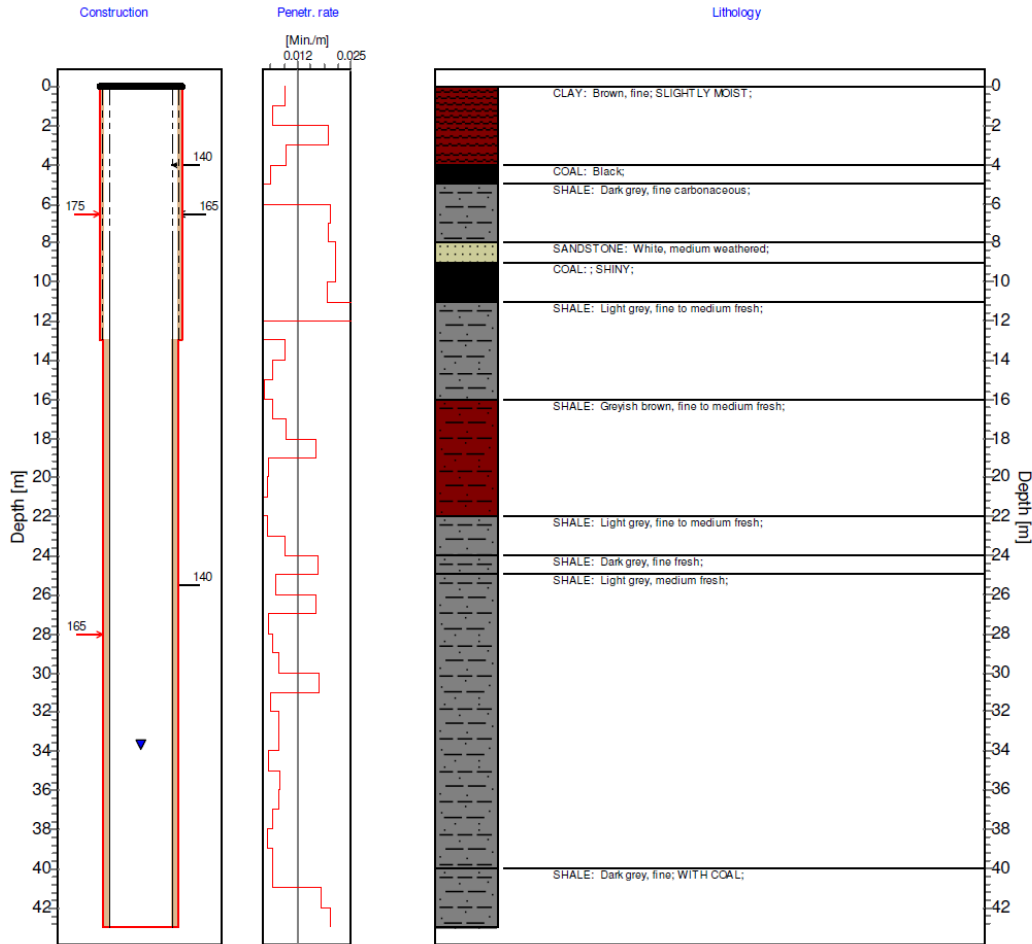Page 1

BASIC SITE INFORMATION: Site Identifier: Number: T6 Site type: Borehole
Distr./Farm No.: Site Name/Des.:
Region Type: Region Descr.:

Longitude [°]:	Reg./BB.: 11-041	Topo-set.: Flat surface, plain
Latitude [°]:	G-Nr.:	Site status: Unused
Altitude [m]:		Site purp.: Observation
Coord. acc.: Accurate to within 1 unit		Use applic.: Industrial - mining
Coord. meth.: Global Positioning System		Equipment: No equipment

Depth [m]:	45.00
Col. ht. [m]:	0.31
Diam. [mm]:	175
Drain. reg.:	
Rep. inst.:	

Coordinate System: Geographic Decimal Degrees (Longitude/Latitude), WGS 1984

Construction and Geohydrological Legend

——	Hole	165 →	Hole diameter [mm]	▭	Gravel (> 2mm)
— - —	Casing (plain / perforated, sloted)	← 152	Casing diameter [mm]		
——	Screen / Mesh Screen	▼	Waterlevel measured: 18/03/11		
——	Piezometer	0:50 →	Piezometer (Nr. & Diameter [mm])		

Construction Penetr. rate [Min./m] Lithology

SOIL: Brown, medium;
SOIL: Yellowish brown, medium;
SOIL: Brown, medium; DRY;
SHALE: Brown, medium;
SHALE: Grey, medium; WET;
SHALE: Dark grey, fine carbonaceous;
COAL: ; WET;
SHALE: Grey; WET;

Depth [m]

175 165 140

165

140

COMMENT:

Borehole logged by Mike Barnes

User name and adress

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Borehole Construction and Geological Log (T7)

Date compiled: 2011/03/18

BASIC SITE INFORMATION:

Site Identifier:	
Number: T7	**Site type:** Borehole
Distr./Farm No.:	**Site Name/Des.:**
Region Type:	**Region Descr.:** MPUMALANGA

Longitude [°]:	**Reg./BB.:** 11-041	**Topo-set.:** Flat surface, plain	**Depth [m]:** 45.00
Latitude [°]:	**G-Nr.:**	**Site status:** Unused	**Col. ht. [m]:** 0.77
Altitude [m]:		**Site purp.:** Observation	**Diam. [mm]:** 175
Coord. acc.: Accurate to within 1 unit		**Use applic.:** Industrial - mining	**Drain. reg.:**
Coord. meth.: Global Positioning System		**Equipment:** No equipment	**Rep. inst.:**

Coordinate System: Geographic Decimal Degrees (Longitude/Latitude), WGS 1984

Construction and Geohydrological Legend

Hole	165 →	Hole diameter [mm]	Gravel (> 2mm)
Casing (plain / perforated, sloted)	152 ←	Casing diameter [mm]	
Screen / Mesh Screen	▼	Waterlevel measured: 18/03/11	
Piezometer	0:50 →	Piezometer (Nr. & Diameter [mm])	

Construction Penetr. rate Lithology

Construction column markers: 175, 140, 165, 140
Penetr. rate [Min/m] 0.005 0.01

Lithology:
- SAND: Brown, fine to medium; MOIST;
- SAND: Bluish brown, fine to medium carbonaceous; WITH SHALE;
- SAND: Brown, fine;
- SANDSTONE: Dark grey, fine weathered;
- SANDSTONE: Cream, fine laminated;
- SHALE: Dark grey, fine laminated; WITH SANDSTONE;
- COAL: ;
- SHALE: Dark grey, fine fresh;

COMMENT:
Borehole logged by Mike Barnes

User name and adress

Page 1

Borehole Construction and Geological Log (T8)

BASIC SITE INFORMATION:

Site Identifier:	**Number:** T8	**Site type:** Borehole

Distr./Farm No.:   **Site Name/Des.:**

Region Type: **Region Descr.:** MPUMALANGA

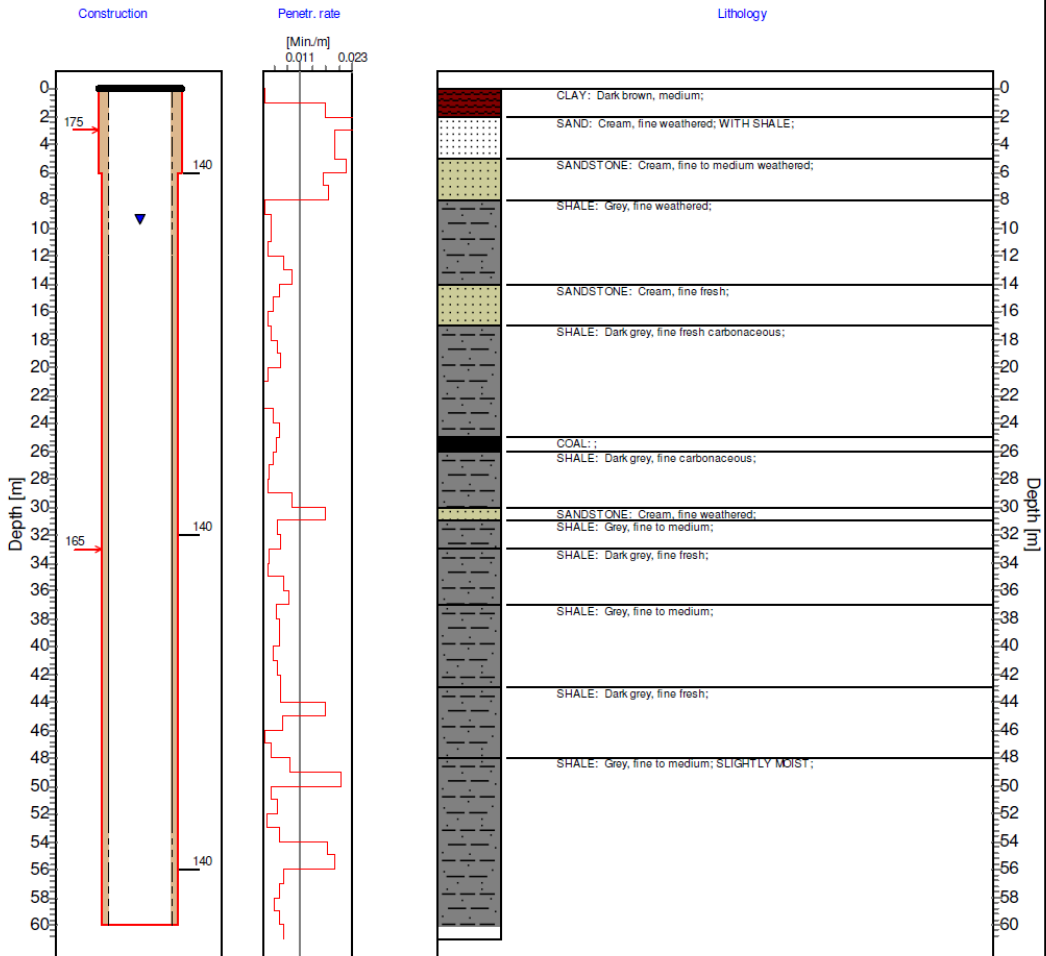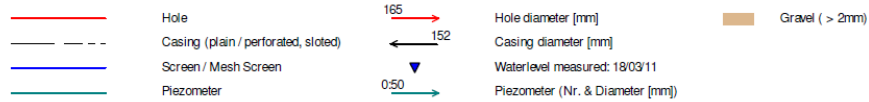|			
Longitude [°]:	**Reg./BB.:** 11-041	**Topo-set.:** Flat surface, plain	**Depth [m]:** 60.00
Latitude [°]:	**G-Nr.:**	**Site status:** Unused	**Col. ht. [m]:** 0.28
Altitude [m]:		**Site purp.:** Observation	**Diam. [mm]:** 175
Coord. acc.: Accurate to within 1 unit		**Use applic.:** Industrial - mining	**Drain. reg.:**
Coord. meth.: Global Positioning System		**Equipment:** No equipment	**Rep. inst.:**

Coordinate System: Geographic Decimal Degrees (Longitude/Latitude), WGS 1984

Construction and Geohydrological Legend

Hole	165 → Hole diameter [mm]	▦ Gravel (> 2mm)
Casing (plain / perforated, sloted)	← 152 Casing diameter [mm]	
Screen / Mesh Screen	▼ Waterlevel measured: 18/03/11	
Piezometer	0:50 → Piezometer (Nr. & Diameter [mm])	

Construction   **Penetr. rate**   **Lithology**

[Min./m] 0.011   0.023

Depth [m]

175
140
165
140
140

Lithology (Depth [m]):

- CLAY: Dark brown, medium;
- SAND: Cream, fine weathered; WITH SHALE;
- SANDSTONE: Cream, fine to medium weathered;
- SHALE: Grey, fine weathered;
- SANDSTONE: Cream, fine fresh;
- SHALE: Dark grey, fine fresh carbonaceous;
- COAL: ;
- SHALE: Dark grey, fine carbonaceous;
- SANDSTONE: Cream, fine weathered;
- SHALE: Grey, fine to medium;
- SHALE: Dark grey, fine fresh;
- SHALE: Grey, fine to medium;
- SHALE: Dark grey, fine fresh;
- SHALE: Grey, fine to medium; SLIGHTLY MOIST;

COMMENT:

Borehole logged by Mike Barnes

User name and adress

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