# DECANT OF SIGMA COLLIERY

By

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Submitted in Fulfilment of the Requirement for the Degree of Master of Science
in the Faculty of Natural Sciences and Agriculture, Institute for Groundwater
Studies, University of the Free State, Bloemfontein.

June 2013

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# Declaration

June 2013

I, Lize Wessels, hereby declare that the thesis submitted by me for the Master of Science Degree in the Faculty of Natural and Agricultural Sciences, Institute for Groundwater Studies, at the University of the Free State, is my own independent work and have not previously been submitted by me at another University/Faculty. I declare that all sources cited or quoted are indicated and acknowledged by means of a list of references.

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

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Lize Wessels

# Acknowledgements

I hereby wish to extend my gratitude to all who have motivated and helped me in the completion of this thesis:

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# List of Abbreviations

| | |
|---|---|
| 3-D | three dimensional |
| AMD | acid and metalliferous drainage |
| ARD | acid rock drainage |
| EC | electrical conductivity |
| GMWL | global meteoric water line |
| MIW | mining influenced water |
| NAMD | neutral alkaline mine drainage |
| NMD | neutral mine drainage |
| RO | reverse osmosis |
| SD | saline drainage |
| SLS | sodium lauryl sulphate |
| TDS | total dissolved solids |
| INAP | International Network for Acid Prevention |
| CCP's | coal combustion products |
| LOI | loss on ignition |
| FA | fly ash |
| ICP | Inductively Coupled Plasma Spectroscopy |
| IC | ion chromatography |
| XRF | x-ray fluorescence spectrometry |

# 1.    Introduction

## 1.1.   Background Information

Coal is the most abundant source of fossil fuel in the world. This is also the case in South Africa, where according to the Department of Energy (2013), 77 percent of South Africa's primary energy needs are provided by coal.

A large coal-mining industry has developed in South Africa, resulting from the fact that many of the deposits in the country can be exploited at extremely favourable costs. According to the Department of Energy (2013), about 51 percent of South African coal mining is done underground and about 49 percent is produced by open-cast methods. According to Jeffrey (2005), coal is found in 18 coalfields in South Africa (Figure 1-1). A map of the coalfields is shown in Figure 1-1.  These coalfields are mainly located in KwaZulu-Natal, Mpumalanga, Limpopo and the Free State, with lesser amounts in Gauteng, the North West Province and the Eastern Cape.
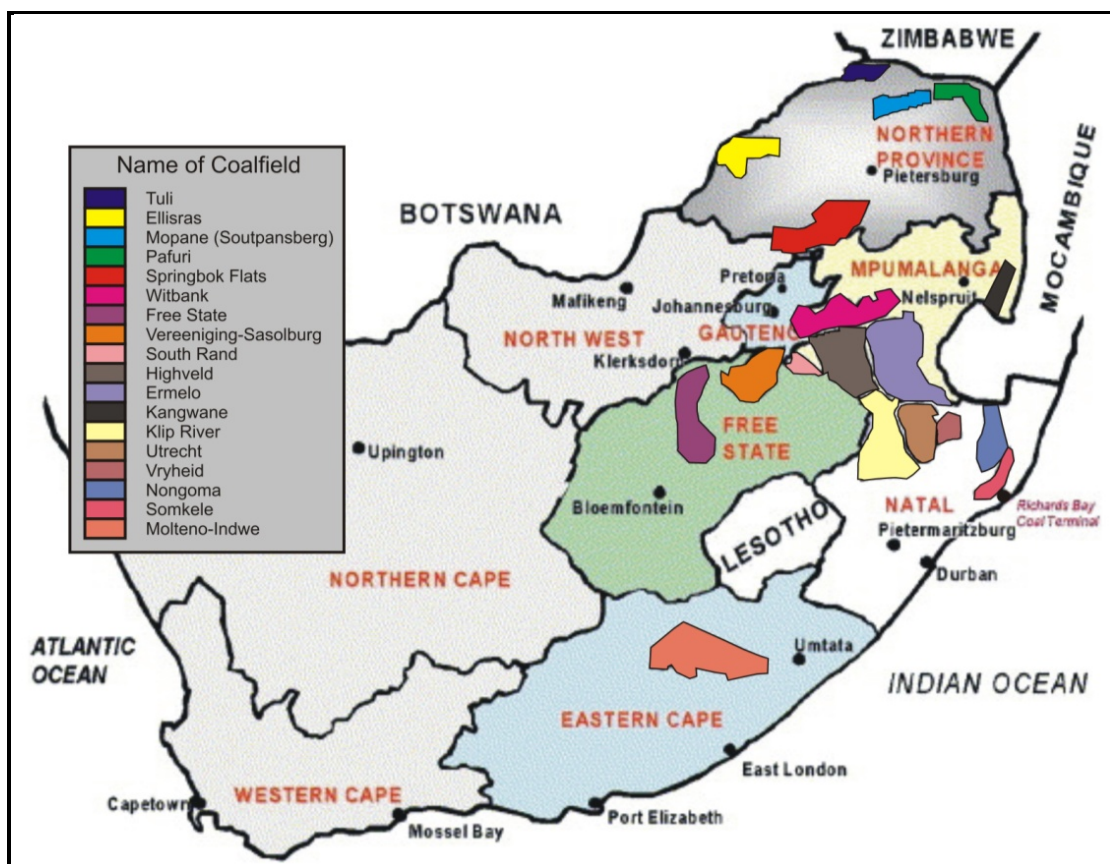


*Figure 1-1: The Coalfields of South Africa modified after Pinetown, et al., (2007).*

Mining at Sigma Colliery in the Vereeniging-Sasolburg Coalfield was ceased in 2004 after which the mine was flooded. The colliery is in the fortunate position that it has a very complete and concise monitoring programme in place. Throughout its lifespan, over 200 boreholes were drilled in and around the mine. Since 1999, an ashfilling project has been undertaken by the colliery to stabilise mine workings located beneath the main roads in the vicinity. A key issue remains if the mine will eventually decant, and what the quality of the water will be. This is important for the future planning of the company, as this will determine if a water treatment plant is necessary and what the specifications for such a plant will be, if needed.

## 1.2. Objective of the thesis

The objective of this study was:

- To determine the water quality of each aquifer associated with the mining area.
- To determine the overall electrical conductivity profile of the mine to aid in the overall management of the mine.
- To delineate possible decant positions with the help of water levels and to determine what the water quality of the possible decanting water will be.
- To discuss the use of fly ash as a backfilling material in underground mines with the help of case studies.
- To determine if ashfilling is a viable option for Sigma Colliery.

## 1.3  Structure of the thesis

Chapter 1 provides a short background discussion on the history of the study area, the reasons for doing the project and the structure of the thesis.

Chapter 2 is a general discussion on the impacts that coal mining has on groundwater and how it could be mitigated.

Chapter 3 is a general discussion about decant of open-pit and underground mines.

Chapter 4 provides the background information on the study area.

Chapter 5 discusses the methodology that was followed to obtain the data that was used during this study.

Chapter 6 comprises of a discussion of the water levels of the different aquifer systems in the study area and the trends observed over time.

Chapter 7 involves a discussion on the hydrochemical profiling of the boreholes and the development of the 3-D electrical conductivity image.

Chapter 8 is an expansion on the 3-D electrical conductivity image. In this image, sections are created where shallow water levels are observed and are discussed in conjunction with 3-D electrical conductivity images.

Chapter 9 is an electrical conductivity study of the study area and different specified water levels.

Chapter 10 comprises of a general discussion of the water levels in the area for the different aquifer systems.

Chapter 11 discusses the possible decant positions identified in Chapter 8 and classifies the possible decanted water according to the International Network for Acid Prevention (INAP) 2009, as discussed in Chapter 2.

Chapter 12 involves a discussion of the isotopic analysis that was done on certain boreholes in the area and the observations made.

Chapter 13 comprises a discussion on the use of fly ash in the backfilling of mine voids and an Australian case study where this has been done successfully.

Chapter 14 is a brief comparison of Sigma Colliery and Goodna Mine that was discussed in the case study in Chapter 12.

Chapter 15 contains a discussion on whether ash filling is a viable option for Sigma Colliery.

Chapter 16 serves as a list of references used.

# 2. Coal Mining and Groundwater

## 2.1 The impact of coal mining on groundwater

The two main ways in which coal mining impacts groundwater resources are by affecting the groundwater quality and the groundwater quantity.

### 2.1.1 How groundwater quantity is impacted

According to Barnes and Vermeulen (2012), loss of groundwater quantity is caused by the removal of water that has entered the mining operations, resulting in a depression cone. The natural underground hydrological conditions are altered through the creation of paths of less resistance and this result in water entering the mining area. The water therefore has to be pumped from the mine workings. Surrounding water users may be impacted in that rivers and wetlands can become dry, and that static water levels of boreholes may be lowered which directly impacts the borehole yields.

### 2.1.2 How groundwater quality is impacted

The groundwater quality is affected in that coal mine drainage forms. Coal mine drainage can range widely in composition from "acid rock drainage" (ARD), "saline drainage" (SD), "acid mine drainage" or "acid and metalliferous drainage" (AMD), "mining influenced water" (MIW) and "neutral mine drainage" (NMD) (International Network for Acid Prevention (INAP), 2009). According to Rose and Cravotta (1998), coal mine drainage will typically have elevated concentrations of sulphate ($SO_4$), iron (Fe), manganese (Mn) and aluminium (Al), as well as common elements such as calcium, sodium, potassium and magnesium. They also reported that the pH is most commonly in the ranges 3 to 4.5 or 6 to 7.

A series of reactions and stages that usually progress from near neutral to more acidic pH conditions results in ARD. In addition to ARD, neutral mine drainage or saline drainage may result from the oxidation process where there are sufficient base minerals to neutralize the ARD. NMD is characterised by elevated metals in solution at near neutral pH. SD contains high levels of sulphate at neutral pH without significant metal concentrations and saline drainage's principal dissolved constituents are then sulphate, magnesium and calcium ions (De Jager, 1976) (International Network for Acid Prevention (INAP), 2009).

Although the water quality resulting from sulphide mineral oxidation does not lend itself to precise compartmentalization, Figure 2-1 illustrates the various types of drainage. Neutral mine drainage and saline drainage can occur together (i.e., near neutral pH with elevated metals and sulphate).
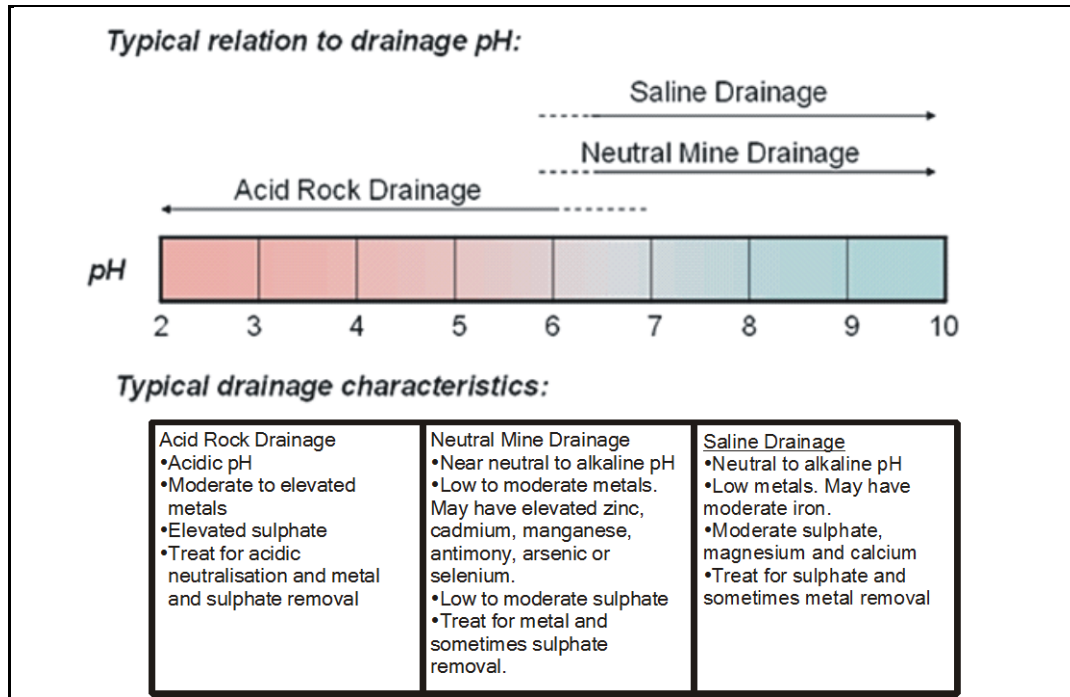


*Figure 2-1: Types of drainage produced by sulphide oxidation (International Network for Acid Prevention (INAP), 2009).*

### 2.1.2.1 Acid rock drainage (ARD), neutral mine drainage (NMD) and saline drainage (SD)

The primary process responsible for the generation of ARD, NMD and SD is the weathering of sulphide minerals. In some cases, the generation of ARD, NMD and SD may also be due to oxidation of elemental sulphur. According to Funke (1983), sulphur can be found in all coal seams in the three forms of organic sulphur, sulphate sulphur and sulphide sulphur. The predominant form is sulphide sulphur and is found as pyrite and markasite. Both pyrite and markasite have the same chemical composition of $FeS_2$, but different crystalline structures. Pyrite occurs the most commonly of the two ores and is the mineral of most relevance from and acid-generation perspective. This is because of its concentration, grain size and distribution which may be the most important factors affecting the production of acidic mine waters according to the International Network for Acid Prevention (INAP), 2009. Only these two ores produce

acid when exposed to moisture and air and this reaction is termed "acid rock drainage" (ARD).  Lottermoser (2010) reported that AMD waters of coal mines are characterised by low pH, as well as high electrical conductivity (EC), total dissolved solids (TDS), sulphate, nitrate, iron, aluminium, sodium, calcium and magnesium values.  He further stated that coal mine waters aren't necessarily acidic and that many coal mine waters have near neutral pH values.  Such waters typically contain elevated TDS values and exhibit high EC values.

Other sulphides commonly found in ore deposits are listed in Table 2-1.

*Table 2-1: Common sulphides known or inferred to generate acid when oxidised (International Network for Acid Prevention (INAP), 2009).*

| Mineral | Formula |
|---|---|
| Common sulphides known (inferred) to generate acid with oxygen as the oxidant: | |
| Pyrite, marcasite | $FeS_2$ |
| Pyrrhotite | $Fe_{1-x}S$ |
| Bornite | $Cu_5FeS_4$ |
| Arsenopyrite | $FeAsS$ |
| Enargite/famatinite | $Cu_3AsS_4/Cu_3SbS_4$ |
| Tennantite/tetrahedrite | $(Cu,Fe,Zn)_{12}As_4S_{13}/(Cu,Fe,Zn)_{12}Sb_4S_{13}$ |
| Realgar | $AsS$ |
| Orpiment | $As_2S_3$ |
| Stibnite | $Sb_2S_3$ |
| Common sulphides that may generate acid with ferric iron as the oxidant: | |
| All of the above plus: | |
| Sphalerite | $ZnS$ |
| Galena | $PbS$ |
| Chalcopyrite | $CuFeS_2$ |
| Covellite | $CuS$ |
| Cinnabar | $HgS$ |
| Millerite | $NiS$ |
| Pentlandite | $(Fe,Ni)_9S_8$ |
| Greenockite | $CdS$ |

### 2.1.2.1.1 Characteristics of acid rock drainage, neutral mine drainage and saline drainage

A combination of chemical, physical and biological factors govern the complex processes of the generation, release, mobility and attenuation of ARD, NMD and SD. Whether ARD, NMD or SD enters the environment depends largely on the characteristics of the sources, pathways and receptors involved. A summary of the sources, pathways and receiving environment is illustrated in Figure 2-2. The commodity, climate, mine facility and mine phase determine these sources, pathways and receiving environments (International Network for Acid Prevention (INAP), 2009). The sources include the mine and process wastes and the mine and process facilities that contain reactive sulphide and potentially neutralising minerals involved in mitigation of acidity. According to the International Network for Acid Prevention (INAP, 2010), the relative abundance and characteristics of these sulphides and neutralising minerals play a very important role in determining the nature of the discharge being generated. They also stated that the seasonal effects, the climate and the hydraulic characteristics of the mine or process waste/facility that represents the source are related to the pathways and transport mechanisms. Whether a mine discharge is continuous or intermittent, dilute or highly concentrated may be determined by climate or seasonal effects which in turn have an effect on the nature of the drainage. The receiving environment may also alter the nature of the mine drainage. Some examples of receiving environments include groundwater, surface water or wetlands and all of these receiving environments can change the original characteristics of the mine discharge (decant) through a combination of physical mixing, chemical and biological reaction (International Network for Acid Prevention (INAP), 2009).
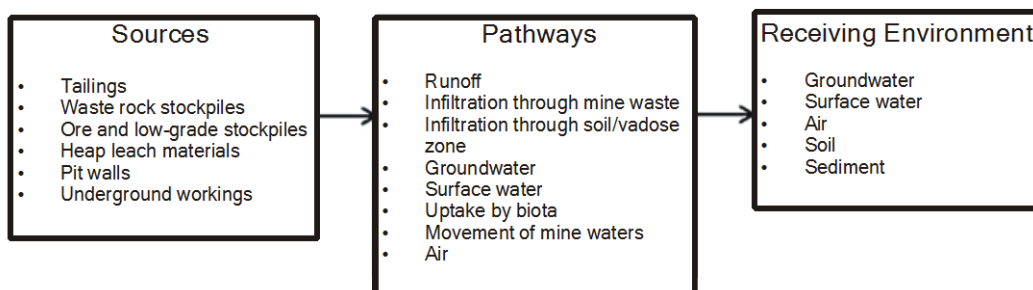


*Figure 2-2: Generalised conceptual model of sources, pathways and receiving environment at a mine or processing site (International Network for Acid Prevention (INAP), 2009).*

### 2.1.2.1.2  The sulphide oxidation process

Sulphide minerals in ore deposits are formed under reducing conditions in an absence of oxygen.  These minerals can become unstable and oxidise when they are exposed to atmospheric oxygen or oxygenated waters due to mining, mineral processing, excavation, or other earthmoving processes.  A model describing the oxidation of pyrite is illustrated in Figure 2-3 and the sulphide oxidation process will be further summarised by using the GARD Guide from the International Network for Acid Prevention (INAP), 2009.
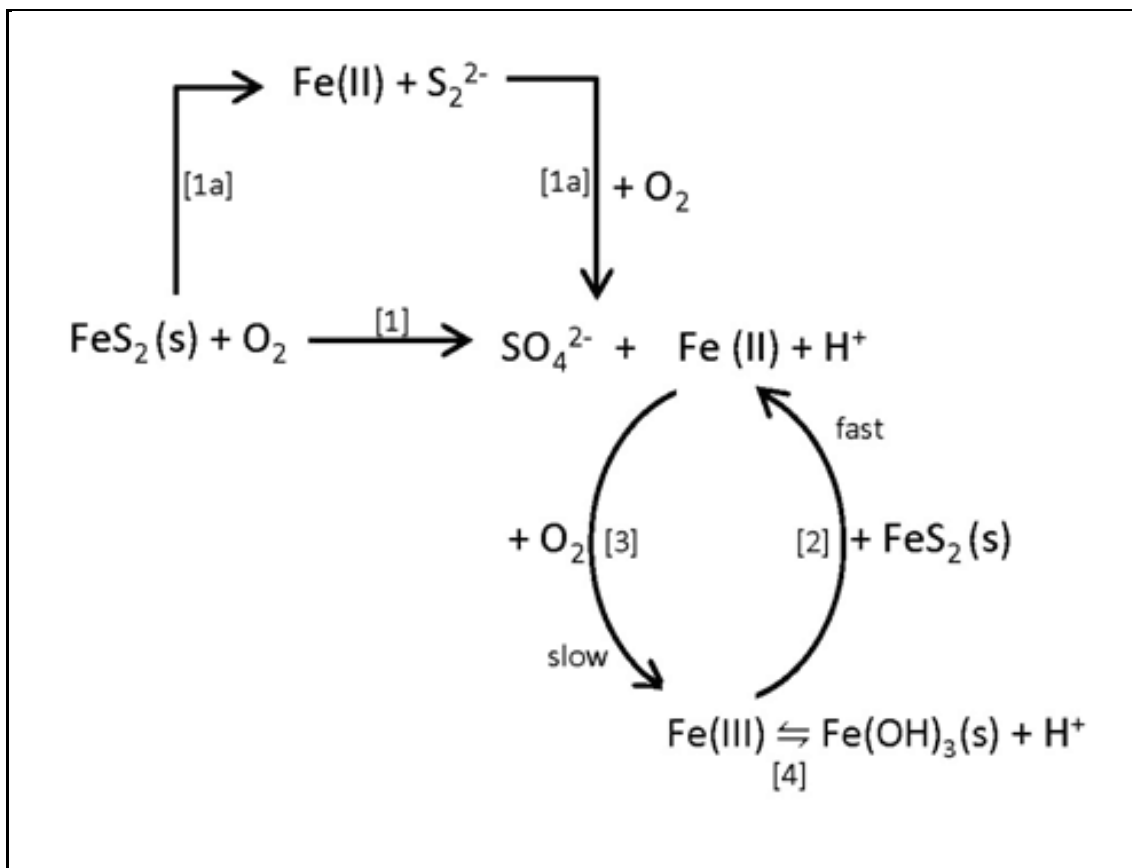


Figure 2-3: Model for the oxidation of pyrite (International Network for Acid Prevention (INAP), 2009).

Three basic ingredients are required for pyrite oxidation which is: pyrite, oxygen and water.  The overall pyrite oxidation reaction is generally written as:

Equation 2-1: $FeS_2 + 7/2O_2 + H_2O = Fe^2{}^+ + 2SO_4{}^2- + 2H^+$
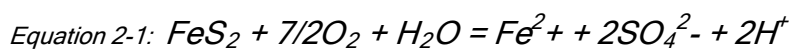
The reaction described in Equation 2-1 can occur either abiotically or it can be mediated through microorganisms.  Pyrite can also be dissolved and then oxidized as seen in reaction 1a on Figure 2-3 (reaction [1a] on Figure 2-3) in addition to direct

oxidation. Atmospheric oxygen acts as the oxidant most of the time. A much less prominent process, due to its limited solubility, is oxygen that dissolved in water. This can also result in pyrite oxidation. The following reaction describes how aqueous ferric iron can also oxidise pyrite:

Equation 2-2: $FeS_2 + 14Fe^3 + + 8H_2O = 15Fe^2 + + 2SO_4^{2-} + 16H^+$
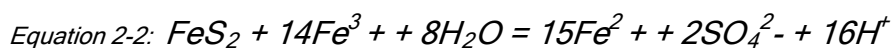
This reaction generates significantly more acidity per mole of pyrite oxidised and is 2 to 3 orders of magnitude faster than the reaction with oxygen, but is limited to conditions such as acidic conditions, in which significant amounts of dissolved ferric iron occur. Reaction 1 in Figure 2-3 is therefore the reaction through which pyrite oxidation is generally initiated at circumneutral or higher pH. This reaction is then followed by reaction 2 in Figure 2-3 where conditions have become adequately acidic at about a pH of 4.5 and lower. Hereafter, a third reaction is required to generate and replenish ferric iron through oxidation of ferrous iron by oxygen and is described by the following equation:

Equation 2-3: $Fe^2 + + ¼O_2 + H^+ = Fe^3 + + ½H_2O$
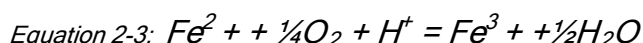
In reaction 3, indicated on Figure 2-3, oxygen is required to produce ferric iron from ferrous iron. The bacteria that may activate this reaction are organisms that require oxygen for aerobic cellular function and are mainly members of the Acidithiobacillus genus. Although the oxygen requirement may be less than for abiotic oxidation, some nominal amount of oxygen is therefore still needed for this process to be affective when it is catalised by bacteria.

The fate of the ferrous iron generated through reaction 1 in Figure 2-3 is a process of environmental importance related to pyrite oxidation. The Ferrous iron can be removed from solution under slightly acidic to alkaline conditions through oxidation and subsequent hydrolysis and the formation of a relatively insoluble iron hydroxide. When it is assumed that the nominal composition of ferrihydrite for this phase is [Fe(OH)3], the reaction can be summarised as follow:

Equation 2-4: $Fe^2 + + ¼O_2 + 2½H_2O = Fe(OH)_3 + 2H^+$
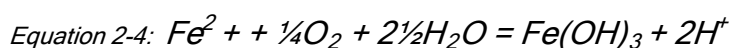
When conditions are not acidic and reactions 1 and 4 in Figure 2-3 are combined, it is noticeable that double the amount of acidity relative to reaction 1 is produced through the oxidation of pyrite. This reaction can be summarised as follow:

*Equation 2-5:* *FeS2 + 15/4O2 + 7/2H2O = Fe(OH)3 + 2SO42- + 4H+*
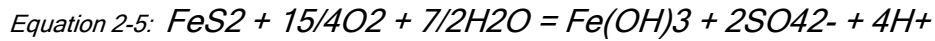
When conditions become highly acidic in mine waters a variety of microorganisms may be the only form of life. Some of the bacterial fauna include iron and sulphur oxidising-bacteria, such as Acidithiobacillus Ferrooxidans and Acidithiobacillus Thiooxidans which play an important role in sulphide oxidation and the formation of ARD, NMD, or SD. Due to microbial mediation many important geochemical reactions take place against thermodynamic expectations, because bacteria can couple a thermodynamically unfavourable reaction with a reaction that yields net energy. The iron conversion reaction rate has been shown to increase by a factor of hundreds to as much as one million times, relative to the corresponding abiotic rates. This is due to the bacteria species which in turn affects the rate of pyrite oxidation. Although the exact reaction mechanism of pyrite oxidation on a molecular level is still under investigation, the rate-limiting step is the production of ferric iron from ferrous iron through microbial catalysis. In Figure 2-4 a schematic illustration of the normalised relative oxidation rates, with and without bacterial mediation as a function of pH, is provided.
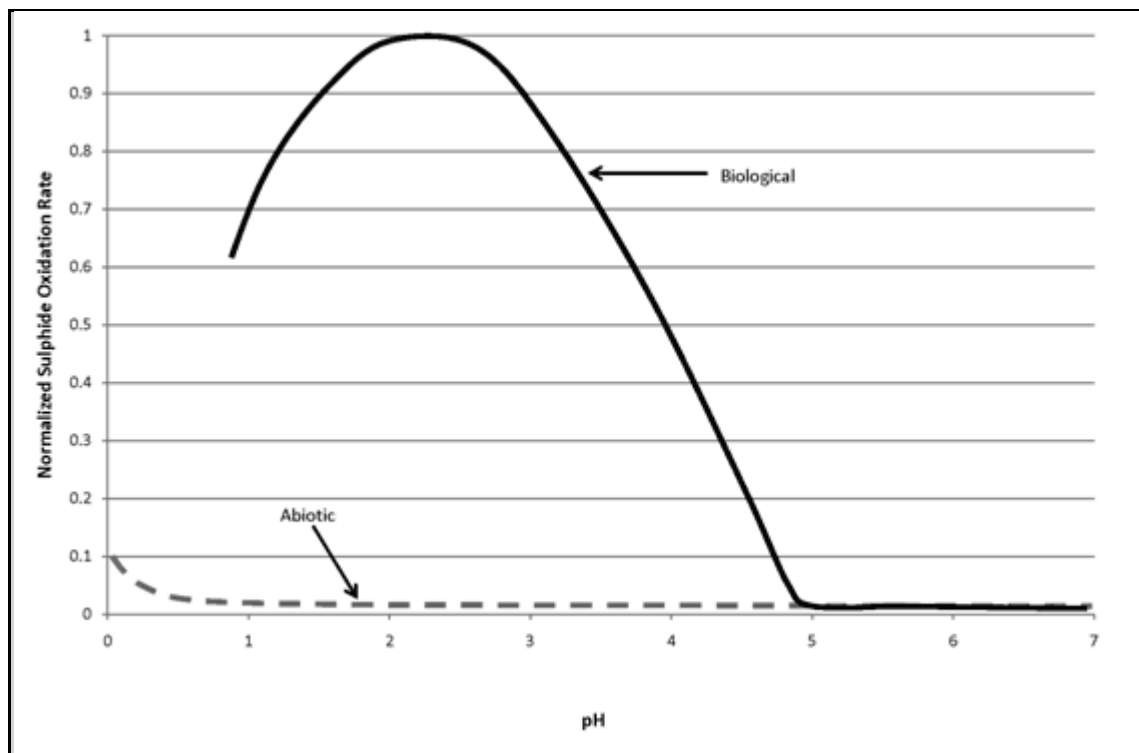


*Figure 2-4: Schematic illustration of normalised sulphide oxidation rates with and without bacterial mediation (International Network for Acid Prevention (INAP), 2009).*

### 2.1.2.1.3  Neutralisation reactions

Neutralization reactions play a key role in determining the compositional characteristics of drainage originating from sulphide oxidation.  Neutralisation of ARD happens when ARD has been neutralised by a reaction with carbonate minerals, such as dolomite $(CaMg)(CO_3)_2$  and calcite $(CaCO_3)$.  It can also form from rock that contains little pyrite.  Dissolution of carbonate minerals produces alkalinity, which promotes the removal of Fe, Al and other metal ions from solution and neutralises acidity. According to Rose and Cravotta (1998), neutralisation of ARD however does not usually affect concentrations of $SO_4$.  They also proclaim that the carbonate minerals can occur as layers of dolostone or limestone in the overburden above coal, in small veins cutting the rock, or as cement in sandstone or shale.  Using calcite as an example, the initial reaction with an acid solution will be:

Equation 2-6:   $2H^2 \ = \ Ca^{2+} \ + \ H_2CO_3 \ (aq)$
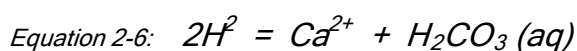
In the event of a gas phase being present, the $H_2CO_3$ may partly decompose and exsolve into the gas phase:

Equation 2-7: $H_2CO_3 \ (aq) \ = \ CO_2 \ (g) \ + \ H_2O \ (l)$
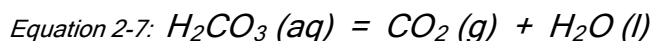
When ARD is then neutralised further with carbonate to pH values greater than 6.3, the product is bicarbonate $(HCO_3^-)$:

Equation 2-8: $CaCO_3 \ + \ H^+ \ = \ Ca^{2+} \ + \ HCO_3^-$
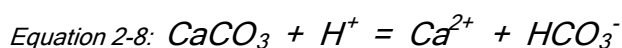
The general result of ARD neutralised by co-existing minerals will be a neutral pH, high sulphate concentration, high total dissolved solids and staining.

Table 2-2 provides an overview of the ranges of neutralization potential and buffering pH for a number of common minerals. As is immediately obvious, carbonate minerals generate significantly more neutralization potential than silicate minerals, while they also tend to buffer at higher pH values. Effective neutralization in practice is therefore generally directly related to the abundance of non-Fe/Mn carbonate minerals.

Table 2-2: Typical NP Values and pH buffering ranges for some common minerals (International Network for Acid Prevention (INAP), 2009).

| Groups | Formula | Buffer pH | Neutralisation Potential Range (kg CaCo3/tonne) |
|---|---|---|---|
| **Carbonates** | | | 500-1.350 |
| calcite, aragonite | $CaCO_3$ | 5.5 - 6.9 | |
| dolomite | $CaMg(CO_3)_2$ | 5.3 - 6.8 | |
| siderite | $FeCO_3$ | 5.1 - 6.0 | |
| malachite | $Cu_2CO_3(OH)_2$ | 5.1 - 6.0 | |
| **Oxides** | | | |
| gibbsite | $Al(OH)_3$ | 3.7 - 4.3 | |
| limonite/goethite | $FeOOH$ | 3.0 - 3.7 | |
| ferrihydrite | $Fe(OH)_3$ | 2.8 - 3.0 | |
| **Jarosite** | $KFe_3(SO_4)_2(OH)_6$ | 1.7 - 2.0 | |
| **Aluminosilicates** | | 0.5 - 1.5 | |
| **Feldspar Group** | | | |
| K-feldspar | $(K,Na)AlSi_3O_8$ | | 0.5-1.4 |
| albite (Ab100-Ab50) | $NaAlSi_3O_8$ | | 0.5-2.6 |
| anorthite (An51-An100 | $CaAl_2Si_2O_8$ | | 5.3-12.5 |
| **Pyroxene Group** | $(Me)(Si,Al)_2O_6$ | | 0.5-9.5 |
| **Amphibole Group** | $(Me)_{7-8}((Si,Al)_4O_{11})(OH)_2$ | | 0.2-8.1 |
| **Mica Group** | | | |
| muscovite | $KA_{l2}(AlSi_3O_{10})(OH)_2$ | | 0.3 |
| biotite | $K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$ | | 2.7-8.8 |
| **Chlorite Group** | $(Mg,Fe,Al)_6(Al,Si)_4O_{10}(OH)_8$ | | 0.8-21.6 |
| **Clay Group** | $(Me)(Si,Al)_4O_{10}(OH)_2$ | | 2.7-29 |
| **Garnet Group** | $(Ca,Mg,Fe,Mn)_3(Al,Fe,Cr)_2(SiO_4)_3$ | | 1.3-6.3 |
| **Apatite Group** | $Ca_5(PO_4)_3(F,Cl,OH)$ | | 2.7-11.3 |
| **Miscellaneous** | | | |
| talc | $Mg_3Si_4O_{10}(OH)_2$ | | 1.7 |
| serpentine | $Mg_6Si_4O_{10}(OH)_8$ | | 15.1-87.6 |
| epidote | $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$ | | 1.0-3.0 |
| wollastonite | $CaSiO_3$ | | 440 |

## 2.1.2.1.4  Prevention and mitigation of ARD

The three main areas of focus in the prevention and mitigation of ARD is chemical inhibition of the acid generating reactions, inhibition of the microbes responsible for catalyzing the acid generating reactions and physical or geotechnical treatments to minimise water contact and leaching.

### 2.1.2.1.4.1  Chemical inhibition of the acid generating reactions

The collection and treatment of acid waters is well established and the common treatment method is neutralisation with alkaline materials and precipitation of metals

such as hydroxides. According to Office of Surface Mining (2009), the direct mixing and contact of lime with pyritic materials appears to be the most successful, but indirect treatments such as alkaline recharge and borehole injection have also yielded mixed results. Egiebor and Oni (2007) have reported that other non-conventional materials like fly ash, bentonite, kaolinite, spent lime and cement have also been used to neutralise AMD.

### 2.1.2.1.4.2 Inhibition of the microbes responsible for catalysing the acid generating reactions

The catalytic role of bacteria, such as Thiobacillus ferrooxidans in pyrite oxidation, is well known. Egiebor and Oni (2007) reported that the control of ARD formation through the elimination or inhibition of the catalytic bacteria by the use of bactericides has been studied by several investigators. Kleinmann & Erickson (1983) investigated the inhibiting effects of anionic surfactants, sodium lauryl sulphate (SLS), alkyl benzene sulphonate and alpha olefin sulphonate on Thiobacillus ferrooxidans. They concluded that SLS was the most effective in limiting bacterial population. They also noticed that by inhibiting bacterial activity the biotic oxidation of pyrite and ferrous iron, and therefore AMD, was significantly reduced.

According to Egiebor & Oni (2007) many other bactericides have been investigated for use as inhibitors of microorganisms in AMD, including sodium benzoate, potassium sorbate, sodium chloride and thymol.

### 2.1.2.1.5 Physical or geotechnical treatments to minimise water contact and leaching

### 2.1.2.1.5.1 Submergence or flooding

When flooding a mine, the level of oxygen is reduced to a minimum so that the oxidation of the sulphur cannot occur. During this process, a reservoir of underground water is formed. The galleries and mine shafts are cut off from neither air when they are filled with water and there can consequently not be be any oxidation of pyrites, therefore nor acidic water being produced. According to Fernandez-Rubio *et al.,* (1987) the efficiency of underground mine flooding is subject to whether the water can be retained inside the mine, but this cannot always be guaranteed on a long term basis. It often happens that the Hermetic seal will leak with time. Cracks, which formed due to subsidence, may frequently reach the surface; air can then enter the mine and cause acidic water to form. To prevent this from happening it is necessary to seal all highly permeable zones at the surface. Boreholes drilled in and around the mine will also act

as waterways allowing contaminated water to infiltrate other sources of water under low hydraulic head (Fernandez-Rubio *et al.*, 1987). It is therefore essential to seal all the boreholes interconnected with the mine workings before flooding a mine.

Hydrochemical stratification also occurs in the water of flooded underground mines. According to Fernandez-Rubio *et al.,* (1987) the water in the top layer is the highest quality, whereas the water at the bottom is contaminated.

### 2.1.2.1.6  Treatment options for AMD

Treatment of AMD involves chemical neutralisation of the acidity followed by precipitation of iron and other suspended solids. According to Office of Surface Mining (2009), treatment systems will include:

- Equipment for feeding the neutralising agent to the AMD;
- means for mixing the AMD and the neutralising agent;
- procedures for ensuring iron oxidation and;
- settling ponds for removing iron, manganese and other co-precipitates.

Chemicals usually used for AMD treatment include limestone, hydrated lime, soda ash, caustic soda and ammonia.

#### 2.1.2.1.6.1  Lime stone [CaCO$_3$]

When treating AMD with limestone the calcium content of the limestone should be as high as possible. Limestone has been used for decades to raise pH and precipitate metals in AMD. Reason being that it has the lowest material cost and is the easiest and safest to handle of all AMD chemicals. According to Skousen *et al.,* (2000) its successful application has been limited due to its low solubility and tendency to develop an external coating of Fe(OH)$_3$ when added to AMD. In cases where pH is low and mineral acidity is also relatively low, finely ground limestone may be dumped in streams directly, or the limestone may be ground by water-powered rotating drums and metered into the stream.

#### 2.1.2.1.6.2  Hydrated Lime [Ca(OH)$_2$]

Hydrated lime is a commonly used chemical for treating AMD. It is usually sold in powder form that tends to be hydrophobic, and extensive mechanical mixing is required

to disperse it in water. According to Skousen *et al.*, (2000) hydrated lime is particularly useful and cost effective in large flow and high acidity situations where a lime treatment plant with a mixer or aerator is constructed to help dispense and mix the chemical with the water.

### 2.1.2.1.6.3 Soda ash [Na$_2$CO$_3$]

According to Office of Surface Mining (2009) soda ash is especially effective for the treatment of small AMD flows in remote areas and low amounts of acidity and metals. Soda ash is formed as solid briquettes and is gravity fed into water by the use of bins or barrels.

### 2.1.2.1.6.4 Caustic soda [NaOH]

Caustic soda is often used in remote locations in low flow and high acidity situations and where AMD has high manganese content. Skousen *et al.*, (2000) reported that the system can be gravity fed by dropping liquid caustic soda directly into the AMD. Caustic soda is very soluble in water, disperses rapidly and raises the pH of water very quickly. The chemical is denser than water and should be applied at the surface of ponded water. Using liquid NaOH to treat AMD has the drawback in that it is very costly and dangerous to handle.

### 2.1.2.1.6.5 Ammonia [NH$_3$]

Anhydrous ammonia is effective in treating AMD that has high ferrous iron and/or manganese content. Ammonia is extremely soluble in water and reacts rapidly. It behaves as a strong base and can easily raise the pH of receiving water to 9.2. Injection of ammonia into AMD is one of the fastest ways to raise water pH. According to Skousen *et al* (2000) ammonia is lighter than water and should therefore be injected near the bottom of the pond. Ammonia costs less than caustic soda, but is however difficult and dangerous to use and can affect biological conditions downstream from the mining operations.

# 3. Decant of Open-Pit and Underground Mines

"Researcher finds new acid water threat" (News24 5 October 2011), "Emergency plans for rising acid water" (News24 4 March 2012) and " Acid mine water treatment accelerated" (News24 17 May 2012) are just a few of the headlines concerning mine water decant recently published in the South African media. This indicates the sensitivity of mine water decant as a topic in South Africa.

According to the Mineral and Petroleum Resources Development Act (RSA 2002: 49), no closure certificate may be issued unless it has been confirmed by the Inspector of Mines and the Department of Water Affairs, indicating that the management of pollution to water resources has been addressed. It is therefore vitally important to manage mine water decant very carefully.

Usually after mining has ceased at an underground mine, the mines closes down and is left to fill up with water. As the mine fills up, the water can be forced out onto the surface through cracks, shafts, adits and boreholes. This is as a result of hydrological differences and usually occurs at the lowest interconnections between the surface and the mine. This process is called mine water decant of an underground mine. Decant of an opencast mine happens when the mine water in an open cast mine overflows.

According to Vermeulen and Usher (2006) the main ways in which the decant of a flooded and unflooded underground mine differ from each other is the location and the method of discharge. Discharge of unflooded mines happens at the lowest elevation in the mine connected to the surface and the discharge of flooded mines occurs through conduits such as cracks, adits, shafts and boreholes at the lowest elevation at which the mine meets the surface. This may be far above the lowest elevation of the mine.

Vermeulen and Usher (2006) also provided examples of different scenarios of decant of unflooded underground mines which will be discussed with the help of Figure 3-1 to Figure 3-3. Figure 3-1 illustrates an unflooded colliery with two seams very close to each other which are connected by boreholes and fractures. Water from the upper seam decants at a hole caused by structural failure. This hole is at the same elevation as the low lying area and the water flows into a dam. Due to the fact that the bottom seam (2 Seam) is at a lower elevation than the surface, it will stay filled. Figure 3-2 illustrates a scenario of an unflooded colliery where a single seam was mined. According to Vermeulen and Usher (2006), this mine will also decant before it is totally

flooded, due to an outcrop, fracture or adit. Figure 3-3 illustrates two different positions for a seam. In position 1, the adit is higher than the entire seam and the whole seam will flood. Decant will only start to occur when the water level in the aquifer reaches the elevation of the adit. When the seam is in position 2, the adit is only higher than parts of the seam and the mine will decant before it is totally flooded.
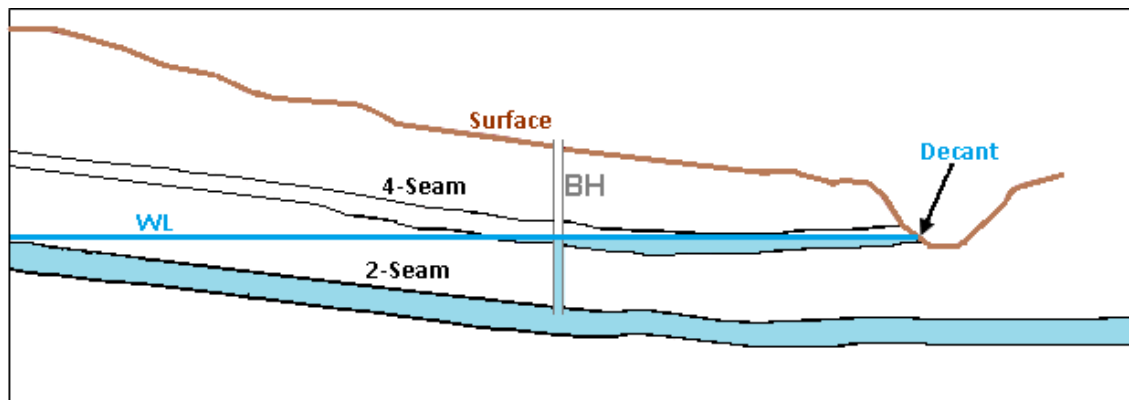


Figure 3-1: Decant illustration of an unflooded mine with two seams mined. Modified after Vermeulen and Usher (2006).
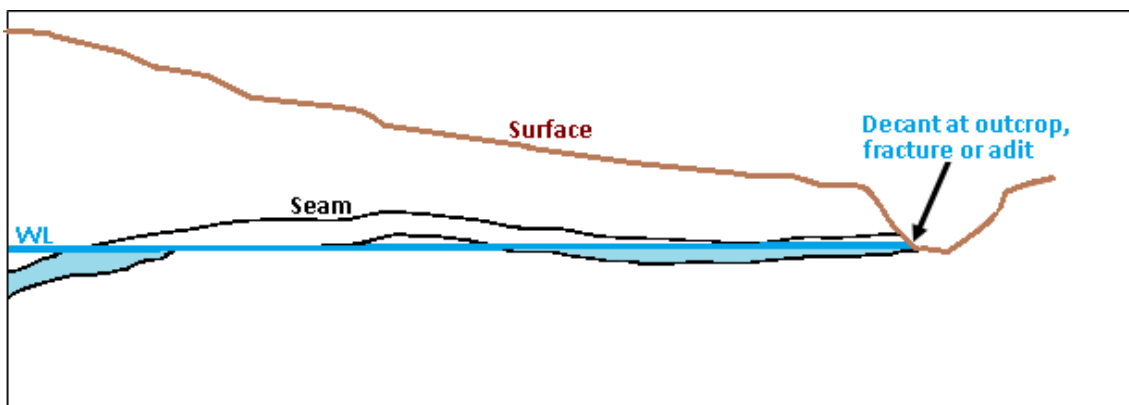


Figure 3-2: Decant illustration of an unflooded mine where only one seam was mined. Modified after Vermeulen and Usher (2006).
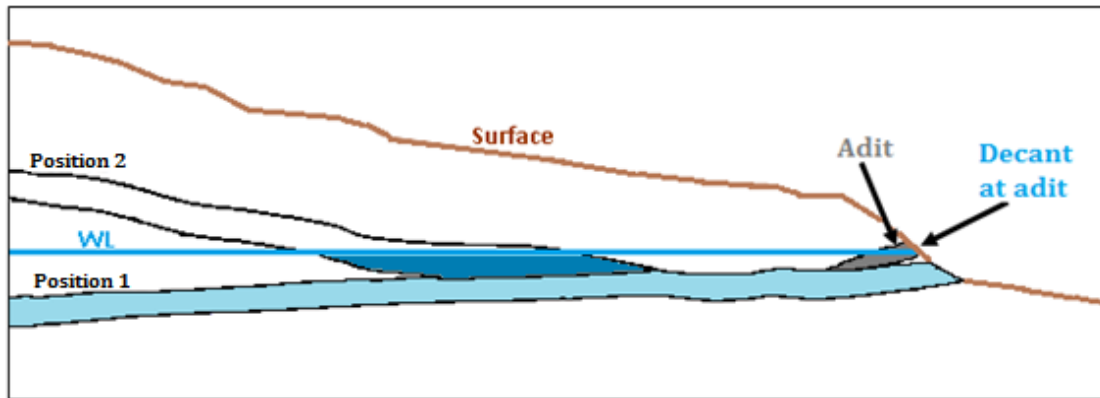
*Figure 3-3: Decant illustration where the position of the seam in a shallow mine determines if the mine will flood or not. Modified after Vermeulen and Usher (2006).*

Vermeulen and Usher (2006) also provide examples of decant in flooded underground collieries and these will be discussed in Figure 3-4 to Figure 3-6 . Figure 3-4 is a decant illustration where the elevation of the seam at one side of the colliery is higher than the surface elevation at another part of the mine. The underground sections need to be sealed or otherwise a piezometric level is created over the entire mine. This piezometric pressure that was created will cause decant from the seam through a conduit, such as a borehole or a fracture, at the lowest connection to the surface. Figure 3-5 illustrates a situation which is very unique. The 2 Seam and 4 Seam are connected through a borehole and the 2 Seam decants if the 4 Seam fills up. The water in the 4 Seam creates piezometric pressure and this forces the water out at a borehole whose collar elevation is lower than the piezometric level created at the 4 Seam. Some parts of the cavity of the 4 Seam does not fill up due to a ridge in the coal floor. Different oxidation scenarios can therefore prevail for different seams in this colliery. Figure 3-6 depicts a colliery where fractures caused by subsidence resulted in areas of different permeability. These can range from single fractures to vast areas. The permeability in these areas wil be higher (>K) than the surrounding strata (<K) and influx of water along these areas will occur more quickly than through the surrounding strata. Water wil rise more quickly in the areas of higher permeability when the mining cavity is filled. In the higher permeability areas, a piesometric level will be created. In the event of the influx into the higher permeability areas being higher than the lateral flux along the strata, the piesometric level will keep rising. This will eventually lead to decant at boreholes, or fractures with surface elevations lower than the piesometric level.
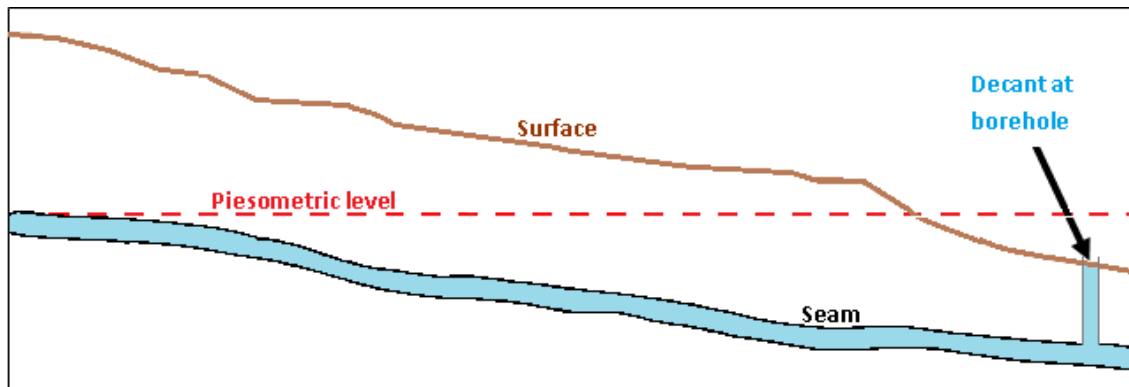
*Figure 3-4: Decant illustration of a flooded colliery where the seam elevation in one area of the mine is higher than the surface elevation in another area. Modified after Vermeulen and Usher (2006).*
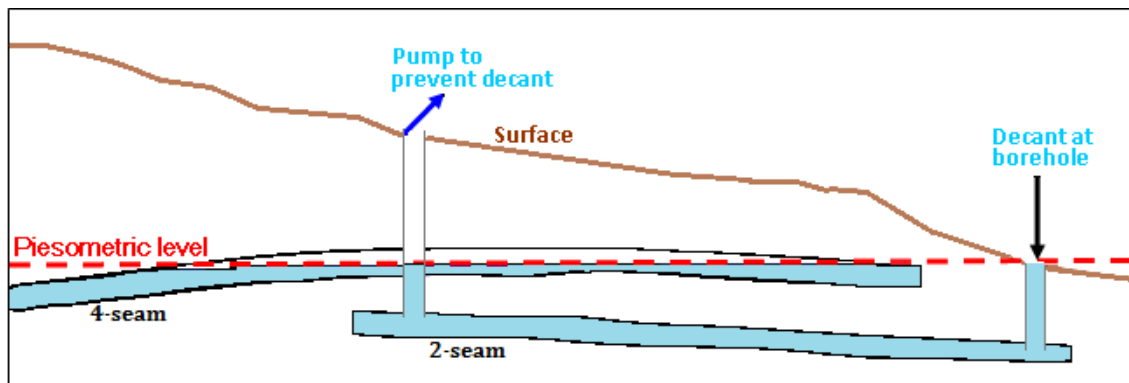


*Figure 3-5: Decant illustration of a flooded colliery where one seam decants because of piesometric pressure created by water in a seam above. Modified after Vermeulen and Usher (2006).*
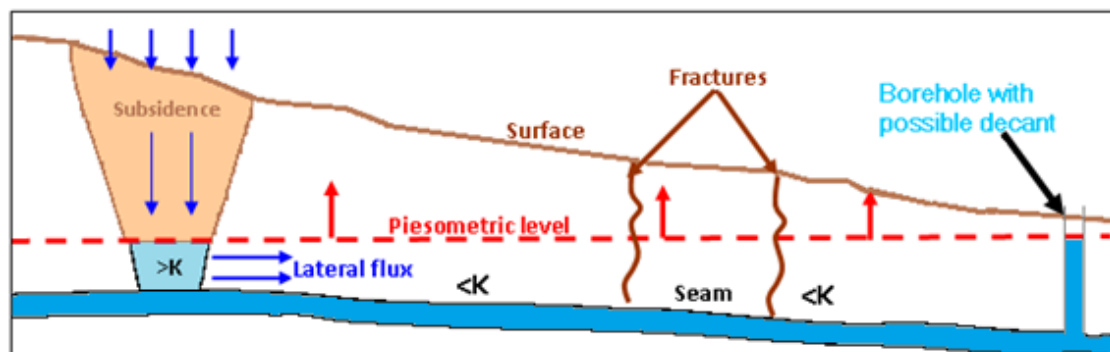


*Figure 3-6: Decant illustration where different permeability conditions prevail above a colliery. Modified after Vermeulen and Usher (2006).*

3-4

Lukas. E (2012) compared an opencast mine to a bucket with lots of holes in the side of it (Figure 3-7). When the bucket is placed in a pool of water, the water will flow through the holes in the bucket. Besides a few other parameters, the rate at which this happens is dependent on the size of the holes and the gradient between the water levels inside and outside the bucket. Once the gradient between the water levels becomes approximately zero, the water will stop flowing. If water is added to the bucket, the water will flow out of the bucket until the gradient is approximately zero again. In the event that the holes are very small and a lot of water is quickly added to the bucket, the water will not be able to flow through the small holes and the bucket will start to overflow or decant.
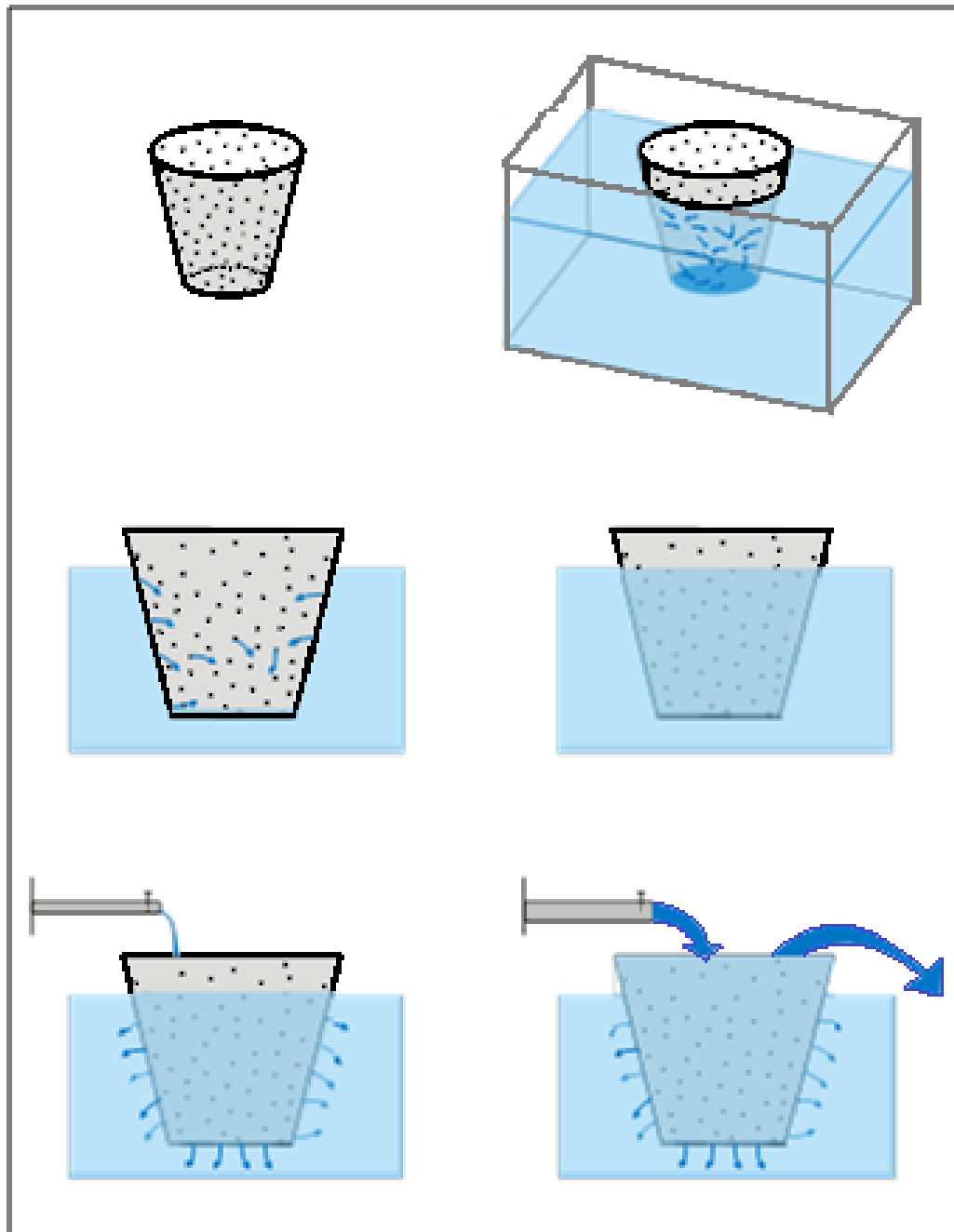
*Figure 3-7: Opencast bucket model. Modified after Lukas (2012).*

According to Lukas (2012) a rehabilitated opencast mine in an aquifer that is isotropic, unconfined and homogeneous without any evaporation and precipitation, will never decant.  The water in the pit will continue to rise until equilibrium is reached between the water levels in the pit and in the surrounding rock.  Water entering the opencast mine at the upstream will leave the pit downstream (Figure 3-8).  The same opencast mine in an area with rainfall and evapotranspiration, but without runoff, will also never

decant as long as the evapotranspiration is higher than the rainfall (Figure 3-9). The rainfall events will cause the water level in the pit to fluctuate accordingly.
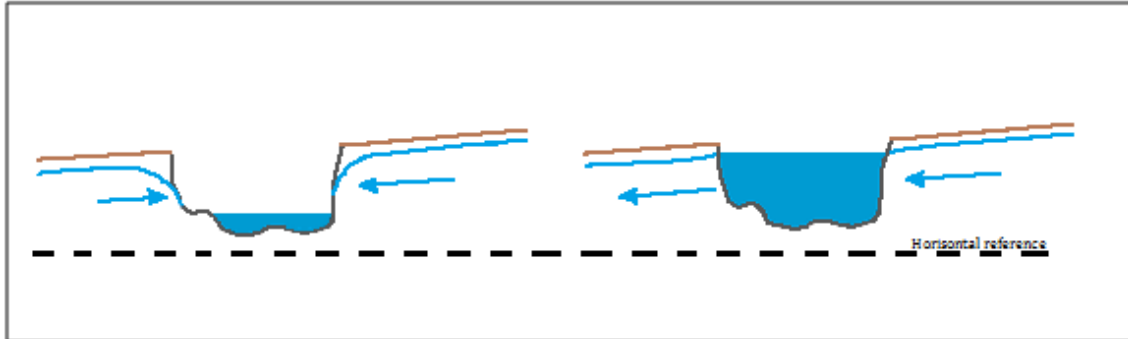


*Figure 3-8: Rehabilitated opencast pit without rainfall and evapotranspiration. Modified after Lukas (2012).*
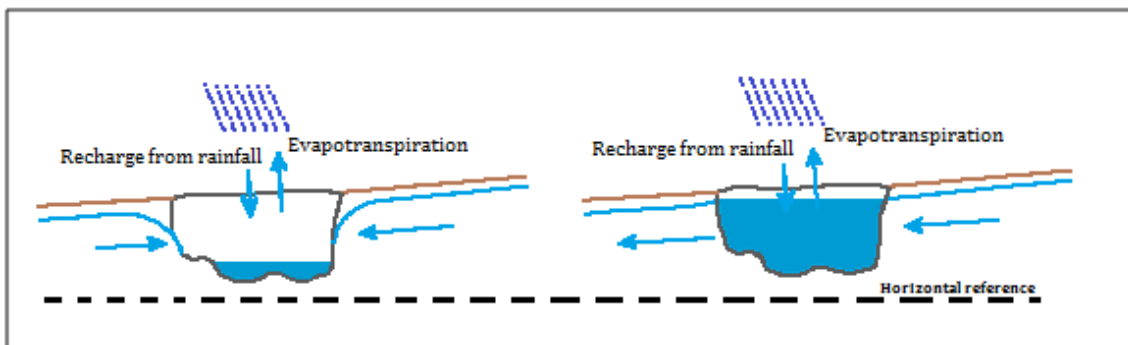


*Figure 3-9: Rehabilitated opencast pit with rainfall and evapotranspiration but no run-off. Modified after Lukas (2012).*

According to Lukas (2012), if run-off is added to the scenario in the picture it will change drastically. Faster recharge of the spoils will then occur due to the run-off from the surrounding areas towards the rehabilitated spoils and the higher porosity of the spoils which results in a higher hydraulic conductance. To calculate the volume of water that may enter the pit it is very important to determine the extent of the area receiving precipitation that can run-off into the rehabilitated pit. The rehabilitation must be constructed in such a way that no water from surrounding areas can run-off onto the rehabilitated pit. This is to keep the amount of water in the pit to a minimum.
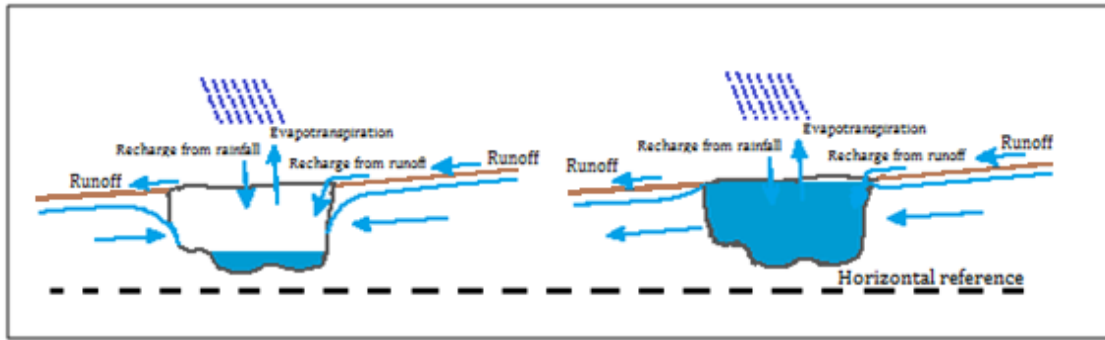
*Figure 3-10: Rehabilitated opencast pit with rainfall, evapotranspiration and run-off. Modified after Lukas. (2012).*

# 4. Project Study Area

## 4.1 Introduction and physical setting

The study area is located in the far northern parts of the Free State Province (Figure 4-1) with the Vaal River forming the border between Gauteng and the Free State. Sasolburg is a large industrial town that was established in 1954 to provide housing and facilities to Sasol employees. The first installation (Sasol 1) was a pilot plant to refine oil from coal, due to the lack of petroleum reserves.

The project area is situated adjacent to the town of Sasolburg (Figure 4-1) in the Free State Province, Republic of South Africa. The main water course in the project area is the Vaal River which borders the project area in the north, just above the Vaal barrage. The main road above the project area is the Parys-Sasolburg road. The New Vaal Colliery and the defunct Cornelia Colliery is situated to the east of the project area (Van Tonder and Vermeulen, 2008).
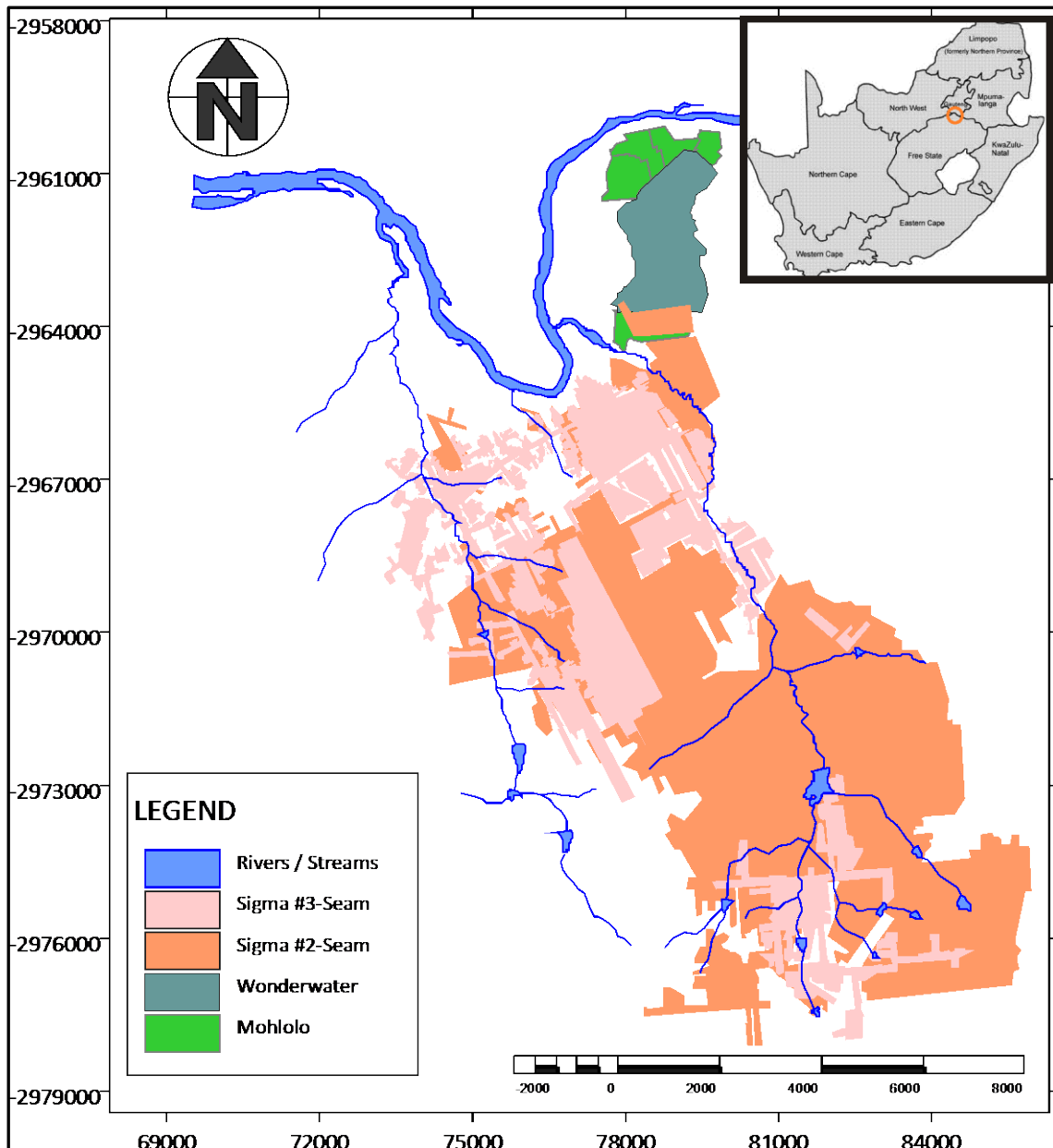
*Figure 4-1: Locality map of Sigma Colliery showing the locality of the colliery within South Africa, rivers in the area, the 3 seam and 2 seam areas that was mined out, Mohlolo Underground Mine and Wonderwater Open Pit Mine.*

## 4.2   Topography and drainage

Sigma Colliery has a regional topography (Figure 4-2) that has a gentle sloping surface towards the Vaal River.   Two rivers intersect this surface, namely the Leeu and Riet Spruits.   The lowest surface elevations (1421 mamsl) are found along the Vaal River. The highest surface elevations are found in the southern and eastern parts of the area and the surface elevations in these areas can go up to 1500 mamsl.
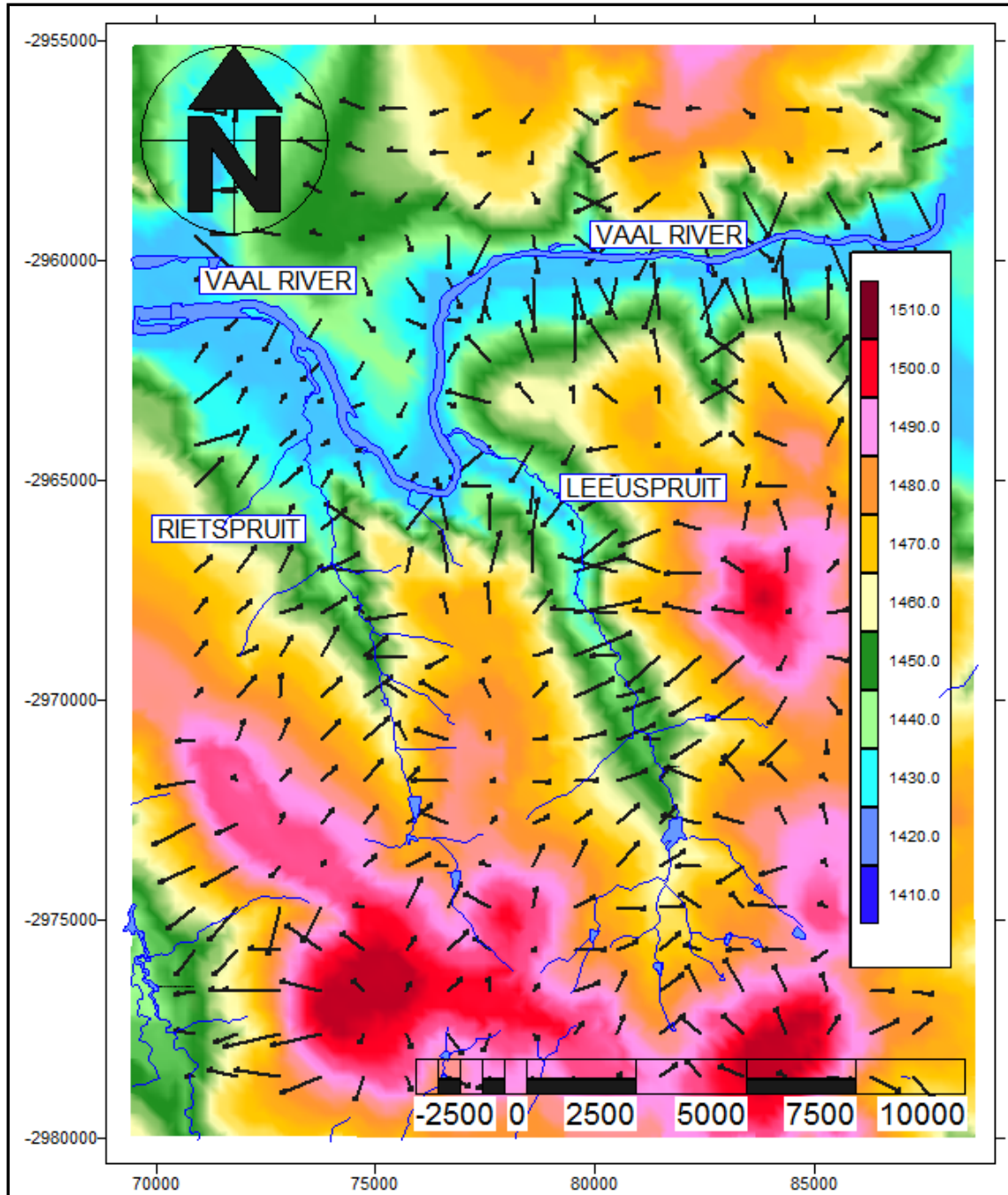
*Figure 4-2:  Surface contours for Sigma Colliery. The project area is situated in quaternary catchment C22K which is located within the Upper Vaal Water Management Area (Figure 4-4) and is drained by four rivers/ spruits (Figure 4-3).  The Vaal River that is situated north of the project area is the main system. Soon after passing the mine site the Vaal River flows into the Barrage, which is one of the extraction points for water supply to Gauteng.  Irrigation also occurs along the Vaal River.  The Vaal River system is a perennial river system.  East of Sasolburg the area is drained by Taaibosspruit and this is a perennial system and has no influence on the Colliery.  Rietspruit and Leeuspruit are both non-perennial systems which overlies the Colliery.  Both these streams have an influence on the mine, especially in areas of subsidence (Van Tonder and Vermeulen, 2008).*
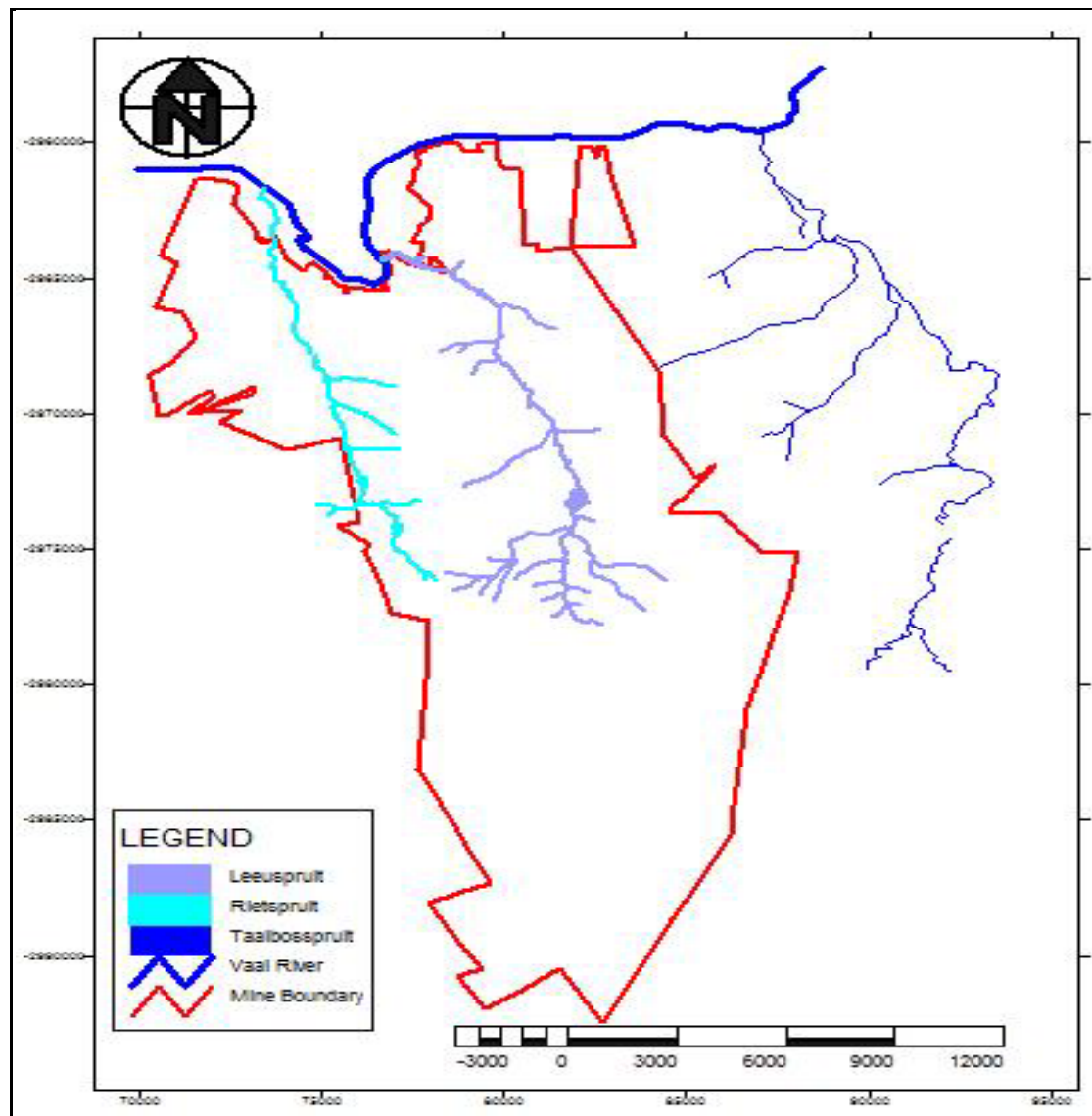
Figure 4-3: Rivers and streams that drain the area.

*Figure 4-4: Water Management Areas (WMA) of South Africa (Nomquphu, et al., 2007).*

## 4.3  Climate

Sasolburg is situated at a high altitude with a fairly dry climate and large seasonal temperature variation.  Rainfall in the Sasolburg (Figure 4-5) region occurs mainly during the summer months and the average annual rainfall from 2001 to 2011 was 530 mm (SA Weather Service - Rainfall station: Vereeniging 0438784 3).  The lowest rainfall generally occurs in July and the highest rainfall in January. Maximum temperatures (Figure 4-6) range from 30.7 °C in summer to 16.5 °C in winter.  The minimum temperatures (Figure 4-7) range from 17.1 °C in the summer to -2.3 °C in winter.
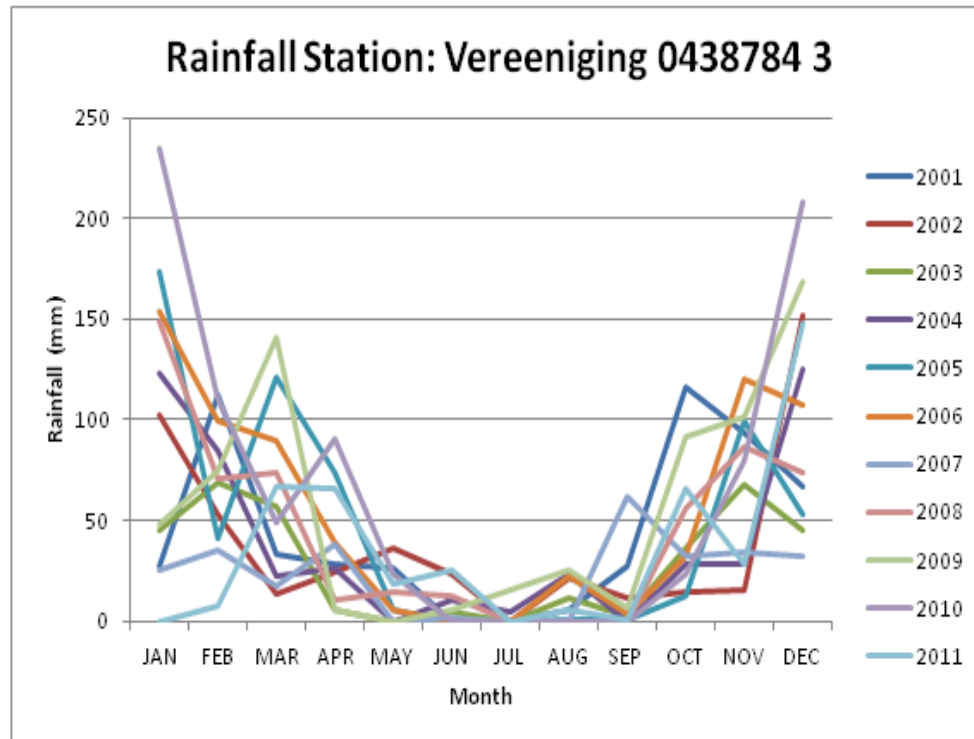
Figure 4-5:  Rainfall for Sasolburg from 2001 to 2011.
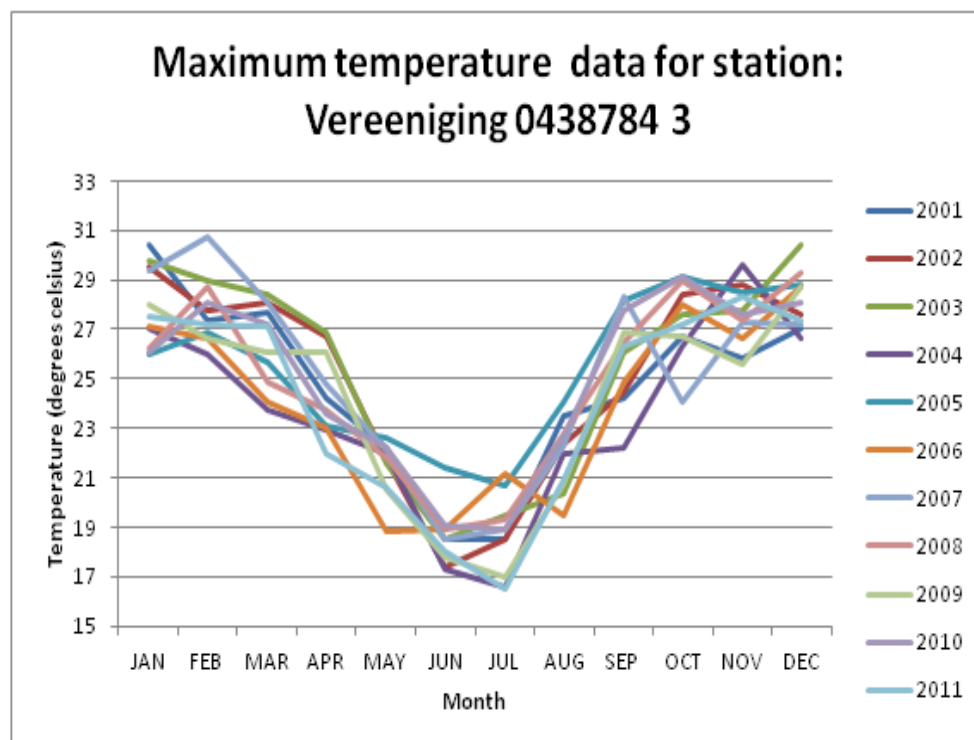


Figure 4-6:  Maximum temperatures for Sasolburg from 2001 to 2011.
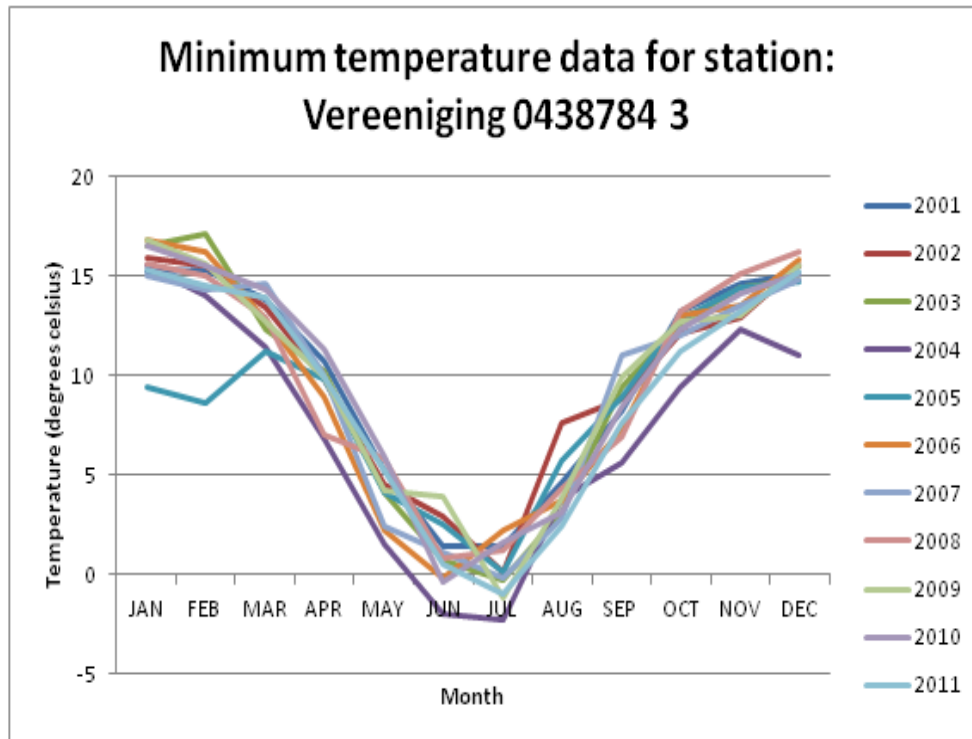
*Figure 4-7:  Minimum temperatures for Sasolburg from 2001 to 2011.*

## 4.4   Land use

Land use in and surrounding the study area is dominated by cultivated dry land.  The main crops that are cultivated are maize and wheat.  Some cattle farming activity also occurs in the area.

*Figure 4-8: Typical maize and cattle farming within the study area.*

## 4.5   Geology

### 4.5.1   Regional

Sigma Colliery is situated in the Sasolburg-Vereeniging Coalfield (Figure 4-9), which is situated in the Karoo Supergroup.  All the South African coal deposits are hosted within the Karoo Supergroup of Late Carboniferous to Middle Jurassic Age (320 – 180 Ma). The great Gondwana basin comprises parts of Southern Africa, India, Antarctica, Australia and South America and the South African coal deposits were formed in this basin.  The geomagnetic pole positions during the late part of the Palaeozoic suggest that the climate of South Africa changed from glacial to periglacial. This implies that South African coal was formed in a cold to cool climate (Snyman, 1998).

Coal deposits within the main Karoo basin are present in the Vryheid Formation of the Ecca Group, the Normandien Formation of the Beaufort Group and also in the Molteno Formation in the Eastern Cape.  The two major tectonic settings in which coal deposits are found is stable cratonic platforms and fault–bounded rift basins.  Coal deposits in the main Karoo basin are typical of stable cratonic platforms (Snyman, 1998).
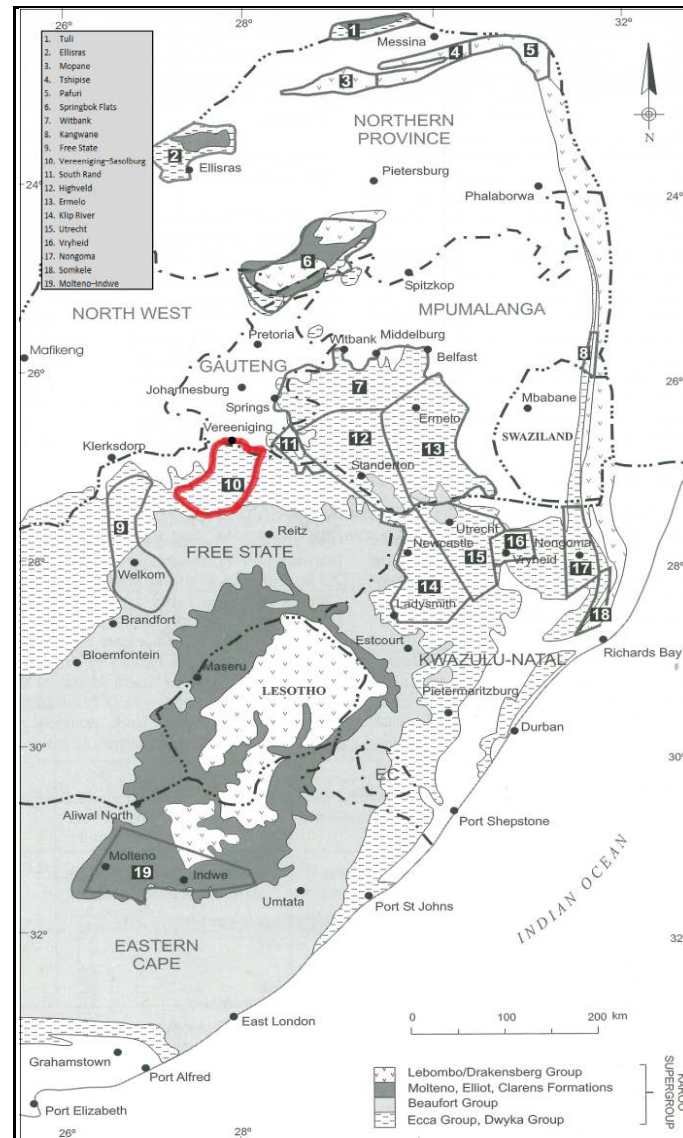
*Figure 4-9: The coalfields of South Africa with the Vereeniging–Sasolburg coalfield encircled in red modified after Snyman (1998).*

### 4.5.2   Local

The lava and dolomite of the Ventersdorp and Transvaal Systems respectively is found to underlie the Sigma Basin.  This broad valley, or long narrow structure, is about 9.5km wide and trends about 129km north-south from the Vaal River to beyond Dover Station.  The rim of the basin has an average depth of around 90m and the rim is quite steep, generally 1 in 12 (De Jager, 1976).

The palaeo-surface within the basin is characterised by ridges and valleys trending parallel to the long axis of the basin before the deposition of the Karoo rocks.  The areal

distribution, the nature and thickness and the chemical properties of the sediments and the interbedded coal seams were controlled by the unevenness of the palaeotopography. Except for where hills and ridges prevented its deposition, the Dwyka tillite extends over the whole basin and is up to 45m thick. The deposition of the tillite partially smoothed the palaeotopography, but a possibly badly-drained, uneven basin remained (De Jager, 1976).

About 200 million years ago the coal bearing strata in this area was deposited within the Vryheid and Dwyka formations, which forms part of the Karoo Supergroup of sedimentary rock. Remainders of glacial, fluvial, and open-water depositional activities are found within the sedimentary rock (De Beer. *et al.,* 1991).

According to De Beer *et al* there are four mineable coal seams found in the Sigma basin. They are number 1, 2A, 2B and 3 coal seams, as identified from the base upwards. The coal seams are situated between 20m and 250m below surface and extend over an area of approximately 300km$^2$. The general southward dip of the strata, together with a northward sloping land surface which drains towards the Vaal River, can be seen to have caused the wide variation in depth below surface.

Throughout the basin number 2A, 2B and 3 coal seams can be found. The distance between the coal seams are variable and increases towards the south for number 2B and 3 coal seams. Between number 2A and 2B seams there are rarely more than 100cm of mudstone and in some areas no parting between the two seams. This results in a combined seam thickness of 6m and more. The overburden generally consists of medium-to coarse-grained sandstone, dolerite, siltstone, mudstone and shale and in the far northern regions a thick, unconsolidated sand unit (De Beer. *et al.,* 1991).

Between 65 and 85 meters below surface, two dolerite sills have displaced the strata at Sigma Colliery and relatively small faults with a maximum displacement of about 5m have been encountered underground (Snyman, 1998).
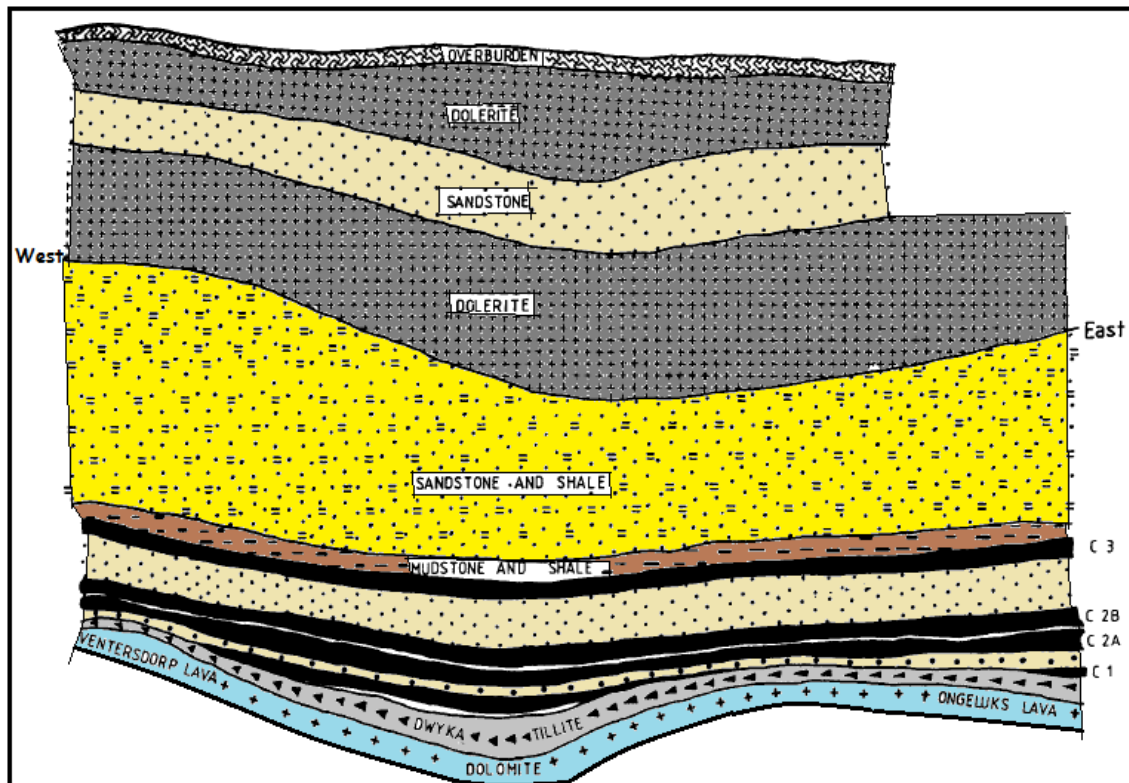
*Figure 4-10: Simplified stratigraphic profile at Sigma Colliery modified after De Beer. et al., (1991).*

## 4.6   Hydrogeology

Five groundwater systems can be found in the Sigma area.  The five groundwater systems comprises of the shallow quaternary and recent types of sediments, the intermediate unweathered/fractured Karoo, the subsidence and backfilled material above the coal horizon, the coal seams (mining area) and the deep Pre-Karoo system comprising the Dwyka tillite and the dolomites below the tillite (Van Tonder, et al., 2007).

### 4.6.1   The weathered/ shallow groundwater system

The upper shallow aquifer consists of soil and weathered rock and is associated with the top 5 to 15 meters in the area.  Water may often be found in boreholes at this horizon.  A thick dolerite sill is present close to the surface in some places.  Recharge in this aquifer occurs through rainfall, which infiltrates into the weathered rock until it reaches impermeable layers of solid rock beneath the weathered zone.

On top of the solid rock movement of groundwater is lateral and in the direction of surface slope. Where the flow paths are obstructed by barriers such as dolerite dykes, palaeotopographic highs in the bedrock, or where the surface topography cuts into the ground water level at streams, the water reappears on the surface. The weathered zone is generally low in yield (0.02 – 0.14 L/s), because of its insignificant thickness (Van Tonder. *et al.,* 2007).

### 4.6.2    The fractured/ intermediate groundwater system

Significant flow of water is limited due to the fact that the grains in the fresh rock below the weathered zone are well cemented. According to Barnard (2000), groundwater occurrence is generally associated with fractures and joints developed locally along bedding planes, with contact zones between different sedimentary lithologies and with fault and associated shear zones. Dolerite sills and dykes are generally impermeable to water movement, except where they are weathered (Van Tonder. *et al.,* 2007).

### 4.6.3    Disturbed aquifer system

This aquifer system comprises of the subsidence and backfilled material above the coal horison.

### 4.6.4    The mined out areas

This aquifer system resulted from the mining of coal and has changed the hydrodynamics of the coal mined area. Since 1999, an ashfilling project was undertaken by the colliery to stabilise mine workings located beneath the main roads in the vicinity. For the purpose of this thesis, this aquifer system will therefore be divided into the Mine Aquifer System and the Ashfill Aquifer System.

### 4.6.4.1   The coal seam/ mined out areas

The coal seam is mined out and will therefore have a much higher transmissivity than the layers above and below it (Van Tonder. *et al.,* 2007). This area includes the defunct Sigma Underground Operation, defunct Wonderwater Strip Mine Operation and the defunct Mohlolo Underground Operation.

### 4.6.4.2  The ashfill areas

Since 1999, an ashfilling project was undertaken by the mine to stabilise the mine workings located beneath the main roads in the vicinity.  The ashfilling created an artificial pressure in these areas and affected the water quality.

### 4.6.5  The deep pre-Karoo rocks

This aquifer system comprises of the Dwyka tillite and the dolomites below the tillite. Although they are discussed separately in this section, they are grouped together as the deep groundwater system in the rest of the thesis.

### 4.6.5.1  Dwyka tillite

The Dwyka tillite groundwater system is situated below the coal seams.  According to Vivier (1996) the Dwyka tillite has very low hydraulic conductivities ($10^{-11}$ to $10^{-12}$ m.s$^{-1}$), and virtually no primary voids. They therefore tend to form more aquitards than aquifers.

### 4.6.5.2  Dolomite

The top section of the dolomite is chert-rich. This chert layer acts as a paleo-channel, and serves as a conduit for water. Due to the high piezometric pressure of this system, where it is not overlaid by tillite, it forces water upwards into and above the coal seam.

## 5. Methodology

### 5.1 Water level measurement

An electronic dip meter (Figure 5-1) was used for this operation to determine the depth of the water level below the collar of the borehole. It is important to always measure this from the collar of the casing to ensure uniform measurement.



*Figure 5-1: Groundwater level measurement with an electronic dip meter in the field.*

### 5.2 Multi – parameter logging

The water column of the 94 accessible and available boreholes within the Sigma mining area was profiled with a multi-parameter probe (Figure 5-2). After the borehole was profiled the data from the probe was downloaded onto a laptop computer. The downloaded borehole profiles were then used to determine where to sample the boreholes. Multi-parameter logs ensure that water qualities are measured as they are

in-situ, without disturbing the water column in the boreholes through sampling. Without such probing, sampling would be meaningless. The advantages of such probing are as follows:

- In-situ measurement of conductivity.
- The position of fractures can be identified, in order to determine the sampling depths.
- Stratification of the water column can be recognised.

This data was then manipulated with the Windows Interpretation System for the Hydrogeologist Program (WISH) for Interpretation.



*Figure 5-2: Multi-parameter probe with different sensors.*

## 5.3 Groundwater sampling

Following the water quality probing in the boreholes, sampling included either a sophisticated pressurised depth sample, or a flow-through bailer (depending on the depth of the sample). The sampling depth and the amount of samples taken at each borehole were determined by the profiling. If stratification was visible on the profile, two or three samples were taken, so that the samples were representative of the whole water column of the borehole. These samples were then named, for example, UG027D (D for deep), UG027M (M for middle) or UG027S (S for shallow). Before each sample was taken, the bailer was cleaned with de-ionised water. The samples were stored in

500ml plastic bottles and transported to the Institute for Groundwater Studies (IGS) Laboratory for analysis.



*Figure 5-3:  Bailers that were used for the groundwater sampling.*

## 5.4   Isotopic sampling

25 boreholes were selected for isotopic analysis.   The boreholes were selected by looking at the spacial distribution over the area, so that the selected samples would be representative of the area.

Water sources which may flow into the Sigma Underground Mine include: water from rainfall; water from the dolomite aquifer; water from Wonderwater; water from the Vaal River and water from the disposal of ash to stabilize the Parys-Sasolburg road. This ash introduced organic substances such as phenol into the underground workings. In other instances, power station fly ash has been introduced into the underground workings; the latest of which was in 2011. In total, about 1 Mm3 ash and water have been introduced into the mine. Excess water from Sigma-Mooikraal Underground Workings has been disposed of in the Wonderwater opencast. The current situation is that most of the Sigma workings are flooded.

### 5.4.1   Natural Isotopes: Deuterium  ($^2$H) and Oxygen 18 ($^{18}$O).

The most commonly employed stable isotopes are $^{18}$O and $^2$H, which are often used for assessment of the "genesis" (origin) of water, particularly in groundwater systems; processes involved in the replenishment (process-tracing); for estimating mixing proportions of different sources or component flows (component-tracing); and studying hydraulic relations between groundwater and surface water or between different aquifer units within a given groundwater system. One of the most important factors governing

the use of these isotopes is the isotopic fractionation occurring during phase changes, i.e. condensation or evaporation, which is mainly a temperature dependent phenomenon. The isotopic changes consequently therefore induced, is a conservative property of the water during its circulation in the hydrological systems, and it is a finger-print of the history of the processes involved in its formation and circulation.

The $^{18}O$ and $^2H$ variations in natural waters show a linear relation as a consequence of the fact that their behaviour during the fractionation processes are similar. The equation derived in this regard was first given (using annual average values of $^{18}0$ and $^2H$) as:

$$\delta\,^2H = 8(\delta\,^{18}O) + 10$$

This equation is generally referred to as the "Meteoric Water Line", and it is very close to the theoretically expected relation. A typical Deuterium vs. Oxygen isotope plot can be seen in Figure 5-4.
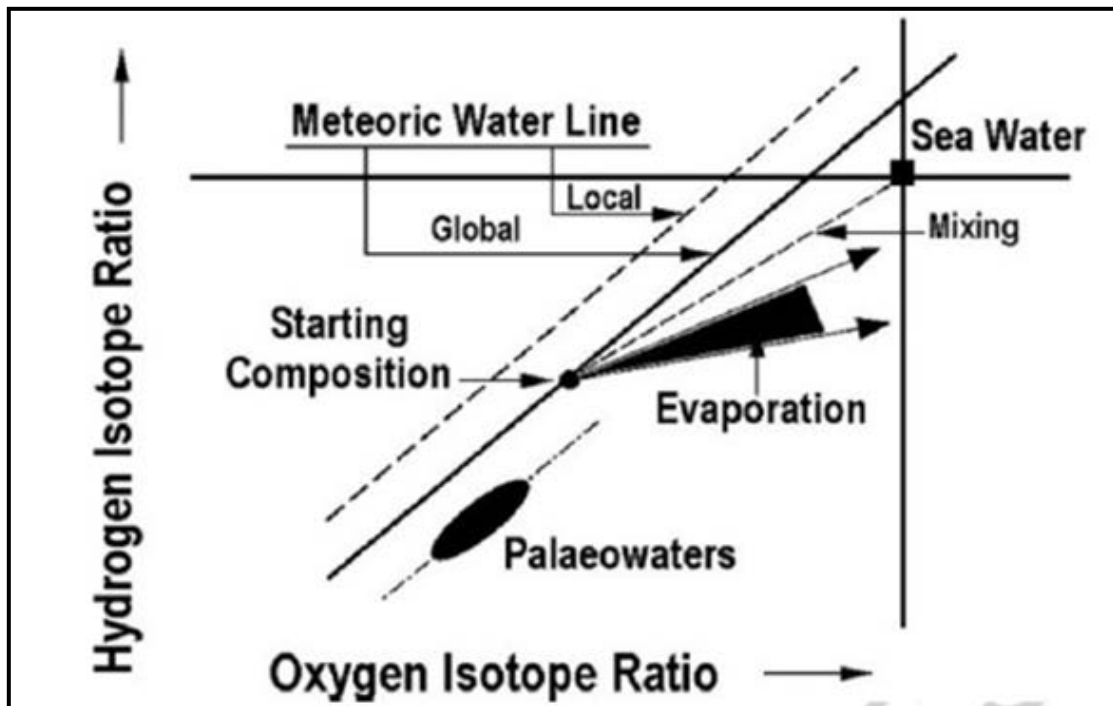


*Figure 5-4: A typical Deuterium versus Oxygen isotope plot.*

## 5.5 Water quality

The elements that were analysed during the water quality analysis of the water samples are: pH, EC , Ca, Mg, Na, K, PAlk, MAlk, F, Cl, $NO_2(N)$, Br, $NO_3(N)$, $PO_4$, $SO_4$, Al, Fe, Mn, $NH_4(N)$, Ba, Co, Cr, Cu, V, Zn, Si and B. The listed elements cover a wide range and are effective indicators of potential pollution in the groundwater due to coal mining. The measurements of the EC provide an indication of the salt quantities in the water while the measurement of the pH gives an indication of the alkalinity of the water samples. The determinations of the water quality were performed using an Inductively Coupled Plasma Spectrometer (ICP).

# 6. Water Levels

The water level of the 94 boreholes that was profiled (Figure 6-1) for each aquifer, was measured with a dipmeter.  The proportional distribution of the water levels measured for each of these 94 profiled boreholes is visible in Figure 6-1.  This proportional distribution is represented by using circles that vary from big too small.  The bigger the circle, the deeper the water level and the smaller the circle, the shallower the water level.  Groundwater level time graphs were then created with the historical data, as well as the most recent water levels obtained.  This was done to determine if there was any water level trends visible over time in an aquifer and to observe water levels of boreholes that became very shallow over time. This could indicate possible decant positions.
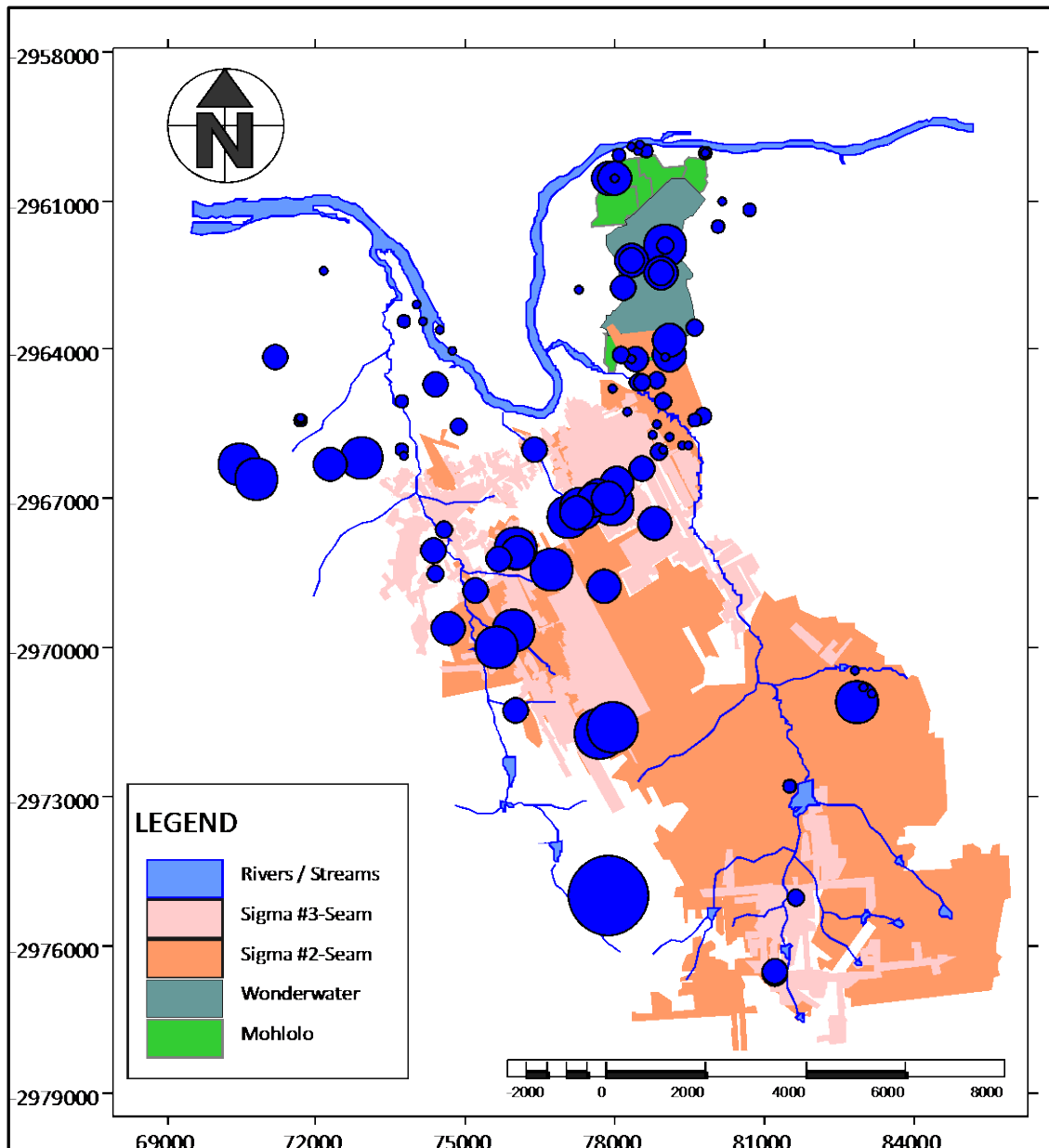
*Figure 6-1: The proportional distribution of all the water levels measured.*

## 6.1 Groundwater levels for the shallow aquifer system

The water level of the 94 boreholes that was profiled (Figure 6-1) for each aquifer, was measured with a dipmeter. The proportional distribution of the water levels measured for each of the 94 profiled boreholes is visible in Figure 6-1. This proportional distribution is represented by using circles that vary from big too small. The bigger the circle, the deeper the water level and the smaller the circle, the shallower the water level. Groundwater level time graphs were then created with the historical data as well

as the most recent water levels obtained.  This was done to see if there was any water level trends visible over time in an aquifer and to observe water levels of boreholes that became very shallow over time which could indicate possible decant positions.
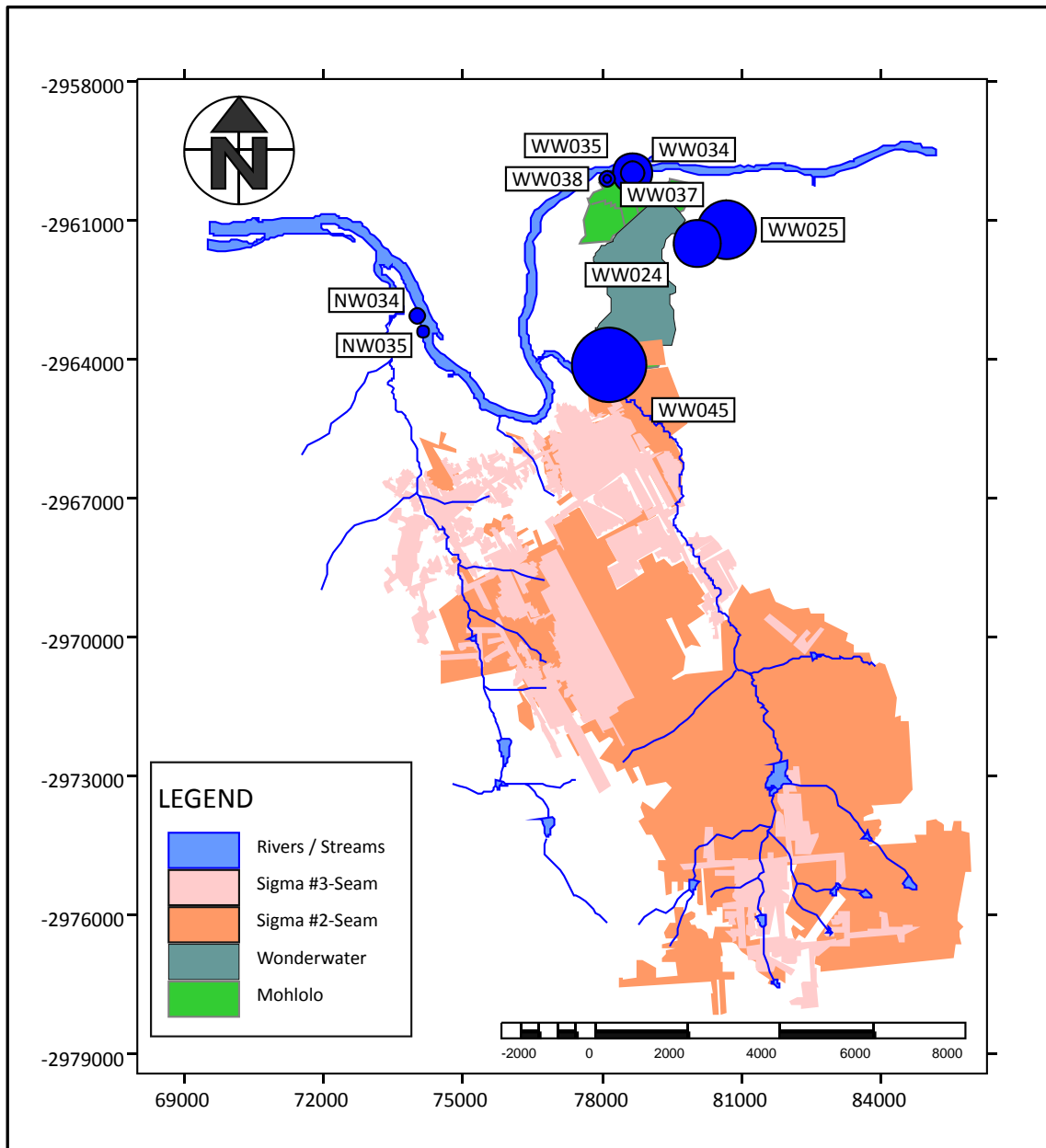


*Figure 6-2: Locality and proportional distribution of water levels of boreholes in the shallow aquifer system.*

The locality and proportional distribution of the water levels measured in the shallow aquifer system can be viewed in Figure 6-2.  The proportional distribution is represented by using circles that vary from big too small.  The bigger the circle, the

deeper the water level and the smaller the circle, the shallower the water level.  The water level depth time graphs can be vied in Figure 6-3 and Figure 6-4.  The water level elevation time graphs for the water levels in the shallow aquifer system can be viewed in Figure 6-5 and Figure 6-6.  The groundwater levels for the boreholes in the shallow aquifer system appear to be fairly stable, with the exception of borehole WW045.  The water levels of borehole WW045 seems to currently be stabilised, but in the past it showed erratic trends of water level rise and decline.  This erratic water level change could be due to undermining.  None of the water levels in the shallow aquifer appear to have become significantly shallower and none of them could be a possible decant position.  The water level versus rainfall of the last ten years can be viewed in Figure 6-7 and Figure 6-8.  The groundwater level depth versus rainfall from 2007 to 2012 can be viewed in Figure 6-9 and Figure 6-10.  This time scale was chosen to see how the water levels behaved after the mine was filled.  From Figure 6-9 it is evident that there is a slight but definite decreasing groundwater level trend for boreholes WW038 and NW035.  The reason for this can be that there was less rain during the rainy season than in previous years.  Borehole WW045 however shows a gradual decrease in water level depth and a reason for this can be that the coal roof of Mohlolo collapsed in 2005, which resulted in the sudden increase in water level depth in 2005.  After this event the water level depth decreased gradually, possibly due to recharge from rainfall. It was suggested by Van Tonder and Vermeulen (2008) that significant volumes of water are seeping from the Vaal River into the Mohlolo, which can also be contributing to the decrease in water level depth.
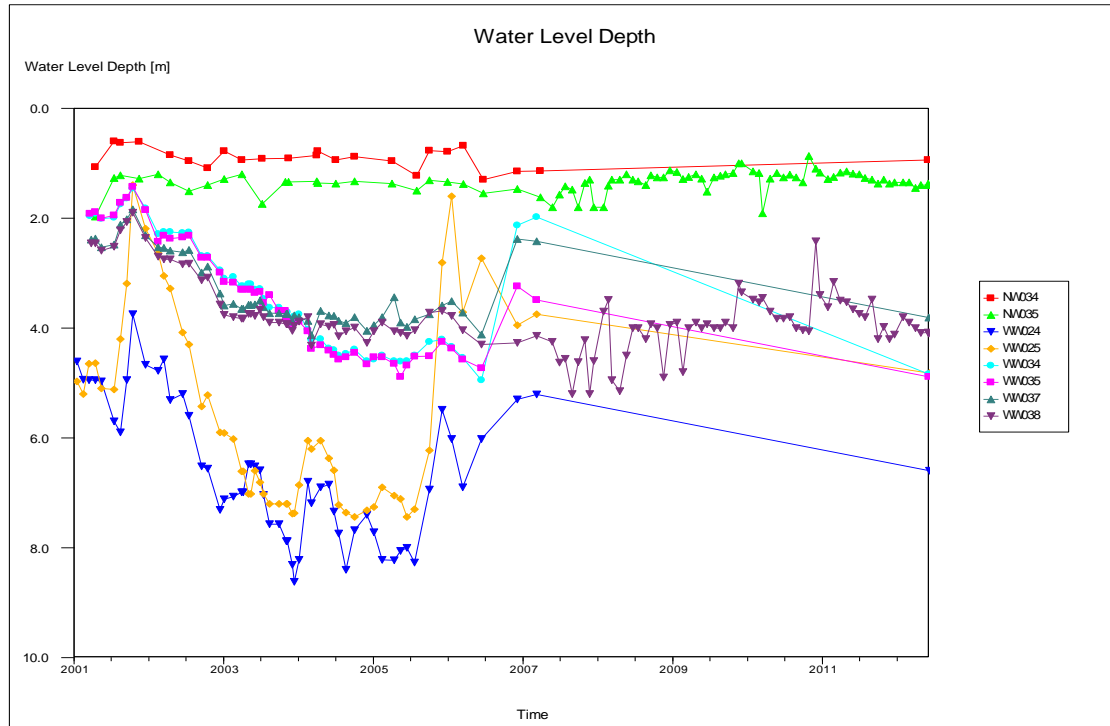
*Figure 6-3: Groundwater level depths for the boreholes NW034, NW035, WW024, WW025, WW034, WW035, WW037 and WW038 in the shallow aquifer system.*
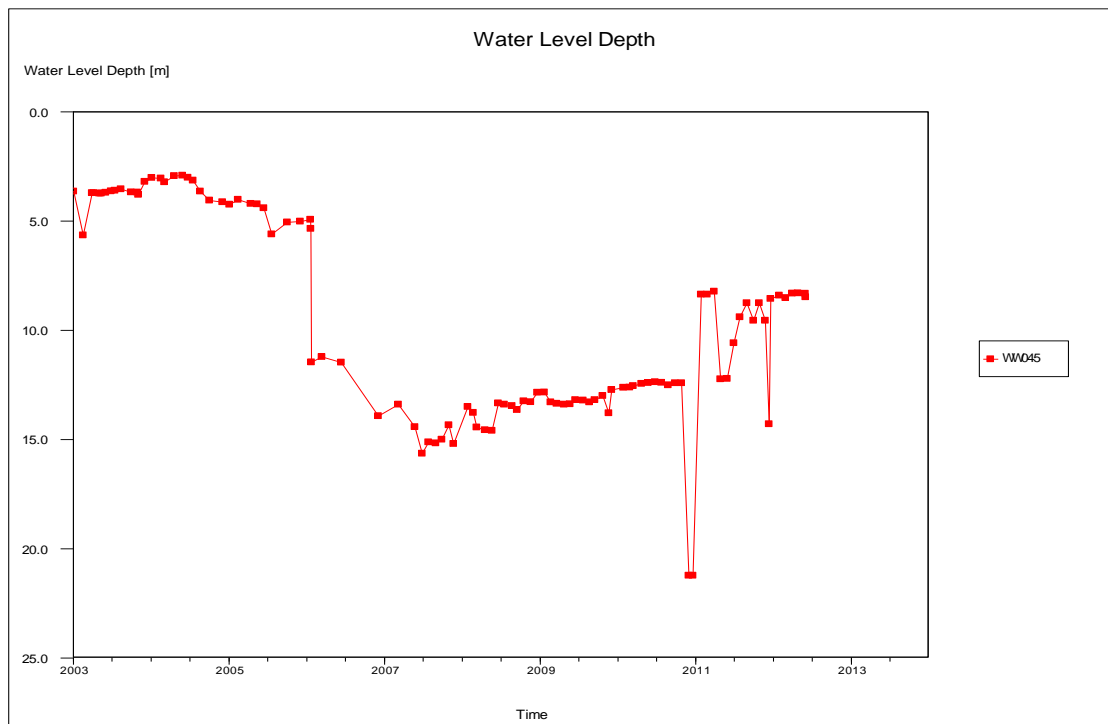


*Figure 6-4: Groundwater level depth for borehole WW045 in the shallow aquifer system.*

6-5
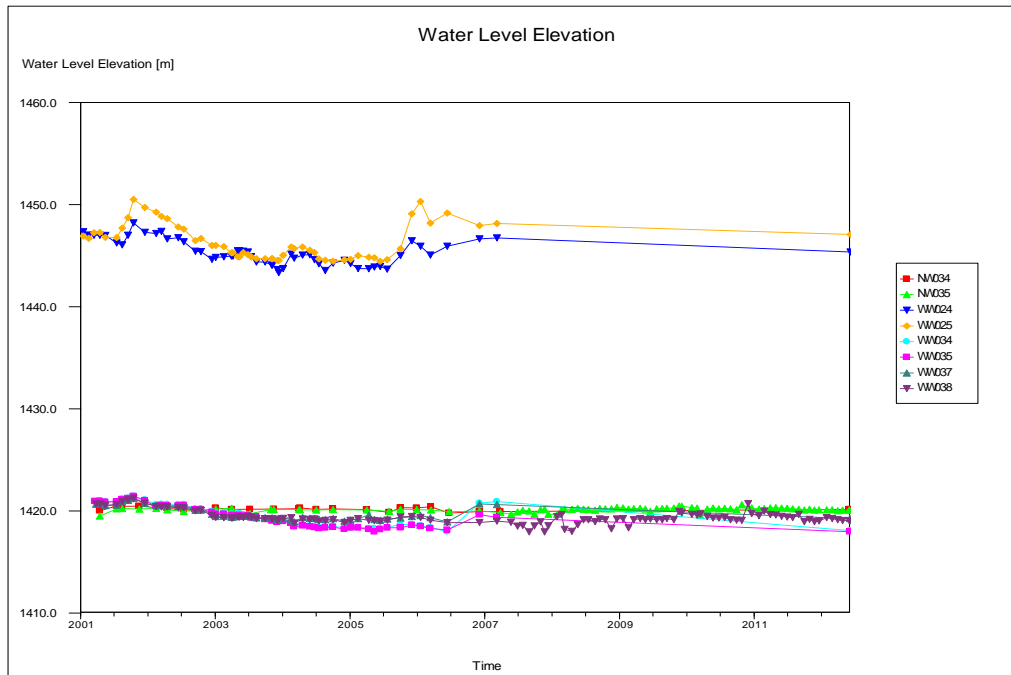
*Figure 6-5: Groundwater level elevations for boreholes NW034, NW035, WW024, WW025, WW034, WW035, WW037 and WW038 in the shallow aquifer system.*
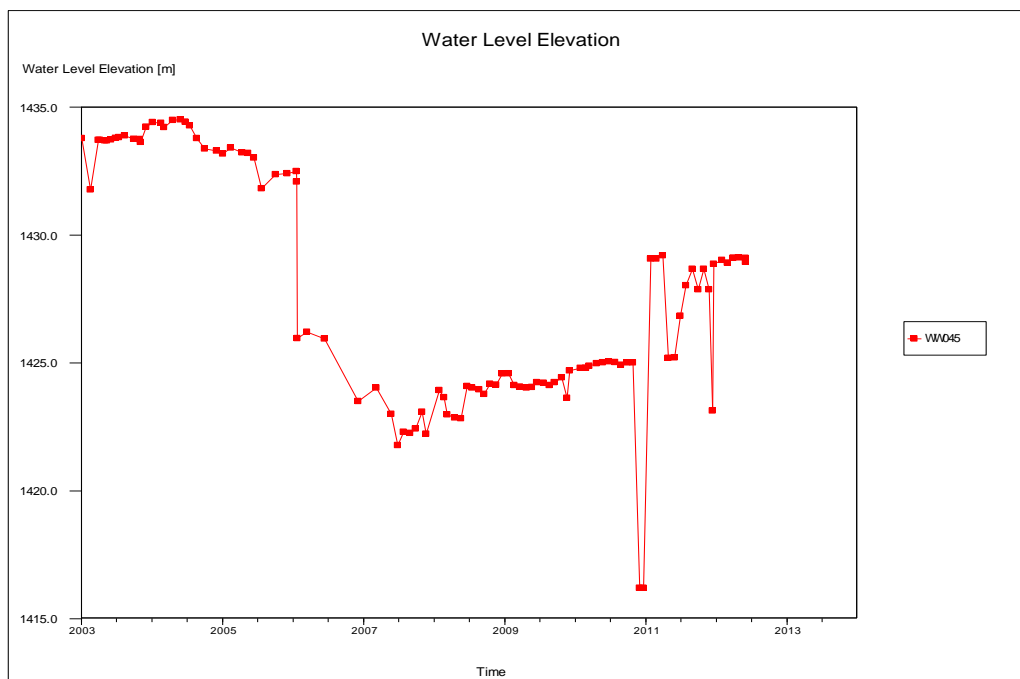


*Figure 6-6: Groundwater level elevation for borehole WW045 in the shallow aquifer system from 2001 to 2012.*
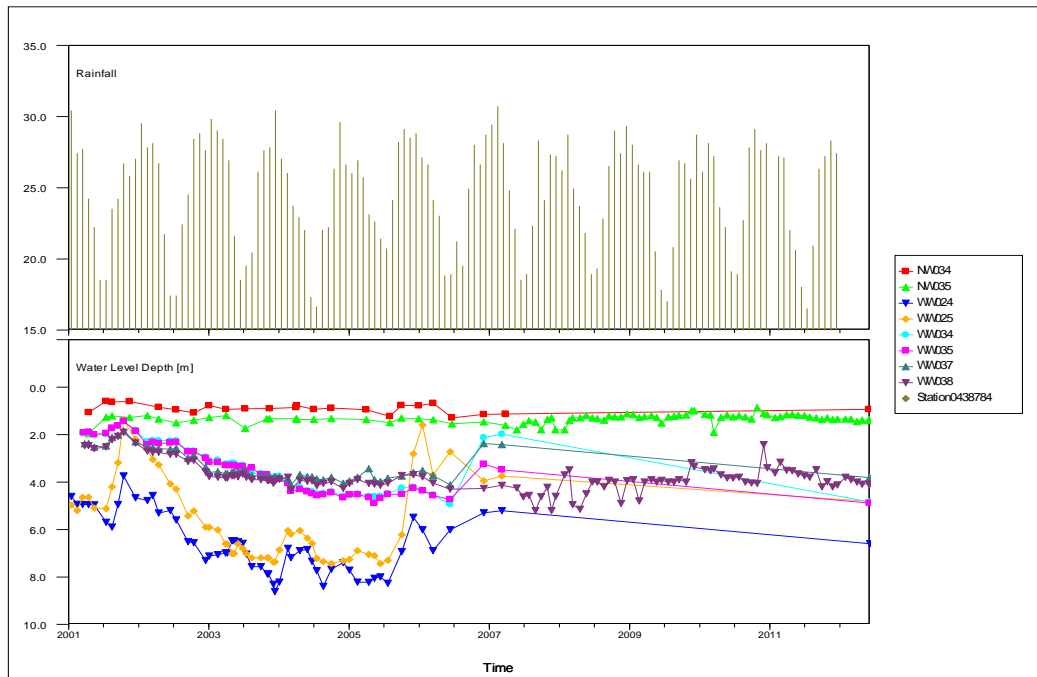
*Figure 6-7: Groundwater level depth and rainfall for boreholes NW034, NW035, WW024, WW025, WW034, WW035, WW037 and WW038 in the shallow aquifer system from 2001 to 2012.*
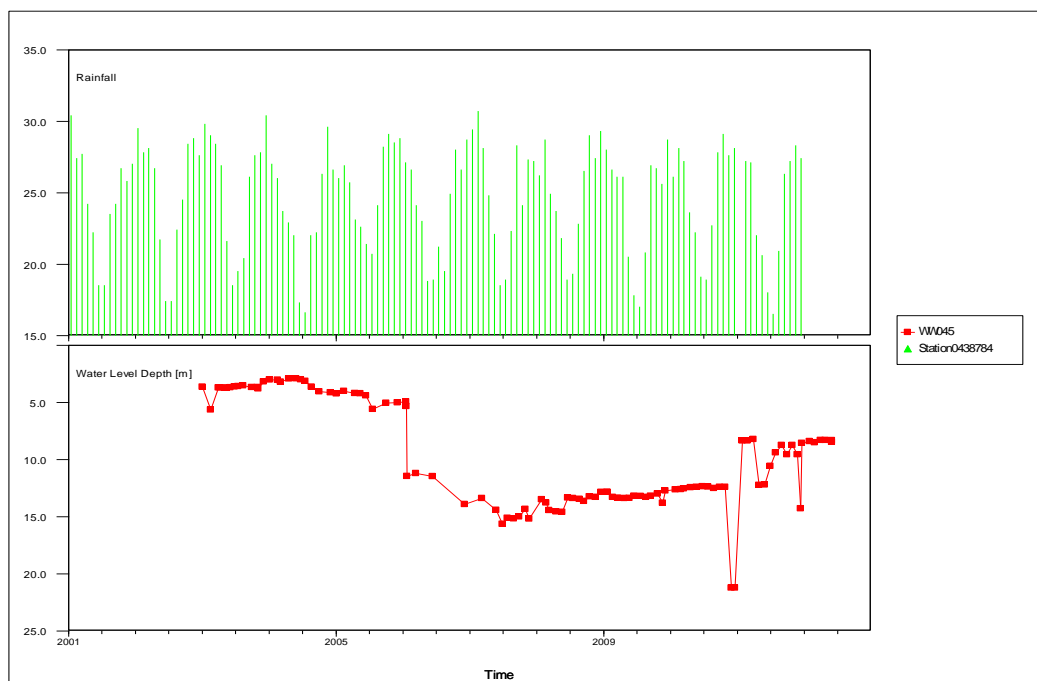


*Figure 6-8: Groundwater level depth and rainfall for borehole WW045 in the shallow aquifer system from 2001 to 2012.*
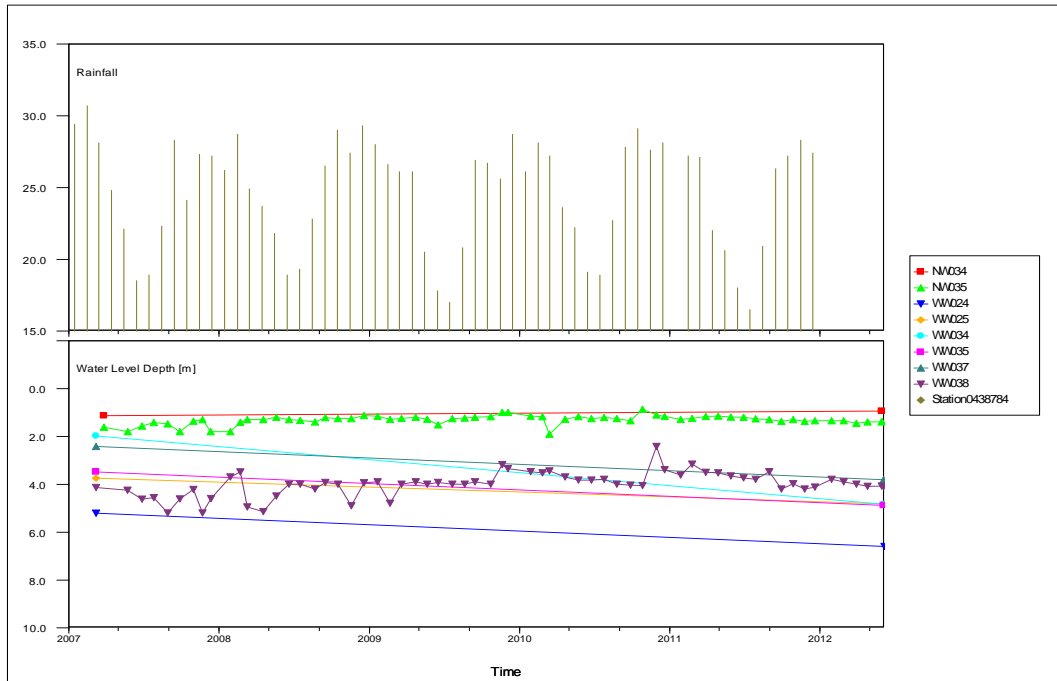
*Figure 6-9: Groundwater level depth and rainfall for boreholes NW034, NW035, WW024, WW025, WW034, WW035, WW037 and WW038 in the shallow aquifer system from 2007 to 2012.*
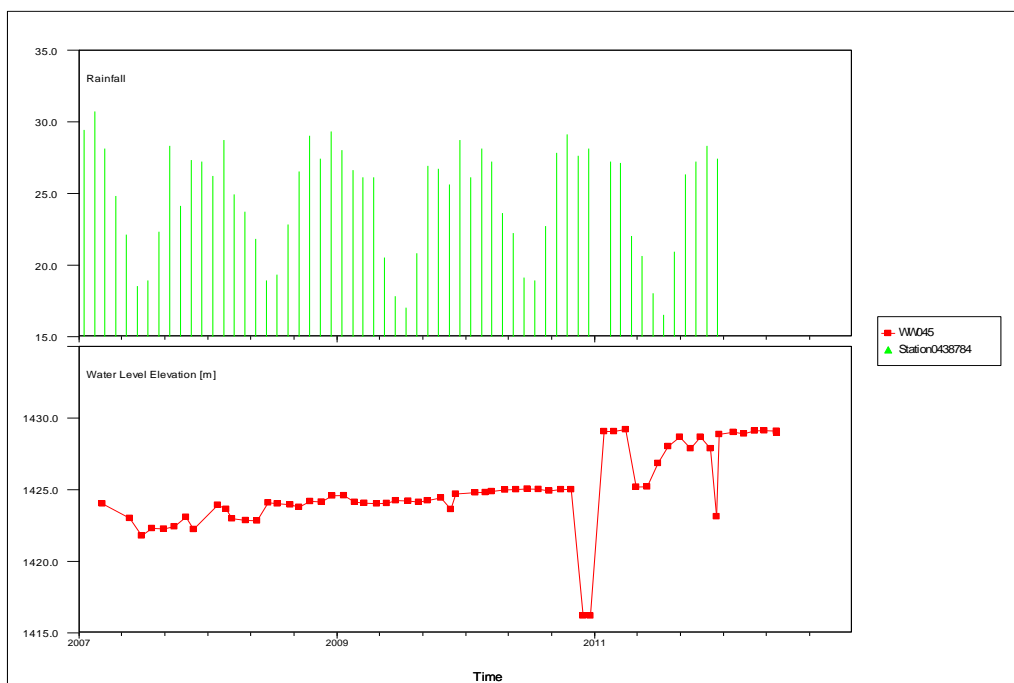


*Figure 6-10: Groundwater level depth and rainfall for borehole WW045 in the shallow aquifer system from 2007 to 2012.*

## 6.2 Groundwater levels for the intermediate aquifer system
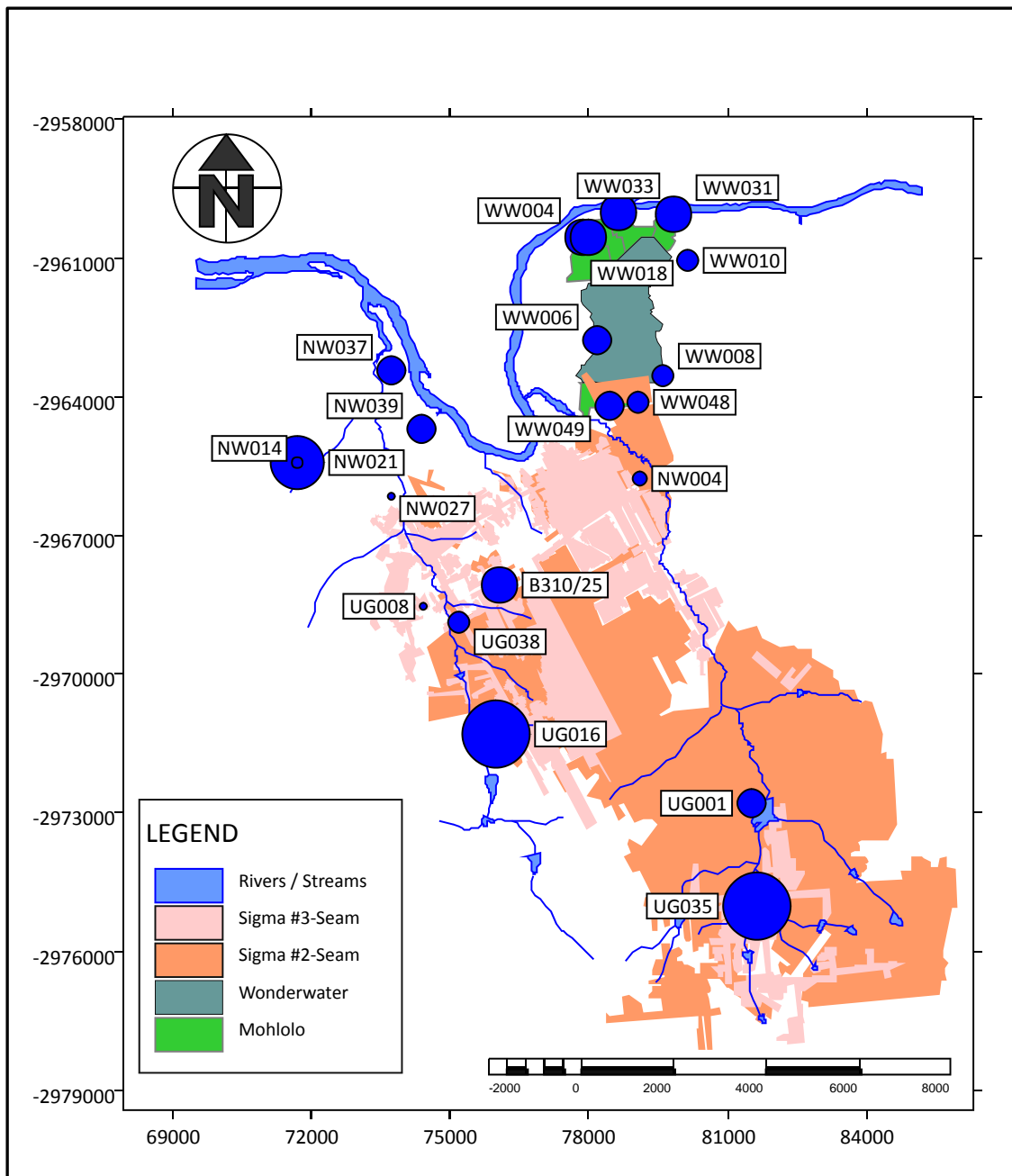


*Figure 6-11: Locality and proportional distribution of the water levels of boreholes in the intermediate aquifer system.*

A slow decrease in the water level depths of the intermediate aquifer system could be observed over time. This could be due to the complete filling of the mine void in 2007. After the mine void was filled, the water level started to stabilise in 2011 and it can be assumed that this system is reaching hydrodynamic equilibrium conditions.

Stabilization of the water levels can be observed in Figure 6-12 and Figure 6-14. The water level depth versus the rainfall can be viewed in Figure 6-16 and Figure 6-17. A definite trend between the rainfall and water level can be observed which could be due to the seasonal variation.
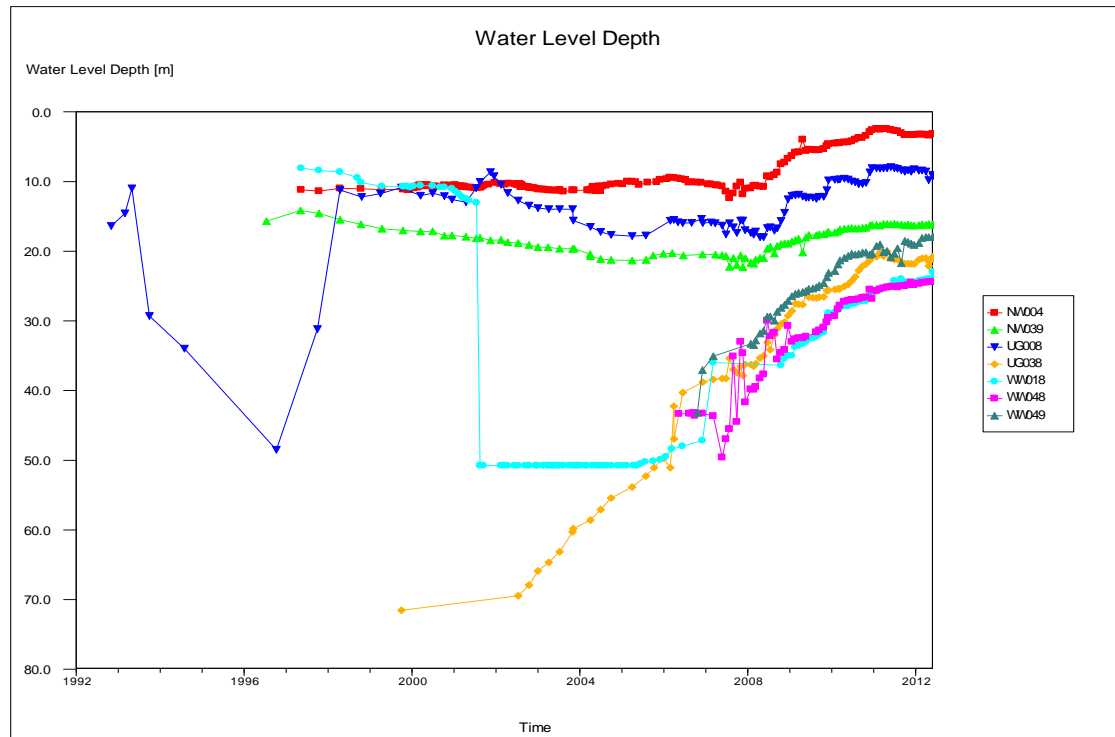


*Figure 6-12: Groundwater level depths for boreholes NW004, NW039, UG008, UG038, WW018, WW048 and WW049 in the intermediate aquifer system.*
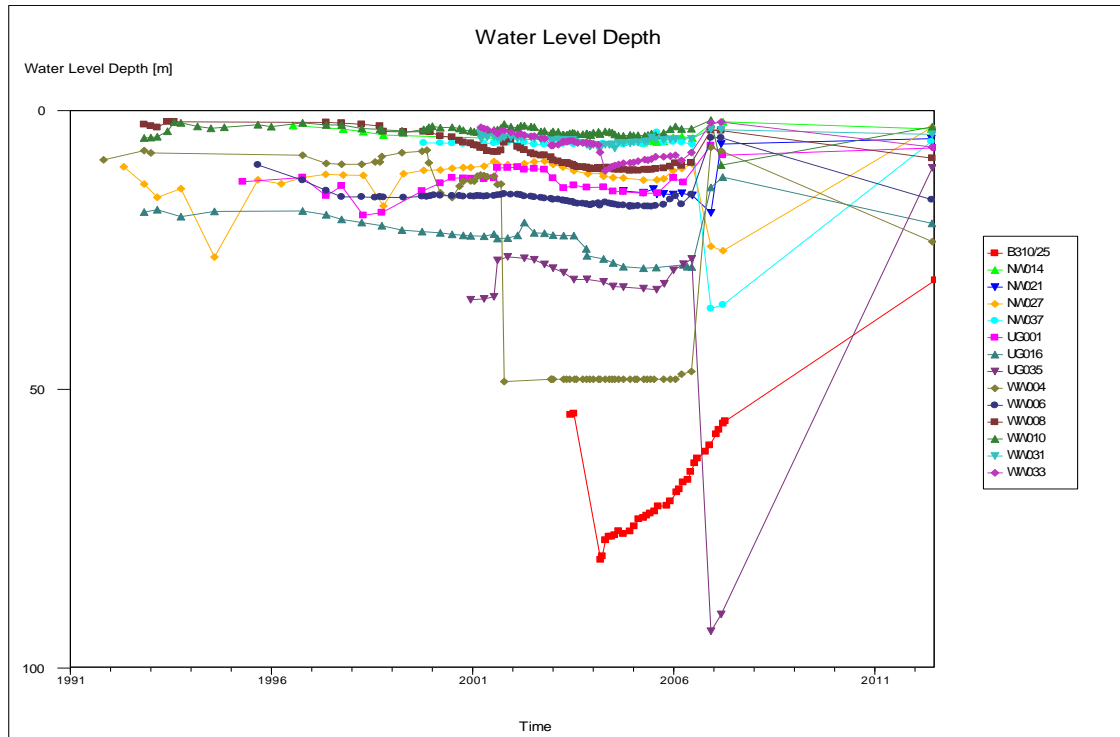
Figure 6-13: Groundwater level depths for boreholes B310/25, NW014, NW021, NW027, NW037, UG001, UG016, UG035, WW004, WW006, WW008, WW010, WW031 and WW033 in the intermediate aquifer system.
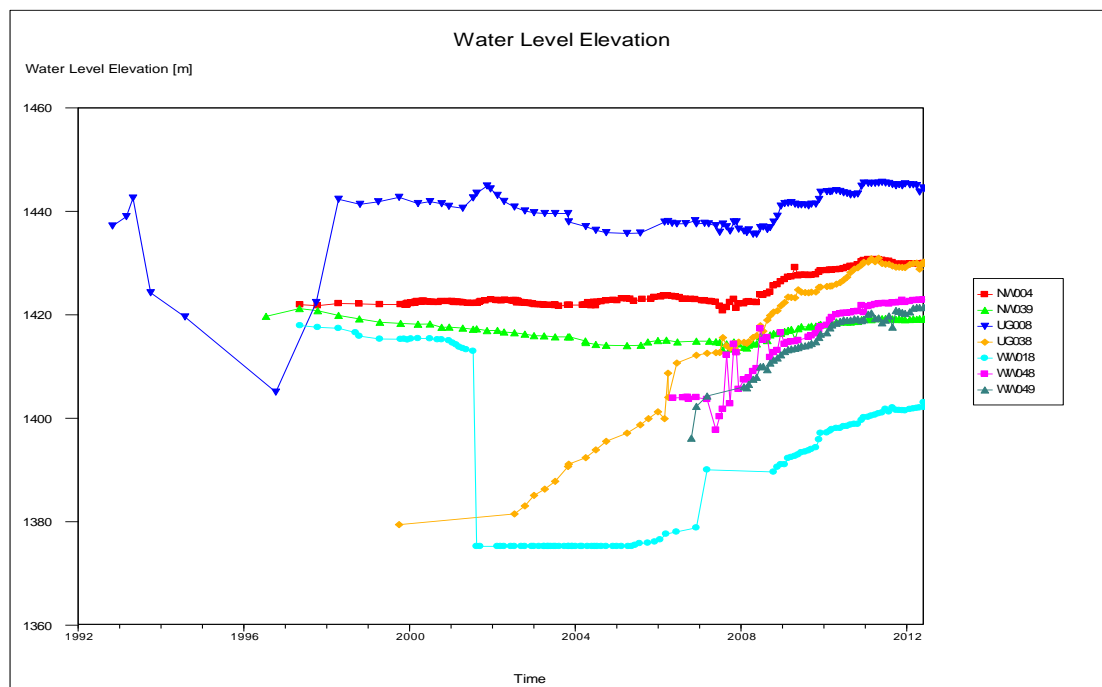


Figure 6-14: Water level elevations for boreholes NW004, NW039, UG008, UG038, WW018, WW048 and WW049 in the intermediate aquifer system.
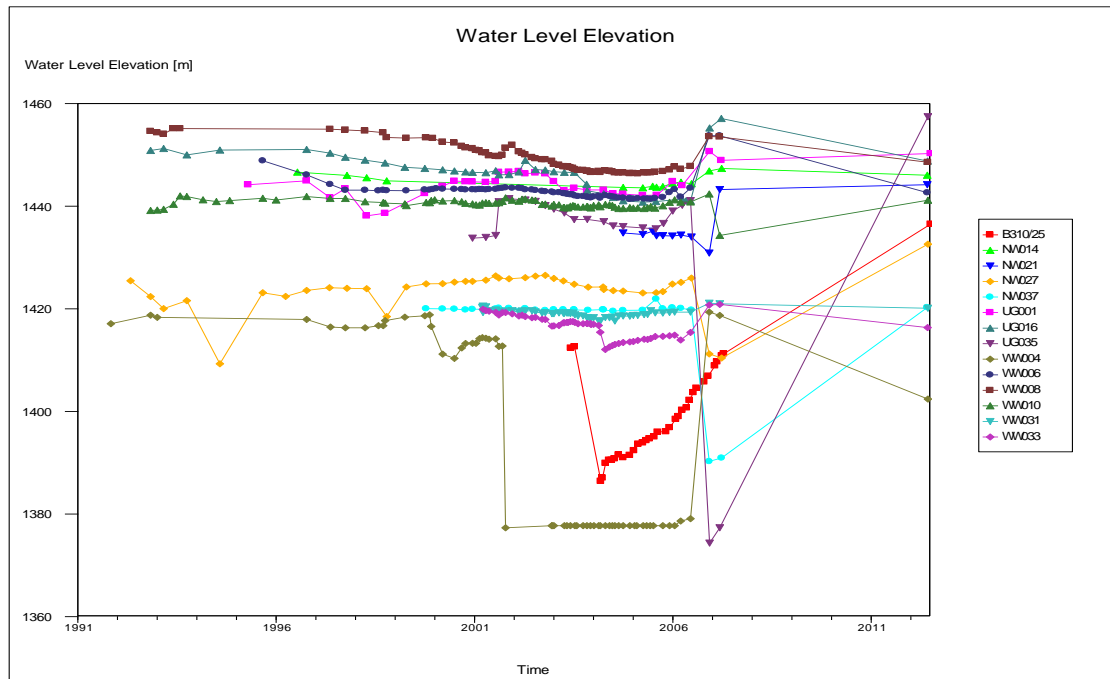
Figure 6-15: Water level elevations for boreholes B310/25, NW014, NW021, NW027, NW037, UG001, UG016, UG035, WW004, WW006, WW008, WW010, WW031 and WW033 in the intermediate aquifer system.
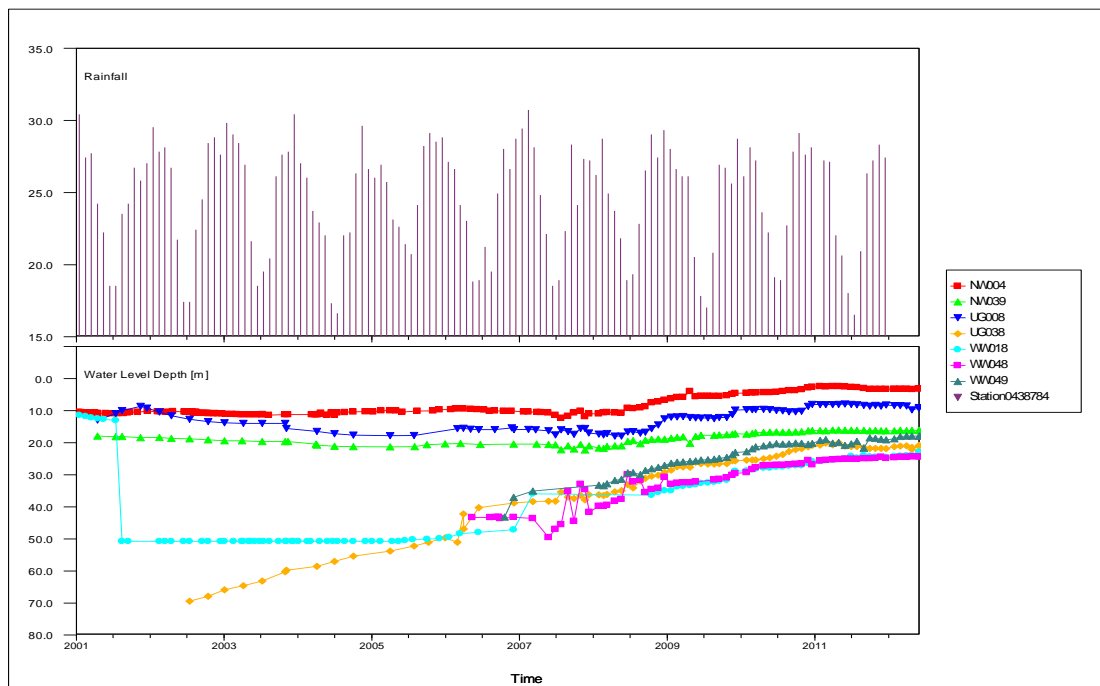


Figure 6-16: Water level depths and rainfall for boreholes NW004, NW039, UG008, UG038, WW018, WW048 and WW049 in the intermediate aquifer system from 2001 to 2012.
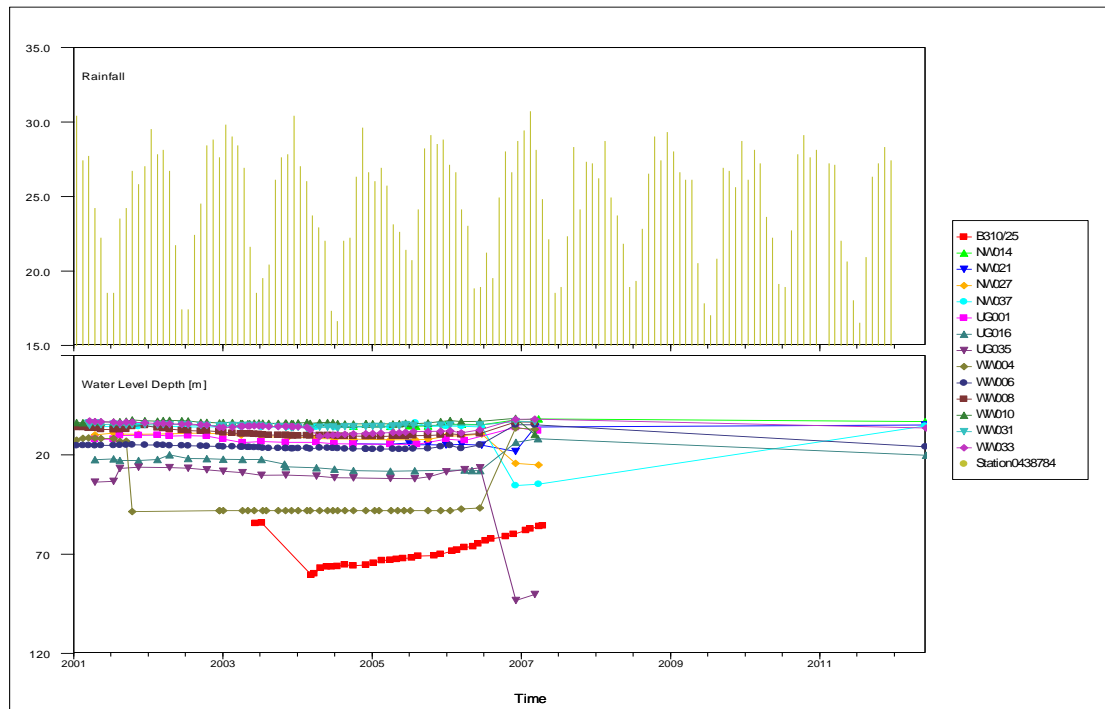
Figure 6-17:   Water level depths and rainfall for boreholes B310/25, NW014, NW021, NW027, NW037, UG001, UG016, UG035, WW004, WW006, WW008, WW010, WW031 and WW033 in the intermediate aquifer system from 2001 to 2012.
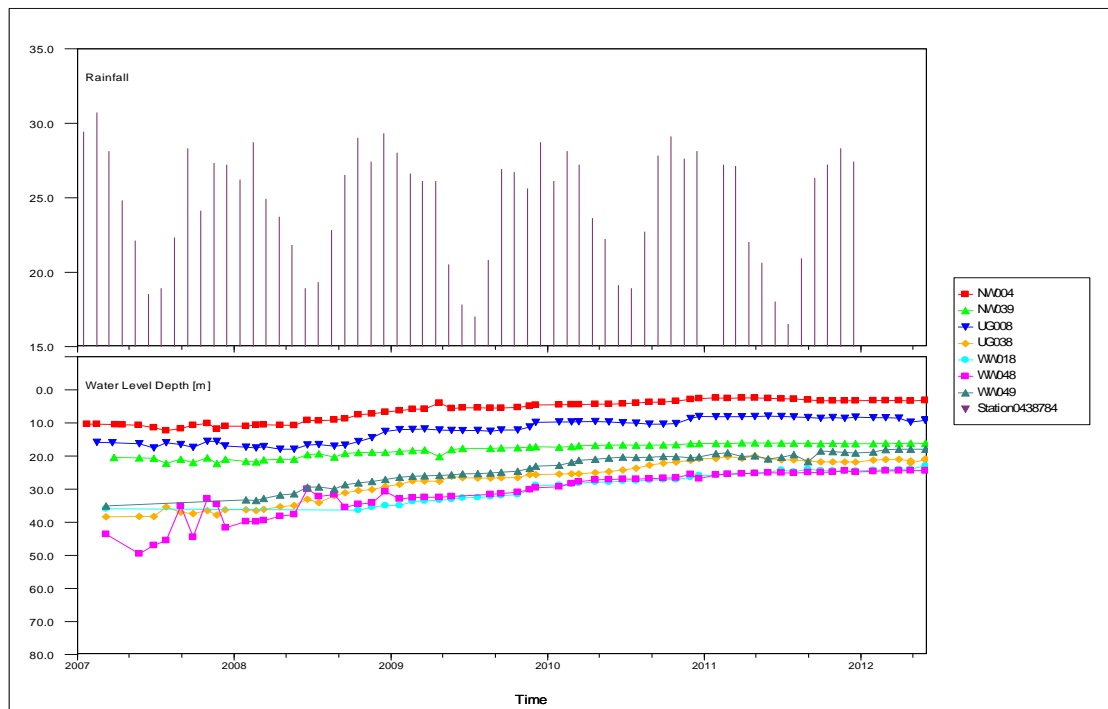


Figure 6-18:    Water level depths and rainfall for boreholes NW004, NW039, UG008, UG038, WW018, WW048 and WW049 in the intermediate aquifer system from 2007 to 2012.
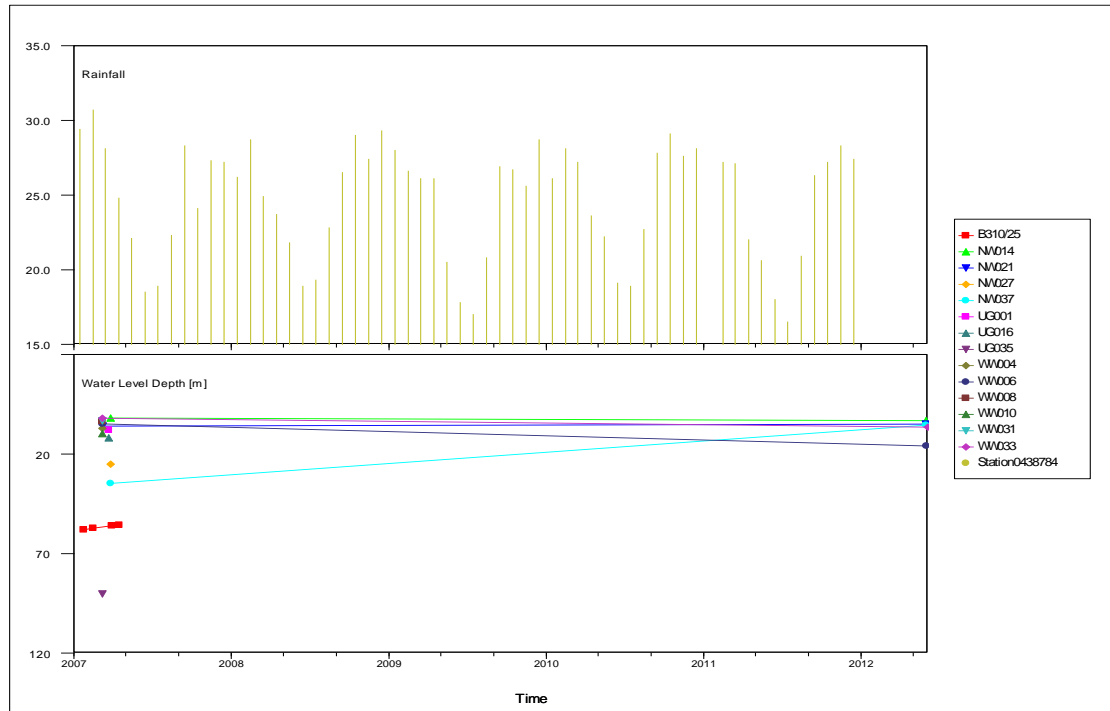
Figure 6-19: Water level depths and rainfall for boreholes B310/25, NW014, NW021, NW027, NW037, UG001, UG016, UG035, WW004, WW006, WW008, WW010, WW031 and WW033 from 2007 to 2012.

## 6.3   Groundwater levels for the deep aquifer system
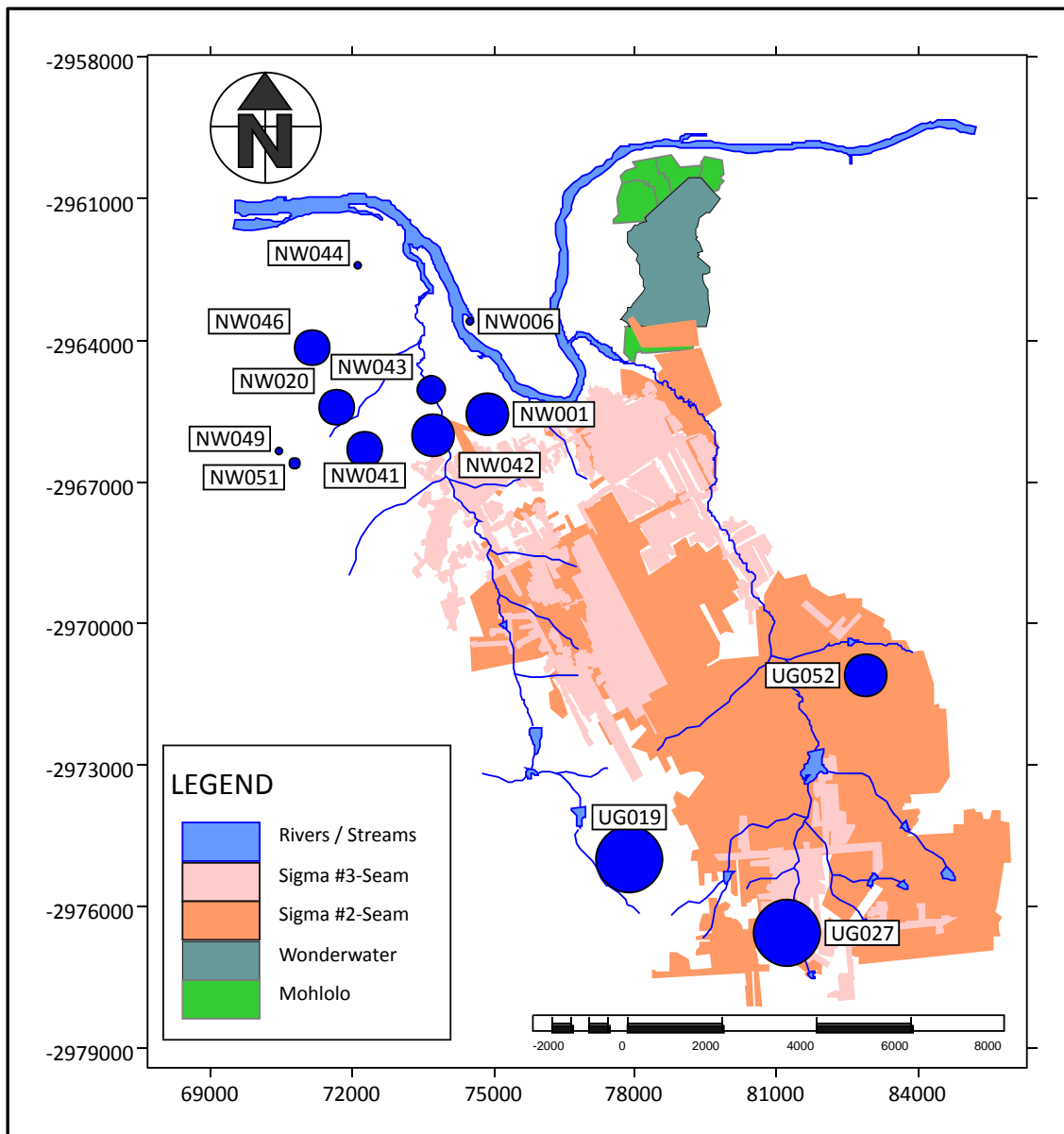


*Figure 6-20: Locality and proportional distribution of the water levels of boreholes in the deep aquifer system.*

In the time graphs (Figure 6-21, Figure 6-22, Figure 6-23 and Figure 6-24) water levels close to decant levels can be observed (borehole NW020).  The water levels do not appear to be fluctuating and should not pose any problems.  The boreholes with deep water levels (boreholes UG019, UG027, NW040 and NW044) indicated a rise in water level in the past, but this appears to be slowing down and stabilising.  It can be assumed that the deep aquifer system is reaching hydrodynamic equilibrium

conditions. The water level depth versus the rainfall can be viewed in Figure 6-25 and Figure 6-26 and seasonal variation due to rainfall can be observed in Figure 6-25 for the boreholes which displays shallower water levels. In Figure 6-26 no seasonal variation could be observed for the boreholes displaying deeper water levels.
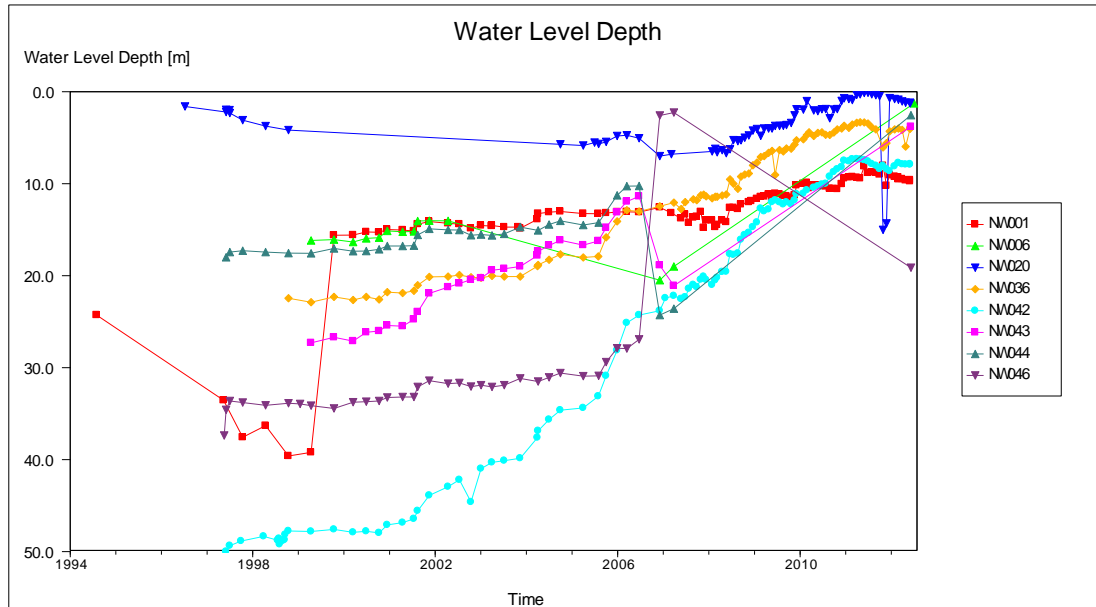


Figure 6-21: Groundwater level depths for boreholes NW001, NW006, NW020, NW036, NW042, NW043, NW044 and NW046 in the deep aquifer system.
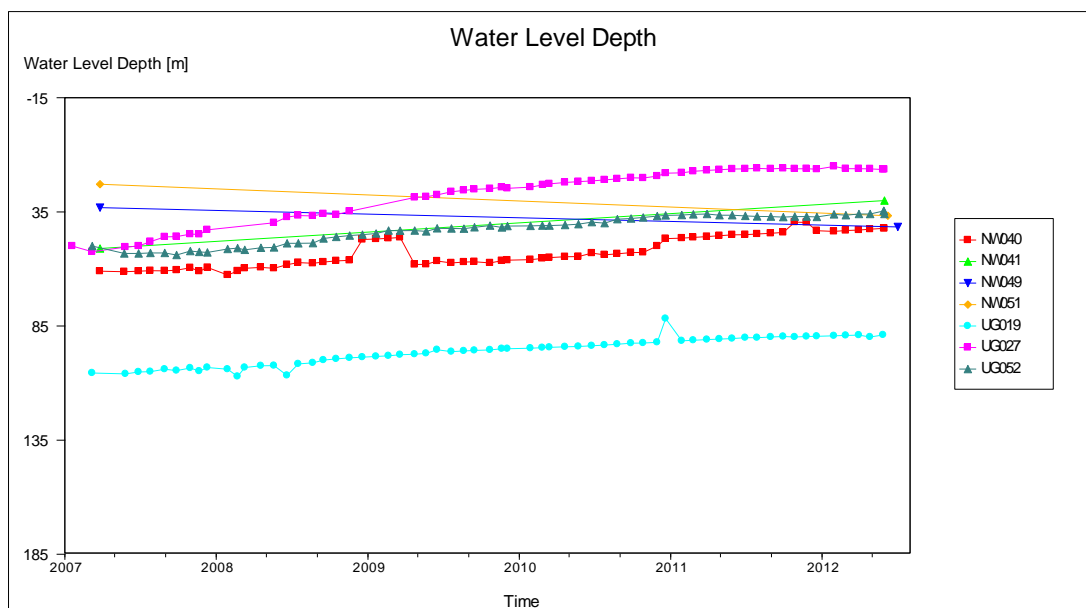


Figure 6-22: Groundwater level depths for boreholes NW040, NW041, NW049, NW051, UG019, UG027 and UG052 in the deep aquifer system.
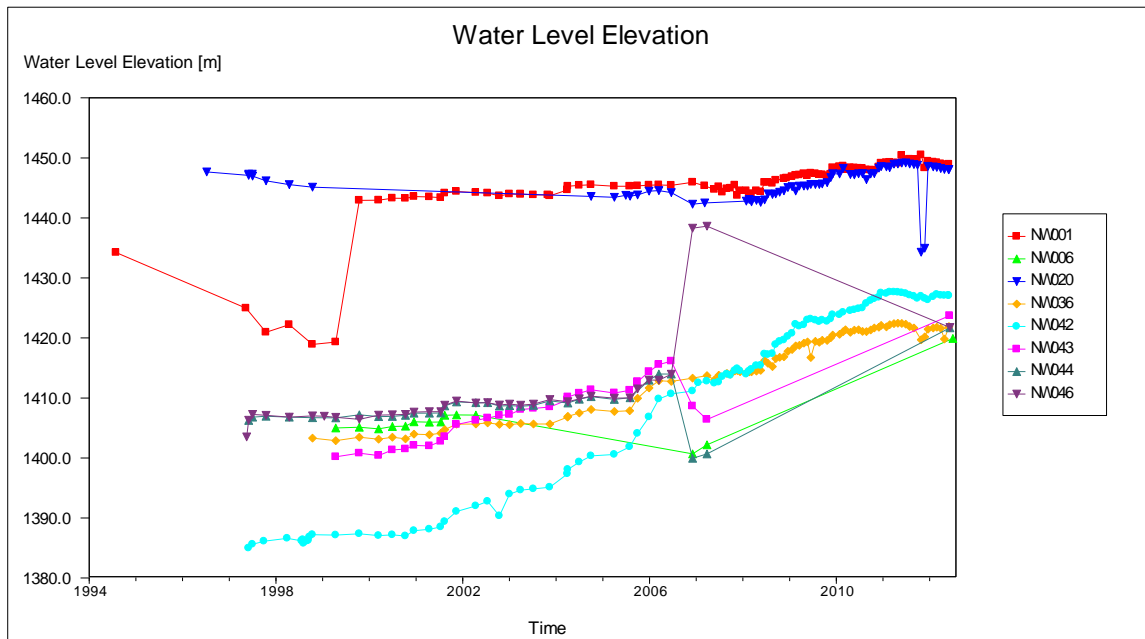
Figure 6-23: Groundwater level elevations for boreholes NW001, NW006, NW020, NW036, NW042, NW043, NW044 and NW046 in the deep aquifer system.
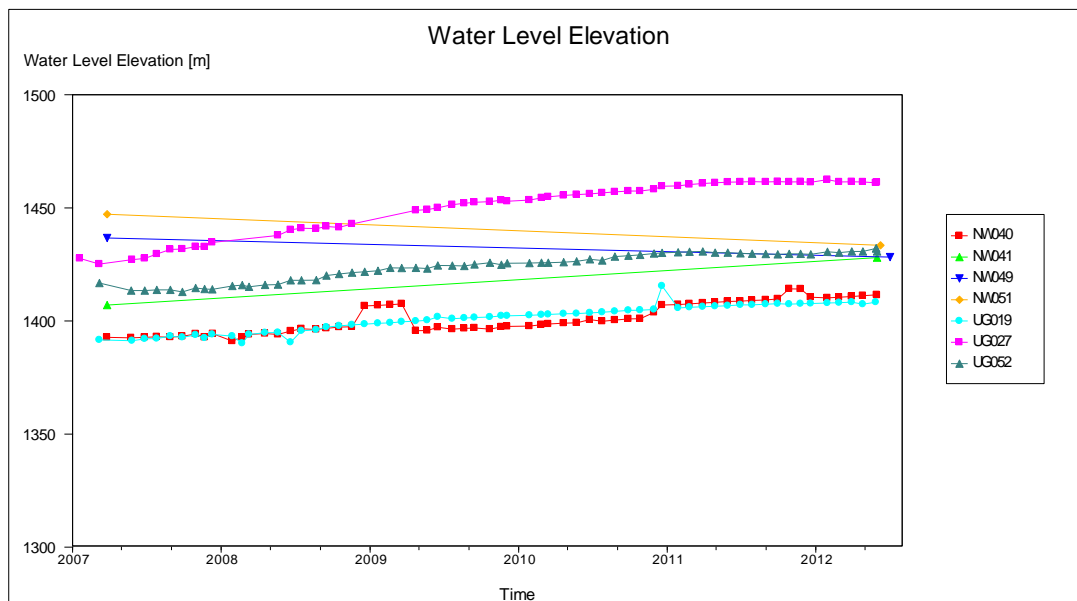


Figure 6-24: Groundwater level elevations for boreholes NW040, NW041, NW049, NW051, UG019, UG027 and UG052 in the deep aquifer system.

6-17
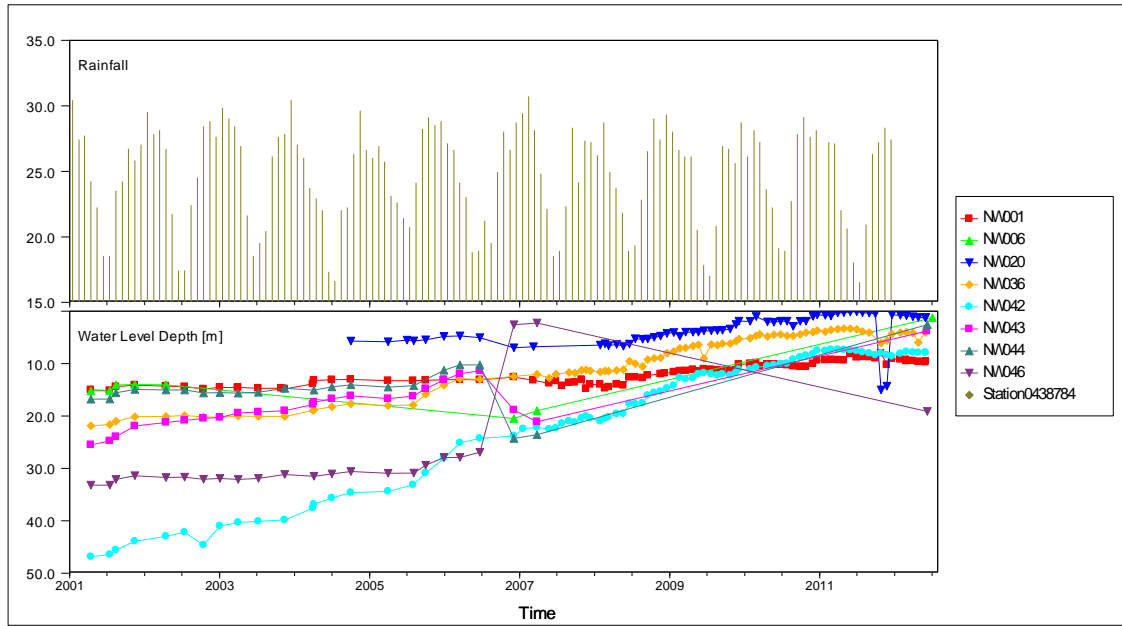
Figure 6-25: Groundwater level depths and rainfall for boreholes NW001, NW006, NW020, NW036, NW042, NW043, NW044 and NW046 in the deep aquifer system from 2001 to 2012.
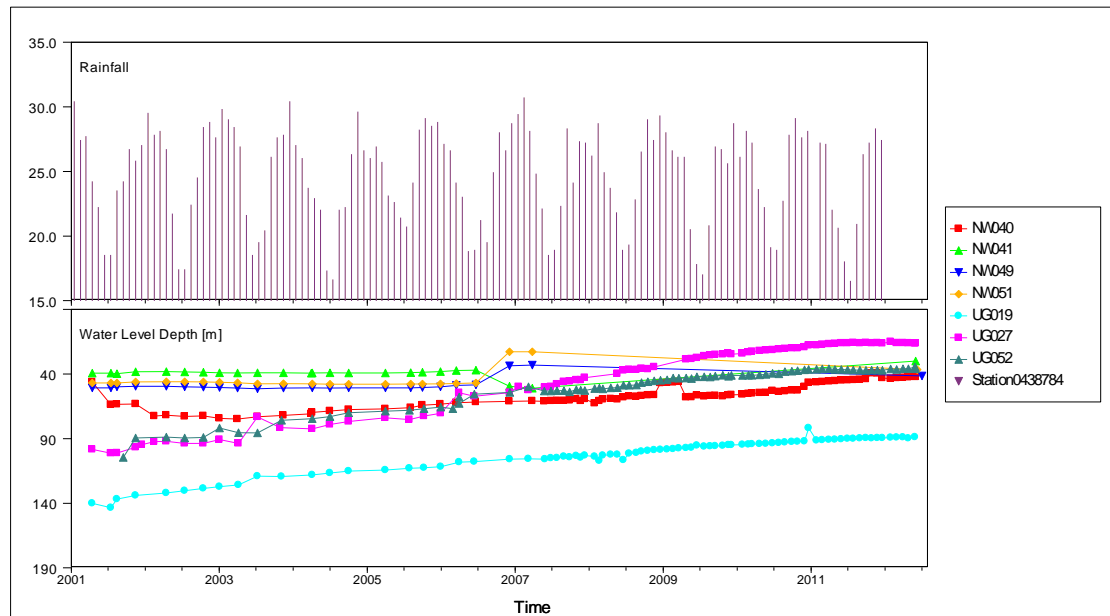


Figure 6-26: Groundwater level depths and rainfall for boreholes NW040, NW041, NW049, NW051, UG019, UG027 and UG052 in the deep aquifer system from 2001 to 2012.
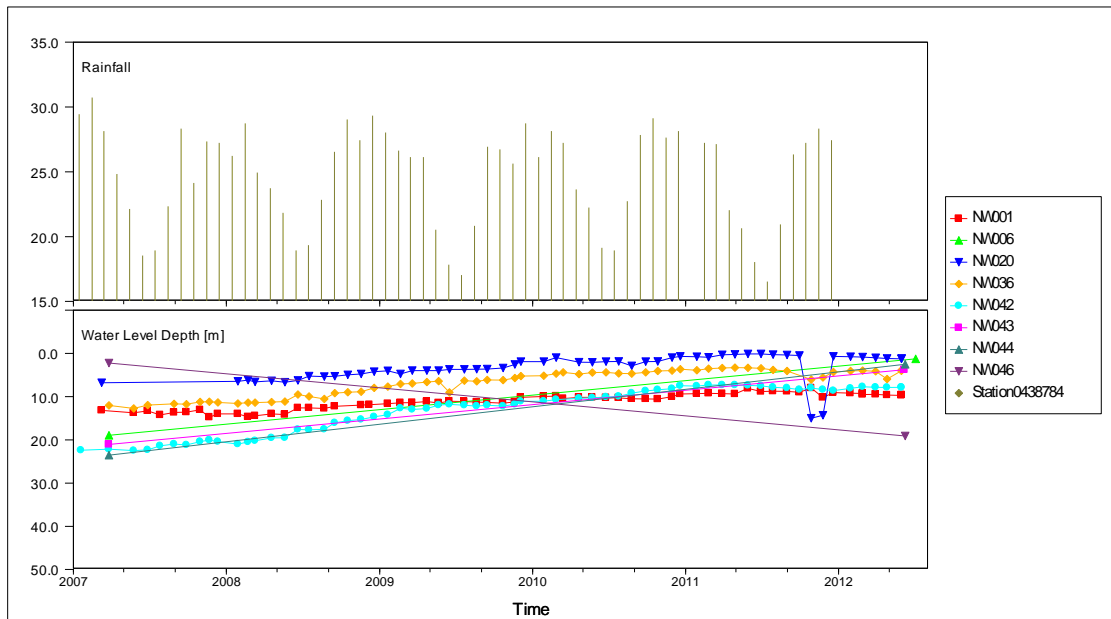
Figure 6-27: Groundwater level depths and rainfall for boreholes NW001, NW006, NW020, NW036, NW042, NW043, NW044 and NW046 in the deep aquifer system from 2007 to 2012.
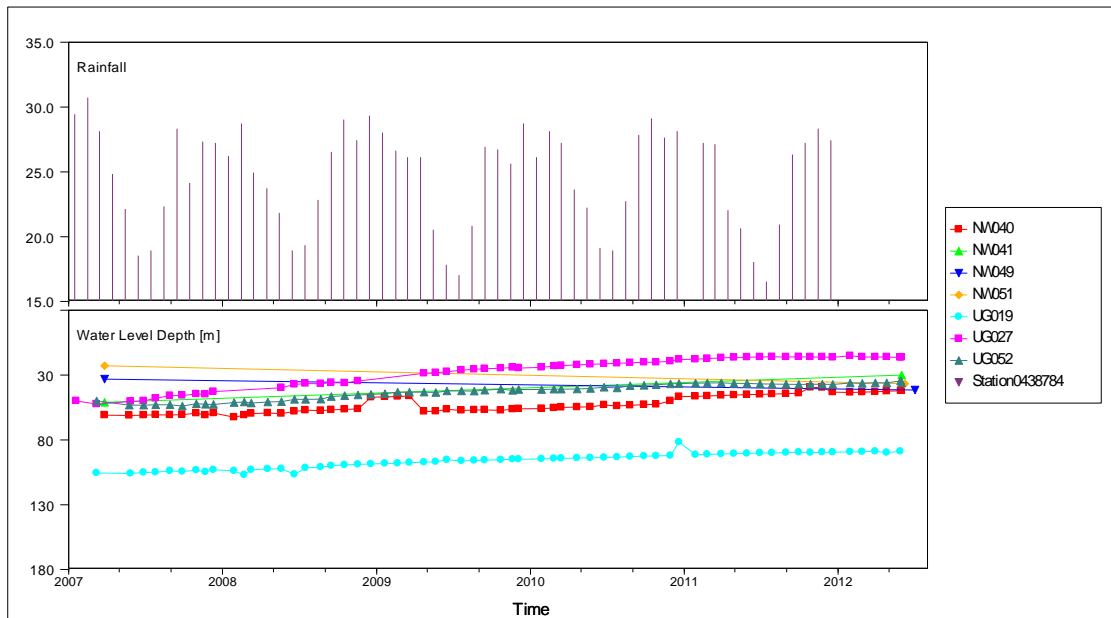


Figure 6-28: Groundwater level depths and rainfall for boreholes NW040, NW041, NW049, NW051, UG019, UG027 and UG052 in the deep aquifer system from 2007 to 2012.

## 6.4   Groundwater levels for the disturbed aquifer system
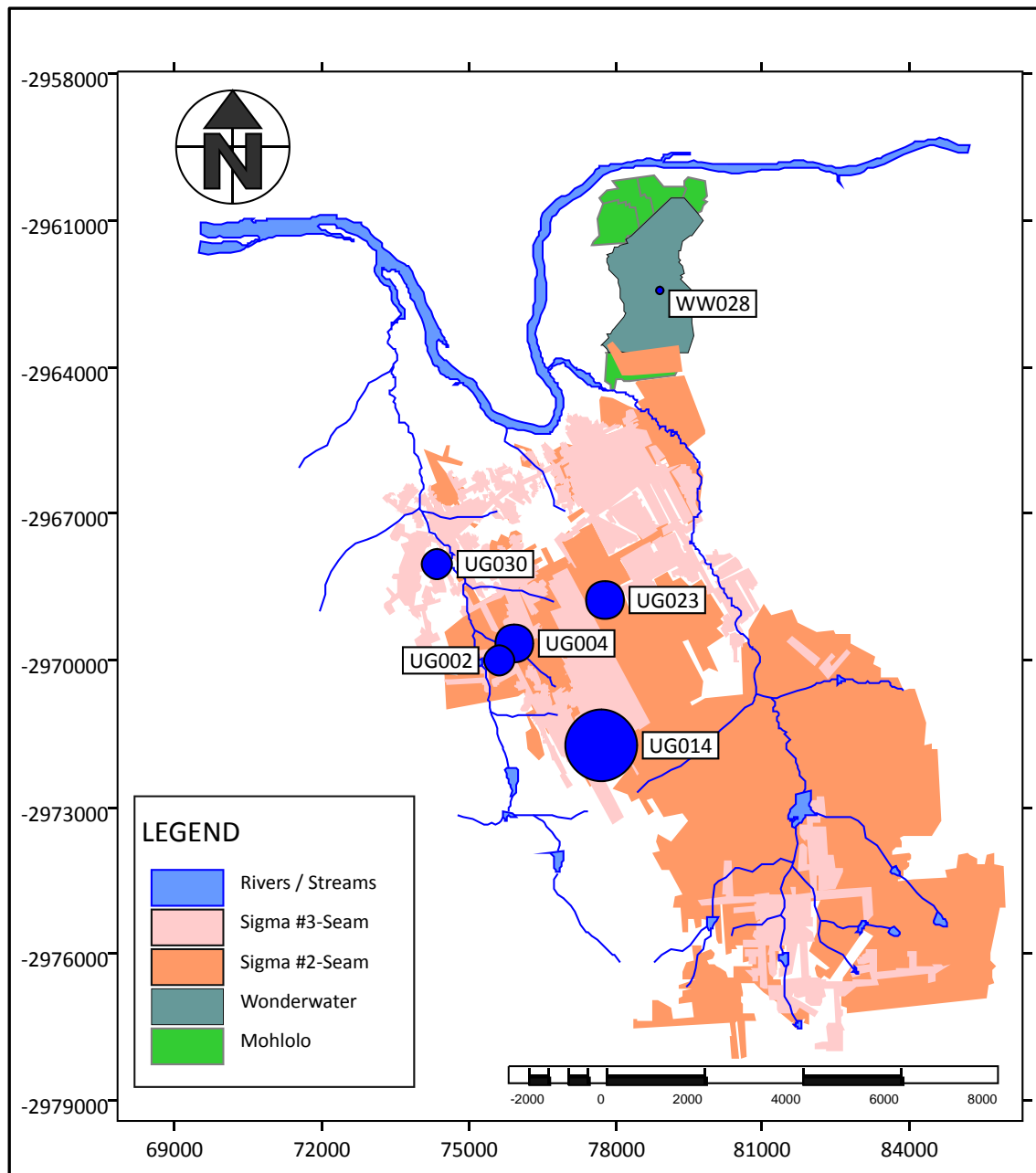


*Figure 6-29: Locality and proportional distribution of the water levels of the boreholes in the disturbed aquifer system.*

The water levels of the boreholes in the disturbed aquifer system (Figure 6-30, Figure 6-31, Figure 6-32 and Figure 6-33) appears to have had very erratic behaviour over time.  This could be attributed to the undermining in the area.  The water level depth versus the rainfall can be viewed in Figure 6-34 and Figure 6-35 and borehole WW028

(Figure 6-34), which has much shallower water levels than the other boreholes and appears to show a seasonal variation in the water levels.
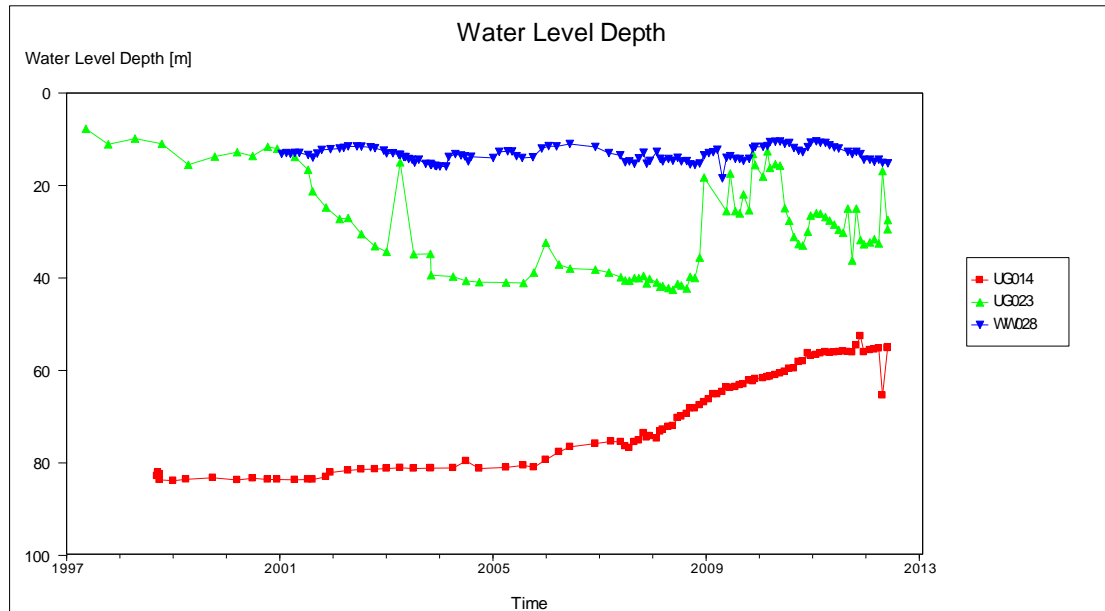


Figure 6-30: Groundwater level depths for boreholes UG014, UG023 and WW028 in the disturbed aquifer system.
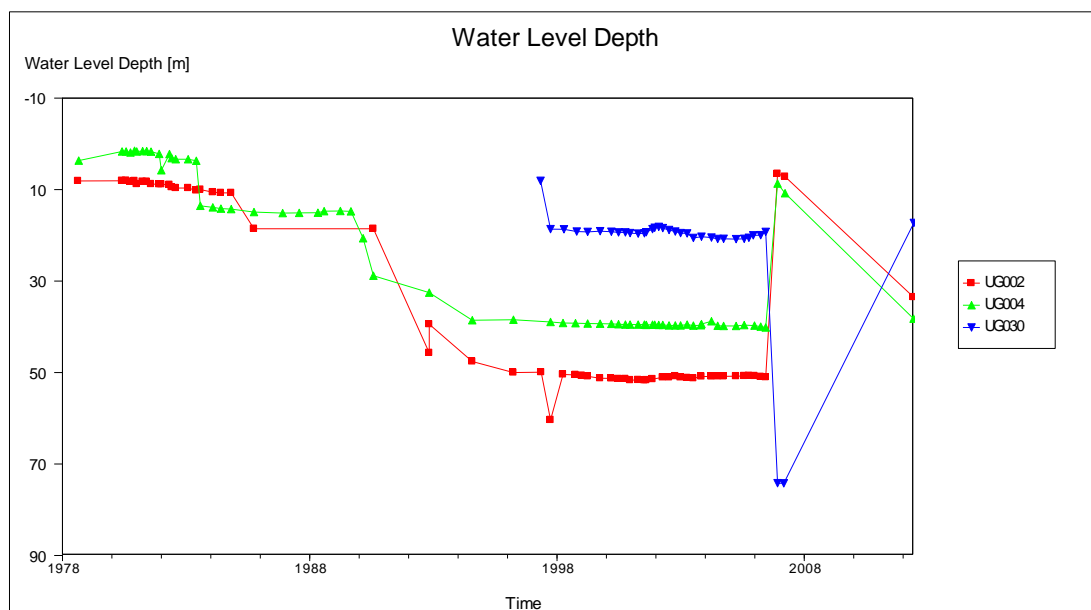


Figure 6-31: Groundwater level depths for boreholes UG002, UG004 and UG030 in the disturbed aquifer system.
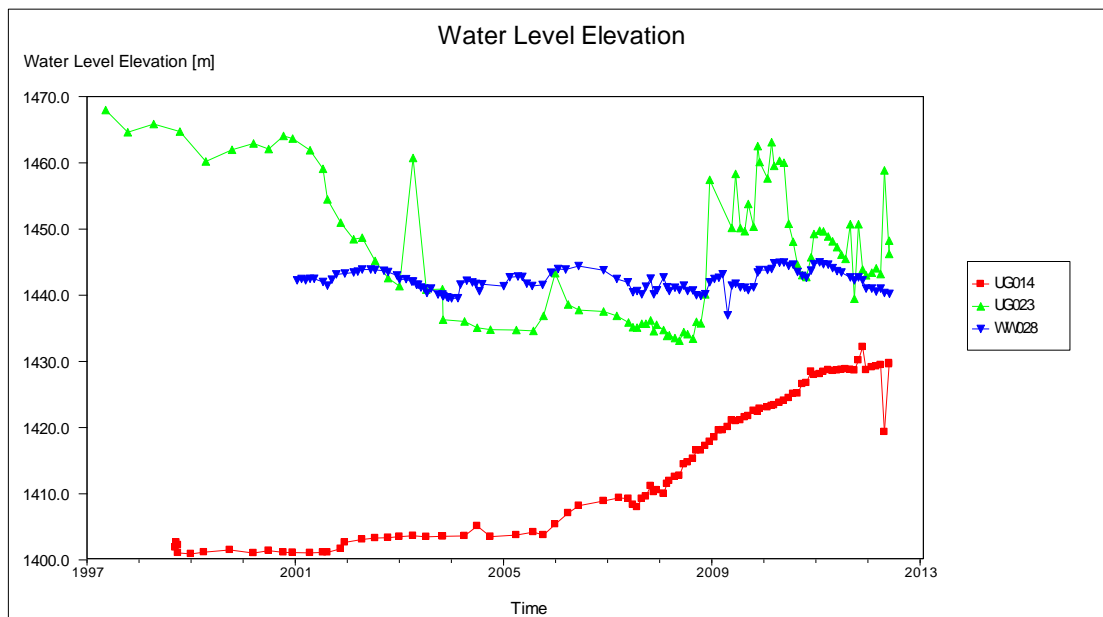
Figure 6-32: Groundwater level elevations for boreholes UG014, UG023 and WW028 in the disturbed aquifer system.
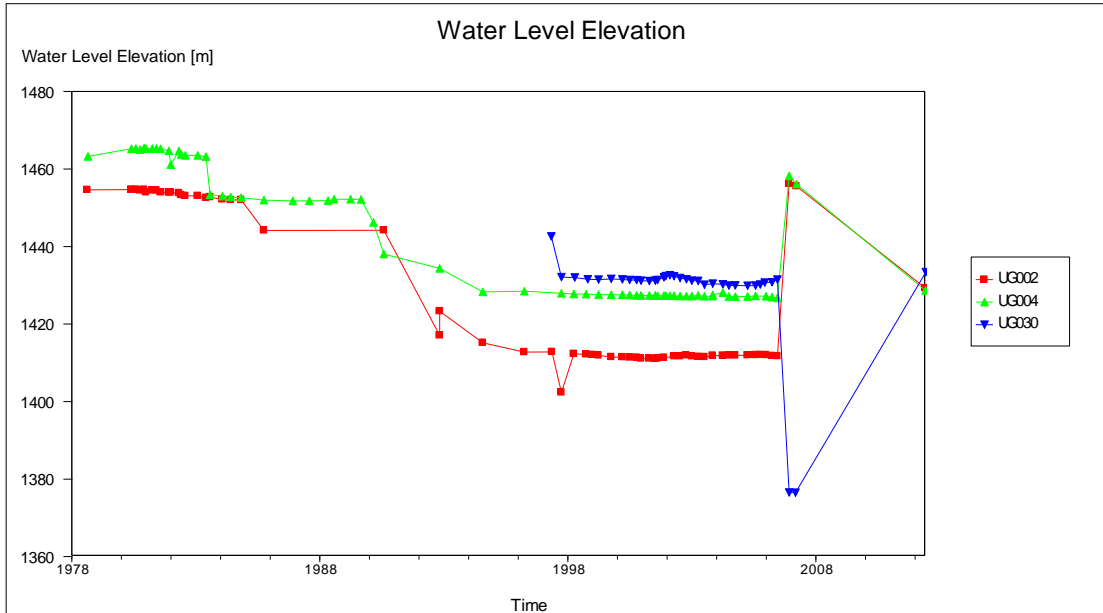


Figure 6-33: Groundwater level elevations for boreholes UG002, UG004 and UG030 in the disturbed aquifer system.
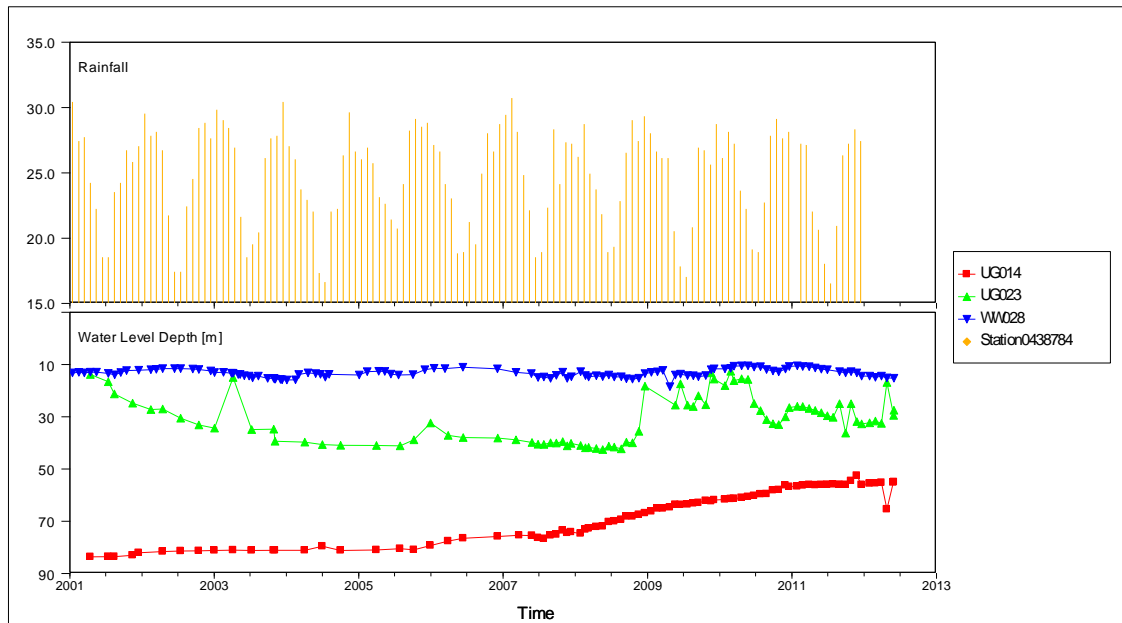
*Figure 6-34: Groundwater level depths and rainfall for boreholes UG014, UG023 and WW028 in the disturbed aquifer system from 2001 to 2012.*
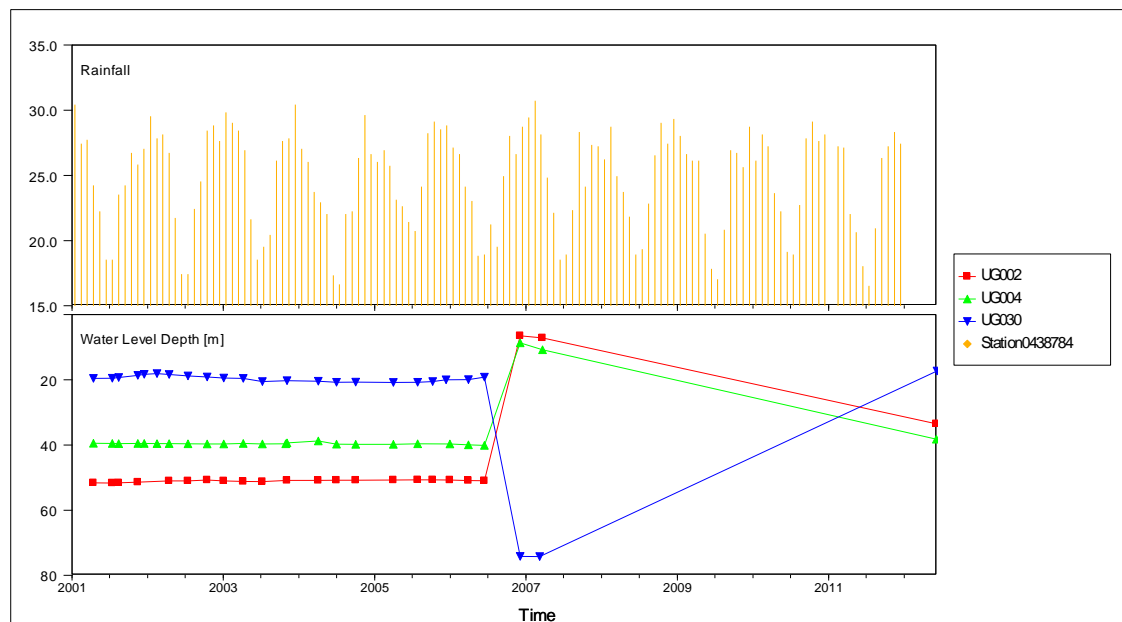


*Figure 6-35: Groundwater level depths and rainfall for boreholes UG002, UG004 and UG030 in the disturbed aquifer system from 2001 to 2012.*
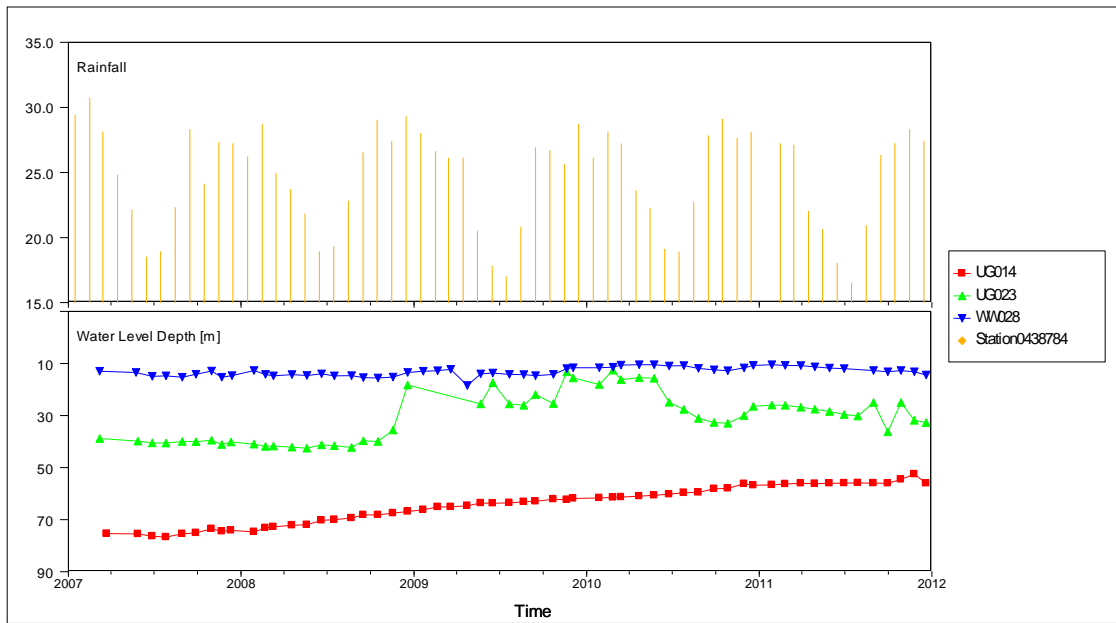
*Figure 6-36: Groundwater level depths and rainfall for boreholes UG014, UG023 and WW028 in the disturbed aquifer system from 2007 to 2012.*
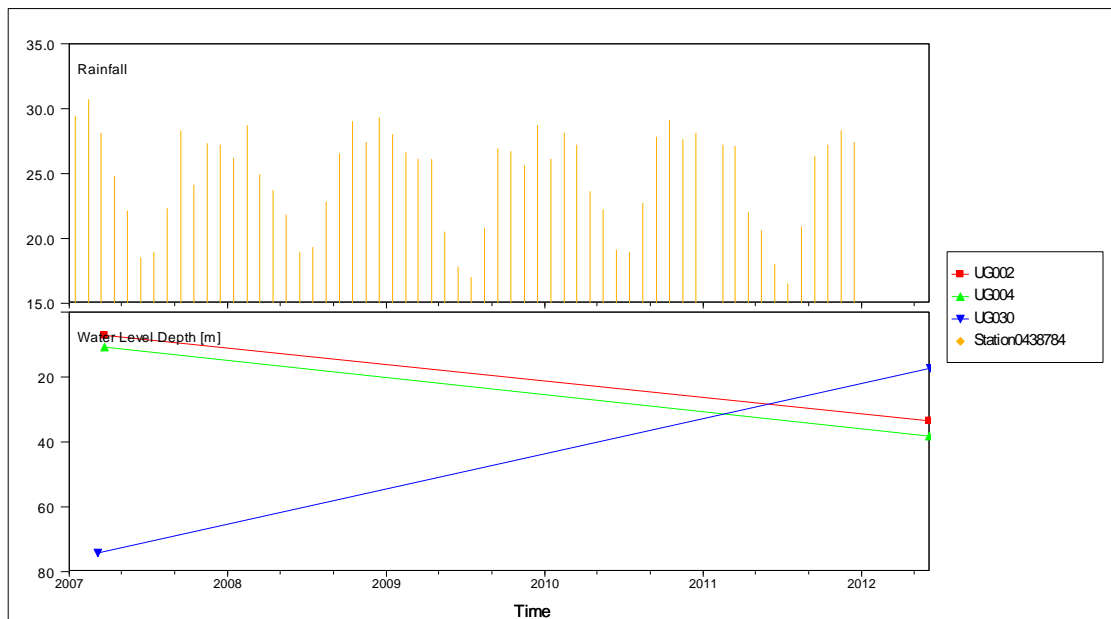


*Figure 6-37: Groundwater level depths and rainfall for boreholes UG002, UG004 and UG030 in the disturbed aquifer system from 2007 to 2012.*

## 6.5  Groundwater levels for the mine aquifer system
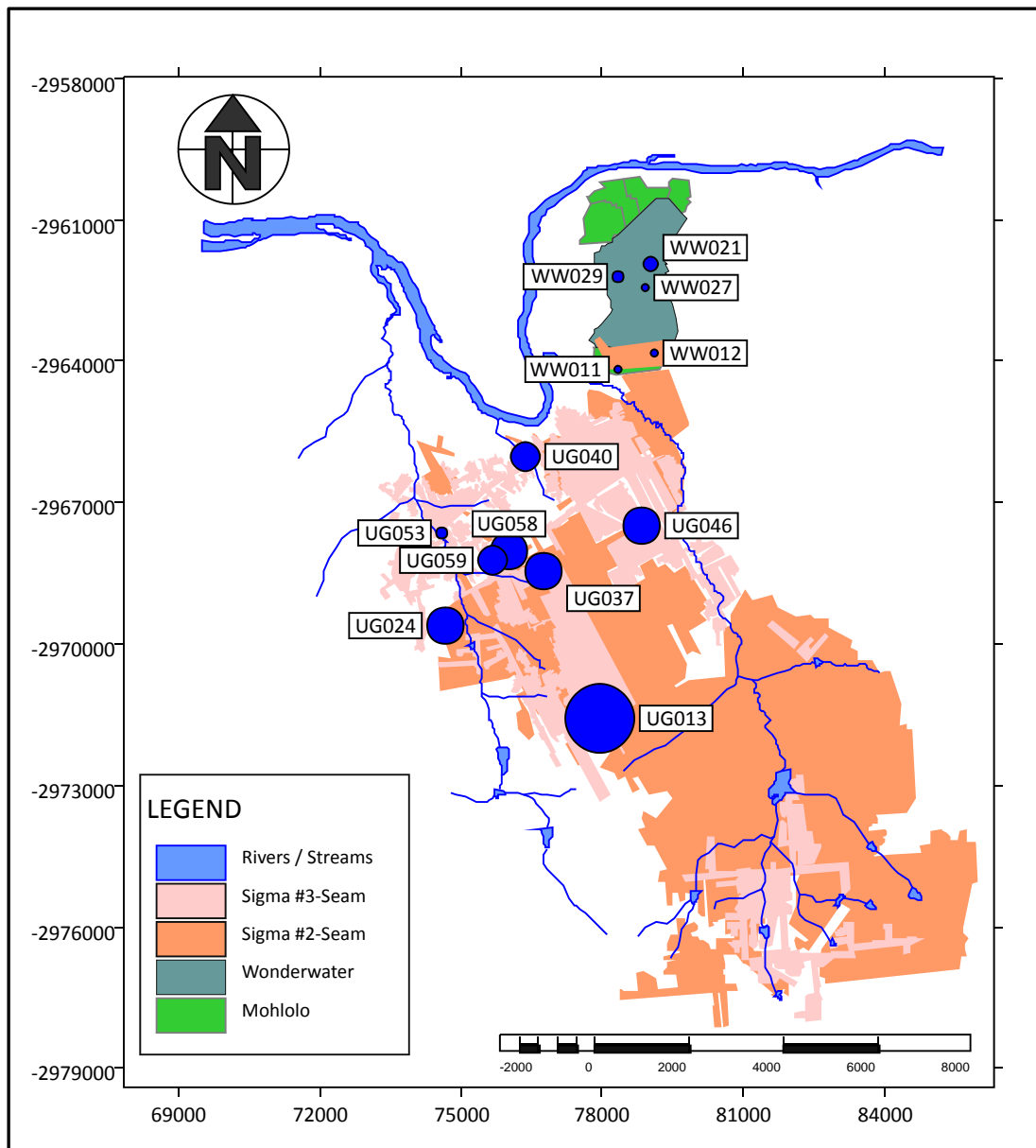


*Figure 6-38: Locality and proportional distribution of the water levels of the boreholes in the mine aquifer system.*

The water level time graphs for Sigma underground (boreholes UG013, UG024, UG037, UG040, UG046, UG053, UG058 and UG059) and Wonderwater (boreholes WW011, WW012, WW021, WW027 and WW029) can be viewed in Figure 6-39, Figure 6-40, Figure 6-41 and Figure 6-42.  The groundwater levels for Sigma underground have shown a steep rise in the past and this can be due to the flooding of the

underground mine. The water levels for Wonderwater have shown a steep rise with time for boreholes WW027 and WW029 and a gentle rise for borehole WW021. The water levels of borehole WW027 (Figure 6-40) shows very erratic behaviour between 2005 and 2009 and this can be due to rehabilitation and backfilling of the strip mine. The water level depth versus the rainfall graph can be viewed in Figure 6-43 and Figure 6-44. Boreholes UG053, UG040, UG046, UG013, UG058 and WW027 all appear to show variation in water levels with the rainfall seasons as the mine was filling up over time.
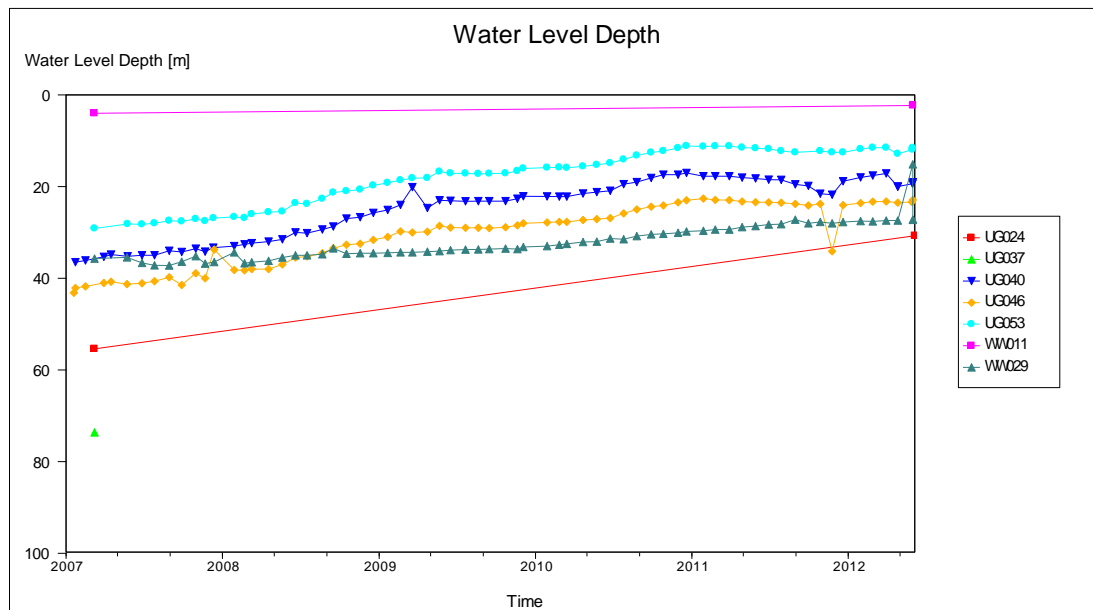


*Figure 6-39: Groundwater level depths of boreholes UG024, UG037, UG040, UG046, UG053, WW011 and WW029 in the mine aquifer system.*
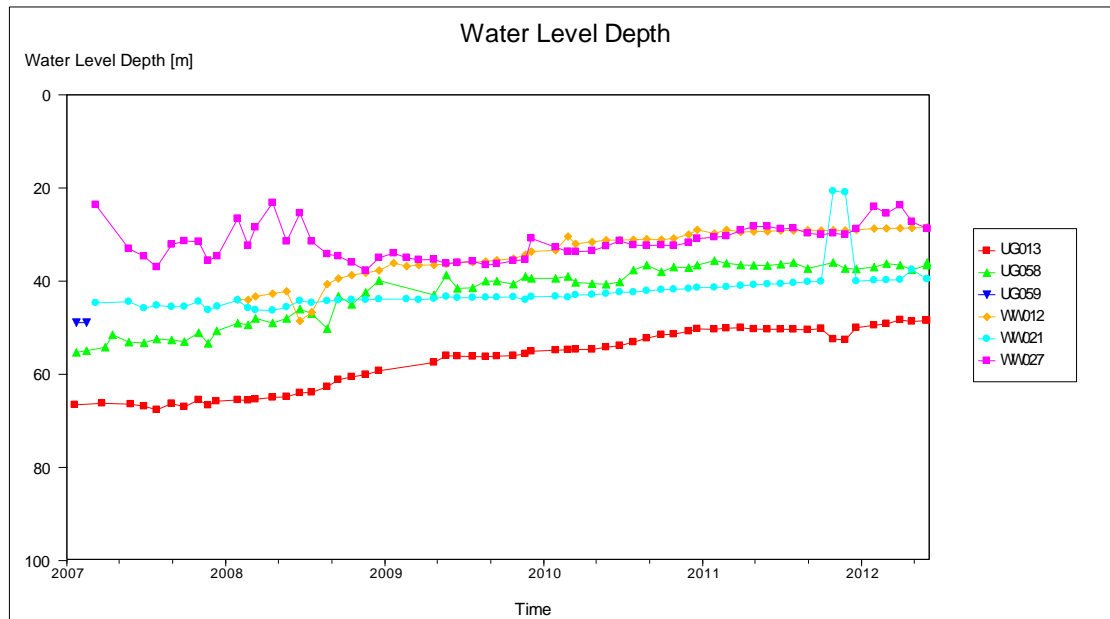
Figure 6-40: Groundwater level depths of boreholes UG013, UG058, UG059, WW012, WW021 and WW027 in the mine aquifer system.
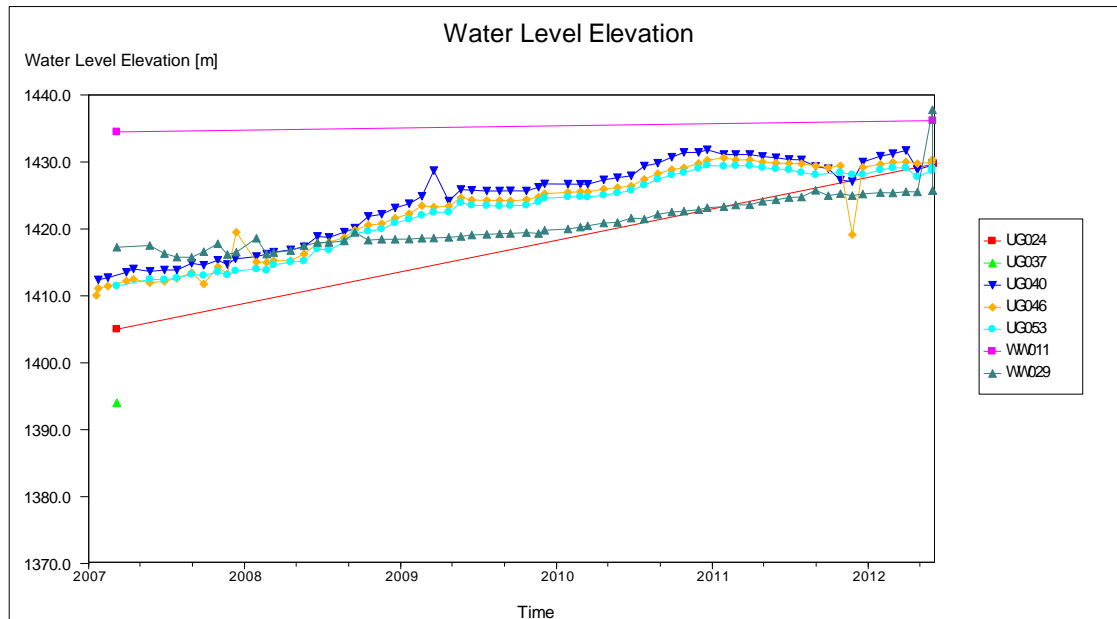


Figure 6-41: Groundwater level elevations of boreholes UG024, UG037, UG040, UG046, UG053, WW011 and WW029 in the mine aquifer system.
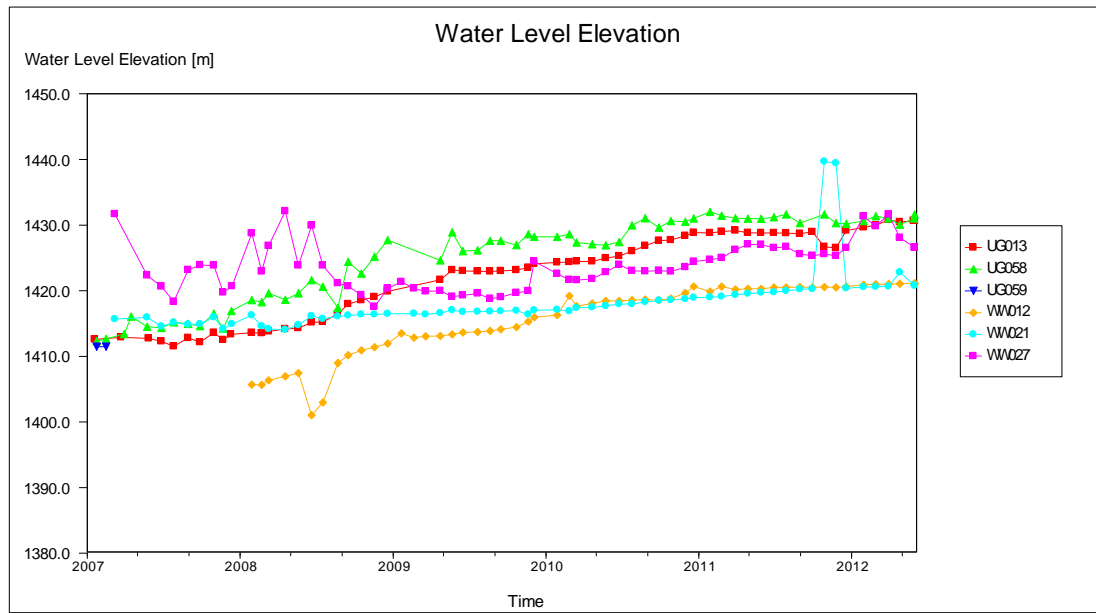
Figure 6-42: Groundwater level elevations of boreholes UG013, UG058, UG059, WW012, WW021 and WW027 in the mine aquifer system.
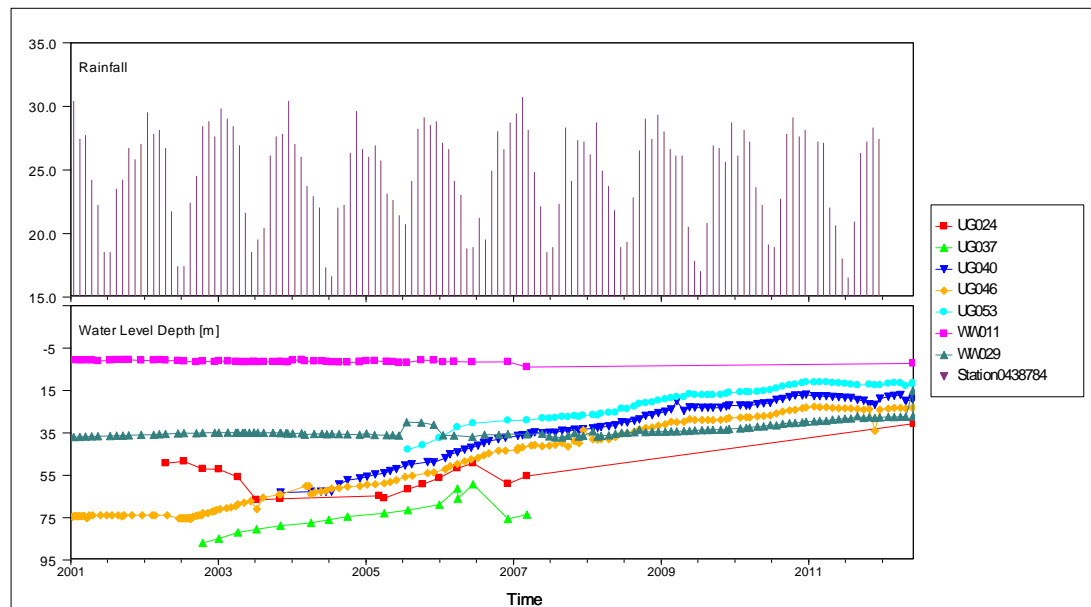


Figure 6-43: Groundwater level depths and rainfall for boreholes UG024, UG037, UG040, UG046, UG053, WW011 and WW029 in the mine aquifer system from 2001 to 2012.
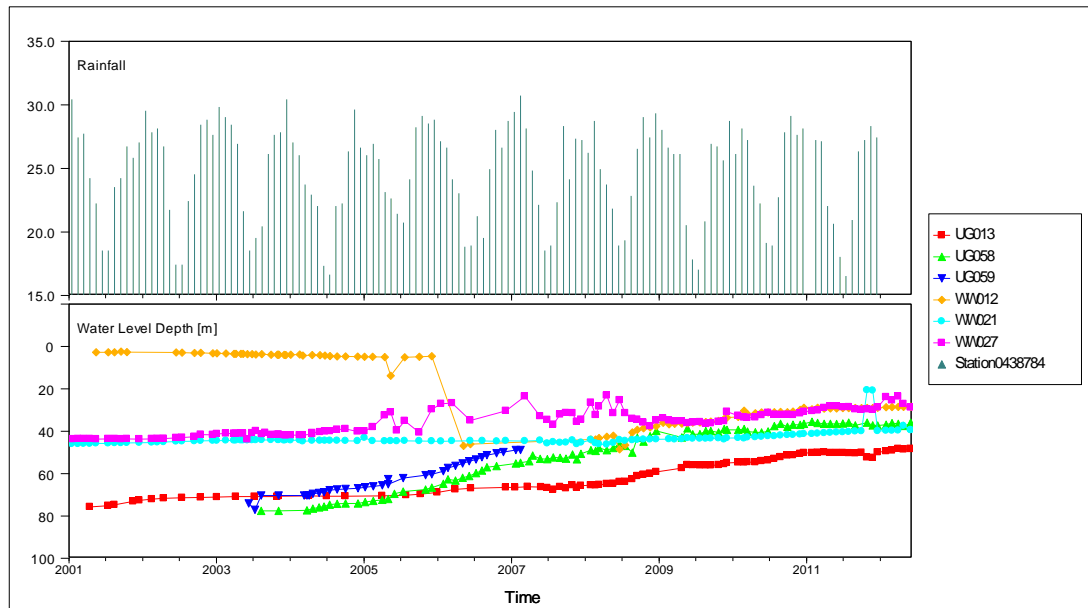
*Figure 6-44: Groundwater level depths and rainfall for boreholes UG013, UG058, UG059, WW012, WW021 and WW027in the mine aquifer system from 2001 to 2012.*
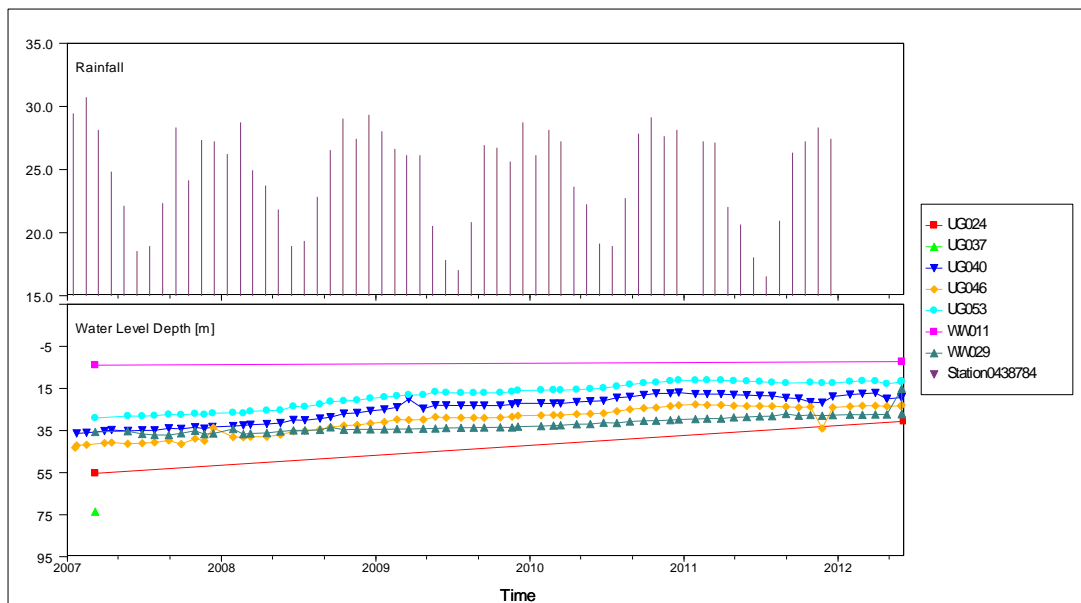


*Figure 6-45: Groundwater level depths and rainfall for boreholes UG024, UG037, UG040, UG046, UG053, WW011 and WW029 in the mine aquifer system from 2007 to 2012.*
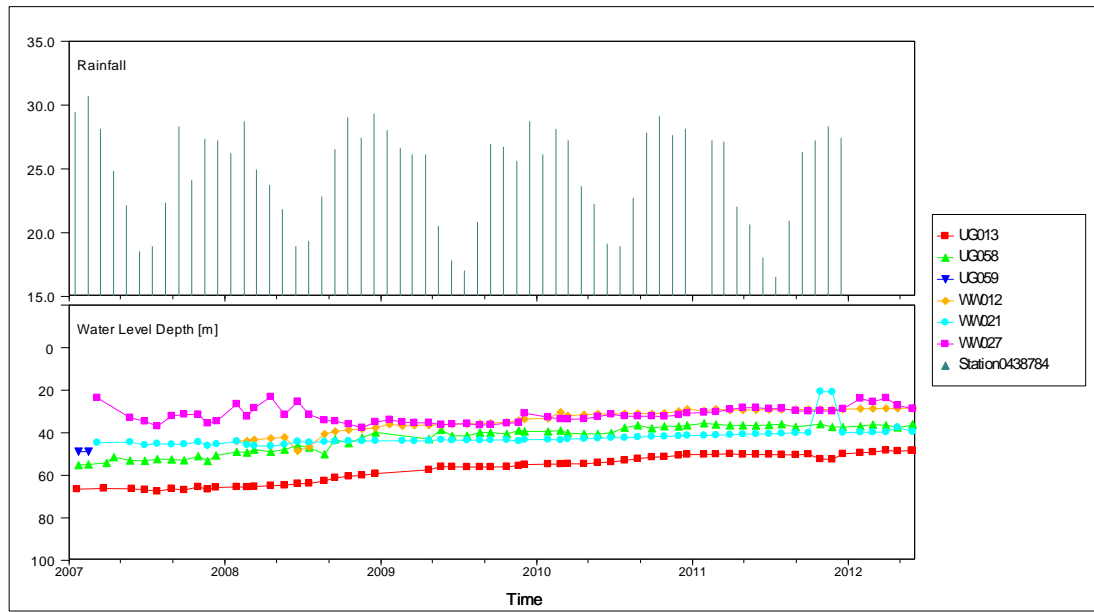
Figure 6-46: Groundwater level depths and rainfall for boreholes UG013, UG058, UG059, WW012, WW021 and WW027 in the mine aquifer system from 2007 to 2012.

## 6.6 Groundwater levels for the boreholes in the ashfill
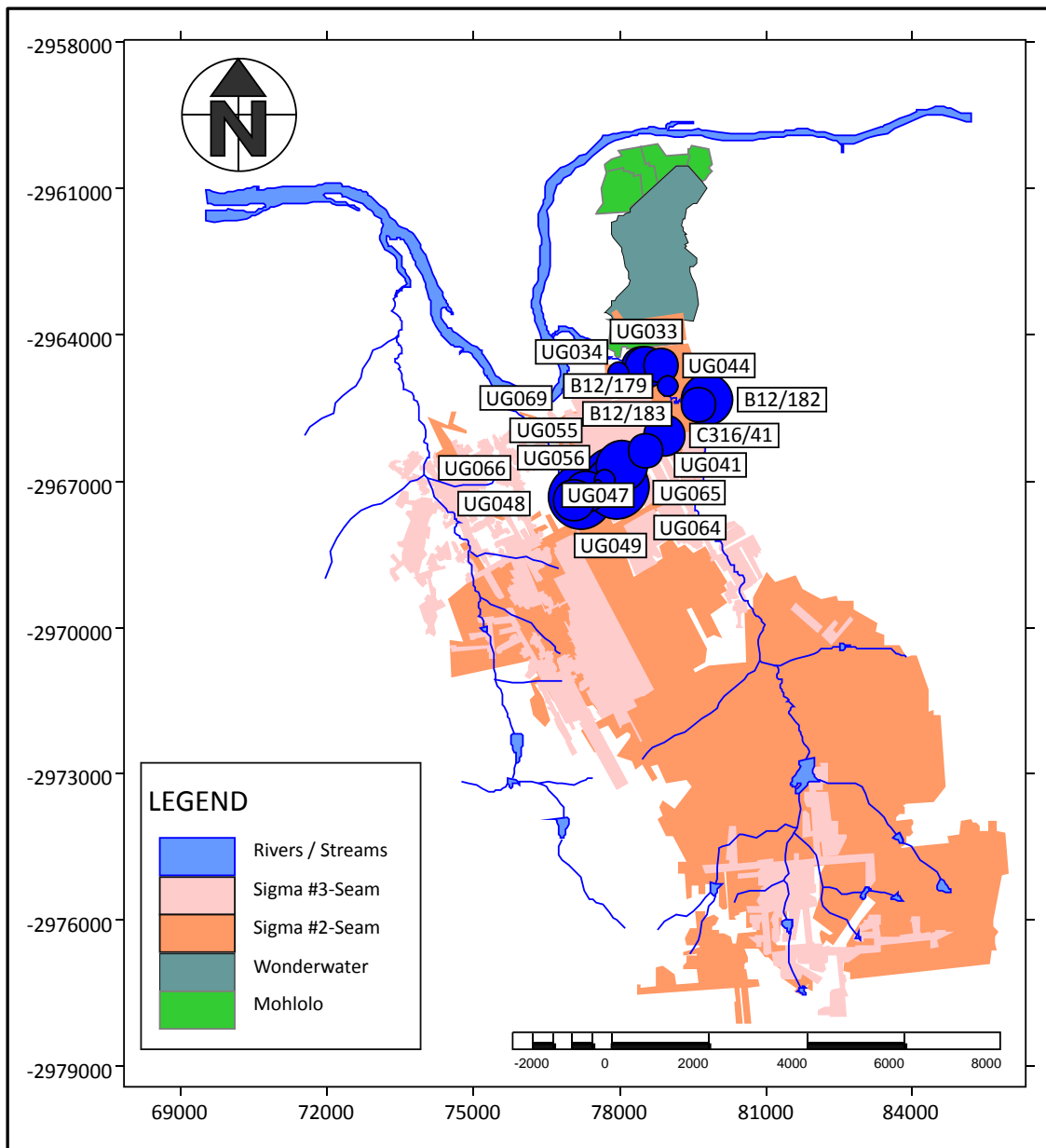


*Figure 6-47: Locality and proportional distribution of the water levels of the boreholes in the ashfill.*

The water level time graphs for the ashfill can be viewed in Figure 6-48, Figure 6-49, Figure 6-50 and Figure 6-51. The water levels of the ashfill boreholes have recently shown a deceleration in water level rise that was caused by the ashfilling of the boreholes. In Figure 6-48 it is clear that borehole UG069 decanted due to ashfilling from September 2009 to March 2012 when ashfilling was ceased. The water level depth versus the rainfall graphs can be viewed in Figure 6-52 and Figure 6-53.

Seasonal variations due to rainfall can be observed in the water levels of boreholes C316/41 and UG041 over time.
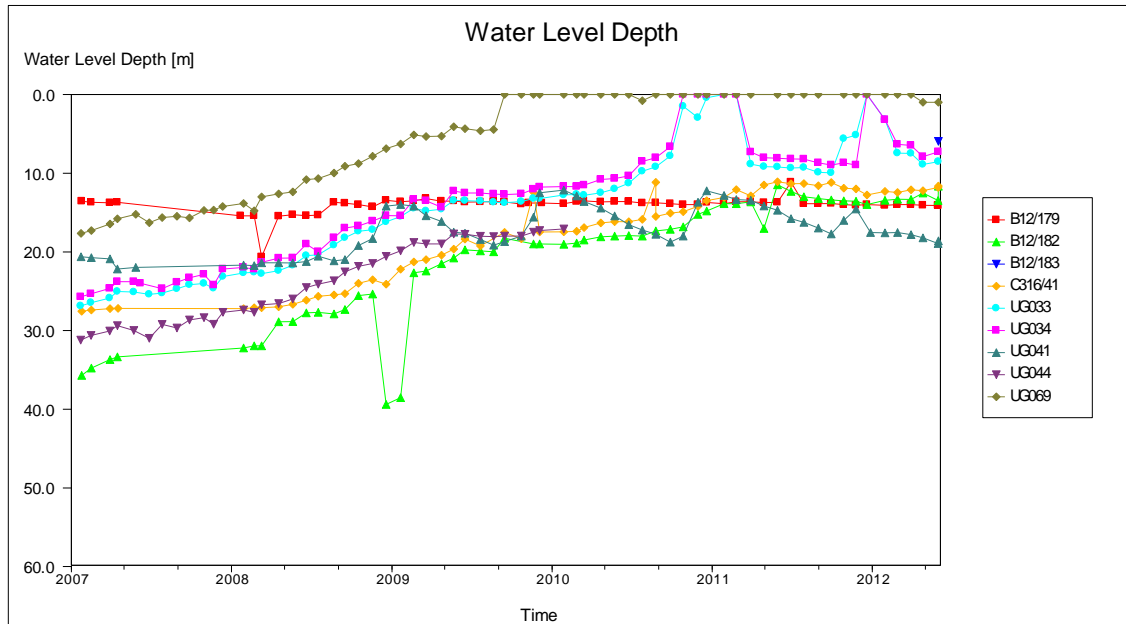


Figure 6-48: Water level depths for boreholes B12/179, B12/182, B12/183, C316/41, UG033, UG034, UG041, UG044 and UG069 in the ashfill.
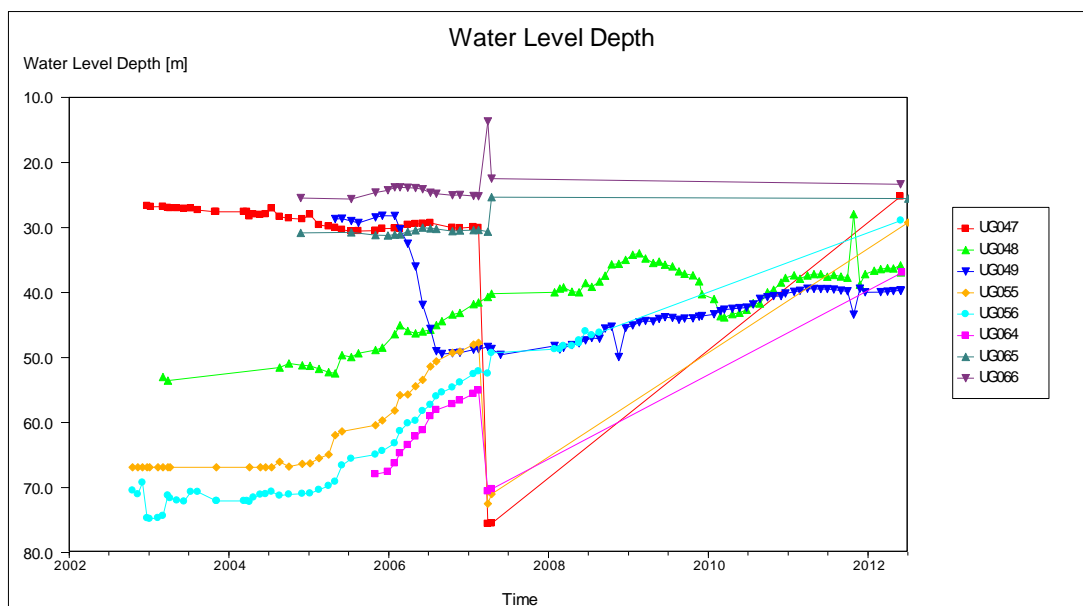


Figure 6-49: Water level depths for boreholes UG047, UG048, UG049, UG055, UG056, UG064, UG065 and UG066 in the ashfill.
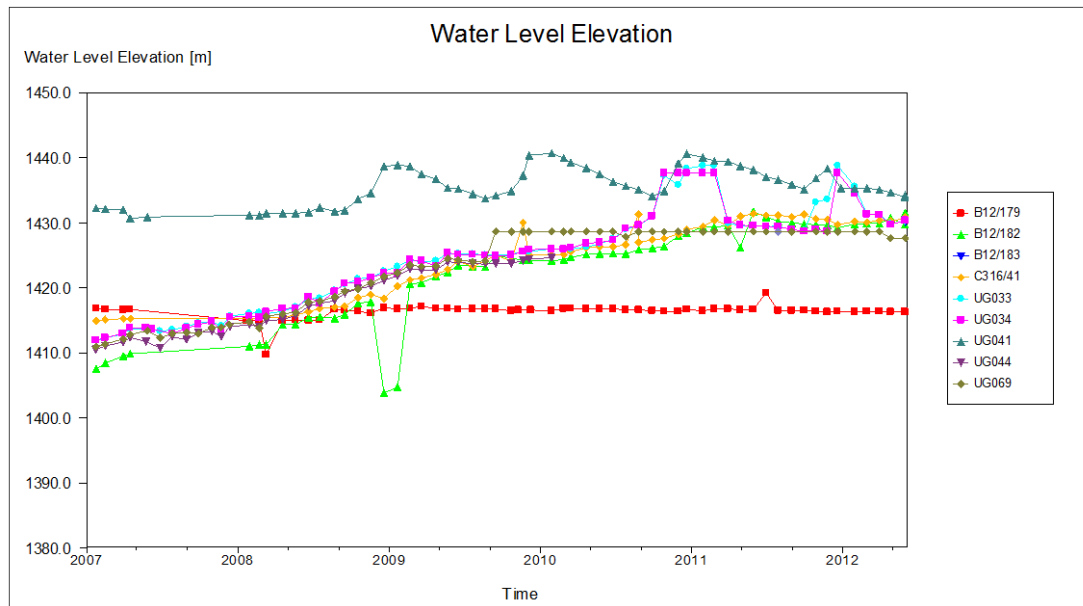
Figure 6-50: Groundwater level elevations for boreholes B12/179, B12/182, B12/183, C316/41, UG033, UG034, UG041, UG044 and UG069 in the ashfill.
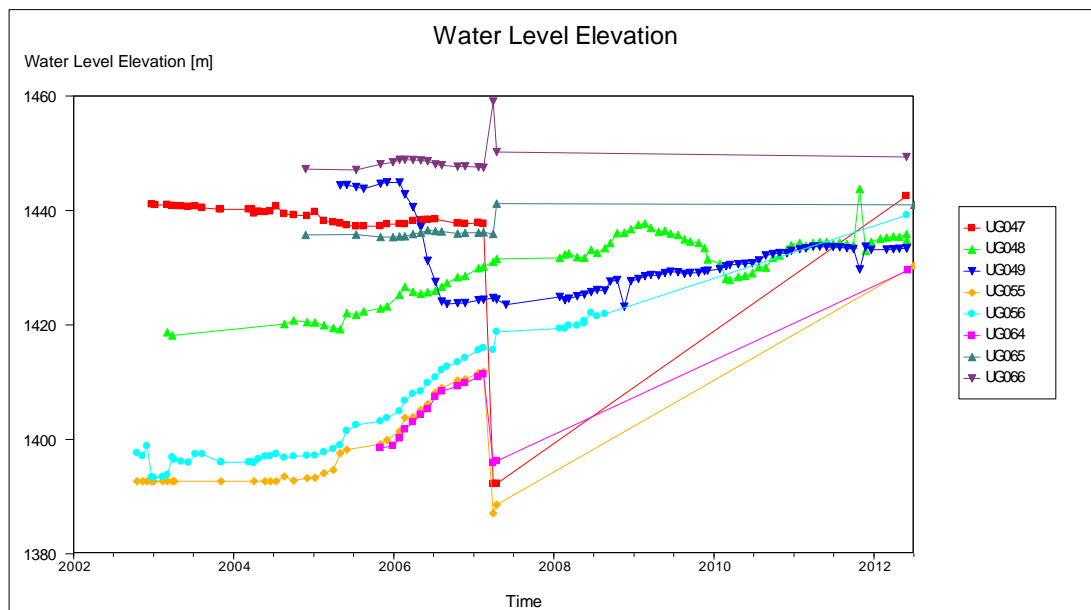


Figure 6-51: Groundwater level elevations for boreholes UG047, UG048, UG049, UG055, UG056, UG064, UG065 and UG066 in the ashfill.
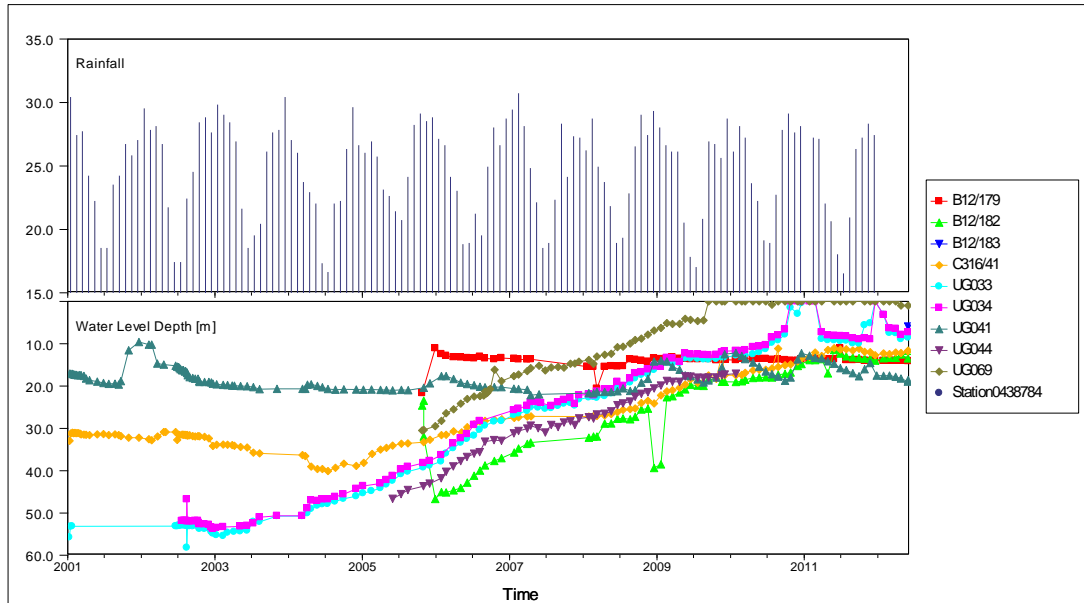
Figure 6-52: Groundwater level depths and rainfall for boreholes B12/179, B12/182, B12/183, C316/41, UG033, UG034, UG041, and UG044 in the ashfill from 2001 to 2012.
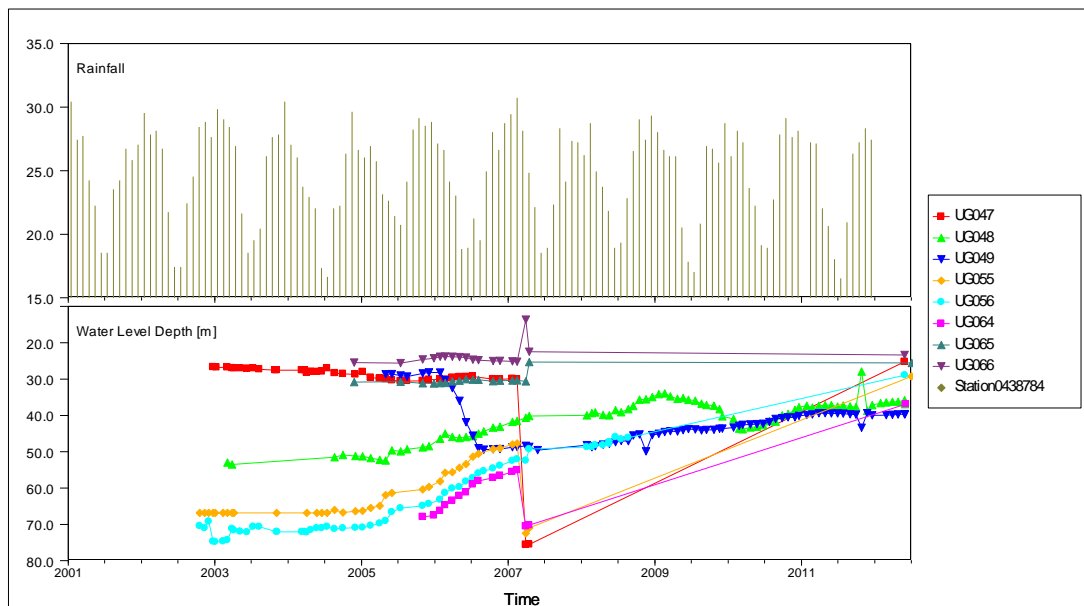


Figure 6-53: Groundwater level depths and rainfall for boreholes UG047, UG048, UG049, UG055, UG056, UG064, UG065 and UG066 in the ashfill from 2001 to 2012.
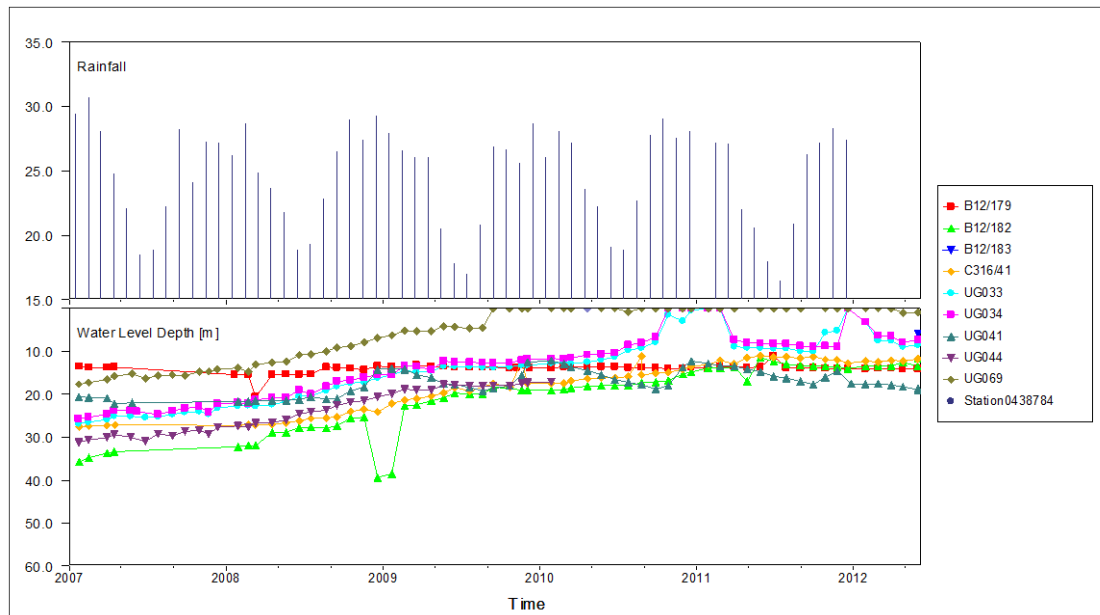
*Figure 6-54: Groundwater level depth and rainfall for boreholes B12/179, B12/182, B12/183, C316/41, UG033, UG034, UG041 and UG044 in the ashfill from 2007 to 2012.*
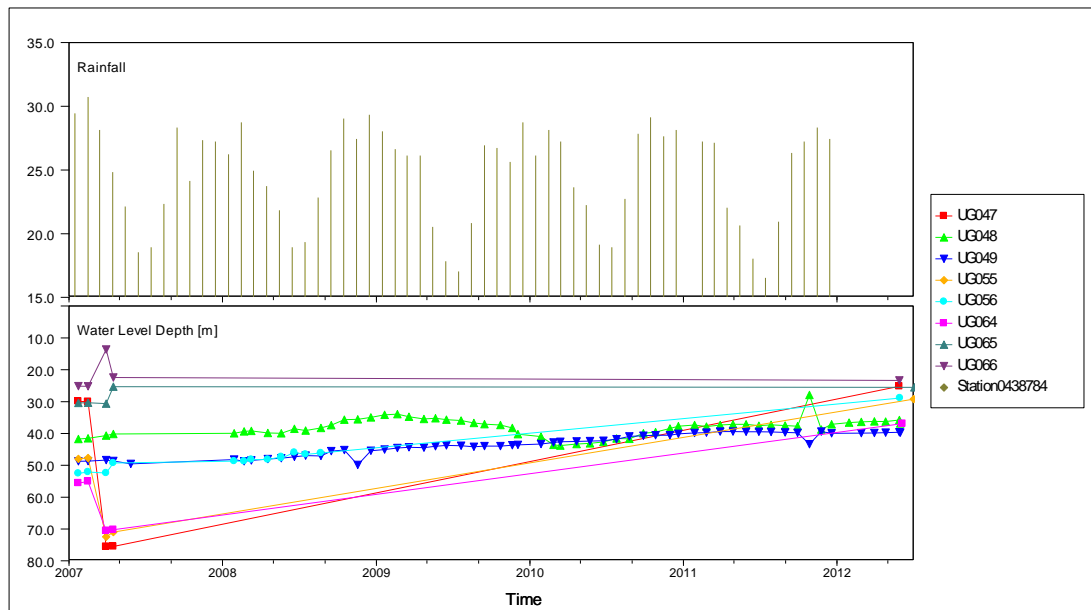


*Figure 6-55: Groundwater level depth and rainfall for boreholes UG047, UG048, UG049, UG055, UG056, UG064, UG065 and UG066 in the ashfill from 2007 to 2012.*

# 7. Hydrochemical Profiling of Boreholes and Development of a 3-D Electrical Conductivity Image

Each available and accessible borehole was profiled with a multi-parameter probe to determine if hydrochemical stratification was visible in the boreholes. A total of 94 boreholes were profiled and are illustrated in conjunction with the ashfill areas on a locality map in Figure 7-1. After the hydrochemical profiling was completed, the downloaded data was entered into a WISH (Windows Interpretation System for the Hydrogeologist) database. WISH was especially developed for Hydrogeologists and is a hybrid between a CAD system, a Geographical Information System, a Chemical analysis package and pumping test programs. It was decided to use the electrical conductivity values to create a three-dimensional image, since electrical conductivity is a measure of the ability of water to conduct an electric current. This is dependent on the concentration of the ions such as carbonate, bicarbonate, chloride, sulphate, nitrate, sodium, potassium, calcium and magnesium present in the water. Most organic compounds dissolved in water do not dissociate into ions, and consequently do not affect the EC. The EC can therefore be a good indication of mine pollution in groundwater. WISH was thereafter used to create the three dimensional image of the whole area and of the electrical conductivities of the 94 boreholes that was profiled in relation to the local topography of the whole area.
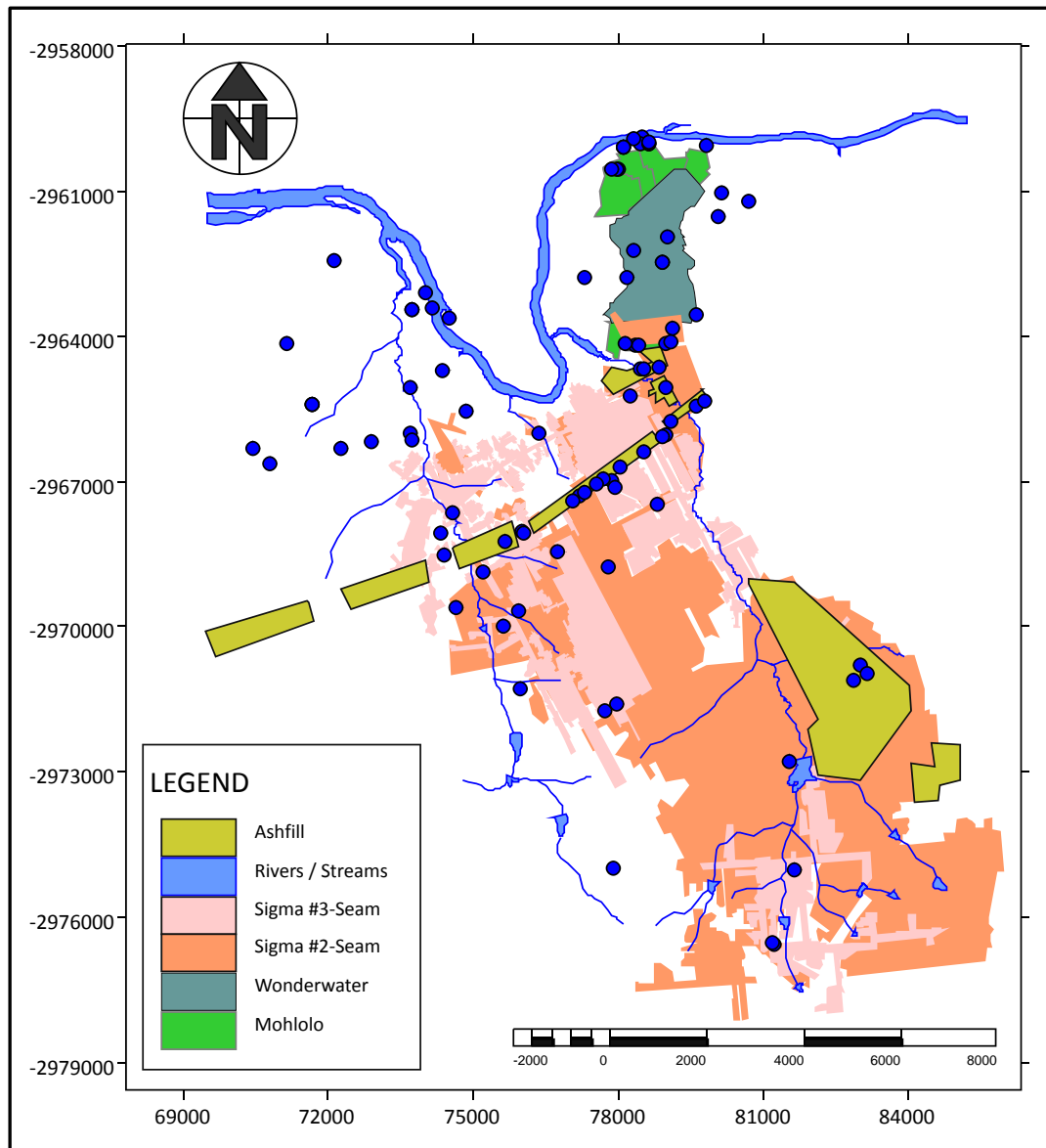
*Figure 7-1: Locality map of all profiled boreholes.*

An example of a typical hydrochemical profile created with the WISH programme can be viewed in Figure 7-2. A three-dimensional image was then created from the electrical conductivity profiles.
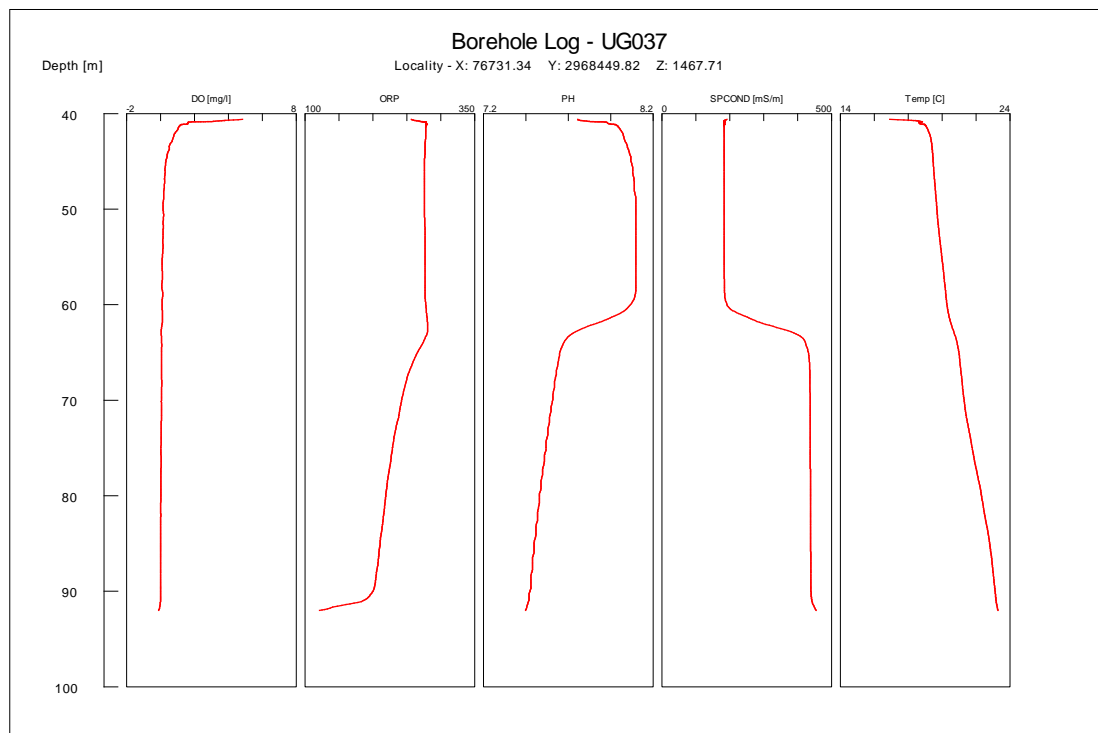
*Figure 7-2: An example of what a hydrochemical profile generated by WISH would look like.*

The three-dimensional image of the electrical conductivity profiles, in relation to the local topography and the underground mining area, can be viewed in *Figure 7-3*. The high electrical conductivity areas (in red and yellow) of the borehole profiles are clearly visible in this image. These areas, in conjunction with the shallow water levels identified in Chapter 6, will then be used to create localised sections and will be discussed in Chapter 8.
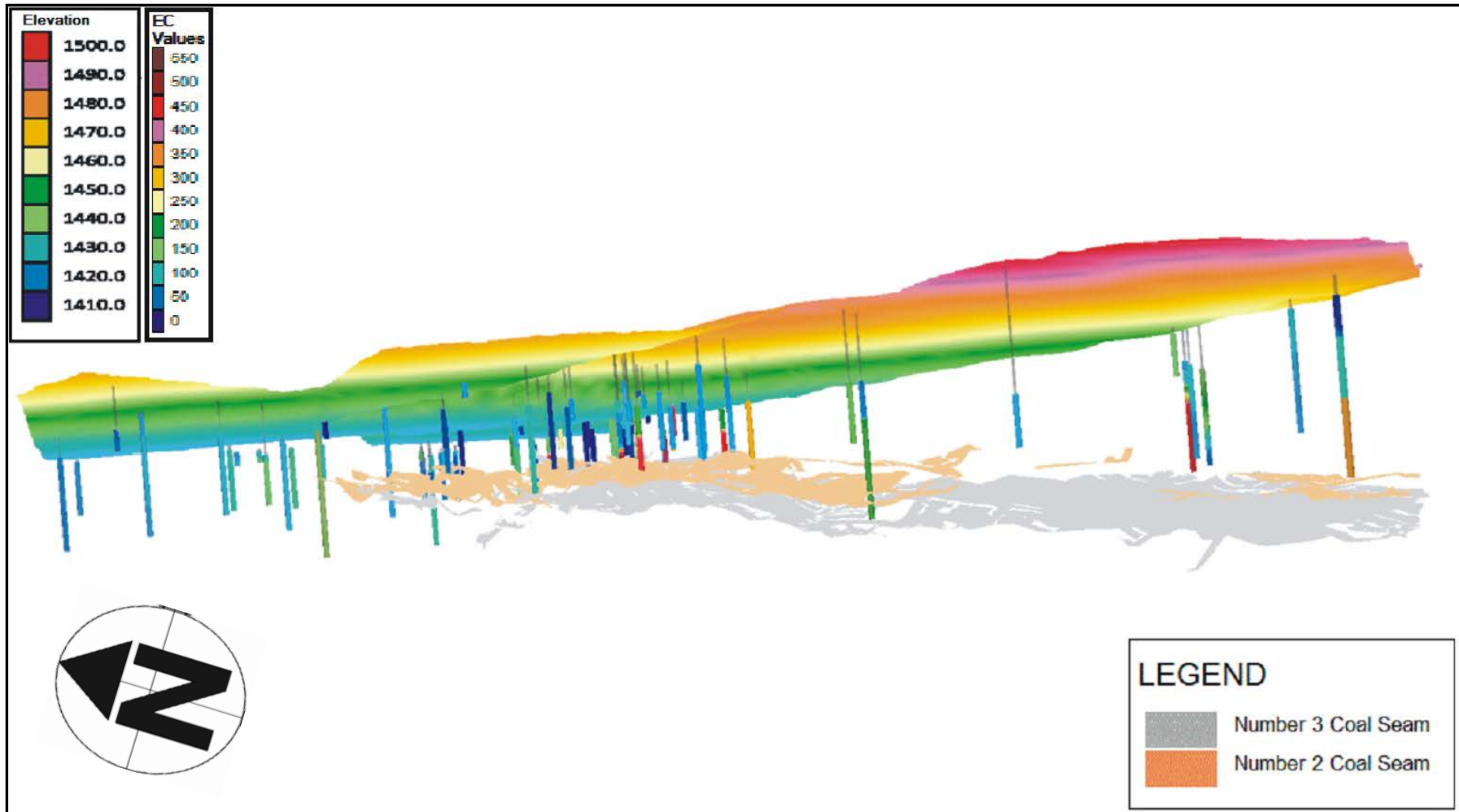
Figure 7-3: A three-dimensional image (of the whole area), of the electrical conductivity profiles of the 94 profiled boreholes in relation to the local topography and the underground mining area.

# 8. Water Levels and 3-D Electrical Conductivity Images of Boreholes

After the development of the 3-D electrical conductivity image in Chapter 7 and the analysis of the water levels of the boreholes in Chapter 6, certain boreholes were identified as possible decanting boreholes.  To get a more concise image of whether decant will occur and what the water quality will be in the event of decant, sections of water level versus topography was created with WISH where the water level was very shallow. The three dimensional image of the electrical conductivities of the boreholes, in close vicinity to these shallow water levels, was then also used to determine the water quality of the possibly decanting water.

The SANS 241:2006 standards are used for the classification of the boreholes according to the EC values.  These standards consist of three classes and are explained in Table 8-1.  According to these standards, anything between zero and 150 mS/m is within the recommended allowable limit and is suitable for lifetime use. Anything between 150 and 370 mS/m is the maximum allowable limit and is suitable for limited duration use only. Anything above 370 mS/m is above the maximum allowable limit and therefore unsuitable for human consumption.

*Table 8-1: Explanation of the SANS 241:2006 drinking water standards with the limits for EC.*

| SABS South African National Standard: Drinking Water, SANS 241:2006 | | EC (mS/m) |
|---|---|---|
| Class 1 | Recommended operational limit - Suitable for lifetime use | 0 |
| Class 2 | Maximum alowable limit - Suitable for limited duration use only | 150 |
| AMA | Above maximum allowable limit - Unsuitable for human consumption | 370 |

Four sections were created with WISH in areas of shallow water levels where possible decant might occur.  These sections are section A1 - A9, section B1 - B5, section C1 - C6 and section D1 - D4.

The locality of section A1 - A9 and a zoomed-in image of section A1 - A9 can be viewed in Figure 8-1.  Section A1 - A9 and the three dimensional image of the electrical conductivities of the boreholes on section A1 - A9 can be viewed in Figure 8-2.

The red encircled areas on Section A1 - A9 (Figure 8-2), are areas where the water level appears to be very shallow, and can be therefore possible decant positions. The second area where the water level appears to be shallow is close to a river. Boreholes close to these areas are identified on the locality map in Figure 8-1.  From the EC logs it is evident that the EC of borehole UG069, which is an ashfill borehole, varies between 400 mS/m and 650 mS/m.  According to the SANS241:2006, these values are above the maximum allowable limit for drinking water standards and therefore the water from boreholes UG069 is therefore unsuitable for human consumption.  In the event of this borehole decanting, the decanted water will be of very poor quality.  This can be substantiated by the water level versus depth graph (Figure 8-4), which clearly shows that borehole UG069 did in fact decant due to the ashfilling from September 2009 to March 2012 when the ashfilling was ceased. The electrical conductivity profile (Figure 8-3) of borehole UG069 also clearly indicates that the EC of the water is above the maximum allowable limits and therefore not suitable for human consumption.  The other boreholes have EC values that vary between 1.7 mS/m and a 99 mS/m. This is within the recommended operational limits for electrical conductivity values (according to SANS241:2006 drinking water standards) and therefore water from these boreholes can therefore be considered suitable for human consumption. In the event of decanting occurring from these boreholes, the water quality of the decanted water will be within the recommended operational limits for electrical conductivity.

The locality of section B1 - B5 and a zoomed-in image of section B1 - B5 can be viewed in Figure 8-5.  Section B1 - B5 and the three dimensional image of the electrical conductivities of the boreholes on section B1 - B5 can be viewed in Figure 8-6.

The areas encircled in red (Figure 8-6) are again areas where the water level appears to be very shallow and can be possible decant positions. The first two areas where the water levels appear to be shallow are close to rivers. Boreholes nearby these areas are visible on the locality map in Figure 8-5. From the three-dimensional image of the electrical conductivity logs it is evident that the EC of these boreholes range between 70 mS/m and 132 mS/m. According to SANS241:2006 drinking water standards, these values are within the recommended operational limits for electrical conductivity values and therefore water from these boreholes can therefore be considered suitable for human consumption. It can be assumed that should decant occur in the areas encircled in red (Figure 8-6), the water quality of the decanting water will be within the recommended operational limits for electrical conductivity.
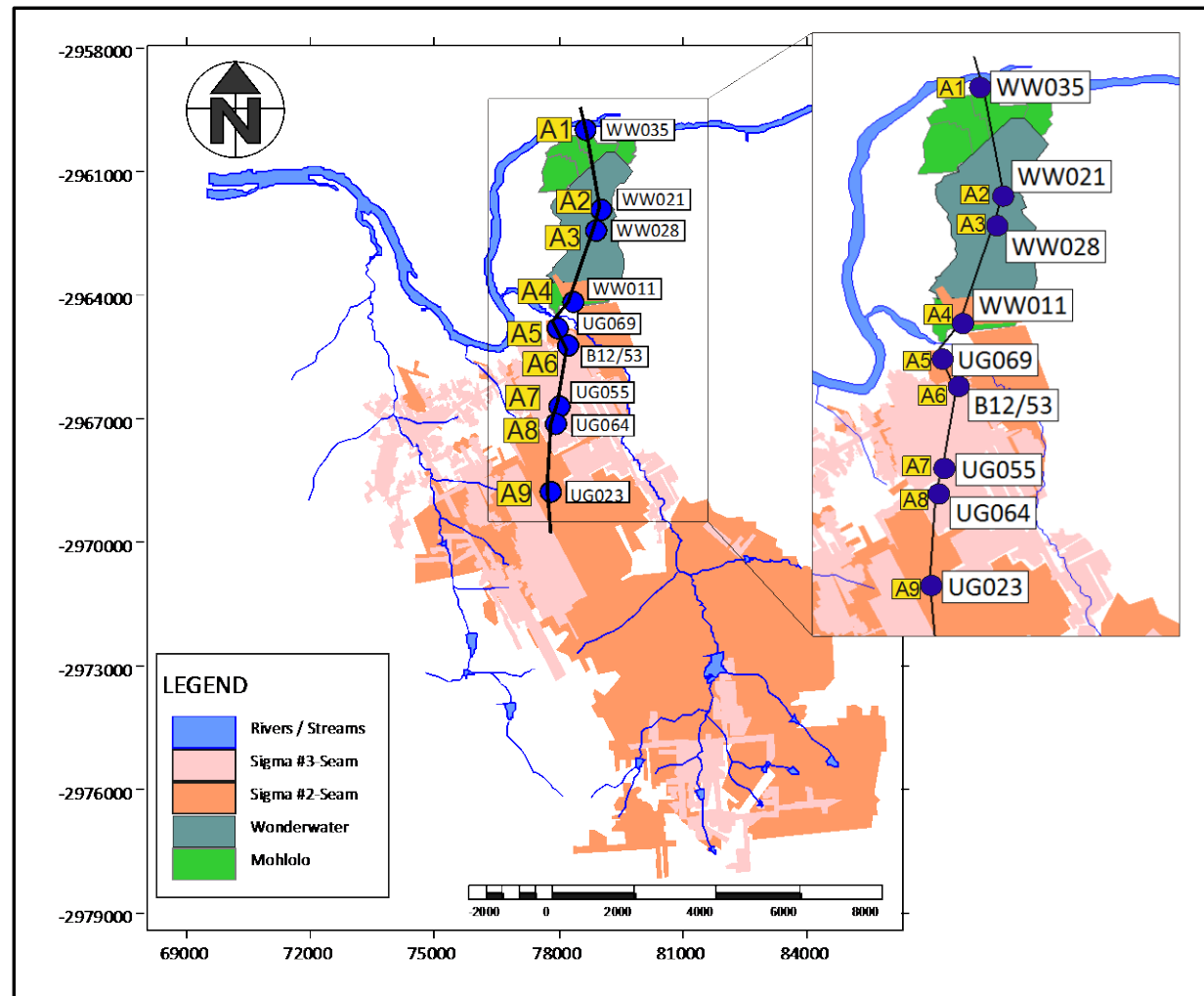
*Figure 8-1: The locality map of section A1 - A9 and a zoomed image of section A1 - A9.*
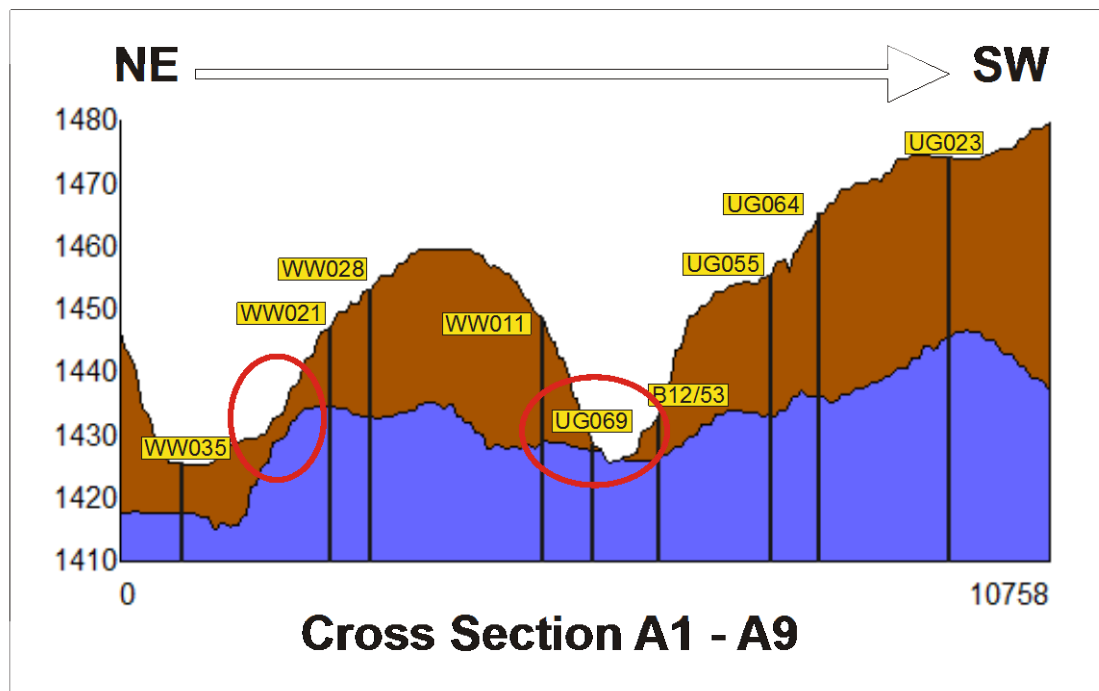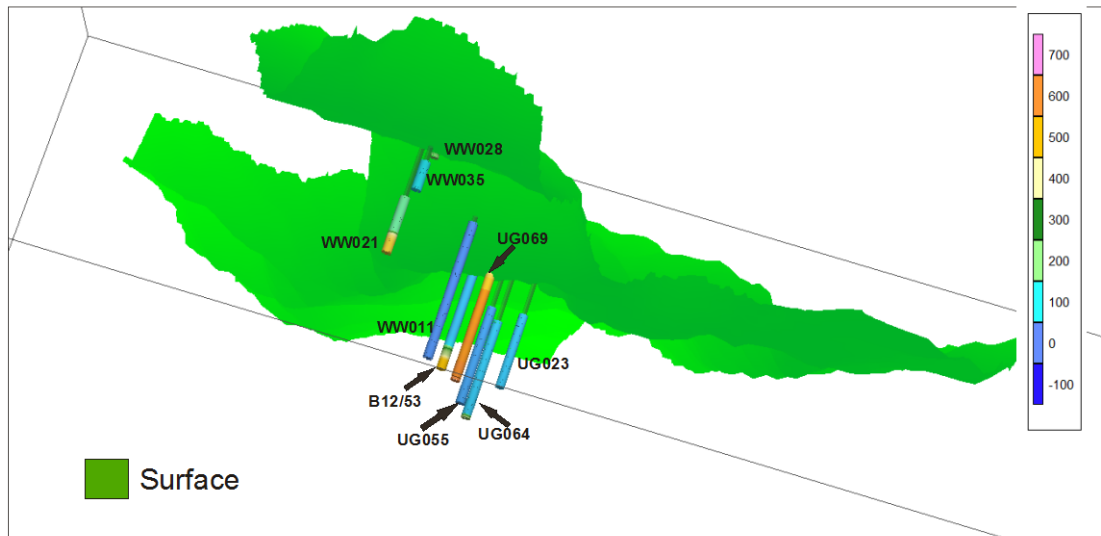
*Figure 8-2: A three dimensional image of the electrical conductivities of the boreholes on section A1 - A9 and section A1 - A9.*
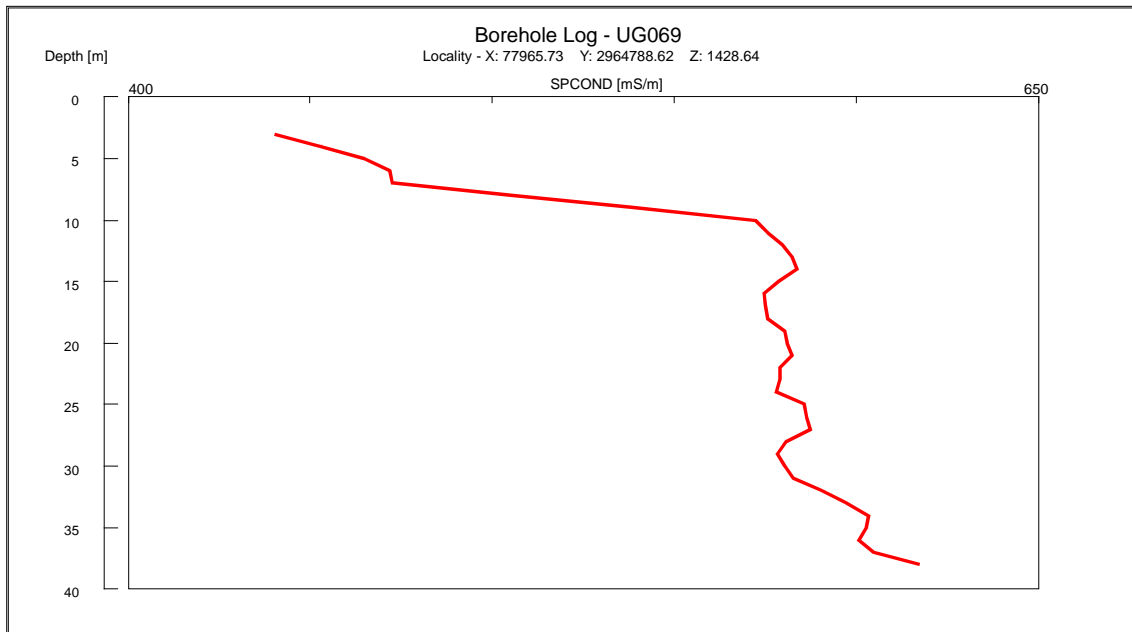
*Figure 8-3: EC log for borehole UG069.*
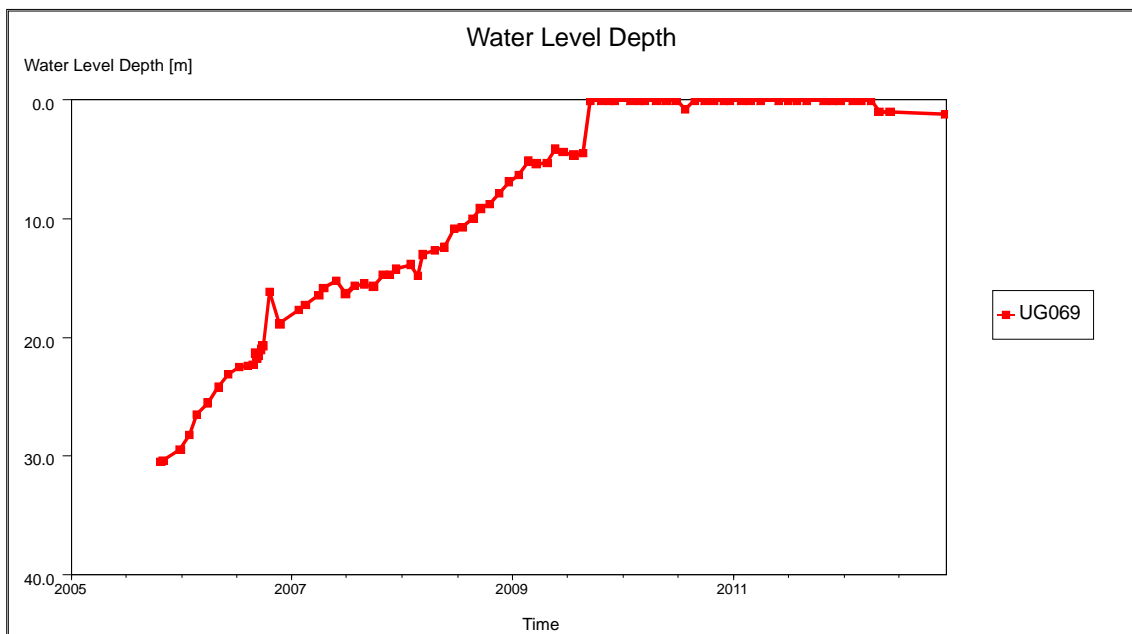


*Figure 8-4: Water level depth graph for borehole UG069.*
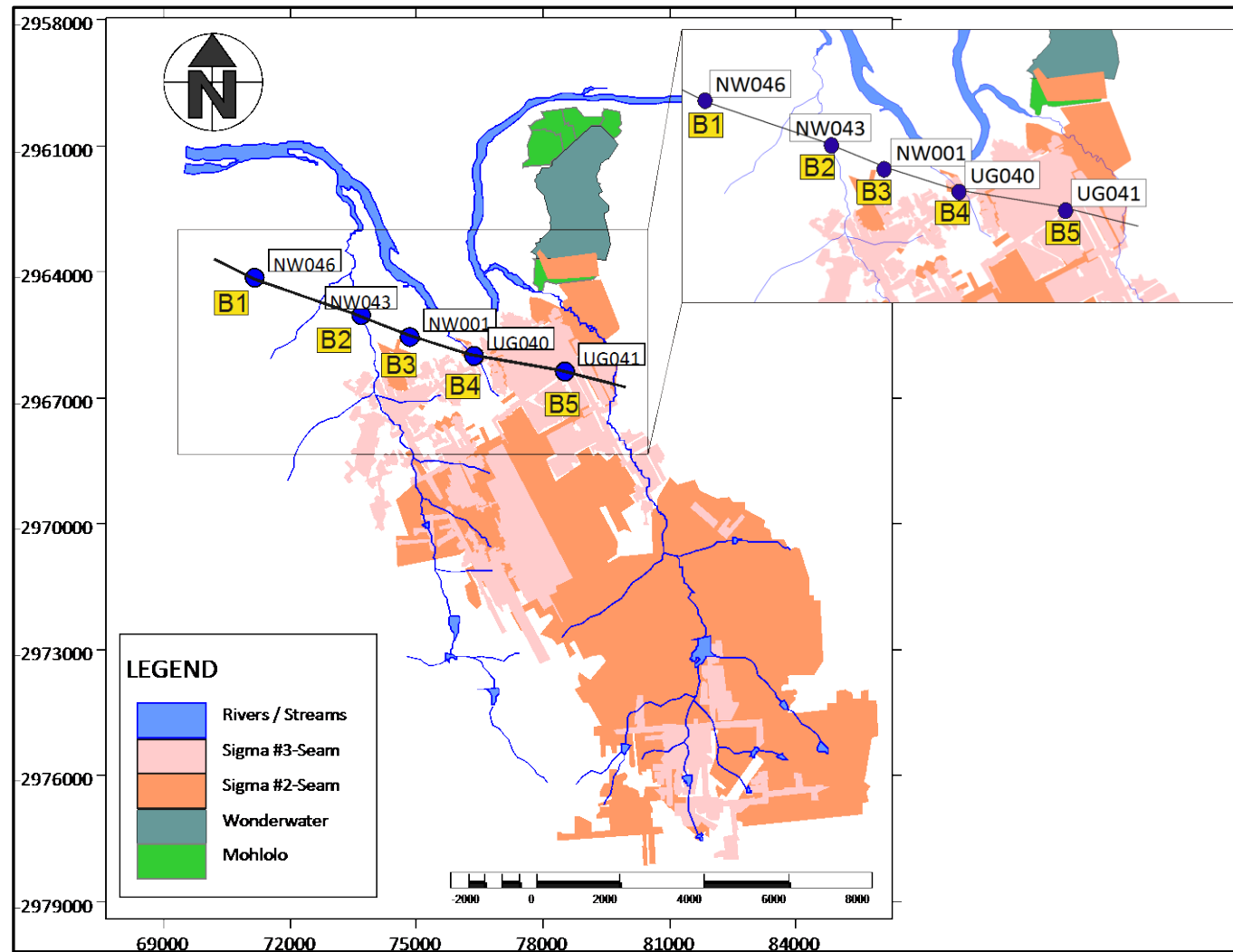
*Figure 8-5: The locality map of section B1 - B5 and a zoomed image of section B1 - B5.*
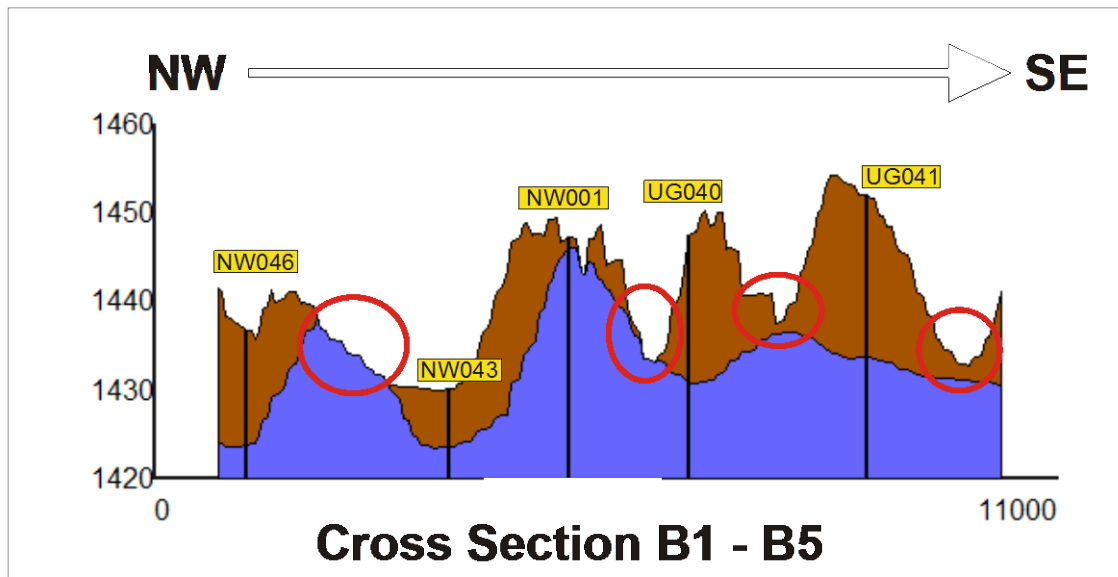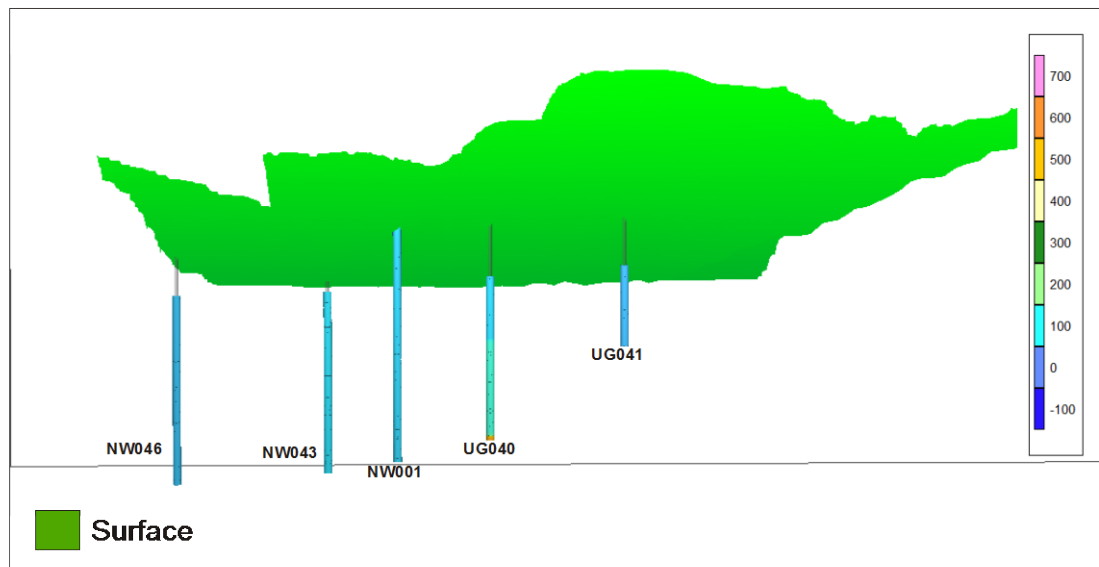
*Figure 8-6: A three dimensional image of the electrical conductivities of the boreholes on section B1 - B5 and section B1 - B5.*

The locality of section C1 - C6 and a zoomed-in image of section C1 - C6 can be viewed in Figure 8-7. Section C1 - C6 and a three dimensional image of the electrical conductivities of the boreholes on section C1 - C6 can be viewed in Figure 8-8.

The area encircled in red (Figure 8-8) is an area where the water level appears to be very shallow and could indicate a possible decant position. Boreholes close to this area are boreholes B12/183 and C316/41 and are identified on the locality map in

Figure 8-7. The EC log for borehole B12/183 in Figure 8-9 clearly indicates that the EC for this borehole is within the maximum allowable limits for electrical conductivity and that the water is only suitable for limited duration use only. No water levels over time were available for borehole B12/183. The EC log for borehole C316/41 in Figure 8-10 indicates that the EC of this borehole is within the recommended operational limits according to SANS241:2006 drinking water standards. According to the water level depth graph for borehole C316/41 in Figure 8-11, the water level has become very shallow in 2011 and 2012, but no decant occurred. The EC values for the boreholes range between 12 mS/m and 450 mS/m. The high EC values are found in borehole B12/183 and can be attributed to the fact that this borehole is an ashfill borehole. Water decant from ashfill boreholes will be due to artificial pressure caused by the ashfill that was pumped into the boreholes. If decant should occur from this borehole, the water quality of the decanted water will be above the maximum allowable limit (according to SANS241:2006 drinking water standards). If any of the other boreholes discussed, or the area surrounding these boreholes, should decant, the water quality of the decanted water will be within the recommended operational limits for electrical conductivity (according to SANS214:2006 drinking water standards).

The locality of section D1 – D4 and a zoomed-in image of section D1 – D4 can be viewed in Figure 8-12. Section D1 – D4 and a three dimensional image of the electrical conductivities of the boreholes on section D1 – D4, can be viewed in Figure 8-13.

The area encircled in red (Figure 8-13) is an area where the water level appears to be fairly shallow and can be a possible area of decant. The boreholes nearby this area are visible on the locality map in Figure 8-12. From the EC logs it is evident that the EC of these boreholes varies between 1.7 mS/m and a 99 mS/m. According to the drinking water standards of SANS214:2006, this is well within the recommended operational limits for electrical conductivity. It can be assumed that in the event of decanting, the water quality of the decanted water will be within the recommended operational limits for electrical conductivity.
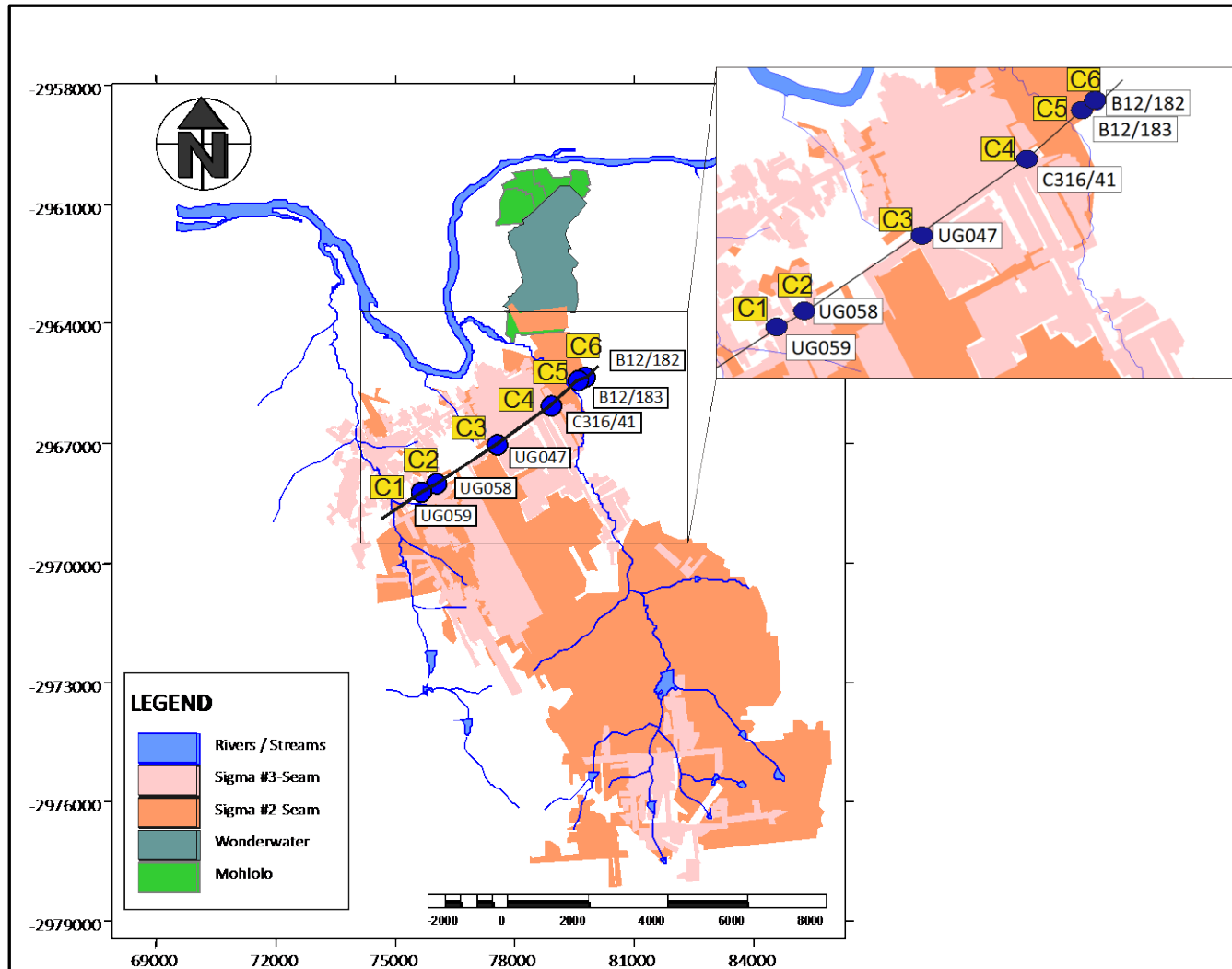
Figure 8-7: The locality map of section C1 - C6 and a zoomed image of section C1 - C6.
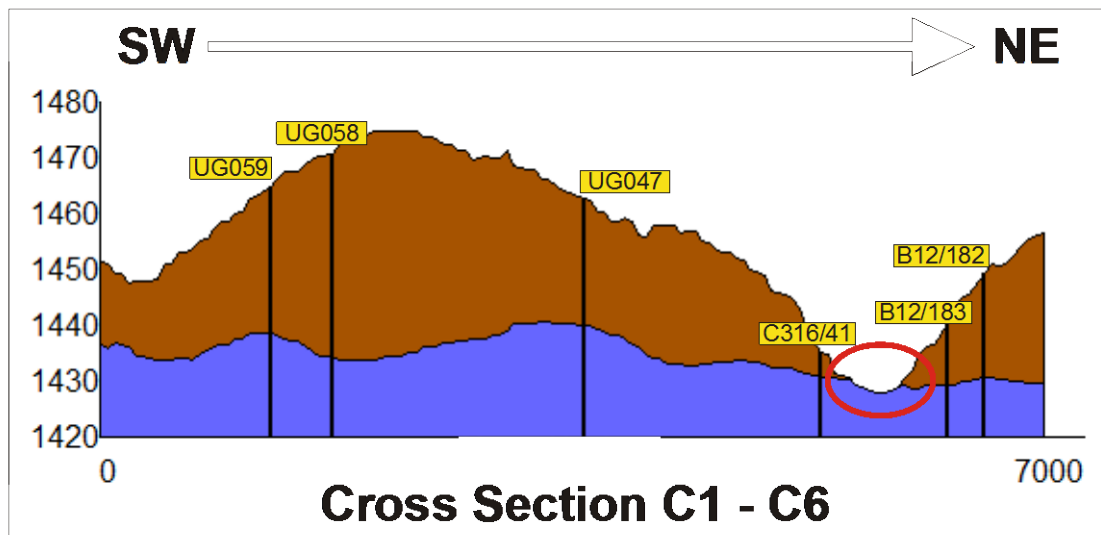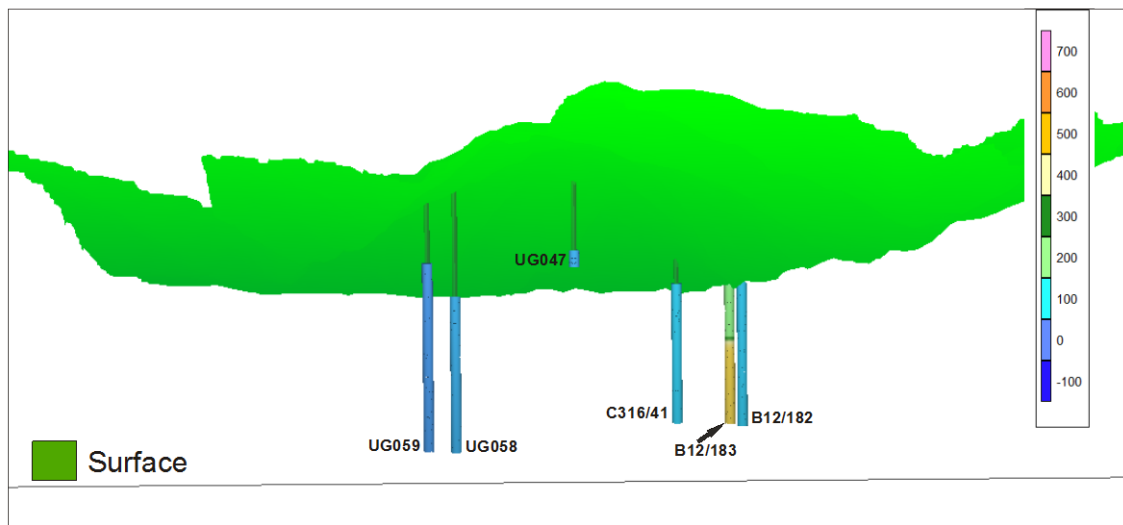
Figure 8-8: A three dimensional image of the electrical conductivities of the boreholes on section C1 - C6 and section C1 - C6.
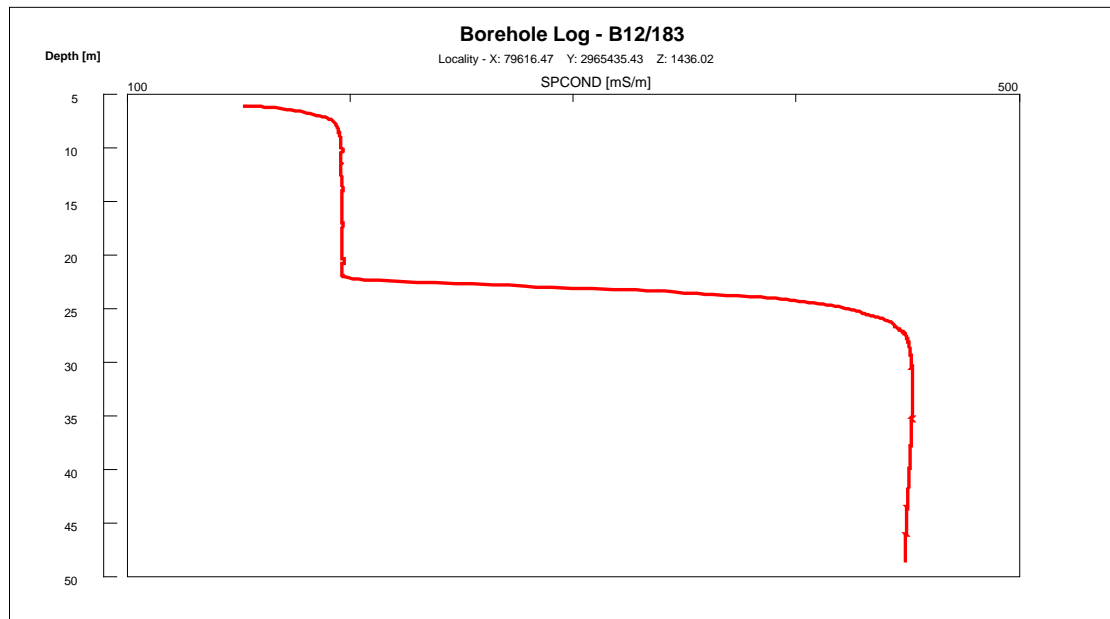
Figure 8-9: EC log for borehole B12/183.
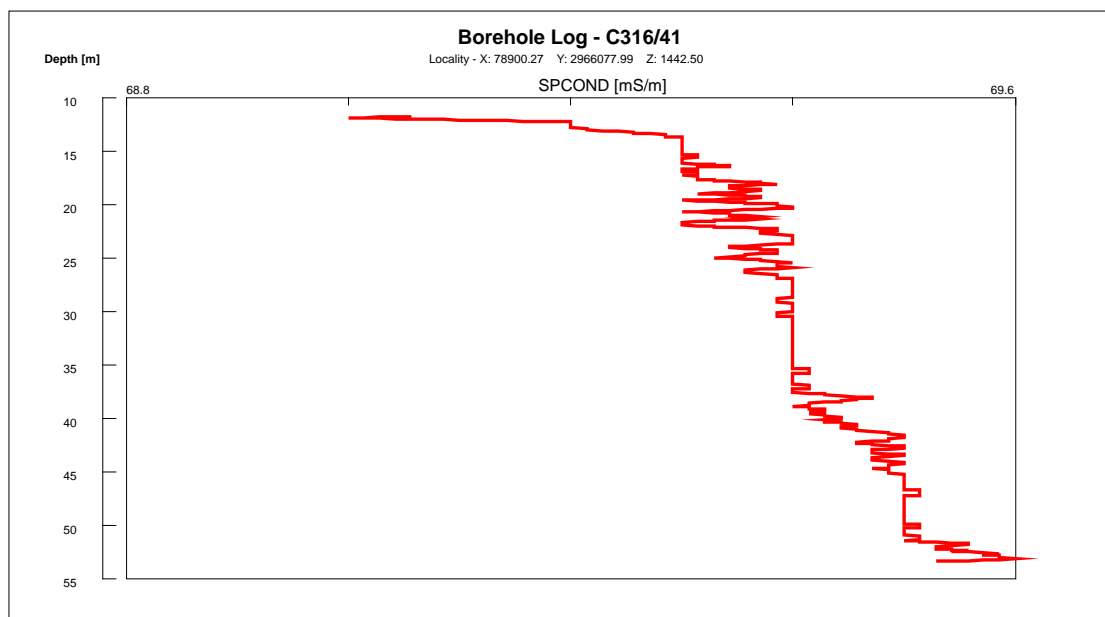


Figure 8-10: EC log for borehole C316/41.
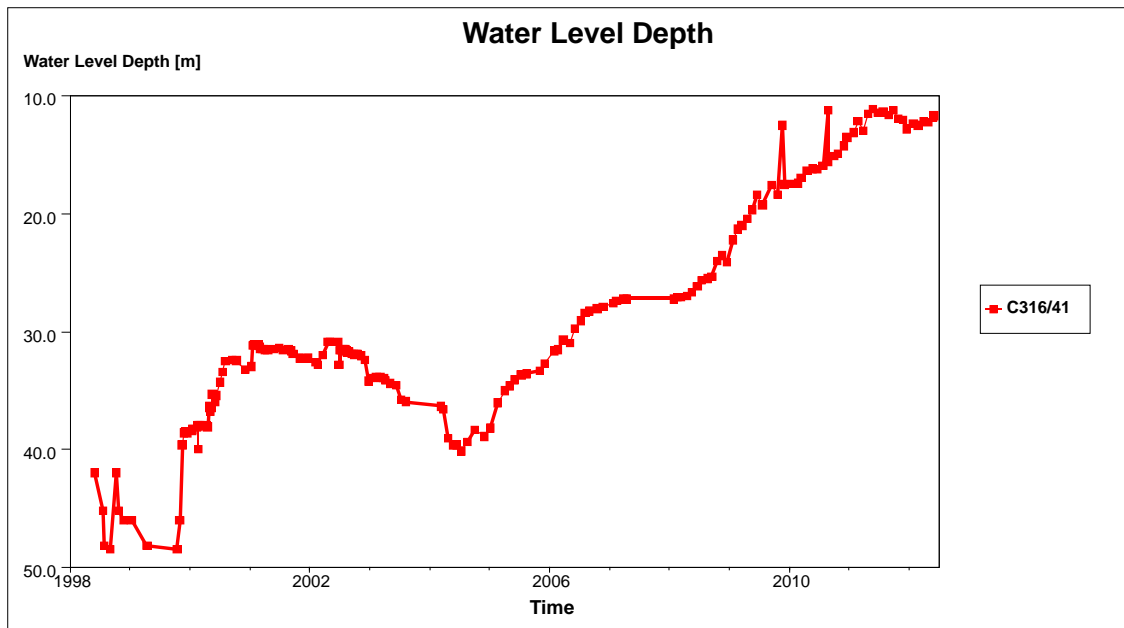
*Figure 8-11:  Water level depth graph for borehole C316/41.*
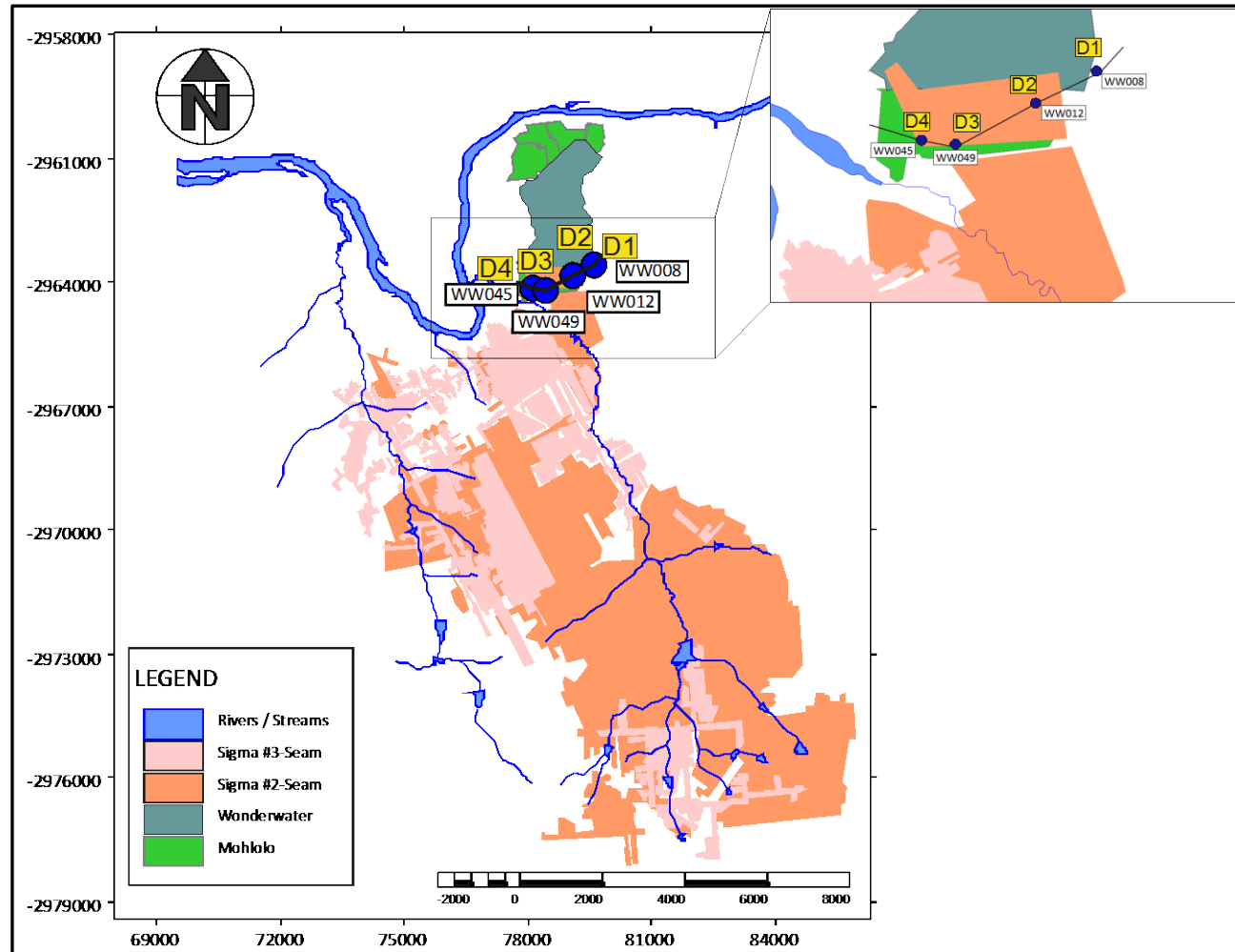
*Figure 8-12: The locality map of section D1 - D4 and a zoomed image of section D1 - D4.*
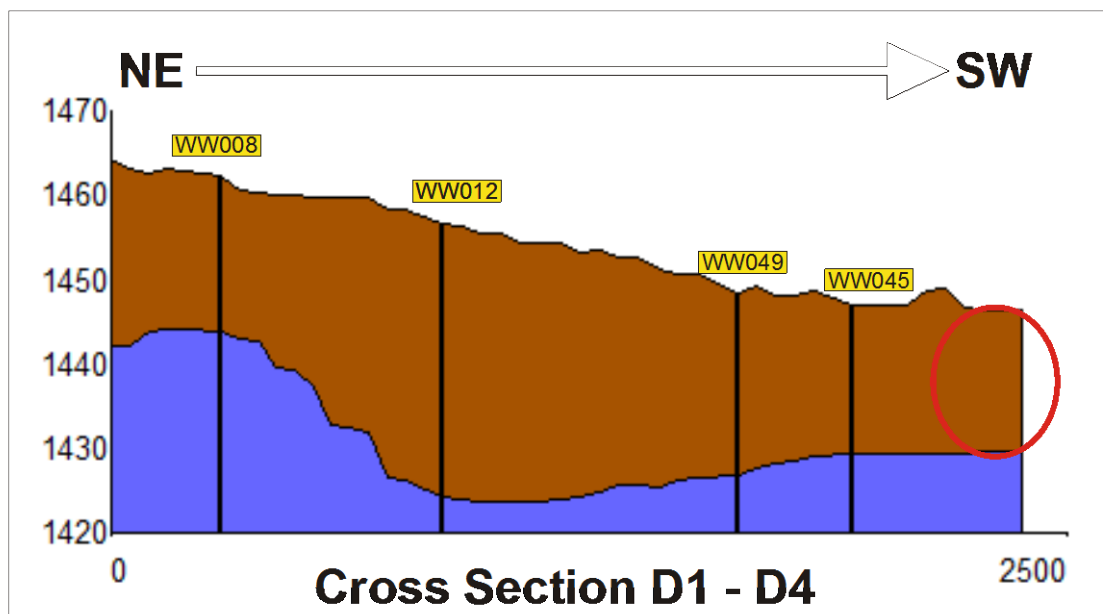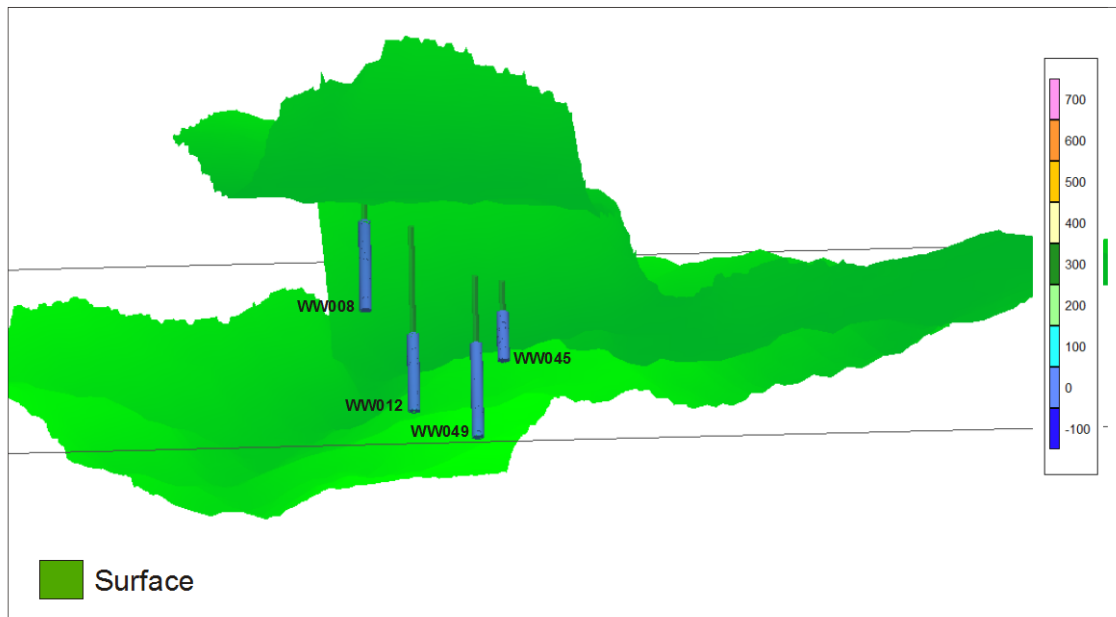
Figure 8-13: A three dimensional image of the electrical conductivities of the boreholes on section D1 - D4 and section D1 - D4.

## 9. Electrical Conductivity Study of the Current Mine Water Scenario

Electrical conductivity (EC) is a measure of the ability of water to conduct an electrical current. This ability is a result of the presence of ions in water such as carbonate, bicarbonate, chloride, sulphate, nitrate, sodium, potassium, calcium and magnesium, all of which carry an electrical charge. Most organic compounds dissolved in water do not dissociate into ions and consequently do not affect the EC. The EC can therefore be a good indication of mine pollution in groundwater.

From the electrical conductivity (EC) profiles of all the boreholes accessible at Sigma Colliery, a three dimensional image (Figure 7-3) was created with WISH. An image of all the boreholes with their water levels can be viewed in Table 9-2. In this chapter, images were created to show the locality of the boreholes and their EC profiles for various depth intervals. Table 9-2 to Table 9-7 shows summaries of the boreholes at their various depth intervals, as well as the EC and $SO_4$ concentrations for each sample taken. This is classed according to the SANS 241:2006 drinking water standards. As discussed in the methodology chapter (Chapter 5) in section 5.3, the sampling depth and the amount of samples taken at each borehole were determined by the profiling. If stratification was visible on the profile, two or three samples were taken so that the samples were representative of the whole water column of the borehole. These samples were then named, for example, UG027D (D for deep), UG027M (M for middle) or UG027S (S for shallow). An explanation of the SANS 241:2006 drinking water standards with the limits for EC and $SO_4$ can be viewed in Table 9-1.

*Table 9-1: Explanation of the SANS 241:2006 drinking water standards with the limits for EC and $SO_4$.*

| SABS South African National Standards: Drinking Water, SANS 241:2006 | | EC (mS/m) | SO4 (mg/l) |
|---|---|---|---|
| Class 1 | Recommended operational limit - Suitable for lifetime use | 0 | 200 |
| Class 2 | Maximum alowable limit - Suitable for limited duration use only | 150 | 400 |
| AMA | Above maximum allowable limit - Unsuitable for human consumption | 370 | 600 |

In Figure 9-2 all boreholes with water levels equal to, or shallower that 5 mbgl, were plotted along with their EC profiles. The EC concentration of boreholes UG069 and B12/53 is above the maximum allowable limit (AMA) at a value of 419 mS/m for UG069, 461 mS/m for B12/53D and a value of 377 mS/m for B12/53S (Table 9-2). The $SO_4$ concentrations of boreholes UG069 (1828 mg/l), B12/53D (1726 mg/l) and B12/53S (1190 mg/l) is also above the maximum allowable limit (according to the

SANS 241:2006 drinking water standards). It should also be noted that UG069 started to decant due to ashfilling in September 2009 and then ceased to decant in March 2012 as soon as the ashfilling was stopped. All the other boreholes (Table 9-1 and Table 9-2) with water levels equal to, or shallower than 5 mbgl, had EC values lower than 150 mbgl. This is within the recommended operational limits according to the SANS 241:2006 drinking water standards.

*Table 9-2: A summary of the water levels, EC values and SO₄ values of the boreholes with water levels equal to or shallower than 5 mbgl.*

| Borehole No | Water level | EC | SO4 |
| --- | --- | --- | --- |
|  |  | mS/m | mg/l |
| B12/53D | 3.26 | 461 | 1726 |
| B12/53S | 3.26 | 377 | 1190 |
| NW004 | 3.18 | 18.3 | 0.64 |
| NW006 | 1.28 | 129 | -5.00 |
| NW014 | 3.3 | 35.1 | 2.03 |
| NW020 | 1.27 | 34.6 | 5.05 |
| NW034 | 0.94 | 78.2 | 167.7 |
| NW035 | 1.4 | 138 | 201.78 |
| NW036 | 4.05 | 115 | -5.00 |
| NW043 | 3.81 | 77.6 | 1.96 |
| NW044 | 2.56 | 62.2 | -0.50 |
| UG069 | 1.2 | 419 | 1828 |
| WW010 | 2.91 | 20.7 | 2.47 |
| WW011 | 2.31 | 13.5 | 25.10 |
| WW025 | 4.82 | 15.0 | 48.23 |
| WW031 | 4.3 | 39 | 0.93 |
| WW034 | 4.84 | 89 | 5.02 |
| WW035 | 4.89 | 88 | 6.10 |
| WW036 | 4.13 | 51 | 0.67 |
| WW037 | 3.81 | 169 | 213.12 |
| WW038 | 4.1 | 38 | 6.27 |
| WW050 | 4.21 | 94 | 67.90 |
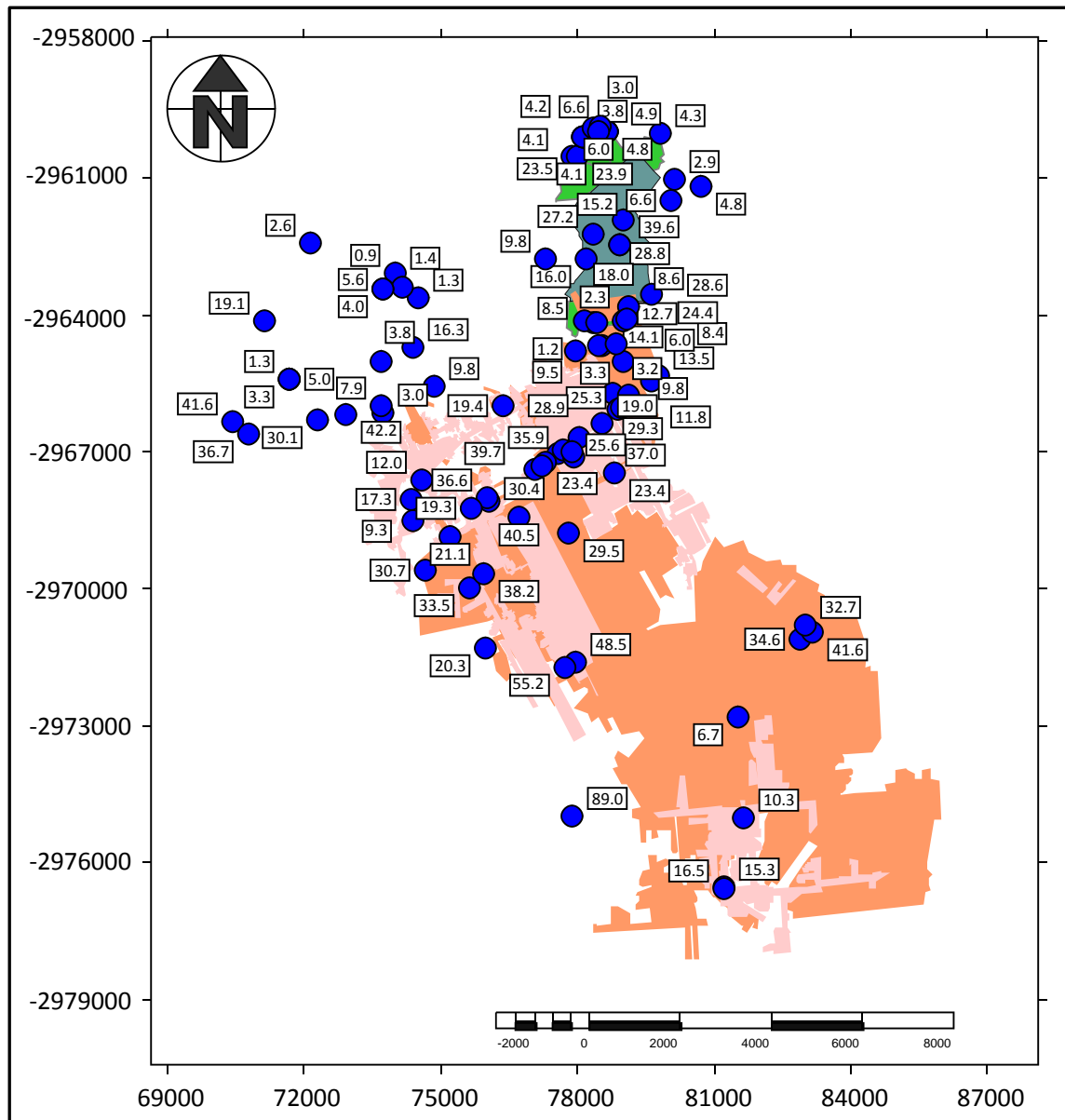
*Figure 9-1: All boreholes with water levels.*
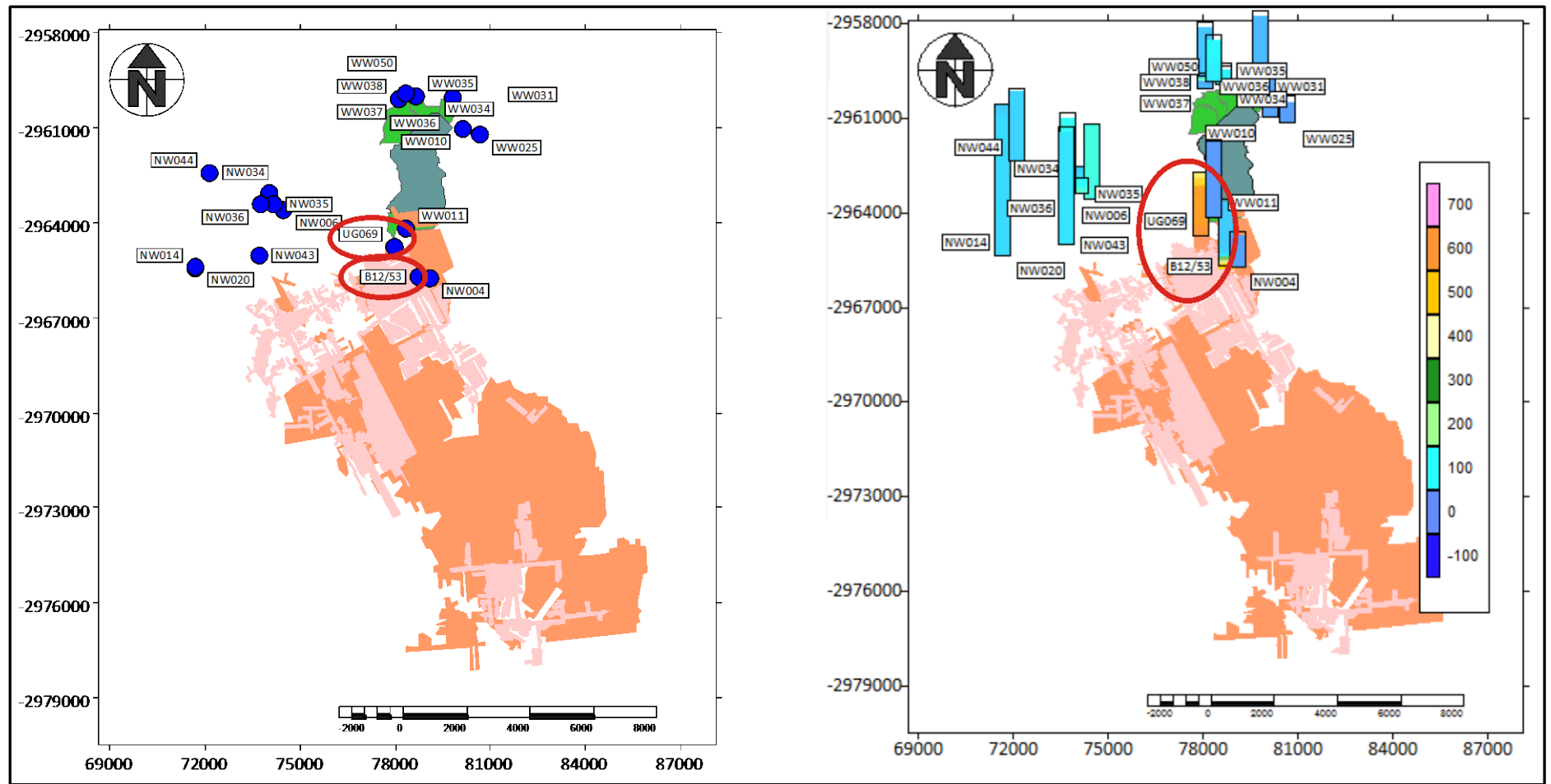
Figure 9-2: All boreholes with water levels equal to, or shallower than 5 mbgl, and their EC profiles.

All the boreholes and their EC profiles with water levels between 5 mbgl and 10 mbgl and equal to 10 mbgl, were plotted in Figure 9-3. Borehole B12/183 (encircled in red in Figure 9-3) is an ashfill borehole and according to SANS 241:2006 drinking water standards, has EC concentrations which are within Class 2. The deep sample (B12/183D) has an EC concentration of 255 mS/m and the middle sample (B12/183M) has an EC concentration of 202 mS/m. These two samples are classified as Class 2 (Table 9-1 and Table 9-3). The shallow sample, B12/183S, has an EC concentration of 106 mS/m which is within the recommended operational limits. The $SO_4$ concentration of B12/183D (1050 mg/l) and B12/183M (803 mg/l) are above the maximum allowable limits, while B12/183S (309 mg/l) are within the maximum allowable limits. The water from this borehole is therefore not suitable for human consumption. Borehole UG001 (151 mS/m) and WW024D (153 mS/m) both have EC concentrations which is within the maximum allowable limits and therefore water from these boreholes are therefore suitable for human consumption for a limited duration use only.

*Table 9-3: A summary of the water levels, EC values and $SO_4$ values of the boreholes with water levels between 5 mbgl and 10 mbgl and equal to 10 mbgl.*

| Borehole No | Water level | EC | SO4 |
|---|---|---|---|
| | | mS/m | mg/l |
| B12/183D | 5.96 | 255 | 1050.00 |
| B12/183M | 5.96 | 202 | 803.00 |
| B12/183S | 5.96 | 106 | 309.00 |
| C316/47 | 9.78 | 48.3 | 1.02 |
| NW001 | 9.75 | 71.2 | 73.50 |
| NW021 | 5.04 | 44.6 | 0.68 |
| NW037 | 5.56 | 87.6 | 3.09 |
| NW042 | 7.88 | 125 | -5.00 |
| UG001 | 6.7 | 151 | 36.57 |
| UG008 | 9.26 | 67.6 | 35.79 |
| UG033 | 9.54 | 144 | 343 |
| UG034 | 8.44 | 145 | 343 |
| WW008 | 8.55 | 9.41 | -0.50 |
| WW015 | 9.8 | 9.03 | 2.89 |
| WW024D | 6.6 | 153 | 296.11 |
| WW024S | | 42.3 | 81.87 |
| WW033 | 6.56 | 45 | 1.36 |
| WW045 | 8.49 | 5.1 | 1.92 |
| WW052 | 5.98 | 71 | 65.00 |

All boreholes with water levels between 10 mbgl and 20mbgl and equal to 20 mbgl, are plotted in Figure 9-4. According to the SANS 241:2006 drinking water standards, borehole UG027 which is encircled in red in Figure 9-4, has EC concentrations (335 mS/m) which is still within the maximum allowable limits (Table 9-1 and Table 9-4). The water from this borehole is therefore suitable for human consumption for a limited duration only.

*Table 9-4: A summary of the water levels, EC values and SO$_4$ values of the boreholes with water levels between 10 mbgl and 20mbgl and equal to 20 mbgl.*

| Borehole No | Water level | EC | SO4 |
|---|---|---|---|
| | | mS/m | mg/l |
| B12/179 | 14.11 | 124 | 112.48 |
| B12/182 | 13.48 | 34.5 | 36.85 |
| C316/41 | 11.82 | 69.4 | 0.51 |
| NW039 | 16.25 | 95.1 | 3.16 |
| NW046 | 19.14 | 56.5 | 22.24 |
| UG027D | 16.53 | 335 | 233.49 |
| UG027M | 16.53 | 20.5 | 1.02 |
| UG027S | 16.53 | 18.1 | 1.13 |
| UG030 | 17.32 | 29.6 | 24.38 |
| UG035 | 10.27 | 91.1 | 67.90 |
| UG040D | 19.36 | 139 | 273.01 |
| UG040S | 19.36 | 75.3 | 128.90 |
| UG041 | 18.96 | 47.5 | 60.70 |
| UG044 | 12.7 | 136 | 18 |
| UG053 | 11.96 | 47.6 | 7.79 |
| UG059 | 19.33 | 24.2 | 15.62 |
| WW006D | 15.99 | 16.5 | 1.26 |
| WW006S | 15.99 | 14.7 | 0.52 |
| WW028 | 15.24 | 112 | 371.42 |
| WW049 | 17.98 | 9.2 | 5.75 |

All boreholes between 20 mbgl and 30 mbgl and equal to 30 mbgl, were plotted in Figure 9-5. Borehole UG046 is encircled in red in Figure 9-5 and has and EC concentration (313 mS/m) which is still within the maximum allowable limits (Table 9-1 and Table 9-5) according to the SANS 241:2006 drinking water standards. Water from this borehole is therefore suitable for human consumption for a limited duration use only.

*Table 9-5: A summary of the water levels, EC values and SO₄ values of the boreholes with water levels between 20 mbgl and 30 mbgl and equal to 30 mbgl.*

| Borehole No | Water level | EC | SO4 |
|---|---|---|---|
| | | mS/m | mg/l |
| UG016 | 20.25 | 62.30 | 10.39 |
| UG023 | 29.49 | 61.20 | 32.83 |
| UG038 | 21.15 | 114.00 | 43.39 |
| UG046 | 23.36 | 313.00 | 57.49 |
| UG047 | 25.26 | 40.50 | 20.60 |
| UG055 | 29.27 | 31.80 | 36.00 |
| UG056 | 28.94 | 63.40 | 8.75 |
| UG065 | 25.58 | 62.30 | 6.96 |
| UG066 | 23.39 | 74.60 | 65.50 |
| WW004 | 23.54 | 42.30 | 76.90 |
| WW012 | 28.55 | 25.45 | 2.63 |
| WW018 | 23.94 | 46.50 | 11.20 |
| WW027 | 28.82 | 136.00 | 502.92 |
| WW029 | 27.23 | 98.00 | 222.00 |
| WW048 | 24.43 | 35.00 | 25.45 |

All the boreholes with water levels between 30 mbgl and 40 mbgl and equal to 40 mbgl, as well as their EC profiles, are displayed in Figure 9-6. Borehole UG072 is encircled in red on Figure 9-6. The deep sample, UG072D, has an EC concentration of 482 mS/m which is above the maximum allowable limits according to the SANS 241:2006 drinking water standards. It also has an $SO_4$ concentration of 520 mg/l which is still within the maximum allowable limits according to the SANS 241:2006 drinking water standards (Table 9-1 and Table 9-6). The middle sample (UG072M) has an EC concentration of 364 mS/m, which is also, still within the maximum allowable limits according to the SANS 241:2006 drinking water standards (Table 9-1 and Table 9-6). The water from borehole UG072 is therefore not suitable for human consumption.

*Table 9-6: A summary of the water levels, EC values and SO₄ values of the boreholes with water levels between 30 mbgl and 40 mbgl and equal to 40 mbgl.*

| Borehole No | Water level | EC | SO4 |
|---|---|---|---|
| | | mS/m | mg/l |
| B310/25 | 30.45 | 63.5 | 13.52 |
| NW041 | 30.13 | 44.6 | -0.50 |
| NW051 | 36.7 | 15.2 | 0.59 |
| UG002 | 33.52 | 108 | 124.14 |
| UG004 | 38.24 | 65.4 | 4.23 |
| UG024 | 30.72 | 106 | 3.74 |
| UG048 | 35.85 | 57.6 | 2.50 |
| UG049 | 39.69 | 62.4 | 3.05 |
| UG052 | 34.63 | 73.2 | 31.46 |
| UG058 | 36.59 | 46.3 | 19.51 |
| UG064 | 36.95 | 62.3 | 21.97 |
| UG072D | 32.68 | 482 | 520.00 |
| UG072M | 32.68 | 364 | 374.65 |
| UG072S | 32.68 | 73.8 | 21.97 |
| WW021D | 39.62 | 96.5 | 422 |
| WW021S | 39.62 | 95.3 | 416 |

All boreholes with water levels deeper than 40 mbgl and their EC profiles are plotted in Figure 9-7. Boreholes UG013, UG014, UG037 and UG071 are encircled in red in Figure 9-7. The deep sample of borehole UG013, UG013D, has an EC concentration (207 mS/m) and an SO₄ concentration (525.34 mg/l) which is still within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards (Table 9-1 and Table 9-7). Water from borehole UG013 is therefore suitable for human consumption for a limited duration use only. Borehole UG014 has an EC concentration of 176 mS/m which is still within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards (Table 9-1 and Table 9-7). Water from this borehole is therefore suitable for human consumption for a limited duration use only. The deep sample of borehole UG037, UG037D, has an EC concentration of 377 mS/m and a SO₄ concentration of 946 mg/l. These are both above the maximum allowable limits of the SANS 241:2006 drinking water standards (Table 9-1 and Table 9-7). The shallow sample of UG037, UG037S, has an EC concentration of 189 mS/m and an SO₄ concentration of 493.13 mg/l. They are therefore both still within the maximum allowable limits of the SANS 241:2006 drinking water standards (Table 9-1 and Table 9-7). Water from borehole UG037 is therefore unsuitable for human consumption. Borehole UG071 has an EC concentration of 218 mS/m, which is within the maximum

allowable limits of the SANS 241:2006 drinking water standards. Water from borehole UG071 is therefore suitable for human consumption for a limited duration use only.

*Table 9-7: A summary of the water levels, EC values and SO$_4$ values of the boreholes with water levels deeper than 40 mbgl.*

| Borehole No | Water level | EC | SO4 |
|---|---|---|---|
| | | mS/m | mg/l |
| NW040 | 42.21 | 75.3 | 77.40 |
| UG013D | 48.47 | 207 | 525.34 |
| UG013S | 48.47 | 55.3 | 58.40 |
| UG014 | 55.18 | 176 | 21.43 |
| UG019D | 88.95 | 74.1 | 1.21 |
| UG019S | 88.95 | 73.4 | 1.14 |
| UG037D | 40.49 | 377 | 946.00 |
| UG037S | 40.49 | 189 | 493.13 |
| UG071 | 41.61 | 218 | 205.08 |
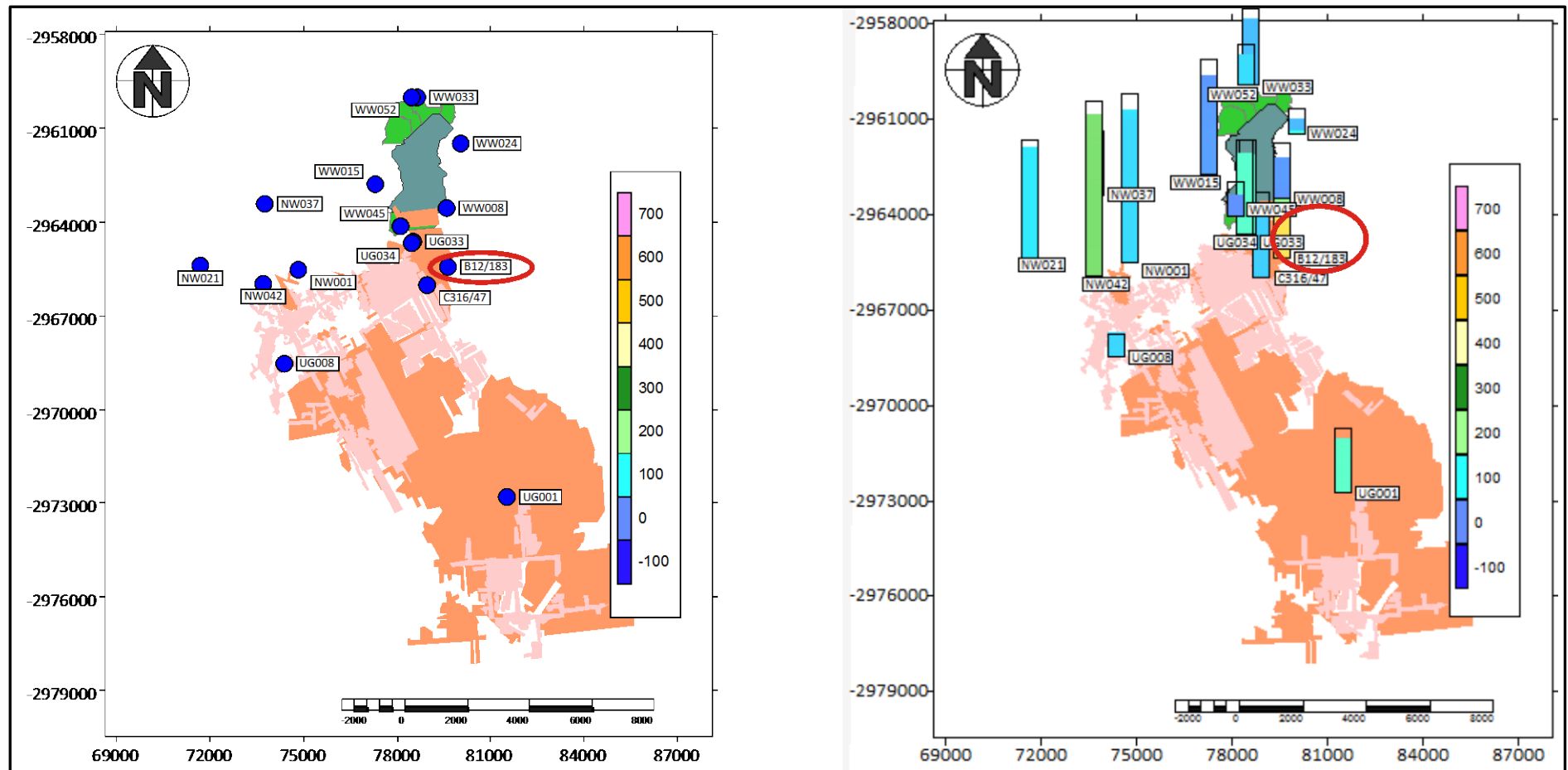
Figure 9-3: All boreholes with water levels between 5 and 10 mbgl and equal to 10 mbgl and their EC profiles.
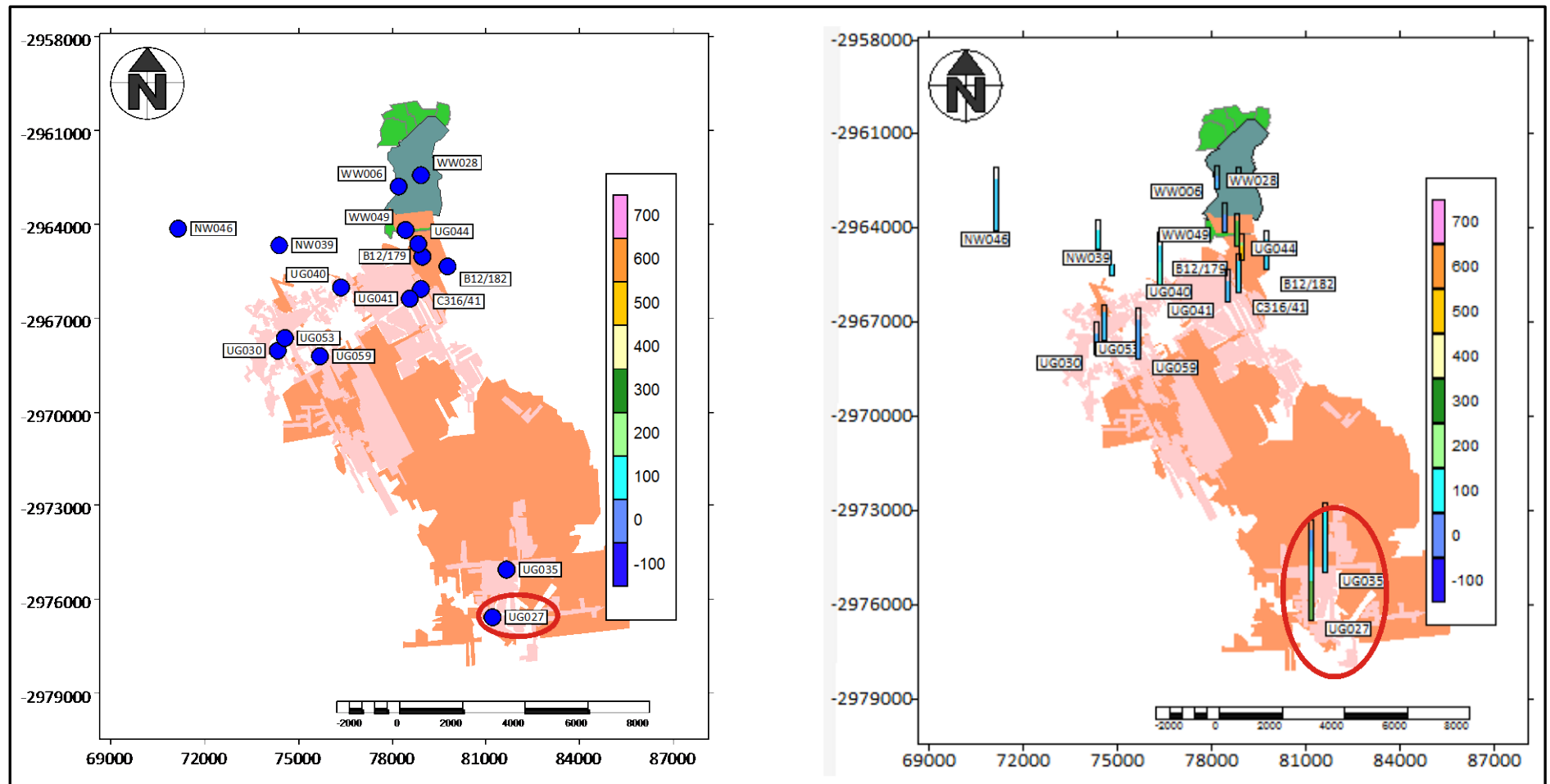
Figure 9-4: All boreholes with water levels between 10 and 20 mbgl and equal to 20 mbgl and their EC profiles.
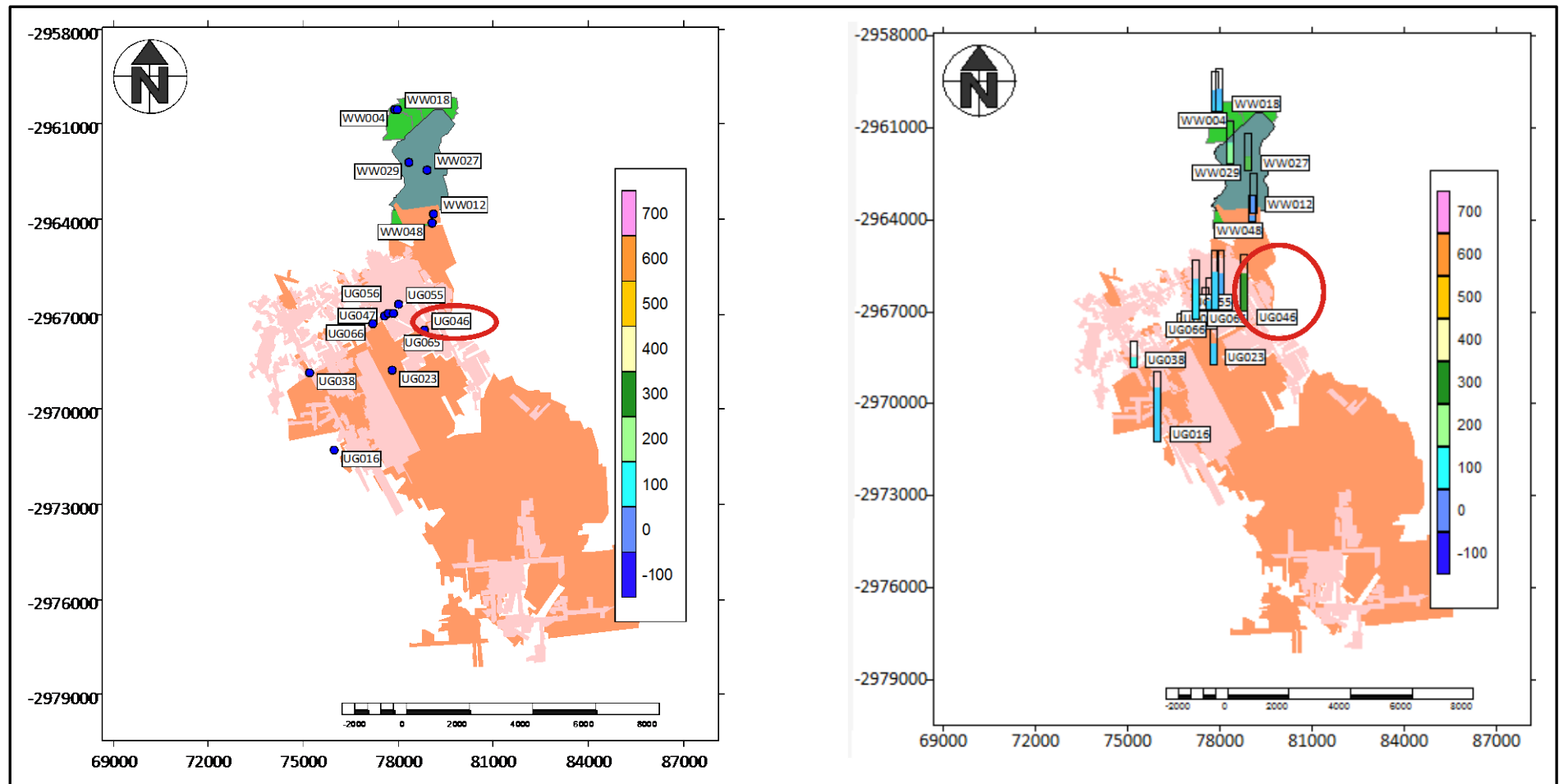
Figure 9-5: All boreholes with water levels between 20 and 30 mbgl and equal to 30 mbgl and their EC profiles.
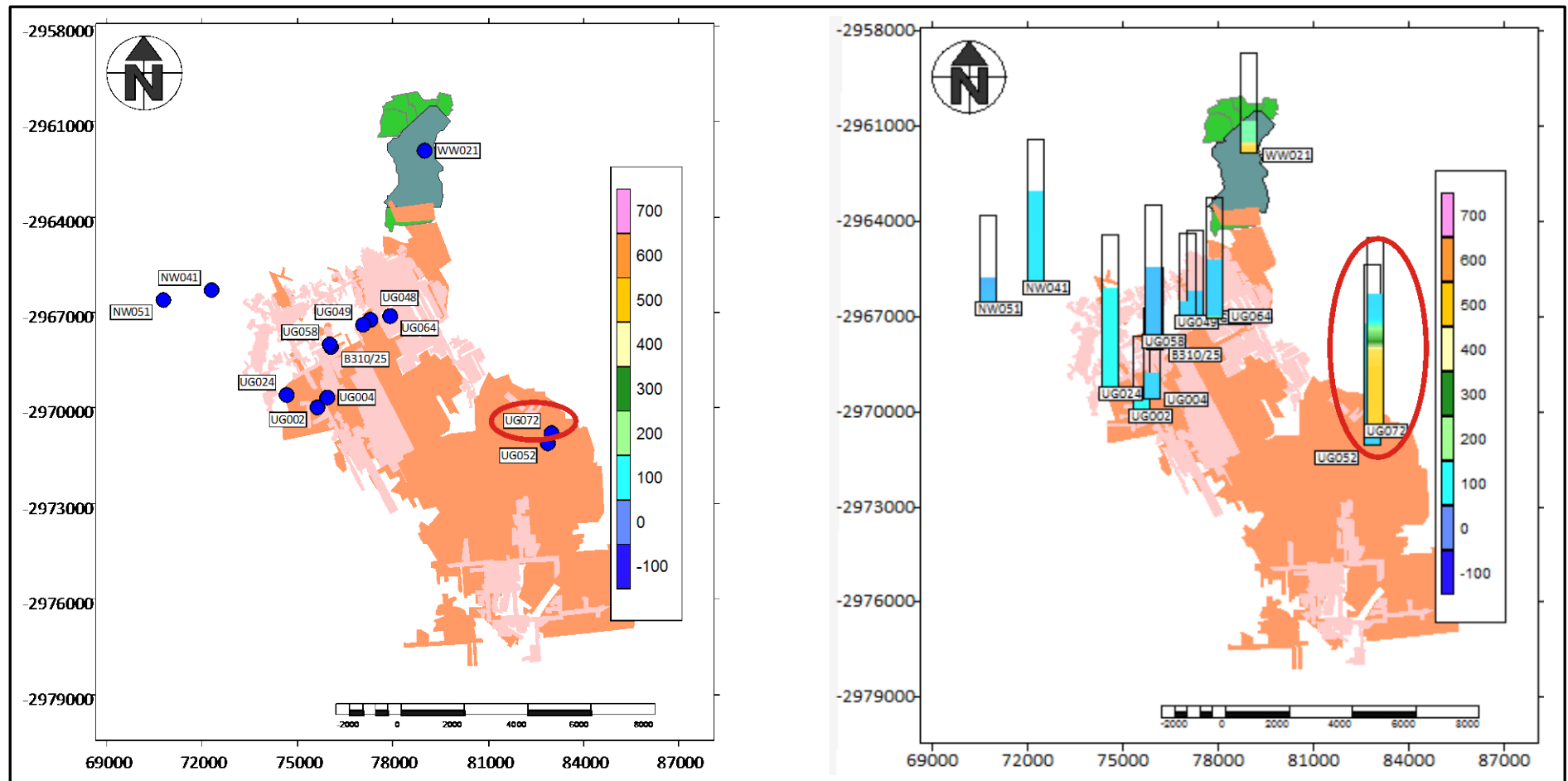
Figure 9-6: All boreholes with water levels between 30 and 40 mbgl and equal to 40 mbgl and their EC profiles.

*Figure 9-7: All boreholes with water levels deeper than 40 mbgl and their EC profiles.*

## 10. Groundwater Quality

Each accessible borehole that was profiled with the multi-parameter probe was sampled and analysed for inorganic constituents. The details of the samples and profiled boreholes are summarised in Table 10-1, Table 10-3, Table 10-5, Table 10-7 and Table 10-9 . Some boreholes will have more than one sample where stratification was observed on the chemical profile, as this was done to obtain a representative sample from a specific aquifer.

The water quality of the boreholes will be discussed for each aquifer. The discussion will include a locality map of the boreholes, a general water quality discussion according to SANS 241:2006 standards and hydrochemical characterisation through interpretive diagrams.

The criteria used for inorganic sampling is the SANS 241:2006 standards. The inorganic water samples are classified as follow and will be the same for all the aquifers discussed:

- Class 1 - **Recommended operational limit** - Suitable for lifetime use (colour coded green).
- Class II - **Maximum allowable limit** - Suitable for limited duration use only (colour coded yellow).
- AMA - **Above maximum allowable limit** - Unsuitable for human consumption (colour coded red).

Only water qualities within Class II (yellow) and Class III (red) are coloured in order to identify problem areas.

The interpretive diagrams used are the Expanded Durov Diagram and STIFF Diagrams. Trilinear diagrams were created using the WISH software.

STIFF Diagrams are graphical representations of water chemical analyses. A polygonal shape is created from three or four horizontal axes extending on either side of a vertical zero axis. Cations are plotted in milli equivalents per litre on the left side of the zero axis, one to each horizontal axis and anions are plotted on the right side. STIFF Diagrams are useful in making a rapid visual comparison between water from

different sources and to ascertain if similarities exist between samples.  An example of a STIFF Diagram is illustrated in Figure 10-2.

The Expanded Durov Diagram uses similar ratio techniques as the Piper Diagram to position the concentrations of the major ions, but six triangular diagrams are however used; three for the anions and three for the cations. The Expanded Durov Diagram is divided into nine areas, each corresponding to a water type.  An example of how the Expanded Durov Diagram and Piper Diagrams are used for water characterisation is illustrated in Figure 10-1.
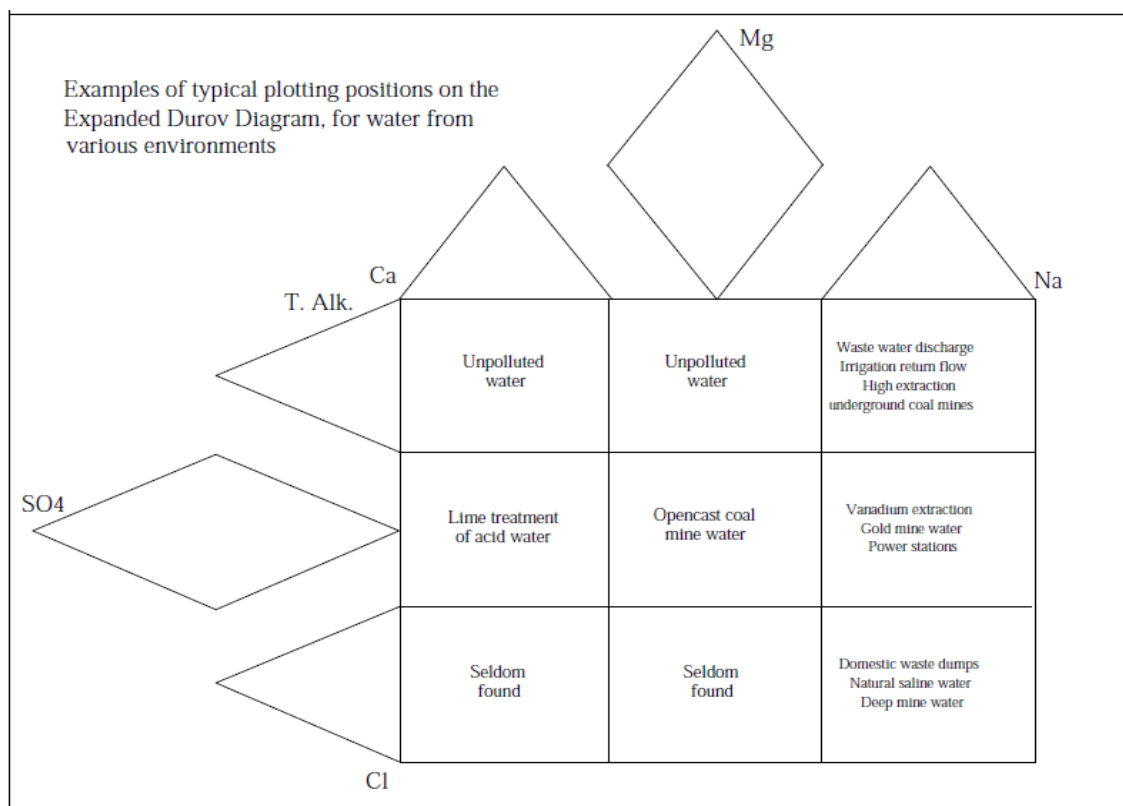


*Figure 10-1: An explanation of the Expanded Durov and Piper Diagrams. Modified after Department of Water Affairs and Forrestry (1998).*
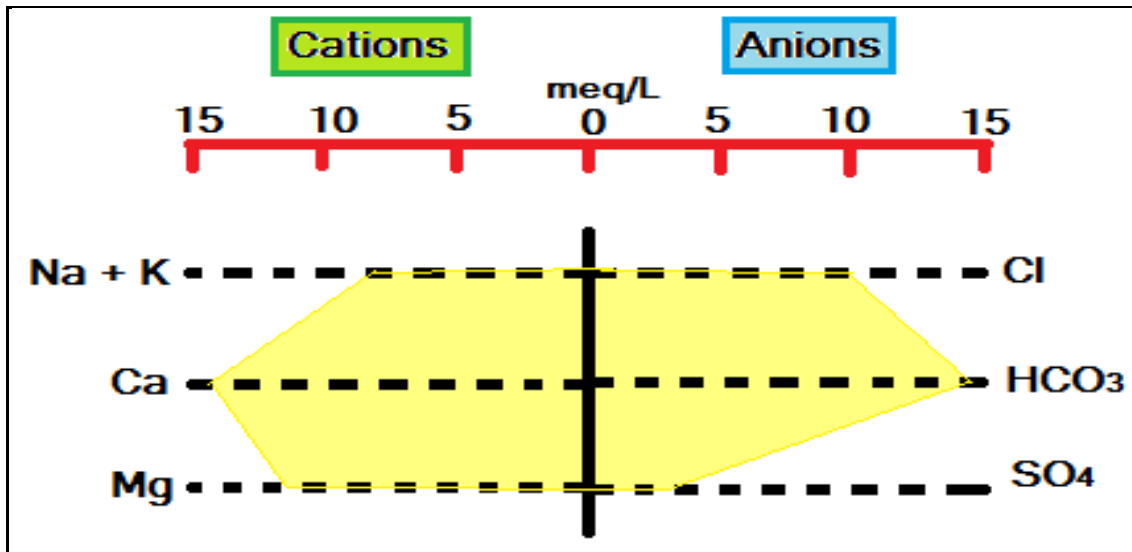
*Figure 10-2: An example of a STIFF Diagram.*

## 10.1 Groundwater quality of the boreholes in the shallow aquifer

A total of 11 boreholes were sampled in the shallow aquifer and a summary of these boreholes can be found in Table 10-1. The locality map of the boreholes in the shallow aquifer can be viewed in Figure 10-3.

*Table 10-1: Summary of the boreholes in the shallow aquifer.*

| Date sampled | Borehole ID | Sample ID | Water level | Sampling depth (mbcl) |
|---|---|---|---|---|
| | | Shallow aquifer | | |
| 06/06/2012 | WW024 | WW024D | 6.60 | 15.00 |
| | | WW024S | | 10.00 |
| 06/06/2012 | WW025 | WW025 | 4.82 | 10.00 |
| 04/06/2012 | WW034 | WW034 | 4.84 | 10.00 |
| 04/06/2012 | WW035 | WW035 | 4.89 | 10.00 |
| 04/06/2012 | WW037 | WW037 | 3.81 | 10.00 |
| 04/06/2012 | WW038 | WW038 | 4.10 | 8.00 |
| 01/06/2012 | WW045 | WW045 | 8.49 | 15.00 |
| 04/06/2012 | WW050 | WW050 | 4.21 | 20.00 |
| 04/06/2012 | WW052 | WW052 | 5.98 | 15.00 |
| 31/05/2012 | NW034 | NW034 | 0.94 | 9.00 |
| 31/05/2012 | NW035 | NW035 | 1.40 | 9.00 |
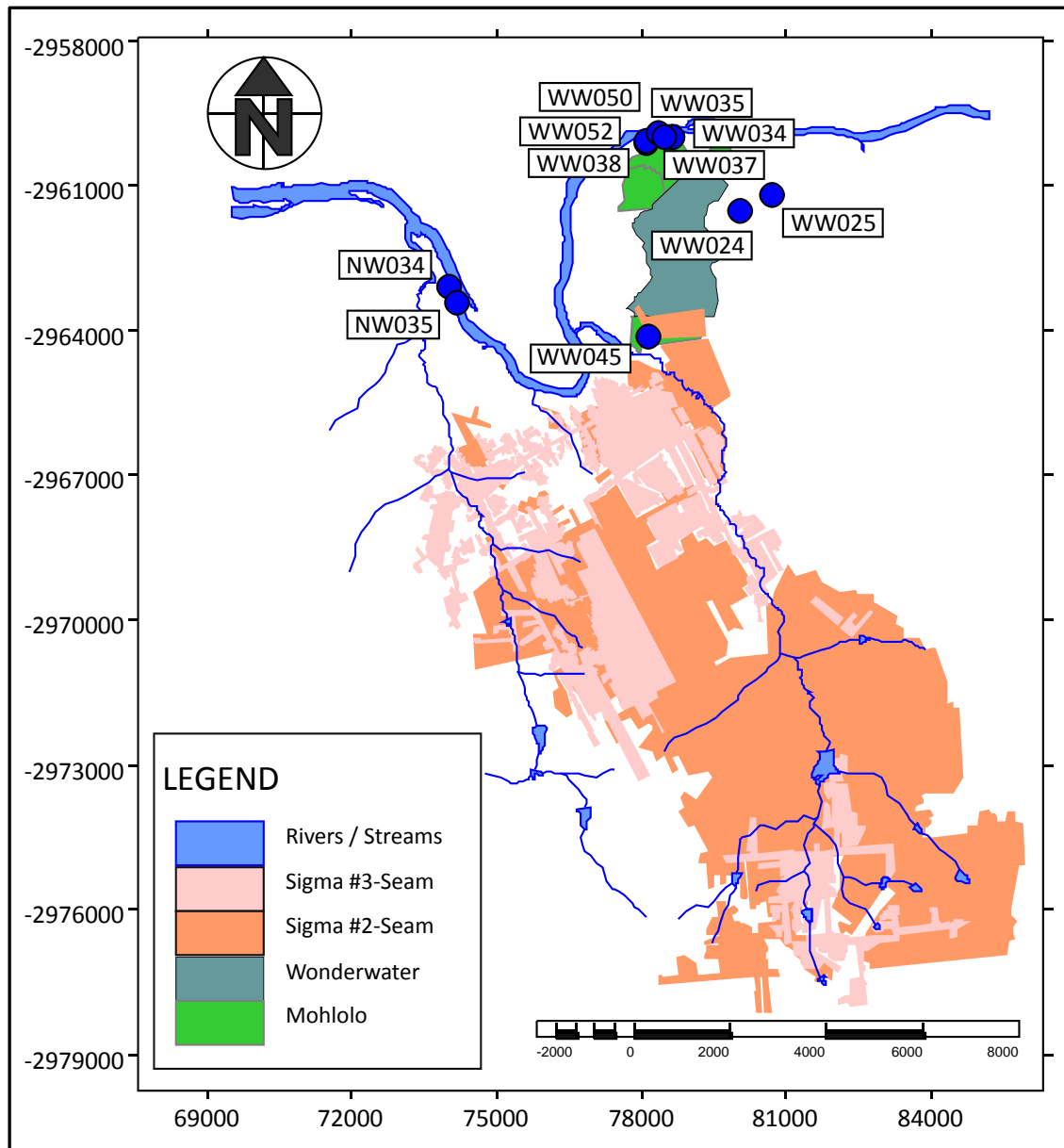
*Figure 10-3: Locality map of the boreholes in the shallow aquifer.*

## 10.1.1 General water quality discussion for boreholes in the shallow aquifer

The water quality results for the boreholes sampled are presented in Table 10-2. In order to identify problem areas, only water qualities within Class II (yellow) and Class III (red) are coloured.

Table 10-2: SANS 241:2006 drinking water standards table of the boreholes in the shallow aquifer.

| Borehole No | | pH | EC | Ca | Mg | Na | K | Palk | Malk | F | Cl | NO2(N) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mS/m | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l |
| | Class 1 | 0-9.5 | 0-150 | 0-150 | 0-70 | 0-200 | 0-50 | | | 0-1 | 0-200 | |
| | Class 2 | 9.5-10 | 151-370 | 151-300 | 71-100 | 201-400 | 51-100 | | | 1-1.5 | 200-600 | |
| | AMA | >10 | >370 | >300 | >100 | >400 | >100 | | | >1.5 | >600 | |
| WW024D | AMA | 7.67 | 153 | 124.48 | 104.43 | 47.89 | 4.244 | 0 | 128 | -0.10 | 270.40 | -0.10 |
| WW024S | Class 1 | 7.40 | 42.3 | 30.58 | 22.71 | 16.18 | 2.160 | 0 | 79 | 0.05 | 25.15 | -0.01 |
| WW025 | Class 1 | 6.92 | 15.0 | 8.45 | 6.23 | 14.42 | 1.377 | 0 | 27 | 0.00 | 7.11 | -0.01 |
| WW034 | Class 2 | 7.98 | 89 | 83.16 | 47.03 | 57.26 | 3.771 | 0 | 399 | 0.02 | 73.54 | -0.01 |
| WW035 | Class 1 | 8.05 | 88 | 79.22 | 46.56 | 55.98 | 3.376 | 0 | 399 | 0.05 | 67.48 | -0.01 |
| WW037 | Class 2 | 8.26 | 169 | 112.23 | 72.69 | 201.39 | 0.431 | 0 | 615 | -0.10 | 96.85 | -0.10 |
| WW038 | Class 2 | 8.45 | 38 | 11.78 | 7.25 | 62.87 | 2.294 | 5.71 | 184 | 0.17 | 14.89 | -0.01 |
| WW045 | Class 1 | 6.79 | 5.1 | 1.33 | 0.65 | 10.20 | 1.195 | 0 | 22.9 | 0.20 | 3.28 | 0.01 |
| WW050 | Class 1 | 8.58 | 94 | 52.76 | 29.62 | 110.41 | 1.242 | 0 | 390 | 0.53 | 49.16 | 0.04 |
| WW052 | Class 1 | 8.20 | 71 | 56.50 | 30.23 | 50.77 | 2.803 | 0 | 245 | 0.02 | 62.10 | -0.01 |
| NW034 | Class 1 | 8.16 | 78.2 | 37.28 | 42.34 | 53.60 | 0.810 | 0 | 98.8 | 0.10 | 97.80 | -0.01 |
| NW035 | Class 2 | 8.19 | 138 | 104.96 | 90.06 | 73.80 | 1.246 | 0 | 330 | -0.10 | 168.99 | -0.10 |

Table 10-2: SANS 241:2006 drinking water standards table of the boreholes in the shallow aquifer (Continued).

| Borehole No | | Br mg/l | NO3(N) mg/l | PO4 mg/l | SO4 mg/l | Al mg/l | Fe mg/l | Mn mg/l | NH4(N) mg/l | Ba mg/l | Co mg/l | Cr mg/l |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Class 1 | | 0-10 | | 0-400 | 0-0.3 | 0-0.2 | 0-0.1 | 0-1 | | 0-0.5 | 0-0.1 |
| | Class 2 | | 10-20 | | 401-600 | 0.3-0.5 | 0.2-2 | 0.1-1 | 1-2 | | 0.5-1 | 0.1-0.5 |
| | AMA | | >20 | | >600 | >0.5 | >2 | >1 | >2 | | >1 | >0.5 |
| WW024D | AMA | -0.40 | 1.46 | -1.00 | 296.11 | <0.004 | 0.000 | 2.736 | | 0.087 | 0.011 | <0.006 |
| WW024S | Class 1 | 0.31 | 8.41 | -0.10 | 81.87 | 0.008 | 0.003 | 0.014 | 0.020 | 0.068 | <0.002 | <0.006 |
| WW025 | Class 1 | -0.04 | 0.32 | -0.10 | 48.23 | 0.019 | 0.005 | 0.013 | 0.010 | 0.074 | <0.002 | <0.006 |
| WW034 | Class 2 | 0.23 | 0.53 | -0.10 | 5.02 | 0.012 | -0.003 | 0.656 | | 0.111 | <0.002 | <0.006 |
| WW035 | Class 1 | 0.18 | 0.47 | -0.10 | 6.10 | 0.020 | 0.002 | 0.010 | | 0.125 | <0.002 | <0.006 |
| WW037 | Class 2 | -0.40 | -0.50 | -1.00 | 213.12 | 0.066 | 0.025 | 0.017 | | 0.149 | <0.002 | <0.006 |
| WW038 | Class 2 | -0.04 | -0.05 | -0.10 | 6.27 | 0.074 | 0.282 | 0.012 | | 0.014 | <0.002 | <0.006 |
| WW045 | Class 1 | -0.04 | 0.26 | -0.10 | 1.92 | 0.044 | 0.103 | 0.006 | 0.000 | 0.007 | <0.002 | <0.006 |
| WW050 | Class 1 | 0.14 | -0.05 | -0.10 | 67.90 | 0.163 | 0.095 | 0.019 | | 0.330 | <0.002 | <0.006 |
| WW052 | Class 1 | 0.18 | -0.05 | 0.21 | 65.00 | 0.053 | 0.037 | 0.042 | 0.020 | 0.313 | 0.003 | <0.006 |
| NW034 | Class 1 | 0.29 | 3.59 | -0.10 | 167.7 | <0.004 | 0.004 | 0.013 | | 0.093 | <0.002 | <0.006 |
| NW035 | Class 2 | -0.40 | 0.96 | -1.00 | 201.78 | <0.004 | -0.011 | 0.014 | | 0.163 | <0.002 | <0.006 |

Table 10-2: SANS 241:2006 drinking water standards table of the boreholes in the shallow aquifer (Continued).

| Borehole No | | Cu | U | V | Zn | Si | B | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | | | | | |
| | Class 1 | 0-1 | 0-4 | 0-0.2 | 0-5 | | 0-2 | | | | | |
| | Class 2 | 1-2 | 4-8 | 0.2-0.5 | 5-10 | | 2-4 | | | | | |
| | AMA | >2 | >8 | >0.5 | >10 | | >4 | | | | | |
| WW024D | AMA | 0.009 | <0.010 | <0.010 | 0.022 | 8.123 | 0.132 | | | | | |
| WW024S | Class 1 | 0.003 | <0.010 | <0.010 | 0.016 | 13.880 | 0.087 | | | | | |
| WW025 | Class 1 | 0.004 | <0.010 | <0.010 | 0.015 | 5.040 | 0.083 | | | | | |
| WW034 | Class 2 | 0.003 | <0.010 | <0.010 | 0.004 | 13.158 | 0.129 | | | | | |
| WW035 | Class 1 | 0.005 | 0.011 | <0.010 | 0.005 | 12.968 | 0.125 | | | | | |
| WW037 | Class 2 | 0.003 | 0.047 | 0.112 | 0.012 | 20.637 | 0.108 | | | | | |
| WW038 | Class 2 | 0.005 | <0.010 | <0.010 | 0.007 | 1.797 | 0.092 | | | | | |
| WW045 | Class 1 | 0.001 | <0.010 | <0.010 | 0.006 | 7.107 | 0.073 | | | | | |
| WW050 | Class 1 | 0.007 | <0.010 | 0.191 | 0.013 | 12.782 | 0.712 | | | | | |
| WW052 | Class 1 | 0.004 | <0.010 | 0.036 | 0.010 | 12.328 | 0.096 | | | | | |
| NW034 | Class 1 | 0.006 | <0.010 | <0.010 | 0.015 | 9.630 | 0.066 | | | | | |
| NW035 | Class 2 | 0.003 | 0.014 | <0.010 | 0.007 | 12.667 | 0.064 | | | | | |

The proportional distribution of electrical conductivity and the magnesium concentrations are illustrated in Figure 10-4 and Figure 10-5.

According to Table 10-2, most of the boreholes in the shallow aquifer are not polluted.

- Sample WW024D have an EC concentration of 153 mS/m and a chloride concentration of 270.4 mg/l. Both these parameters are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards. The magnesium concentration (104.43 mg/l) and the manganese concentration (2.736 mg/l) are both above the maximum allowable limits (Class 3) of the SANS 241:2006 drinking water standards. The water from borehole WW024 is therefore classified as AMA (above the maximum allowable limits) of the SANS 241:2006 drinking water standards and is therefore not suitable for human consumption.

- Borehole WW034 has a manganese concentration of 0.656 mg/l which is within the maximum allowable limits of the SANS241:2006 drinking water standards. Water from this borehole is therefore in Class 2 of the SANS 241:2006 drinking water standards and is suitable for human consumption for a limited duration use only.

- Borehole WW037 has an electrical conductivity concentration of 169 mS/m, a magnesium concentration of 72.69 mg/l and a sodium concentration of 201.39 mg/l. All of these parameters are still within the maximum allowable limits of the SANS 241:2006 drinking water standards. Water from borehole WW037 is therefore in Class 2 of the SANS 241:2006 drinking water standards and is suitable for human consumption for a limited duration use only.

- Borehole WW038 has an iron concentration of 0.282 mg/l which is still within the maximum allowable limits of the SANS 241:2006 drinking water standards. Water from borehole WW038 is therefore in Class 2 of the SANS 241:2006 drinking water standards and is suitable for human consumption for a limited duration use only.

- Borehole NW035 has a magnesium concentration of 90.06 mg/l which is still within the maximum allowable limits of the SANS 241:2006 drinking water standards. Water from borehole NW035 is therefore in Class 2 of the SANS 241:2006 drinking water standards and is suitable for human consumption for a limited duration use only.
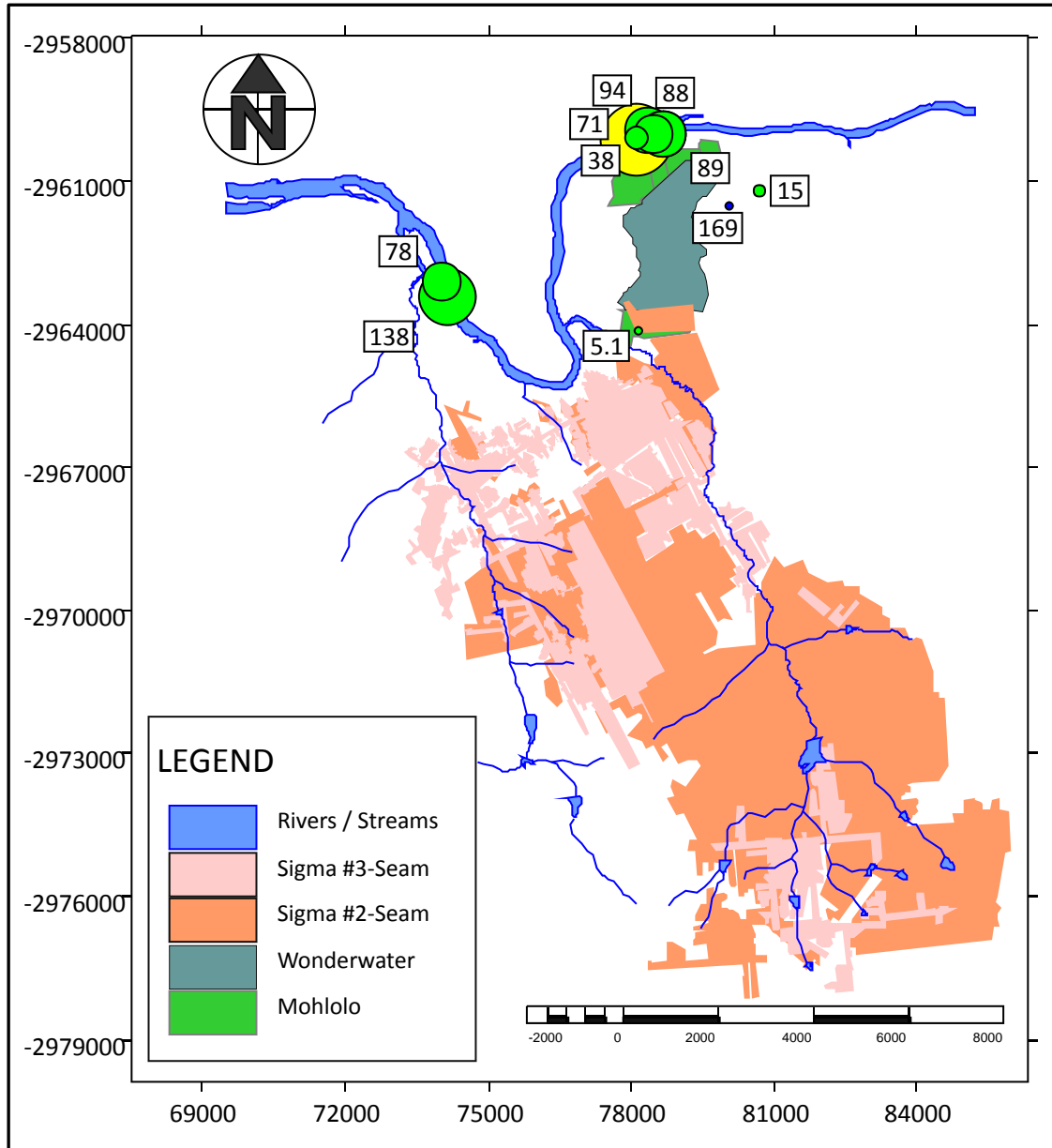
Figure 10-4: Proportional distribution of the electrical conductivity values of the boreholes in the shallow aquifer.
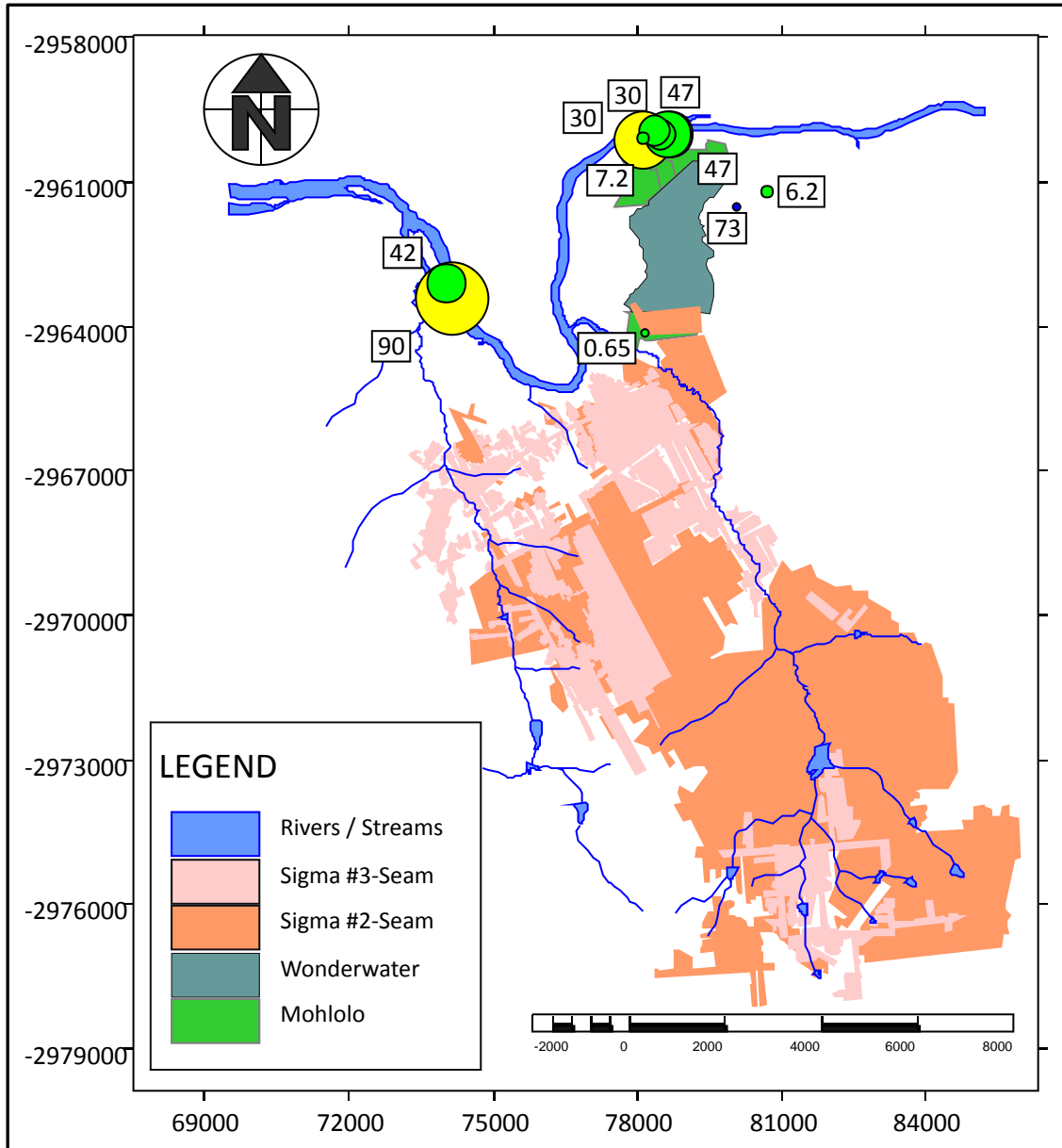
*Figure 10-5: Proportional distribution of the magnesium concentrations of the boreholes in the shallow aquifer.*

### 10.1.2 Hydrochemical characterisation of boreholes in the shallow aquifer through interpretive diagrams

- From the expanded Durov Diagram (Figure 10-6) it can be noted that samples WW034, WW035, WW037, WW050 and WW052 plots in the second area. This indicates that the water from these samples is either magnesium bicarbonate dominant, or calcium magnesium dominant which is typical of unpolluted water.

- Samples WW038 and WW045 plots in the third area. This indicates sodium bicarbonate dominance of the water which could be due to the Ecca geology.
- Samples WW024D, WW024S, WW025, NW035 and NW034 plots in the fifth area. This area indicates that there are no dominant cations or anions present in the water from these samples and can indicate possible impact due to opencast coal mining activity.
- From the stiff diagrams in Figure 10-7 it can be noted that samples WW034 and WW035 are the same type of water and are both calcium/magnesium bicarbonate waters which is typical of unpolluted water.
- Samples WW037, WW038 and WW050 are the same type of water and are sodium bicarbonate dominant water which is typical of high extraction underground coal mining activity.
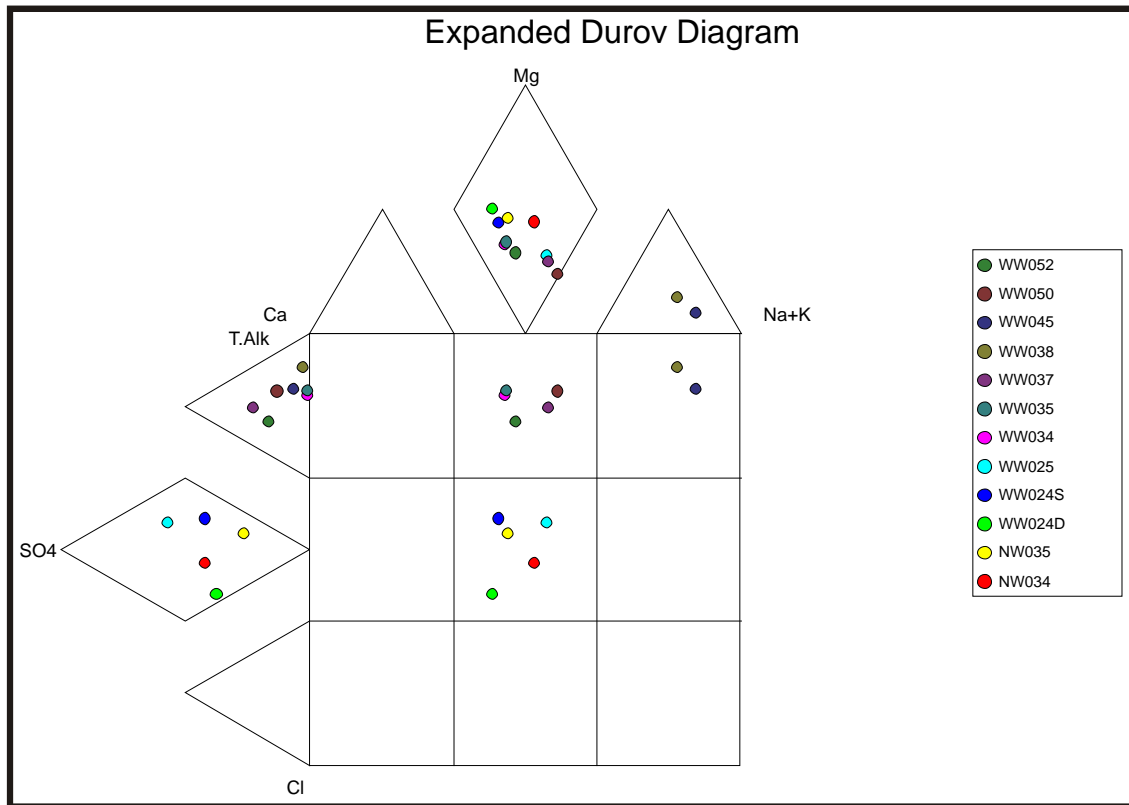


*Figure 10-6: Expanded Durov Diagram of the boreholes in the shallow aquifer.*
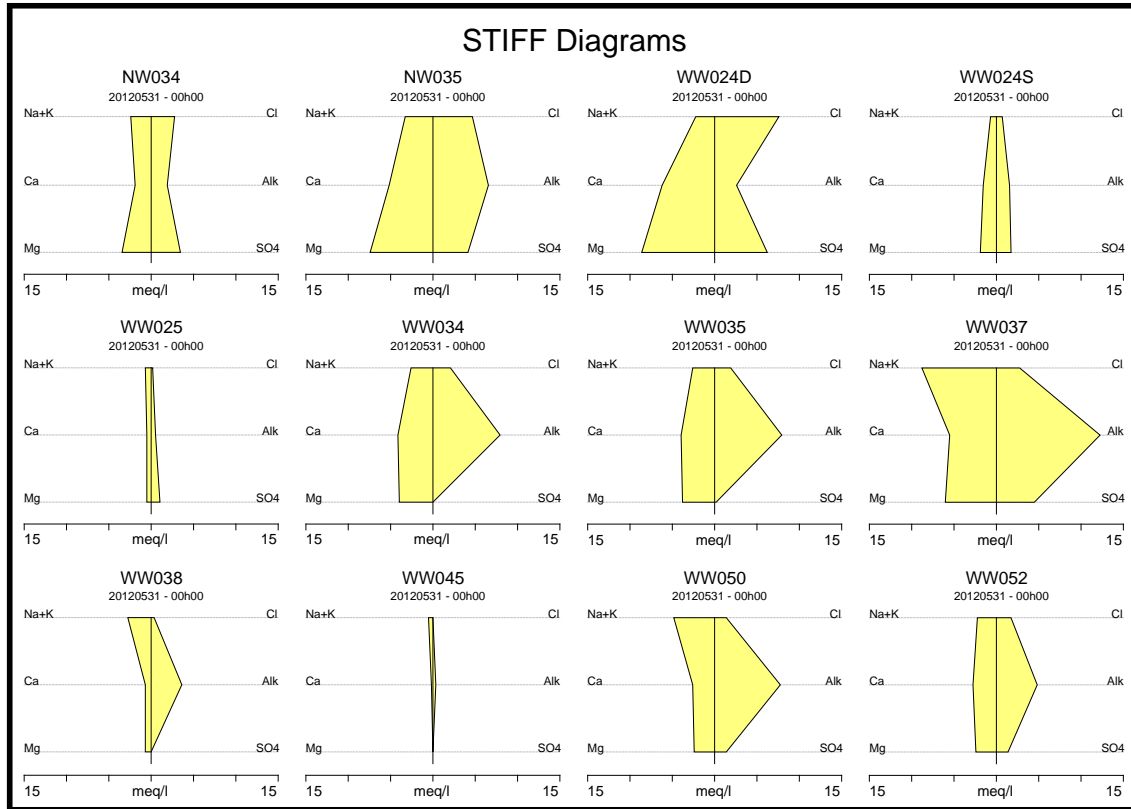
Figure 10-7: STIFF Diagrams of the boreholes in the shallow aquifer.

## 10.2 Groundwater quality of the boreholes in the intermediate aquifer

A total of 22 boreholes were sampled in the intermediate aquifer and a summary of the boreholes are available in Table 10-3. A locality map of the boreholes in the intermediate aquifer can be viewed in Figure 10-8.

Table 10-3: A summary of the boreholes sampled in the intermediate aquifer.

| Date sampled | Borehole ID | Sample ID | Water level | Sampling depth (mbcl) |
|---|---|---|---|---|
| Intermediate aquifer | | | | |
| 06/06/2012 | WW004 | WW004 | 23.54 | 35.00 |
| 01/06/2012 | WW006 | WW006D | 15.99 | 37.00 |
| | | WW006S | | 24.00 |
| 06/06/2012 | WW008 | WW008 | 8.55 | 20.00 |
| 06/06/2012 | WW010 | WW010 | 2.91 | 20.00 |
| 07/06/2012 | WW015 | WW015 | 9.80 | 20.00 |
| 04/06/2012 | WW018 | WW018 | 23.94 | 40.00 |
| 07/06/2012 | WW031 | WW031 | 4.30 | 20.00 |
| 04/06/2012 | WW033 | WW033 | 6.56 | 25.00 |
| 04/06/2012 | WW036 | WW036 | 4.13 | 20.00 |
| 01/06/2012 | WW048 | WW048 | 24.43 | 30.00 |
| 01/06/2012 | WW049 | WW049 | 17.98 | 35.00 |
| 30/05/2012 | NW004 | NW004 | 3.18 | 15.00 |
| 31/05/2012 | NW014 | NW014 | 3.30 | 17.00 |
| 31/05/2012 | NW021 | NW021 | 5.04 | 22.00 |
| 31/05/2012 | NW037 | NW037 | 5.56 | 20.00 |
| 31/05/2012 | NW039 | NW039 | 16.25 | 30.00 |
| 02/07/2012 | UG001 | UG001 | 6.70 | 15.00 |
| 30/05/2012 | UG008 | UG008 | 9.26 | 25.00 |
| 05/06/2012 | UG016 | UG016 | 20.25 | 35.00 |
| 08/06/2012 | UG035 | UG035 | 10.27 | 20.00 |
| 30/05/2012 | UG038 | UG038 | 21.15 | 30.00 |
| 02/07/2012 | B310/25 | B310/25 | 30.45 | 45.00 |
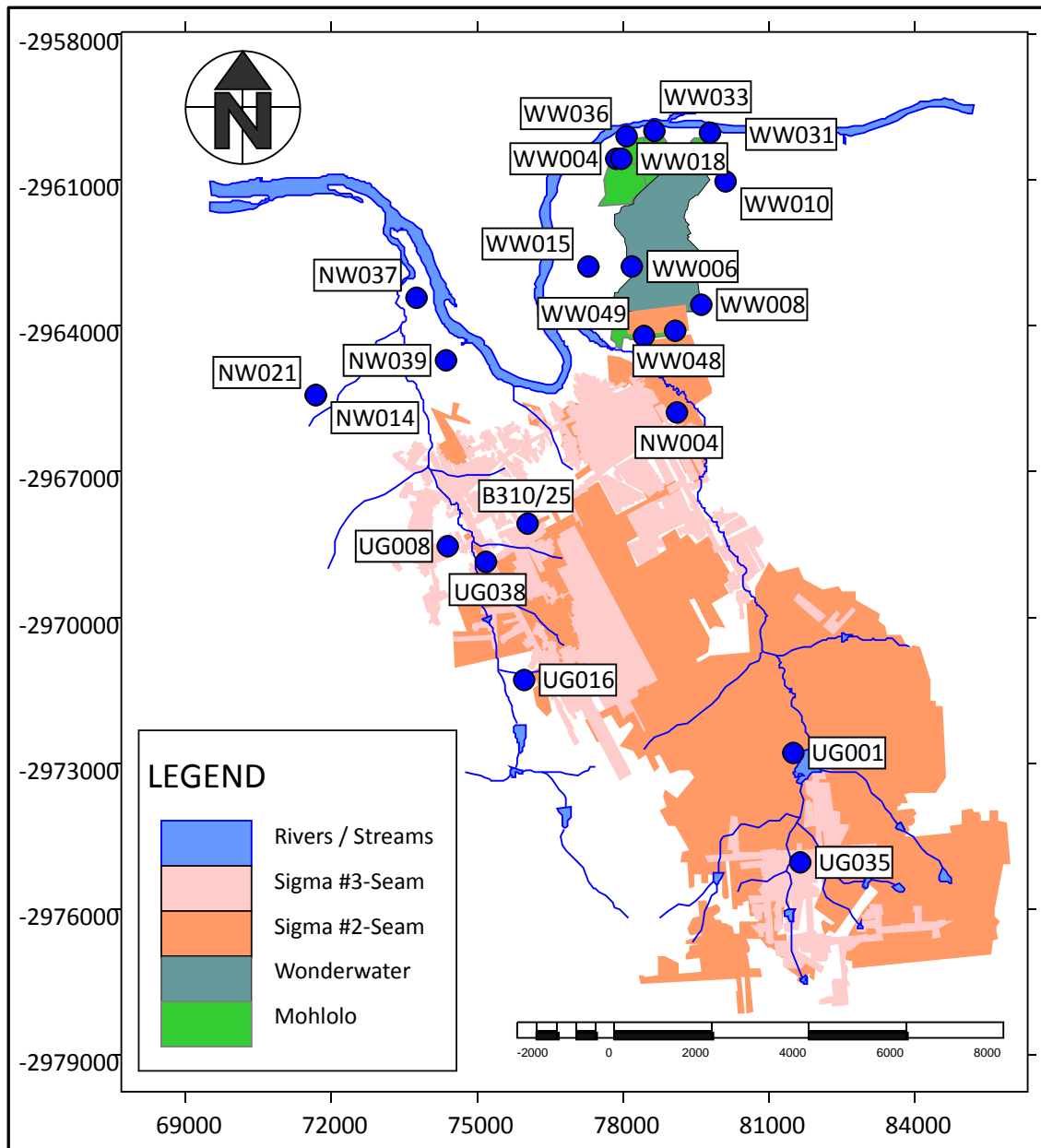
*Figure 10-8: Locality map of the boreholes in the intermediate aquifer.*

## 10.2.1 General water quality discussion for the boreholes in the intermediate aquifer

The proportional distribution of the electrical conductivity can be viewed in Figure 10-9. The SANS 241:2006 table for the intermediate aquifer can be viewed in Table 10-4.

- Sample WW006D has a nitrate concentration of 15.17 mg/l which is still within the maximum allowable limits of the SANS 241:2006 drinking water standards. Water from borehole WW006 is therefore in Class 2 of the SANS 241:2006

drinking water standards and is suitable for human consumption for a limited duration use only.

- Borehole WW036 has a fluoride concentration of 1.97 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards. The high fluoride concentration could be attributed to the local geology as leaching of certain secondary minerals, for example apatite and fluorspar, which will elevate fluoride concentrations. Water from borehole WW036 is therefore AMA (above the maximum allowable limits) of the SANS 241:2006 drinking water standards and is not suitable for human consumption.

- Borehole WW048 has an iron concentration of 0.543 mg/l which is still within the maximum allowable limits of the SANS 241:2006 drinking water standards. Water from borehole WW048 is therefore in Class 2 of the SANS 241:2006 drinking water standards and is suitable for human consumption for a limited duration use only.

- Borehole NW021 has a fluoride concentration of 2.40 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards. This high fluoride concentration could be attributed to the local geology. Water from borehole NW021 is therefore AMA (above the maximum allowable limit) and not suitable for human consumption.

- Borehole NW037 has a fluoride concentration of 2.80 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards. This high fluoride concentration could be attributed to the local geology. Water from borehole NW037 is therefore AMA (above the maximum allowable limit) and not suitable for human consumption.

- Borehole UG001 has an EC concentration of 151 mS/m which is within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards. Borehole UG001 also have a nitrate concentration of 49.33 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards. This high nitrate concentration could be attributed to the feeding paddocks in the vicinity of the borehole. Water from borehole UG001 is therefore AMA (above the maximum allowable limits) of the SANS 241:2006 drinking water standards and is not suitable for human consumption.

- Borehole UG038 has a fluoride concentration of 1.05 mg/l and a nitrate concentration of 11.40 mg/l. Both these parameters are within the maximum allowable limits of the SANS 241:2006 drinking water standards and is suitable for human consumption for a limited duration use only.

Table 10-4: SANS241:2006 water standards table for the boreholes in the intermediate aquifer.

| Borehole No | | pH | EC | Ca | Mg | Na | K | Palk | Malk | F | Cl | NO2(N) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mS/m | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l |
| | Class 1 | 0-9.5 | 0-150 | 0-150 | 0-70 | 0-200 | 0-50 | | | 0-1 | 0-200 | |
| | Class 2 | 9.5-10 | 151-370 | 151-300 | 71-100 | 201-400 | 51-100 | | | 1-1.5 | 200-600 | |
| | AMA | >10 | >370 | >300 | >100 | >400 | >100 | | | >1.5 | >600 | |
| WW004 | Class 1 | 7.57 | 42.3 | 29.69 | 11.69 | 32.93 | 2.646 | 0 | 82 | 0.07 | 38.19 | -0.01 |
| WW006D | Class 2 | 6.82 | 16.5 | 10.20 | 5.41 | 11.90 | 2.591 | 0 | 20 | 0.07 | 6.39 | -0.01 |
| WW006S | Class 1 | 7.09 | 14.7 | 10.90 | 5.75 | 6.65 | 3.041 | 0 | 42 | 0.09 | 4.01 | -0.01 |
| WW008 | Class 1 | 5.90 | 9.41 | 6.98 | 1.97 | 7.22 | 2.954 | 0 | 9.1 | 0.02 | 9.89 | -0.01 |
| WW010 | Class 1 | 7.29 | 20.7 | 16.41 | 6.95 | 14.49 | 2.059 | 0 | 97 | 0.04 | 1.89 | -0.01 |
| WW015 | Class 1 | 6.95 | 9.03 | 8.19 | 3.78 | 6.23 | 1.891 | 0 | 53 | 0.08 | 0.92 | -0.01 |
| WW018 | Class 1 | 9.07 | 46.5 | 2.72 | 13.77 | 83.90 | 2.540 | 18.6 | 232 | 0.34 | 8.06 | 0.01 |
| WW031 | Class 1 | 8.16 | 39 | 16.85 | 8.72 | 57.15 | 1.573 | 0 | 204 | 0.62 | 11.41 | -0.01 |
| WW033 | Class 1 | 8.18 | 45 | 20.22 | 10.05 | 63.18 | 1.670 | 0 | 247 | 0.61 | 4.27 | -0.01 |
| WW036 | AMA | 8.26 | 51 | 14.95 | 7.44 | 95.32 | 1.726 | 0 | 272 | 1.97 | 6.76 | -0.01 |
| WW048 | Class 2 | 8.18 | 35 | 30.54 | 14.85 | 27.79 | 2.938 | 0 | 172 | 0.28 | 1.33 | -0.01 |
| WW049 | Class 1 | 7.27 | 9.2 | 3.27 | 1.48 | 13.80 | 1.338 | 0 | 39 | 0.13 | 3.95 | 0.01 |
| NW004 | Class 1 | 7.48 | 18.3 | 3.04 | 2.61 | 34.32 | 1.782 | 0 | 89.4 | 0.43 | 5.52 | 0.01 |
| NW014 | Class 1 | 7.97 | 35.1 | 15.43 | 10.09 | 50.93 | 1.061 | 0 | 194 | 0.39 | 4.29 | -0.01 |
| NW021 | AMA | 8.07 | 44.6 | 14.86 | 7.48 | 72.16 | 2.994 | 0 | 232 | 2.40 | 5.14 | -0.01 |
| NW037 | AMA | 8.42 | 87.6 | 29.94 | 14.67 | 141.95 | 2.210 | 6.46 | 374 | 2.80 | 74.10 | -0.01 |
| NW039 | Class 1 | 8.47 | 95.1 | 20.23 | 11.60 | 186.58 | 2.908 | 9.57 | 495 | 0.50 | 25.20 | -0.01 |
| UG001 | AMA | 7.28 | 151 | 147.18 | 40.89 | 99.74 | 8.133 | 0 | 396 | 0.28 | 126.27 | 0.14 |
| UG008 | Class 1 | 7.79 | 67.6 | 40.33 | 7.02 | 98.20 | 1.245 | 0 | 284 | 0.25 | 14.32 | 0.02 |
| UG016 | Class 1 | 7.96 | 62.3 | 14.61 | 6.83 | 115.22 | 1.271 | 0 | 311 | 0.14 | 17.97 | -0.01 |
| UG035 | Class 1 | 8.14 | 91.1 | 37.65 | 29.92 | 119.68 | 1.318 | 0 | 234 | 0.06 | 129.90 | -0.01 |
| UG038 | Class 2 | 8.16 | 114 | 54.32 | 31.35 | 168.79 | 32.354 | 0 | 499 | 1.05 | 48.11 | -0.10 |
| B310/25 | Class 1 | 8.29 | 63.5 | 49.04 | 18.91 | 69.24 | 6.111 | 0 | 311 | 0.09 | 21.38 | -0.01 |

Table 10-4: SANS241:2006 water standards table for the boreholes in the intermediate aquifer (Continued).

| Borehole No | | Br mg/l | NO3(N) mg/l | PO4 mg/l | SO4 mg/l | Al mg/l | Fe mg/l | Mn mg/l | NH4(N) mg/l | Ba mg/l | Co mg/l | Cr mg/l |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Class 1 | | 0-10 | | 0-400 | 0-0.3 | 0-0.2 | 0-0.1 | 0-1 | | 0-0.5 | 0-0.1 |
| | Class 2 | | 10-20 | | 401-600 | 0.3-0.5 | 0.2-2 | 0.1-1 | 1-2 | | 0.5-1 | 0.1-0.5 |
| | AMA | | >20 | | >600 | >0.5 | >2 | >1 | >2 | | >1 | >0.5 |
| WW004 | Class 1 | -0.04 | 0.15 | -0.10 | 76.90 | <0.004 | 0.090 | 0.013 | | 0.136 | <0.002 | <0.006 |
| WW006D | Class 2 | -0.04 | 15.17 | -0.10 | 1.26 | 0.011 | 0.159 | 0.010 | 0.010 | 0.048 | <0.002 | <0.006 |
| WW006S | Class 1 | -0.04 | 7.40 | -0.10 | 0.52 | <0.004 | 0.145 | 0.008 | 0.010 | 0.064 | <0.002 | <0.006 |
| WW008 | Class 1 | -0.04 | 6.96 | 0.10 | -0.50 | <0.004 | 0.027 | 0.030 | 0.000 | 0.075 | <0.002 | <0.006 |
| WW010 | Class 1 | 0.04 | 2.53 | -0.10 | 2.47 | <0.004 | 0.021 | 0.010 | | 0.018 | <0.002 | <0.006 |
| WW015 | Class 1 | -0.04 | 0.06 | -0.10 | 2.89 | 0.010 | 0.083 | 0.027 | 0.000 | 0.031 | <0.002 | <0.006 |
| WW018 | Class 1 | -0.04 | 0.67 | -0.10 | 11.20 | 0.034 | -0.004 | 0.008 | | 0.007 | <0.002 | <0.006 |
| WW031 | Class 1 | 0.10 | 0.11 | -0.10 | 0.93 | <0.004 | -0.007 | 0.009 | | 0.119 | <0.002 | <0.006 |
| WW033 | Class 1 | -0.04 | 0.10 | -0.10 | 1.36 | 0.056 | 0.062 | 0.010 | | 0.151 | <0.002 | <0.006 |
| WW036 | AMA | -0.04 | 0.07 | -0.10 | 0.67 | 0.034 | 0.018 | 0.011 | | 0.097 | <0.002 | <0.006 |
| WW048 | Class 2 | -0.04 | -0.05 | 0.10 | 25.45 | 0.018 | 0.543 | 0.015 | | 0.033 | <0.002 | <0.006 |
| WW049 | Class 1 | -0.04 | -0.05 | -0.10 | 5.75 | 0.036 | 0.114 | 0.008 | 0.010 | 0.006 | <0.002 | <0.006 |
| NW004 | Class 1 | 0.05 | 1.16 | -0.10 | 0.64 | <0.004 | -0.016 | 0.006 | | 0.013 | <0.002 | <0.006 |
| NW014 | Class 1 | 0.05 | 0.07 | -0.10 | 2.03 | 0.115 | 0.047 | 0.020 | | 0.052 | <0.002 | <0.006 |
| NW021 | AMA | 0.07 | 0.68 | -0.10 | 0.68 | <0.004 | -0.006 | 0.009 | | 0.156 | <0.002 | <0.006 |
| NW037 | AMA | 0.29 | 0.10 | -0.10 | 3.09 | 0.008 | 0.004 | 0.008 | | 0.251 | <0.002 | <0.006 |
| NW039 | Class 1 | 0.12 | 0.38 | -0.10 | 3.16 | 0.005 | -0.017 | 0.010 | | 0.320 | <0.002 | <0.006 |
| UG001 | AMA | -0.40 | 49.33 | -1.00 | 36.57 | 0.011 | -0.015 | 0.020 | | 0.387 | <0.002 | <0.006 |
| UG008 | Class 1 | 0.17 | 7.05 | -0.10 | 35.79 | 0.024 | -0.010 | 0.015 | | 0.119 | <0.002 | <0.006 |
| UG016 | Class 1 | 0.21 | 0.18 | -0.10 | 10.39 | 0.024 | 0.004 | 0.011 | | 0.037 | <0.002 | <0.006 |
| UG035 | Class 1 | 0.58 | 0.31 | -0.10 | 67.90 | 0.013 | 0.007 | 0.017 | | 0.036 | <0.002 | <0.006 |
| UG038 | Class 2 | -0.40 | 11.40 | -1.00 | 43.39 | 0.034 | -0.010 | 0.016 | | 0.127 | <0.002 | <0.006 |
| B310/25 | Class 1 | 0.05 | 0.13 | -0.10 | 13.52 | 0.053 | -0.007 | 0.011 | | 0.229 | <0.002 | <0.006 |

Table 10-4:  SANS241:2006 water standards table for the boreholes in the intermediate aquifer (Continued).

| Borehole No | | Cu | U | V | Zn | Si | B | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | | | | | |
| | Class 1 | 0-1 | 0-4 | 0-0.2 | 0-5 | | 0-2 | | | | | |
| | Class 2 | 1-2 | 4-8 | 0.2-0.5 | 5-10 | | 2-4 | | | | | |
| | AMA | >2 | >8 | >0.5 | >10 | | >4 | | | | | |
| WW004 | Class 1 | 0.004 | <0.010 | <0.010 | 0.013 | 1.541 | 0.186 | | | | | |
| WW006D | Class 2 | 0.003 | <0.010 | <0.010 | 0.018 | 10.971 | 0.169 | | | | | |
| WW006S | Class 1 | 0.002 | <0.010 | <0.010 | 0.009 | 5.086 | 0.147 | | | | | |
| WW008 | Class 1 | 0.002 | <0.010 | <0.010 | 0.010 | 0.806 | 0.125 | | | | | |
| WW010 | Class 1 | 0.002 | <0.010 | <0.010 | 0.009 | 3.544 | 0.126 | | | | | |
| WW015 | Class 1 | 0.004 | <0.010 | <0.010 | 0.018 | 6.849 | 0.168 | | | | | |
| WW018 | Class 1 | 0.003 | <0.010 | <0.010 | 0.000 | 0.025 | 0.967 | | | | | |
| WW031 | Class 1 | 0.001 | <0.010 | <0.010 | 0.005 | 5.215 | 0.669 | | | | | |
| WW033 | Class 1 | 0.004 | <0.010 | <0.010 | 0.010 | 3.745 | 0.871 | | | | | |
| WW036 | AMA | 0.002 | <0.010 | <0.010 | 0.007 | 2.711 | 1.507 | | | | | |
| WW048 | Class 2 | 0.002 | <0.010 | <0.010 | 0.013 | 10.791 | 0.398 | | | | | |
| WW049 | Class 1 | 0.003 | <0.010 | <0.010 | 0.012 | 15.196 | 0.111 | | | | | |
| NW004 | Class 1 | 0.002 | <0.010 | <0.010 | 0.014 | 0.864 | 0.151 | | | | | |
| NW014 | Class 1 | 0.007 | <0.010 | 0.016 | 0.011 | 16.794 | 0.066 | | | | | |
| NW021 | AMA | 0.002 | <0.010 | <0.010 | 0.005 | 2.791 | 0.756 | | | | | |
| NW037 | AMA | 0.004 | <0.010 | <0.010 | 0.007 | 6.137 | 0.693 | | | | | |
| NW039 | Class 1 | 0.002 | <0.010 | <0.010 | 0.004 | 5.371 | 1.501 | | | | | |
| UG001 | AMA | 0.004 | <0.010 | <0.010 | 0.013 | 12.753 | 0.173 | | | | | |
| UG008 | Class 1 | 0.003 | <0.010 | <0.010 | 0.008 | 17.208 | 0.131 | | | | | |
| UG016 | Class 1 | 0.003 | <0.010 | <0.010 | 0.004 | 16.311 | 0.238 | | | | | |
| UG035 | Class 1 | 0.004 | <0.010 | <0.010 | 0.008 | 5.851 | 0.212 | | | | | |
| UG038 | Class 2 | 0.013 | <0.010 | <0.010 | 0.014 | 19.502 | 1.649 | | | | | |
| B310/25 | Class 1 | 0.006 | <0.010 | <0.010 | 0.018 | 12.718 | 0.377 | | | | | |
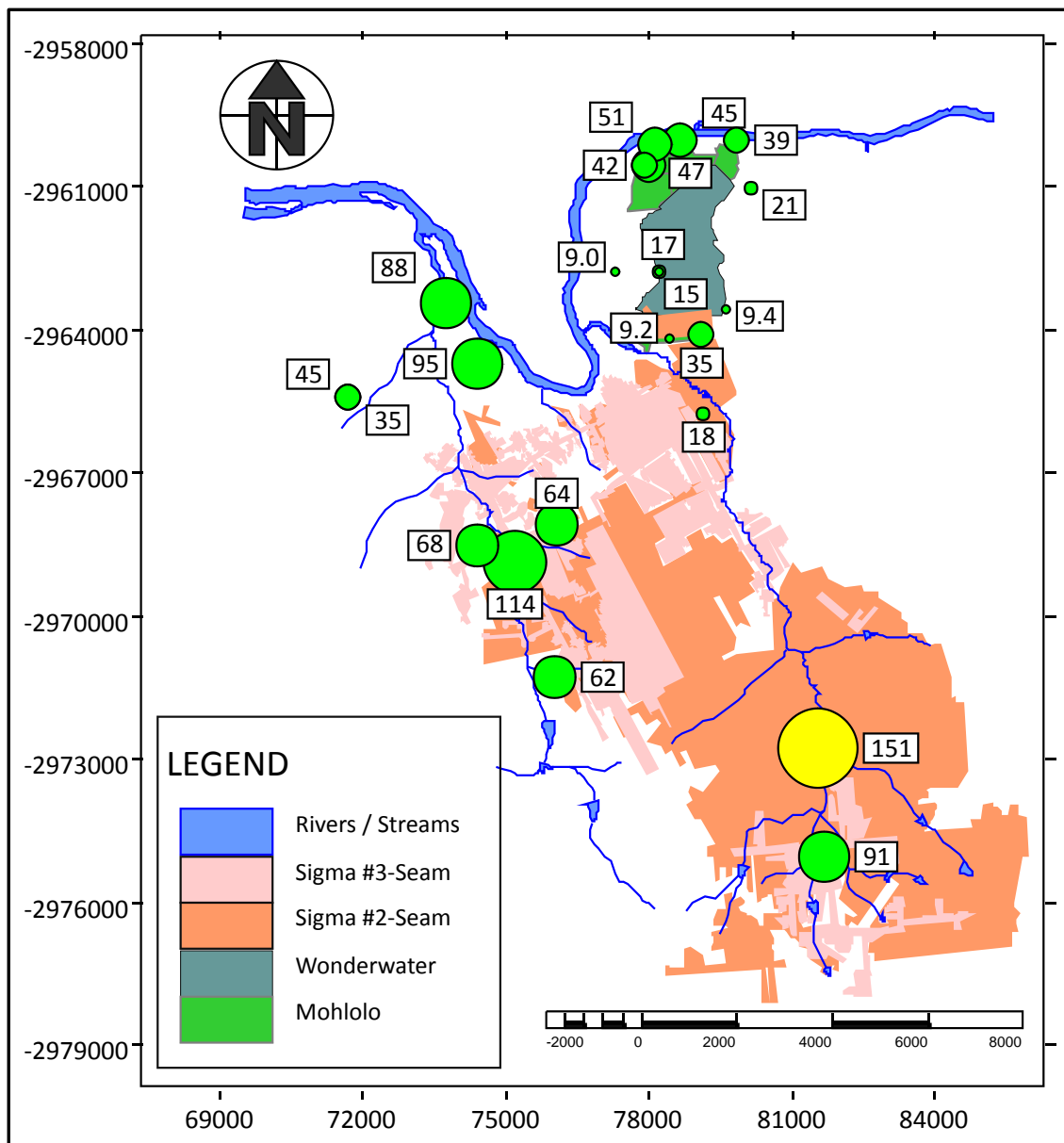
*Figure 10-9: Proportional distribution of the electrical conductivity values of the boreholes in the intermediate aquifer.*

## 10.2.2 Hydrochemical characterisation of boreholes in the intermediate aquifer through interpretive diagrams

- According to the expanded Durov Diagram in Figure 10-10, samples WW048, WW015, WW010, WW006S, WW006D, UG001 and B310/25 are unpolluted.
- Samples WW049, WW036, WW033, WW031, WW018, UG038, UG016, UG008, NW039, NW037, NW021, NW014 and NW004 are typical of water from high extraction underground coal mines.

- Sample WW004 is magnesium and sulphate dominant water which is typical of opencast coal mine water.
- Sample UG035 is sulphate and sodium dominant water which could possibly be due to ash in the water.
- Samples WW008 are magnesium and chloride dominant water which is seldom found in Karoo rocks.
- From the stiff diagrams in Figure 10-11 it is evident that samples B310/25, NW004, NW014, NW021, NW037, NW039, UG008, UG016, UG035, UG038, WW018, WW031, WW033 and WW036 are all the same type of water and is sodium bicarbonate dominant water which is typical of normal Ecca water (typical of this area).
- Samples WW006D, WW006S, WW010, WW015 and WW048 are the same type water and are calcium/magnesium bicarbonate dominant water, which is typical of unpolluted water.
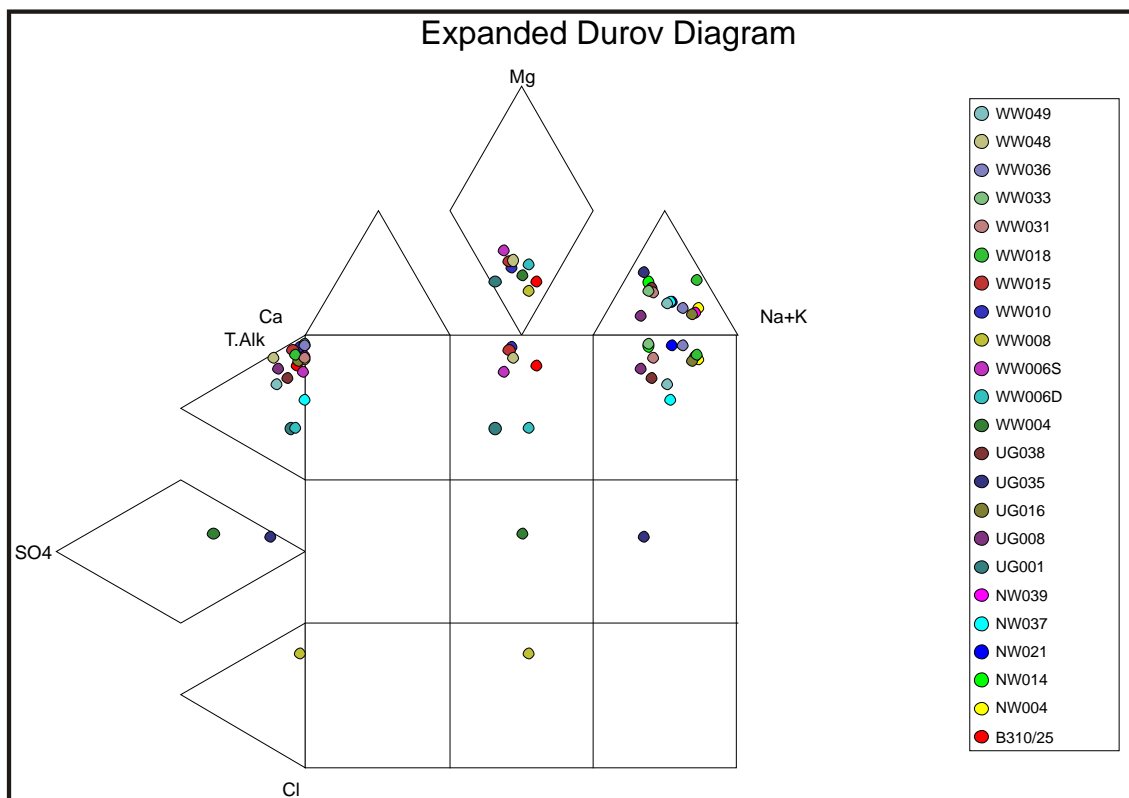


*Figure 10-10: Expanded Durov Diagram of the boreholes in the intermediate aquifer.*
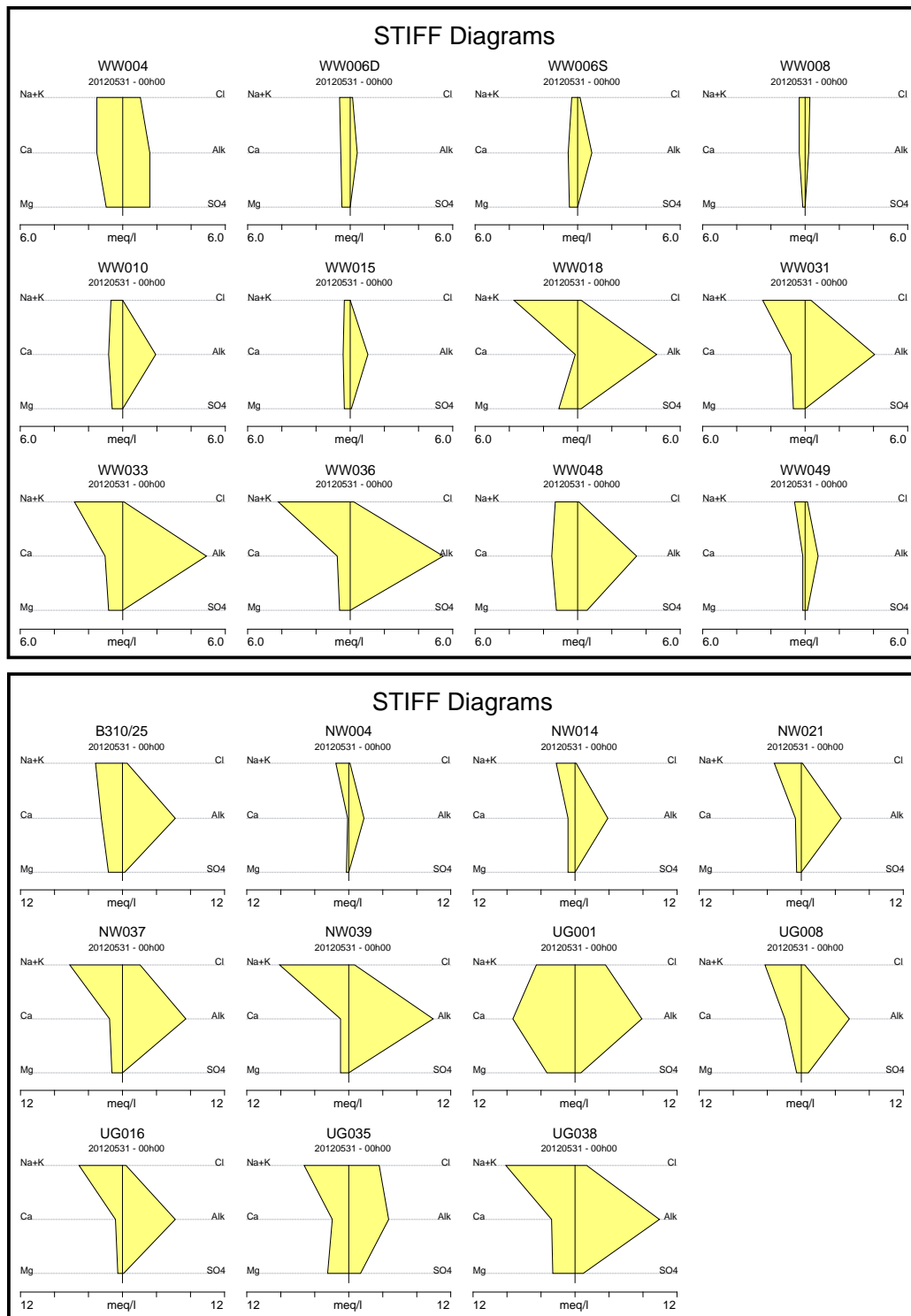
Figure 10-11: STIFF Diagrams of boreholes in the intermediate aquifer.

## 10.3 Groundwater quality of the boreholes in the deep aquifer

A total of 16 boreholes were sampled in the deep aquifer and a summary of the boreholes are available in Table 10-5. A locality map of the sampled boreholes in the deep aquifer can be viewed in Figure 10-3.

*Table 10-5: A summary of the boreholes sampled in the deep aquifer.*

| Date sampled | Borehole ID | Sample ID | Water level | Sampling depth (mbcl) |
|---|---|---|---|---|
| Deep aquifer | | | | |
| 31/05/2012 | NW001 | NW001 | 9.75 | 25.00 |
| 03/07/2012 | NW006 | NW006 | 1.28 | 20.00 |
| 31/05/2012 | NW020 | NW020 | 1.27 | 15.00 |
| 31/05/2012 | NW036 | NW036 | 4.05 | 20.00 |
| 31/05/2012 | NW040 | NW040 | 42.21 | 60.00 |
| 31/05/2012 | NW041 | NW041 | 30.13 | 45.00 |
| 31/05/2012 | NW042 | NW042 | 7.88 | 30.00 |
| 07/06/2012 | NW043 | NW043 | 3.81 | 15.00 |
| 08/06/2012 | NW044 | NW044 | 2.56 | 10.00 |
| 08/06/2012 | NW046 | NW046 | 23.36 | 30.00 |
| 08/06/2012 | NW051 | NW051 | 36.70 | 50.00 |
| 28/05/2012 | UG019 | UG019D | 88.95 | 130.00 |
| | | UG019S | | 100.00 |
| 28/05/2012 | UG027 | UG027D | 16.53 | 150.00 |
| | | UG027M | | 50.00 |
| | | UG027S | | 25.00 |
| 29/05/2012 | UG052 | UG052 | 34.63 | 90.00 |
| 29/05/2012 | UG071 | UG071 | 41.61 | 60.00 |
| 28/05/2012 | UG072 | UG072D | 32.68 | 115.00 |
| | | UG072M | | 65.00 |
| | | UG072S | | 40.00 |
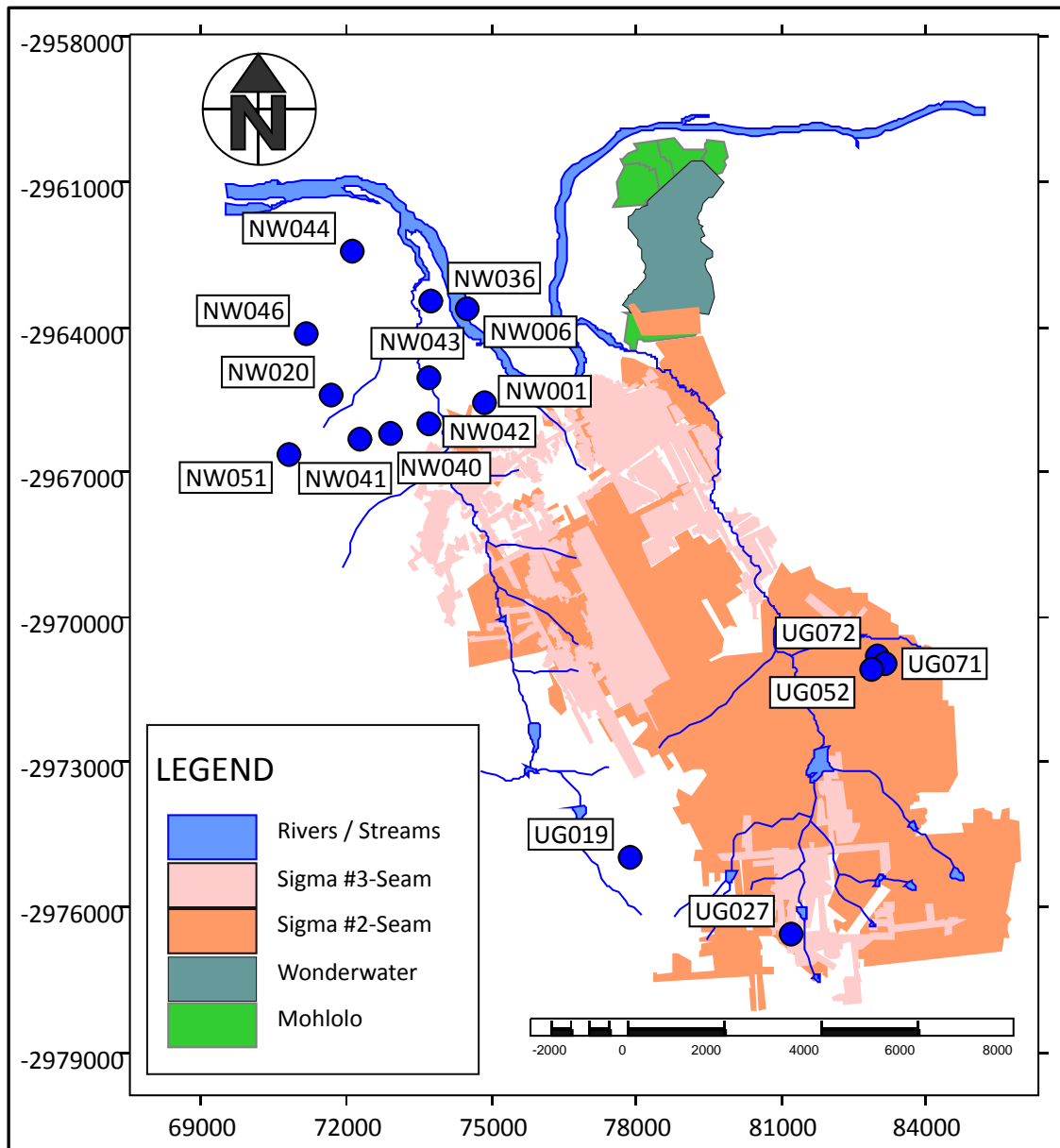
*Figure 10-12: Locality map of boreholes in the deep aquifer.*

### 10.3.1 General water quality discussion for the boreholes in the deep aquifer

The SANS 214:2006 table for the deep aquifer can be viewed in Table 10-6.

- Borehole NW006 has a sodium concentration of 261.87 mg/l and a chloride concentration of 238.86 mg/l. Both these parameters have concentrations which are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards. Borehole NW006 also has a fluoride concentration of

2.79 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards and can be attributed to the local geology.  Water from borehole NW006 is therefore not suitable for human consumption.

- Borehole NW036 has a sodium concentration of 258.46 mg/l which is within the maximum allowable limits of the SANS 241:2006 drinking water standards. It also has a fluoride concentration of 9.61 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards.  The high fluoride concentration can be attributed to the local geology.  The water from borehole NW036 is therefore not suitable for human consumption.

- Borehole NW040 has a fluoride concentration of 2.62 mg/l, an aluminium concentration of 1.792 mg/l and an iron concentration of 4.547 mg/l.  Al of these parameters is above the maximum allowable limits of the SANS 241:2006 drinking water standards.  Borehole NW040 also has a manganese concentration of 0.103 mg/l which is within the maximum allowable limits of the SANS 241:2006 drinking water standards.  Water from borehole NW040 is therefore not allowable for human consumption.

- Borehole NW041 has a fluoride concentration of 2.67 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards and can be attributed to the local geology.  Water from borehole NW041 is therefore not suitable for human consumption.

- Borehole NW042 has a sodium concentration of 274.74 mg/l, which is within the maximum allowable limits of the SANS 241:2006 drinking water standards, and a fluoride concentration of 5.16 mg/l, which is above the maximum allowable limits of the SANS 241:2006 drinking water standards.  The high fluoride concentration could be attributed to the local geology.  Water from borehole NW042 is therefore not suitable for human consumption.

- Borehole NW043 has an iron concentration of 0.348 mg/l which is within the maximum allowable limits and water from this borehole is therefore suitable for human consumption for a limited duration use only.

- Borehole NW044 has a fluoride concentration of 2.87 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards. Water from this borehole is therefore not suitable for human consumption.

- Borehole NW046 indicated a fluoride concentration of 2.61 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards. Water from this borehole is therefore not suitable for human consumption.

- Borehole NW051 has a fluoride concentration of 2.08 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards. Water from this borehole is therefore not suitable for human consumption.

- Sample UG027D indicated and EC concentration of 335 mS/m, a calcium concentration of 153.21 mg/l and a magnesium concentration of 83.26 mg/l. All of the above mentioned parameters have concentrations which are within the maximum allowable limits of the SANS 241:2006 drinking water standards. Sample UG027D also has a sodium concentration of 454.77 mg/l and a chloride concentration of 901 mg/l. Both these concentrations are above the maximum allowable limits of the SANS 241:2006 drinking water standards and can be attributed to salt "pockets" that are sometimes found in the geology of this area. Water from borehole UG027 is therefore not suitable for human consumption.

- Borehole UG071 has an EC concentration of 218 mS/m which is within the maximum allowable limits of the SANS 241:2006 drinking water standards, and a sodium concentration of 547.30 mg/l, which is above the maximum allowable limits of the SANS 241:2006 drinking water standards. Sodium occurs abundantly in the shale of the Free State coalfields. Water from borehole UG071 is therefore not suitable for human consumption.

- Sample UG072D has an EC concentration of 482 mS/m and a sodium concentration of 1277.34 mg/l. Both these parameters have concentrations which are above the maximum allowable limits of the SANS 241:2006 drinking water standards. Sample UG072D also has a sulphate concentration of 520 mg/l which is within the maximum allowable limits of the SANS 241:2006 drinking water standards.

- Sample UG072M has an EC concentration of 364 mS/m which is within the maximum allowable limits of the SANS 241:2006 drinking water standards. Sample UG027M also has a sodium concentration of 971.71 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards.

- Sample UG072S has a nitrate concentration of 13.22 mg/l which is within the maximum allowable limits according of the SANS 241:2006 drinking water standards.

- Borehole UG072 is in close vicinity to stock piles which may be the cause for the elevated concentrations that were discussed. Water from borehole UG072 is therefore above the maximum allowable limits of the SANS 241:2006 drinking water standards and is not suitable for human consumption.

The proportional distribution of the electrical conductivity and sodium concentration can be viewed in Figure 10-13 and Figure 10-14 respectively.

Table 10-6: SANS241:2006 water standards table for the boreholes in the deep aquifer.

| Borehole No | | pH | EC | Ca | Mg | Na | K | Palk | Malk | F | Cl | NO2(N) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mS/m | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l |
| | Class 1 | 0-9.5 | 0-150 | 0-150 | 0-70 | 0-200 | 0-50 | | | 0-1 | 0-200 | |
| | Class 2 | 9.5-10 | 151-370 | 151-300 | 71-100 | 201-400 | 51-100 | | | 1-1.5 | 200-600 | |
| | AMA | >10 | >370 | >300 | >100 | >400 | >100 | | | >1.5 | >600 | |
| NW001 | Class 1 | 8.29 | 71.2 | 76.12 | 49.90 | 21.18 | 1.116 | 0 | 289 | 0.09 | 28.17 | 0.03 |
| NW006 | AMA | 8.75 | 129 | 2.18 | 0.86 | 261.87 | 2.302 | 18.1 | 289 | 2.79 | 238.86 | -0.10 |
| NW020 | Class 1 | 8.16 | 34.6 | 28.82 | 11.10 | 27.75 | 2.406 | 0 | 186 | 0.09 | 2.24 | -0.01 |
| NW036 | AMA | 8.53 | 115 | 1.15 | 0.57 | 258.46 | 1.325 | 9.23 | 433 | 9.61 | 108.71 | -0.10 |
| NW040 | AMA | 9.49 | 75.3 | 1.62 | 0.85 | 170.83 | 1.022 | 44.3 | 266 | 2.62 | 20.93 | -0.01 |
| NW041 | AMA | 8.23 | 44.6 | 2.97 | 1.57 | 100.48 | 1.695 | 0 | 210 | 2.67 | 18.02 | -0.01 |
| NW042 | AMA | 8.81 | 125 | 1.22 | 0.53 | 274.74 | 1.519 | 16.7 | 388 | 5.16 | 179.27 | -0.10 |
| NW043 | Class 2 | 8.32 | 77.6 | 14.67 | 26.98 | 118.21 | 3.626 | 2.92 | 376 | 0.19 | 40.26 | -0.01 |
| NW044 | AMA | 8.32 | 62.2 | 3.90 | 3.15 | 131.79 | 2.203 | 1.93 | 161 | 2.87 | 113.80 | -0.01 |
| NW046 | AMA | 8.21 | 56.5 | 7.92 | 6.22 | 110.20 | 2.304 | 0 | 267 | 2.61 | 7.59 | -0.01 |
| NW051 | AMA | 7.42 | 15.2 | 4.95 | 3.90 | 20.98 | 1.624 | 0 | 62.5 | 2.08 | 10.77 | -0.01 |
| UG019D | Class 1 | 8.20 | 74.1 | 3.62 | 1.46 | 161.48 | 1.542 | 0 | 271 | 0.21 | 81.10 | -0.01 |
| UG019S | Class 1 | 8.01 | 73.4 | 4.24 | 1.54 | 157.33 | 1.384 | 0 | 269 | 0.21 | 80.80 | -0.01 |
| UG027D | AMA | 7.90 | 335 | 153.21 | 83.26 | 454.77 | 6.250 | 0 | 364 | 0.39 | 901.00 | -0.10 |
| UG027M | Class 1 | 6.80 | 20.5 | 11.74 | 3.73 | 14.18 | 5.444 | 0 | 48.5 | 0.11 | 21.91 | -0.01 |
| UG027S | Class 1 | 6.80 | 18.1 | 12.01 | 3.67 | 12.96 | 5.446 | 0 | 46 | 0.10 | 21.11 | -0.01 |
| UG052 | Class 1 | 8.16 | 73.2 | 12.67 | 5.03 | 160.08 | 1.895 | 0 | 282 | 0.94 | 66.80 | -0.01 |
| UG071 | AMA | 8.58 | 218 | 7.63 | 6.81 | 547.30 | 4.101 | 28.2 | 1008 | 0.50 | 39.40 | -0.10 |
| UG072D | AMA | 8.57 | 482 | 10.74 | 9.70 | 1277.34 | 5.740 | 39.5 | 2319 | 0.78 | 80.14 | -0.10 |
| UG072M | AMA | 8.61 | 364 | 9.96 | 9.24 | 971.72 | 6.174 | 25.7 | 1730 | 0.86 | 54.05 | 0.63 |
| UG072S | Class 2 | 8.09 | 73.8 | 52.67 | 15.13 | 84.89 | 6.067 | 0 | 285 | 0.17 | 20.91 | 0.75 |

Table 10-6: SANS241:2006 water standards table for the boreholes in the deep aquifer (Continued).

| Borehole No | | Br | NO3(N) | PO4 | SO4 | Al | Fe | Mn | NH4(N) | Ba | Co | Cr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l |
| | Class 1 | | 0-10 | | 0-400 | 0-0.3 | 0-0.2 | 0-0.1 | 0-1 | | 0-0.5 | 0-0.1 |
| | Class 2 | | 10-20 | | 401-600 | 0.3-0.5 | 0.2-2 | 0.1-1 | 1-2 | | 0.5-1 | 0.1-0.5 |
| | AMA | | >20 | | >600 | >0.5 | >2 | >1 | >2 | | >1 | >0.5 |
| NW001 | Class 1 | 0.14 | 0.97 | -0.10 | 73.50 | <0.004 | -0.014 | 0.011 | | 0.120 | <0.002 | <0.006 |
| NW006 | AMA | 0.96 | -0.50 | -1.00 | -5.00 | 0.019 | 0.020 | 0.011 | | 0.010 | <0.002 | <0.006 |
| NW020 | Class 1 | -0.04 | 0.08 | -0.10 | 5.05 | <0.004 | 0.148 | 0.016 | | 0.298 | <0.002 | <0.006 |
| NW036 | AMA | 1.08 | -0.50 | -1.00 | -5.00 | 0.013 | 0.054 | 0.007 | | 0.011 | <0.002 | <0.006 |
| NW040 | AMA | 0.22 | 0.74 | -0.10 | 77.40 | 1.792 | 4.547 | 0.103 | | 0.053 | 0.005 | <0.006 |
| NW041 | AMA | 0.23 | 0.17 | -0.10 | -0.50 | 0.007 | -0.006 | 0.007 | | 0.007 | <0.002 | <0.006 |
| NW042 | AMA | 0.58 | -0.50 | -1.00 | -5.00 | 0.036 | 0.137 | 0.009 | | 0.008 | <0.002 | <0.006 |
| NW043 | Class 2 | 0.36 | 0.84 | -0.10 | 1.96 | 0.011 | 0.348 | 0.012 | | 0.047 | <0.002 | <0.006 |
| NW044 | AMA | 0.54 | 0.70 | -0.10 | -0.50 | <0.004 | 0.035 | 0.005 | 0.070 | 0.017 | <0.002 | <0.006 |
| NW046 | AMA | -0.04 | 0.24 | -0.10 | 22.24 | <0.004 | 0.000 | 0.006 | | 0.052 | <0.002 | <0.006 |
| NW051 | AMA | 0.05 | -0.05 | -0.10 | 0.59 | 0.063 | 0.150 | 0.010 | | 0.004 | <0.002 | <0.006 |
| UG019D | Class 1 | 0.46 | 0.33 | -0.10 | 7.90 | 0.017 | -0.005 | 0.008 | | 0.028 | <0.002 | <0.006 |
| UG019S | Class 1 | 0.53 | 0.40 | -0.10 | 10.67 | 0.023 | -0.007 | 0.009 | | 0.022 | <0.002 | <0.006 |
| UG027D | AMA | 0.81 | 1.52 | -1.00 | 233.49 | 0.033 | -0.003 | 0.021 | | 0.039 | <0.002 | <0.006 |
| UG027M | Class 1 | -0.04 | 3.07 | -0.10 | 1.02 | <0.004 | -0.005 | 0.010 | 0.020 | 0.022 | <0.002 | <0.006 |
| UG027S | Class 1 | -0.04 | 3.04 | -0.10 | 1.13 | 0.009 | 0.006 | 0.010 | 0.020 | 0.024 | <0.002 | <0.006 |
| UG052 | Class 1 | 0.44 | 0.09 | -0.10 | 31.46 | 0.017 | -0.012 | 0.011 | | 0.063 | <0.002 | <0.006 |
| UG071 | AMA | -0.40 | 0.52 | -1.00 | 205.08 | 0.030 | -0.008 | 0.015 | | 0.010 | <0.002 | <0.006 |
| UG072D | AMA | -0.40 | -0.50 | -1.00 | 520.00 | 0.009 | -0.013 | 0.013 | | 0.100 | <0.002 | <0.006 |
| UG072M | AMA | 0.41 | 0.74 | -1.00 | 374.65 | 0.036 | -0.004 | 0.017 | | 0.040 | <0.002 | <0.006 |
| UG072S | Class 2 | -0.04 | 16.22 | -0.10 | 21.97 | 0.008 | -0.012 | 0.014 | | 0.115 | <0.002 | <0.006 |

Table 10-6:  SANS241:2006 water standards table for the boreholes in the deep aquifer (Continued).

| Borehole No | | Cu | U | V | Zn | Si | B | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | | | | | |
| | Class 1 | 0-1 | 0-4 | 0-0.2 | 0-5 | | 0-2 | | | | | |
| | Class 2 | 1-2 | 4-8 | 0.2-0.5 | 5-10 | | 2-4 | | | | | |
| | AMA | >2 | >8 | >0.5 | >10 | | >4 | | | | | |
| NW001 | Class 1 | 0.002 | <0.010 | 0.020 | 0.009 | 30.264 | 0.054 | | | | | |
| NW006 | AMA | 0.003 | <0.010 | <0.010 | 0.001 | 0.491 | 1.128 | | | | | |
| NW020 | Class 1 | 0.003 | <0.010 | <0.010 | 0.008 | 10.335 | 0.072 | | | | | |
| NW036 | AMA | 0.002 | <0.010 | <0.010 | 0.001 | 2.944 | 1.393 | | | | | |
| NW040 | AMA | 0.061 | <0.010 | 0.023 | 0.015 | 6.831 | 1.311 | | | | | |
| NW041 | AMA | 0.002 | <0.010 | <0.010 | 0.003 | 1.216 | 0.793 | | | | | |
| NW042 | AMA | 0.002 | <0.010 | <0.010 | 0.000 | 2.688 | 1.354 | | | | | |
| NW043 | Class 2 | 0.002 | <0.010 | <0.010 | 0.008 | 6.134 | 0.906 | | | | | |
| NW044 | AMA | 0.001 | <0.010 | <0.010 | 0.002 | 1.047 | 0.598 | | | | | |
| NW046 | AMA | 0.001 | <0.010 | <0.010 | 0.003 | 2.419 | 1.248 | | | | | |
| NW051 | AMA | 0.001 | <0.010 | <0.010 | 0.006 | 0.593 | 0.418 | | | | | |
| UG019D | Class 1 | 0.003 | <0.010 | <0.010 | 0.002 | 5.350 | 0.373 | | | | | |
| UG019S | Class 1 | 0.004 | <0.010 | <0.010 | 0.002 | 5.239 | 0.367 | | | | | |
| UG027D | AMA | 0.014 | <0.010 | 0.015 | 0.014 | 21.798 | 0.441 | | | | | |
| UG027M | Class 1 | 0.005 | <0.010 | <0.010 | 0.009 | 0.905 | 0.097 | | | | | |
| UG027S | Class 1 | 0.005 | <0.010 | <0.010 | 0.009 | 1.019 | 0.090 | | | | | |
| UG052 | Class 1 | 0.004 | <0.010 | <0.010 | 0.004 | 4.283 | 0.491 | | | | | |
| UG071 | AMA | 0.005 | <0.010 | <0.010 | 0.004 | 3.647 | 1.281 | | | | | |
| UG072D | AMA | 0.007 | <0.010 | <0.010 | -0.002 | 4.172 | 2.943 | | | | | |
| UG072M | AMA | 0.011 | <0.010 | <0.010 | 0.009 | 4.618 | 2.403 | | | | | |
| UG072S | Class 2 | 0.010 | <0.010 | <0.010 | 0.012 | 4.475 | 0.529 | | | | | |
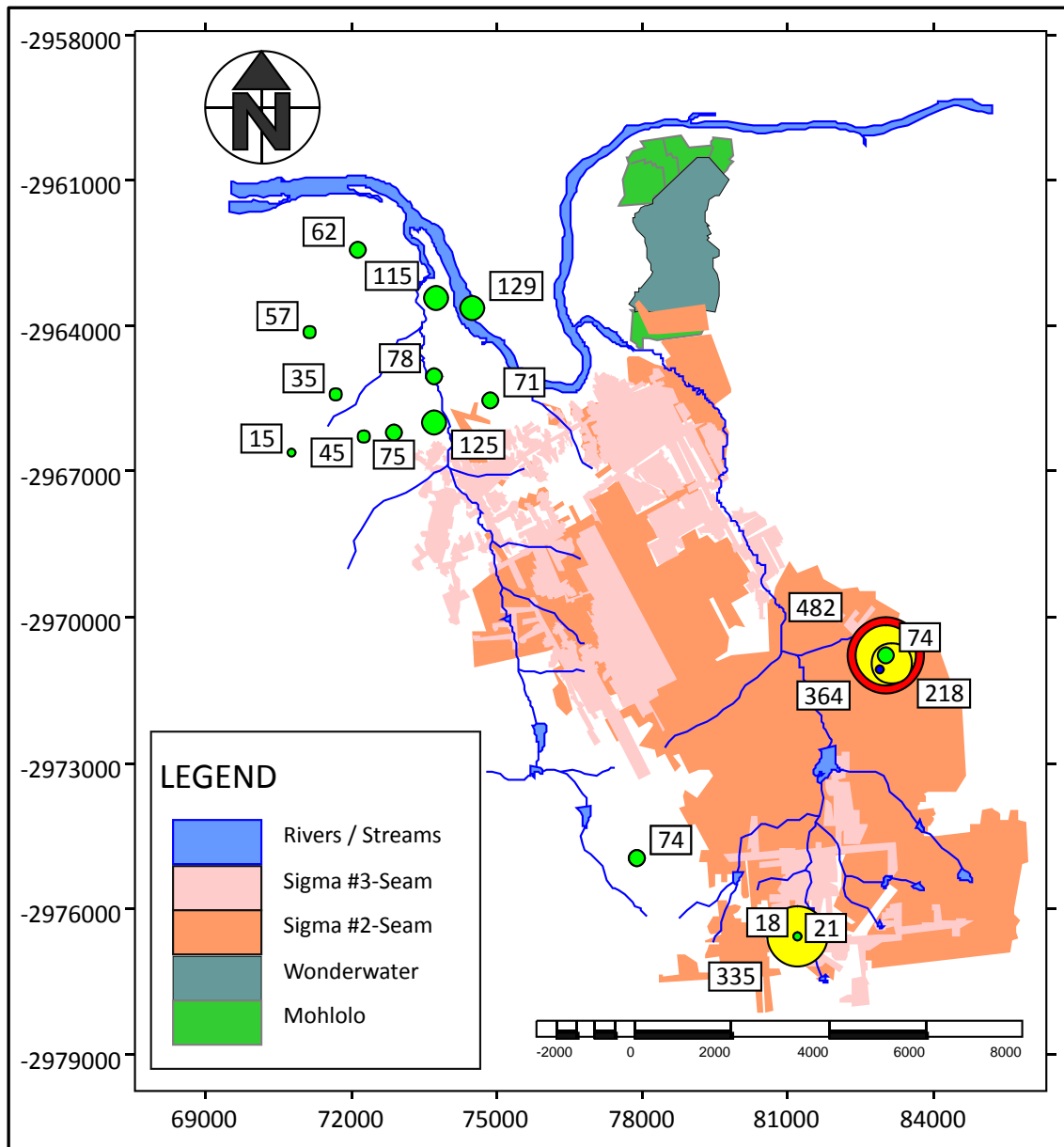
*Figure 10-13: Proportional distribution of the electrical conductivity values of the boreholes in the deep aquifer.*
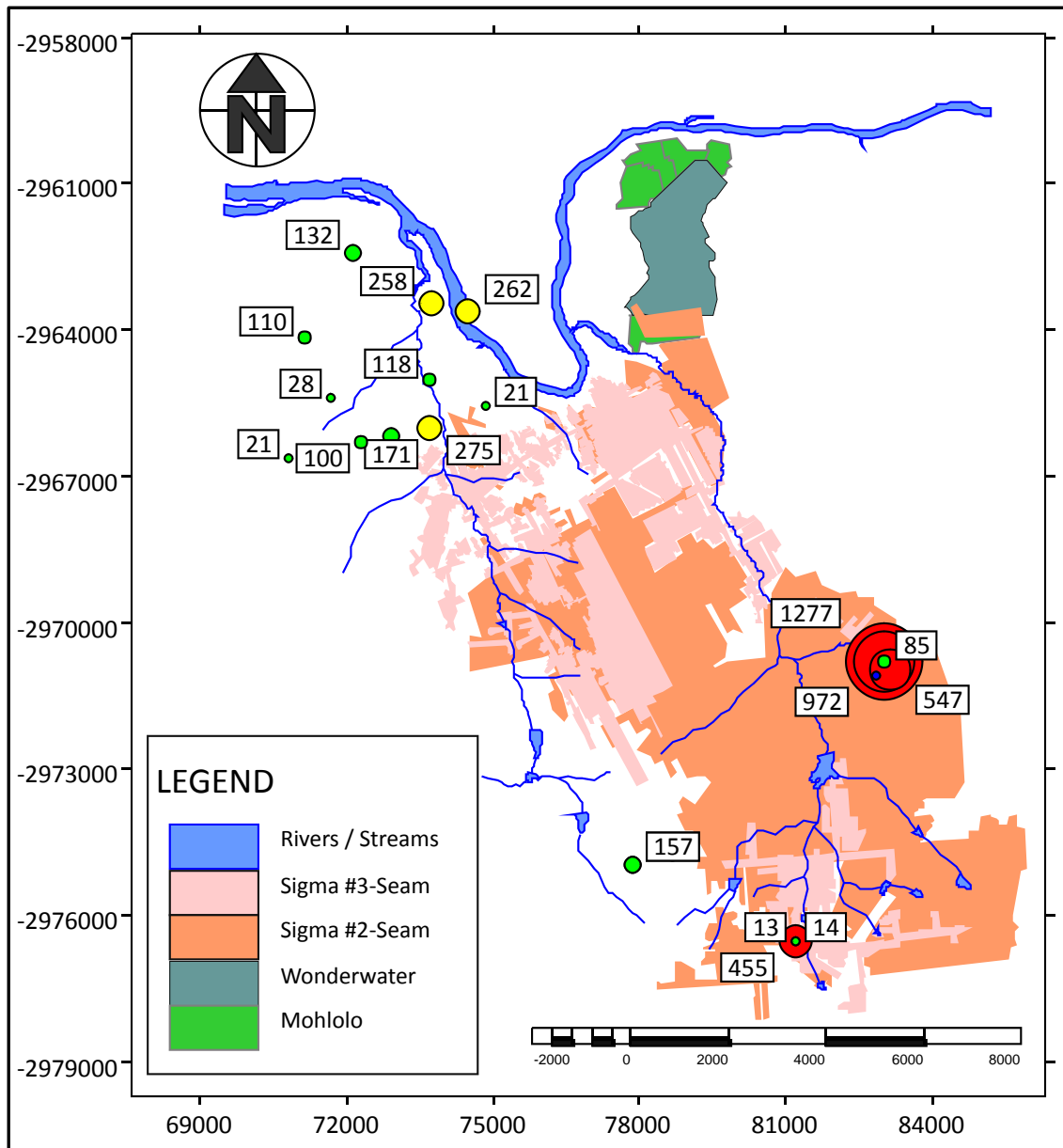
*Figure 10-14: Proportional distribution of the sodium concentrations of the boreholes in the deep aquifer.*

## 10.3.2 Hydrochemical characterisation of boreholes in the deep aquifer through interpretive diagrams

- According to the expanded Durov Diagram in Figure 10-15, samples UG072S, UG027S, UG027M, NW020 and NW001 plots in the second area which is associated with magnesium bicarbonate dominant water. This is typical of unpolluted water.

- Samples UG072M, UG071, UG052S, UG027D, UG019S, UG019D, NW051, NW046, NW043, NW042, NW041, NW040 and NW036 plots in the third area which is associated with sodium bicarbonate water. This is typical of water from high extraction coal mines.

- Sample NW044 plots in the area associated with sulphate and sodium dominance.

- Samples UG027D and NW006 plots in the ninth area which is associated with chloride and sodium dominant water and could be due to the salt "pockets" found in the geology of the area.
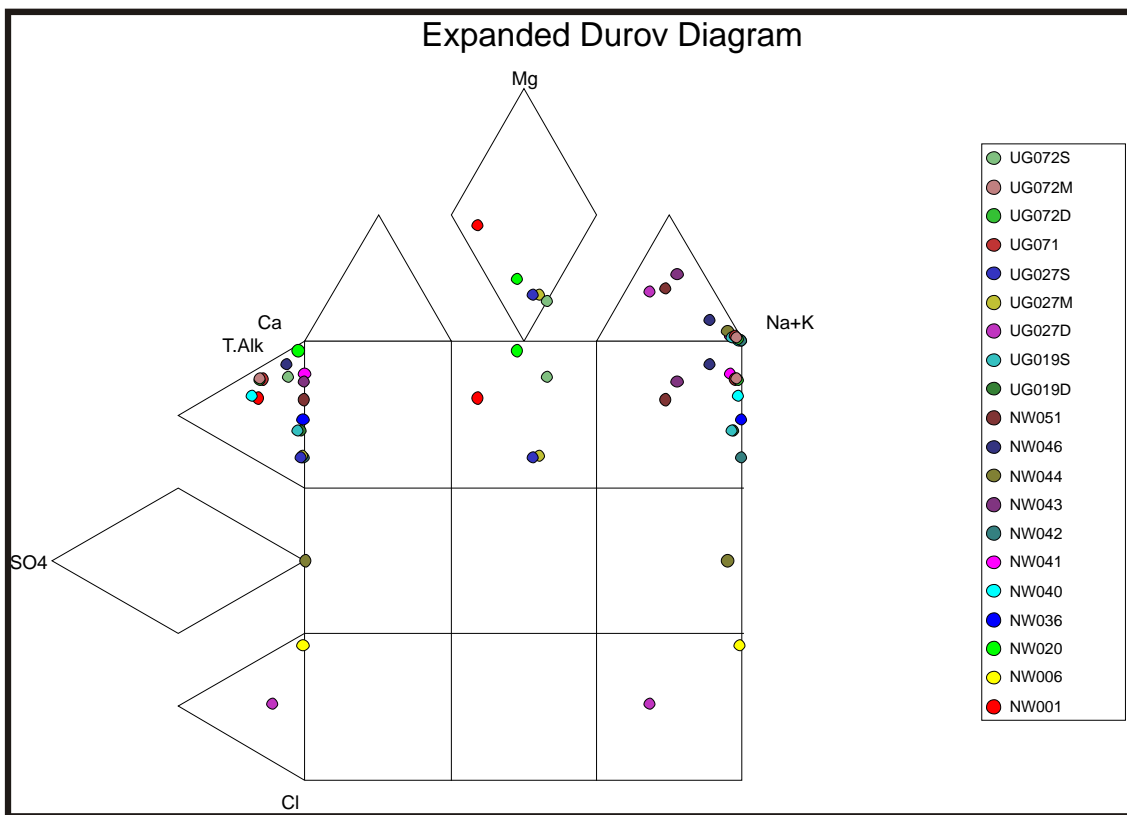


Figure 10-15: Expanded Durov Diagram of the boreholes in the deep aquifer.

- According to the stiff diagrams in Figure 10-16 samples NW006, NW036, NW040, NW041, NW042, NW043, NW044, NW043, UG019D, UG019S, UG052, UG071, UG072D and UG072M are all the same type of water and sodium bicarbonate type water, which indicates that it is unpolluted water.
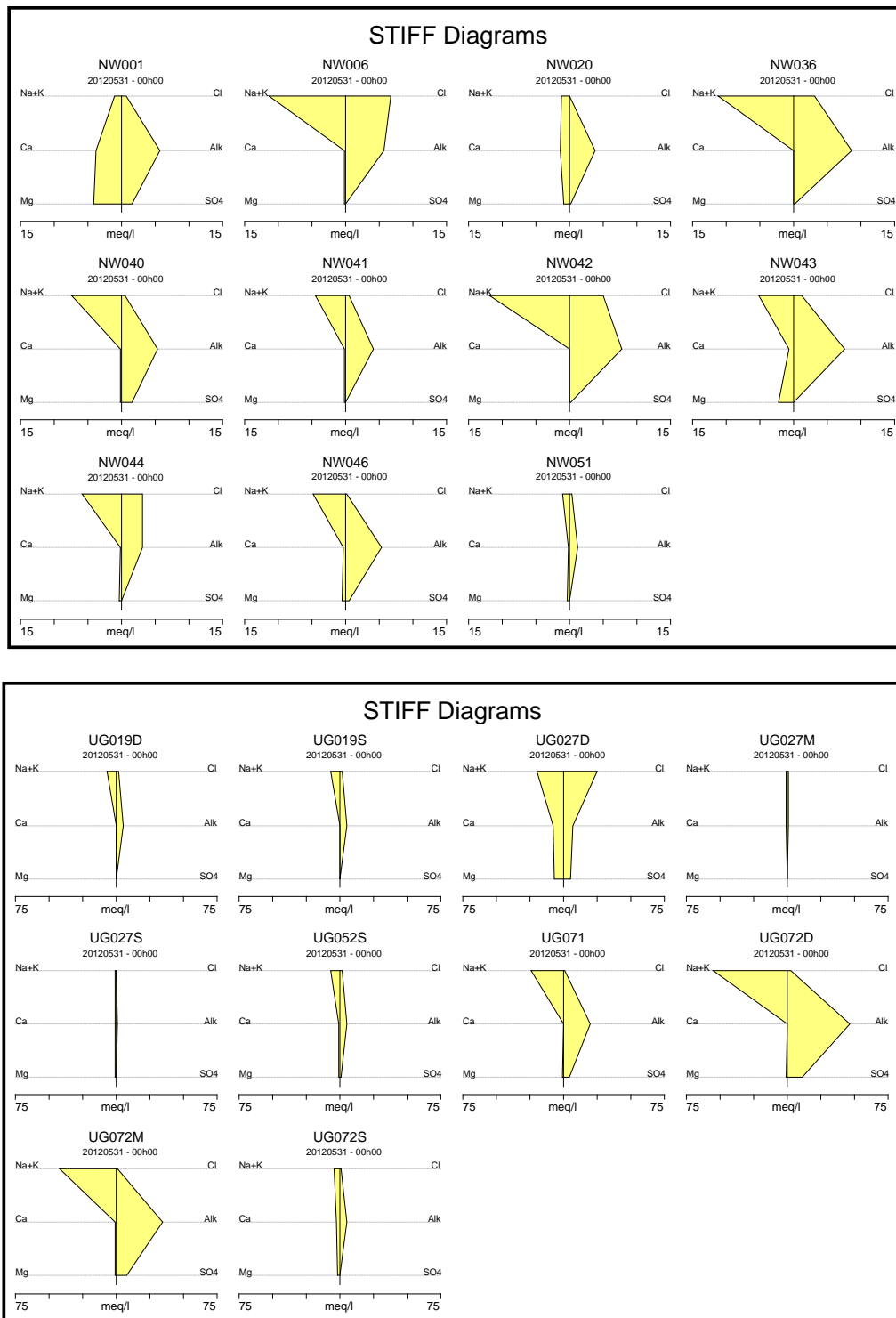
*Figure 10-16: STIFF Diagrams of boreholes in the deep aquifer.*

## 10.4 Groundwater quality of the boreholes in the disturbed aquifer

A total of five boreholes were sampled in the disturbed aquifer and a summary of the sampled boreholes are available in Table 10-7.   A locality map of the sampled boreholes in the disturbed aquifer can be viewed in Figure 10-17.

*Table 10-7:  A summary of the sampled boreholes in the disturbed aquifer.*

| Date sampled | Borehole ID | Sample ID | Water level | Sampling depth (mbcl) |
|---|---|---|---|---|
| Disturbed aquifer | | | | |
| 05/06/2012 | UG002 | UG002 | 33.52 | 40.00 |
| 05/06/2012 | UG004 | UG004 | 38.24 | 50.00 |
| 28/05/2012 | UG014 | UG014 | 55.18 | 70.00 |
| 30/05/2012 | UG023 | UG023 | 29.49 | 60.00 |
| 07/06/2012 | UG030 | UG030 | 17.32 | 25.00 |
| 01/06/2012 | WW028 | WW028 | 15.24 | 16.00 |
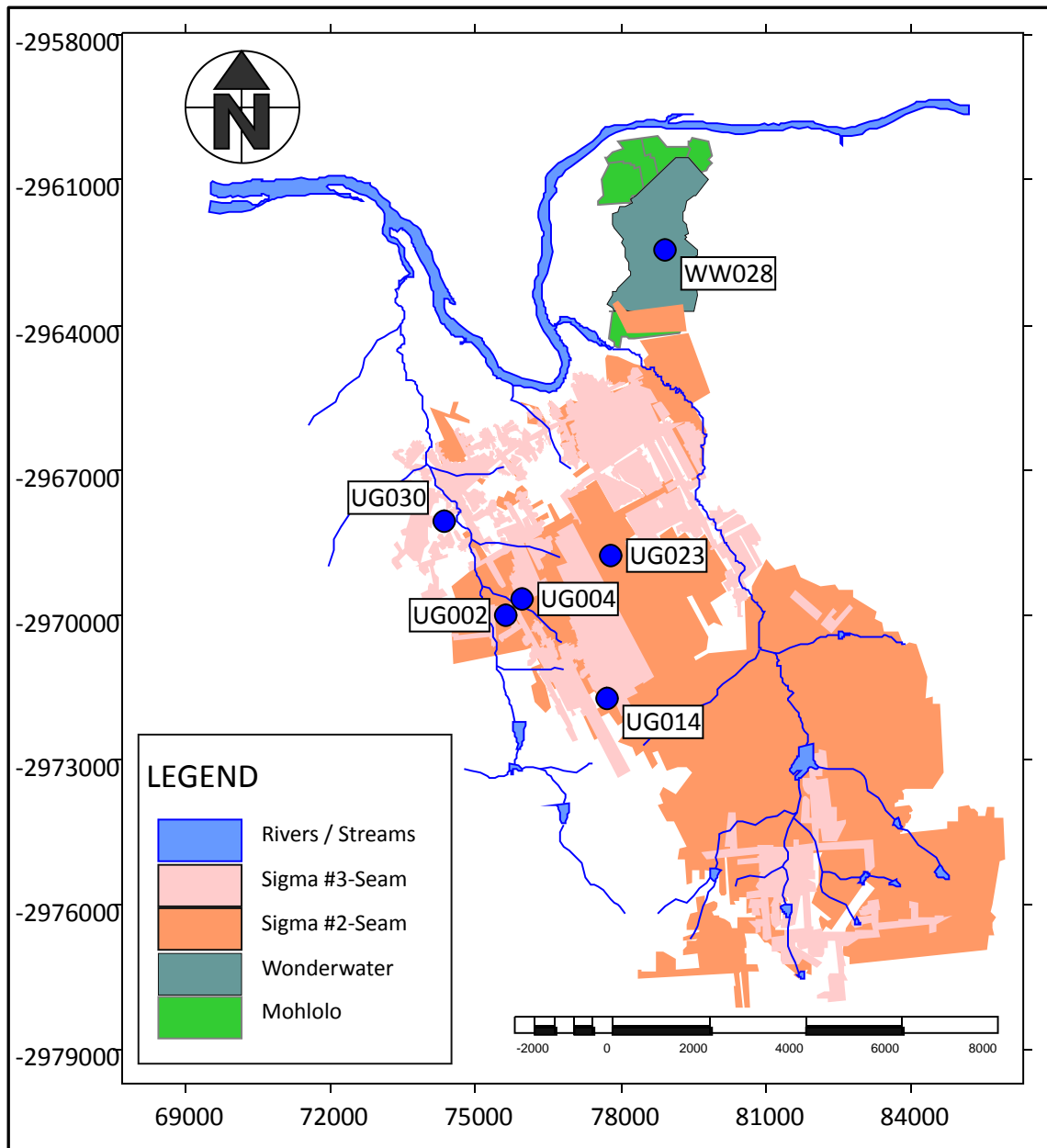
*Figure 10-17: Locality of the boreholes in the disturbed aquifer.*

### 10.4.1 General water quality discussion for the boreholes in the disturbed aquifer

The proportional distribution of the electrical conductivity and of the nitrate concentration of boreholes in the disturbed aquifer can be viewed in Figure 10-18 and Figure 10-19. The SANS 241:2006 table of the water quality of boreholes in the disturbed aquifer can be viewed in Table 10-8.

- Borehole UG014 has an EC concentration of 173 mS/m which is within the maximum allowable limits of the SANS 241:2006 drinking water standards. Borehole UG014 also has a sodium concentration of 438.97 mg/l and a fluoride concentration of 2.09 mg/l. The high sodium concentration could be attributed to the fact that sodium occurs abundantly in the shale of the Free State. Both these parameters have concentrations which are above the maximum allowable limits of the SANS 241:2006 drinking water standards. Water from this borehole is therefore not suitable for human consumption.

- Borehole UG023 has a nitrate concentration of 21.25 mg/l which is above the maximum allowable limit of the SANS 241:2006 drinking water standards. This could be due to the farming activity such as cattle grazing and fertilization of crops in the area. Water from this borehole is therefore not suitable for human consumption.

- Borehole UG030 has a nitrate concentration of 18.9 mg/l which is within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards. This can be attributed to the farming activity in the area. Water from this borehole is therefore suitable for human consumption for a limited duration use only.

- Borehole WW028 has a magnesium concentration of 76.17 mg/l which is within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards. Water from this borehole is therefore suitable for human consumption for a limited duration use only.

Table 10-8: SANS241:2006 water standards table for the boreholes in the disturbed aquifer

| Borehole No | | pH | EC | Ca | Mg | Na | K | Palk | Malk | F | Cl | NO2(N) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mS/m | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l |
| | Class 1 | 0-9.5 | 0-150 | 0-150 | 0-70 | 0-200 | 0-50 | | | 0-1 | 0-200 | |
| | Class 2 | 9.5-10 | 151-370 | 151-300 | 71-100 | 201-400 | 51-100 | | | 1-1.5 | 200-600 | |
| | AMA | >10 | >370 | >300 | >100 | >400 | >100 | | | >1.5 | >600 | |
| UG002 | Class 1 | 7.63 | 108 | 81.10 | 44.89 | 108.22 | 5.665 | 0 | 446 | 0.12 | 27.43 | -0.10 |
| UG004 | Class 1 | 7.70 | 65.4 | 35.75 | 15.99 | 80.97 | 5.208 | 0 | 343 | 0.11 | 9.51 | 0.02 |
| UG014 | AMA | 8.21 | 176 | 12.48 | 4.34 | 438.97 | 4.649 | 7.25 | 930 | 2.09 | 52.63 | -0.01 |
| UG023 | AMA | 7.72 | 61.2 | 59.56 | 21.46 | 38.39 | 6.552 | 0 | 188 | 0.11 | 24.93 | -0.01 |
| UG030 | Class 2 | 6.91 | 29.6 | 22.56 | 11.91 | 15.89 | 1.820 | 0 | 36 | 0.04 | 19.67 | -0.01 |
| WW028 | Class 2 | 7.90 | 112 | 147.26 | 76.17 | 16.45 | 10.234 | 0 | 297 | -0.10 | 3.46 | -0.10 |

| Borehole No | | Br | NO3(N) | PO4 | SO4 | Al | Fe | Mn | NH4(N) | Ba | Co | Cr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l |
| | Class 1 | | 0-10 | | 0-400 | 0-0.3 | 0-0.2 | 0-0.1 | 0-1 | | 0-0.5 | 0-0.1 |
| | Class 2 | | 10-20 | | 401-600 | 0.3-0.5 | 0.2-2 | 0.1-1 | 1-2 | | 0.5-1 | 0.1-0.5 |
| | AMA | | >20 | | >600 | >0.5 | >2 | >1 | >2 | | >1 | >0.5 |
| UG002 | Class 1 | -0.40 | -0.50 | -1.00 | 124.14 | 0.015 | -0.015 | 0.018 | | 0.158 | <0.002 | <0.006 |
| UG004 | Class 1 | 0.05 | 0.61 | -0.10 | 4.23 | 0.015 | -0.007 | 0.013 | | 0.258 | <0.002 | <0.006 |
| UG014 | AMA | 0.25 | 0.73 | -0.10 | 21.43 | 0.035 | -0.012 | 0.013 | | 0.065 | <0.002 | <0.006 |
| UG023 | AMA | 0.08 | 21.25 | -0.10 | 32.83 | 0.008 | -0.010 | 0.015 | | 0.017 | <0.002 | <0.006 |
| UG030 | Class 2 | 0.07 | 18.90 | -0.10 | 24.38 | 0.005 | -0.005 | 0.015 | 0.000 | 0.251 | <0.002 | <0.006 |
| WW028 | Class 2 | -0.40 | -0.50 | -1.00 | 371.42 | 0.009 | -0.004 | 0.011 | | 0.037 | <0.002 | <0.006 |

| Borehole No | | Cu | U | V | Zn | Si | B | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | | | | | |
| | Class 1 | 0-1 | 0-4 | 0-0.2 | 0-5 | | 0-2 | | | | | |
| | Class 2 | 1-2 | 4-8 | 0.2-0.5 | 5-10 | | 2-4 | | | | | |
| | AMA | >2 | >8 | >0.5 | >10 | | >4 | | | | | |
| UG002 | Class 1 | 0.004 | <0.010 | <0.010 | 0.009 | 8.911 | 1.007 | | | | | |
| UG004 | Class 1 | 0.004 | <0.010 | <0.010 | 0.004 | 8.913 | 0.281 | | | | | |
| UG014 | AMA | 0.006 | <0.010 | <0.010 | 0.004 | 5.507 | 1.111 | | | | | |
| UG023 | AMA | 0.004 | <0.010 | 0.018 | 0.008 | 22.464 | 0.123 | | | | | |
| UG030 | Class 2 | 0.005 | <0.010 | <0.010 | 0.015 | 15.044 | 0.074 | | | | | |
| WW028 | Class 2 | 0.005 | <0.010 | <0.010 | 0.010 | 5.262 | 0.328 | | | | | |
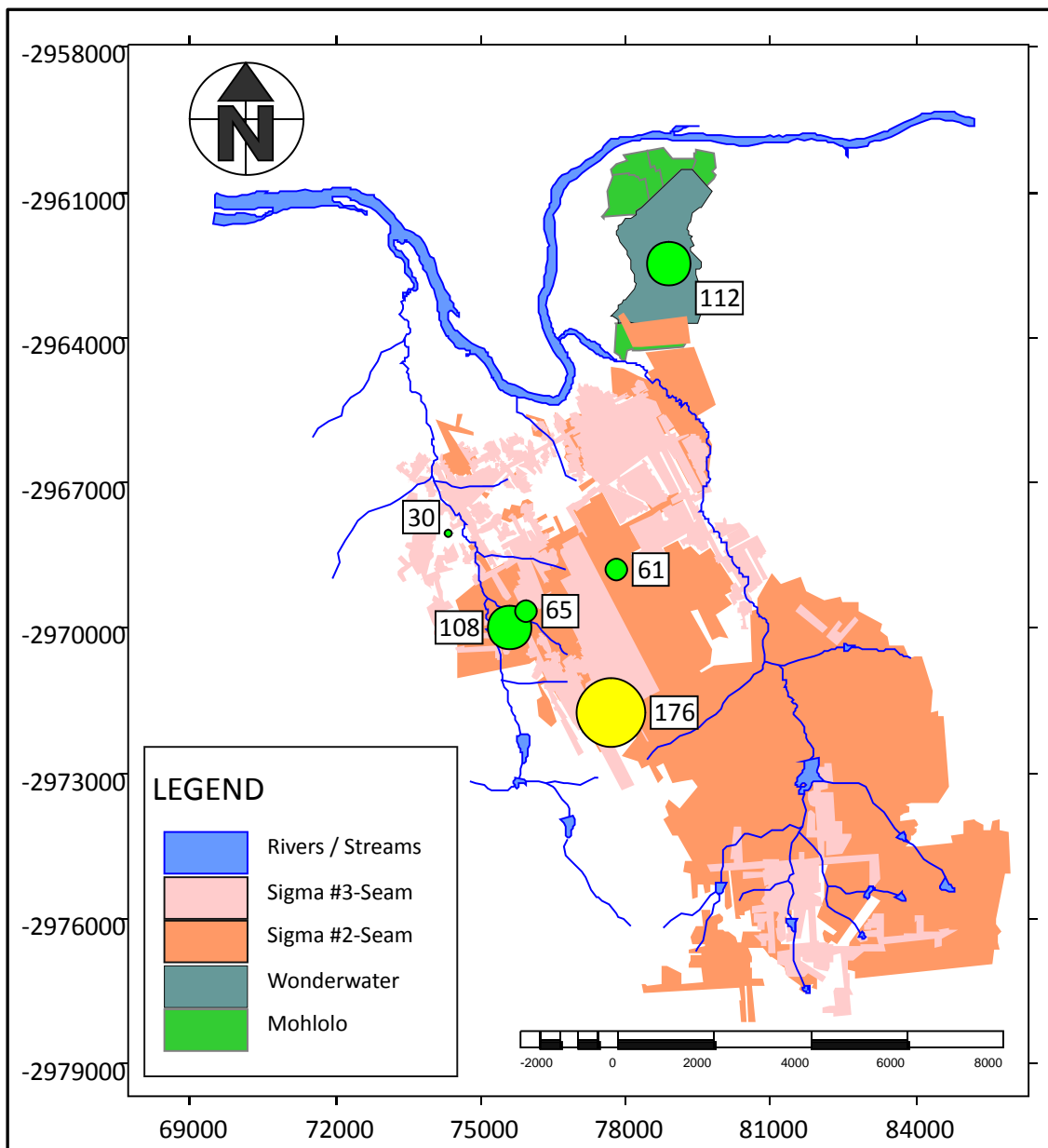
Figure 10-18: The proportional distribution of the electrical conductivity values of boreholes in the disturbed aquifer.
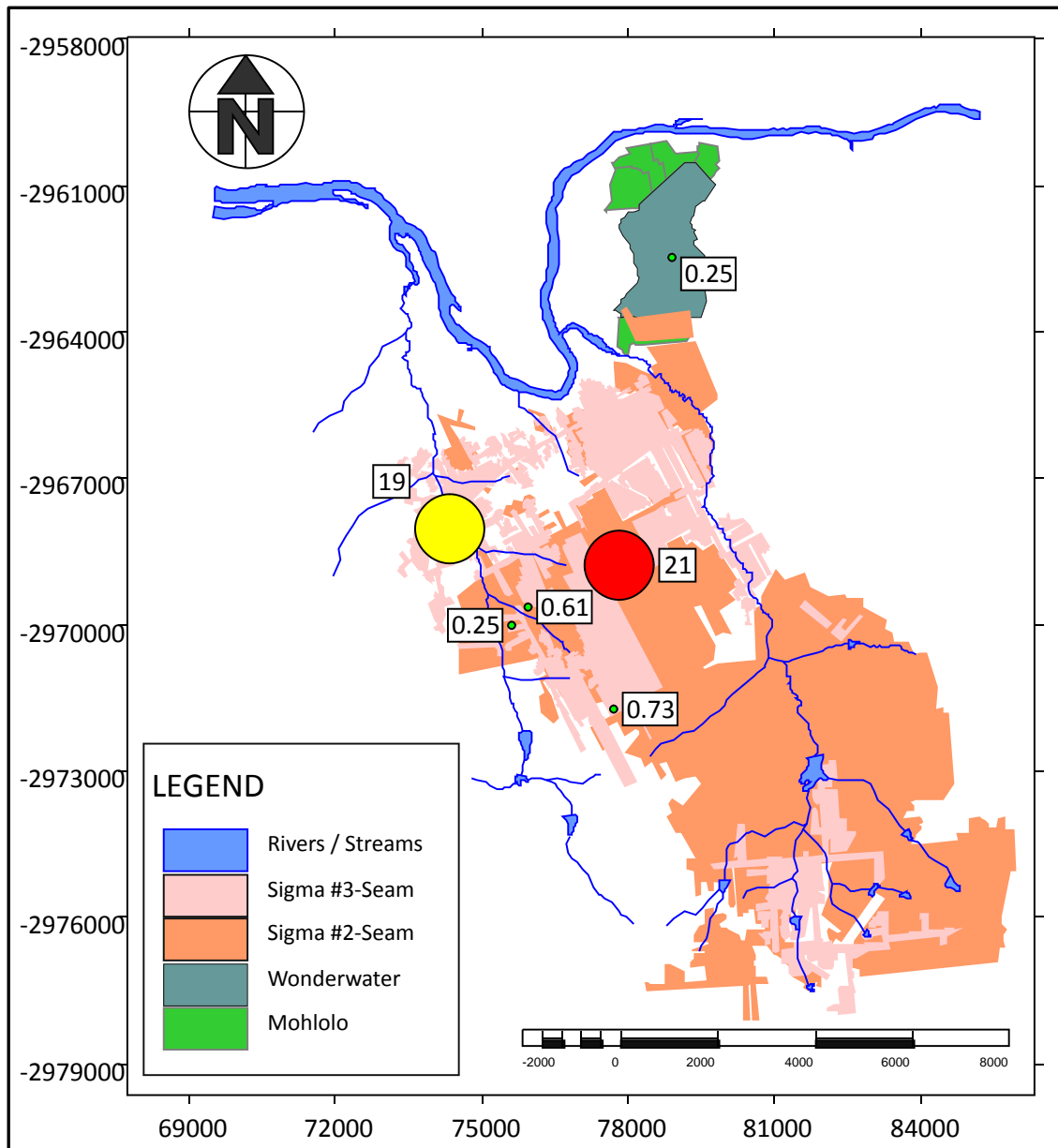
*Figure 10-19: The proportional distribution of the nitrate concentrations of the boreholes in the disturbed aquifer.*

## 10.4.2 Hydrochemical characterisation of boreholes in the disturbed aquifer through interpretive diagrams

- According to the expanded Durov Diagram in Figure 10-20, samples UG002 and UG023 plots in the second area of the diagram. This indicates calcium magnesium dominant water (or bicarbonate magnesium dominant water) which is typical of unpolluted water.

- Samples UG004 and UG014S are in the third area of the diagram which is indicative of sodium bicarbonate dominant water. This is typical of water from high extraction coal mines.
- Sample WW028 is in the fourth area and indicates sulphate and calcium dominance in the water.
- Sample UG030 is in the fifth area of the diagram which is indicative of no dominant anions or cations and indicates water resulting from dissolution or mixing.

## Expanded Durov Diagram
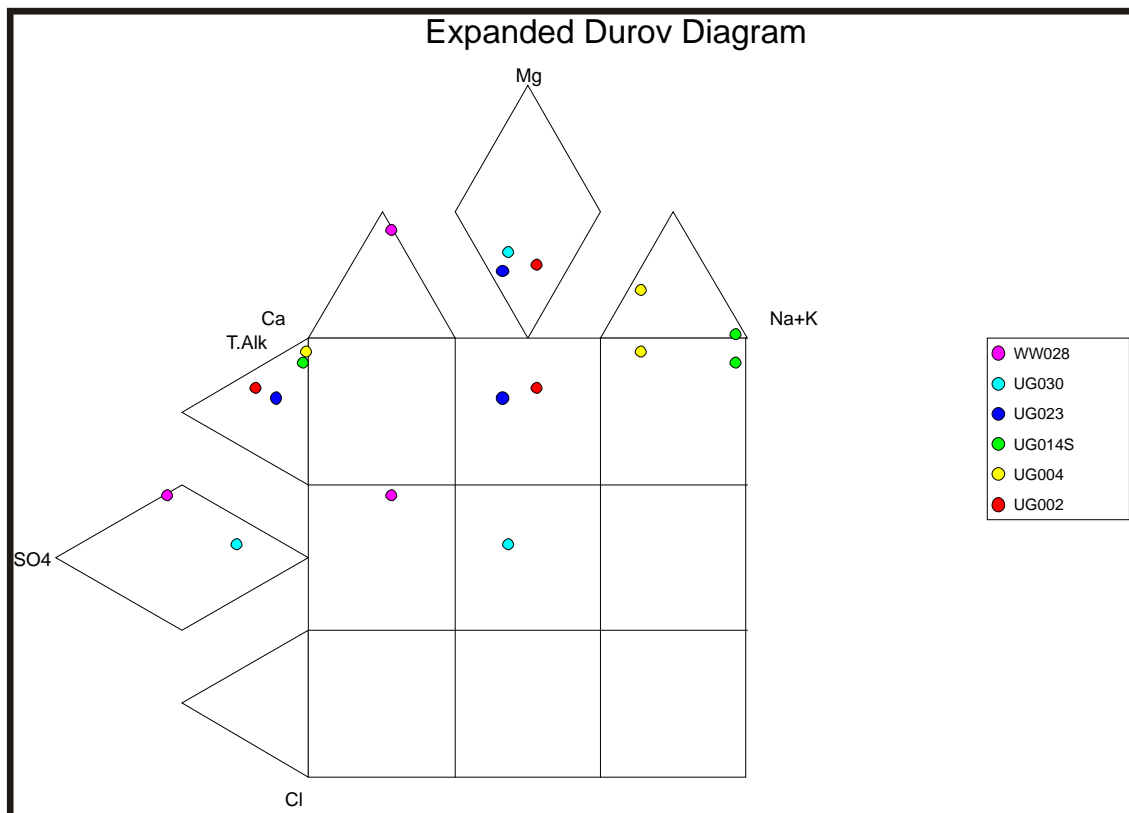
*Figure 10-20: Expanded Durov Diagram of the boreholes in the disturbed aquifer.*

- According to the stiff diagrams in Figure 10-21 samples UG002 and UG023 is the same type of water. They are bicarbonate magnesium dominant water which is typical of Karoo formation water.
- Samples UG004 and UG014S are both sodium bicarbonate waters which is typical of waters in high extraction coal mine areas like this one.
- Borehole UG030 has no dominant ions or cations, which indicates water resulting from dissolution or mixing.

- Borehole WW028 indicates sulphate calcium dominant water.
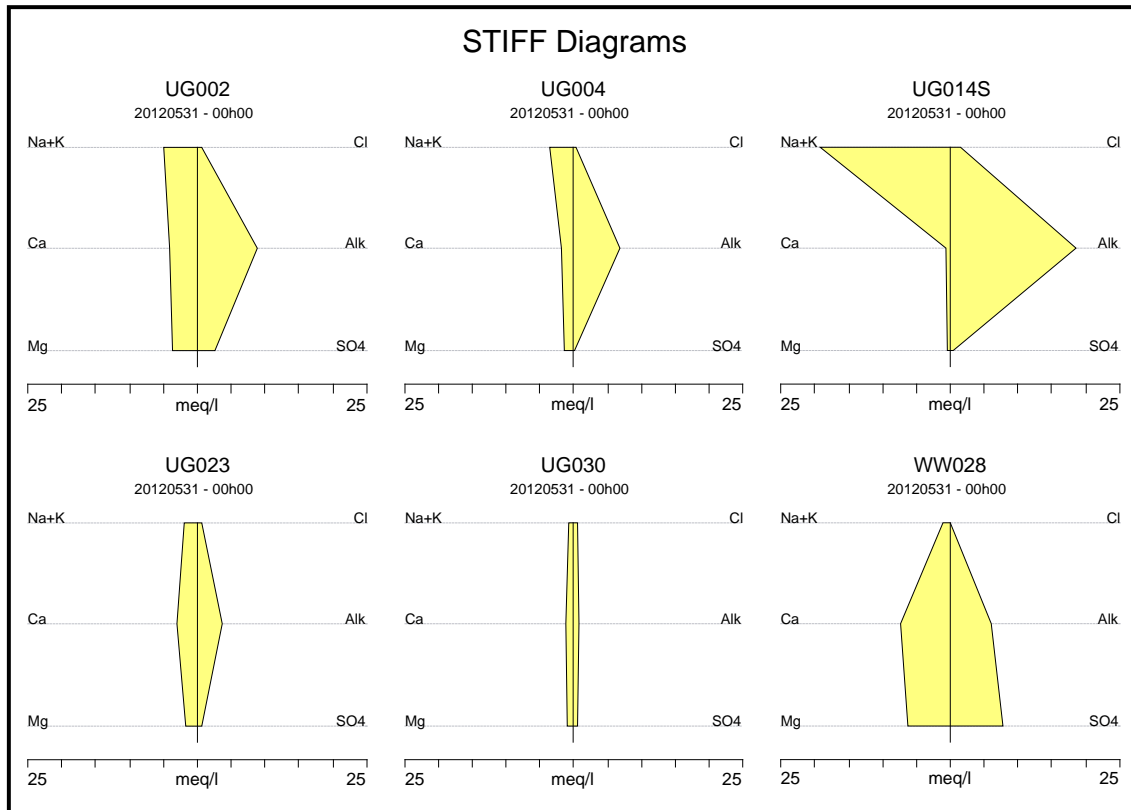


*Figure 10-21: STIFF Diagrams of the boreholes in the disturbed aquifer.*

## 10.5 Groundwater quality of the boreholes in the ashfill

A total of 18 boreholes were sampled in the ashfill and a summary of the sampled boreholes are available in Table 10-9. A locality map of the boreholes sampled in the ashfill can be viewed in Figure 10-22.

Table 10-9:  A summary of the boreholes sampled in the ashfill.

| Date sampled | Borehole ID | Sample ID | Water level | Sampling depth (mbcl) |
|---|---|---|---|---|
| Ashfill | | | | |
| 30/10/2012 | UG033 | UG033 | 9.54 | 30.00 |
| 30/10/2012 | UG034 | UG034 | 8.44 | 30.00 |
| 30/05/2012 | UG041 | UG041 | 18.96 | 50.00 |
| 30/10/2012 | UG044 | UG044 | 12.70 | 30.00 |
| 29/05/2012 | UG047 | UG047 | 25.26 | 30.00 |
| 29/05/2012 | UG048 | UG048 | 35.85 | 50.00 |
| 29/05/2012 | UG049 | UG049 | 39.69 | 55.00 |
| 02/07/2012 | UG055 | UG055 | 29.27 | 50.00 |
| 30/05/2012 | UG056 | UG056 | 28.94 | 39.00 |
| 05/06/2012 | UG064 | UG064 | 36.95 | 50.00 |
| 03/07/2012 | UG065 | UG065 | 25.58 | 35.00 |
| 29/05/2012 | UG066 | UG066 | 23.39 | 40.00 |
| 03/12/2012 | UG069 | UG069 | 1.20 | 35.00 |
| 31/05/2012 | B12/179 | B12/179 | 14.11 | 30.00 |
| 31/05/2012 | B12/182 | B12/182 | 13.48 | 30.00 |
| 31/05/2012 | B12/183 | B12/183D | 5.96 | 40.00 |
| | | B12/183M | | 25.00 |
| | | B12/183S | | 12.00 |
| 30/05/2012 | C316/41 | C316/41 | 11.82 | 20.00 |
| 30/05/2012 | C316/47 | C316/47 | 9.78 | 20.00 |
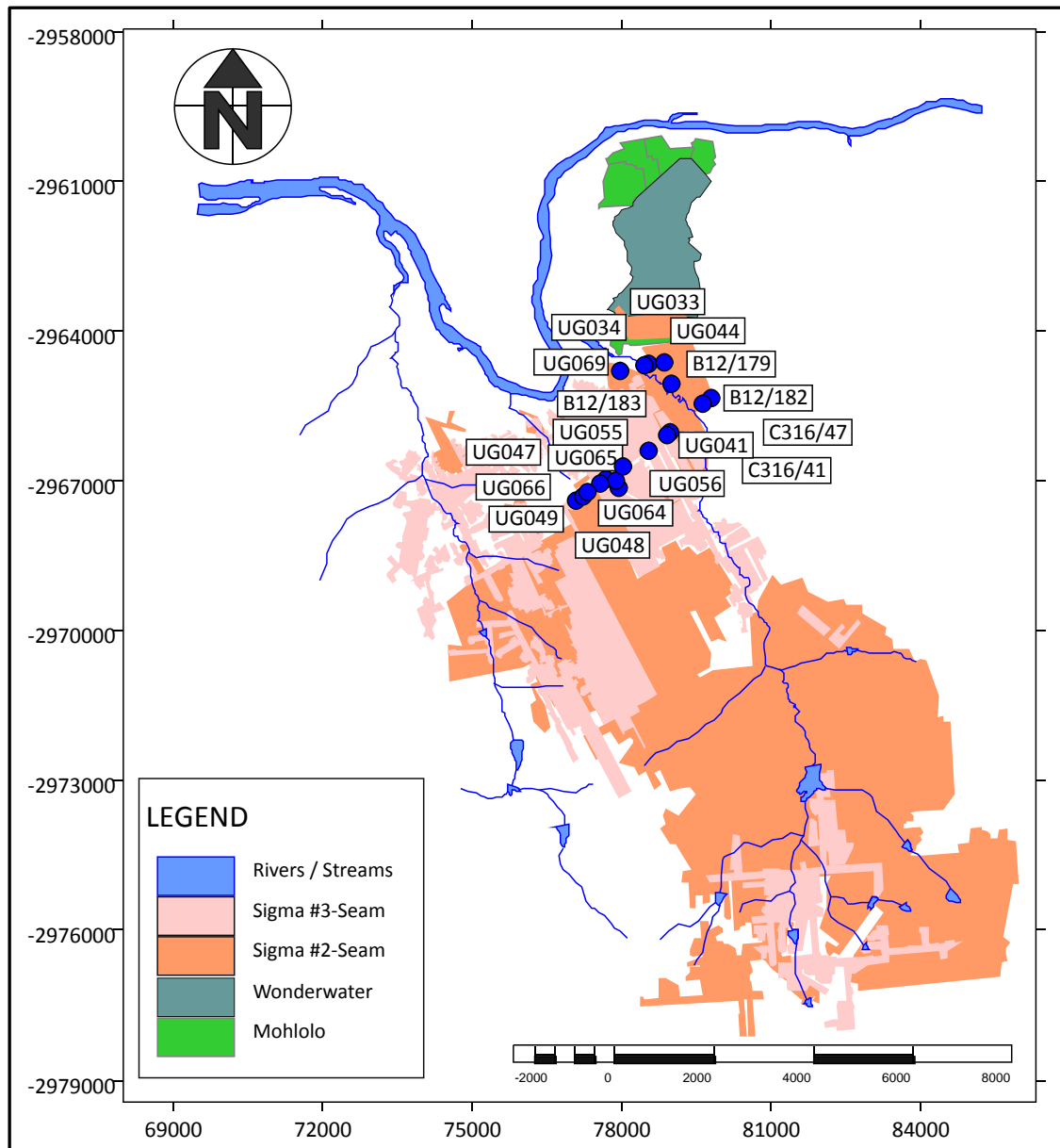
*Figure 10-22: The locality of the boreholes in the ashfill.*

## 10.5.1 General water quality discussion of the boreholes in the ashfill

The proportional distribution of the electrical conductivity and sulphate concentration can be noted in Figure 10-23 and Figure 10-24. The SANS 241:2006 table for drinking water standards of the boreholes in the ashfill can be viewed in Table 10-10.

- Borehole UG033 has a pH of 9.68, a sodium concentration of 255.5 mg/l, a chloride concentration of 210.41 mg/l and a boron concentration of 2.775. All of

these parameters have concentrations which are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards. Borehole UG033 also has an ammonium concentration of 3.1 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards. The reason for the high ammonium concentration can be attributed to the fly ash used for the ashfilling. Water from borehole UG033 is therefore unsuitable for human consumption.

- Borehole UG034 has a pH of 9.81, a sodium concentration of 258.8 mg/l, a chloride concentration of 210.02 mg/l and a boron concentration of 2.823 mg/l. All of these chemical parameters have concentrations which are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards. Borehole UG034 also has an ammonium concentration of 3 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards. The reason for the high ammonium concentration could be attributed to the fly ash used for the ashfilling. Water from borehole UG034 is therefore unsuitable for human consumption.

- Borehole UG044 has a pH of 11.19, an aluminium concentration of 5.039 mg/l and an ammonium concentration of 2.8 mg/l. All of these chemical parameters have concentrations which are above the maximum allowable limits of the SANS 241:2006 drinking water standards. The reason for the high aluminium and ammonium concentrations could be attributed to the fly ash used for the ashfilling. Water from borehole UG044 is therefore unsuitable for human consumption.

- Borehole UG069 has an EC concentration of 419 mS/m, a magnesium concentration of 141 mg/l, a sodium concentration of 648 mg/l, a sulphate concentration of 1828 mg/l, an aluminium concentration of 1 mg/l and a chromium concentration of 1 mg/l. All of these chemical parameters have concentrations which are above the maximum allowable limits of the SANS 241:2006 drinking water standards. Borehole UG069 also has a calcium concentration of 221 mg/l, a manganese concentration of 1 mg/l, an ammonium concentration of 1 mg/l, a copper concentration of 1 mg/l and a boron concentration of 3.7 mg/l. All of these chemical parameters are within the maximum allowable limits of the SANS 241:2006 drinking water standards. These elevated concentrations can be attributed to the fly ash used in the ashfilling. It is known that UG169 did decant due to artificial pressure from the ashfilling from September 2009 to March 2012 when the ashfilling was ceased. The decanting water from borehole UG069 would therefore have been of very

poor quality and above the maximum allowable limits of the SANS 241:2006 drinking water standards. This water would not have been suitable for human consumption.

- Borehole B12/179 has a pH of 9.58 and a chloride concentration of 203.49 mg/l. These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards. Borehole B12/179 also has an aluminium concentration of 0.753 mg/l, an ammonium concentration of 39.25 mg/l and a boron concentration of 4.254 mg/l. These concentrations are above the maximum allowable limits of the SANS 241:2006 drinking water standards and can be attributed to the fly ash used during the ashfilling process. Water from borehole B12/179 is therefore not suitable for human consumption.

- Sample B12/183D has an EC concentration of 255 mS/m, a calcium concentration of 194.48 mg/l and a manganese concentration of 0.13 mg/l. These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards. Sample B12/183D also has a fluoride concentration of 1.65 mg/l, a sulphate concentration of 1050 mg/l, an ammonium concentration of 37 mg/l and a boron concentration of 14.932 mg/l. These concentrations are above the maximum allowable limits of the SANS 241:2006 drinking water standards.

- Sample B12/183M has an EC concentration of 202 mS/m and a calcium concentration of 187.83 mg/l. These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards. Sample B12/182M also has a fluoride concentration of 2.40 mg/l, a sulphate concentration of 803 mg/l and a boron concentration of 8.940 mg/l. These concentrations are above the maximum allowable limits of the SANS 241:2006 drinking water standards and can be attributed to the fly ash used during the ash filling process.

- Sample B12/183S has a fluoride concentration of 3.37 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards. Sample B12/183S also has a sulphate concentration of 309 mg/l, an aluminium concentration of 0.483 mg/l, a manganese concentration of 0.165 mg/l and an ammonium concentration of 1.210 mg/l.

- The reason for the elevated concentrations in borehole B12/183 could be attributed to the fly ash used during the ash filling process. Borehole B12/183 has the possibility for decanting due to artificial pressure caused by the ashfill that was pumped into the boreholes. If decant should therefore occur from this borehole, the water will be of a poor quality and above the maximum allowable

limits of the SANS 241:2006 drinking water standards.  It will be unsuitable for human consumption (see pages 8-7 and 8-8).

- Borehole C316/47 has a manganese concentration of 0.224 mg/l and a boron concentration of 3.007 mg/l.  These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards and water from this borehole is therefore suitable for human consumption for a limited duration use only.

*Table 10-10: SANS 241:2006 water standards table for the ashfill boreholes.*

| Borehole No | | pH | EC | Ca | Mg | Na | K | Palk | Malk | F | Cl | NO2(N) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mS/m | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l |
| | Class 1 | 0-9.5 | 0-150 | 0-150 | 0-70 | 0-200 | 0-50 | | | 0-1 | 0-200 | |
| | Class 2 | 9.5-10 | 151-370 | 151-300 | 71-100 | 201-400 | 51-100 | | | 1-1.5 | 200-600 | |
| | AMA | >10 | >370 | >300 | >100 | >400 | >100 | | | >1.5 | >600 | |
| UG033 | AMA | 9.68 | 144 | 38.6 | 0.6 | 255.5 | 7.5 | 35.8 | 55 | 0.63 | 210.41 | -0.10 |
| UG034 | AMA | 9.81 | 145 | 40.4 | 0.5 | 258.8 | 7.7 | 40 | 60 | 0.63 | 210.02 | -0.10 |
| UG041 | Class 1 | 7.86 | 47.5 | 39.03 | 21.74 | 21.34 | 2.203 | 0 | 161 | 0.06 | 10.16 | -0.01 |
| UG044 | AMA | 11.19 | 136 | 103.7 | 0.1 | 165.1 | 27.6 | 165 | 246 | 0.12 | 184.84 | -0.10 |
| UG047 | Class 1 | 8.45 | 40.5 | 14.41 | 12.19 | 54.42 | 9.126 | 4.57 | 181 | 0.29 | 17.71 | -0.01 |
| UG048 | Class 1 | 8.03 | 57.6 | 57.75 | 30.32 | 36.27 | 11.107 | 0 | 327 | 0.05 | 5.08 | -0.01 |
| UG049 | Class 1 | 7.97 | 62.4 | 10.50 | 4.37 | 142.00 | 3.112 | 0 | 292 | 0.44 | 30.44 | -0.01 |
| UG055 | Class 1 | 7.42 | 31.8 | 22.27 | 9.09 | 23.78 | 3.418 | 0 | 91 | 0.04 | 7.49 | -0.01 |
| UG056 | Class 1 | 8.04 | 63.4 | 29.74 | 13.24 | 89.87 | 5.511 | 0 | 328 | 0.07 | 14.52 | -0.01 |
| UG064 | Class 1 | 8.14 | 62.3 | 16.83 | 6.71 | 111.95 | 3.659 | 0 | 294 | 0.28 | 16.48 | 0.01 |
| UG065 | Class 1 | 7.98 | 62.3 | 50.57 | 24.24 | 51.05 | 7.326 | 0 | 333 | 0.05 | 12.57 | 0.01 |
| UG066 | Class 1 | 8.08 | 74.6 | 72.24 | 45.60 | 31.51 | 7.877 | 0 | 345 | 0.06 | 9.29 | 0.01 |
| UG069 | AMA | 7.20 | 419.00 | 221.00 | 141.00 | 648.00 | 11.00 | 0.00 | 721.00 | 0.50 | 62.00 | 1.00 |
| B12/179 | AMA | 9.58 | 124 | 2.49 | 0.86 | 183.10 | 33.598 | 98.6 | 253 | 0.62 | 203.49 | -0.10 |
| B12/182 | Class 1 | 8.29 | 34.5 | 2.31 | 1.31 | 64.53 | 4.667 | 0 | 86.1 | 0.64 | 30.71 | -0.01 |
| B12/183D | AMA | 8.08 | 255 | 194.48 | 55.94 | 192.21 | 29.874 | 0 | 75.2 | 1.65 | 190.72 | -0.10 |
| B12/183M | AMA | 8.26 | 202 | 187.83 | 32.35 | 163.05 | 27.145 | 0 | 46.8 | 2.40 | 145.03 | 0.65 |
| B12/183S | AMA | 5.72 | 106 | 87.61 | 1.09 | 119.00 | 21.579 | 0 | 14.4 | 3.37 | 92.69 | 2.35 |
| C316/41 | Class 1 | 8.22 | 69.4 | 38.45 | 19.61 | 103.41 | 3.064 | 0 | 371 | 0.57 | 8.70 | 0.02 |
| C316/47 | Class 2 | 6.75 | 48.3 | 12.30 | 3.10 | 86.70 | 10.100 | 0 | 141 | 0.84 | 7.84 | 32.39 |

Table 10-10:  SANS 241:2006 water standards table for the ashfill boreholes (Continued).

| Borehole No | | Br | NO3(N) | PO4 | SO4 | Al | Fe | Mn | NH4(N) | Ba | Co | Cr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l |
| | Class 1 | | 0-10 | | 0-400 | 0-0.3 | 0-0.2 | 0-0.1 | 0-1 | | 0-0.5 | 0-0.1 |
| | Class 2 | | 10-20 | | 401-600 | 0.3-0.5 | 0.2-2 | 0.1-1 | 1-2 | | 0.5-1 | 0.1-0.5 |
| | AMA | | >20 | | >600 | >0.5 | >2 | >1 | >2 | | >1 | >0.5 |
| UG033 | AMA | -0.40 | -0.50 | -1.00 | 343 | 0.104 | 0.027 | 0.008 | 3.100 | 0.029 | <0.002 | <0.006 |
| UG034 | AMA | 0.56 | -0.50 | -1.00 | 343 | 0.113 | 0.029 | 0.005 | 3.000 | 0.028 | <0.002 | <0.006 |
| UG041 | Class 1 | 0.16 | 4.99 | -0.10 | 60.70 | 0.016 | -0.014 | 0.017 | | 0.077 | <0.002 | <0.006 |
| UG044 | AMA | -0.40 | -0.50 | -1.00 | 18 | 5.039 | 0.006 | -0.004 | 2.800 | 0.763 | <0.002 | <0.006 |
| UG047 | Class 1 | -0.04 | -0.05 | -0.10 | 20.60 | 0.018 | -0.011 | 0.013 | | 0.034 | <0.002 | <0.006 |
| UG048 | Class 1 | 0.04 | 0.09 | -0.10 | 2.50 | 0.016 | -0.013 | 0.016 | | 0.061 | <0.002 | <0.006 |
| UG049 | Class 1 | 0.29 | 1.84 | -0.10 | 3.05 | 0.027 | -0.004 | 0.012 | | 0.076 | <0.002 | <0.006 |
| UG055 | Class 1 | 0.10 | 7.21 | -0.10 | 36.00 | 0.007 | -0.011 | 0.013 | 0.010 | 0.076 | <0.002 | <0.006 |
| UG056 | Class 1 | 0.07 | 0.29 | -0.10 | 8.75 | 0.016 | -0.011 | 0.012 | | 0.380 | <0.002 | <0.006 |
| UG064 | Class 1 | -0.04 | 0.91 | -0.10 | 21.97 | 0.015 | -0.005 | 0.009 | | 0.129 | <0.002 | <0.006 |
| UG065 | Class 1 | 0.06 | 0.32 | -0.10 | 6.96 | 0.021 | -0.013 | 0.018 | | 0.308 | <0.002 | <0.006 |
| UG066 | Class 1 | 0.09 | 4.55 | -0.10 | 65.50 | 0.027 | -0.014 | 0.020 | 0.200 | 0.115 | <0.002 | <0.006 |
| UG069 | AMA | | | 0.90 | 1828.00 | 1.00 | 0.00 | 1.00 | 1.00 | | | 1.00 |
| B12/179 | AMA | -0.40 | -0.50 | -1.00 | 112.48 | 0.753 | 0.033 | 0.019 | 39.250 | 0.007 | <0.002 | <0.006 |
| B12/182 | Class 1 | -0.04 | 1.11 | -0.10 | 36.85 | 0.108 | 0.010 | 0.007 | | 0.018 | <0.002 | <0.006 |
| B12/183D | AMA | -0.40 | -0.50 | -1.00 | 1050.00 | 0.063 | 0.001 | 0.130 | 37.000 | 0.042 | <0.002 | <0.006 |
| B12/183M | AMA | -0.40 | -0.50 | -1.00 | 803.00 | 0.088 | 0.000 | 0.019 | | 0.062 | <0.002 | <0.006 |
| B12/183S | AMA | -0.40 | -0.50 | -1.00 | 309.00 | 0.483 | 0.016 | 0.165 | 1.210 | 0.086 | <0.002 | <0.006 |
| C316/41 | Class 1 | 0.07 | 1.76 | -0.10 | 0.51 | 0.019 | 0.025 | 0.011 | | 0.306 | <0.002 | <0.006 |
| C316/47 | Class 2 | -0.04 | 0.09 | -0.10 | 1.02 | <0.004 | 0.018 | 0.224 | 0.010 | 0.106 | <0.002 | <0.006 |

Table 10-10: SANS 241:2006 water standards table for the ashfil boreholes (Continued).

| Borehole No | | Cu mg/l | U mg/l | V mg/l | Zn mg/l | Si mg/l | B mg/l | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Class 1 | 0-1 | 0-4 | 0-0.2 | 0-5 | | 0-2 | | | | | |
| | Class 2 | 1-2 | 4-8 | 0.2-0.5 | 5-10 | | 2-4 | | | | | |
| | AMA | >2 | >8 | >0.5 | >10 | | >4 | | | | | |
| UG033 | AMA | 0.006 | | | 0.013 | 8.376 | 2.775 | | | | | |
| UG034 | AMA | 0.005 | | | 0.008 | 9.270 | 2.823 | | | | | |
| UG041 | Class 1 | 0.004 | <0.010 | 0.018 | 0.009 | 21.849 | 0.074 | | | | | |
| UG044 | AMA | 0.003 | | | 0.002 | 3.673 | 0.616 | | | | | |
| UG047 | Class 1 | 0.003 | <0.010 | <0.010 | 0.004 | 2.222 | 0.547 | | | | | |
| UG048 | Class 1 | 0.003 | <0.010 | <0.010 | 0.006 | 11.356 | 0.095 | | | | | |
| UG049 | Class 1 | 0.003 | <0.010 | <0.010 | 0.004 | 3.142 | 1.371 | | | | | |
| UG055 | Class 1 | 0.003 | <0.010 | <0.010 | 0.006 | 14.566 | 0.081 | | | | | |
| UG056 | Class 1 | 0.006 | <0.010 | <0.010 | 0.008 | 8.250 | 0.175 | | | | | |
| UG064 | Class 1 | 0.003 | <0.010 | <0.010 | 0.010 | 7.044 | 0.333 | | | | | |
| UG065 | Class 1 | 0.004 | <0.010 | <0.010 | 0.009 | 10.998 | 0.074 | | | | | |
| UG066 | Class 1 | 0.004 | <0.010 | <0.010 | 0.009 | 22.836 | 0.069 | | | | | |
| UG069 | AMA | 1.00 | | | 1.00 | | 3.70 | | | | | |
| B12/179 | AMA | 0.017 | <0.010 | <0.010 | 0.015 | 3.389 | 4.254 | | | | | |
| B12/182 | Class 1 | 0.003 | <0.010 | <0.010 | 0.004 | 2.209 | 0.999 | | | | | |
| B12/183D | AMA | 0.009 | <0.010 | <0.010 | 0.038 | 0.188 | 14.932 | | | | | |
| B12/183M | AMA | 0.011 | <0.010 | <0.010 | 0.026 | 0.214 | 8.940 | | | | | |
| B12/183S | AMA | 0.020 | <0.010 | <0.010 | 0.139 | 0.275 | 1.447 | | | | | |
| C316/41 | Class 1 | 0.003 | <0.010 | <0.010 | 0.009 | 3.844 | 1.157 | | | | | |
| C316/47 | Class 2 | 0.005 | <0.010 | <0.010 | 0.014 | 1.378 | 3.007 | | | | | |
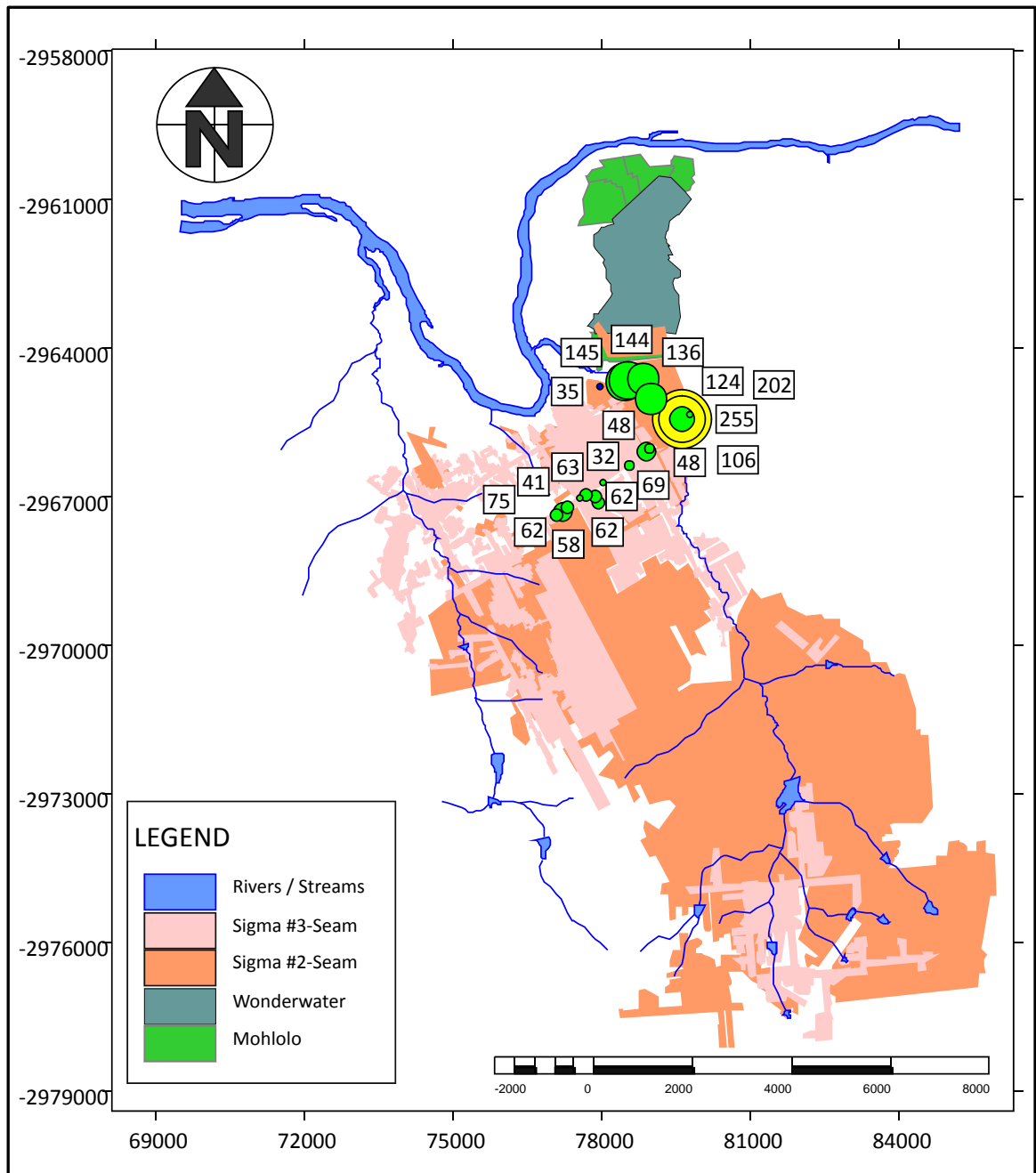
*Figure 10-23: The proportional distribution of the electrical conductivity values in the ashfill.*
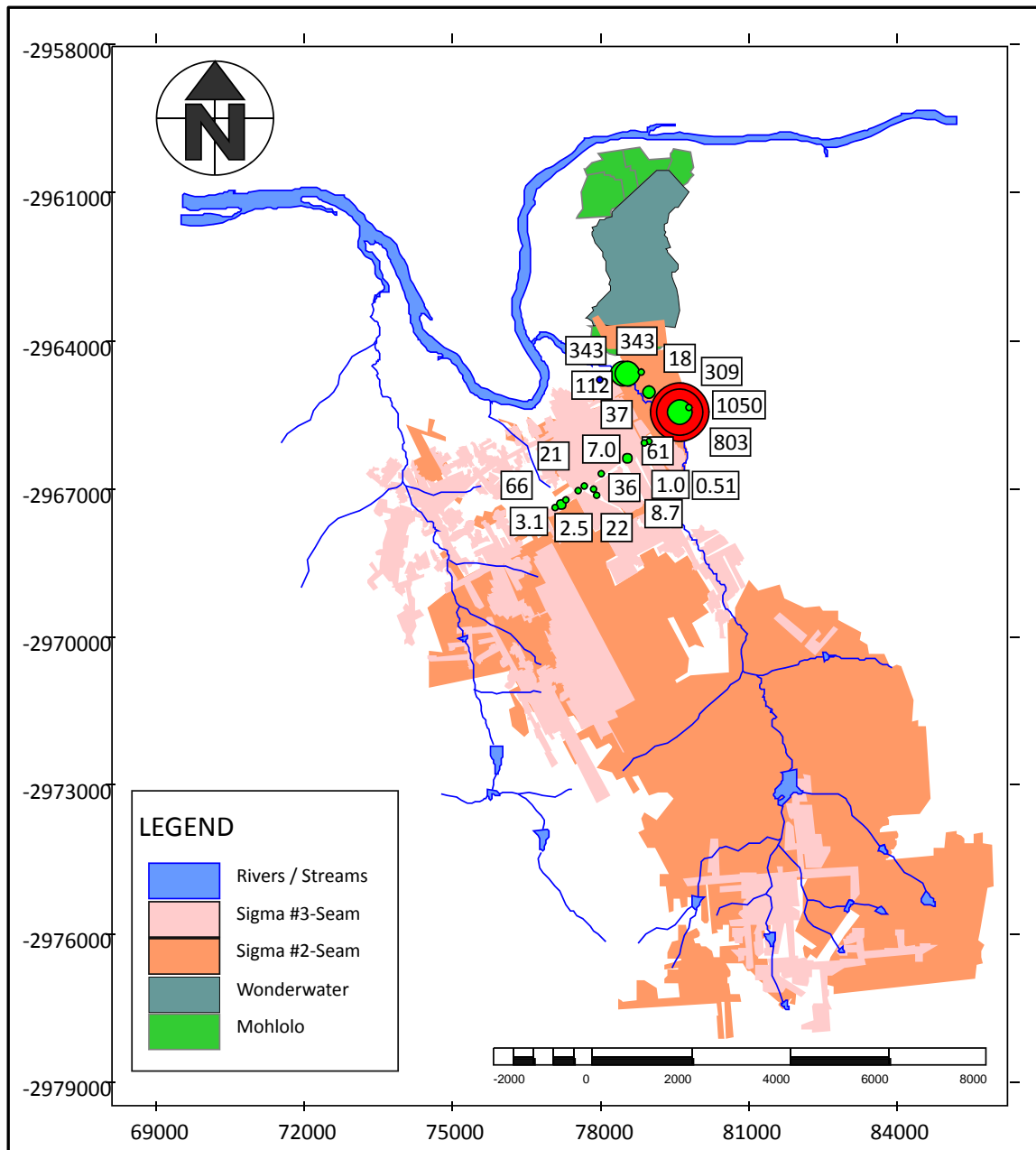
*Figure 10-24: Proportional distribution of the sulphate concentrations of the boreholes in the ashfill.*

## 10.5.2 Hydrochemical characterisation of the boreholes in the ashfill through interpretive diagrams

- According to the expanded Durov Diagram in Figure 10-25, samples UG066, UG065, UG055, UG048 and UG041 plots within the second area of the diagram which indicates magnesium bicarbonate dominant water (typical of unpolluted water).

- Samples UG064, UG056, UG049, UG047, C316/47, C316/41 and B12/182 plots in the third area of the diagram and are characterised as sodium bicarbonate dominant water, which is typical of high extraction underground coal mines.

- Samples B12/183M and B12/183D plots in the fifth area of the diagram and is magnesium sulphate dominant water which is typical of mine water.

- Samples B12/183S and B12/179 plots in the sixth field of the diagram which indicates sodium sulphate dominant water. This could be due to the ashfill of the borehole.
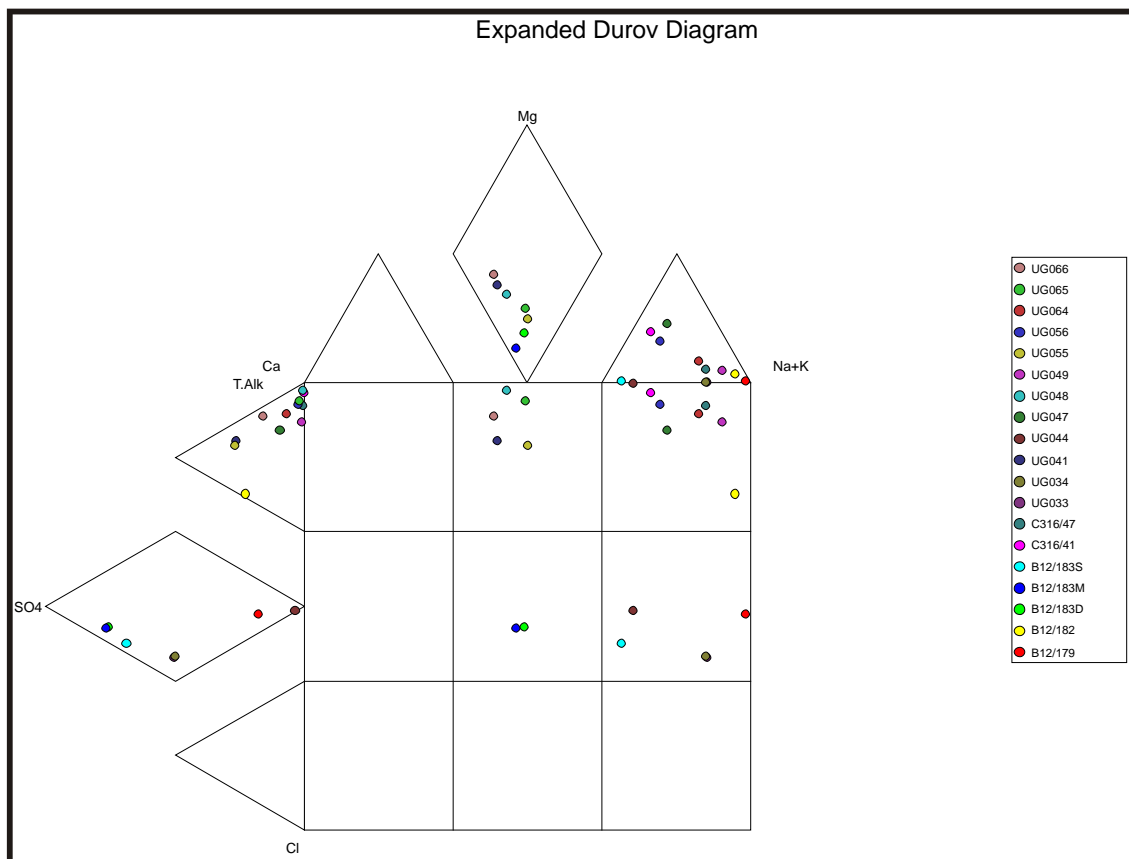


*Figure 10-25: Expanded Durov Diagram of the boreholes in the ashfill.*

- According to the stiff diagrams in Figure 10-26 samples UG066, UG065, UG055, UG048 and UG041 are all magnesium bicarbonate type water which indicates that the water is not polluted.

- Samples UG064, UG056, UG049, UG047, C316/47, C316/41 and B12/182 are all sodium bicarbonate type water which is typical of boreholes in high extraction coal mines.
- Samples B12/183S, B12/183M and B12/183D are all a sodium sulphate type water which indicates that the water is impacted by the ashfill.
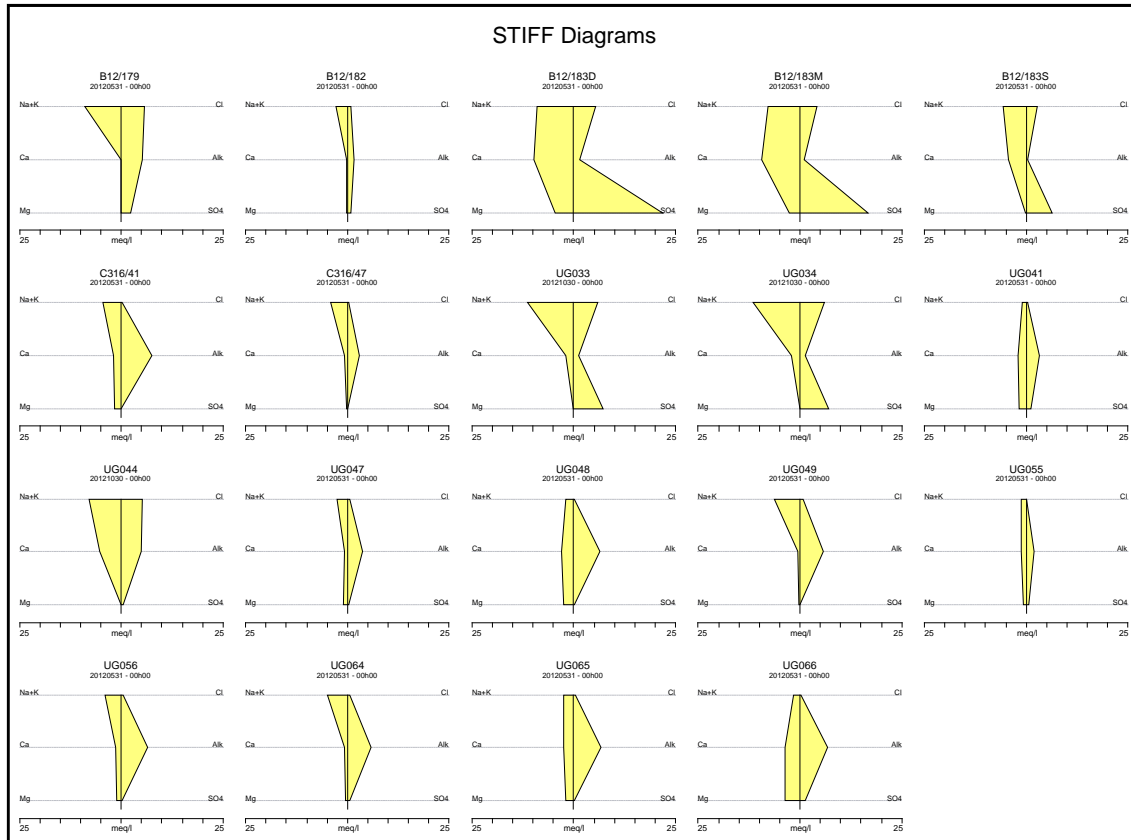


*Figure 10-26: STIFF Diagrams of the boreholes in the ashfill.*

## 10.6 Groundwater quality of boreholes in the mine

A total of 14 boreholes were sampled in the mine and a summary of the sampled boreholes are available in Table 10-11. A locality map of the boreholes sampled in the mine can be viewed in Figure 10-27.

*Table 10-11:  A summary of the boreholes sampled in the mine.*

| Date sampled | Borehole ID | Sample ID | Water level | Sampling depth (mbcl) |
|---|---|---|---|---|
| | | | Mine | |
| 29/05/2012 | UG013 | UG013D | 48.47 | 130 |
| | | UG013S | | 65 |
| 05/06/2012 | UG024 | UG024 | 30.72 | 50 |
| 03/07/2012 | UG037 | UG037D | 40.49 | 70 |
| | | UG037S | | 45 |
| 30/05/2012 | UG040 | UG040D | 19.36 | 65 |
| | | UG040S | | 40 |
| 29/05/2012 | UG046 | UG046 | 23.36 | 35 |
| 30/05/2012 | UG053 | UG053 | 11.96 | 30 |
| 30/05/2012 | UG058 | UG058 | 36.59 | 50 |
| 02/07/2012 | UG059 | UG059 | 19.33 | 35 |
| 01/06/2012 | WW011 | WW011 | 2.31 | 15 |
| 01/06/2012 | WW012 | WW012 | 28.55 | 45 |
| 01/06/2012 | WW021 | WW021D | 39.62 | 55 |
| | | WW021S | | 41 |
| 01/06/2012 | WW027 | WW027 | 28.82 | 40 |
| 01/06/2012 | WW029 | WW029 | 27.23 | 40 |
| 30/10/2012 | B12/53 | B12/53D | 3.26 | 40 |
| | | B12/53S | | 10 |
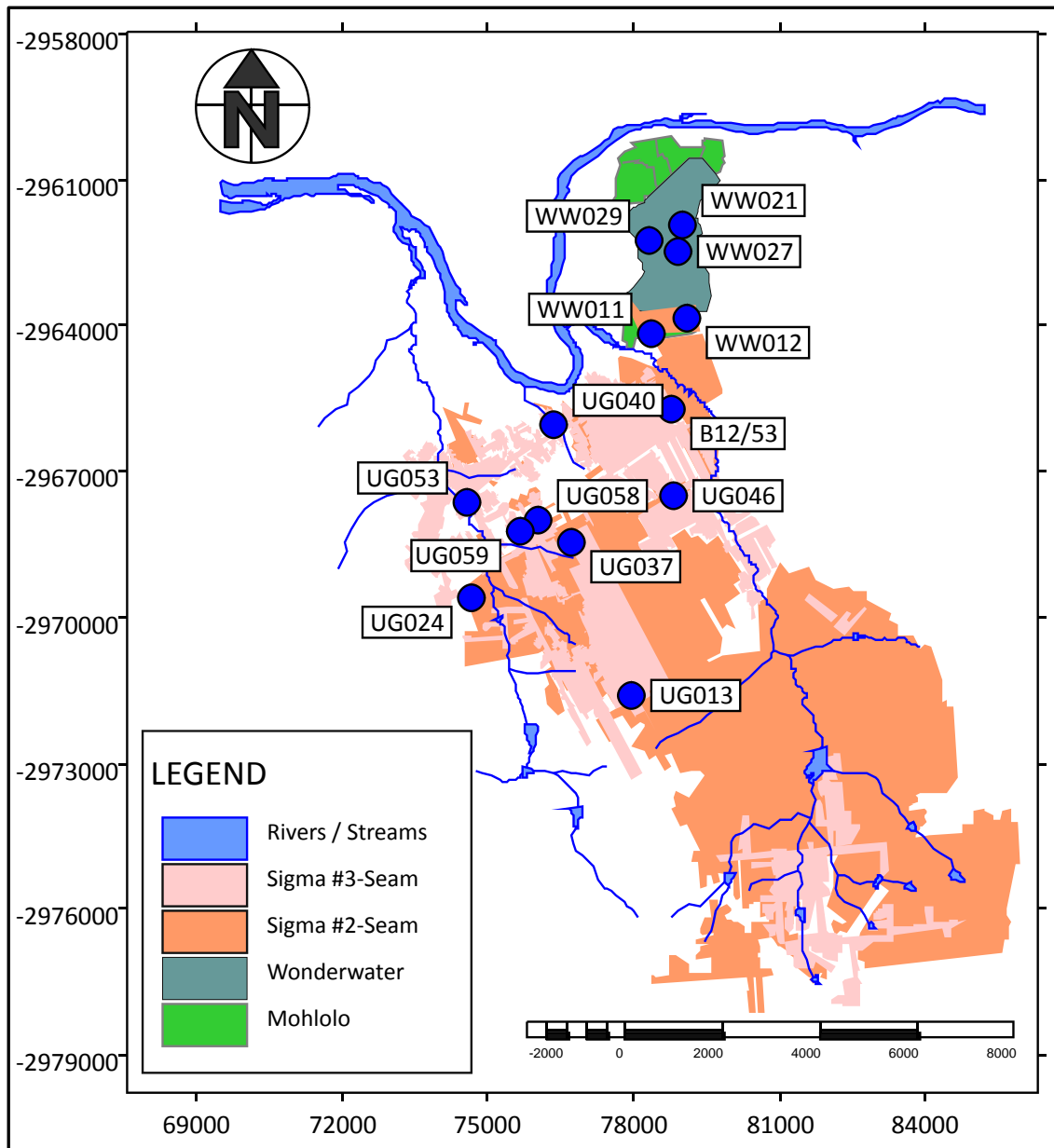
*Figure 10-27: Locality map of the boreholes in the mine.*

## 10.6.1 General water quality discussion for the boreholes in the mine

The proportional distribution of the electrical conductivity, sulphate and sodium concentrations of boreholes in the mine can be viewed in Figure 10-28, Figure 10-29 and Figure 10-30 respectively. The SANS 241:2006 table for the water quality standards of the boreholes in the mine can be viewed in Table 10-12.

- Sample UG013D has an EC concentration of 207 mS/m and a sulphate concentration of 525.34 mg/l.  These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards.  Sample UG013D also has a sodium concentration of 468.37 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards.

- Water from borehole UG013 is therefore above the maximum allowable limit of the SANS 241:2006 drinking water standards and is not suitable for human consumption.

- Borehole UG024 has a fluoride concentration of 3.39 mg/l which is above the maximum allowable limits of the SANS 241:2006 drinking water standards.  Water from this borehole is therefore not suitable for human consumption.

- Sample UG037D has an EC concentration of 377 mS/m, a sodium concentration of 806.53 mg/l and a sulphate concentration of 946 mg/l.  These concentrations are above the maximum allowable limits of the SANS 241:2006 drinking water standards.

- Sample UG037S has an EC concentration of 189 mS/m, a sodium concentration of 384.78 mg/l and a sulphate concentration of 493.13 mg/l.  These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards.

- The water from borehole UG037 is therefore above the maximum allowable limits of the SANS 241:2006 drinking water standards and is not suitable for human consumption.

- Sample UG040D has a sodium concentration of 294.35 mg/l and a fluoride concentration of 1.37 mg/l.  These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards.

- Water from borehole UG040 is therefore within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards and is suitable for human consumption for a limited duration use only.

- Borehole UG046 has an EC concentration of 313 mS/m which is within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards.  Borehole UG046 also has a sodium concentration of 848.03 mg/l and a fluoride concentration of 3.80 mg/l.  The reason for the high EC concentration is the very high alkalinity of 1814 mg/l.  These concentrations are above the maximum allowable limits of the SANS 241:2006 drinking water standards.  Water from borehole UG046 is therefore above the maximum

allowable limits of the SANS 241:2006 drinking water standards and is not suitable for human consumption.

- Sample WW021D has a magnesium concentration of 74.18 mg/l, a sulphate concentration of 422 mg/l and a manganese concentration of 0.123 mg/l. These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards.

- Sample WW021S has a magnesium concentration of 73.58 mg/l, a sulphate concentration of 416 mg/l and a manganese concentration of 0.139 mg/l. These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards.

- Water from borehole WW021 is therefore within the maximum allowable limits of the SANS 241:2006 drinking water standards and is suitable for human consumption for a limited duration use only.

- Borehole WW027 has a calcium concentration of 189.87 mg/l, a magnesium concentration of 83.28 mg/l and a sulphate concentration of 502.92 mg/l. These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards and water from this borehole is therefore suitable for human consumption for a limited duration use only.

- Sample B12/53D has an EC concentration of 461 mS/m, a sodium concentration of 1085.2 mg/l and a sulphate concentration of 1726 mg/l. These concentrations are above the maximum allowable limits of the SANS 241:2006 drinking water standards. Sample B12/53D also has an ammonium concentration of 1.3 mg/l and a boron concentration of 3.481 mg/l. These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards.

- Sample B12/53S has a pH of 9.67, an ammonium concentration of 1.3 mg/l and a boron concentration of 3.659 mg/l. These concentrations are within the maximum allowable limits (Class 2) of the SANS 241:2006 drinking water standards. Sample B12/53S also has and EC concentration of 377 mS/m, a sodium concentration of 867.5 mg/l and a sulphate concentration of 1190 mg/l. These concentrations are above the maximum allowable limits of the SANS 241:2006 drinking water standards.

- Water from borehole B12/53 is therefore above the maximum allowable limits of the SANS 241:2006 drinking water standards and is not suitable for human consumption.

Table 10-12: SANS 241:2006 water standards table for the boreholes in the mine.

| Borehole No | | pH | EC | Ca | Mg | Na | K | Palk | Malk | F | Cl | NO2(N) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mS/m | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l |
| | Class 1 | 0-9.5 | 0-150 | 0-150 | 0-70 | 0-200 | 0-50 | | | 0-1 | 0-200 | |
| | Class 2 | 9.5-10 | 151-370 | 151-300 | 71-100 | 201-400 | 51-100 | | | 1-1.5 | 200-600 | |
| | AMA | >10 | >370 | >300 | >100 | >400 | >100 | | | >1.5 | >600 | |
| UG013D | AMA | 8.20 | 207 | 8.44 | 4.04 | 468.37 | 3.129 | 0 | 525 | 0.59 | 31.60 | -0.10 |
| UG013S | Class 1 | 9.05 | 55.3 | 1.04 | 0.23 | 116.59 | 0.687 | 25.6 | 181 | 0.09 | 11.83 | 0.02 |
| UG024 | AMA | 7.92 | 106 | 30.14 | 12.59 | 196.41 | 3.207 | 0 | 511 | 3.39 | 50.40 | -0.01 |
| UG037D | AMA | 7.62 | 377 | 80.08 | 26.32 | 806.53 | 6.832 | 0 | 1013 | 0.94 | 62.22 | 0.53 |
| UG037S | Class 2 | 8.1 | 189 | 29.79 | 6.26 | 384.78 | 5.048 | 0 | 459 | 0.30 | 40.19 | -0.10 |
| UG040D | Class 2 | 8.18 | 139 | 5.27 | 3.02 | 294.35 | 2.188 | 0 | 397 | 1.37 | 27.91 | -0.10 |
| UG040S | Class 1 | 8.31 | 75.3 | 18.07 | 49.51 | 79.31 | 1.294 | 1.3 | 261 | 0.26 | 20.57 | -0.01 |
| UG046 | AMA | 8.74 | 313 | 3.00 | 1.48 | 848.03 | 2.619 | 93.43 | 1814 | 3.80 | 82.49 | -0.10 |
| UG053 | Class 1 | 8.14 | 47.6 | 21.91 | 11.33 | 67.11 | 2.322 | 0 | 233 | 0.26 | 18.21 | -0.01 |
| UG058 | Class 1 | 7.96 | 46.3 | 49.63 | 16.97 | 27.73 | 5.556 | 0 | 199 | 0.04 | 7.54 | -0.01 |
| UG059 | Class 1 | 7.31 | 24.2 | 16.70 | 6.23 | 21.45 | 3.616 | 0 | 73.1 | 0.04 | 9.26 | -0.01 |
| WW011 | Class 1 | 6.93 | 13.5 | 5.66 | 3.06 | 13.78 | 3.444 | 0 | 26 | 0.01 | 4.19 | 0.01 |
| WW012 | Class 1 | 6.94 | 13.5 | 7.63 | 3.87 | 10.72 | 3.086 | 0 | 36 | 0.08 | 6.04 | -0.01 |
| WW021D | Class 2 | 6.20 | 96.5 | 24.90 | 74.18 | 51.84 | 24.412 | 0 | 10.0 | 0.03 | 5.82 | 9.38 |
| WW021S | Class 2 | 5.94 | 95.3 | 21.32 | 73.58 | 52.62 | 25.255 | 0 | 5.3 | 0.05 | 6.55 | -0.01 |
| WW027 | Class 2 | 8.02 | 136 | 189.87 | 83.28 | 20.45 | 9.574 | 0 | 364 | -0.10 | 2.39 | -0.10 |
| WW029 | Class 1 | 7.71 | 98 | 112.04 | 60.76 | 21.71 | 7.013 | 0 | 317 | 0.21 | 10.16 | -0.01 |
| B12/53D | AMA | 9.45 | 461 | 4.4 | 52.6 | 1085.2 | 10.3 | 153 | 670 | 0.06 | 108.88 | -0.10 |
| B12/53S | AMA | 9.67 | 377 | 3.0 | 18.7 | 867.5 | 12.2 | | 627 | 0.15 | 166.08 | -0.10 |

Table 10-12: SANS 241:2006 water standards table for the boreholes in the mine (Continued).

| Borehole No | | Br | NO3(N) | PO4 | SO4 | Al | Fe | Mn | NH4(N) | Ba | Co | Cr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l |
| | Class 1 | | 0-10 | | 0-400 | 0-0.3 | 0-0.2 | 0-0.1 | 0-1 | | 0-0.5 | 0-0.1 |
| | Class 2 | | 10-20 | | 401-600 | 0.3-0.5 | 0.2-2 | 0.1-1 | 1-2 | | 0.5-1 | 0.1-0.5 |
| | AMA | | >20 | | >600 | >0.5 | >2 | >1 | >2 | | >1 | >0.5 |
| UG013D | AMA | -0.40 | 4.00 | -1.00 | 525.34 | 0.109 | 0.029 | 0.022 | | 0.015 | <0.002 | <0.006 |
| UG013S | Class 1 | 0.11 | 6.57 | -0.10 | 58.40 | 0.179 | 0.096 | 0.010 | | 0.000 | <0.002 | <0.006 |
| UG024 | AMA | 0.30 | 1.52 | -0.10 | 3.74 | 0.024 | -0.012 | 0.015 | | 0.201 | <0.002 | <0.006 |
| UG037D | AMA | -0.40 | 1.43 | -1.00 | 946.00 | 0.020 | -0.003 | 0.077 | 0.000 | 0.035 | <0.002 | <0.006 |
| UG037S | Class 2 | -0.40 | 1.66 | -1.00 | 493.13 | 0.036 | -0.008 | 0.016 | | 0.040 | <0.002 | <0.006 |
| UG040D | Class 2 | -0.40 | -0.50 | -1.00 | 273.01 | 0.039 | -0.007 | 0.013 | | 0.025 | <0.002 | <0.006 |
| UG040S | Class 1 | 0.07 | 0.10 | -0.10 | 128.90 | 0.020 | -0.009 | 0.018 | | 0.034 | <0.002 | <0.006 |
| UG046 | AMA | -0.40 | 0.65 | 0.31 | 57.49 | 0.037 | -0.003 | 0.012 | | 0.022 | <0.002 | <0.006 |
| UG053 | Class 1 | 0.08 | 0.42 | -0.10 | 7.79 | 0.014 | 0.015 | 0.060 | | 0.097 | <0.002 | <0.006 |
| UG058 | Class 1 | 0.11 | 7.81 | -0.10 | 19.51 | 0.009 | -0.009 | 0.015 | | 0.116 | <0.002 | <0.006 |
| UG059 | Class 1 | 0.16 | 6.63 | -0.10 | 15.62 | 0.007 | -0.011 | 0.010 | | 0.059 | <0.002 | <0.006 |
| WW011 | Class 1 | -0.04 | 2.41 | -0.10 | 25.10 | 0.022 | 0.080 | 0.006 | 0.010 | 0.055 | <0.002 | <0.006 |
| WW012 | Class 1 | -0.04 | 5.82 | -0.10 | 2.63 | <0.004 | 0.002 | 0.009 | | 0.036 | <0.002 | <0.006 |
| WW021D | Class 2 | -0.04 | 0.10 | -0.10 | 422 | 0.007 | 0.007 | 0.132 | | 0.026 | <0.002 | <0.006 |
| WW021S | Class 2 | -0.04 | 7.96 | -0.10 | 416 | 0.017 | 0.006 | 0.139 | | 0.030 | <0.002 | <0.006 |
| WW027 | Class 2 | -0.40 | -0.50 | -1.00 | 502.92 | <0.004 | 0.062 | 0.012 | | 0.022 | <0.002 | <0.006 |
| WW029 | Class 1 | 0.14 | 0.94 | -0.10 | 222 | 0.020 | 0.053 | 0.096 | 0.300 | 0.033 | <0.002 | <0.006 |
| B12/53D | AMA | -0.40 | -0.50 | 1.10 | 1726 | 0.014 | 0.018 | 0.005 | 1.300 | 0.004 | <0.002 | <0.006 |
| B12/53S | AMA | -0.40 | -0.50 | 1.08 | 1190 | 0.017 | 0.018 | 0.004 | 1.300 | 0.004 | <0.002 | <0.006 |

Table 10-12:  SANS 241:2006 water standards table for the boreholes in the mine (Continued).

| Borehole No | | Cu | U | V | Zn | Si | B | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | | | | | |
| | Class 1 | 0-1 | 0-4 | 0-0.2 | 0-5 | | 0-2 | | | | | |
| | Class 2 | 1-2 | 4-8 | 0.2-0.5 | 5-10 | | 2-4 | | | | | |
| | AMA | >2 | >8 | >0.5 | >10 | | >4 | | | | | |
| UG013D | AMA | 0.005 | <0.010 | 0.029 | 0.005 | 15.187 | 1.038 | | | | | |
| UG013S | Class 1 | 0.004 | <0.010 | 0.059 | 0.002 | 24.013 | 0.463 | | | | | |
| UG024 | AMA | 0.006 | <0.010 | <0.010 | 0.007 | 4.322 | 1.310 | | | | | |
| UG037D | AMA | 0.009 | <0.010 | <0.010 | 0.015 | 8.348 | 1.875 | | | | | |
| UG037S | Class 2 | 0.010 | <0.010 | <0.010 | 0.013 | 11.195 | 0.778 | | | | | |
| UG040D | Class 2 | 0.007 | <0.010 | <0.010 | 0.006 | 5.546 | 0.417 | | | | | |
| UG040S | Class 1 | 0.005 | <0.010 | <0.010 | 0.007 | 10.699 | 0.135 | | | | | |
| UG046 | AMA | 0.007 | <0.010 | <0.010 | 0.004 | 1.307 | 1.955 | | | | | |
| UG053 | Class 1 | 0.004 | <0.010 | <0.010 | 0.005 | 3.513 | 0.194 | | | | | |
| UG058 | Class 1 | 0.003 | <0.010 | <0.010 | 0.008 | 12.572 | 0.066 | | | | | |
| UG059 | Class 1 | 0.005 | <0.010 | 0.015 | 0.009 | 20.167 | 0.064 | | | | | |
| WW011 | Class 1 | 0.003 | <0.010 | <0.010 | 0.013 | 3.554 | 0.117 | | | | | |
| WW012 | Class 1 | 0.003 | <0.010 | <0.010 | 0.016 | 18.389 | 0.151 | | | | | |
| WW021D | Class 2 | 0.008 | <0.010 | <0.010 | 0.018 | 0.376 | 0.133 | | | | | |
| WW021S | Class 2 | 0.010 | <0.010 | <0.010 | 0.025 | 0.427 | 0.122 | | | | | |
| WW027 | Class 2 | 0.003 | <0.010 | <0.010 | 0.008 | 4.118 | 0.393 | | | | | |
| WW029 | Class 1 | 0.005 | <0.010 | <0.010 | 0.015 | 6.827 | 0.266 | | | | | |
| B12/53D | AMA | 0.005 | | | 0.003 | 0.311 | 3.481 | | | | | |
| B12/53S | AMA | 0.002 | | | 0.002 | 0.004 | 3.659 | | | | | |
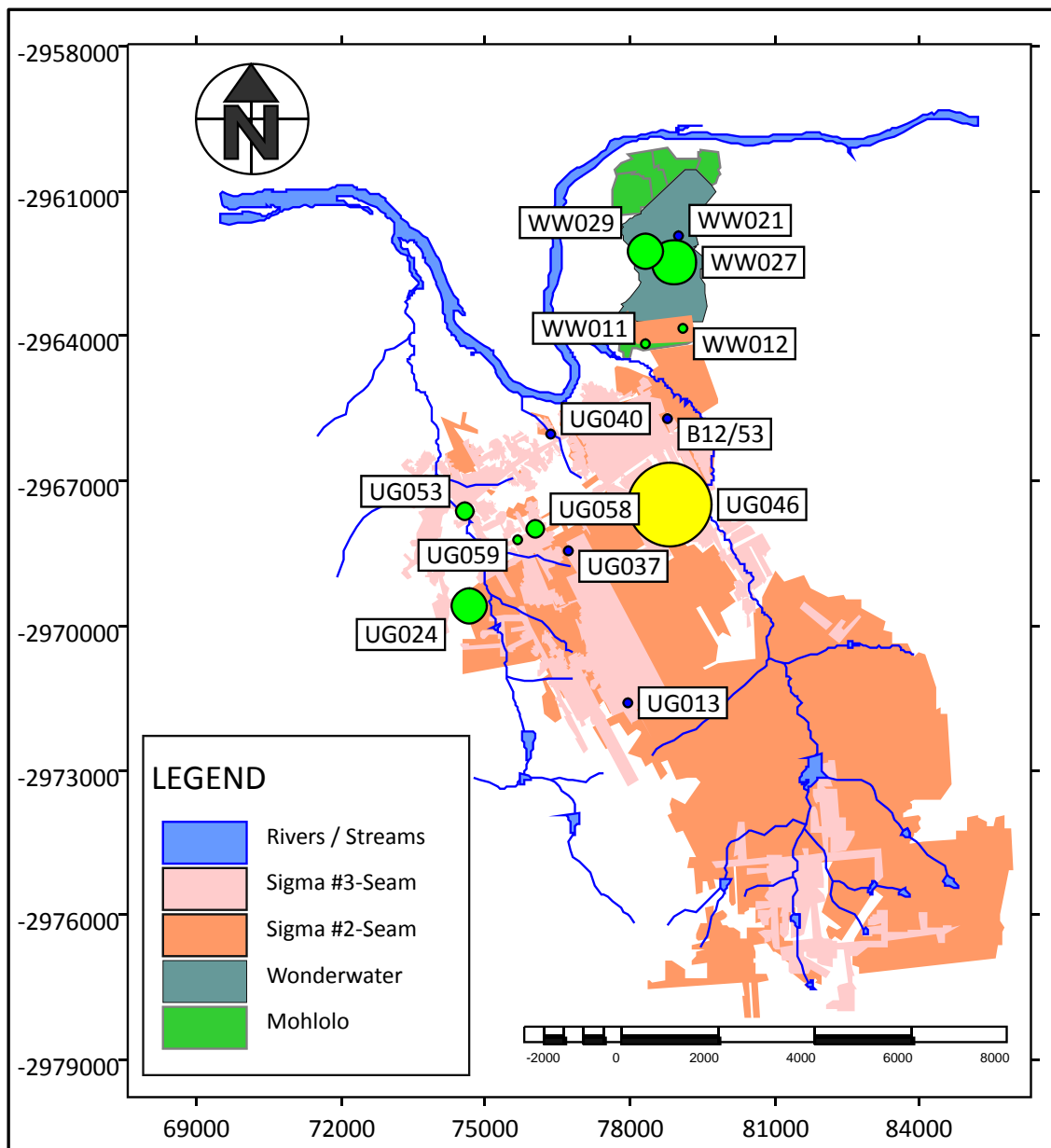
*Figure 10-28: The proportional distribution of the electrical conductivity values of the boreholes in the mine.*
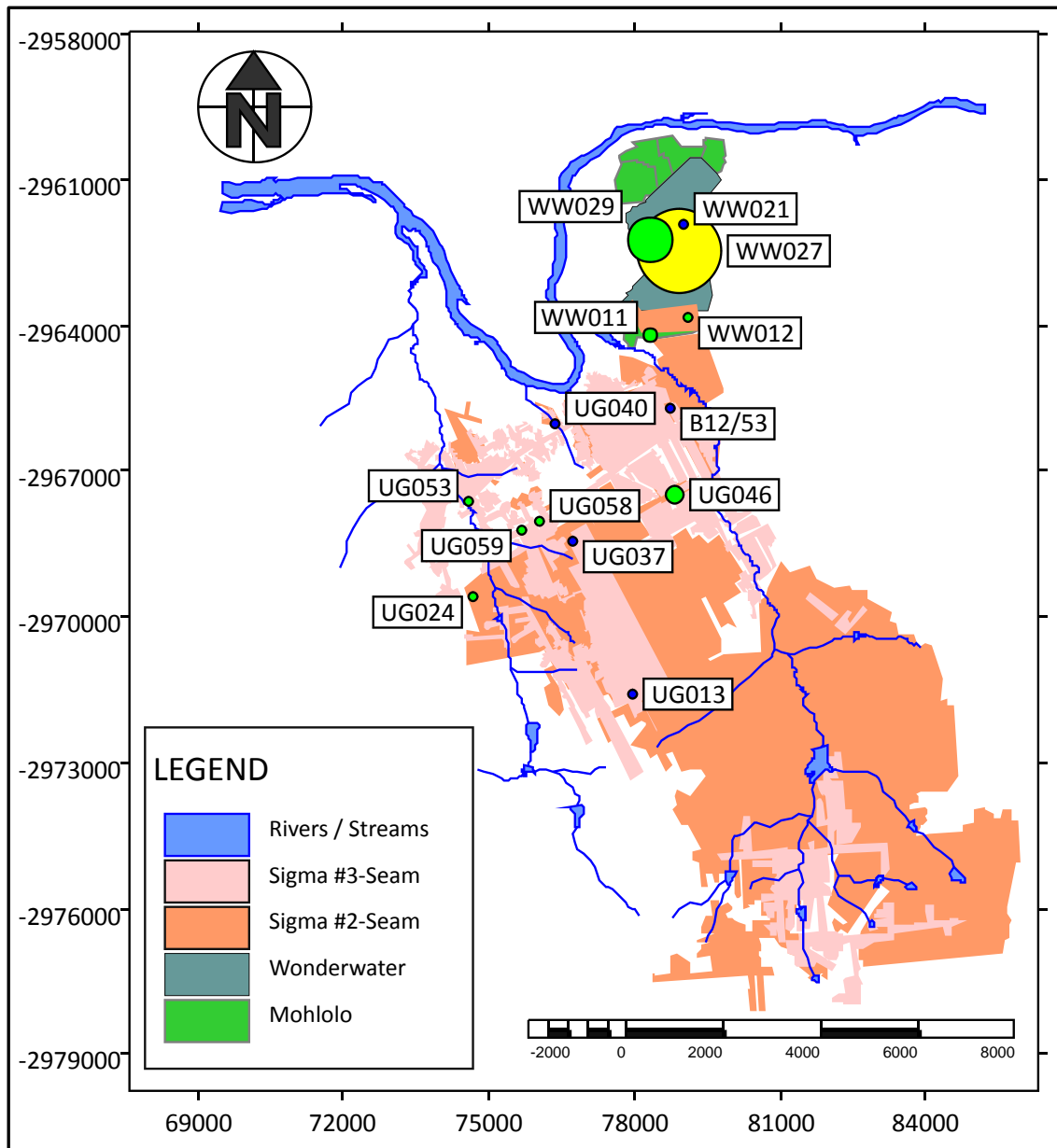
Figure 10-29: The proportional distribution of the sulphate concentrations of the boreholes in the mine.
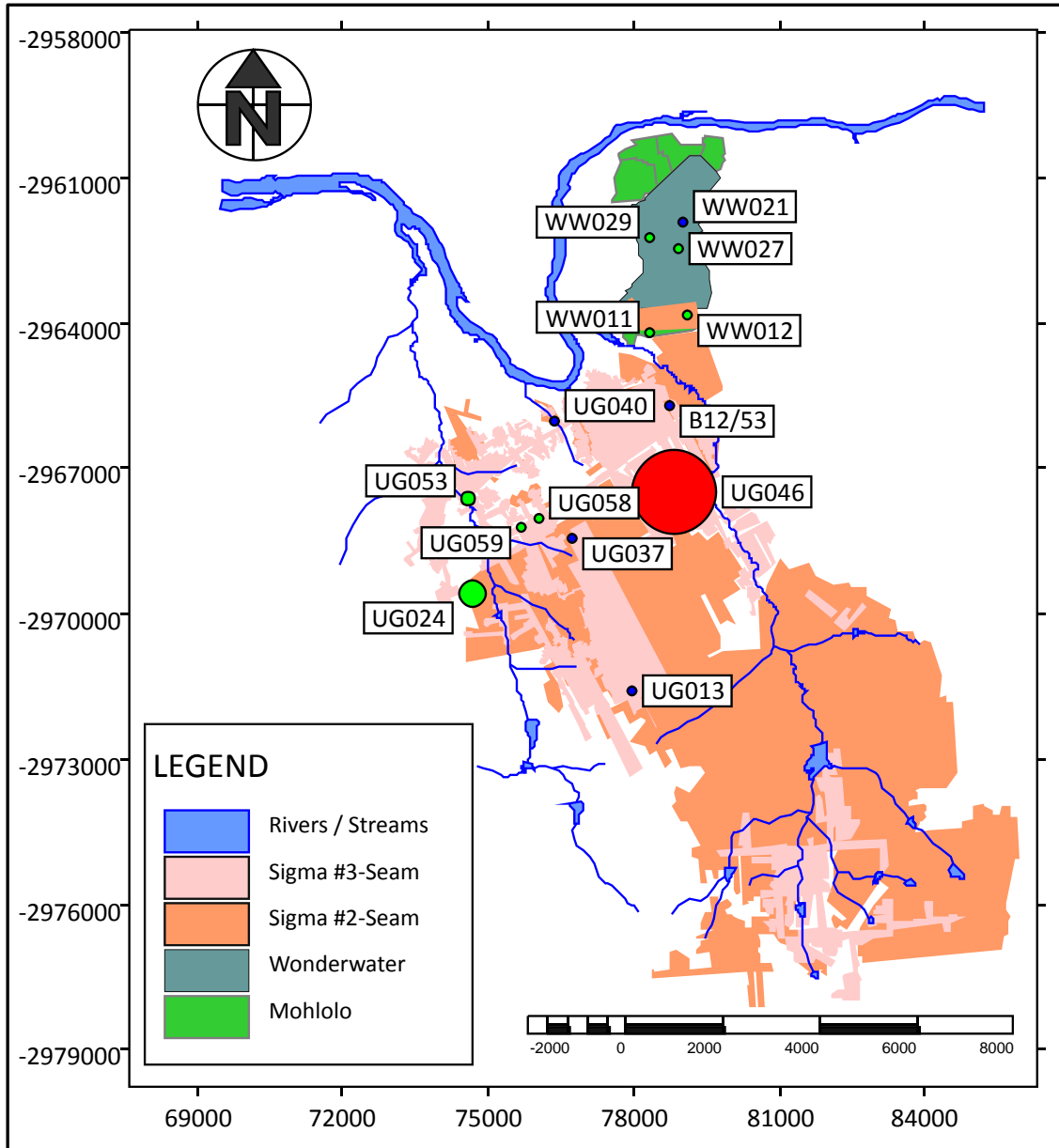
*Figure 10-30: The proportional distribution of the sodium concentrations of the boreholes in the mine.*

### 10.6.2 Hydrochemical characterisation of the boreholes in the mine through interpretive diagrams

- According to the expanded Durov Diagram in Figure 10-31, samples WW029, WW012, UG059, UG058 and UG040S plots in the second field of the diagram which is characterised by magnesium bicarbonate dominant water. This is typical of unpolluted water.

- Samples UG053, UG046, UG040D, UG024 and UG013S plots in the third area of the diagram, which is characterised as sodium bicarbonate water. This is typical of high extraction coal mines.
- Sample WW027 plots in the fourth field of the diagram which is associated with sulphate dominant water.
- Samples WW021S and WW021D plots in the fifth field of the diagram, which is magnesium sulphate dominant water and is typical of opencast coal mine water.
- Samples WW011, UG037S, UG037D, UG013D, B12/53D and B12/53S plots in the sixth field of the diagram, which is associated with sulphate and sodium dominant water and could have been due to impacts from the ashfill.
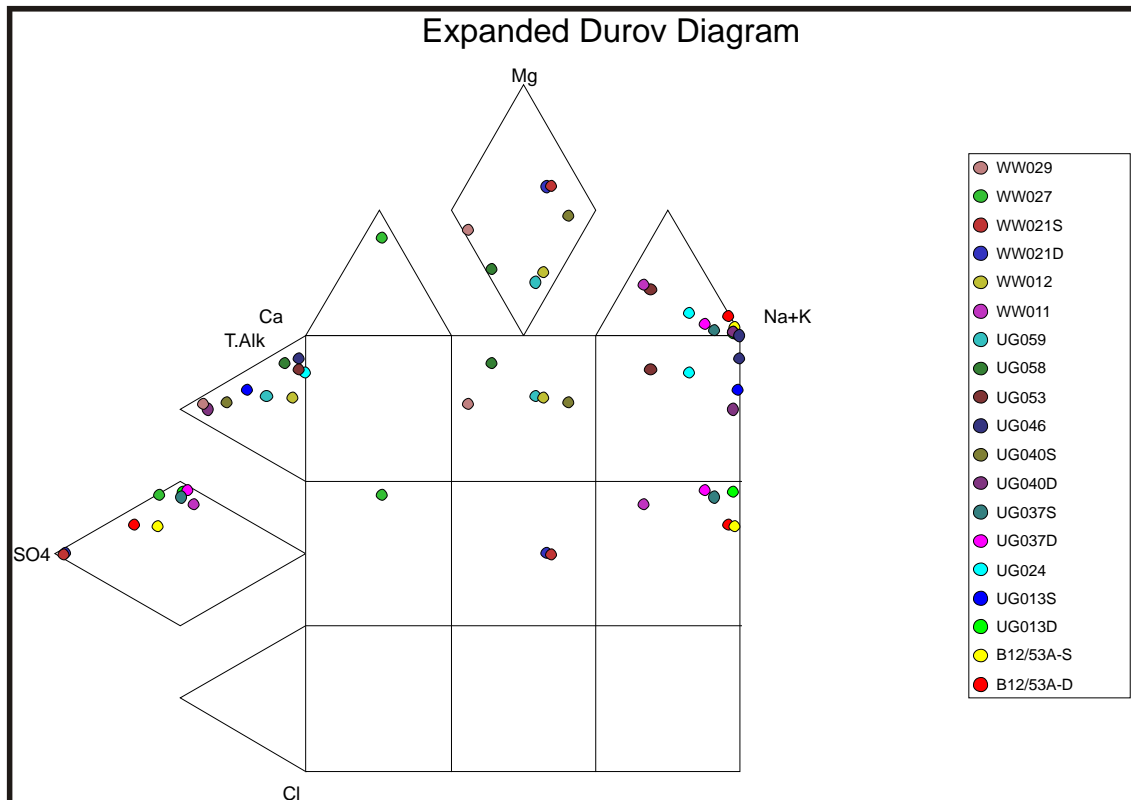


*Figure 10-31: Expanded Durov Diagram of the boreholes in the mine.*

- From the stiff diagrams in Figure 10-32 samples UG013D, UG013S, UG037D and UG037S are all sodium sulphate dominant water which can be due to high extraction underground coal mining.

- Samples UG024, UG046, UG053, UG013S and UG040D are all sodium bicarbonate dominant water, which is typical of high extraction underground coal mines.

- Samples WW021S and WW021D are magnesium sulphate dominant water, which is typical of opencast coal mine water.

- Samples B12/53D and B12/53S both are sodium sulphate dominant water, which could be due to the affects of the coal mine.
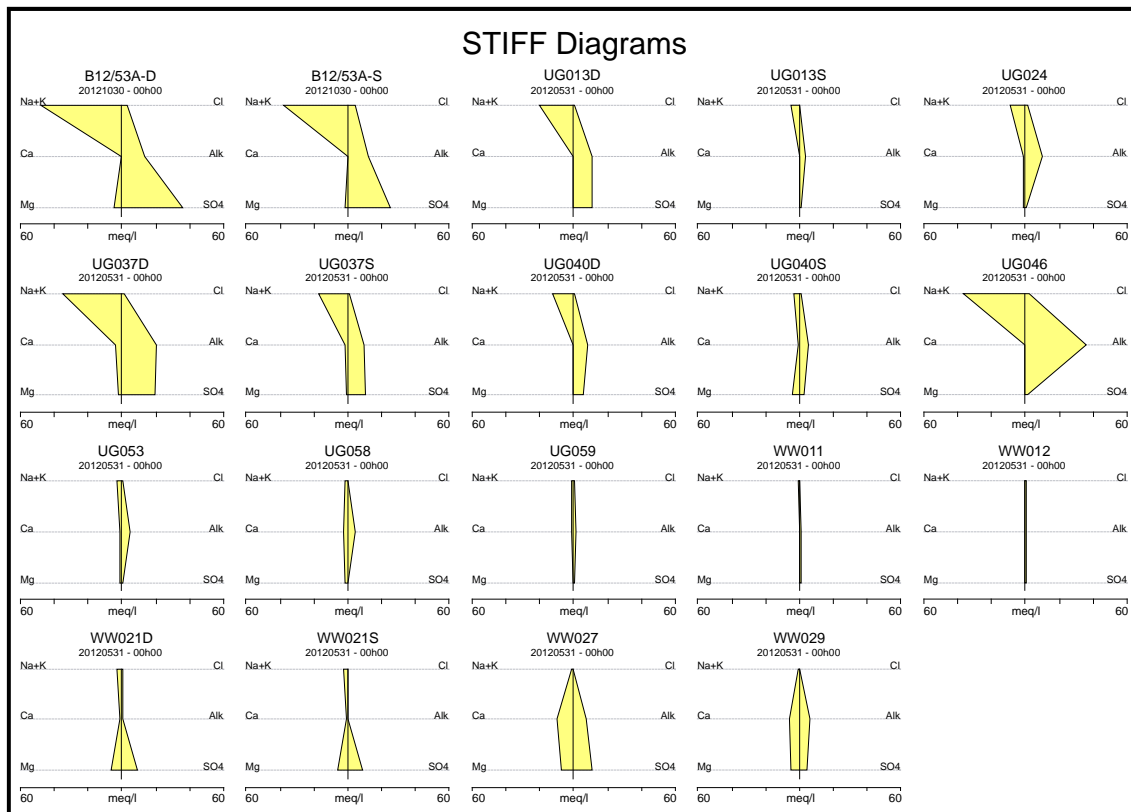


*Figure 10-32: STIFF Diagrams of the boreholes in the mine.*

## 11. Discussion of Decant Positions at Sigma Colliery and the Classification of the Possible Decant Water According to the International Network for Acid Prevention (INAP).

In Chapter 3 (page 3-3 to 3-4) the different decant possibilities in flooded and underground collieries from Vermeulen and Usher (2006) is discussed. In this chapter, the possible and known decant areas, as discussed in chapter 8, will be compared to these decant possibilities. The chemical composition of the possible decanting water will also be classified according to the International Network for Acid Prevention (INAP) 2009, as indicated on page 2-1.
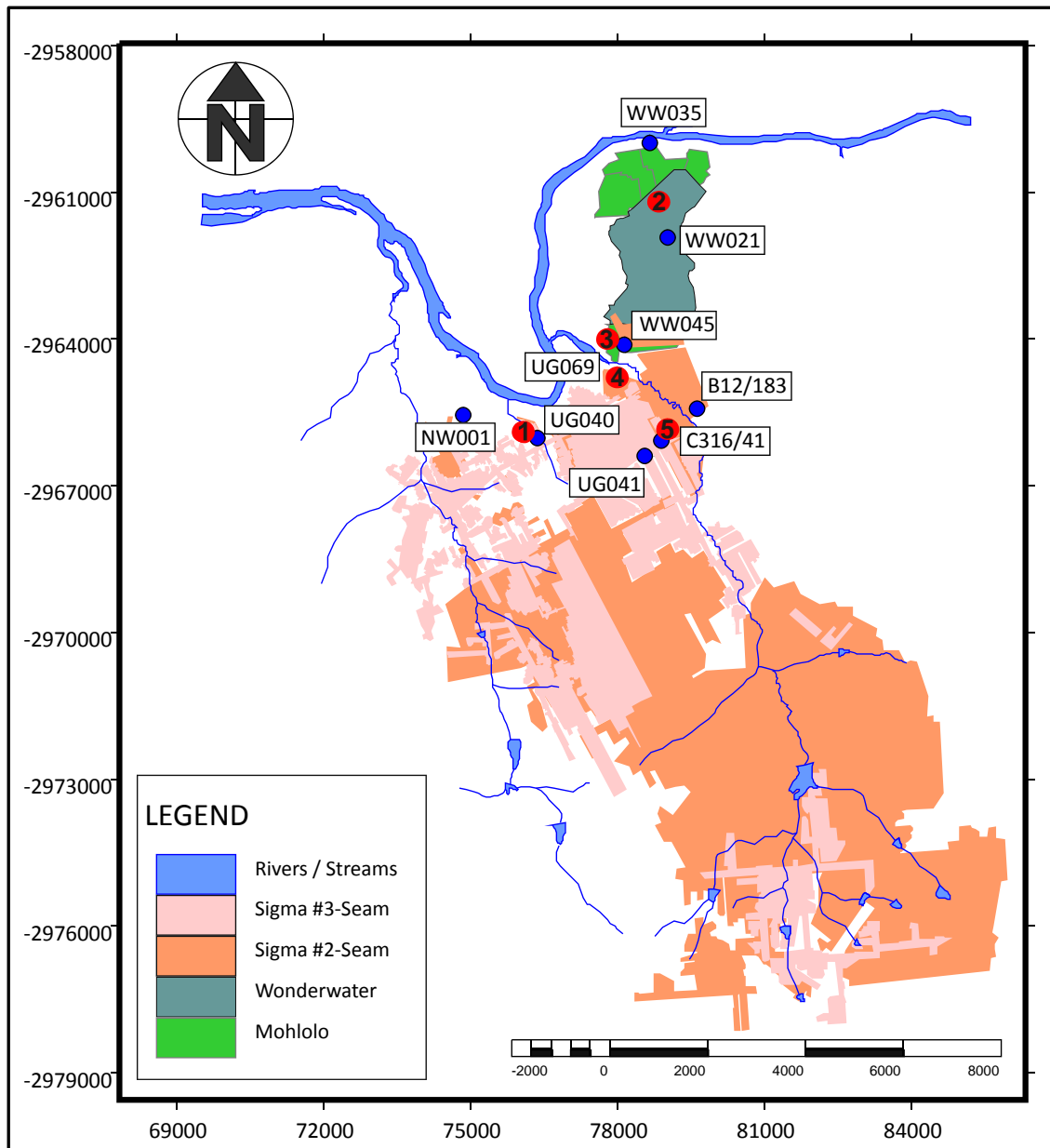
*Figure 11-1: The locality of known and possible decant positions, numbered from one to five, in relation to boreholes in close vicinity to these areas.*

In Figure 11-1 the locality of the possible decant positions, as discussed in Chapter 8, are visible in relation to the boreholes in close vicinity to these areas. The known and possible decant positions are indicated in red on the map and are numbered from 1 to 5.

## 11.1 Decant position 1

Decant position 1 (Figure 11-1) is situated on a river very close to borehole UG040. Thus far, no known decant has occurred at this position. This possible decant position was located on B1-B5 in Chapter 8 (Fig 8-5 and Fig 8-6). As discussed in Chapter 3 (page 3-1 to 3-4), the discharge of flooded collieries happens through conduits like fractures and shafts at the lowest elevation at which the mine meets the surface. Borehole UG040 is connected to Seam 3, and since the mine is already flooded, decant of this borehole is very unlikely. This possible decant position can therefore not be compared to any of the decant illustrations discussed by Vermeulen and Usher (2006) in Chapter 3. In this scenario, decant will only occur if an artificial pressure is created by filling boreholes close to this possible decant area (such as borehole UG040) with ash.

Since borehole UG040 is the closest borehole to this possible decant position, the water from borehole UG040 will be used to classify the possible decanting water according to INAP. The water quality of borehole UG040 was discussed in Chapter 10 (page 10-53 to 10-65) and to classify the water it will be used in conjunction with the explanation of the INAP classification in Chapter 2 (page 2-1 and 2-2). In Table 10-12 it is evident that the water from borehole UG040 indicates a neutral to alkaline pH (8.18), low metals, and low sulphate (273.01 mg/l). According to the International Network for Acid Prevention (2009), water from this borehole will therefore be classified as Neutral Mine Drainage (NMD) (Figure 2-1).

## 11.2 Decant position 2

Decant position 2 (Figure 11-1) is situated between boreholes WW035 and WW021 and in the Wonderwater Opencast Mine Area. This possible decant position was located on section A1-A9 in Chapter 8 (Figure 8-1 and Figure 8-2). A discussion of Lukas. E (2012) decant of an opencast mine was provided in Chapter 3 (page 3-4 to 3-7). This possible decant scenario can therefore be compared to Figure 3-10 (in Chapter 3, page 3-7), where a rehabilitated opencast pit with rainfall, evapotranspiration and runoff, is present.

Since borehole WW021 is located within the Wonderwater Opencast Mine Area, and is the closest to the possible decant area, the water from borehole WW021 will be used to classify the possible decanting water (according to INAP). The water quality of borehole WW021 was discussed in Chapter 10 (page 10-53 to 10-65) and will be used in conjunction with the explanation of the INAP classification in Chapter 2 (page 2-1 and 2-2) to classify the water. In Table 10-12 it is evident that the water from borehole WW021 indicates a neutral pH (6.2), low metals with elevated manganese (0.13 mg/l) concentrations and moderate sulphate (422 mg/l). According to the International Network for Acid Prevention (2009), water from this borehole will therefore be classified as Neutral Mine Drainage (NMD) (Figure 2-1).

## 11.3 Decant position 3

Decant position 3 (Figure 11-1) is situated very close to borehole WW045. This possible decant position is located on section D1-D4 in Chapter 8 (Figure 8-12 and Figure 8-13). Since this borehole is located in the shallow aquifer and not in the mine, decant is very unlikely. No comparisons to the examples of decant for flooded underground collieries by Vermeulen and Usher (2006) could therefore be made.

Since borehole WW045 is the closest borehole to this possible decant position it will be used to classify the possible decanting water (according to INAP). The water quality of borehole WW045 was discussed in Chapter 10 (page 10-3 to 10-12) and will be used in conjunction with the explanation of the INAP classification in Chapter 2 (page 2-1 and 2-2) to classify the water. In Table 10-2 it is evident that the water from borehole WW045 indicates a neutral pH (6.79). All the other chemical parameters are low and no mine drainage is therefore visible in borehole WW045 (Figure 2-1).

## 11.4 Decant position 4

Decant position 4 is borehole UG069 (fig 11-1), which is a known as decant position. Borehole UG069 is located on section A1-A9 in Chapter 8 (Figure 8-1 and Figure 8-2). Borehole UG069 was forced to decant due to the artificial pressure created by the ashfilling.

The water quality of borehole UG069 was discussed in Chapter 10 (page 10-41 to page 10-53) and will be used in conjunction with the explanation of the INAP classification in Chapter 2 (page 2-1 and 2-2) to classify the water. In Table 10-10 it is evident that borehole UG069 has a neutral pH (7.2), elevated manganese (1 mg/l) and high sulphate (1828 mg/l), which is characteristic of Neutral Mine Drainage (NMD). Borehole UG069 also has high calcium (221 mg/l) and magnesium (141 mg/l) concentrations which, according to Figure 2-1 in Chapter 2, tends to a more Saline Drainage (SD). In this situation it is possible that NMD and SD are occurring together as discussed in Chapter 2, page 2-2.

## 11.5 Decant position 5

Decant position 5 (Figure 11-1) is situated very close to borehole C316/41. This possible decant position is located on section C1-C6 in Chapter 8 (Figure 8-7 and Figure 8-8). Borehole C316/41 is an ashfill borehole and will only decant if an artificial pressure is created and the water is forced to decant because of the ashfill.

The water quality of borehole C316/41 was discussed in Chapter 10 (page 10-41 to page 10-53) and will be used in conjunction with the explanation of the INAP classification in Chapter 2 (page 2-1 and 2-2) to classify the water. In Table 10-10 it is evident that borehole C316/41 has a neutral to alkaline pH (8.22). All the other chemical parameters are low and no mine drainage is therefore visible in borehole C316/41 (Figure 2-1).

# 12. Isotopic analysis

A total of 25 groundwater samples that were chosen by spacial distribution were sent to the Centre of Water Resources Research at the University of Kwazulu-Natal for Deuterium and Oxygen-18 analyses. The locality map of the boreholes that was chosen for isotopic analysis is illustrated in Figure 12-1 and a summary of the results from the isotopic analysis is available in Table 12-1.
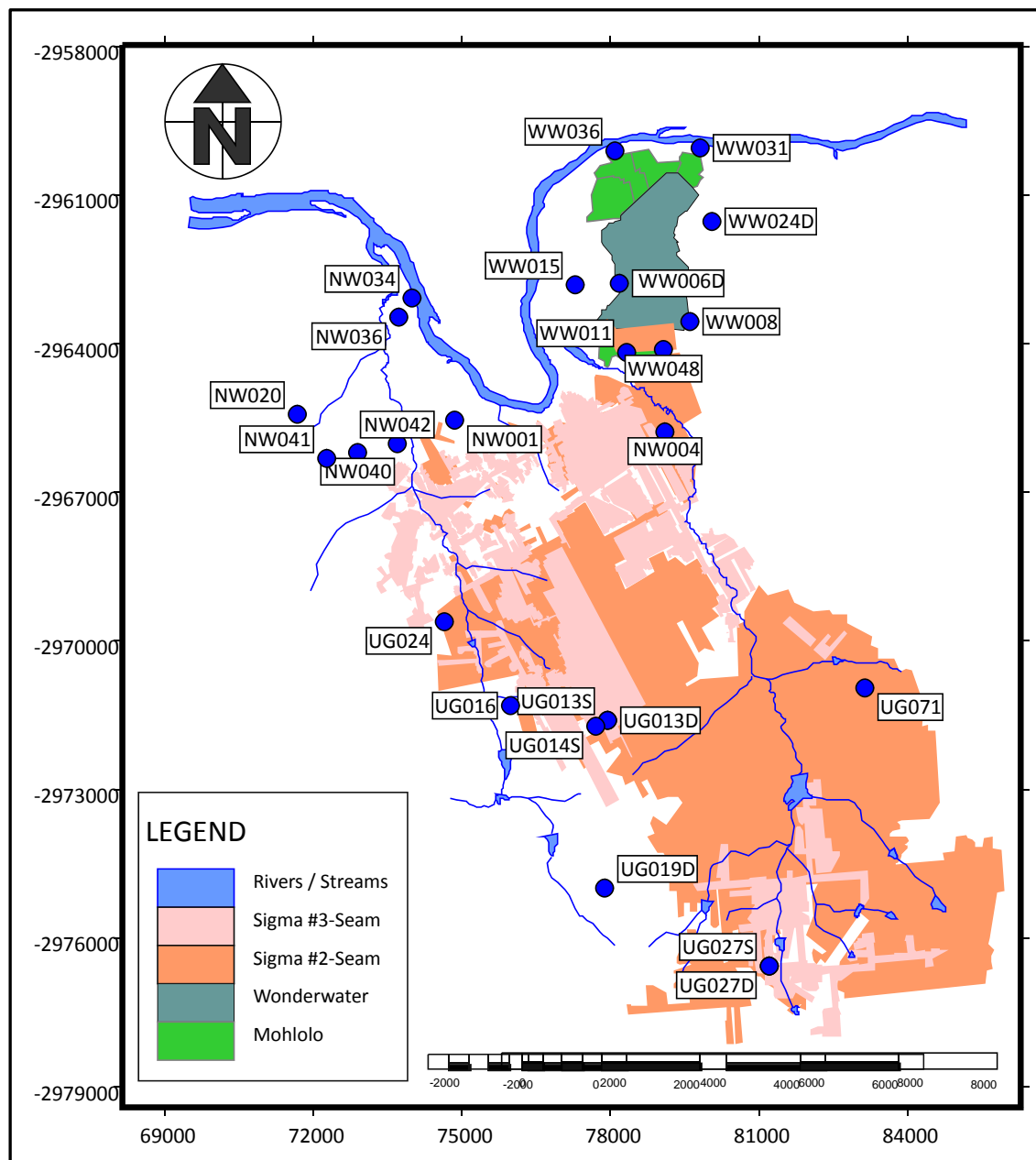


*Figure 12-1: Locality map of boreholes that were selected for isotopic sampling.*

Table 12-1:  Summary of the results from the Deuterium ($\delta^2$H) and Oxygen-18 ($\delta^{18}$) analyses.

| Sample No. | Sample Name | Analysis Date | $\delta^2$H Reportable Value (permil) | $\delta^2$H Standard Deviation (permil) | $\delta^{18}$O Reportable Value (permil) | $\delta^{18}$O Standard Deviation (permil) |
|---|---|---|---|---|---|---|
| 1 | UG019D | 14/08/2012 | -28.02 | 1.35 | -5.05 | 0.21 |
| 2 | UG027S | 14/08/2012 | -37.51 | 0.88 | -6.23 | 0.21 |
| 3 | NW036 | 14/08/2012 | -25.94 | 1.44 | -4.62 | 0.26 |
| 4 | WW024D | 14/08/2012 | -11.59 | 1.26 | -2.77 | 0.08 |
| 5 | NW041 | 14/08/2012 | -25.54 | 0.71 | -4.82 | 0.11 |
| 6 | NW040 | 14/08/2012 | -31.01 | 1.48 | -5.54 | 0.16 |
| 7 | UG071S | 14/08/2012 | -23.96 | 2.6 | -4.39 | 0.18 |
| 8 | NW020 | 14/08/2012 | -21.32 | 1.44 | -4.2 | 0.19 |
| 9 | WW036 | 14/08/2012 | -18.6 | 1.08 | -3.99 | 0.04 |
| 10 | NW042 | 14/08/2012 | 9.28 | 1.78 | 0.09 | 0.23 |
| 11 | WW008 | 14/08/2012 | -15.49 | 1.54 | -3.77 | 0.19 |
| 12 | WW048 | 14/08/2012 | -21.44 | 0.91 | -4.65 | 0.22 |
| 13 | UG024 | 14/08/2012 | -25.71 | 1.9 | -5.23 | 0.07 |
| 14 | UG027D | 14/08/2012 | -17.05 | 1.49 | -3.56 | 0.16 |
| 15 | UG013S | 14/08/2012 | -13.49 | 1.45 | -3.55 | 0.1 |
| 16 | WW006D | 14/08/2012 | -19.91 | 1.16 | -4.27 | 0.12 |
| 17 | NW034 | 14/08/2012 | -0.63 | 1.04 | -1.1 | 0.22 |
| 18 | WW015 | 14/08/2012 | -22.79 | 1.48 | -4.93 | 0.22 |
| 19 | NW001 | 14/08/2012 | -17.72 | 0.91 | -3.79 | 0.12 |
| 20 | NW004 | 14/08/2012 | -15.31 | 1.5 | -3.78 | 0.24 |
| 21 | UG016 | 14/08/2012 | -27.83 | 1.11 | -5.39 | 0.17 |
| 22 | UG013D | 14/08/2012 | -16.2 | 0.92 | -3.98 | 0.15 |
| 23 | WW011 | 14/08/2012 | -15.88 | 1.67 | -3.87 | 0.17 |
| 24 | UG014S | 14/08/2012 | -22.64 | 1.05 | -4.69 | 0.13 |
| 25 | WW031 | 14/08/2012 | -18.74 | 0.74 | -4.22 | 0.15 |

From Figure 12-2 it is evident that all the analysed samples plot on the global meteoric water line (GMWL).  It can therefore be assumed that all the samples are water from the same source, recharge water.  The orange coloured sample (NW042) on the graph (Figure 12-2) is a dolomitic borehole and plots away from the other samples. This is because the recharge for this borehole is in a different area than the other boreholes. The samples coloured purple (sample NW034), pink (sample WW024D) and red (sample UG027S) also plots away from the other samples and from this we can assume that they also have different recharge regions.  The remaining 21 samples (samples UG019D, NW036, NW041, NW040, UG071S, NW020, WW036, WW008, WW048, UG024, UG027D, UG013S, WW006D, WW015, NW001, NW004, UG016, UG013D, WW011, UG014S and WW031) all plot in a group on the global meteoric water line.  From this it can be deduced that they all have the same recharge region.
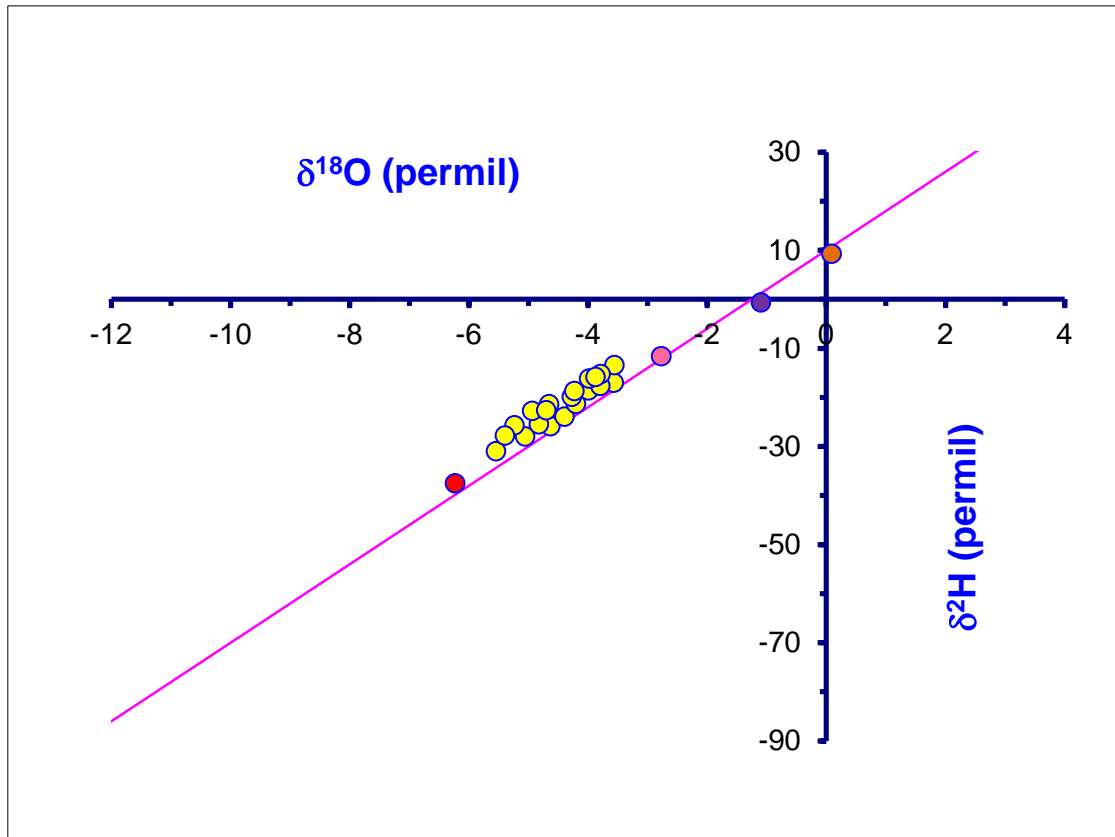
*Figure 12-2: Sample values and the global meteoric water line (GMWL).*

## 13. The Backfilling of Mine Voids with Fly Ash

The extraction of coal results in the creation of mining-induced voids that need to be managed in some way and the placement of backfill is one of the tools that may be used to manage these voids. According to Grice (1998), backfill refers to "any waste material that is placed into voids mined underground for the purposes of either disposal, or to perform some engineering function." Coal utilisation generates large amounts of end products, which includes fly ash, and is mostly disposed of in storage locations such as dams, dry ash disposal systems and landfill. In achieving sustainability of coal combustion, there is a need to address the waste generation and for a more environmentally friendly and cost effective method of waste management and utilisation to be put in place. According to Ward *et al.*, (2006) there are a number of beneficial purposes in which coal ash may be used as backfill in underground coal mines. They include:

- Grouting or infilling of active or abandoned underground openings to control subsidence, ground movement or water flow;
- Amelioration of unfavourable water quality (such as acidic pH) associated with mining;
- Provision of a sealing medium to control water seepage or contaminant migration, or to deal with underground fires and spontaneous combustion problems.

According to Ward *et al.,* (2006), some of the advantages of using fly ash for backfilling in coal mines are that it has favourable geomechanical properties; it has a capacity for placement in a flowable paste or in slurry form and it is available in large quantities from power stations near many mine sites. Fly ash may also have properties which can be used to ameliorate mine-related problems such as the generation of acid waters.

According to Eskom (2010) almost 90 percent of the ash produced at Eskom Power Stations in the generation of fly process is called fly ash. Reason being that the coal is pulverised into a very fine dust before being fed into boilers to ensure efficient combustion. Larger particles of ash, called coarse or bottom ash, which make up the rest of the ash produced at the power station drop down from the furnace, and collect at the bottom in the ash hopper of the boiler. The fly ash is removed from the exhaust gases from the boiler by means of electrostatic precipitators or bag filter systems. After

being removed from the collecting hoppers, the fly ash and coarse ash is stacked on huge dumps or ash dams (slurry dams).

## 13.1 The general properties of fly ash

Fly ash is a pozzolan which is a siliceous or siliceous and aluminous material which, in itself, possesses little or no cementitious value. It will in a finely divided form and in the presence of water react chemically with calcium hydroxide at ordinary temperature, to form compounds possessing cementitious properties. According to Rai *et al.*, (2010), in addition to having Pozzolanic properties, fly ash also has the ability to harden and gain strength in the presence of water alone. Fly ash consists of fine, non plastic and powdery particles that are predominantly spherical in shape, either solid or hollow and mostly glassy in nature. The carbonaceous material in fly ash is composed of angular particles and the particle size distribution of most bituminous coal fly ash is similar to that of silt. Although sub-bituminous coal fly ash is also silt-sized, it is normally slightly coarser than bituminous coal fly ash. The colour of fly ash can vary from tan to gray to black and depends on the amount of unburned carbon in the ash.

## 13.2 The chemical properties of fly ash

There are basically four ranks/types of coal and each of them vary in heating value, chemical composition, ash content and geological origin. These four types/ranks are anthracite, bituminous, sub-bituminous and lignite and the chemical properties of the fly ash are influenced to a great extent by the coal being burned and the handling and storage techniques. According to Ahmaruzzaman (2009), fly ash is also sometimes classified according to the type of coal from which the ash was derived. He explained that the principal components of bituminous coal fly ash are silica, alumina, iron oxide and calcium, with varying amounts of carbon, as measured by loss on ignition (LOI). Lignite and sub-bituminous coal fly ash is characterised by higher concentrations of calcium and magnesium oxide, as well as lower carbon content, compared to bituminous coal fly ash. Very little anthracite coal is burned in utility boilers, so there are only small amounts of anthracite coal fly ash. Table 13-1 has a comparison of the normal range of chemical constituents of bituminous coal fly ash with those of sub-

bituminous coal fly ash and lignite coal fly ash. From the data in Table 13-1 it is evident that lignite and sub-bituminous coal fly ash has a higher calcium oxide content and lower loss of ignition than fly ash from bituminous coal fly ash.

Table 13-1: Normal range of chemical composition for fly ash produced from different coal types. (Ahmaruzzaman, 2009).

| Component (wt%) | Bituminous | Sub-bituminous | Lignite |
|---|---|---|---|
| $SiO_2$ | 20 – 60 | 40 – 60 | 15 – 45 |
| $Al_2O_3$ | 5 – 35 | 20 – 30 | 10 – 25 |
| $Fe_2O_3$ | 10 – 40 | 4 – 10 | 4 – 15 |
| CaO | 1 – 12 | 5 – 30 | 15 – 40 |
| MgO | 0 – 5 | 1 – 6 | 3 – 10 |
| $SO_3$ | 0 – 4 | 0 – 2 | 0 – 10 |
| $Na_2O$ | 0 – 4 | 0 – 2 | 0 – 6 |
| $K_2O$ | 0 – 3 | 0 – 4 | 0 – 4 |
| LOI | 0 – 15 | 0 – 3 | 0 – 5 |

## 13.3 Case studies

### 13.3.1 Development of a co-disposal protocol for the neutralization and amelioration of acid mine drainage with fly ash (South Africa)

Surender and Petrik (2005) conducted a study to investigate the potential of co-disposing AMD with fly ash at laboratory and pilot plant scale. The goals of this study were to develop a co-disposal protocol aimed at the neutralisation of AMD and reduction of heavy metal content. The co-disposal process was first tested at laboratory scale and was based on three parameters, namely: ash neutralisation potential, final desired pH and the heavy metal removal. Batch processes were conducted at both laboratory and pilot scale by the direct mixing of fly ash with AMD at various predetermined ratios.

Fly ash that originated from a power plant in the Highveld Region of South Africa was selected for the study and large quantities were collected from the electrostatic precipitator. The chemical analysis of the fly ash, prior to the co-disposal tests, was performed by x-ray fluorescence (XRF) spectrometry. AMD samples from a colliery in the same vicinity as the selected fly ash was selected for the co-disposal studies. This

specific AMD had very low pH, high acidity and corresponding elevated sulphate concentrations.  The acidity, pH, EC and chemical analysis of the AMD was done prior to conducting the co-disposal tests.

From the conducted laboratory studies, it was evident that the pH decreased steadily for all ratios with a corresponding decrease in conductivity.  There was also a reduction in the sulphate concentrations, which could be attributed to the precipitation of gypsum at low pH, ettringite at high pH and other metal sulphate species at intermediate pH. Aluminium hydroxide precipitates above pH 5.2 which resulted in reduced concentrations of aluminium in the final solution.  A significant reduction in iron, sulphate and aluminium concentrations was noted at all FA:AMD ratios.  An almost complete removal of iron and aluminium and 96% reduction in sulphate was achieved by co-disposing AMD with fly ash in the laboratory studies.  The laboratory tests indicated that a 1:3 ratio was optimum for fly ash and AMD co-disposal.

The pilot scale studies were conducted in a similar manner as the laboratory studies, except for much larger quantities of fly ash and AMD that was used.  Since the laboratory tests indicated that a 1:3 ratio was optimum for fly ash and AMD co-disposal, constant variations in the quality of the fly ash and AMD required verification and optimisation of this ratio at pilot scale.  Results obtained from the pilot studies conducted indicated that Greater than 90% of Aluminium and Iron was removed from the original AMD.  In this case, a FA:AMD ratio of 1:4 was effective in neutralising the AMD and removal of the major contaminants.  The quality of the post co-disposal water is such that it could be applied in other process applications, while the sludge component could be pumped into underground mines to further treat AMD or to prevent AMD formation.  Further pilot scale investigations showed a deviation in the expected results in that the pH did not increase to the desired pH levels.  Additional investigation and analysis of the fly ash indicated that the fly ash contained a large percentage of unburned carbon, which was attributed to problems with the parent coal and combustion at the power plant.  From this it is evident that the optimised co-disposal process may change with varying AMD quality and fly ash composition and full chemical analysis of both the fly ash and AMD must therefore be conducted prior to co-disposal.

From this study, it can be concluded that the use of fly ash for the neutralisation and amelioration of AMD has been successfully implemented at both laboratory and pilot scale.  Alkaline fly ash effectively neutralises AMD and the increased pH allows for the

removal of certain heavy metals by precipitation. This co-disposal protocol has been optimised at pilot scale, but due to the variation in chemical composition of both the fly ash and AMD, large scale treatment plant will require further optimisation. The co-disposal process allows for low cost water treatment and may be feasibly applied in large-scale plants.

### 13.3.2 Ipswich Motorway Upgrade – Filling of abandoned Coal Mines (Australia)

According to the report done by Millar and Holz (2010) the 8km upgrade of the Ipswich Motorway between Dinmore and Goodna, Australia, started in mid-2009 and was completed in 2012. During the preliminary project design stage it was discovered that some sections of the motorway was to be constructed over abandoned coal mines. These mines were in operation from the mid 1800's to about 1987. Most of the coal in these abandoned coal mines has been extracted using the "bord and pillar" techniques. Over the years, subsidence events have been recorded in and around the immediate vicinity of the Ipswich Motorway.

The geology of the mined out areas comprises of sedimentary rocks including conglomerate, sandstone, shale and coal from a number of formations at different locations. These include, in increasing age, the Raceview Formation, the Aberdare Conglomerate and the Blackstone and Tivoli. The productive Tivoli Formation sedimentary rocks are overlied by tertiary claystone and sandstones of the Redbank Plains Formation, which comprises the rocks under the western end of the motorway site.

Three mines were found to potentially affect the service life and operational safety of the Ipswich Mororway, namely:

- Goodna Mine
- New Redbank Mine
- Westfalen No 3 Mine

The Goodna Mine was identified as posing the greatest risk in terms of potential subsidence during the design life of the motorway and will be the only mine discussed.

The Goodna Mine workings are at an average depth of 30m below the existing ground level and were flooded with contaminated water. Observations indicated that this mine comprised of 'bord and pillar geometry' that comprised of 6 to 7m rooms separated by 3m rectilinear support pillars. No mine plans were available for this mine and the overall extent of the mine workings directly beneath the motorway were therefore determined by surface drilling. The overburden depth ranged from about 20m to 35m in the vicinity of the motorway. To confirm the boundaries of the mine workings and the presence of mine voids, a total of 100 boreholes (percussion drilled and core) were drilled. Multi-level workings were not encountered using deep (70m) boreholes and these investigations revealed that the void levels were in general highly irregular. Hydraulic connectivity tests indicated that there was a good connectivity present between the voids.

The mine extent was determined by specialised sonar equipment. To ensure that all voids were intersected with paste injection holes, it was necessary to maintain a tight 4m grid pattern due to the varying nature of the bord and pillar widths and layout.

A pillar stability assessment and a risk assessment was done, after which a number of remedial measures were considered to mitigate the risk of a potential mine collapse. All available options were considered and it was decided to completely fill all the voids within the motorway corridor.

### 13.3.2.1 A brief overview of the Goodna Mine water chemistry

The mine shafts are filled with contaminated groundwater and require extraction of the groundwater from the shafts. The groundwater emanating from the shafts was characterised by low pH, high heavy metal concentrations and high dissolved salt loads. Due to the high salt content and the requirement to re-use the water for on-site concrete batching, reverse osmosis (RO) was required for final treatment of the groundwater. A summary of the water quality before and after treatment are illustrated in Table 13-2.

Table 13-2: Summary of the water quality of the mine water pre- and post-treatment. Modified after Virotec Global Solutions (2011).

| Parameter | Before Treatment | After Treatment | RO Feed Water Requirements |
|---|---|---|---|
| pH | 3.5 - 4.0 | 7.0 | 6.5 - 7.5 |
| Aluminium | 55.4 | 0.005 | <1.0 |
| Iron | 80.7 | 0.005 | <1.0 |
| Manganese | 2.29 | 0.87 | <1.0 |
| Suspended Solids | 15 | 0.08 | <1.0 |

### 13.3.2.2 The fill material

The paste used as the fill material was a mixture of crusher dust, fly ash from the Swanbank Power Station, cement and water.  Experiments were done in the preparatory stages to design the most economical paste mix that was able to meet specified strength and workability requirements.  Laboratory testing supported these experiments.

The contaminated waste water extracted from the mine was treated by the plant using double reverse osmosis. 80 percent of this water was used onsite in mix manufacture and dust suppression, while 20 percent of the reactive organic compound contaminated (ROC) water was used in paste mix production.

### 13.3.2.3 Drill and fill methodology

Even though the mine workings extended outside the motorway corridor, only the area of the mine beneath the motorway was required to be filled.  The need existed to construct a barrier on the "down dip" side of the fill zone to form and impenetrable boundary for subsequent "up dip" filling and was therefore introduced.  A series of holes of 150mm diameter were drilled to known depths in the mine. This was to achieve the boundary.  The holes were spaced at 2m centres in a "zig zag" pattern for the full plan length of the mine location, and for some distance beyond, to ensure the barrier wall boreholes intersected all voids.  The barrier wall was then created by using a "mound" of low strength, low slump paste. This was pumped into the voids at a controlled pressure, spreading across the ceiling of the void to provide a ceiling to floor plug (Figure 13-1).  A complete barrier wall was created through the overlapping off injection points.  Hereafter, the bulk filling of the mine could commence.
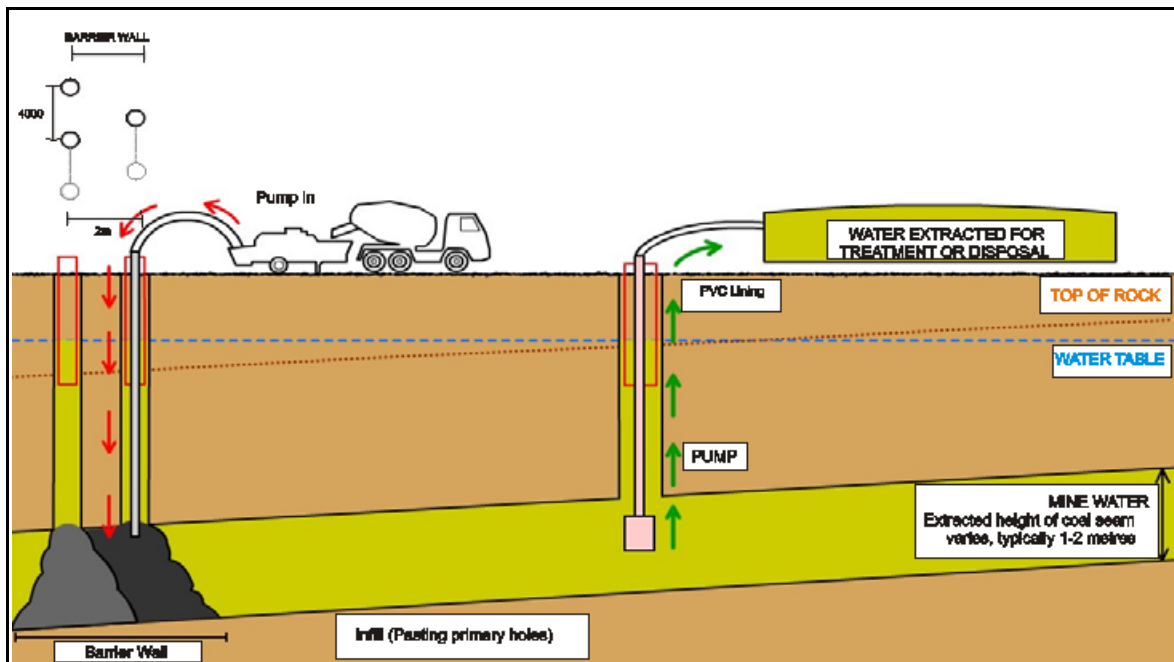
*Figure 13-1: Initial construction of the barrier wall and water extraction. Modified after Millar and Holz (2010).*

Some of the mine workings had a very erratic nature of the bord and pillar layout and a series of holes were consequently drilled in a 4m grid pattern "up dip" of the barrier and for the full length of the mine.  These holes were injected with a high slump paste from the barrier wall in the "up dup" direction (Figure 13-2), until the full width of the future motorway footprint (plus a distance beyond) was filled.
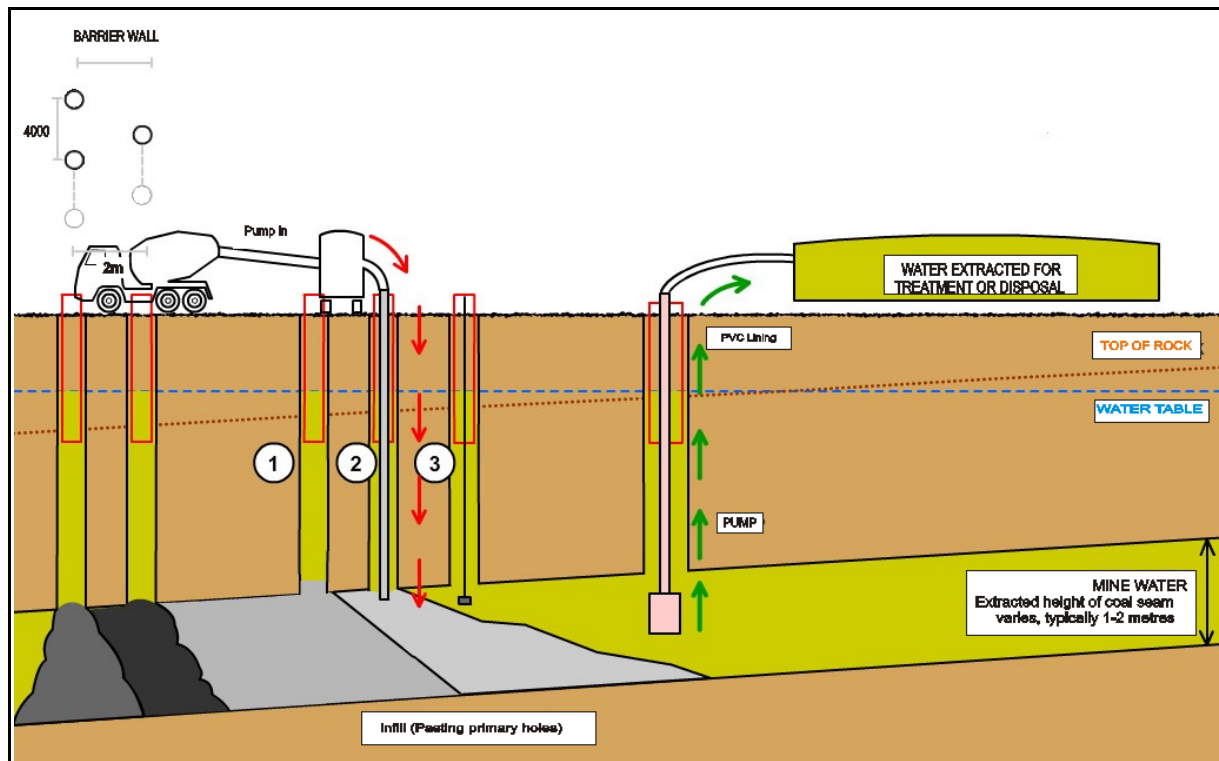
*Figure 13-2: Bulk filling with high slump paste. Modified after Millar and Holz (2010).*

Concerns arose that if the water table was artificially raised or lowered it could result in environmental damage, or have an impact on the stability of the mine. The problem was overcome by ensuring that the volume of water extracted was equal to the volume of paste injected into the mine. The injection and extraction pumps had to operate simultaneously and the water extracted had to be hydraulically connected to the paste injection hole.

### 13.3.2.4 Conclusion

The mine filling operations, as well as the careful handling and treating of the extracted mine water, was considered successful. The end result ensured fully stabilised mine workings beneath the motorway corridor, which guarantees the safety of motorists for the next 100 years and beyond.

## 14.    A Brief Comparison of Sigma Colliery and Goodna Mine

A comparison of Sigma Colliery and Goodna Mine is summarised in Table 14-1.  The chemistry data that was available for Goodna mine only included pH, aluminium, iron and manganese, and only these parameters were therefore used for the comparison with Sigma Colliery for each aquifer.

It is evident from the comparison of the mine water chemistry in Table 14-1 that the mine water from Sigma Colliery is neutral to slightly alkaline, whereas the Goodna Mine water is acidic.  The heavy metal concentrations (aluminium, iron and manganese) of the Goodna Mine water pre-treatment are all above the maximum allowable limits of the SANS241:2006 drinking water standards. The concentrations for Sigma Colliery are all within the ideal to acceptable range of the SANS241:2006 drinking water standards, except for the manganese concentration of the ashfill borehole which is still within the allowable limits.

Both these mines did backfilling of the mine voids through ashfilling to stabilise mine workings beneath roads.  Both were also flooded when the ashfilling was conducted. Goodna Mine injected a high slump fly ash paste into the mine voids, while simultaneously pumping equal volumes of contaminated water out of the mine to prevent environmental damage. This prevented mine water decant and the subsidence of the mine roof from occurring.

Sigma Colliery injected fly ash slurry into the mine voids after the mine was flooded, without pumping any water out of the mine voids. This resulted in decant of borehole UG069 and their ashfilling project was therefore not considered successful when compared with the ashfilling of Goodna Mine.

*Table 14-1: A summary of the comparison of Sigma Colliery and Goodna Mine.*

| | SIGMA COLLIERY | GOODNA MINE |
|---|---|---|
| **The country in which the mine is situated** | South Africa. | Australia. |
| **Geology** | Sigma Colliery is situated in the Sasolburg-Vereeniging Coalfield. The stratigraphy of this coal field is typical of the coal-bearing strata of the Karoo Sequence. The succession consists of pre-Karoo rocks (dolomites of the Chuniespoort Group of the Transvaal Sequence) overlain by the Dwyka Formation, followed by the Ecca Group sediments, of which the Vryheid Formation is the coal-bearing horizon. Mainly the lava of the Ventersdorp and Hekpoort Groups underlie the coal. The Karoo Formation is present over the whole area and consists mainly of sandstone, shale and coal of varying thickness. | The bedrock geology comprises sedimentary rocks including conglomerate, sandstone, shale and coal of a number of formations including, in increasing age, the Raceview Formation, the Aberdare Conglomerate and the Blackstone and Tivoli. Tertiary claystone and sandstone of the Redbank Plains Formation, overlies the productive Tivoli Formation sedimentary rocks here. |
| **Age of the coal** | Late Carboniferous to Permian. | Mesozoic. |
| **Mining method** | Bord and pillar, pillar extraction and longwall mining. | Bord and pillar mining. |
| **Is the mine flooded?** | Mine is flooded. | Mine is flooded. |
| **Mine water chemistry** | *(see Sigma Colliery Aquifers table below)* | *(see Goodna Mine table below)* |
| **Why was the ashfilling of the mine voids conducted?** | To stabilise the mine workings located beneath the Sasolburg-Parys Road (R26) and Leeuspruit. | To stabilise the mine workings beneath the Ipswich Motorway from Dinsmore to Goodna. |
| **Was the ashfilling of the mine voids successful?** | No | Yes |

**Sigma Colliery Aquifers**

| Parameter | Shallow | Intermediate | Deep | Disturbed | Mine | Ashfill |
|---|---|---|---|---|---|---|
| pH | 8.26 | 7.95 | 7.9 | 7.70 | 7.62 | 8.08 |
| Aluminium | 0.066 | 0.024 | 0.033 | 0.015 | 0.020 | 0.063 |
| Iron | 0.025 | 0.004 | -0.003 | -0.007 | -0.003 | 0.001 |
| Manganese | 0.017 | 0.011 | 0.021 | 0.013 | 0.077 | 0.130 |

**Goodna Mine**

| Parameter | Pre-treatment | Post-treatment |
|---|---|---|
| pH | 3.5 - 4 | 7.0 |
| Aluminium | 55.4 | 0.005 |
| Iron | 80.7 | 0.005 |
| Manganese | 2.29 | 0.87 |

## 15.    Is Ashfilling a Viable Option at Sigma Colliery?

Since 1999, an ashfilling project was undertaken at Sigma Colliery.  The aim of this project was backfilling to stabilise mine workings located beneath the Sasolburg-Parys Road (R26) and underneath Leeuspruit.  According to a report done by Jones and Wagener Consulting Civil Engineers (2001), the ash used for the back filling was fine ash obtained from the waste stream generated by Sasol One in Sasolburg.  The ash was pumped in a slurry form and deposited hydraulically to the Sigma Underground Workings beneath the Sasolburg-Parys Road (R26).

Van Tonder *et al.*, (2003) described a conceptual model of Sigma Colliery in 2003 and this will be used to describe the typical conditions at Sigma Colliery without the influence of the ashfilling, as well as the effect ashfilling has on the typical conditions at the colliery.

Figure 15-1 illustrates a typical situation at Sigma Underground Mine.  Some important characteristics, as quoted from the conceptual model in the report done by Van Tonder *et al.*, (2003) are:

- The transmissivity (T)-value of the mined coal seam is very high (in the order of thousands) and the storativity (S) is also very high (62 percent in the mined out section as opposed to approximately 0.1 percent in typical Karoo aquifers).
- Once the mine has filled up with water, a horizontal piesometric level will occur (this piesometric level is also horizontal during the filling up process).  If the piesometric level intersects the surface, decant could take place at the point of intersection (if there is a link such as a borehole), between this position and the mine.
- The rate at which the piesometric level rises is dependent on (a) the amount of influx from the top layers (or along subsidence areas) - denoted by the symbol $I_t$,  (b) the amount of influx from the bottom layers (denoted by $I_b$) and (c) the amount of lateral groundwater outflow (denoted by Qo) downstream from the mined out area. If $I_t > I_b + Qo$, the mine will decant. However, if  $Qo + I_b > I$, the mine will not decant and the worst that can occur is that mine water will flow towards the bottom layer.
- The Sigma Underground Mine is partially underlain by dolomite, which has a very high transmissivity.  The dolomite had a piesometric level of 1403 mamsl,

which is lower than the water level of the top aquifer, but higher than the piezometric level of the mined out coal seams. It is therefore expected that a large amount of water was flowing from the dolomite aquifer towards the mine (during mining, water was flowing from the floor of the mine). About 10 percent of the dolomitic aquifer is in direct contact with the Coal Seams.

- Once the mine has filled up with water, the piesometric level of the mine will rise with the storage coefficient value of the mine (and not the specific yield), as conditions have changed from unconfined to confined. The flux from the overlying aquifers into the mine aquifer will decrease as the two water levels approach each other (Figure 15-1). The flux from the dolomite aquifer towards the mine will also decrease as the mine level increases. Once the level of the mine aquifer is higher than that of the dolomite aquifer, water from the mine will flow towards the dolomite aquifer. It is only once the mine level increases above that of the level of the top weathered aquifer that decant could occur (the rate of decant will be equal to the flux of the mine aquifer towards the top aquifer, which will be a function of the direct recharge into the mine aquifer). The chances of the water level of the mine increasing above the water level of the top aquifer are very small, because the dolomite has a much higher transmissivity value than the top aquifer. Water will therefore flow from the mine aquifer towards the bottom dolomite aquifer.

- In the case of the study area it is expected that most of the recharge will take place along subsidence, which will act as preferred pathways.
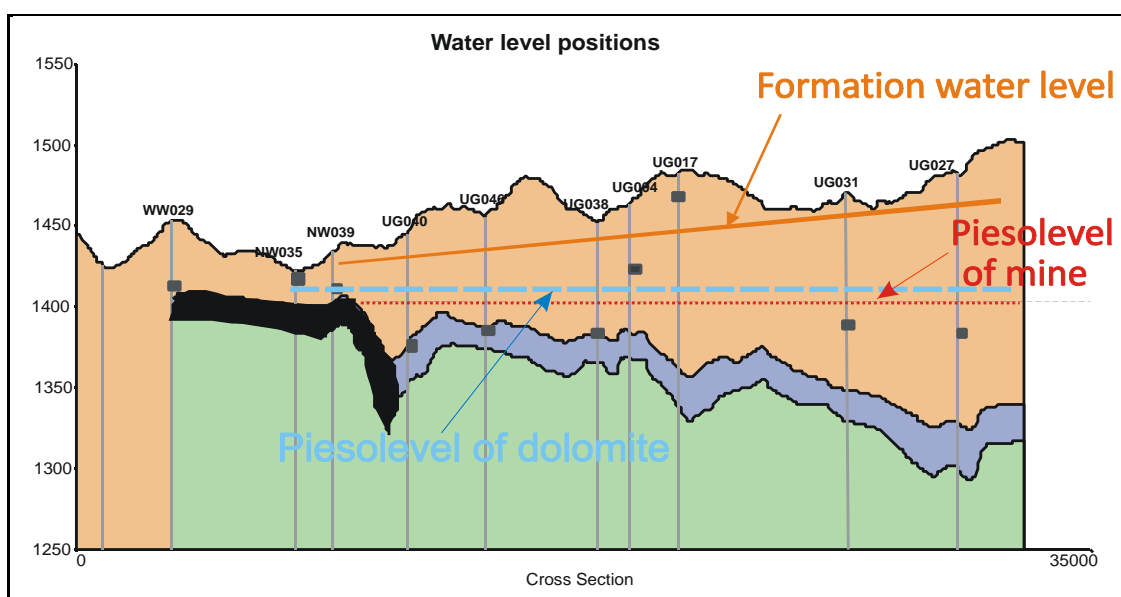


*Figure 15-1: Conceptual model of Sigma Underground Mine. Modified after Van Tonder et al, (2003).*

From the study of Sigma Colliery, the following conclusions and recommendations can be made:

- The ashfilling used turned out to be a viable option when there was still mine void space available before the mine was filled up with water from the flooding.
- Since the mine voids were filled with water and the fine ash slurry was pumped into the mine voids, the conditions as described above was disturbed in that the void space in the mine was decreased with some volume of water.
- The storage of the strata above is not enough for the water that was pumped in with the ash and the water is therefore forced to decant.
- The only place where decant and pollution of the shallow aquifer is evident is where ashfilling has been done.
- The situation improves as soon as the ashfilling is ceased and this can be substantiated by the water level and water quality behaviour of borehole UG069. The water levels of borehole UG069 has been at decanting levels from September 2009 to March 2012 (Figure 15-3) after which the water level started to decrease again after the ashfilling was ceased. From the electrical conductivity profiling done of borehole UG069 (Figure 15-2) (after the ashfilling was ceased) the profile already indicates that the upper part of the water column is of a better quality than deeper down.
- It is therefore recommended that in the event that the company would like to continue with the ashfilling, they should pump water out of the mine to provide void space and prevent decant.
- The ash slurry should simultaneously be injected into the mine with the water that is pumped out. This should be pumped in equal volumes, which will prevent other problems such as the collapsing of the mine roof.
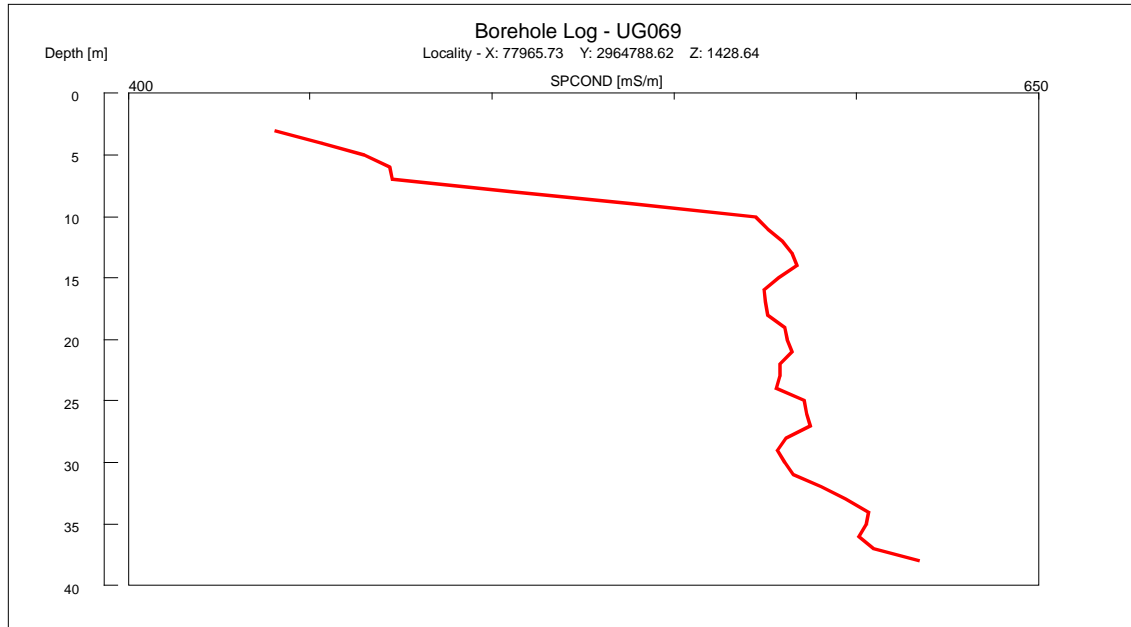
Figure 15-2: Electrical conductivity profile of borehole UG069.
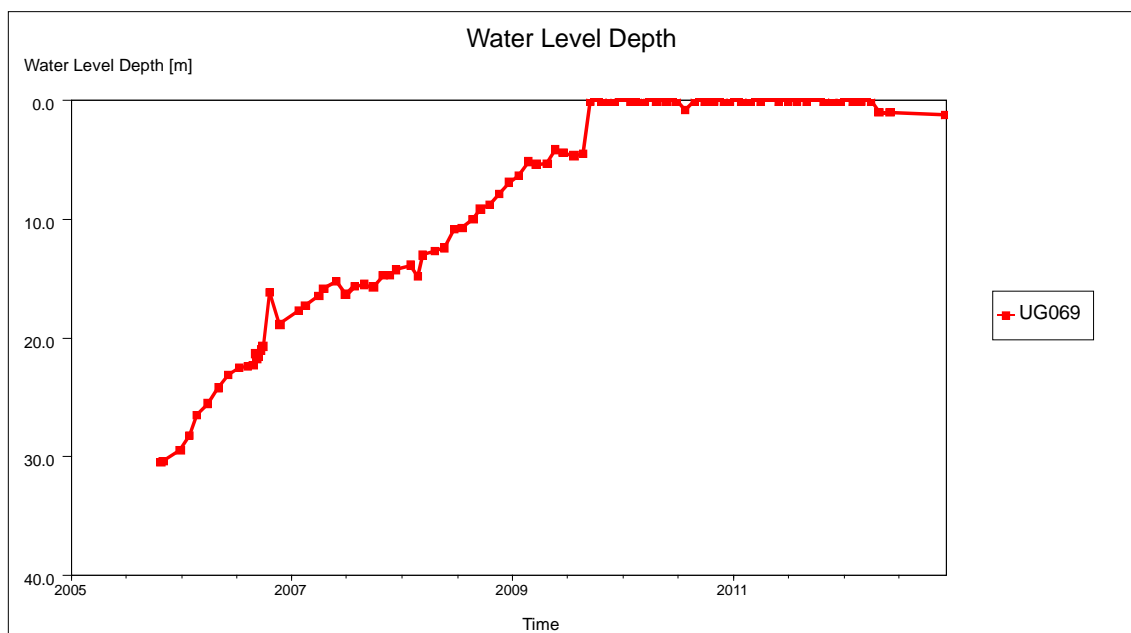


Figure 15-3: Water level depth time graph of borehole UG069.

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## Summary

This study of Sigma Colliery was intended:

- To determine the water quality of each aquifer associated with the mining area.
- To determine the overall electrical conductivity profile of the mine to aid in the overall management of the mine.
- To delineate possible decant positions with the help of water levels and to determine what the water quality of the possible decanting water will be.
- To discuss the use of fly ash as a backfilling material in underground mines with the help of case studies.
- To determine if ashfilling is a viable option for Sigma Colliery.

From the study of Sigma Colliery, the following conclusions and recommendations could be made in this document:

- A total of 12 samples were obtained from the shallow aquifer, classified according to the SANS 241:2006 drinking water standards and discussed in this document.  Only sample WW024D was classed as above the maximum allowable limit and not suitable for human consumption.  Four samples were classed within Class 2, suitable for human consumption for a limited duration use only.  A total of seven samples were classed as Class 1, suitable for human consumption.
- A total of 23 samples were obtained from the intermediate aquifer, classified according to the SANS 241:2006 drinking water standards and discussed in this document.  Samples WW036, NW021, NW037 and UG001 were classed as above the maximum allowable limit and not suitable for human consumption.  Three samples were classed as Class 2, suitable for human consumption for a limited duration use only while 16 samples were classed as Class 1, suitable for human consumption.
- A total of 21 samples were obtained from the deep aquifer system, classified according to the SANS 241:2006 drinking water standards and discussed in this document.  Samples NW006, NW036, NW040, NW041, NW042, NW044, NW046, NW051, UG027D, UG071, UG072D and UG072M were classed as above the maximum allowable limit and not suitable for human consumption.  Two samples were classed within Class 2, suitable for human consumption for a

limited duration use only and seven samples were classed as Class 1, suitable for human consumption.

- A total of six samples were obtained from the disturbed aquifer system, classified according to the SANS 241:2006 drinking water standards and discussed in this document. Samples UG014 and UG023 were classed as above the maximum allowable limit and not suitable for human consumption. Two samples were classed within Class 2, suitable for human consumption for a limited duration use only and two samples were classed as Class 1, suitable for human consumption.

- A total of 20 samples were obtained from the ashfill boreholes, classified according to the SANS 241:2006 drinking water standards and discussed in this document. Samples UG033, UG034, UG044, UG069, B12/179, B12/183D, B12/183M and B12/183S were classed as above the maximum allowable limit and not suitable for human consumption. Only one sample (sample C316/47) was classed within Class 2, suitable for human consumption for a limited duration use only and 11 samples were classed as Class 1, suitable for human consumption.

- A total of 19 samples were obtained from the mine boreholes, classified according to the SANS 241:2006 drinking water standards and discussed in this document. Samples UG013D, UG024, UG037D, UG046, B12/53D and B12/53S were classed as above the maximum allowable limit and not suitable for human consumption. Five samples were classed within Class 2, suitable for human consumption for a limited duration use only and eight samples were classed as Class 1, suitable for human consumption.

- All 94 boreholes were profiled and a three-dimensional image of the whole area was created with the use of the electrical conductivity profiles. From this image created, varies possible decant areas were identified and the water quality of these possible decant areas were discussed.

- The ashfilling used turned out to be a viable option when there was still mine void space available before the mine was filled up with water from the flooding.

- Since the mine voids were filled with water and the fine ash slurry was pumped into the mine voids, the conditions was disturbed in that the void space in the mine was decreased with some volume of water.

- The storage of the strata above is not enough for the water that was pumped in with the ash and the water is therefore forced to decant.

- The only place where decant and pollution of the shallow aquifer is evident is where ashfilling has been done.

- The situation improves as soon as the ashfilling is ceased and this can be substantiated by the water level and water quality behaviour of borehole UG069. The water levels of borehole UG069 has been at decanting levels from September 2009 to March 2012 (Figure 15-3) after which the water level started to decrease again after the ashfilling was ceased. From the electrical conductivity profiling done of borehole UG069 (Figure 15-2) (after the ashfilling was ceased) the profile already indicates that the upper part of the water column is of a better quality than deeper down.

- In this document it is therefore recommended that in the event that the company would like to continue with the ashfilling, they should pump water out of the mine to provide void space and prevent decant.

- The ash slurry should simultaneously be injected into the mine with the water that is pumped out. This should be pumped in equal volumes, which will prevent other problems such as the collapsing of the mine roof.

## Opsomming

Die doel van die studie van Sigma Steenkoolmyn was die volgende:

- Om die water kwaliteit van elke akwifeer, wat geassosieer is met die myn area, te bepaal.
- Om die algemene elektriese geleidingsvermoë profiel van die myn te bepaal om te dien as hulpmiddel in die bestuur van die myn.
- Om moontlike areas van myn-oorloop te identifiseer met behulp van water vlakke en om die water kwaliteit van die moonlike myn-oorloop areas te bepaal.
- Om die gerbruik van vliegas as 'n terugvullings material in ondergrondse myne met behulp van gevallestudies te bespreek.
- Om die lewensvatbaarheid van terugvulling van Sigma Steenkoolmyn met vliegas te bepaal.

Vanuit hierdie studie van Sigma Steenkoolmyn kon die volgende gevolgtrekkings en aanbevelings gemaak word:

- 'n Totaal van 12 monsters was van die vlak akwifeer geneem, geklassifiseer volgens die SANS 241:2006 drinkwater standaarde en in hierdie dokument bespreek. Slegs monster WW024D was geklassifiseer as bo die maksimum toegelate waarde en is dus nie geskik vir menslike verbruik nie. Vier monsters was as Klas 2 geklassifiseer en is geskik vir menslike verbruik vir slegs 'n beperkte duur. 'n Totaal van sewe monsters was geklassifiseer as Klas 1 en is dus geskik vir menslike verbruik.
- 'n Totaal van 23 monsters was van die intermediere akwifeer geneem, geklassifiseer volgens die SANS 241:2006 drinkwater standaarde en in hierdie dokument bespreek. Monsters WW036, NW021, NW037 en UG001 was geklassifiseer as bo die maksimum toegelate waarde en is dus nie geskik vir menslike verbruik nie. Drie monsters was as Klas 2 geklassifiseer en is geskik vir menslike verbruik vir slegs 'n beperkte duur. 'n Totaal van 16 monsters was geklassifiseer as Klas 1 en is dus geskik vir menslike verbruik.
- 'n Totaal van 21 monsters was van die diep akwifeer geneem, geklassifiseer volgens die SANS 241:2006 drinkwater standaarde en in hierdie dokument bespreek. Monsters NW006, NW036, NW040, NW041, NW042, NW044, NW046, NW051, UG027D, UG071, UG072D and UG072M was geklassifiseer

as bo die maksimum toegelate waarde en is dus nie geskik vir menslike verbruik nie. Twee monsters was as Klas 2 geklassifiseer en is geskik vir menslike verbruik vir slegs 'n beperkte duur. Sewe monsters was geklassifiseer as Klas 1 en is dus geskik vir menslike verbruik.

- n Totaal van ses monsters was van die versteurde akwifeer geneem, geklassifiseer volgens die SANS 241:2006 drinkwater standaarde en in hierdie dokument bespreek. Monsters UG014 and UG023 was geklassifiseer as bo die maksimum toegelate waarde en is dus nie geskik vir menslike verbruik nie. Twee monsters was as Klas 2 geklassifiseer en is geskik vir menslike verbruik vir slegs 'n beperkte duur. Twee monsters was ook geklassifiseer as Klas 1 en is dus geskik vir menslike verbruik.

- n Totaal van 20 monsters was van die boorgate in die vliegas geneem, geklassifiseer volgens die SANS 241:2006 drinkwater standaarde en in hierdie dokument bespreek. Monsters UG033, UG034, UG044, UG069, B12/179, B12/183D, B12/183M en B12/183S was geklassifiseer as bo die maksimum toegelate waarde en is dus nie geskik vir menslike verbruik nie. Slegs een monster (monster C316/47) was as Klas 2 geklassifiseer en is geskik vir menslike verbruik vir slegs 'n beperkte duur. 11 monsters was ook geklassifiseer as Klas 1 en is dus geskik vir menslike verbruik.

- 'n Totaal van 19 monsters was van die boorgate in die myn geneem, geklassifiseer volgens die SANS 241:2006 drinkwater standaarde en in hierdie dokument bespreek. Monsters UG013D, UG024, UG037D, UG046, B12/53D en B12/53S was geklassifiseer as bo die maksimum toegelate waarde en is dus nie geskik vir menslike verbruik nie. Fyf monsters was as Klas 2 geklassifiseer en is geskik vir menslike verbruik vir slegs 'n beperkte duur en agt monsters was ook geklassifiseer as Klas 1 en is dus geskik vir menslike verbruik.

- 'n Drie-dimensionele figuur van die hele area is met behulp van die elektriese geleidings profiele van die 94 boorgate geskep. Met behulp van hierdie figuur kon verskeie moontlike myn-oorloop areas geidentifiseer word en die water kwaliteit van die areas is bespreek.

- Die terugvulling met vliegas was nog 'n lewensvatbare opsie toe daar nog myn leemte ruimte beskikbaar was voordat die myn opgevul was met water as gevolg van die oorstroming van die myn.

- Vandat die myn leemtes gevul is met water en die vliegas in die myn leemtes ingepomp is, het die toestande verander, in dat leemtes in die myn afgeneem het met 'n sekere volume water.

- Die strata bo die myn het nie genoeg storings vermoë om die water wat saam met die vliegas ingepomp is ook te hanteer nie en die water word dus geforseer om uit te loop.

- Die enigste area waar myn-oorloop en besoedeling van die vlak akwifeer sigbaar is, is waar terugvulling van die myn met vliegas plaasgevind het.

- Hierdie situasie verbeter sodra die terugvulling met die vliegas gestaak word en hierdie stelling kan deur die water kwaliteit en water vlak gedrag van boorgat UG069 beaam word.  Die water vlak van boorgat UG069 het van September 2009 to Maart 2012 oorgeloop (Figure 15-3).  Die water vlak het weer begin afneem na die terugvulling met vliegas gestaak is.  Die elektriese geleidings profiel (Figure 15-2) van boorgat UG069 (na terugvulling met vliegas gestaak was) dui alreeds aan dat die boonste deel van die water kolom van 'n beter kwaliteit is as die dieper deel van die water kolom.

- In hierdie dokument word dit aanbevel dat indien die maatskappy wil voortgaan met die terugvulling van die myn met vliegas, water uit die myn gepomp moet word om myn leemte spasie te verskaf en dus sodoende myn-oorloop te voorkom.

- Dit word ook aanbeveel dat die inpomp van die vliegas mengsel tegelyk met die uitpomp van water uit die myn moet plaasvind.  Gelyke volumes moet in- en uit gepomp word om sodoende ander moontlike probleme, soos byvoorbeeld die ingee van die dak van die myn, te voorkom.