

Investigation of the acid mine drainage potential of the Kopanang rock dump, Vaal Reefs

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ABSTRACT

The Kopanang rock dump is one of several rock dumps in the Vaal Reefs gold mining area that may have an impact on the surface and groundwater quality. Few Acid Mine Drainage (AMD) studies exist on rock dumps in the South African gold industry due to the overwhelming acid generation from slime dams. Due to the existence of sulfide minerals in the Kopanang rock dump, there is a possibility that acid generation can occur, depending on the mineralogical composition of the rocks. If the rock dump generates acid it will increase the possibility of heavy metal leaching and pollute the underlying aquifers. The aim of this study was to determine whether the dump generates acid and if so to quantify the acid generation and the impact it has on the surface and groundwater.

From this study it was concluded that the rock dump has a potential to produce acid resulting in AMD. However, the inherent minerals in the rock dump (calcite, dolomite, mica and chlorite) have a neutralising effect on the produced acid that may form. Furthermore, the underlying dolomite acts as a buffer for any residual acid. There is, however, evidence of water pollution around the waste rock dump and in the groundwater adjacent to the rock dump. This polluted water has a neutral pH with elevated uranium and sulfate concentrations. The final conclusion was that the waste rock dump produces neutral mine drainage (NMD). An additional finding was that high run-off water from the rock dump infiltrates through the prevailing bedding planes and joints in the underlying dolomites. This, together with the weight of the rock dump, contributed to the formation of small sinkholes.

UITTREKSEL

Die Kopanang rotshoop is een van vele rotshope in die Vaal Reefs goudmynarea wat 'n impak mag toon op die oppervlak- en grondwater-kwaliteit. Min studies in verband met die potensiaal van suurmyndreinerings bestaan oor rotshope in die Suid Afrikaanse goudindustrie as gevolg van die oorweldigende suurvorming van slikdamme. Weens die voorkoms van sulfiedminerale in die Kopanang rotshoop, is daar 'n moontlikheid dat suurvorming kan plaasvind, afhangende van die mineralogiese samestelling van die gesteentes. Indien die rotshoop suur genereer, sal dit die moontlikheid van swaarmetaalloging verhoog en die omliggende waterdraers besoedel. Die doel van hierdie studie was om vas te stel of die hoop wel suur genereer en indien dit wel die geval was, die suurvorming te kwantifiseer en die impak daarvan vas te stel op die oppervlak- en grondwater.

Uit hierdie studie kan die gevolgtrekking gemaak word dat hierdie rotshoop die potensiaal toon om suur te genereer wat suurmyndreinerings kan veroorsaak. Die inherente minerale in die rotshoop (kalsiet, dolomite, mika en chlorite) het egter 'n neutraliserende effek op die geproduseerde suur wat mag vorm. Verder tree die onderliggende dolomiet op as 'n buffer vir enige oorblywende suur. Daar is wel bewyse van waterbesoedeling rondom die rotshoop en in die grondwater reg langs die hoop. Hierdie besoedelde water het 'n neutrale pH met verhoogde uranaan- en sulfaatkonsentrasies. Die finale gevolgtrekking is dat die rotshoop neutrale myndreinerings veroorsaak. 'n Bykomende bevinding was dat hoë-snelheidsafloop langs die rotshoop deur die bestaande vlakke en nate in die onderliggende dolomiete infiltreer. Dit, te same met die gewig van die rotshoop, dra by tot die ontstaan van klein sinkgate.

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1. INTRODUCTION

1.1 The Kopanang waste rock dump

The Kopanang waste rock dump is situated on Pretorius Kraal 53, near Vaal Reefs (Figure 1.1) and is one of several mine dumps in the area. Kopanang gold mine was established in the early 1980's and has currently a 12-year life of mine. The mine dump (Figure 1.2) was surveyed on the 22nd of June 2006 and has a 240 801 m² footprint. It has a volume of 9 101 006 m³, weighs 15 171 377 tons and a bulk density of 1.65 (ton/m³). From this land survey up to the end of the life of the mine there will be another 1 401 872 m³ or 2 313 090 tons added due to underground development. Its estimated gold value is 0.28 g/t and uranium value is 0.016 kg/t, its sulfur content is 0.13% (Williams, 1998).

The rock dump consists mainly of the following rock types: dolomite, lava, several quartzites, conglomerates and several non-economic reef conglomerate packages, which are characterised by up to 80% sulphide minerals in the matrix. Most of the waste material comes from footwall development to get access to the reef horizon, namely the Vaal Reef that is extensively mined, or the 'C' Reef, of which is mined in small quantities at Kopanang mine. This footwall development, or cross cuts and haulages are mined in the Stilfontein Formation that forms part of the Johannesburg Subgroup in the Witwatersrand Supergroup. Other materials such as iron and mining equipment (explosive boxes, cement) are also present in smaller quantities.

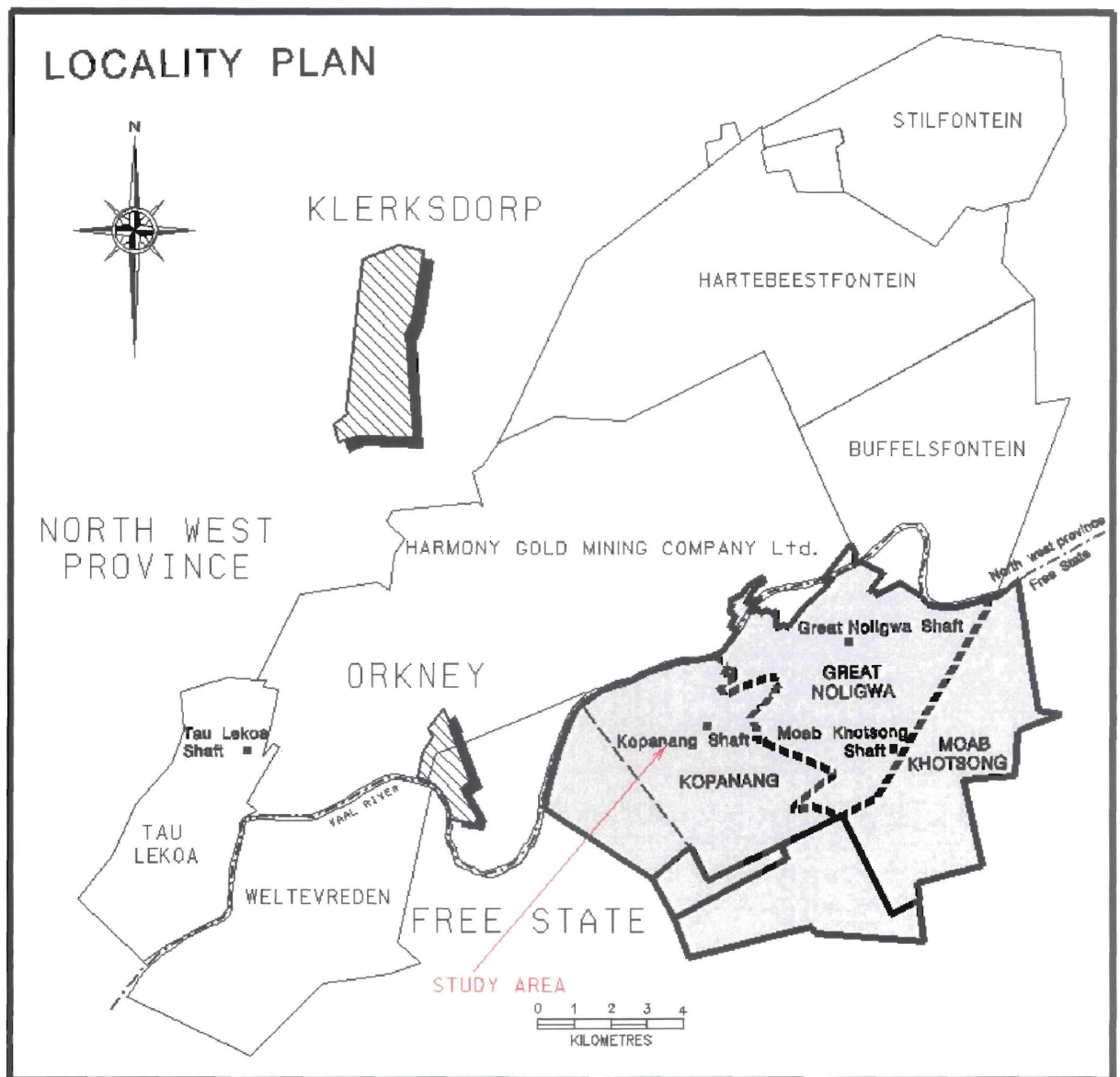


Figure 1.1: Location of the Kopenang mine. The coordinates in the middle of the rock dump is S26° 58.831'; E 026° 44.646'

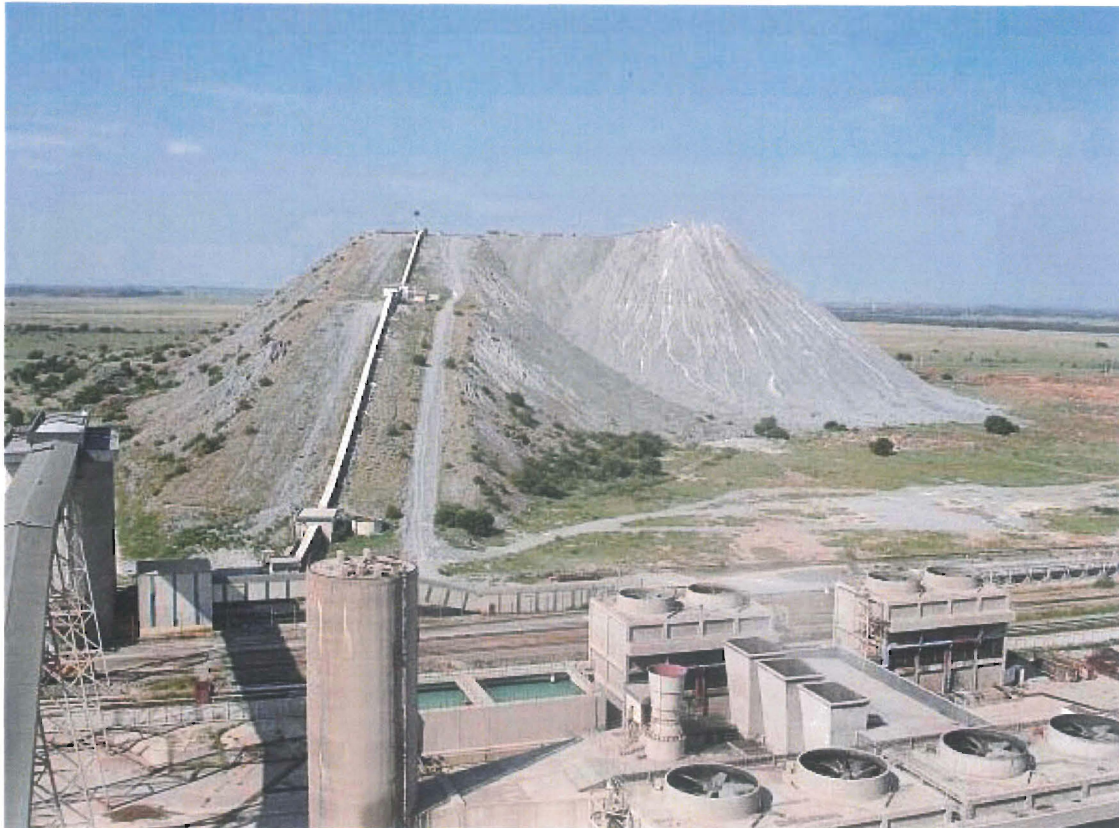


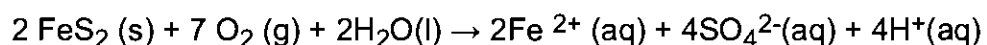
Figure 1.2: Photograph of the Kopanang rock dump

The bulk of these rock types comes from the Witwatersrand Supergroup and very little is published about the acid mine drainage potential of these waste rocks from underground development, comprising the rock dumps. There was however, research done about Acid Mine Drainage (AMD) and other pollutants that derived from slimes dams (Naicker *et al.*, 2003; Winde & Sandham, 2004; Nengovhela *et al.*, 2006) which is the waste product from the reef horizon after the gold extraction process.

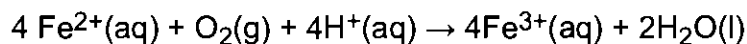
1.2 Acid mine drainage (AMD)

Acid Mine Drainage (AMD) is produced when sulfide-bearing material is exposed to oxygen, water and sulphur oxidizing bacteria, such as *Thiobacillus ferrooxidans*. The production of AMD usually – but not exclusively – occurs in iron sulfide-aggregated rocks (Akcil & Koldas, 2004). Due to mining activity, minerals in the rocks that are stable under the earth's surface are brought up to surface where they are exposed to oxygen and water. Characterized by low pH and high concentrations of heavy metals (for example, uranium, lead, chromium etc.) and sulfate, AMD can severely contaminate surface and groundwater, as well as soils.

Although a host of chemical processes contribute to AMD, pyrite oxidation is by far the greatest contributor. The pyrite oxidation rate can be influenced by a number of external factors for example: temperature, permeability of the rock dump, gaseous diffusion and convection in the rock dump, moisture content, pyrite concentration, and surface area of pyrite (Lefebvre *et al.*, 2001). A general equation for this process is:



The oxidation of the sulfide to sulfate solubilises the ferrous iron (iron(II)), which is subsequently oxidised to ferric iron (iron(III)):



Either of these reactions can occur spontaneously or can be catalysed by microorganisms that derive energy from the oxidation reaction. The ferric irons produced can also oxidise additional pyrite:



The net effect of these reactions is to release H^+ , which lowers the pH and maintains the solubility of the ferric iron.

Many studies have been conducted globally to understand the processes and effects of AMD, for example: The South Dump of the Doyon mine in Canada and the Ronnenberg mining industry in Germany (Lefebvre *et al.*, 2001). Other examples are from Avoca (South East Ireland) and the upper Arkansas River, Colorado, USA (Kimball *et al.*, 1995; Gray, 1997). The current and future liabilities associated with AMD have significant financial implications for countries. In Australia the cost of managing potentially acid generating wastes at operating mine sites is estimated to be about \$60 million per year and that of Canada are estimated to be between C\$2 and C\$5 billion. This includes costs for cover installation, selective placement of wastes and water treatment as appropriate (Harries, 1997).

It is evident that AMD is a widespread problem and also exists in the South African mining industry, especially in the gold and coal industries where sulfide minerals are associated with these commodities (Akcil & Koldas, 2004; Geldenhuis & Bell, 2004; Nengovhela *et al.*, 2006). In some countries strict legislation is in place to guide and assist mining companies with AMD problems, for example, Canada (Government of British Columbia, 2007). In the century-old gold industry in South Africa little knowledge existed on AMD derived from rock

dumps in the gold industry, and the result today is widespread environmental degradation.

The South African legislation provides guidelines for the mining industry to operate sustainably under the Mineral and Petroleum Resources Development Act (South Africa, 2002). This act stipulates in section 37 (2) “... *mining operation must be conducted in accordance with generally accepted principles of sustainable development by integrating social, economic and environmental factors into the planning and implementation of prospecting and mining projects...*”. Mines are sometimes skeptical to publish environmental reports, such as AMD investigations due to the negative implications that it may have. One example of such a report is that of South Deep Gold Mine (2002).

This gold mine has two waste rock dumps and the older rock dump shows significant acid generation and heavy metal leaching with elevated sulfate concentrations. The younger waste rock dump indicates no potential for acid mine drainage. This report emphasizes that the geochemical composition of the two different rock types play a vital role in the acid generation potential, and that rock dumps may contribute to the acid mine drainage problem of the area. Rehabilitation of the older rock dump is necessary to minimise the liability of the mine and to reduce the negative affect of AMD on the receiving environment.

There are eight boreholes in the vicinity of the Kopanang rock dump, Vaal Reefs, which are currently being monitored for water quality by the Department of Environmental Management, AngloGold Ashanti (Figure 1.3). At this stage relatively high concentrations of sulfate (SO_4^{2-}) and nitrate (NO_3^{1-}) are detected in the ground water (Labuschagne, 2005). These concentrations influence the aquifer system in the dolomites, which are a few hundred metres away from the Vaal River. Due to sufficient concentrations of gold and uranium in the dump no

rehabilitation is considered at this stage but will probably be reclaimed at a later stage.



Figure 1.3: Location of the monitoring boreholes around the Kopanang rock dump

1.3 Problem statement

Due to the existence of sulfide minerals in the rock dump, acid generation can occur, depending on the net neutralizing potential in the rock. The elevated sulfate concentration in the groundwater may also be a result of AMD. If the rock dump generates acid it will increase the possibility of heavy metal leaching and pollute the underlying aquifers. The aim of this study was to determine whether the dump generates acid and, if so, to quantify the acid generation and the impact it has on the ground and surface water.

1.4 Research questions

In order to reach a conclusion on the AMD potential from the rock dump the following questions had to be answered.

- 1.4.1 What influence does the geological setting of the area have on the AMD potential of the rock dump?
- 1.4.2 What are the mineral composition and the geochemistry in the rock dump?
- 1.4.3 What are the sulfide occurrence and minerals in the rock dump that could control AMD?
- 1.4.4 Does on-site monitoring data from underground and surface water give any indication of AMD?
- 1.4.5 Do static tests indicate any AMD potential using samples from the waste rock dump?
- 1.4.6 What mitigation type will give the best deliverables for AMD control?

1.5 Methodology

The procedure for evaluating AMD potential consists of several laboratory tests, mineralogical investigations and field work.

1.5.1 The geological setting of the area was investigated, using existing geological maps and field investigations, to determine if it has any influence on the AMD potential of the rock dump.

1.5.2 During this study period there were no published guidelines available to determine the size and number of samples to be taken in order to get a representative sample of a rock dump to determine AMD potential. Therefore, seven 5kg samples were taken from the conveyor belt (to be more representative from the different areas being mined) at different days over a period of four weeks. All of these samples were fresh samples with limited exposure to the atmosphere and water. The seven 5kg samples were crushed by a jaw crusher and milled. Five hundred grams of each sample were taken to make up one large composite sample and milled again. The composite sample was sent for X-ray fluorescence (XRF) analysis to determine the major and trace element composition of the rock dump as well as X-ray diffraction (XRD) analysis for the identification of the mineralogical composition of the rock dump. One composite sample, from the Vaal Reef for comparison purposes was also sent for XRD and XRF analysis.

1.5.3 The mineral composition and sulfide occurrence were macroscopically identified in drill core from all the main stratigraphic units encountered in the mine. Rock samples from the dump were reviewed likewise.

1.5.4 Five run-off samples from the toe of the rock dump were taken on the following day after heavy rains and analysed for any pollutants. There were only five rain showers with sufficient water accumulation during the sampling period from April 2005 to November 2006. Data from underground monitoring water

boreholes around the waste rock dump were analysed and compared to the run-off samples to identify any correlation of pollutants.

1.5.5 Together with the seven samples from (refer to 1.5.2) and another seven samples taken from the conveyer belt, also taken over a period of four weeks were sent for Acid Base Accounting (ABA) (Sobek *et al.*, 1978) and Net Acid Generation (NAG) tests (Miller *et al.*, 1997). The analyses of two reef samples are used as a quality control measure because of the high concentration of sulfides in the reef package. These static tests are an indication of the possibility of any AMD potential from the rocks on the rock dump. Depending on the results of these tests it will be decided if any additional dynamic tests should be done or not.

1.5.6 A literature study was made to propose possible mitigation programs. These mitigation deliverables depend on the observed quantity of pollution as determined per ABA and NAG analysis.

2. DATA COLLECTION AND RESULTS

2.1 Geological characterisation of the rock dump and the area surrounding the rock dump

A geological map of the Vaal Reefs area was obtained from the AngloGold Ashanti field office. The study area is only a small portion of the bigger Vaal Reefs area and the geological map was modified using Cadsmine software to highlight the main geological features of the study area (Figure 2.1). Field work was also done to confirm all the geological features in the study area, which include three sinkholes that were identified around the rock dump.

The rock dump is located on top of dolomites ($\text{CaMg}(\text{CO}_3)_2$) of the Chuniespoort Group, which forms part of the Transvaal Supergroup (Figure 2.1). The thickness of the dolomite in the area of the rock dump is 250m as indicated by the drill core of the PK 10 surface hole that was drilled in 1960 and is situated 300 metres from the centre of the rock dump (Watts, 2005). The dolomites are surrounded by chert rich gravel, which is the remnant after the dissolution of the dolomite. A significant unconformity appears to the south-east of the rock dump where sediments from the younger Karoo Supergroup outcrop. Several faults cut through the area and the main bedding plane direction is NNE-SSW.

During the shaft sinking process, dolomites from the Chuniespoort Formation, and Ventersdorp lavas were deposited on the rock dump. These rock materials make up a very small percentage of the rock dump. Most of the rock materials are from the Witwatersrand Supergroup. The main part of the development to access the Vaal Reef horizon is situated in the footwall of the Vaal Reef, namely

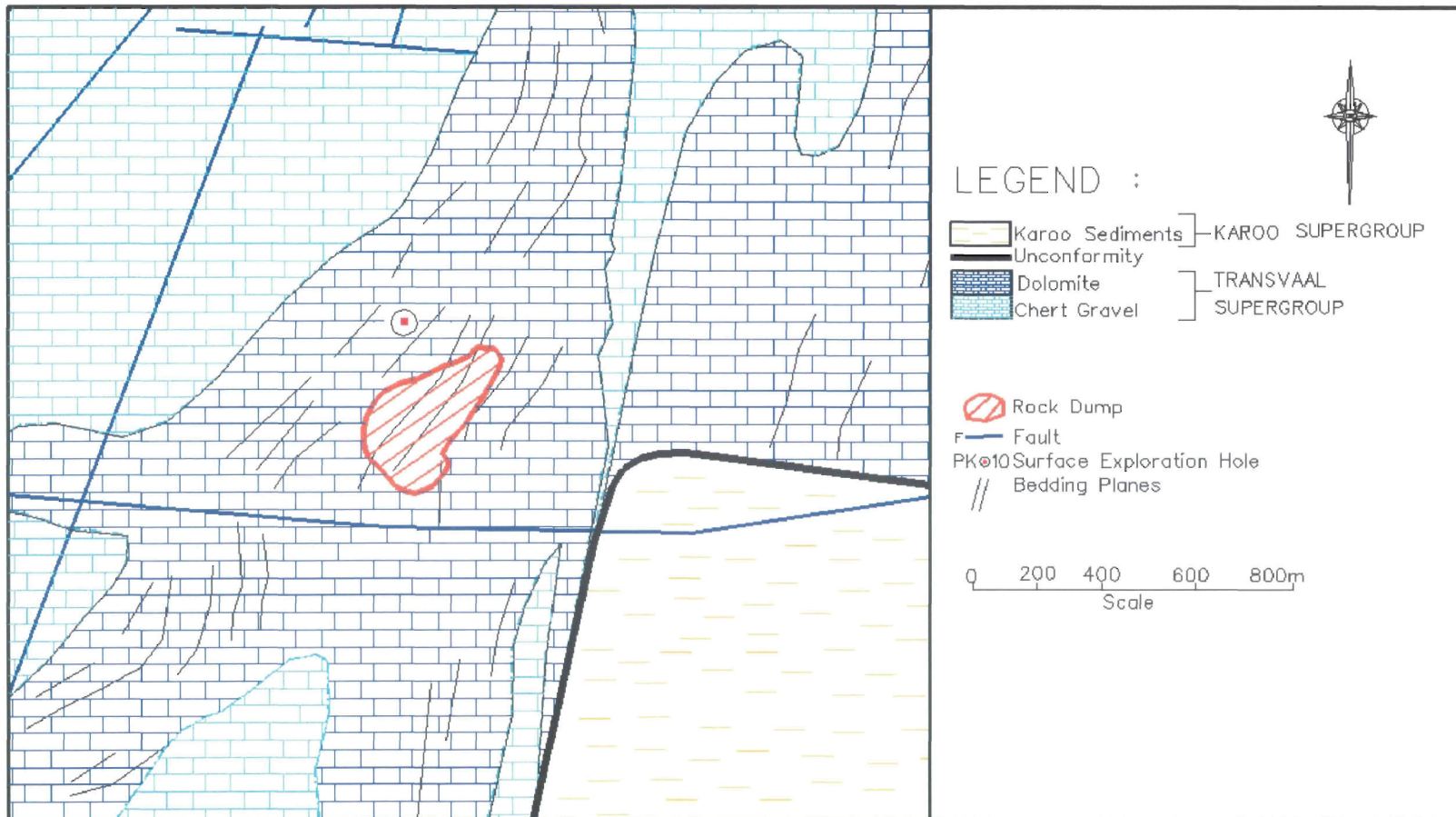


Figure 2.1: Surface geology of the Kopanang rock dump area. The coordinates of the middle of the rock dump are S026° 58.831'; E 026° 44.646'. The Vaal River is approximately 4 km to the northwest of the rock dump. The infra-structure of the mine is shown in Figure 1.3.

the Stilfontein Formation. Therefore most of the material in the rock dump is from the Stilfontein Formation. The Stilfontein Formation consists mainly of quartzites and scattered conglomerate bands where up to 80% of the matrix exists as sulfide minerals like pyrite (FeS_2). Mafic dykes of the Ventersdorp Supergroup and faults, represented by cataclasites, are present within the Stilfontein Formation and therefore make up a small percentage of the rock dump. Minor sulfide minerals, such as chalcopyrite (CuFeS_2) occur within the mafic dykes.

2.2 Total whole rock composition of the rock dump and the Vaal Reef

2.2.1 X-ray diffraction (XRD) analysis

To determine the mineral composition of the rock dump, a composite sample, as described in 1.5.2, was analysed by XRD. The XRD analysis was done using a Siemens D500 X-ray system equipped with a 2.2kW Cu long fine focus tube, variable slit, secondary graphite monochromator, sample spinner and 40 position automated sample changer. $\text{Cu}_{K\alpha}$ radiation was used and the composite sample of the waste rock dump, in random powder preparation, was scanned from 2° to $65^\circ 2\theta$ at a speed of $0.02^\circ 2\theta$ steps size/1 sec and generator settings of 40 kV and 30mA. For comparison, a sample of the Vaal Reef, taken off the reef belt, was also analysed.

Phase identification is based on SIEMENS DIFFRAC^{Plus} - EVA evaluation program and the JCDD (JCPDS) Inorganic/Organic Data Base. Phase concentrations are determined as semi quantitative estimates, using relative peak heights/areas proportions (Brime, 1985).

The composite sample from the rock dump shows that quartz, chlorite and mica are the abundant mineral phases with minor amounts of pyrophyllite and illite/smectite and trace amounts of amphibole, dolomite and calcite (Table 2.1). The Vaal Reef sample is mainly composed of quartz with accessory pyrophyllite, mica, chlorite, and illite/smectite, as well as trace amounts of amphibole, dolomite and calcite. In comparison to the rock dump composite the Vaal Reef sample has a higher quartz and pyrophyllite content (71% vs. 53% quartz and 12% vs. 7% pyrophyllite) than the composite rock dump sample, while the mica and chlorite content are lower than the composite rock dump sample. It is important to note that calcite and dolomite are present in all the samples, although in trace amounts. Although pyrite was not detected in this analysis it is well known that pyrite should be present. Refer to section 2.3 for macroscopic identification of pyrite in the Vaal Reef, as well as waste rock, i.e. footwall (Figures 2.2 and 2.3). The apparent absence of pyrite can be ascribed to the level of detection for XRD analysis.

Table 2.1: Results of the XRD analyses of the rock dump composite and Vaal Reef belt sample giving semi-quantitative mineral concentrations

Mineral	Composition (%)	
	Composite sample	Reef belt sample
Calcite	Trace	<1
Dolomite	1	<1
Quartz	53	71
Mica	15	9
Chlorite	20	6
Amphibole	1	<1
Pyrophyllite	7	12
Illite/Smectite Interstratification	3	2

Annalist: Cloete (2006) Council for Geoscience

2.2.2 X-ray fluorescence (XRF) analysis

XRF analysis was used to determine the chemical composition of the waste rock dump, as well as the Vaal Reef. As for the XRD analysis, the composite sample and the Vaal Reef belt sample were used to determine the concentrations of the major and trace elements.

For major element analysis the milled sample ($<75\ \mu$ fraction) was roasted at $1000\ ^\circ\text{C}$ for at least 3 hours to oxidise Fe^{2+} and S and to determine the loss on ignition (L.O.I.). Glass disks were prepared by fusing 2 g roasted sample and 8 g 12-22 flux consisting of 35% LiBO_2 and 64.71% $\text{Li}_2\text{B}_4\text{O}_7$ at $1050\ ^\circ\text{C}$. For trace element analysis 12 g milled sample and 3 g Hoechst wax was mixed and pressed into a powder briquette by a hydraulic press with the applied pressure at 25 ton. The glass disks and wax pellets were analysed with a PANalytical Axios X-ray fluorescence spectrometer equipped with a 4 kW Rh tube (Cloete and Truter, 2001).

The most abundant major elements for both the composite rock dump and Vaal Reef samples are SiO_2 , 79.77 weight percentage wt % for the composite sample and 87.23 wt % for the Vaal Reef sample, and Al_2O_3 , 10.05 wt % for the composite sample and 7.54 wt % for the Vaal Reef sample (Table 2.2). $\text{Fe}_2\text{O}_3(\text{t})$ is fairly high in the composite rock dump sample with a concentration weight percentage of 3.74 wt % and 1.72 wt % in the reef sample. This is due to the ferromagnetic minerals, chlorite, mica, amphibole and pyrite. Unfortunately sulphur is not reported in the results of the analyses of the rock dump composite sample and the reef belt sample. Sulphur will be part of the LOI (loss on ignition), which includes all the volatile elements.

Table 2.2: Results of the XRF analyses of the composite rock dump and Vaal Reef belt samples

Major Elements	Major Element Concentration (wt %)	
	Composite sample	Reef belt sample
SiO ₂	79.77	87.23
TiO ₂	0.29	0.26
Al ₂ O ₃	10.05	7.54
Fe ₂ O ₃ (t)	3.74	1.72
MnO	0.064	0.012
MgO	1.25	0.17
CaO	0.77	0.09
Na ₂ O	0.13	0.16
K ₂ O	1.53	1.06
P ₂ O ₅	0.03	0.03
Cr ₂ O ₃	0.026	0.021
L.O.I	2.32	1.59
TOTAL	99.98	99.91
H ₂ O ⁻	0.11	0.95

Analyst: Cloete (2006) Council for Geoscience.

The trace element compositions do not show any significant differences between the composite sample from the rock dump and the Vaal Reef sample, except for elevated concentrations of Pb (29 ppm in the composite sample vs. 120ppm in the Vaal Reef sample), Th (7ppm in the composite sample vs. 30 ppm in the Vaal Reef sample), U (22ppm in the composite sample vs. 192ppm in the Vaal Reef sample) and Zr (107ppm in the composite sample vs. 239 ppm in the Vaal Reef sample) (Appendix 1).

2.3 Macroscopic identification of sulfide occurrence in the drill core, as well as the rock dump

Drill core from underground cover and exploration holes were used to determine the sulfide occurrence in the footwall. This was done in randomly chosen holes in the whole developed area in the mine.

Macroscopic pyrite occurs as stringers in the argillaceous quartzite and as matrix constituent in the conglomerate bands (Figures 2.2 and 2.3). In the footwall there is no consistency in the pyrite occurrence. In some conglomerate bands the pyrite is absent and in other conglomerate bands the pyrite concentration can be up to 80% in the matrix, based on visual estimation. By visual comparison the sulfide concentration is relatively much higher in the Vaal Reef (Figure 2.3) than in the footwall conglomerates (Figure 2.2). Frimmel (2005) ascribed this to hydrothermal activity close to the Vaal Reef. The Vaal Reef material, however, is not deposited on the rock dump, but transported to the plant for treatment and recovery of gold.

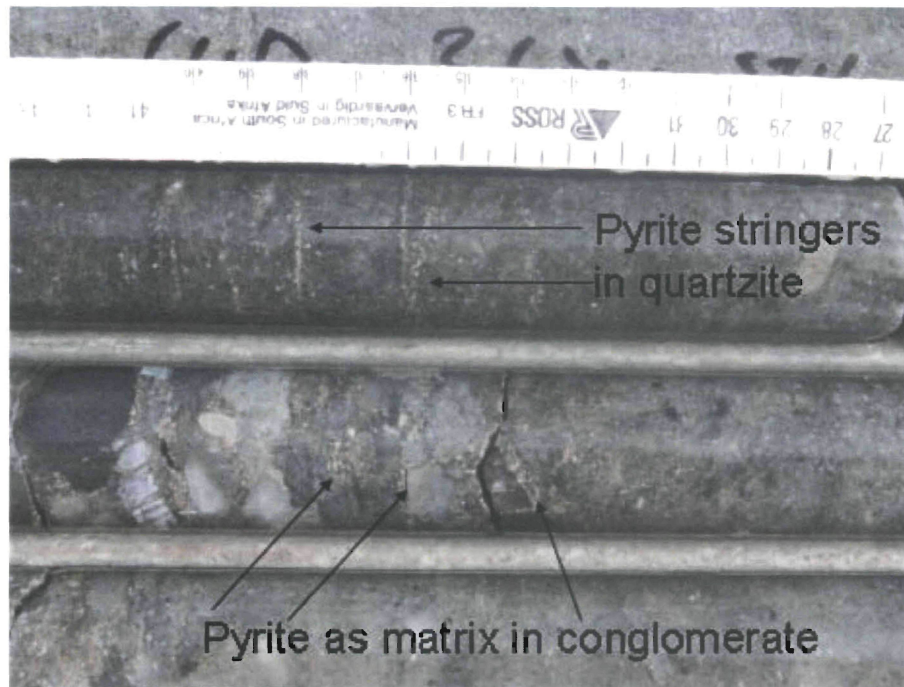


Figure 2.2: Photograph showing pyrite occurrence in the footwall



Figure 2.3: Photograph showing pyrite occurrence in the Vaal Reef

2.4 Surface water samples from the rock dump and groundwater monitoring boreholes

2.4.1 Run-off samples from the rock dump

After heavy rains small ponds of water form around the foot of the northern and north-western side of the rock dump for short periods of time (Figure 2.4). Five water samples were taken from the run-off water in two liter clean plastic containers for chemical analysis (Appendix 2). At the sampling point the cup was removed of the sample bottle and no contamination took place from the hands or environment. The sample bottle was plunged into the water and filled with water and the cup was replaced. The samples were clearly marked and sent immediately to the Midvaal Water Company for analysis.

The first of the run-off samples, KRD01, was taken in April 2006 at the end of the rainy season. This sample shows that very little pollutants exist in the water and that only sulfate (SO_4) is concentrated enough that it falls into the Class II category. This means that a person is only allowed exposure to the water for a limited period of time: for sulfate (SO_4) it is 7 years (SANS 241, 2005). Otherwise this sample is suitable for human consumption. Class I water is considered to be acceptable for lifetime consumption.

The other four samples, KRD02, KRD03, K04, and K05, were taken in the beginning of the new rainy season in August and September 2006. The assay results of these samples indicate high proportions of pollutants in the water. KRD02 have an electrical conductivity of 411 mS/m, dissolved solids 3339 mg/l, calcium (Ca) 410 mg/l, sodium (Na) 510 mg/l, sulfate (SO_4) 1036 mg/l, arsenic (As) 0.12 mg/l, manganese (Mn) 0.12 mg/l and uranium (U) 0.62 mg/l. KRD03

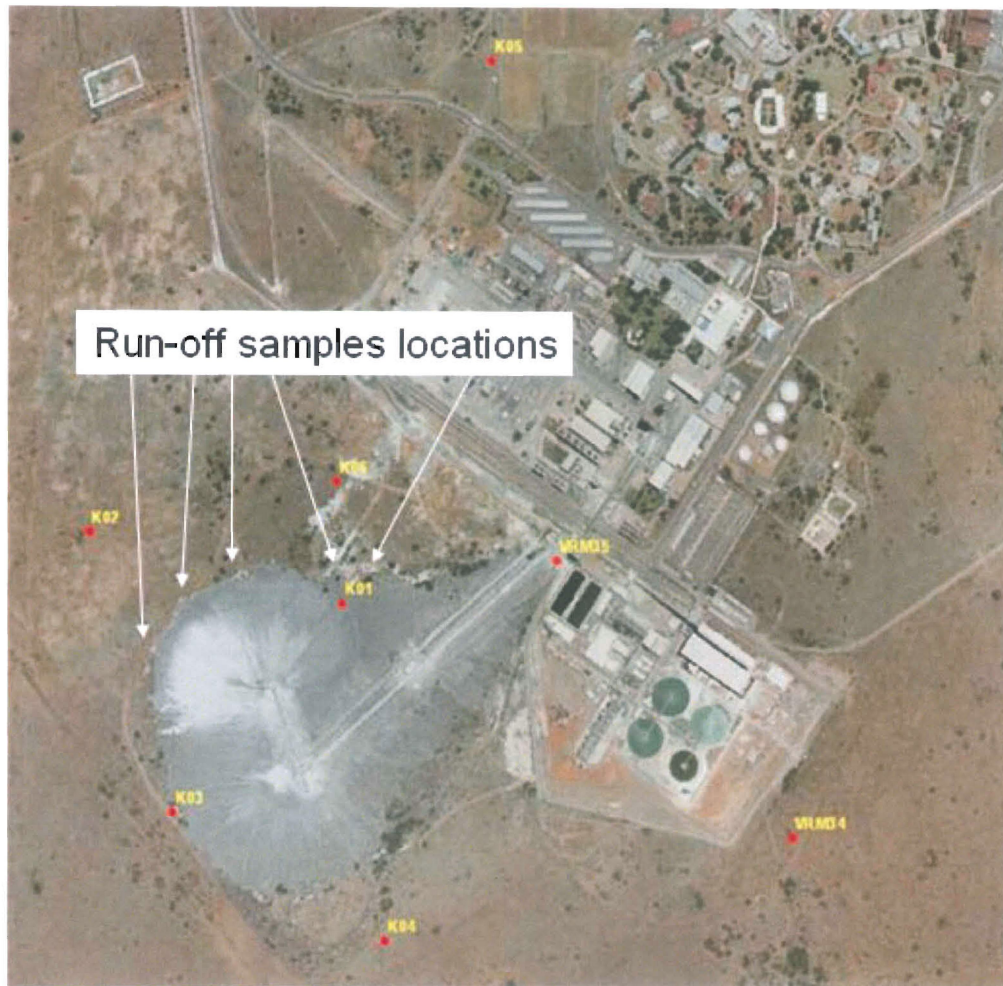


Figure 2.4: Locations of the run-off samples around the Kopanang rock dump

have the same pollutants, electrical conductivity of 381 mS/m, dissolved solids 3104 mg/l, calcium (Ca) 340 mg/l, sodium (Na) 520 mg/l, sulfate (SO_4) 737 mg/l, arsenic (As) 0.12 mg/l, manganese (Mn) 0.16 mg/l and uranium (U) 0.25 mg/l. The water from samples KRD02 and KRD03 do not fall into class II water, based on these high concentrations and are not deemed fit for consumption. KO4 have even more pollutants than KRD02 and KRD03 with, an electrical conductivity of 8840 mS/m, ammonia (N) 4.6 mg/l, calcium (Ca) 470 mg/l, chloride (Cl) 525 mg/l, nitrate (N) 19 mg/l, potassium (K) 64 mg/l, sodium (Na) 1200 mg/l, sulfate (SO_4) 822 mg/l, arsenic (As) 0.1 mg/l, manganese (Mn) 0.33 mg/l and uranium

(U) 0.63 mg/l. K05 have similar results as K04, electrical conductivity 9670 mS/m, ammonia (N) 11 mg/l, calcium (Ca) 800 mg/l, chloride (Cl) 278 mg/l, nitrate (N) 14 mg/l, potassium (K) 97 mg/l, sodium (Na) 1200 mg/l, sulfate (SO_4) 1358 mg/l, arsenic (As) 0.15 mg/l, manganese (Mn) 0.59 mg/l and uranium (U) 0.67 mg/l. These high concentrations of pollutants are more than the standard of Class II water allows and the water is not fit for consumption.

2.4.2 Groundwater monitoring boreholes

All the data from the eight groundwater monitoring boreholes around the Kopanang rock dump (Figure 1.3) are stored in a central database called Pivot and have been exported to Excel spreadsheets (Appendix 3). Borehole K01 is not in use any longer due to the transgression of the rock dump.

Boreholes K03 and VRM35 have relative high concentrations of sulfate (SO_4) and calcium (Ca), which are above the limit of 400 SO_4 mg/l and 150 Ca mg/l for Class I water (Appendix 3 (b) and (f)). It can also be noticed that there is a steady increase of sulfate (SO_4) over the past 8 years in borehole K03 (Figure 2.5). There are also three data points from borehole K05 (Appendix 3 (d)) that was measured in 2004 that are above the standard of sulfate (SO_4) and calcium (Ca) concentrations. The concentration of nitrate is also high in most of the boreholes exceeding 1000 mg/l. No heavy metal concentration, including uranium, was analysed. The rest of the data indicates the water quality is in standard, including the pH, according to SANS 241 (2005).

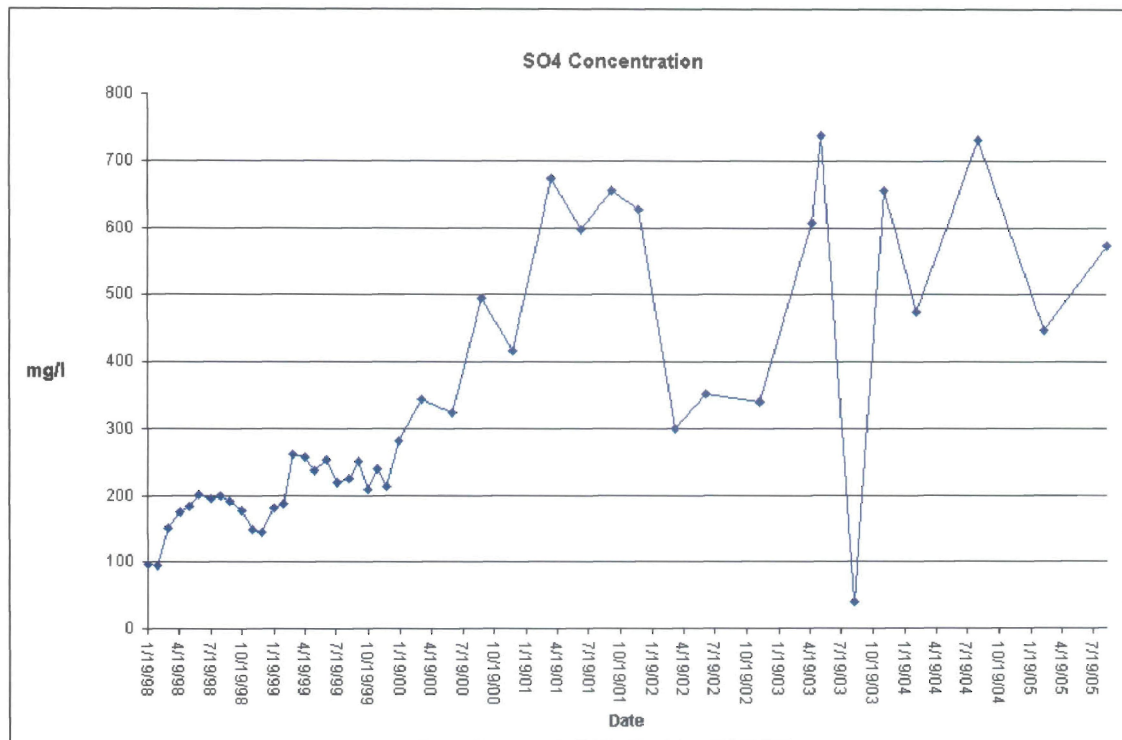


Figure 2.5: Graph of sulfate (SO₄) concentration over time in the K03 groundwater monitoring borehole, Kopanang mine.

2.5 Static tests to determine the acid generation potential of the rock dump

In the underground development process there are at least 90 areas from different levels where waste rock is produced and hoisted. The waste rock is then kept in a silo before it is transported on a waste belt and deposited on the dump.

Fourteen waste rock samples and two reef samples were taken and sent for ABA and NAG analysis. The fourteen waste rock samples were taken from the waste belt over 4 weeks to ensure that all the samples were fresh and that no oxidation took place prior to collection and that it is representative of the mine's different rock types. The samples were also taken on different dates. The reef samples

were taken on the reef belt before the reef was transported to the plant for treatment. All the samples weighed more than 5 kilograms and were put in elephant bags and clearly marked and sealed before they were transported to Waterlab in Pretoria for the static analyses.

2.5.1 Acid Base Accounting (ABA)

Static ABA testing, using the Sobek (also called the Lawrence) test is done on rock samples after it was milled. The ABA test is a static prediction test method, designed to examine the balance between the acid producing and acid consuming components of a sample. The method does not take the relative rates of acid production and consumption into account.

The acid production (AP) is calculated by assuming that all the sulfide-sulfur present converts to sulfuric acid at a production of four moles of hydrogen iron per mole of pyrite oxidised. The sulfide content of a sample is determined with a LECO furnace (induction furnace-infrared analysis). First an initial total sulfur assay is completed, then the oxidisable sulfur component is roasted off and a second LECO assay is performed to determine residual sulfur assays which are defined as the sulfide-sulfur concentration. As element S will also be oxidised and removed through the roasting process, where S is present in significant quantities it could result in an overestimation of the sulfide-sulfur content.

A fizz test is used to determine the amount of acid to be added initially in the neutralization determination; this gives the neutralising potential (NP). A small portion of the sample is placed on a watch glass or Petri dish and a drop of a 25% solution of hydrochloric acid is added. The strength of the reaction between the sample and the acid is observed and a “fizz” rating assigned based on the table below (Table 2.3).

Table 2.3: Fizz test for rock samples

Observation	Fizz Rating	Amount of 0.1N HCl to be added
No Reaction at all, no sulphide odour	1	20 (ml)
Slow bubbling, very slight reaction	2	20 (ml)
Lots of bubbling, mild reaction, sulphide odour	3	20 (ml) or 40 (ml)
Volcano effect, continual bubbling, sulphide odour	4	40 (ml)

According to Sobek, *et al.* (1978).

The neutralising potential (NP) is determined by treating a portion of the sample with excess hydrochloric acid (HCl) at ambient temperature for 24 hours. Sufficient acidity for reaction is maintained by adding acid as necessary. After the acid treatment, any unconsumed acid is titrated with a standardised base to a pH of 8.3. The calcium carbonate (CaCO_3) equivalent of the acid consumed is then calculated.

In addition to the sulfur specification, carbonate analysis, fizz test and NP determination, a paste pH test is also completed on the samples by mixing a portion of the sample with water at a low liquid to solid ratio and measuring the pH of the resulting paste.

The data obtained during the tests is then used to calculate the acid/base ratio (net NP, NP/AP ratio) and classify the sample as either potentially acid forming (Type I), intermediate (Type II) or non-acid forming (Type III), see Table 2.4.

Table 2.4: Acid Base Accounting classification

*In border line cases the sample may be classified into the more acid forming category

According to Sobek *et al.* (1978)

ROCK CLASSIFICATION		
TYPE I	Potentially Acid Forming	Total S(%) > 0.25% and AP:NP ratio 1:1 or less
TYPE II	Intermediate	Total S(%) > 0.25% and AP:NP ratio 1:3 or less
TYPE III	Non-Acid Forming	Total S(%) < 0.25% and AP:NP ratio 1:3 or greater

Table 2.5: Acid Base Accounting results for the waste rock samples (1-7 and 10 – 16) and the Vaal Reef samples (8 and 9)

Sample I.D.	Paste pH	Total S(%)	Acid Generation Potential (AP) CaCO₃ (kg/t)	Neutralisation Potential (NP) CaCO₃ (kg/t)	Netto Neutralisation Potential (NNP) CaCO₃ (kg/t)	AP:NP Ratio	Rock Type
Sample 1	8.60	0.058	1.81	19.5	17.69	1 : 10.7	III
Sample 2	8.24	0.174	5.44	7.25	1.81	1 : 1.3	II
Sample 3	9.21	0.236	7.38	32.5	25.13	1 : 4.4	III
Sample 4	8.53	0.093	2.91	8.75	5.84	1 : 3.0	III
Sample 5	8.60	0.159	4.97	6.25	1.28	1 : 1.3	II
Sample 6	7.88	0.147	4.59	5.75	1.16	1 : 1.3	II
Sample 7	8.89	0.171	5.34	7.50	2.16	1 : 1.4	III
Sample 8	8.78	0.524	16.38	2.00	-14.13	1 : 0.12	I
Sample 9	7.93	0.361	11.28	2.00	-9.28	1 : 0.2	I
Sample 10	9.07	0.07	2.19	18.25	16.06	1 : 8.3	III
Sample 11	7.74	0.227	7.09	8.50	1.41	1 : 1.2	II
Sample 12	6.95	0.08	2.50	4.00	1.50	1 : 1.6	III
Sample 13	7.54	0.196	6.13	10.50	4.38	1 : 1.7	III
Sample 14	8.20	0.172	5.38	9.75	4.38	1 : 1.8	III
Sample 15	8.29	0.199	6.22	13.5	7.28	1 : 2.2	III
Sample 16	7.64	0.086	2.69	0.00	-2.69	1 : 2.9	II

Analysis done at Waterlab, Pretoria

All the waste samples (1-7 and 10-16) from the rock dump are either Type II or Type III (Table 2.5). This means that the samples have an intermediate chance for acid forming, or have a non-acid forming potential. The Vaal Reef samples, samples 8 and 9, are Type 1. These samples have the potential to form acid. The total sulfur percentages in all the samples, including the Vaal Reef samples, are less than 1 percent.

The acid generation potential (AP) of the Vaal Reef samples are much higher than the waste rock samples, 16.38 CaCO_3 (kg/t) and 11.28 CaCO_3 (kg/t), whilst the netto neutralisation potential (NNP) is very low for the Vaal Reef samples, -14.13 CaCO_3 (kg/t) and -9.28 CaCO_3 (kg/t) (Table 2.5).

2.5.2 Net Acid Generation (NAG)

The static NAG test is also performed using samples that are milled. In the NAG test the sample reacts with hydrogen peroxide overnight (up to 24 hours) to encourage complete oxidation of all oxidisable sulfur species. The available neutralising minerals also react with the sulfide minerals. The excess hydrogen peroxide is then boiled off and the sample is allowed to cool down to room temperature.

The pH of the resulting solution is then measured before titration with sodium hydroxide to a pH of 4.5 and a pH of 7. The net result is determined to be either one of acid generation or not. The test can give neither rates of reaction, nor any information on resultant leachate quality.

From the NAG tests it is clear that most of the samples will produce some acid over time (Table 2.6). Samples 8 and 9 from the reef belt will, respectively,

produce 19.8 H₂SO₄/t and 19.4 kg H₂SO₄/t over time, which is much more than that of the rock dump samples, 0 H₂SO₄/t to 8.6 H₂SO₄/t. The highest value from the rock dump is sample 6 that will produce 8.6 kg H₂SO₄/t over time. Samples 1, 3 and 10 will produce no acid.

Table 2.6: Net Acid Generation test results for the waste rock dump samples (1-7 and 10 – 16) and the Vaal Reef samples (8 and 9)

*After reaction with 15% H₂O₂, the pH of the sample was higher than 4.5. According to the NAG method the titration figure should therefore be 0ml.

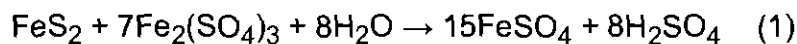
Sample ID	NAGpH : pH(H ₂ O ₂)	Volume NaOH (ml) [0.1N]	NAG kg H ₂ SO ₄ /t
			pH : 4.5
Sample #1	4.87	*0.0	*0.0
Sample #2	3.41	3.4	6.7
Sample #3	4.89	*0.0	*0.0
Sample #4	4.18	0.6	1.2
Sample #5	3.16	3.1	6.1
Sample #6	2.81	4.4	8.6
Sample #7	3.37	2.4	4.7
Sample #8	2.26	10.1	19.8
Sample #9	2.52	9.9	19.4
Sample #10	6.70	*0.0	*0.0
Sample #11	3.41	2.4	4.7
Sample #12	3.01	4.0	7.8
Sample #13	3.82	1.5	2.9
Sample #14	3.85	1.1	2.2
Sample #15	4.33	0.2	0.4
Sample #16	3.65	2.0	3.9

Analyses done at Waterlab, Pretoria

3. DISCUSSION OF THE RESULTS

3.1 Geological characterisation of the rock dump and the area surrounding the rock dump

The fact that the Kopanang rock dump is underlain by dolomites plays a vital role in the geochemistry of the water beneath and around the rock dump. From the ABA and NAG tests, it is clear that the rock dump has the potential to produce sulfuric acid over time (Tables 2.5 and 2.6). The dump is in operation since the early 1980's and from the water quality analysis, both that of surface and groundwater, there is little to no indication that the water is acidic. This can be contributed to the neutralising effect of the dolomite on any acidic water which is formed due to the oxidation of sulfide minerals in the rock dump that could produce sulfuric acid, according to the following equation.



The chemical reaction for dolomite dissolution by sulfuric acid is:



The dolomite reacts as a buffer for acidic water that could form because of the oxidation of sulfides in the rock dump. Due to this neutralising effect sulfates form as a byproduct and is one of the reasons why the sulfate concentrations is high in the borehole water around the rock dump with the pH values ranging from 6.8 to 8.7.

The waste rock dump shows a prevailing drainage system that result in high velocity of the run-off resulting in erosion of the waste dump. The high run-off water infiltrates through the prevailing bedding planes and joints (Figure 2.1) into the underlying dolomites that trigger the mobilisation of dolomitic overburden by sub-surface erosion. This erosion alters the total pressure in the underground cavities that were formed by acid rain during the geological history in the dolomite formation. The equilibrium change and the weight of the waste rock dump cause sinkhole formation (Buttrick and van Schalkwyk, 1998). No dewatering of any kind is taking place near the waste rock dump and the three small sinkholes, on average 18 cubic metres in size, occur next to the waste rock dump (Figure 3.1).



Figure 3.1: Sinkhole formation near the waste rock dump, Kopanang mine

The only surface water that occurs in this area is after heavy rains with puddles forming at the toe of the rock dump due to run-off. This implies that no soil, which

does not come into contact with the run-off water, will be contaminated with sulfates.

3.2 Total whole rock composition of the rock dump and the Vaal Reef

From the XRD and XRF analyses the difference in mineralogical and chemical composition between the reef and waste rock samples can be ascribed to the different rock types, namely the Vaal Reef, consisting mainly of quartz and pyrophyllite, while the rock dump consist mainly of quartz, chlorite and mica. Higher concentrations of gangue minerals, like mica and chlorite, are observed in the waste rock dump than in the reef samples (Table 2.1), which can be ascribed to the immaturity of the conglomerate. The high quartz content of the reef belt samples indicates the more mature conglomerates of the Vaal Reef. The elements Ca, Mg, Fe and Al are also more abundant in the waste rock dump (Table 2.2). The reason for this is that mica and chlorite are more common minerals in the rock dump than in the Vaal Reef and these minerals contain these elements. The elevated concentrations of lead (Pb), thorium (Th), uranium (U) and zircon (Zr) in the Vaal Reef are a result of the minerals uraninite and zircon in the reef conglomerate (Frimmel & Minter, 2002). Leaching of U, Th and Pb from uraninite and its alteration product coffinite has possible pollution potential. The concentrations of these elements in the run-off and groundwater (Section 3.4) will confirm or cancel this possibility out.

The influence of the whole rock composition was already highlighted in the ABA and NAG tests where the mineralogy determines the acid forming potential. The total sulfur (S) and the neutralising potential of a sample determine its classification. In order to understand the outcome of the ABA and NAG tests, the total whole rock composition must be determined, this is also emphasised by studied made by Morin and Hutt (1999).

3.3 Sulfide occurrence in the drill core and the rock dump

Most of the sulfide minerals that occur on the rock dump are pyrite that is derived from the footwall. The pyrite grains forming part of the matrix in the waste rock are disseminated and no areas exist with high pyrite concentrations, so called "hot spots". In some conglomerate bands there are high concentrations of pyrite (80% of matrix) and in other it is very low ($< 10\%$). Since all the waste rock material originating from different areas in the mine is deposited at the same time on the rock dump, the sulfide distribution on the rock dump can be seen as fairly homogeneous, which was also proven by Williams (1998). When looking at the oxidation of the pyrite, the rock dump must be seen as a whole entity rather than different segments of the rock dump that will simplify the understanding of the oxidation of pyrite process. Depending on the design and construction of the rock dump, it is, however, possible that certain waste rock dumps can have higher oxidation rates in certain areas of the rock dump than in other areas due to uneven temperatures, moisture content and grain size in the rock dump (Molson *et al.*, 2005).

3.4 Surface water samples from the rock dump and groundwater monitoring boreholes

Results from the water analyses of the run-off samples show that this water is highly contaminated with elements N, Ca, Cl, K, Na, SO_4 , As, and U (Appendix 2), except that of sample KRD01, showing elevated concentration in SO_4 and U. This can be ascribed to the fact that this sample was taken after a long and wet rainy season. The low concentrations of pollutants in the water can be explained due to the flushing out of pollutants such as sulfate (SO_4), calcium (Ca), sodium (Na) etc. during the rainy season. Similar results were observed by researchers such as: Harries and Richie, 1992; Kim and Kim, 2004; Olias *et al.*, 2004

regarding AMD. The high concentration of uranium (U) has the highest potential for a negative environmental impact (Coetzee, 2004).

The high concentration of pollutants, such as sulfate (737-1358 mg/l), calcium (340-800 mg/l), sodium (510-1200 mg/l), and others, in the rest of the run-off samples indicates that the new rainy season influenced the surface water quality dramatically. This will however decrease as the rainy season continues flushing the pollutants out. There is some correlation between the elements found in the rocks on the rock dump (Table 2.2) and the elements that are pollutants in the run-off water (Appendix 2), namely Ca, Mg, K, Na, Al and Mn. These elements occur in the rocks on the rock dump. The only trace element that was detected as a pollutant is As (Appendix 1 and 2). The most probable origin of the element As is the mineral arsenopyrite (FeAsS), a hydrothermal mineral. Due to the low quantities of As, it can be assumed that the mineral arsenopyrite occurs in low quantities and was therefore not detected during the XRD analysis. Sulfate is detected in the ABA analysis (Table 2.5) as total S% reported by Williams (1998) at the Vaal Reef operation. The high nitrate and nitrite concentrations come from the explosives that are used to break up the rock in the mining process (Labuschagne, 2005). The high concentration of Uranium (U, ranging from 0.16 mg/l up to 0.67 mg/l) in the samples is a result of the minerals uraninite and zircon.

The overall quality of the water in the monitoring boreholes is better than that of the run-off samples with only KO3 and VRM35 showing consistent high concentrations of sulfate (SO_4) and calcium (Ca). The high concentrations of sulfate (SO_4 , average of 924 mg/l) and calcium (Ca, average of 220 mg/l) in KO5 during 2004 are difficult to explain because of the large distance from this borehole to the waste rock dump (Figure 1.3), it may be that there was a different source for these pollutants closer to these boreholes during that time period. It is

important to note that all of the water samples that were tested show neutral pH with values ranging from 6.5 to 8.8.

The relative high concentrations of sulfate (SO_4) and calcium (Ca) in monitoring borehole KO3 and VRM35, which is right next to the rock dump, can be explained with reactions 1 and 2, where the sulfate is a product of the oxidation process of pyrite and the calcium is a product of the dolomite dissolution by the acid.

There can be several reasons why there are less minor pollutants, such as manganese (Mn), arsenic (As), sodium (Na), chloride (Cl) etc. in the groundwater than in the run-off samples.

- The first reason may be because of dilution of the polluted run-off water with other “clean” groundwater sources. The run-off samples are right next to the pollutant source, in this case the waste rock dump, and dilution can take place between the point where the sample for analysis was taken, up to the point where it becomes part of the aquifer system.
- Further reasoning can be that there are different water chambers or compartments underground (Buttrick & Van Schalkwyk, 1998) and that the run-off samples do not influence all these water compartments in the same way.
- The timing of sampling can be another possibility, as pollutants could have been flushed out after heavy rains.

The most probable reason, however, is that of dilution from other water sources. It is also important to note that the geohydrological characteristics of the area were not included in this study.

3.5 Static tests to determine the acid generation potential of the rock dump

3.5.1 Acid Base Accounting (ABA)

From the ABA analysis it is clear that there is a possibility for the rock dump to produce acid. There are five samples that show intermediate possibilities to form acid and nine that show no acid forming potential. The two reef samples, which were analysed for reference purposes, show the potential for acid generation. The reason for this is the general high quantity of sulfide, which is implied by the relative high %S (total), in the samples (Table 2.5), and the low NP of these samples. The waste rock samples have a smaller potential for acid forming due to the higher NP and lower sulfide content as implied by the low %S(total) values (Table 2.5). This can be ascribed to the differences in the mineral concentrations between the waste rock and the reef. The mineral species, calcite and dolomite, exists in small quantities in the waste rock that can neutralise acid. The occurrence of calcite in these samples is formed as a secondary mineral in the Witwatersrand Basin and the typical reaction with sulfuric acid is:



The CaSO_4 can form a salt deposit at the waste rock dump and can later dissolve in rain water.

Mica and chlorite also have neutralising potential under acidic conditions (Ritchie, 1994; Craw, 2000) and the XRD results (Table 2.1) show that mica and chloride are more abundant in the waste rock samples (15% and 20%) than in the reef samples (9% and 6%).

3.5.2 Net Acid Generation (NAG)

This test shows that most of the samples will produce acid (Table 2.6). Only three samples show that no acid will be formed over time, whilst the two reef samples indicate high volumes of acid forming. This again correlates with the high sulfide content in the two reef samples as implied by the relative high %S (total) and the high AP in the ABA analysis (Table 2.5).

The NAG test does not indicate an NP in a sample as in the case of ABA tests. This is one of the reasons why the ABA and NAG tests must be done together. Morin and Hutt (1999) also argued there might be around 5-15% discrepancies between these two methods. However, the NAG test indicates that there is sufficient sulfide in most of the samples to generate acid over time. Depending on the NP of that rock itself this acid may be neutralised and no acid may be introduced to the receiving environment.

3.6 Mitigation for pollutant water

The run-off water is contaminated mostly with non-metal elements and mitigation measures thereof need priority over the ground water in the area of the rock dump. Much more pollutants are concentrated in this water than in the ground water and this water can have a negative effect on human, animal and plant life if they come into contact with it. The Mineral and Petroleum Resources Development Act, No 28, of 2002 section (42) requires the mine to have an environmental management plan or environmental management programme in place for the waste rock dump (South Africa, 2002). The mitigation of the polluted run-off water must be part of this programme.

Since the contaminated water from run-off only exists for short periods of time, it will be unpractical to treat this water. The best way to mitigate this problem is to keep elements that may be negatively influenced by this water away from it. Meaning that top soils that might get into contact with this water, must be removed and stored somewhere else and that no people and livestock be allowed in the area of the waste rock dump. At this stage no fences exist around the waste rock dump and livestock from farmers can get access to the area. Fences must be erected and it will keep elements away from the contaminated water and hazardous sinkholes. These sinkholes can also be filled up with topsoil to avoid any accidents and further environmental degradation.

The groundwater must be monitored to see if any concentration of pollutants increases. If it does increase it may have a negative effect on a large scale when it introduces pollutants into the nearby Vaal River and other aquifer systems. It might be considered at that stage to pump this water out for treatment. This will also have other impacts on the area, for example, an increase in sinkhole formation which is closely connected to the drastic lowering of groundwater.

4. SYNTHESIS

4.1 Conclusions

The following conclusions were reached in accordance with the posed research questions:

4.1.1 The influence of the geological setting in the area on AMD control

The underlying dolomite acts as a buffer for any residual acid that may be introduced into the receiving environment as indicated by the neutral pH of the groundwater (Appendices 2 and 3).

4.1.2 The mineral composition and the geochemistry in the rock dump

The composite sample from the rock dump shows that quartz, chlorite and mica are the abundant mineral phases with minor amounts of pyrophyllite and illite/smectite and trace amounts of amphibole, dolomite and calcite (Table 2.1). The most abundant major elements for the composite rock dump sample are SiO_2 , 79.77 weight percentage wt % for the composite sample and 87.23 wt % for the Vaal Reef sample, and Al_2O_3 , 10.05 wt % for the composite sample and 7.54 wt % for the Vaal Reef sample (Table 2.2).

4.1.3 The sulfide occurrence and minerals in the rock dump that control AMD

Macroscopic pyrite occurs as stringers in the argillaceous quartzite and as matrix constituent in the conglomerate bands (Figures 2.2 and 2.3) and the sulphur in these minerals may form acid (Table 2.6). However, the inherent minerals in the rock dump; calcite, dolomite, mica and chlorite (Table 2.1) have the potential to neutralise the produced acid that may form.

4.1.4 Surface and groundwater quality

There is evidence of water pollution around the waste rock dump and in the groundwater adjacent to the rock dump, for example an electrical conductivity of 411 mS/m, dissolved solids 3339 mg/l, calcium (Ca) 410 mg/l, sodium (Na) 510 mg/l, sulfate (SO_4) 1036 mg/l. This polluted water has a neutral pH (6.8-7.2) with limited heavy metal concentration, namely arsenic (As) 0.12 mg/l, manganese (Mn) 0.12 mg/l and uranium (U) 0.62 mg/l.

4.1.5 Static tests indication on AMD potential

The Kopanang waste rock dump has the potential to produce acid that may cause acid mine drainage (Table 2.6).

4.1.6 Additional findings

From the study it can be concluded that the waste rock dump produce neutral mine drainage (NMD). One of the main factors causing the NMD of the waste rock dump is the mineralogical influence on the acidity of the water from the rock

dump. In this case, the neutralising effect of the inherent minerals on any acid produced.

An additional finding was that high run-off water from the rock dump infiltrates through the prevailing bedding planes and joints (Figure 2.1) into the underlying dolomites that trigger the mobilisation of dolomitic overburden by sub-surface erosion. This erosion alters the total pressure in the underground cavities that were formed by acid rain during the geological history in the dolomite formation. This equilibrium change and the weight of the waste rock dump cause sinkhole formation. This high velocity of the rain water also results in erosion channels on the waste rock dump that causes finer material to be spread out along the perimeter of the waste rock dump that increases the footprint.

4.2 Recommendations

At this stage there is no need to treat the contaminated water since the concentration of the pollutants in the groundwater are low and the run-off water exists only for short periods of time. The small sinkholes around the waste rock dump can be filled up with topsoil and the area around the waste rock dump must be fenced off.

From the AMD prediction model of Morin and Hutt (1999), it is clear that the mineralogy and geochemistry play a vital role to predict AMD. However, they did not take into consideration the role that the external geology might play in the prediction of AMD. In the case of the Kopanang waste rock dump, the geological setting has a major influence in the outcome of the AMD prediction results, namely the neutralisation of any acid that may form due to the dissolution of the dolomites and the inherent minerals, chlorite and mica, that neutralise any sulfuric acid that form. Morin and Hutt (1999) also see the AMD prediction model

as a whole and do not see it necessary to divide the model into different phases. The XRD, XRF, ABA and NAG results from the Kopanang waste rock dump study indicated that there is no need for expensive and time consuming analyses, such as kinetic tests at this stage.

For these reasons the model of Morin and Hutt (1999) can be modified and set up into two different phases (Figure 4.1). Phase one consists of the relatively inexpensive analyses, namely: geological setting, on-site monitoring data, mineralogy, static tests and total whole rock analyses. In this study the total costs for these analyses were about R35 000. Also, this phase is not time consuming, and can give a good indication if further analyses are required to define the AMD potential. The geological setting is also added to determine if it has any AMD potential influence.

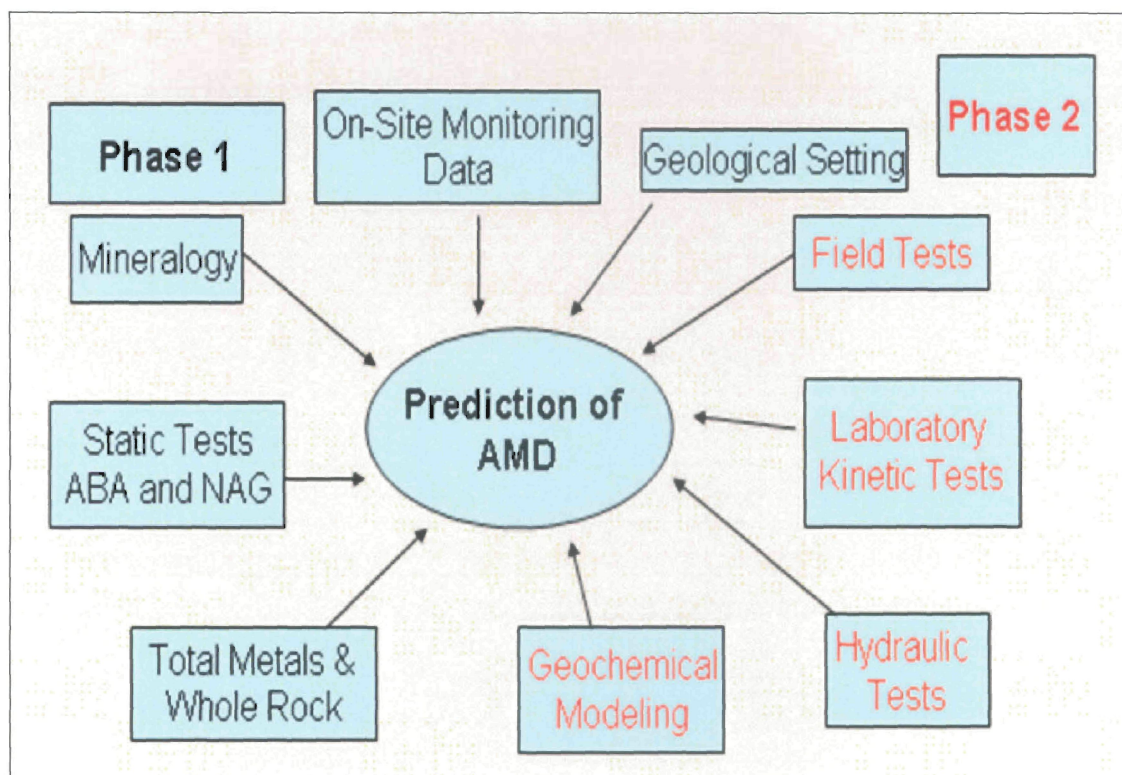


Figure 4.1: Modified model for the prediction of AMD potential (after Morin & Hutt, 1999)

Phase two, the more advanced, expensive and time consuming phase includes the following analyses: geochemical modeling, hydraulic tests, laboratory kinetic tests and field tests. Some of these analyses like the kinetic tests can take months to complete and can cost more than ten fold than that of the analyses used in phase one. However, this phase is very important to define and quantify AMD and will help to mitigate AMD. Specially, when geochemical modeling is done and pollution plumes can be visualized.

It is important to investigate the AMD potential of all the different waste rock dumps and slime dams from the mining industry since AMD is site specific and to conclude what their influence are on the environment. All this mining waste must be categorised according to their AMD activity with their reclamation or rehabilitation potential in order to mitigate their pollution. At the current high gold price (\$900 - \$1 000 per ounce), more of this mining waste will become more feasible to reclaim and also more finance must be made available by the different mining houses to exert AMD studies.

A question that needs to be investigated is what influence the time period has on the AMD model, since the older waste rock dump of the South Deep gold mine indicates AMD and the younger waste rock dump indicates no AMD and their mineralogical composition is more or less the same.

The extent of the uranium (U) concentration in the surface and groundwater must be investigated and heavy metal concentrations in the monitoring boreholes must be included in the water analysis. This study gives evidence that waste rock dumps from gold mines add as a potential source for uranium contamination in groundwater.

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APPENDICES

Appendix 1: XRF analysis of the trace elements in the composite rock dump and Vaal Reef belt samples. Analyst: Cloete, 2006, Council for Geoscience.

Trace Elements	Trace Element Concentration (ppm)	
	Composite sample	Reef belt sample
As	39	70
Ba	368	239
Bi	<3	<3
Br	<2	<2
Ce	52	76
Co	15	18
Cr	168	129
Cs	<5	<5
Cu	21	17
Ga	11	9
Ge	<1	<1
Hf	<3	5
La	29	43
Mo	<2	<2
Nb	4	6
Nd	21	32
Ni	69	43
Pb	29	120
Rb	55	41
Sc	8	3
Se	<1	<1
Sm	<10	<10
Sr	47	38
Ta	<2	<2
Th	7	30
U	22	192
V	45	21
W	<3	<3
Y	11	17
Yb	<2	<2
Zn	46	55
Zr	107	239

Appendix 2: Water analysis of the five surface / run-off water samples (KRD01, KRD02, KRD03, K04 and K05) taken after heavy rains. Analyst: J.W.D. Pietersen, Midvaal Water Company.

(a) KRD01

Sample number				3345
Identification on container				KRD 01 Rock Dump
Determinand	Units	Class II (max. allowable for limited duration)	Method number	
Physical and organoleptic requirements				
Electrical conductivity at 25°C (aesthetic)	mS/m	150 - 370	WL 2	109
pH value at 25°C (aesthetic)	pH units	4.0 - 10.0	WL 1	8.7
Chemical requirements - macro-determinand				
Ammonia (operational)	mg/l N	1.0 - 2.0	GL 2 (GL1)	0.8
Calcium (aesthetic/operational)	mg/l Ca	150 - 300	ICP 1	130
Chloride (aesthetic)	mg/l Cl	200 - 600	WL 9(WL9A)	42
Fluoride (health)	mg/l F	1.0 - 1.5	GL 4	0.2
Magnesium (aesthetic/health)	mg/l Mg	70 - 100	ICP 1	9
Nitrate and nitrite (health)	mg/l N	10 - 20	GL 3 (GL5)	31
Potassium (operational/health)	mg/l K	50 - 100	ICP 1	16
Sodium (health)	mg/l Na	200 - 400	ICP 1	100
Sulphate (aesthetic/health)	mg/l SO ₄	400 - 600	WL 10	257
Zinc	mg/l Zn	5.0 - 10	ICP 1	<0.01
Total Alkalinity	mg/l CaCO ₃		WL8(WL8A)	45
Chemical requirements - micro-determinand				
Aluminium (health)	mg/l Al	0.3 - 0.5	ICP 1	0.20
Arsenic (health)	mg/l As	0.01 - 0.05	ICP 1	0.05
Cadmium (health)	mg/l Cd	0.005 - 0.01	ICP 1	<0.001
Total Chromium (health)	mg/l Cr	0.1 - 0.5	ICP 1	<0.01
Copper (health)	mg/l Cu	1.0 - 2.0	ICP 1	0.01
Cyanide (free)	mg/l CN		N 3	<0.005
Iron (aesthetic/operational)	mg/l Fe	0.20 - 2.0	ICP 1	<0.01
Lead (health)	mg/l Pb	0.02 - 0.05	ICP 1	<0.006
Manganese (aesthetic)	mg/l Mn	0.10 - 1.0	ICP 1	0.02
Uranium	mg/l U		ICP 1	0.16
Gold	mg/l Au		ICP 1	<0.01

Appendix 2 (cont.): Water analysis of the five surface / run-off water samples (KRD01, KRD02, KRD03, K04 and K05) taken after heavy rains. Analyst: J.W.D. Pietersen, Midvaal Water Company.

(b) KRD02 and KRD03.

Sample number				5027	5028
Identification on container				KRD 02	KRD 03
Determinand	Units	Class I (recommended operational)	Method number		
Physical and organoleptic requirements					
Electrical conductivity at 25°C (aesthetic)	mS/m	< 150	WL 2	411	381
Dissolved solids at 180°C (aesthetic)	mg/l	< 1000	WL 6	3339	3104
pH value at 25°C (aesthetic)	pH units	5,0 – 9,5	WL 1	7,2	7,0
Chemical requirements - macro-determinand					
Ammonia (operational)	mg/l N	< 1,0	GL 2 (GL1)	1,8	1,3
Calcium (aesthetic/operational)	mg/l Ca	< 150	ICP 1	410	340
Chloride (aesthetic)	mg/l Cl	< 200	WL 9(WL9A)	129	122
Fluoride (health)	mg/l F	< 1,0	GL 4	0,2	0,2
Magnesium (aesthetic/health)	mg/l Mg	< 70	ICP 1	33	25
Nitrate and nitrite (health)	mg/l N	< 10	GL 3 (GL5)	6,0	9,4
Potassium (operational/health)	mg/l K	< 50	ICP 1	32	30
Sodium (health)	mg/l Na	< 200	ICP 1	510	520
Sulphate (aesthetic/health)	mg/l SO ₄	< 400	WL 10	1036	737
Zinc	mg/l Zn	< 5,0	ICP 1	<0,01	<0,01
Chemical requirements - micro-determinand					
Aluminium (health)	mg/l Al	< 0,3	ICP 1	<0,01	<0,01
Arsenic (health)	mg/l As	< 0,01	ICP 1	0,12	0,12
Cadmium (health)	mg/l Cd	< 0,005	ICP 1	<0,001	<0,001
Chromium	mg/l Cr	< 0,10	ICP 1	<0,01	<0,01
Copper (health)	mg/l Cu	< 1,0	ICP 1	<0,002	<0,002
Iron (aesthetic/operational)	mg/l Fe	< 0,20	ICP 1	0,01	<0,01
Lead (health)	mg/l Pb	< 0,02	ICP 1	<0,006	<0,006
Manganese (aesthetic)	mg/l Mn	< 0,10	ICP 1	0,12	0,16
Mercury (health)	mg/l Hg	< 0,001	ICP 1	<0,001	<0,001
Selenium (health)	mg/l Se	< 0,02	ICP 1	<0,01	<0,01
Cyanide	mg/l CN		N 4	<0,005	<0,005
Gold	mg/l Au		ICP 1	0,01	<0,01
Total Alkalinity	mg/l CaCO ₃		WL 8(WL8A)	39	26
Uranium	mg/l U		ICP 1	0,62	0,25

Appendix 2 (cont.): Water analysis of the five surface / run-off water samples (KRD01, KRD02, KRD03, K04 and K05) taken after heavy rains. Analyst: J.W.D. Pietersen, Midvaal Water Company.

(c) K04 and K05.

Sample number				6640	6641
Identification on container				K04	K05
Determinand	Units	Class I (recommended operational)	Method number		
Physical and organoleptic requirements					
Electrical conductivity at 25°C (aesthetic)	mS/m	< 150	WL 2	8,840	9,670
pH value at 25°C (aesthetic)	pH units	5,0 – 9,5	WL 1	6,8	6,9
Chemical requirements - macro-determinand					
Ammonia (operational)	mg/l N	< 1,0	GL 2 (GL1)	4,6	11
Calcium (aesthetic/operational)	mg/l Ca	< 150	ICP 1	470	800
Chloride (aesthetic)	mg/l Cl	< 200	WL 9(WL9A)	525	278
Fluoride (health)	mg/l F	< 1,0	GL 4	0,3	0,5
Magnesium (aesthetic/health)	mg/l Mg	< 70	ICP 1	67	78
Nitrate and nitrite (health)	mg/l N	< 10	GL 3 (GL5)	19	14
Potassium (operational/health)	mg/l K	< 50	ICP 1	64	97
Sodium (health)	mg/l Na	< 200	ICP 1	1,200	1,200
Sulphate (aesthetic/health)	mg/l SO ₄	< 400	WL 10	822	1,358
Zinc	mg/l Zn	< 5,0	ICP 1	<0,01	<0,01
Chemical requirements - micro-determinand					
Aluminium (health)	mg/l Al	<0,3	ICP 1	0,13	0,15
Arsenic (health)	mg/l As	<0,01	ICP 1	0,10	0,15
Cadmium (health)	mg/l Cd	<0,005	ICP 1	0,003	0,004
Chromium	mg/l Cr	<0,10	ICP 1	<0,01	<0,01
Copper (health)	mg/l Cu	<1,0	ICP 1	0,007	0,003
Iron (aesthetic/operational)	mg/l Fe	<0,20	ICP 1	<0,01	<0,01
Lead (health)	mg/l Pb	<0,02	ICP 1	<0,006	<0,006
Manganese (aesthetic)	mg/l Mn	<0,10	ICP 1	0,33	0,59
Mercury (health)	mg/l Hg	<0,001	ICP 1		
Selenium (health)	mg/l Se	<0,02	ICP 1		
Cyanide	mg/l CN		N 4	<0,005	<0,005
Gold	mg/l Au		ICP 1		
Total Alkalinity	mg/l CaCO ₃		WL8(WL8A)	55	113
Uranium	mg/l U		ICP 1	0,63	0,67

Appendix 3: Ground water analyses of the monitoring boreholes (K02, K03, K04, K05, K06, VRM34, and VRM35) retrieved from the central database Pivot.

(a) Borehole K02

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	DATEMEAS	pH	EC	TDS	SS	CN_Tot	Cl	NO3	SO4	Fe	Mn	Ca	Mg	Na	K	TALK
2	19/01/1998 00:00	7.5	70	118	6		20		30	0.25	0.2	43	5	1	0.5	40
3	16/02/1998 00:00	7.4	66	345	35		22	47	32	0.5	0.5	36	51	24	0	138
4	16/03/1998 00:00	7.6	72	467	28		22	90	21	0.5	0.4	73	30	1	1	300
5	20/04/1998 00:00	7.6	69	400	16		12	6	7	0.5	0.4	67	23	11	1	325
6	18/05/1998 00:00	7.2	62	350	482	0.5	12	19	18	0.5	0.4	70	41	4	1	296
7	15/06/1998 00:00	7	78	305	245	0.5	12	49	19	0.5	0.4	70	39	6	1	300
8	20/07/1998 00:00	7.3	70	348	10	0.5	14	5	26	0.5	0.4	70	39	6	1	291
9	17/08/1998 00:00	7.2	66	308	20	0.5	12	26	26	0.5	0.4	83	62	6	1	328
10	14/09/1998 00:00	7.1	67	351	140	0.5	12	26	19	0.5	0.4	77	40	6	1	295
11	19/10/1998 00:00	7.4	62	350	99		12	26	19	0.5	0.4	99	53	5	1	304
12	16/11/1998 00:00	7.6	64	398	115	0.5	12	25	12	0.5	0.4	122	47	5	1	306
13	14/12/1998 00:00	7.4	64	328	279	0.5	12	23	19	0.8	0.8	128	70	5	1	304
14	18/01/1999 00:00	6.7	66	338	116	0.5	14	19	12	0.6	0.4	79	58	5	1	312
15	16/02/1999 00:00	7.9	64	334	129	0.5	12	20	13	0.5	0.4	87	47	4	1	305
16	16/03/1999 00:00	7.8	63	295	633	0.5	10	21	4	0.9	0.5	97	88	4	1	365
17	20/04/1999 00:00	8.5	61	310	711	0.5	14	18	9	1.3	0.6	193	116	3	1	447
18	17/05/1999 00:00	7.7	63	325	184	0.5	16	21	16	0.9	0.5	84	58	13	1	318
19	21/06/1999 00:00	8	62	338	239	0.5	16	19	12	0.5	0.4	89	47	4	1	298
20	19/07/1999 00:00	7.8	68	310	27	0.5	20	1	11	0.5	0.4	114	42	3	2	320
21	23/08/1999 00:00	7.7	79	438	40	0.5	18	19	17	0.5	0.4	128	43	17	1	325
22	20/09/1999 00:00	7.7	66	434	722	0.5	20	23	32	1	0.8	198	104	5	1	301
23	18/10/1999 00:00	7.5	73	396	235	0.5	16	16	35	0.5	0.4	133	88	7	1	329
24	15/11/1999 00:00	7.7	84	253	140	0.5	24	24	26	0.7	0.4	138	78	4	0.7	323
25	13/12/1999 00:00	7.4	71	318	236	0.5	10	22	5	0.5	0.4	74	41	4	1	294
26	17/01/2000 00:00	7.6	80	344	68	0.5	10	25	9	0.5	0.4	70	37	4	2	304
27	19/06/2000 00:00	7.7	65	269	220	0.5	12	23	19	0.5	0.4	78	39	4	1	298
28	11/12/2000 00:00	7.4	76	275	85	0.5	10	23	13	0.5	0.4	90	43	5	1	308
29	26/06/2001 00:00	7.2	70	326	266	0.5	10	25	7	0.5	0.4	93	49	4	1	306
30	10/12/2001 00:00	7.5	58	323	84	0.5	14	25	9	0.5	0.4	68	40	4	1	316
31	01/05/2002 00:00	7.6	57.4	339	114	0.5	18	51	21	0.5	0.5	141	41	1	6	320
32	24/06/2002 00:00	7.4	67	259.3	8	0.5	8.4	35.8	54	0.5	0.4	84	52	5	2	156
33	26/05/2003 00:00	7.3	69	345	31	0.5	10	21	40	0.5	0.4	56	39	6	2	300
34	24/11/2003 00:00	7.5	59	344	43	0.5	16	20	13	0.5	0.4	59	39	13	1	295
35	25/05/2004 00:00	7.3	72	346	28	0.5	20	35	28	0.5	0.4	68	44	11	0.8	300
36	22/11/2004 00:00	7	62	366	85	0.5	16		35	0.5	0.4	67	40	11	1	285
37	23/05/2005 00:00	7.4	69	358	434	0.5	18	36	37	1	0	79	43	10	1	318
38	05/12/2005 00:00	7.1	66	344	5	0.5	10	25	190	0.5	0.4	36	39	32		270
39	01/06/2006 00:00	8.2	66	461	16		22	46	18	0.5	0.4	71	38	33	0.4	285

Appendix 3: Ground water analyses of the monitoring boreholes (K02, K03, K04, K05, K06, VRM34, and VRM35) retrieved from the central database Pivot.

(b) Borehole K03

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	DATEMEAS	pH	EC	TDS	SS	CN_Tot	Cl	NO3	SO4	Fe	Mn	Ca	Mg	Na	K	TALK
2	19/01/1998 00:00	7.2	175	1518	59	0.5	78	692	96	0.5	0.4	151	77	101	1	160
3	16/02/1998 00:00	7.1	222	1687	27	0.5	82	1082	95	0.5	0.4	164	88	140	1	146
4	16/03/1998 00:00	7.2	272	1907	210	0.5	96	185	151	0.5	0.4	196	103	205	1	130
5	20/04/1998 00:00	7.2	276	1966	215	0.5	108	1288	174	0.5	0.4	203	108	230	2	142
6	18/05/1998 00:00	7.1	265	2038	39	0.5	106	1270	182	0.5	0.4	225	114	240	2	122
7	15/06/1998 00:00	7.4	270	2300	22		104	132	202	0.5	0.4	210	110	242	2	123
8	20/07/1998 00:00	7.2	288	2304	438	0.5	108	1233	194	0.5	0.4	210	105	225	1	132
9	17/08/1998 00:00	7.4	275	1870	22	0.5	104	1236	198	0.5	0.4	206	102	230	1	132
10	14/09/1998 00:00	6.7	267	2093	12	0.5	100	1120	190	0.5	0.4	346	118	246	2	142
11	19/10/1998 00:00	7.8	249	2128	31	0.5	94	1065	177	0.5	0.4	178	93	212	1	151
12	16/11/1998 00:00	7.7	230	2110	112	0.5	80	847	148	0.5	0.4	164	95	175	2	148
13	14/12/1998 00:00	7.6	221	1720	134	0.5	94	1062	145	0.5	0.4	155	94	278	1	164
14	18/01/1999 00:00	7.8	219	2015	146	0.5	82	1005	181	0.5	0.4	151	100	156	1	182
15	16/02/1999 00:00	8.1	234	1964	26	0.5	86	625	187	0.5	0.4	174	98	214	1	170
16	16/03/1999 00:00	7.6	247	2130	10	0.5	88	695	262	0.5	0.4	191	92	251	2	146
17	20/04/1999 00:00	7.5	274	1006	33	0.5	76	165	258	0.5	0.4	164	63	118	1	148
18	17/05/1999 00:00	7.5	237	1762	93	0.5	80	108	237	0.5	0.4	187	95	249	2	150
19	21/06/1999 00:00	7.5	237	2044	32	0.5	88	1014	254	0.5	0.4	170	109	208	1	162
20	19/07/1999 00:00	7.5	233	1718	61	0.5	94	1112	219	0.5	0.4	185	103	252	1	172
21	23/08/1999 00:00	7.4	233	1810	55	0.5	80	940	226	0.5	0.4	200	112	179	1	158
22	20/09/1999 00:00	7.5	253	2277	37	0.5	98	238	252	0.5	0.4	197	96	215	2	154
23	18/10/1999 00:00	7.6	200	1842	80	0.5	78	25	209	0.5	0.4	201	102	190	1	164
24	15/11/1999 00:00	7.4	221	2148	53	0.5	108	1141	240	0.5	0.4	214	98	216	2	155
25	13/12/1999 00:00	6.8	222	1925	74	0.5	92	1020	213	0.5	0.4	196	104	195	1	163
26	17/01/2000 00:00	7.6	222	2241	56	0.5	100	1174	282	0.5	0.4	189	112	229	2	158
27	20/03/2000 00:00	8.2	194	2470	20	0.5	92	347	343	0.5	0.4	206	127	324	4	124
28	19/06/2000 00:00	7.7	171.9	1874	53	0.5	70	805	323	0.5	0.4	249	99	149	4	187
29	11/09/2000 00:00	7.8	290	2386	26	0.5	86	1171	494	0.5	0.4	202	130	325	2	148
30	11/12/2000 14:23	7.7	296	1383	9	0.5	10	22	417	1	0.4	178	117	340	1	73
31	02/04/2001 00:00	7.3	290	1592	85	0.5	78	435	673	0.5	0.4	208	82	262	2	95
32	26/06/2001 00:00	7.9	209	1827	102	0.5	52	609	596	0.5	0.4	165	97	225	2	150
33	25/09/2001 00:00	7.3	238	1985	24	0.5	56	766	656	0.5	0.4	186	108	238	2	83
34	10/12/2001 00:00	7.5	201	1745	45	0.5	48	523	628	0.5	0.4	165	92	234	2	135
35	27/03/2002 00:00	8.2	115	850	116	0.5	26	190	299	0.5	0.4	98	49	185	1	140
36	24/06/2002 00:00	7.5	135	1070	59	0.5	30		352	0.5	0.4	112	64	128	2	140
37	25/11/2002 00:00	7.5	155	1166	9	0.5	36	365	340	0.5	0.4	125	70	121	1	170
38	29/04/2003 00:00	7.5	196	1648	8	0.5	34	340	607	0.5	0.4	153	94	170	1	185
39	26/05/2003 00:00	7.4	194	1592	26	0.5	28	366	738	1	0	189	94	168	1	156
40	25/08/2003 00:00	7.9	360	1380	32	0.5	20	231	41	0.5	0.4	161	76	126	10	175
41	24/11/2003 00:00	7.3	197	1494	8	0.5	32	222	656	0.5	0.4	167	91	229		140
42	23/02/2004 00:00	7.1	354	2980	668		276	99	475	0.5	0.4	379	178		1.6	360
43	23/08/2004 00:00	7.4	188	1433	14		28	351	731	0.5	0.4	161	77	107	1.2	165
44	28/02/2005 00:00	7.7	141	1042	24		55	69	446	0.5	0.4	117	68	69	1	235
45	29/08/2005 00:00	8	149	1239	10		16	81	572	0.5	0.4	115	72	132	2	185

Appendix 3: Ground water analyses of the monitoring boreholes (K02, K03, K04, K05, K06, VRM34, and VRM35) retrieved from the central database Pivot.

(c) Borehole K04

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	DATEMEAS	pH	EC	TDS	SS	CN_Tot	Cl	NO3	SO4	Fe	Mn	Ca	Mg	Na	K	TALK
2	19/01/1998 00:00	7.1	117	779	19	0.5	56	136	184	0.5	0.4	108	60	67	1	300
3	16/02/1998 00:00	7.1	125	743	21	0.5	52	145	173	0.5	0.4	105	58	69	1	280
4	16/03/1998 00:00	7.1	130	821	60	0.5	60	26	226	0.5	0.4	110	61	77	1	275
5	20/04/1998 00:00	7.2	126	793	91	0.5	64	118	200	0.5	0.4	109	66	72	1	324
6	18/05/1998 00:00	7.1	123	841	71	0.5	66	142	219	0.5	0.5	124	64	78	1	313
7	15/06/1998 00:00	7.2	126	860	99	0.5	67	133	204	0.5	0.4	125	67	74	1	294
8	20/07/1998 00:00	7.6	144	984	48	0.5	82	143	264	0.5	0.4	161	66	95	1	319
9	17/08/1998 00:00	7.3	146	915	35	0.5	74	148	263	0.5	0.4	131	67	102	1	316
10	14/09/1998 00:00	7.1	148	960	18	0.5	80	125	270	0.6	0.6	114	75	104	1	319
11	19/10/1998 00:00	7.6	151	1028	31	0.5	74	141	289	0.5	0.4	125	64	104	1	320
12	16/11/1998 00:00	7.5	143	949	55	0.5	70	131	267	0.5	0.4	121	69	94	1	310
13	14/12/1998 00:00	7.5	139	904	51	0.5	68	145	249	0.6	0.4	126	70	97	1	304
14	18/01/1999 00:00	7.5	139	894	89	0.5	74	135	251	0.5	1.5	103	66	93	1	297
15	16/02/1999 00:00	7.8	136	91	66	0.5	74	146	245	0.5	0.4	120	64	115	1	298
16	16/03/1999 00:00	7.6	129	884	6	0.5	68	109	250	0.5	0.4	128	63	93	1	308
17	20/04/1999 00:00	7.7	138	2198	25	0.5	90	636	263	0.5	0.4	242	93	270	1	303
18	17/05/1999 00:00	7.5	140	1006	21	0.5	74	42	260	0.5	0.4	127	65	106	1	290
19	21/06/1999 00:00	7.4	141	978	16	0.5	70	142	267	0.5	0.4	104	79	82	1	289
20	19/07/1999 00:00	7.5	142	908	22	0.5	80	425	257	0.5	0.4	118	70	111	0.7	290
21	23/08/1999 00:00	7.4	142	894	38	0.5	72	135	258	0.5	0.4	120	80	87	1	272
22	20/09/1999 00:00	7.4	147	1052	28	0.5	86	138	300	0.5	0.4	131	64	109	2	322
23	18/10/1999 00:00	7.5	137	944	34	0.5	78	120	279	0.5	0.4	145	75	107	1	306
24	15/11/1999 00:00	7.4	137	1006	93	0.5	90	137	301	0.5	0.5	134	61	116	1	321
25	13/12/1999 00:00	7.3	138	973	14	0.5	82	120	277	0.5	0.4	137	73	113	1	311
26	17/01/2000 00:00	7.4	122	986	35	0.5	86	134	295	0.5	0.4	117	68	104	1	310
27	20/03/2000 00:00	7.9	114	908	14	0.5	76	89	248	0.5	0.4	121	74	120	2	308
28	19/06/2000 00:00	7.7	66	408	7	0.5	20	66	84	0.5	0.4	100	40	79	2	225
29	11/09/2000 00:00	7.5	83	625	19	0.5	56	110	157	0.5	0.4	83	54	73	1	268
30	11/12/2000 00:00	7.7	86	545	12	0.5	28	82	125	0.5	0.4	64	46	50	1	130
31	02/04/2001 00:00	7.3	96	704	50	0.5	36	32	189	0.5	0.5	83	37	51	1	300
32	26/06/2001 00:00	8	71	434	47	0.5	20	25	195	0.5	0.4	66	40	35	1	230
33	25/09/2001 00:00	7.4	83	525	44	0.5	24	74	125	0.5	0.4	53	37	42	1	240
34	10/12/2001 00:00	7.5	48	305	40	0.5	10	29	146	0.5	0.4	44	29	14	1	175
35	27/03/2002 00:00	8.2	82	526	31	0.5	28	60	140	0.5	0.4	53	42	45	1	230
36	26/05/2003 00:00	7.2	135	880	7	0.5	54	121	317	1	0	129	70	91	2	292
37	24/11/2003 00:00	7	125	843	10	0.5	40	116	252	0.5	0.4	53	39	61		140
38	25/05/2004 00:00	7.9	80	604	25		59	71	119	0.5	0.4	70	37	65	0.2	125
39	22/11/2004 00:00	7.6	76	475	43		20	42	144	0.6	0.5	40	38	55	0.46	112
40	23/05/2005 00:00	8.1	45	277	17		14	18	39	0.5	0.4	41	19	2	1	190
41	05/12/2005 00:00	7.7	47	290	13		10	26	42	0.5	0.4	46	29	11	2	185
42	01/06/2006 00:00	7.7	40	240	2		8		22	0.25	0.2	8	3	1	0.5	20

Appendix 3: Ground water analyses of the monitoring boreholes (K02, K03, K04, K05, K06, VRM34, and VRM35) retrieved from the central database Pivot.

(d) Borehole K05

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	DATEMEAS	pH	EC	TDS	SS	CN Tot	Cl	NO3	SO4	Fe	Mn	Ca	Mg	Na	K	TALK
2	19/01/1998 00:00	7.1	125	848	10	0.5	94	96	277	0.5	0.4	122	59	76	4	218
3	16/02/1998 00:00	7.1	144	780	5	0.5	82	104	290	0.5	0.4	116	57	83	4	218
4	16/03/1998 00:00	7.1	136	854	11	0.5	88	65	286	0.5	0.4	115	55	81	4	190
5	20/04/1998 00:00	7.2	135	828	12	0.5	90	98	299	0.5	0.4	120	59	75	5	230
6	18/05/1998 00:00	7.1	128	839	10	0.5	90	78	284	0.5	0.4	128	58	76	4	205
7	15/06/1998 00:00	7	124	850	2	0.5	84	80	277	0.5	0.4	123	57	71	4	214
8	20/07/1998 00:00	7.5	127	836	7	0.5	84	19	277	0.5	0.4	141	55	73	4	216
9	17/08/1998 00:00	7.3	128	804	5	0.5	78	86	294	0.5	0.4	119	56	71	4	216
10	14/09/1998 00:00	7.4	127	810	3	0.5	84	72	286	0.5	0.4	102	62	72	4	227
11	19/10/1998 00:00	7.5	124	812	17	0.5	82	83	268	0.5	0.4	107	53	65	4	222
12	16/11/1998 00:00	7.5	125	850	8	0.5	98	74	269	0.5	0.4	109	58	70	4	227
13	14/12/1998 00:00	7.5	122	757	72	0.5	90	99	244	0.5	0.4	101	55	66	5	230
14	18/01/1999 00:00	7.6	128	812	10	0.5	92	93	251	0.5	0.4	91	62	45	3	237
15	16/02/1999 00:00	7.7	123	829	22	0.5	102	64	251	0.5	0.4	121	60	74	3	208
16	16/03/1999 00:00	7.7	116	774	6	0.5	104	22	248	0.5	0.4	123	54	64	3	200
17	20/04/1999 00:00	7.7	63	418	16	0.5	14	47	212	0.5	0.4	109	36	19	1	306
18	17/05/1999 00:00	7.6	118	878	37	0.5	92	1	221	0.5	0.4	115	57	71	3	217
19	21/06/1999 00:00	7.4	142	882	6	0.5	104	67	284	0.5	0.4	107	49	71	3	230
20	19/07/1999 00:00	8	94	212	4	0.5	28	28	27	0.5	0.4	93	47	35	0.7	297
21	23/08/1999 00:00	7.4	137	780	24	0.5	84	69	246	0.5	0.4	126	64	60	2	228
22	20/09/1999 00:00	7.5	140	783	11	0.5	88	45	243	0.5	0.4	110	53	62	3	226
23	18/10/1999 00:00	7.5	129	795	14	0.5	94	80	293	0.5	0.4	138	63	78	3	226
24	15/11/1999 00:00	7.2	116	746	32	0.5	98	80	266	0.5	0.4	121	53	68	3	230
25	13/12/1999 00:00	7.1	116	802	5	0.5	86	80	227	0.5	0.4	112	59	64	3	232
26	11/12/2000 00:00	8	114	856	4	0.5	100	96	319	0.5	0.4	72	58	89	5	59
27	26/06/2001 00:00	7.9	126	866	6	0.5	88	79	276	0.5	0.4	114	61	70	4	230
28	25/09/2001 00:00	7.4	120	1335	8	0.5	86	94	265	0.5	0.4	82	62	69	3	223
29	29/10/2001 00:00	7.1	113	804	3	0.5	84	72	250	0.5	0.4	93	55	78	3	220
30	10/12/2001 00:00	7.3	128	906	1	0.5	88	77	309	0.5	0.4	107	62	90	4	210
31	27/03/2002 00:00	8.2	100	697	16	0.5	68	75	230	0.5	0.4	91	43	56	5	175
32	24/06/2002 00:00	7	104	732	37	0.5	64		238	0.5	0.4	104	51	66	20	200
33	25/11/2002 00:00	7.4	123	854	14	0.5	78	82	279	0.5	0.4	118	56	61	4	205
34	29/04/2003 00:00	7.2	126	926	16	0.5	78	81	285	0.5	0.4	102	61	70	15	225
35	25/08/2003 00:00	8.1	172	869	7	0.5	22	57	59	0.5	0.4	105	56	46	6	180
36	25/02/2004 00:00	7.8	110	680	1		70	34	199	0.5	0.4	102	36		10	225
37	23/08/2004 00:00	6.9	238	1885	356		170	23	882	0.5	1.1	197	95	120	13.3	215
38	22/11/2004 00:00	7.1	375	3235	2		430	133	1649	0.5	3.18	376	48	626	2.89	51
39	22/11/2004 00:00	7.1	224	1920	1431		212	41	967	1.2	1	203	109	268	1	101
40	28/02/2005 00:00	7.7	105	686	32		70	57	165	0.5	0.4	66	49	47	2	225
41	29/08/2005 00:00	8.3	99	642	3		26	50	196	0.5	0.4	42	48	93	2	368

Appendix 3: Ground water analyses of the monitoring boreholes (K02, K03, K04, K05, K06, VRM34, and VRM35) retrieved from the central database Pivot.

(e) Borehole K06

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	DATEMEAS	pH	EC	TDS	SS	Cl	NO3	SO4	Fe	Mn	Ca	Mg	Na	K	TALK
2	25/05/2004 00:00	7.8	126	973	254	62	242	295	0.5	0.4	106	48	147	1.2	215
3	23/08/2004 00:00	7.1	134	940	1169	57	128	307	0.5	0.4	104	60	67	1.5	210
4	22/11/2004 00:00	7.2	117	874	429	70	134	291	0.6	0.5	78	65	164	10	92
5	28/02/2005 00:00	7.5	104	712	415	38	75	181	0.5	0.4	60	53	49	2	280
6	23/05/2005 00:00	7.8	94	668	289	58	100	176	0.5	0.4	75	33	23	1	240
7	29/08/2005 00:00	8	92	581	43	28	54	167	0.5	0.4	27	47	95	1	218
8	05/12/2005 00:00	7.7	105	746	123	40	0	207	0.5	0.4	84	56	7	1	210
9	01/06/2006 00:00	7.5	80	640	167	34		154	0.25	0.2	40	4	5	0.5	20

(f) Borehole VRM34

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	DATEMEAS	pH	EC	TDS	SS	Cl	NO3	SO4	Fe	Mn	Ca	Mg	Na	K	TALK
2	23/05/2005 00:00	8.8	56	317	3	36	15	14	0.5	0.4	50	26	29	1	235
3	21/02/2000 00:00	8.4	50	228	60	44	4	51	0.5	0.4	42	10	20	5	104
4	21/08/2000 00:00	7.2	58	386	47	44	40	36	0.5	0.4	71	8	35	1	273
5	26/02/2001 00:00	7.1	73	390	2	46	29	25	0.5	0.4	1	15	17	1	261
6	26/05/2003 00:00	6.9	69	350	3	40	26	29	1	0	66	34	34	1	300
7	24/11/2003 00:00	6.7	57	304	8	24	23	9	0.5	0.4	24	25	18		190
8	25/05/2004 00:00	6.5	48	398	1	55	16	8	0.5	0.4	44	21	31	0.5	220

(g) Borehole VRM35

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	DATEMEAS	pH	EC	TDS	SS	CN Tot	Cl	NO3	SO4	Fe	Mn	Ca	Mg	Na	K	TALK
2	02/05/2006 00:00	7.5	122	1000	85		46		387	0.9	0.2	464	40	151	15	115
3	26/10/2004 00:00	7.7	205	1665	70		192	84	744	0.4	0.06	184	68	507	15.6	280
4	10/05/2005 00:00	7.6	147	1082	106		62	770	501	0.5	0.4	122	33	533	13	200
5	24/11/2003 00:00	7.1	160	1156	126	0.5	52	84	481	0.5	0.4	128	53	165		215
6	26/04/2004 00:00	7.9	155	1247	65		78	72	528	0.6	0.7	320	188	376	17	200
7	11/05/2002 00:00	7.4	159	1310	7	0	63	5.8	539	0.13	1.6	80	50	166	15	217
8	02/06/2002 00:00	7.5	151	1039	117	0.5	48	59	503	0.5	0.4	166	38	142	13	210
9	24/06/2002 00:00	7.3	136	1064	110	0.5	236		484	0.5	0.4	162	39	131	12	115
10	29/07/2002 00:00	7.4	153	1138	144	0.5	40	71	498	0.5	0.4	171	43	139	13	230
11	25/11/2002 00:00	7.5	158	1178	27	0.5	48	16	521	0.5	0.4	206	56	100	11	230
12	29/04/2003 00:00	7.6	133	1079	47	0.5	60	62	465	0.5	0.4	124	39	122	14	250
13	26/05/2003 00:00	7.4	132	930	33	0.5	40	60	444	1	0	160	46	103	11	256
14	25/08/2003 00:00	7.5	142	1330	237	0.5	40	16	573	0.5	0.4	197	59	51	19	230