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THE IMPACT OF GOLD AND COAL MINE RESIDUE ON WATER RESOURCES IN THE ROODEPOORT AND NEWCASTLE AREAS

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DECLARATION OF ORIGINALITY

This is to certify that the work is entirely my own and not of any other person, unless explicitly acknowledged (including citation of published and unpublished sources). The work has not previously been submitted in any form to the University of Pretoria or to any other institution for assessment for any other purpose.

Signed ____

Date ____

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EXECUTIVE SUMMARY

Large quantities of tailings are produced during gold and coal mining activities. These tailings consist of ash dumps, waste rock dumps, in-pit deposits and any other heap, pile or accumulation of residue in the tailings or slimes dams. It has been reported that these tailings can have a significant impact on water quality in the vicinity of gold and coal residues in South Africa. Water quality deterioration in the vicinity of gold and coal mines in the Johannesburg and other areas has been reported. However, little information is available on the potential impact of residues on water quality near Roodepoort and Newcastle where gold and coal, respectively, are mined.

The objective of this investigation was therefore to determine the potential impact of gold and coal mine residues on the environment in the vicinity of Roodepoort and Newcastle. Secondary objectives were to identify the metal constituents of gold and coal mine residues, to evaluate and define the current knowledge with regard to the short-term water quality impact of gold and coal residues in terms of concentration of metals leaching from the residues, to assess the potential impact of gold and coal tailings on the water environment within the study areas and to suggest methods to prevent pollution from taking place.

Acid Base Accounting (ABA), Toxicity Characteristics Leaching (TCLP), Acid Rain Leaching Procedure (ARLP) and Inductively Plasma Coupled – Mass Spectrometry (IPC-MS) were used as tools to determine the potential impact of gold and coal tailings on the environment.

Acid Base Accounting comprises two components that show the potential of the mine residue to produce acid mine drainage, that is, the total sulphur and the net neutralisation potential (NNP). It has been reported that any pyrite mine residue containing more than 0.5% total sulphur may generate acid mine drainage. Mine residues with a net neutralisation potential of less than zero ppt $CaCO_3$ produce acid drainage.

The acid base accounting results show that the gold and coal mine residues contain sulphur which has the potential to produce acid mine drainage.

Lithium (Li), sodium (Na) magnesium (Mg), aluminium (Al), potassium (K), calcium (Ca), iron (Fe), manganese (Mn) and nickel (Ni) were identified to be present in the gold mine residue.

The concentrations of some of the metals that leached from the gold residue according to the TCLP tests were as follows: Al (22 mg/L); Ca (242 mg/L); Fe (29 mg/L); Mn (88 mg/L) and Ni (87 mg/L). The metals that leached from the gold residue according to the ARLP results were as follows: Na (43 mg/L); Al (169 mg/L); Ca (246 mg/L); Fe (771 mg/L); Mn (16 mg/L) and Ni (11 mg/L). Higher concentrations of metals generally leached from the gold residue with the ARLP test than with the TCLP test.

The sulphate concentration up-stream of the gold residue was determined at 225 mg/L. This concentration increased to 3 490 mg/L at the decanting point and to 11 577 mg/L downstream of the decanting point. The surface and possibly groundwater are therefore polluted with sulphates.

Lithium (Li), sodium (Na), magnesium (Mg), aluminium (Al), potassium (K), calcium (Ca), iron (Fe), manganese (Mn) and nickel (Ni) were identified to be present in the coal mine residue. The concentrations of some of the metals that leached from the coal residue according to the TCLP tests were as follows: Al (3 mg/L); Ca (56 mg/L); Fe (0.21 mg/L); Mn (1 mg/L) and Ni (0.082 mg/L). The metals that leached from the coal residue according to the ARLP test results were as follows: Na (3 mg/L); Al (15 mg/L); Ca (136 mg/L); Fe (0.91 mg/L); Mn (1 mg/L) and Ni (0.07 mg/L). Higher concentrations of metals generally leached from the coal residue with ARLP test than with the TCLP test.

The sulphate concentration up-stream of the coal residue was determined at 26 mg/L. This concentration increased to 3 615 mg/L at the decanting point and to 6 509 mg/L downstream of the decanting point. The surface and possibly groundwater are therefore polluted with sulphate.

The upstream Na (26 mg/L), Ca (41 mg/L), Fe (0,02 mg/L), Mn (3 mg/L) and Ni (0.065 mg/L) concentrations were low in the case of the gold residues. These concentrations at the decanting point were: Na (289 mg/L); Ca (266 mg/L); Fe (0.2 mg/L); Mn (0.01 mg/L) and Ni (2 mg/L). Fifty metres downstream these concentrations were: Na (140 mg/L); Ca (389 mg/L); Fe (722 mg/L); Mn (395 mg/L) and Ni (15 mg/L). There was a significant increase in the metal concentration from up-stream of the gold residue, to the decanting point and further downstream of the gold residue. The surface and possibly ground water are therefore polluted by the metals leaching from the gold residue.

The upstream Na (5 mg/L), Ca (8 mg/L), Fe (0,12 mg/L), Mn (0.015 mg/L) and Ni (0.05 mg/L) concentrations were low in the case of the coal residues. These concentrations at the decanting point were: Na (189 mg/L); Ca (337 mg/L); Fe (68 mg/L); Mn (13 mg/L) and Ni (0.06 mg/L). Fifty metres downstream these concentrations were: Na (65 mg/L); Ca (129 mg/L); Fe (0.48 mg/L); Mn (5 mg/L) and Ni (0.06 mg/L). There was a significant increase in the metal concentration from up-stream of the coal residue, to the decanting point and further downstream of the coal residue. The surface and possibly ground water are therefore polluted by the metals leaching from the coal residue.

The gold and coal mine residues are polluting the surface and possibly ground water. Therefore, in order to ameliorate the current status within the Roodepoort and Newcastle catchments, mitigation and management measures such as that the residues should be covered and capped with soil material that would prevent infiltration of the oxygen and rain water into the soil, are recommended. A more comprehensive water quality analysis of the surroundings of the residues is also suggested to be able to better quantify the extent of the problem.

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ABBREVIATIONS

Acid-Base Accounting	ABA
Acid Mine Drainage	AMD
Acid Potential	AP
Toxicity Characteristics Leaching Procedure	TCLP
Acid Rain Leaching Procedure	ARLP
Inductively Plasma Coupled- Mass Spectrometry	IPC-MS
Net Neutralisation Potential	NNP
Parts per million	ppm
Parts per billion	ppb
Parts per ton	ppt
X-Ray Diffraction	XRD
Atomic Absorption Spectroscopy	AAS
Maximum Potential Acidity	MPA
Neutralisation Potential	NP

CHAPTER 1

1. INTRODUCTION

1.1. Study Background

Gold and coal mining activities produce large quantities of residues. These residues have the potential to have a negative impact on surface and groundwater if not managed properly. Gold and Coal mining follow different processes in order to produce waste in the form of residues. These residues emanate from processing of the ores and the tailings have the potential to change the quality of the surface and ground water such that the water is not fit for use (Broadhurst et al., 2007).

Run-off or seepage from residue facilities may compromise the beneficial use of water resources in the surrounding area (Water Quality Protection Guidelines No. 2 of Department of Minerals and Energy (Western Australia, 2000)). Rosner (1999) reported that the seepage from the tailings is generally characterized by low pH as well as elevated concentrations of toxic substances. Typical contaminants released from residues may lead to an increase in acidity, salt and heavy metal content in the surface water and groundwater. According to Singh (1998), mining wastes pollute the water in its surrounding such that it is not fit for use.

Poor management of the residues from mining activities resulted in the escape of seepage that adversely affecting soils and water quality and thus pose a threat to dolomite aquifers. Heavy metals contaminants such as Co, Ni and Zn are found in the soils and water where mine residues are located and acidification results in the long-term remobilization of large quantities of contaminants into the groundwater (Rosner et al., 2000). According to Ashley et al. (2004), unconfined tailing dams are the source of the problem. The partly oxidized sulphide-bearing mine wastes contain abundant sulphides and oxidation products and possess extreme As and Pb and elevated Ag, Cd, Cu, Sb and Zn concentrations. Acidic seepage (pH 1.9 – 6.0) from residues contain extreme As, Pb and Zn and elevated concentrations of Cd, Cu and Sb.

Studies in South Africa have indicated that gold and coal mine residues affect water quality adversely (DWAF, 2004). These studies were conducted in the Johannesburg area (Sakoane, 2005). However, little information is available regarding the impact of gold and coal mining activities in the Roodepoort and Newcastle areas in South Africa.

1.2. Study Area

The Roodepoort (Figure 1.1) and Newcastle (Figure 1.2) sub-catchment areas were selected for this study.

The gold mine residue (Figure 1.1) is situated 18 km south-west of Roodepoort, Gauteng. The area covered by this study consists of the dump with a maximum height of 68 m above the natural ground elevation. The dump was constructed close to an unnamed water stream. In addition, one decanting point was observed next to the mine residue dump. DWAF (2004) reported that the water quality is poor within the area. However the source of the impact is not known.

The coal mine residue dump (Figure 1.2) is situated approximately 15 km south of Newcastle, KwaZulu-Natal. The area covered by the study consists of the discard dump with a maximum height of approximately 55 m above the natural ground elevation. Localised groundwater pollution problems have been reported in the vicinity and it is not known what the source of the pollution is (DWAF, 2004).

Figure 1.3 indicates the location of the coal and gold mine residue dumps within South Africa. It is worth noting that the coal mine residue is within the KwaZulu-Natal province while the gold mine residue dump is located in Gauteng province.

Figure 1.1: Gold Mine Residue within the Roodepoort Sub-catchment

Figure 1.2: Coal Mine Residue within the Newcastle Sub-catchment

Figure 1.3: Location of the mine waste facilities in South Africa

1.3. Aim and Objectives

The main objective of this study was to determine the impact of gold and coal mine residues on water resources in the vicinity of the Roodepoort and Newcastle areas. Secondary objectives were:

1. To identify the metal constituents of the gold and coal mine residues in the study area.
2. To determine the concentration of metals leaching from the gold and coal residues.
3. To determine the potential impact of gold and coal residues on the water environment within the study area.

4. To suggest methods to prevent pollution from taking place.

1.4. The outline of Dissertation

The outline of this dissertation is as follows.

An introduction to the study is given in Chapter 1. Chapter 2 summarizes the relevant literature. The experimental procedures are described in Chapter 3 and the results and discussion are presented in Chapter 4. Conclusions and recommendations are given in Chapter 5. The references are shown in Chapter 6 followed by appendices.

CHAPTER 2

2. LITERATURE REVIEW

2.1. Introduction and objectives

The objective of this literature review is to explore studies related to the impact of gold and coal mine residue on water resources.

2.2. Acid Mine Drainage Formation

The rock (overburden) excavated to expose the material of interest (i.e. coal, gold, iron ore) in addition to the waste rock and tailings formed during the processing of valuable minerals, often contain sulphide minerals such as pyrite (FeS_2) that when exposed to air and water, are oxidized and release large quantities of iron and sulphate into solution (Lottermoser, 2007). In addition, hydrogen ions (H^+) are liberated during the oxidation process producing an acidic solution that readily weathers and releases other trace minerals (i.e. copper, zinc, etc.) into solution. This acidic solution is characterised by high heavy metals and sulphate concentrations and low pH.

Many ore deposits including the gold ores of the Witwatersrand contain significant proportions of sulphide minerals such as pyrite ore (Nengovhela et al. 2006). These minerals are chemically stable over long periods of time. However, when exposed to oxidising conditions either by exposure to air in mines or in mining residues, they oxidise and generate sulphuric acid.

The production of acid mine drainage (AMD) is described by four chemical reactions (Lottermoser, 2007):

1 Pyrite reacts with oxygen in the air and water to form a solution of ferrous iron, sulphate and free hydrogen ions (in effect a solution of ferrous iron in sulphuric acid)

$$2\ FeS_2 + 7O_2 + 2H_2O \rightarrow 2\ Fe^{2+} + 4SO_4^{2-} + 4H^+ \qquad (2.2.1)$$

2 The ferrous iron is then converted to ferric iron by the action of acid water in the presence of oxygen. This is the rate determining step for acid mine water production.

$$4\ Fe^{2+} + O_2 + 4H^+ \rightarrow 4\ Fe^{3+} + 2H_2O \qquad (2.2.2)$$

3 The ferric iron may then react with water to form ferric hydroxide, further acidifying the water. This reaction is pH dependant. At pH values below about 3.5, the ferric iron will remain in solution, while at higher pH values it will precipitate, forming a solid phase.

$$4\ Fe^{3+} + 12\ H_2O \leftrightarrow 4\ Fe(OH)_3 + 12H^+ \qquad (2.2.3)$$

4 Finally, the ferric iron acts as an oxidant, oxidising further ferrous iron or pyrite, generating additional acidity. This cyclic generation of acid will continue until the source of ferric iron or pyrite is exhausted. In acidic environments, microbes such as Acidithiobacillus ferroxidants, further accelerates the oxidation of pyrite by increasing the amount of Fe^{3+} in solution. It is important to note that this process can take place in an anoxic environment.

$$FeS_2 + 14\ Fe^{3+} + 8H_2O \rightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16H^+ \qquad (2.2.4)$$

Furthermore, pyrite the most abundant of the sulphide minerals, occurs in nearly all types of geological environments, and is commonly associated with coal, gold and metal ore deposits (Lottermoser, 2007). According to Lottermoser (2007), acid mine drainage is associated with the presence of sulphate and heavy metals (Fe, Cu, Pb, Zn, Cd, Co, Cr, Ni, Hg, Al, Mn, Si, Ca, Na, K, Mg and Ba) in water resources.

2.3. Acid-Base Accounting

Acid-Base Accounting (ABA) was developed at West Virginia University by Richard M. Smith and co-workers (Skousen et al., 1990). Acid-Base Accounting is the balance between the acid-production and acid-consumption properties of a mine waste material (Fey, 2003). According to Brady et al. (1994) acid-base accounting is a screening procedure whereby the acid-neutralising and acid-generating potential of rock samples are determined, and the difference, the net neutralising potential is calculated. The net neutralising potential, and/or the ratio of neutralising to acid-generation potential, is compared with a predetermined value, or set values, to divide samples into categories that either require, or do not require further determinative acid potential generation test work.

Although the potential utility as a water quality predictor was quickly recognised, the early developmental work on ABA was directed mainly toward assessing the agronomic potential of overburden and mine spoil. At that time top soiling was not widely practiced and ABA was useful for identifying overburden as root zone material. The first attempts to define levels for ABA data were the presence of potentially toxic materials having a net ABA of less than -5 ppt $CaCO_3$ (tonnes $CaCO_3$ equivalent/ 1 000 tonnes) (Smith et al., 1974). ABA, as originally developed, and used in Pennsylvania, consists of measuring the acid generating and acid neutralizing potentials of a rock sample. These measurements of Potential Acidity (PA) and Neutralization Potential (NP) are subtracted to obtain a Net Neutralization Potential (NNP) or net Acid-Base balance for the rock as follows:

$$\text{Net Neutralization Potential (NNP)} = \text{NP} - \text{PA} \qquad (2.3.1)$$

The results are customarily reported in tons per thousand tons of overburden or parts per thousand (ppt). The units' designation reflects the agronomic origins of ABA. An acre furrow slice of agricultural soil weighs about 1 000 tons, and liming requirements are usually expressed in tons per acre (tonnes/hectare). The units of measure for ABA are therefore comparable to the lime requirement designations for agricultural lands.

The components of ABA measurements are sometimes referred to by other terms, as they have been adapted for use in metal mining and other applications (Miller and Murray, 1988). The term "Acid Production Potential" (APP) is equivalent to PA, "Acid Neutralizing Capacity" (ANC) is equivalent to NP; and "Net Acid Producing Potential" or NAPP is the same as NNP. The measurements and calculations of NP, PA, and NNP are based on the following assumed stoichiometry (Cravotta et al., 1990):

$$FeS_2 + 2CaCO_3 + 3.75O_2 + 1.5H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 2Ca^{2+} + 2CO_2(g) \qquad (2.3.2)$$

For each mole of pyrite that is oxidized, two moles of calcite are required for acid neutralization. On a mass ratio basis, for each gram of sulphur present, 3.125 grams of calcite are required for acid neutralization. When expressed in parts per thousand of overburden, for each 10 ppt of sulphur (equal to 1 percent sulphur content) present, 31.25 ppt of calcite is required for acid neutralization. Cravotta et al. (1990) noted that the stoichiometry in Equation 2.3.2 is based on the dissolving of carbon dioxide gas out of the spoil system. They suggested that in a closed spoil system, carbon dioxide is not dissolved, and additional acidity from carbonic acid is generated. Cravotta et al. (1990) proposed that up to four moles of calcite might be needed for acid neutralization as follows:

$$FeS_2 + 4\ CaCO_3 + 3.75\ O_2 + 3.5\ H_2O \rightarrow 2\ SO_4^{2-} + Fe\ (OH)_3 + 4\ Ca^{2+} + 4\ HCO_3^{-} \qquad (2.3.3)$$

The stoichiometry of Equation 2.3.3 shows that twice as much calcite would be required for acid neutralization. On a mass basis, for each 10 ppt of sulphur present, 62.5 tons of calcite is needed for acid neutralization in one thousand tons of overburden. The choice of which stoichiometry most closely describes a mine spoil system directly affects the ABA calculation, alkaline addition rates, and prediction of expected post mining water quality. Brady et al. (1992) in analyzing ABA and water quality data from 74 mine sites, showed that correct prediction of post mining net alkalinity was improved from 52 ppb to 57 ppb using a stoichiometric equivalence of 62.5. They also found that the "errors" in prediction become more balanced using a 62.5 factor, with equal proportions of sites erroneously predicted to yield acid water and sites predicted to yield alkaline water. However, a later study initiated by Brady et al. (1994) showed that the 31.25 equivalence factor was most accurate, correctly predicting post mining net alkalinity on 31 of 38 mines (82%), while the 62.5 factor correctly predicted 22 of 38 (58%). The diverse results from these two studies underscore the complex geochemical processes at work and unique character of each mine site. Data reduction methods may also influence site rankings. The mainframe ABA database processes overburden data using both the 31.25 and 62.5 factors. The experience base of ABA interpretation has been built largely on using the 31.25 factor, and this convention is followed in most of the subject literature.

Acid Base Accounting comprises two components that show the potential of the mine residue to produce acid mine drainage, that is the total sulphur and the net neutralisation potential. Brady et al. (1990) reported that any pyrite mine residue containing more than 0.5% total sulphur may generate acid mine drainage while Patterson et al. (1994) mentioned that mine residues with NNP less than less than 0 ppt $CaCO_3$ would produce acid drainage.

According to Bruynesteyn et al. (1984), ABA could be preferred as the most appropriate test because the cost is low and it is a rapid kinetic test; it has been widely used and provides an assessment for the potential of biochemical oxidation. However, Bruynesteyn et al. (1984) indicated that the ABA test has disadvantages such as that the acidification procedure creates an unrealistic condition in that the inhibitory effects of the alkaline components of the waste on oxidation reactions are not evaluated. Furthermore, ABA does not allow evaluation or modelling of the initial AMD production stages in the upper pH ranges.

2.4. Gold Mine Residue

In gold mining and mineral processing, the mine residue produced fall into fine-grained and coarse-grained residue (Best Practice Guideline A2: Water Management for Mine Residue Deposits, 2008). The fine-grained residues are further classified as slimes and tailings while the coarse-grained residue is classified as waste rocks, heap leach pad and overburden. However, for the purpose of this study, fine-grained residue classified as tailings were studied. Figure 2.1 shows a simplified flow sheet of a gold mining process (Broadhurst et al., 2007).

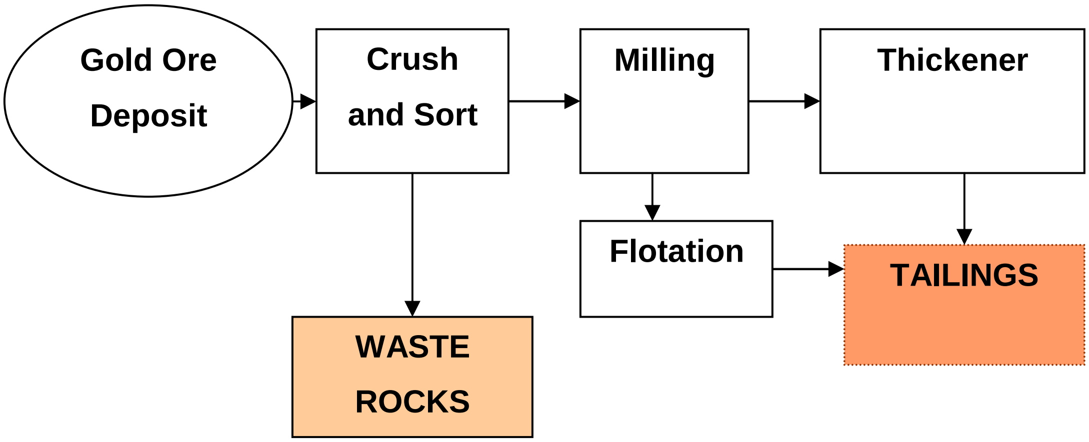

Figure 2.1: Simplified flow sheet for a gold mining process

Residues are generated from the crushing and sorting of gold ore deposits. In addition, waste rocks are also produced from crushing and sorting of gold ore deposits. Thereafter, the crushed ore is processed in the milling process which produces a by-product in the thickener process. Furthermore, the by-product from the milling process is taken through a flotation process, which produces tailings. Tailings are also produced from the thickening process. It should be noted that milling and the flotation include physical and chemical separation techniques (Figure 2.1).

The major impacts of tailings are related to the composition of the tailings, particularly the sulphide minerals, radioactive minerals and processing minerals. The main environmental hazards associated with gold tailings are water pollution (acids, salts heavy metals, radionucleotides, cyanides and sediment load (Hattingh and Deventer, 2004).

Changul et al. (2009) found that mine wastes could become sources of environmental degradation. Geochemical characterization of the gold tailings has been implemented to verify the fact that mine waste could be the source of environmental degradation. They found that the quantitative chemical analyses of gold tailings from the Akara Gold Mine in Ghana slightly differ from one place to the other. Co, Cu, Cd, Cr, Pb, Ni and Zn were found falling within the standard of the Thailand Soil Quality Standards for Habitat and Agriculture. Mn concentrations appear to have higher content than the standards.

Changul et al. (2009) in his investigation reported that leaching tests proved that gold tailings contain low metal concentrations. The acid generating potential of the gold tailings was estimated using Acid Base Accounting (ABA) and net acid generation tests (NAG). The results of the ABA and the NAG tests showed that the gold tailings samples contained a high amount of sulphur. However, they also contain a high acid neutralization capacity. They concluded that base on the tests; gold tailings have no potential to generate Acid Mine Drainage (AMD) including low levels of heavy metals.

Lapakko (1992) studied the potential of gold mine tailings to produce acid. Acid-Base Accounting was used to evaluate the acid producing capacity of gold mine tailings. Inductive Couple-Plasma (ICP) was used to analyze for metals within the gold tailings. The results indicated that sulphur was present in the gold mine tailing. The study concluded that the presence of sulphur provided an initial indication of the acid producing tendency of the gold tailings.

Wray’s (1998) investigation by geochemical analysis of gold tailings revealed that Mo, Sb, Te, Bi and As were all found at elevated levels in stream sediments downstream of the gold tailings site. Furthermore, elevated levels of Pb, Cu and Zn were also noted in stream sediments.

The United State Environmental Protection Agency (1994) reported that gold tailings, waste rocks and heap leach dumps are potentially significant sources of sulphur and heavy metals. These contaminants could infiltrate to the groundwater and released to the surface water and changing the water quality of the ground and surface water.

Ogola et al. (2002) investigated gold tailings sites in the Migori Gold Belt in Kenya and the investigation showed that the concentration of heavy metals mainly Hg, Pb and As were above acceptable levels in the water stream. The Gold tailings at the panning sites contain 6.5 -50 mg/kg of Pb, 0.06-076 mg/kg of As, and 0.46- 1 920 mg/kg of Hg. The concentration of the gold tailings were recorded to contain 3.0-11 075 mg/kg of Pb, 0.014 -1.87 mg/kg of As and 0.28 - 348 mg/kg of Hg downstream of the gold residues. However the highest metal contamination was recorded in the sediments of a water stream. The concentration were 11 075 mg/kg of Pb, 76 mg/kg of As and 1 920 mg/kg of Hg.

Nengovhela et al. (2006) determined if gold tailing in Johannesburg had the potential to generate acid mine drainage. The aim of the study was to determine the elements that could be associated with AMD. Nengovhela reported in the study that the most common culprit in AMD formation was pyrite. Gold tailings samples were collected for analysis purposes. The analysis of the samples showed that Al, Ca, Fe, Zn, Ni, Co, Mg and Na were leaching from the gold residues and X-ray diffraction tests were used to determine the potential of gold residues in generating acid. It was concluded that gold tailings in general has the potential to produce acid mine drainage and that certain elements leaching from the gold tailings were associated with AMD.

The most serious environmental hazard of the mine residues associated with water is acid mine drainage according to Hattingh et al. (2004). Furthermore, Hattingh et al. (2004) concluded that AMD arised when sulphides contained in the mine waste were exposed to oxidation and the product was flushed by water. The research claimed that the impact of AMD was through the seepage emanating from mine waste. The methodology undertaken for this particular study was through conducting a literature survey on the properties of gold tailings and on the environmental impacts associated with gold tailings dams.

Hattingh et al. (2003) also investigated the possible elements that could leach from the gold tailings in the Johannesburg area and associated impacts on the environment. The investigation found that gold tailings contain significant concentrations of potentially hazardous trace elements such as As, Cr, Cu, Ni, Pb, U and Zn. Groundwater quality in close proximity to the gold tailings occasionally showed elevated concentration of trace elements such as As, Cd, Co, Fe, Mn, Ni and CN which exceeded drinking water standards. Thus, the study concluded that the gold tailings, especially around the south of Johannesburg, contributed towards the poor quality of groundwater.

Winde et al. (2004) studies on gold tailings in areas around Johannesburg as a source of waterborne uranium contamination of streams – The Koekemoerspruit, revealed that the Koekemoerspruit has elevated levels of radioactive and chemo-toxic heavy metals such as Fe and Mn. The water samples were collected and analyses were conducted using Inductively Coupled Plasma- Mass Spectroscopy (ICP-MS) while solid waste Atomic Absorption Spectroscopy was used to analyse the leaching from the gold tailings.

Studies by Winde et al. (2004) also showed that tailings of gold mines in the Witwatersrand basin contained elevated levels of chemo-toxic heavy metals such as Fe and Mn. Acid mine drainage emanate from uncontrolled pollution and from slimes. Gold tailings were placed on well-drained dolomite resulting in seepage of dissolved U from tailing deposits into the dolomitic aquifer. The source of contamination was the results of erosion of tailings particles from the gold slime dams (van Tonder et al., 2006).

Chuxia et al. (2006) investigated the possible source of metals associated with AMD in surface water. The findings were that the chemistry of the stream water was affected by acid mine drainage extended at least to a distance of 25 km downstream of the mine water discharge point. Furthermore, the study found that Fe, Zn and Al were the major metals of potential toxicity followed by Mn, Cu, Pb, As, Cd and Ni.

Florea et al. (2005) in their investigation of the possible pollution of water resources found that the most important pollution sources are mine gold tailings. The preliminary study of streams and rivers revealed that the concentration of heavy metals such as Cd, Mn, Cu, Pb and Zn were above accepted limits in the surface water. The concentrations of Cd was 0.71 mg/L, Cu was 1.38 mg/L, Mn was 239 mg/L, Pb was 0.54 mg/L and Zn was 35.37 mg/L. Therefore, it was concluded that gold mine tailings have a negative impact on surface water quality.

Oelofse et al. (2007) reported that the gold tailings in the Johannesburg area are mostly unlined and not vegetated resulting in surface and groundwater contamination. The environmental implications of gold tailing disposal on land include contamination of streams by acid mine drainage, contamination of streams due to surface run-off and infiltration to the groundwater.

Surface impacts like water quality deterioration are mostly from tailings and rock dumps and it adversely affect both groundwater and surface water quality. Sampling was conducted on the fine-grained gold tailings. Sampling was also conducted on spring water and groundwater around the vicinity of the gold tailings. Inductive coupled plasma was used to analyze the chemical constituents of the spring water and groundwater. The groundwater chemistry is shown in Table 2.1

Table 2.1: Groundwater chemistry in the vicinity of the gold tailings dam.

Parameters	Spring water		Natural groundwater	SANS 241 Class I
pH	3.9	X	7.2	5.0-9.5
Electrical Conductivity (mS/m)	265	X	17	< 150
Calcium (mg/L)	262	X	16	< 150
Magnesium (mg/L)	133	X	10	< 70
Sodium (mg/L)	111	√	4	< 200
Potassium (mg/L)	7.8	√	0.5	< 50
Chloride (mg/L)	98	√	2.5	< 200
Sulphate (mg/L)	1516	X	22	< 400
Total Alkalinity (mg/L)	2.5	√	56	Unspecified
Nitrate (mg/L)	4.1	√	1.6	< 10
Fluoride (mg/L)	0.1	√	0.1	< 1.0
Iron (mg/L)	0.103	√	0.031	< 0.2
Manganese (mg/L)	100	X	0.012	< 0.1
Zinc (mg/L)	0.433	√	0.012	< 5.0

The quality of the spring water and ground water was compared to the natural dolomitic groundwater in the wider region. The South African National Standard 241 (SABS 2005) recommended operational limits for Class I drinking water was used for comparison. Oelofse et al. (2007) concluded that acid mine drainage emanating from gold tailings have an impact on the groundwater through the spring water. From these results it is evident that acid mine drainage is impacting on water resources as it is characterized by high sulphates and high salts concentrations and low pH.

2.5. Coal Mine Residue

In the coal mining and mineral process industries, similar as with the gold mining process, the mine residue produced fall into fine-grained and coarse-grained residue (Best Practice Guideline- A2: Water Management for Mine Residue Deposits- July 2008). The fine-grained residues are further classified as slurry while the coarse-grained residues are classified as discard/reject overburden, spoil and stockpile. For the purpose of this study, the coarse-grained residue classified as discard overburden was studied. **Figure 2.2** shows a simplified flow sheet for a coal mining process (Broadhurst et al., 2007).

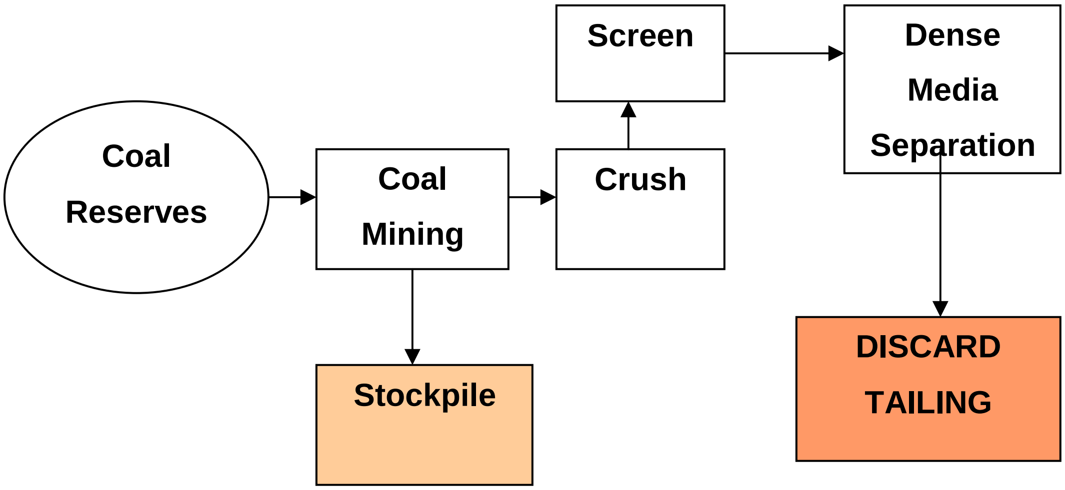

Figure 2.2: Simplified flow sheet of a coal mining process

The coal reserve that is mined is crushed and then taken through a screening process in order to recover more products from the by-product. The by-product is then taken through a dense media separation process which then produces discard residues (**Figure 2.2**)

A geochemical investigation and environmental quality assessment using soil and water were undertaken by Das (2006) during studies on coal mines in India. Soil and coal tailings were collected and analysed for metals (Cr, Cu, Fe, Mn, Ni and Zn). Furthermore, surface and groundwater samples were collected. Water samples were analysed for ions such as Sodium (Na^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Chloride (Cl^-), Nitric acid (HNO_3^-) and Sulphate $(SO_4^{2})^-$. Metal concentrations in soil and water samples were found to be higher than the average acceptable standard composition. Therefore, the coal residues have impacted negatively on the soil and water in the surrounding area.

Das (2006) studied the amount of sulphur in coal tailings and associated metals. It was found that acid mine drainage occurred in the coal dumps in which the sulphur content was found to be in the range of 1-5% in the form of pyrite (FeS_2). It degraded the water quality of the region in terms of lowering the pH of the surrounding water resources and increasing the heavy metals, total suspended solids and total dissolved solids. The leachate water from the overburden dump was found to be enriched in metal concentration, especially iron, copper, manganese and nickel.

Tripathy et al. (2006) studied the possibilities to encounter high concentrations of trace elements in the vicinity of coal ash deposits. Al, Fe, Mn and Pb concentrations were found to be enriched in the water to varying degrees and exceeded the maximum permissible limits prescribed for drinking water. The study showed that concentrations of the elements increased in the downstream direction irrespective of the sampling periods. Mn followed by Ba, V and Cr showed higher concentrations in the river.

Matthess et al. (1982) studied the effects of coal mine waste of Nordrhine-Westphalia (Germany) on groundwater. The objective of the study was to evaluate the effects of coal mine wastes on groundwater quality. Ions like chlorine, sodium and potassium were washed out quickly from coal mine waste causing a measurable deterioration of the groundwater mainly by the chlorides. The predominant effect is the contamination of groundwater by seepage containing sulphate originating from the oxidation of sulphide or organically bound sulphur. The study concluded that leaching of mine tailings caused groundwater deterioration.

Singh (2005) reported in a study entitled “Environmental issues with best management practice of coal mining in India” that acidic water resulted in severe water pollution problems and acidic water commonly named acid mine drainage originated from the weathering and leaching of sulphide minerals waste. The studies did not outline the methodology used to arrive at the conclusion.

Sottnik et al. (2008) determined the chemical composition of acid mine drainage from the coal waste in Slovakia without outlining the methodology used. It was found that the chemical composition of polluted water around the mining waste in Slovakia was acid mine drainage. ICP-MS was used to analyse the ground and surface water within the vicinity of mine waste.

Gaikwad et al. (2008) studied the characteristic of coal tailings and the impact of coal tailings on the water environment in New Delhi in India. It was found that acid mine drainage leached from coal tailings/ discard overburden and that the acid mine drainage was characterized by low pH, high metals concentrations (Fe is the most common), elevated sulphate levels and excessive suspended solids. Surface water and groundwater in the surrounding of the coal tailings tended to be acidic with high concentration level of components of acid mine drainage. Low pH, elevated sulphate levels and high metals concentration were found in the surface and ground waters.

Asker et al. (2008) investigated the impact of Acid Mine Drainage (AMD) from a coal mine waste rock pile on surface water in Svalbard in Russia. Analyses included metal concentrations (Al, Fe, Mn, Zn, Ni, Cr, As and Pb) in runoff and in soil and plants. It was observed that the impact of acid mine drainage degraded plants and the quality of the water. Al, Mn, and As were found at toxic concentrations. It was concluded that Al, Mn and Fe are weathering metals that had a large negative impact on plants and water due to runoff.

Lapakko (1992) findings on the quality of acid water from mine wastes in Minnesota, USA, revealed that acid water was a function of the mine waste composition. Findings revealed that there were three general types of acid releases from mine wastes including iron sulphide oxidation such as pyrite, dissolution of soluble iron sulphate minerals and the dissolution of less soluble sulphate minerals of the jarosite series. Lapakko (1999) further reported that no one analytical method is capable of reliably predicting future drainage chemistry. Therefore, a combination of analytical testing methods should be performed on tailings of both gold and coal tailings.

Maest et al. (2005) reported that sources of gold tailings and coal discard overburden should be examined for the potential to leach metals and any other constituents of concern identified in the source using one or more tests. These tests should include the precipitation leaching procedure, multiple extraction procedure, and toxicity characteristic leaching procedure. Kinetic testing is used to estimate the longer-term potential of mined materials to generate acid and to produce leachate and to estimate rates of oxidation and dissolution of materials.

Komnitsas et al. (2001) said that chemical analysis of gold and coal tailings are usually conducted using atomic absorption spectrophotometry, mineralogical analysis using XRD, particle analysis using wet screening, Multiple Extraction Procedure (Method 1320, US EPA, 1986) (MEP), and Toxicity Characteristics Leaching Procedure (TCLP).

At the Tula coal region, Russia, coal beneficiation wastes with high sulphur content have been placed in tailing dams. One of the most serious environmental problems associated with the surface disposal of coal wastes is the oxidation of the inherent pyrite and generation of acidity. Oxidation of pyrite releases dissolved Fe^{2+}, SO_4^{2-} and H^+ (Komnitsas et al., 2001)

Leachate emanating from coal tailings is characterized by low pH and the leachate varies widely in composition, with elevated concentration of sulphates, iron, manganese, aluminium as well as excessive total dissolved solids. Ferric iron, when discharged to surface water, hydrolyses to produce hydrated iron oxides and acidity is added to the water. The generated acidity lowers the pH of water.

A detailed environmental characterization of coal wastes was carried out by Komnitsas et al., (2001) using the following chemical analysis: AAS, XRD, ABA, NP, MPA and TCLP. The chemical analysis of the coal wastes showed that waste contained elevated concentrations of sulphur, chromium, iron and aluminium. The main minerals identified by XRD were quartz, pyrite and gypsum. TCLP results indicated that the wastes exhibit limited toxicity. Interpretation of all the laboratory experimental data revealed that coal waste metals characteristics (high concentrations), that adversely affect the environment, and therefore, the risk at the disposal area, is considered to be high.

Komnitsas et al. (2001) in his study of coal residue constituents in Greece concluded that coal residue constitute a serious environmental hazard since it is characterized by an elevated content of pyrite, lack of acid consuming minerals and extremely negative neutralizing potential. These wastes are subject to oxidation, therefore, acidic leachates with a very low pH and elevated concentration of hazardous elements are produced contaminating soils, surface water and groundwater and endangering the quality of the ecosystems.

CHAPTER 3

3. EXPERIMENTAL METHODS

3.1. Introduction

The two study areas namely the Roodepoort and Newcastle sub-catchments were selected for this study and the investigation is attempting to establish if the chemical component in the gold and coal residues could be found in the surface water and groundwater in the study area. In order to achieve the objective, both solid and water samples were taken from the residue deposit, decanting point and water streams passing the residue. All samples were subjected to ABA, TCLP, ARLP and Perkin Elmer ELAN 6000 ICP-MS analysis.

3.2. Sampling points

The sampling points for the gold and coal mine residues are shown in Figure 3.1 and Figure 3.2, respectively.

Figure 3.1: Sketch of the sampling point of Gold Mine Residue

The sampling points are shown in green and purple colour.

Figure 3.2: Sketch of the sampling point at the Coal mine residue

3.3. Sampling procedures and Laboratory testing

All liquid samples were collected in 1 litre plastic bottles and sample bottles were labelled with the point of sampling, date and time of sampling. Plastic bottles were rinsed four times with the water to be sampled. The plastic bottle were filled to the top and stored in a cooler box and transported to the laboratory prior to analyses.

Solid samples were collected in 1 litre plastic bottles and sample bottles were labelled with the point of sampling, date and time of sampling. A shovel was used to collect the representative samples.

Water samples were collected upstream and downstream of the gold and coal mine residue as shown in Figure 3.1 and Figure 3.2, respectively. In the absence of boreholes, water samples from the decanting point were considered to be representative of the groundwater in the area.

Gold and coal mine residue samples were collected from the top, side way and toe of the residue dumps.

3.4. Analytical Procedures

The Toxicity Characteristics Leaching Procedure (TCLP), Acid Rain Leaching Procedure (ARLP) and Acid-Base Accounting (ABA) tests were done on the both coal and gold mine residues. Inductive Coupled Plasma MS (ICP-MS) was used to determine the chemical constituents of the leachate emanating from the gold and coal mine residue solid and water samples. The potential of the gold and coal discard tailings producing acid water was assessed using Acid-Base Accounting.

The objective of the TCLP and ARLP was to test the leachability of organic and inorganic waste materials from the residues. The ARLP test is used to test leachability under worst case scenario conditions.

3.4.1. TCLP and ARLP Procedures

The experimental procedures for the TCLP and ARLP tests as done by Council for Geosciences (Council for Geoscience Analytical Procedure, 2003, Guide to the services of the CGS Analytical Laboratory) were as follows:

TCLP Procedure

The solution was prepared by adding 5.7 mL of glacial acetic acid and 64.3 mL of 1N NaOH into a 1000 mL beaker and dilute to the mark with deionised water with a pH of 4.93.

The samples were dried before they could be processed for crushing, splitting and milling. The Council for Geoscience has a room for drying samples. The room is equipped with dehumidifiers which significantly lower the humidity in the room and fans which circulate dry air resulting in the extraction of most of the moisture from the samples. The whole process takes place at room temperature which is very important to prevent the loss of analyte elements. The low temperature drying process also ensures that no mineralogical crystal structure changes occur. The room have the capacity to dry up to ± 600 samples to 20% moisture content within about 3 days.

Twenty grams of a dry waste which passed through a 9.5 mm sieve was weighed and transferred to the extraction bottle. 200mL of the prepared reagent was added to twenty grams of dry waste. The solution was rotated in an agitation apparatus at 30 rpm for 20 hours. The solutions were then filtered and analysed with a Perkin Elmer ELAN 6000 ICP-MS apparatus. The instrument was calibrated using a set of single or multi-element liquid standards.

ARLP Procedure

The Acid Rain Leaching Procedure is based on the fact that carbon dioxide dissolved in rain water to form carbonic acid. The carbonic acid can mobilise organics and/or inorganic in the mine residue. The method thus entails the extraction of a sample of a mine residue with a saturated solution of carbonic acid.

The carbonic acid solution was prepared in a 4 000 mL beaker and diluted to 10 000 mL with double distilled water and acidified to pH 3.6-3.8 with atomic absorption quality HNO_3.

3.4.2. ABA Procedure

The experimental procedure for the ABA test was as follows:
The solution was prepared using purified water, hydrochloric acid/ sulphuric acid – certified grade 0.1N, sodium hydroxide- certified grade 0.1N, Hydrochloric acid – 37% and NaOH pellets AR grade.

Two grams of a dry solid sample was weighed into a 250 mL Erlenmeyer flask and the prepared reagent was added. The solution was then heated to near boiling, swirling the flask until the reaction was complete. 125 mL of distilled water was then added and the flask was heated to 90 degrees Celsius for 60 minutes. The solution was then covered and cooled to room temperature. The cooled solution was titrated against NaOH (standardized) using 0.1N HCL to pH 7.0. The reading remained constant at pH 7.0 for at least 30 seconds.

3.4.3. ICP-MS Procedure

The experimental procedure (Council for Geoscience Analytical Procedure, 2003, Guide to the services of the CGS Analytical Laboratory) for the Perkin Elmer ELAN 6000 ICP-MS was as follows:

The leachates and water samples were introduced to the Perkin Elmer ELAN 6000 ICP-MS. A flow of gas was passed over the end of a tube containing the liquid. The flow of gas sheared the liquid into very small droplets forming an aerosol. The droplets then passed through a chamber that eliminated all droplets except those that had the right size and velocity for introduction into the plasma.

6.4.4 Total Sulphur Analysis (Council for Geoscience Analytical Procedure, 2003, Guide to the services of the CGS Analytical Laboratory)

Samples were weighed into a ceramic combustion boat, covered with a vanadium pentoxide accelerator, and transferred into the combustion furnace at 1050^{o}C. The sample in the presence of the accelerator and added oxygen combusts to form SO_2 in equilibrium with SO_3. This mixture is then conveyed by the nitrogen carrier gas into a second furnace at 825^{0}C and passed over reduced copper, quantitatively converting all SO_3 to SO_2, which is subsequently conveyed to the coulmetric cell of the detector. There, the resulting sulphur dioxide and/or hydrogen sulphide is automatically measured using absolute coulmetric titration. It should be noted that a CM320 Total Sulphur Analyser was used for analysing total sulphur.

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1 Introduction

Acid Base Accounting, TCLP and ARLP results as well as the sulphate concentrations of the gold and coal mine residues up-stream and downstream of the residues are presented in this chapter. The metals concentrations downstream of the mine residues are also shown.

4.2 GOLD MINE RESIDUE

4.2.1 Acid Base Accounting

The acid base accounting calculations are shown in Appendix A. The total sulphur and the NNP of the gold residue as a function of sample location are shown in Figures 4.1 and 4.2, respectively. The detailed results are shown in Appendix B (Table 4.1).

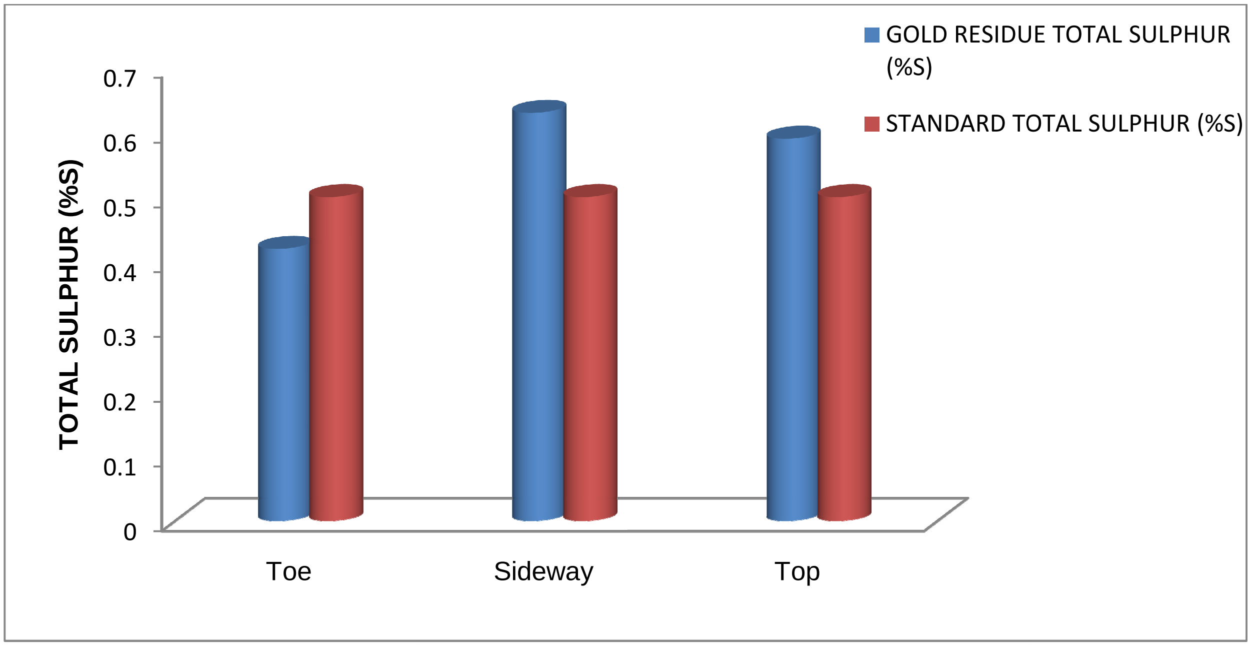

Figure 4.1: Total sulphur concentration (%) as a function of the sample location

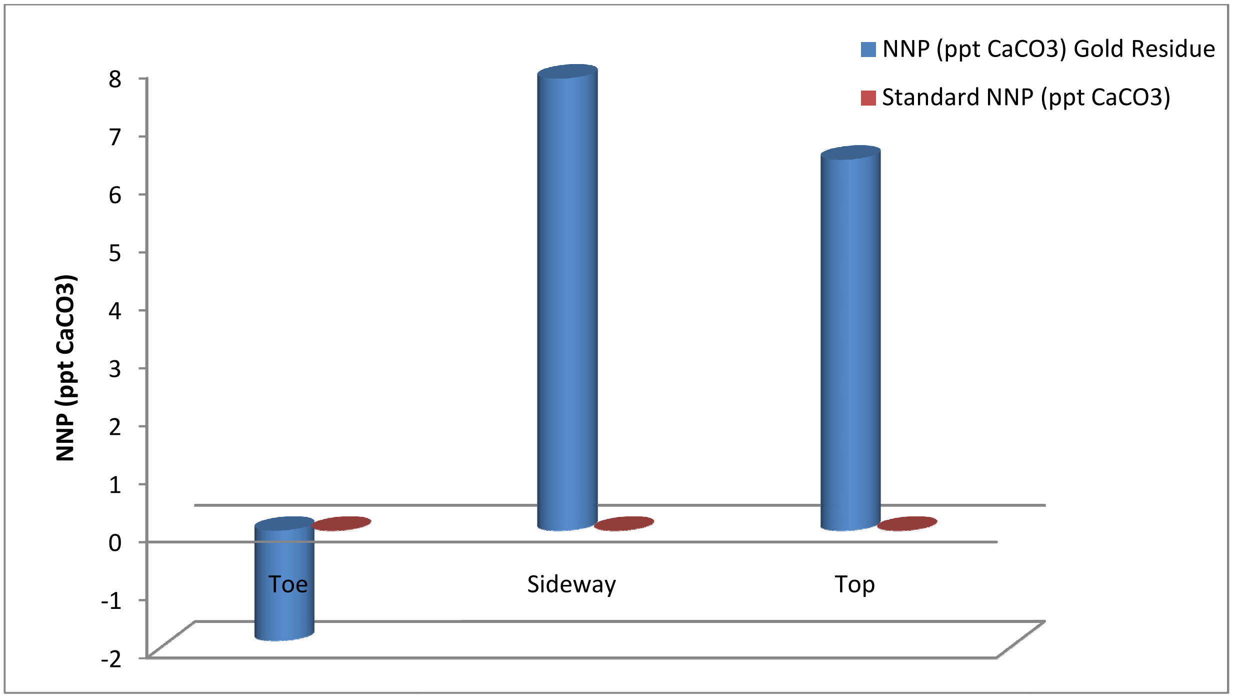

Figure 4.2: NNP as a function of the sample location

The total sulphur (%S) shows that the sideway and the top of the gold mine residue has the potential to produce acid mine drainage because the sulphur concentration of the residue is greater than 0.5% total sulphur. Brady et al. (1990) state that any pyrite mine residue containing more than 0.5% total sulphur has the potential to generate acid mine drainage. However, the total sulphur (%S) at the toe does not show the potential of the residue to produce any acid mine drainage because the percentage sulphur is less than 0.5 percent.

The NNP results indicate that the toe of the gold residue has the potential to generate acid drainage. Patterson et al. (1994) state that mine residues with NNP values less than zero has the potential to produce acid drainage. It is also further observed that the top and sideway of the residue do not have the potential to produce acid drainage because the NNP are greater than zero. Changul (2009) reported that ABA and NAG tests indicated that gold tailings containing high acid neutralisation capacity, has no potential to generate AMD. Therefore, the low sulphur at the toe of the gold tailing has low acid neutralisation capacity, hence the toe indicate the potential to produce AMD. The side way and the top of the gold residue contain high sulphur and high acid neutralisation capacity, hence the low potential to produce AMD. It is concluded that the potential of gold residue to produce AMD mainly depends on its acid neutralisation capacity.

4.2.2 Sulphate concentration results

The sulphate concentration up-stream, at the decanting point and downstream of the gold residue are shown in Figure 4.3 and detailed the results are shown in Table 4.2 (Appendix B).

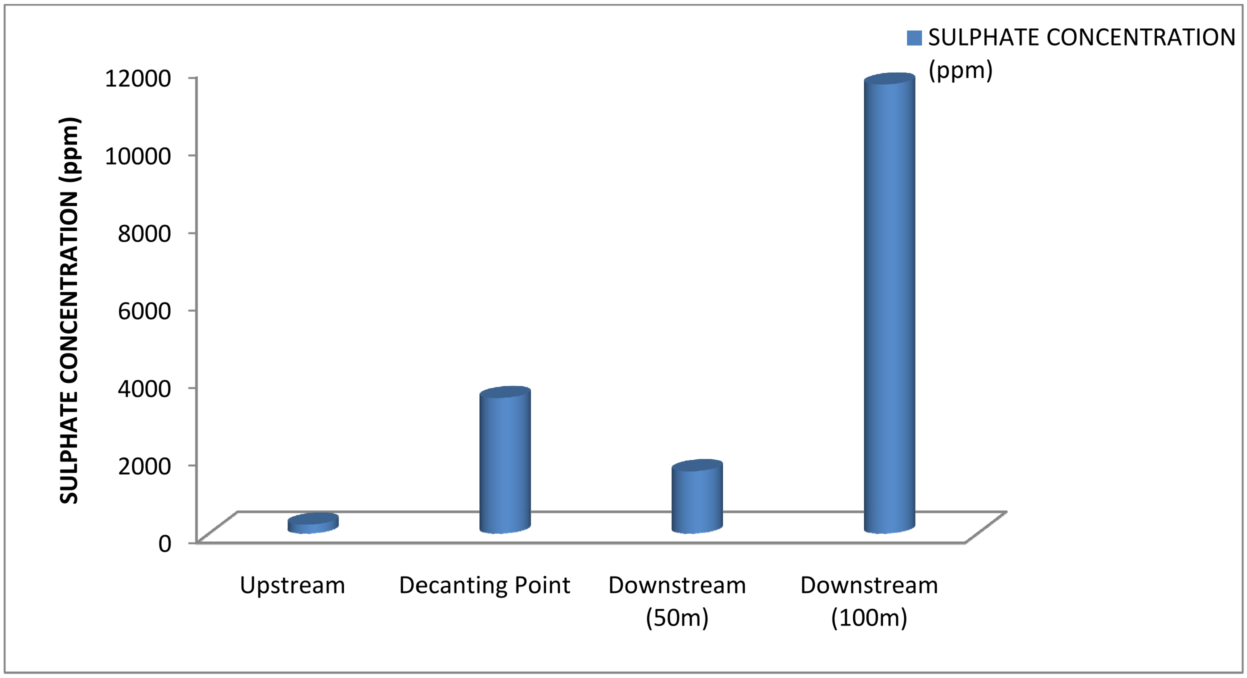

Figure 4.3: Sulphate concentration (ppm) at the different sampling point.

The sulphate concentration at the decanting point is relatively low (3 490 mg/L) compared to the sulphate concentration downstream (100 m) (11 577 mg/L) of the gold residue. The high concentration of sulphates downstream (50 m) (1 061 mg/L) suggests that sulphur from the gold residue is oxidised to produce acid mine drainage. Furthermore, the sulphate concentration shows that the oxidation of the pyrite (FeS_2) in the gold residue has an impact further downstream on the surface water quality. The high sulphate concentration detected at the decanting point (3 490 mg/L) in the vicinity of the gold mine residue suggests that the groundwater has also been polluted with sulphates.

4.2.3 Leaching of metals from the gold residue (TCLP)

The TCLP results of the gold residue as a function of sample location are shown in Figures 4.4. The detailed TCLP results are shown in Table 4.3 (Appendix B).

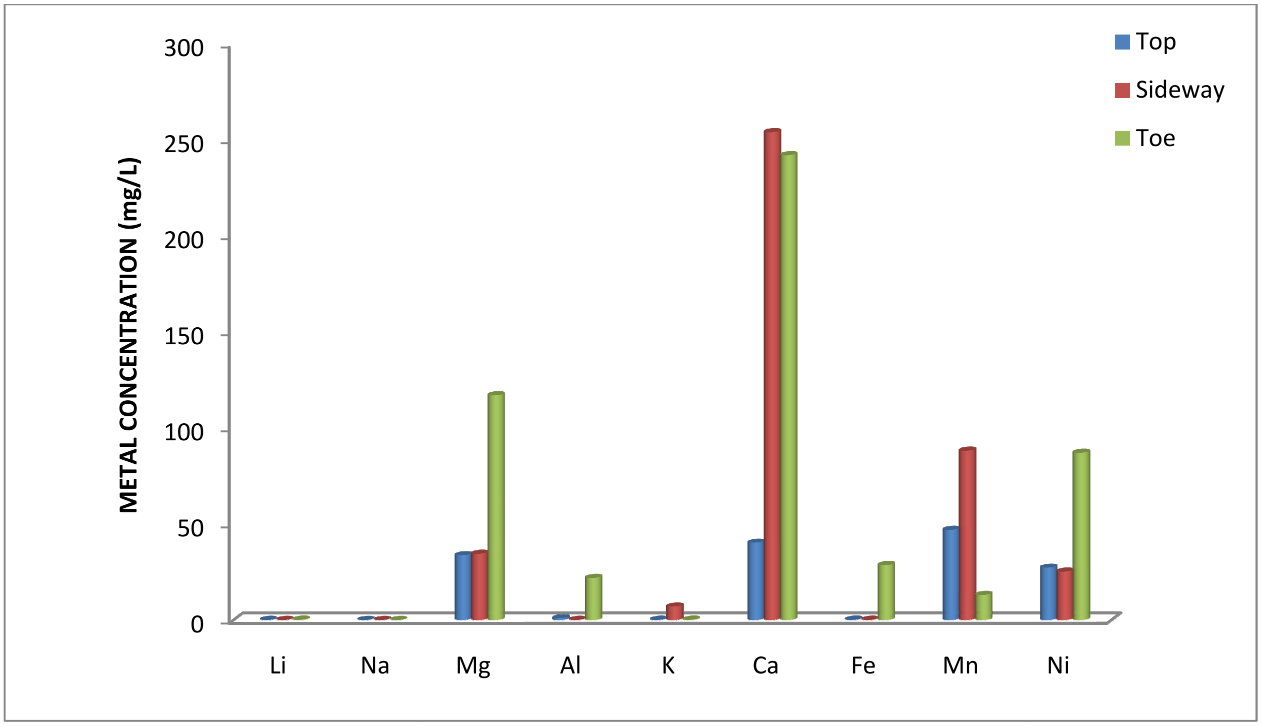

Figure 4.4: Concentration of metals that leach from the top, toe and sideway of the gold residue (TCLP)

The TCLP results show that the elements such as Li, Mg, Al, K, Ca, Fe, Mn and Ni leach from the gold residue with Mg, Al, Fe, Mn, Ni and Ca at higher concentrations. It appears that the toe of the gold residue generally leaches higher concentrations of metals than the side way and the top of the gold residue. The leached elements can be associated with acid mine drainage according to Nengovhela et al. (2006), Hattingh et al. (2003), Winde et al. (2004), Chuxia et al. (2006) and Florea et al. (2005). The high concentration of Na (see Table 4.3, Appendix B) is the result of the use of NaOH during the leaching test.

4.2.4 Leaching of metals from the gold residue (ARLP)

The ARLP results of the gold residue as a function of sample location are shown in Figures 4.5. The detailed ARLP results are shown in Table 4.4 (Appendix B).

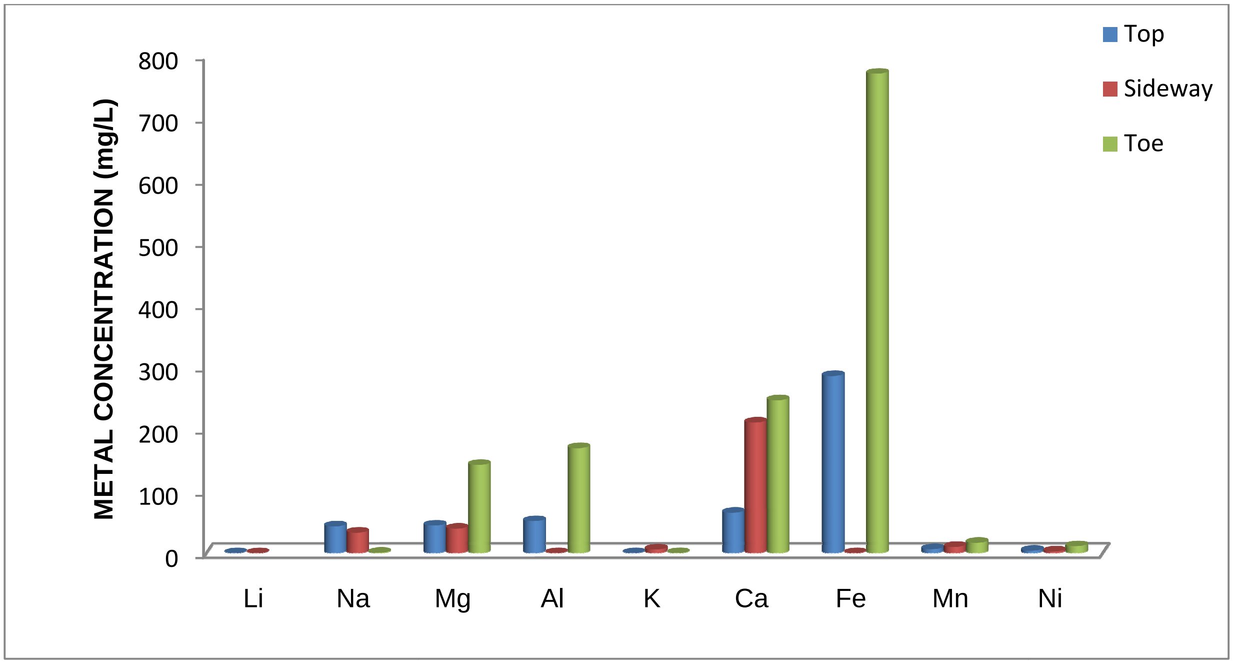

Figure 4.5: Concentration of metals that leach from the top, toe and sideway of the gold residue (ARLP)

The acid rain leaching indicated that Mg, Al, Ca and Fe are leached at higher concentration from the gold residue than was the case with the TCLP data (see Table 4.3 in Appendix B). Higher concentrations of Fe, Ca, Al and Mg leached from the toe than from sideway and the top. The results show that under acid rain conditions Mg, Al, Ca and Fe leaches at a higher concentration.

4.2.5 Concentration of metals upstream and downstream of the gold residue

The concentration of metals upstream and downstream of the gold residue is shown in Figure 4.6 and the detailed results are shown in Table 4.5 (Appendix B).

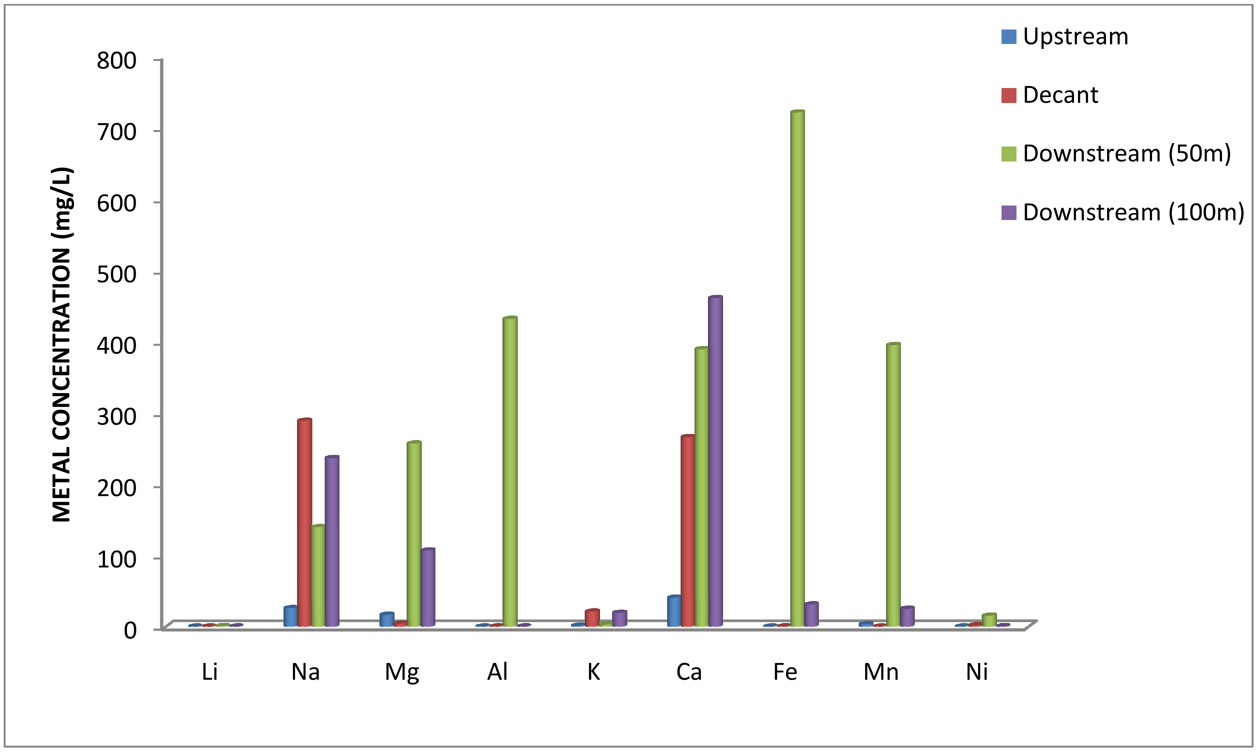

Figure 4.6: Concentration of metals in water samples upstream and downstream of the gold residue.

High concentrations of Na, Mg, Al, Ca, Fe, Mn and Ni were detected downstream of the gold residue. High concentrations of Na, Ca and Ni were also detected at the decanting point. This shows the possibility that the underground water was contaminated with metals. The lower concentration of leached metals 100 metre downstream suggests that dilution could have taken place downstream of the gold residue. However, the concentration of some of the metals remains high.

4.3 COAL MINE RESIDUE

4.3.1 Acid Base Accounting

The total sulphur and the NNP of the coal residue as a function of sample location are shown in Figures 4.7 and 4.8, respectively. The detailed acid base accounting results are shown in Table 4.6 (Appendix C).

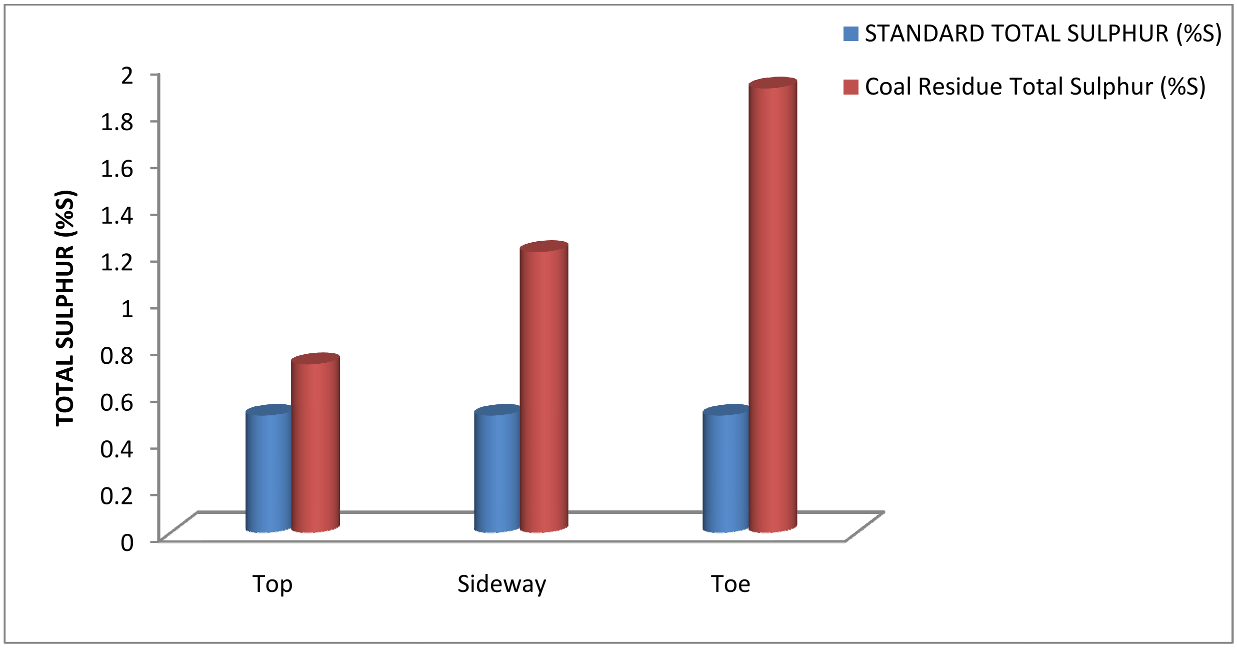

Figure 4.7: Total sulphur concentration as a function of the sample location

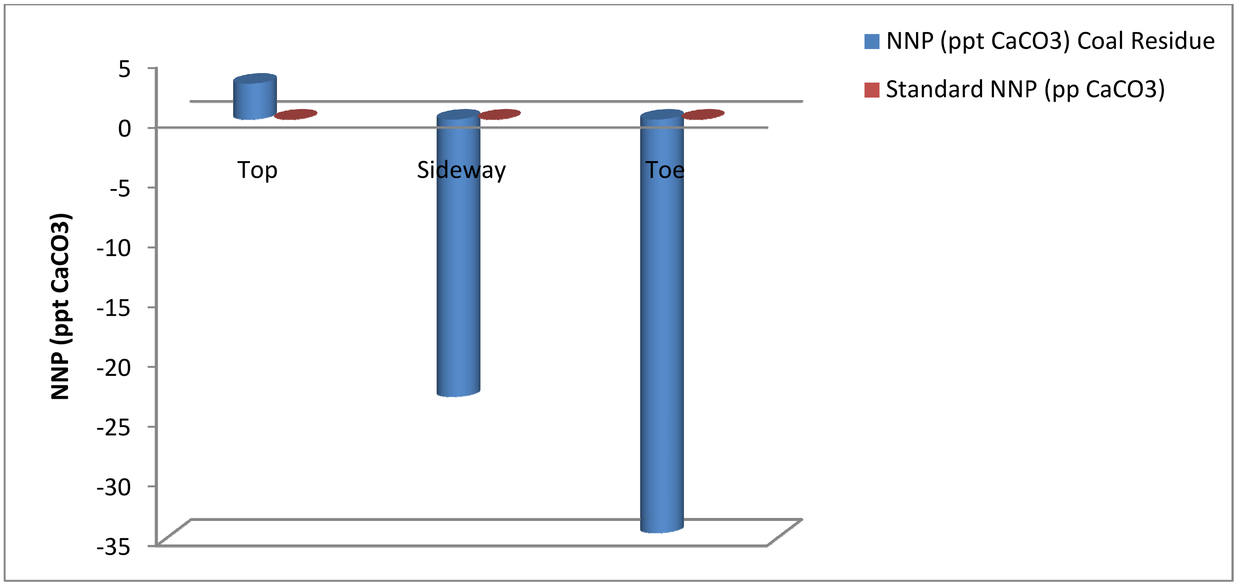

Figure 4.8: NNP as a function of the sample location

The total sulphur (%S) results show that the coal residue has the potential to produce acid mine drainage because the total sulphur concentration (%S) is higher than 0.5% (Brady et al. 1990 and Das 2006). The top, however has a lower sulphur content compared to the sideway and toe of the coal residue. Therefore, the top of the coal residue should produce less acid mine drainage. It is also interesting to note that the NNP results show that the sample from the side way and toe of the coal residue has the potential to produce acid mine drainage. However, it appears that the top of the coal residue has little potential to produce acid mine drainage. It is, however, clear from sulphur and NNP results that the coal residue has the potential to produce acid mine drainage.

4.3.2 Sulphate concentration results

The sulphate concentration downstream of the coal residue is shown in Figure 4.9. The detailed results are shown in Table 4.7 (Appendix C).

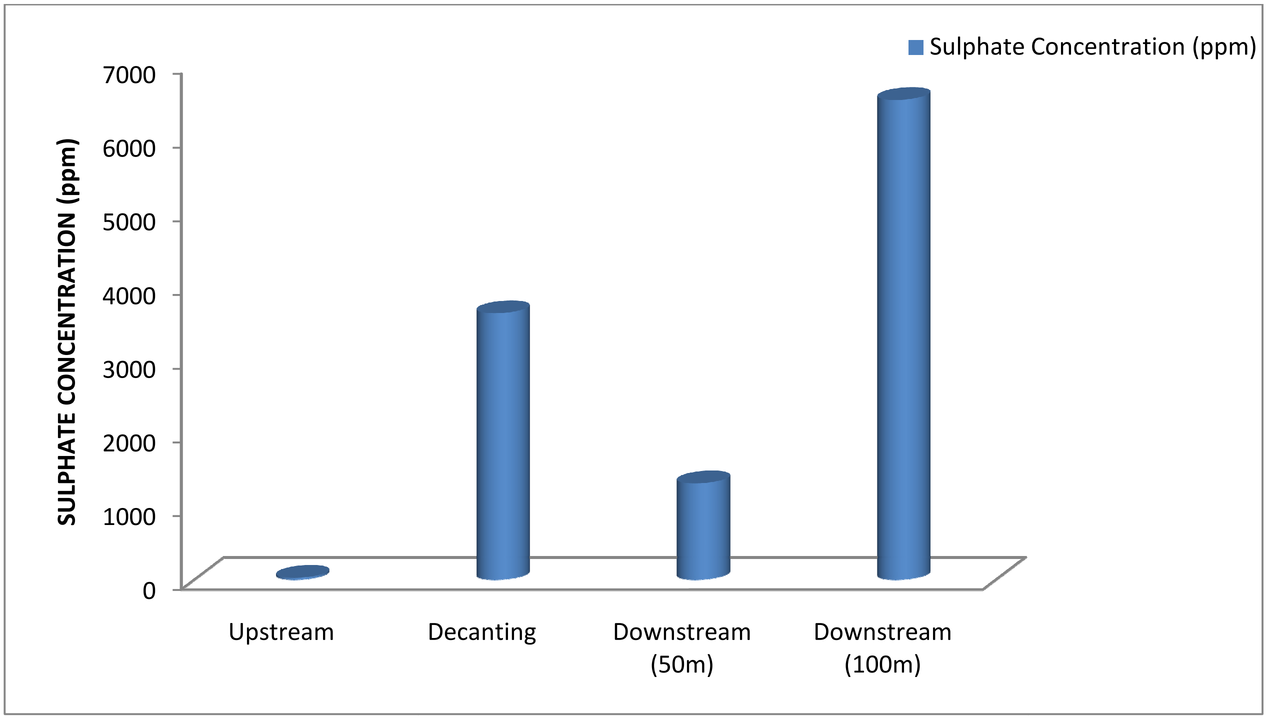

Figure 4.9: Sulphate concentration at the different sampling point.

The sulphur content of the coal residue showed that the residue would produce acid mine drainage (Figure 4.7). The sulphate concentration downstream of coal residue is high (Figure

4.9). This high sulphate concentration downstream suggests that sulphur is oxidised to produce sulphate and thus to produce acid mine drainage. The high sulphate concentration at the decanting point shows that there could be the possibility of groundwater impacted by the coal mine residue.

4.3.3 Leaching of metals from the coal residue (TCLP)

The TCLP results of the coal residue as a function of sample location are shown in Figures 4.10. The detailed TCLP results are shown in Table 4.8 (Appendix C).

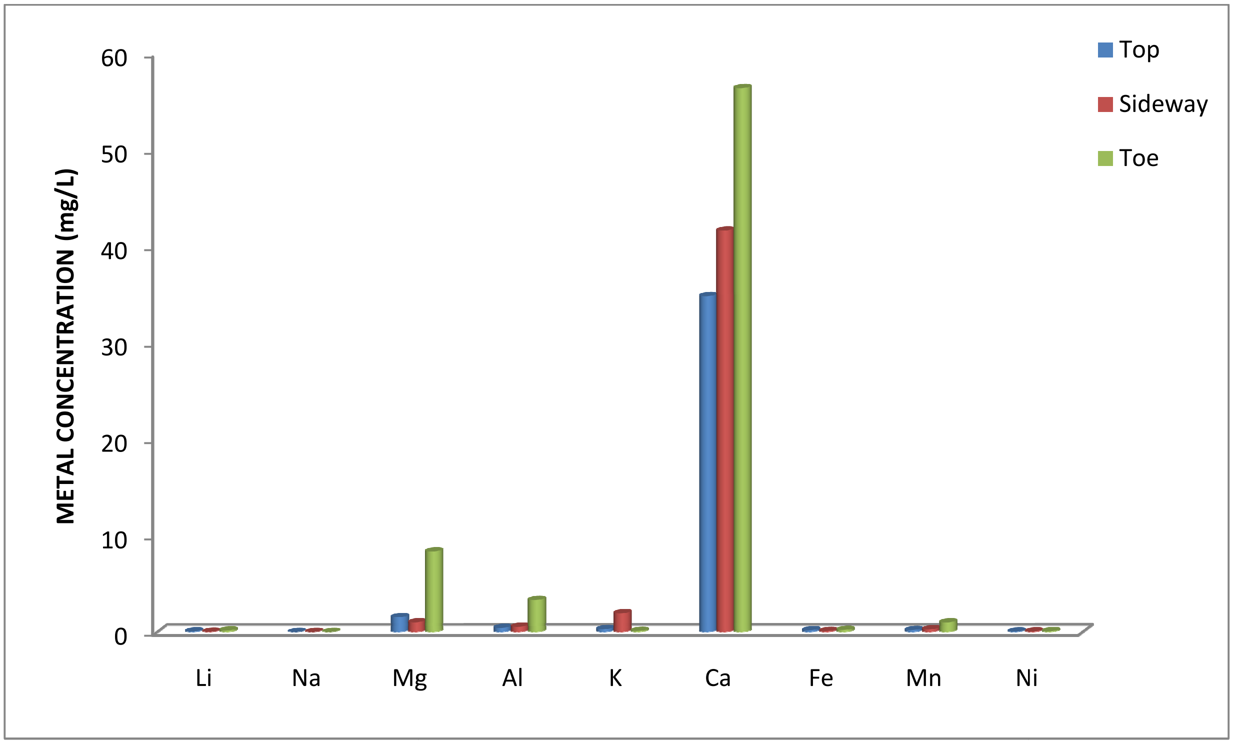

Figure 4.10: Concentration of metals that leach from the coal residue

Calcium, Mg, Al, and Mn leached from the coal residue at relative low concentrations. The leached metals from the coal residue can be associated with acid mine drainage (Lottermoser (2007). The high TCLP leaching test.

4.3.4 Leaching of metals from the coal residue (ARLP)

The ARLP results of the coal residue as a function of sample location are shown in Figures 4.11. The detailed ARLP results are shown in Table 4.9 (Appendix C).

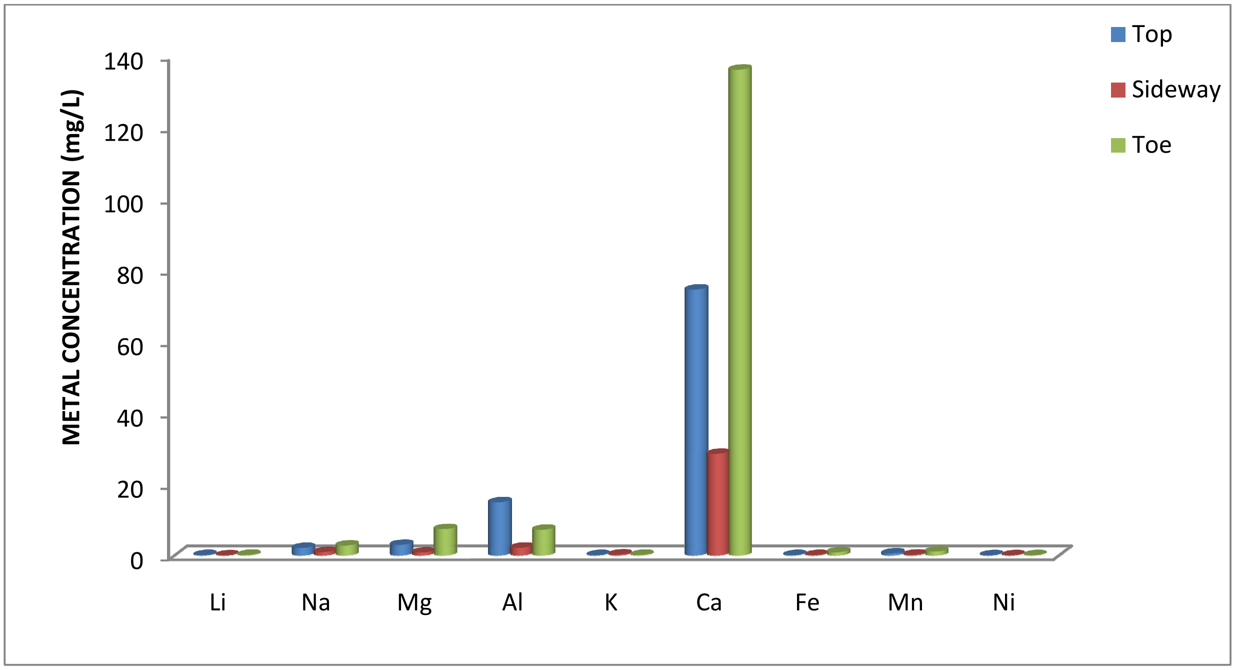

Figure 4.11: ARLP Results of Coal residue

The ARLP results showed that Al and Ca leached at higher concentration from the coal residue than was the case with the TCLP data (Table 4.8 in Appendix C). The toe of the coal residue also leached Ca at higher concentrations than the side way and top of the coal residue. It further appears that Ca leached at higher concentration under acid rain conditions than the other metals. The metals leaching from the residue can be associated with acid mine drainage (Lottermoser (2007)).

4.3.5 Concentration of metals upstream and downstream of the coal residue

The concentration of metals upstream and downstream of the coal residue is shown in Figure 4.12 and detailed results are shown in Table 4.10 (Appendix C).

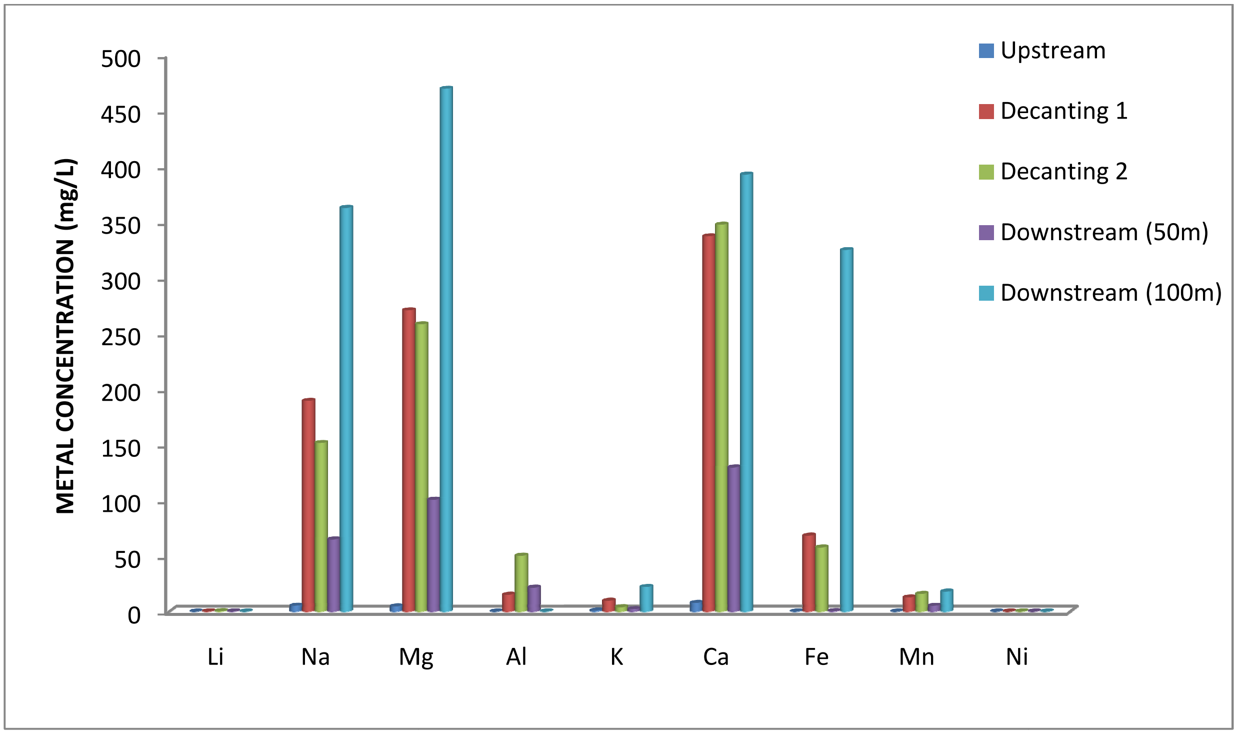

Figure 4.12: Concentration of metals upstream and downstream of the coal residue

Na, Mg, Ca, Fe and Mn are present at higher concentrations downstream of the coal residue than upstream of the coal residue. High concentration of Na, Mg, Ca, Fe and Mn were also observed at the decanting points. Therefore, the surface and groundwater are contaminated with metals originating from the coal residue. Das (2006) indicated that the coal residue negatively impacting the water resources. The high concentrations at the decanting points suggest that the coal residue is leaching metals to possibly the shallow groundwater.

CHAPTER 5

5. CONCLUSIONS AND RECOMMENDATIONS

The main objective of this study was to determine the potential impact of gold and coal mine residues on water resources in the vicinity of the Roodepoort and Newcastle mining areas in South Africa. The following conclusions and recommendations can be made as a result of the investigation.

Both the gold and coal mine residues adversely affect surface and possibly groundwater quality in the vicinity of the mines

5.1. Gold Mine Residue

Lithium (Li), sodium (Na), magnesium (Mg), aluminium (Al), potassium (K), calcium (Ca), iron (Fe), manganese (Mn) and nickel (Ni) were identified to be present in the gold mine residue. The concentrations of some of the metals that leached from the gold residue according to the TCLP test results were as follows: Al (22 mg/L); Ca (242 mg/L); Fe (29 mg/L); Mn (88 mg/L) and Ni (87 mg/L). The metals that leached from the gold residue according to the ARLP test results were as follows: Na (43 mg/L); Al (169 mg/L); Ca (246 mg/L); Fe (771 mg/L); Mn (16 mg/L) and Ni (11 mg/L). Higher concentrations of metals generally leached from the gold residue with the ARLP test than with the TCLP test.

The sulphate concentration up-stream of the gold residue was determined at 225 mg/L. This concentration increased to 3 490 mg/L at the decanting point and to 11 577 mg/L downstream of the decanting point. The surface and possibly groundwater are therefore polluted with sulphates.

The upstream Na (26 mg/L), Ca (41 mg/L), Fe (0,02 mg/L), Mn (3 mg/L) and Ni (0.065 mg/L) concentrations were low. These concentrations at the decanting point were: Na (289 mg/L); Ca (266 mg/L); Fe (0.2 mg/L); Mn (0.01 mg/L) and Ni (2 mg/L). Fifty metres downstream these concentrations were: Na (140 mg/L); Ca (389 mg/L); Fe (722 mg/L); Mn (395 mg/L) and Ni (15 mg/L). There was a significant increase in the metal concentration from up-stream of the gold residue, to the decanting point and further downstream of the gold residue. The surface and possibly ground water are therefore polluted by the metals leaching from the gold residue.

5.2. Coal Mine Residue

Lithium (Li), sodium (Na), magnesium (Mg), aluminium (Al), potassium (K), calcium (Ca), iron (Fe), manganese (Mn) and nickel (Ni) were identified to be present in the coal mine residue. The concentrations of some of the metals that leached from the coal residue according to the TCLP test results were as follows: Al (3 mg/L); Ca (56 mg/L); Fe (0.21 mg/L); Mn (1 mg/L) and Ni (0.082 mg/L). The metals that leached from the coal residue according to the ARLP test results were as follows: Na (3 mg/L); Al (15 mg/L); Ca (136 mg/L); Fe (0.91 mg/L); Mn (1 mg/L) and Ni (0.07 mg/L). Higher concentrations of metals generally leached from the coal residue with the ARLP test than with the TCLP test.

The sulphate concentration up-stream of the coal residue was determined at 26 mg/L. This concentration increased to 3 615 mg/L at the decanting point and to 6 509 mg/L downstream of the decanting point. The surface and possibly groundwater are therefore polluted with sulphate. The upstream Na (5 mg/L), Ca (8 mg/L), Fe (0,12 mg/L), Mn (0.015 mg/L) and Ni (0.05 mg/L) concentrations were low. These concentrations at the decanting point were: Na (189 mg/L); Ca (337 mg/L); Fe (68 mg/L); Mn (13 mg/L) and Ni (0.06 mg/L). Fifty metres downstream these concentrations were: Na (65 mg/L); Ca (129 mg/L); Fe (0.48 mg/L); Mn (5 mg/L) and Ni (0.06 mg/L). There was a significant increase in the metal concentration from up-stream of the coal residue, to the decanting point and further downstream of the coal residue. The surface and possibly ground water are therefore polluted by the metals leaching from the coal residue.

The gold and coal mine residues appear to pollute the surface and possibly ground water. Therefore, in order to ameliorate the current status within the Roodepoort and Newcastle catchments, mitigation and management measures such as that the residues should be covered and capped with soil material that would prevent infiltration of the oxygen and rain water into the soil, are recommended.

5.3. Recommendations

The gold and coal mine residues appear to pollute the surface and possibly ground water. Therefore, in order to ameliorate the current status within the Roodepoort and Newcastle catchments, the following mitigation and management measures are recommended

On-site rehabilitation should comprise of the re-designing of the coal and gold mine residues to minimise or avoid the standing of water on the residues. The design of the residues should allow more run-off storm water from the residues and avoid storm water infiltration into the residues. Run-off should be contained in toe paddocks to prevent sediment load to the surface water. Geohydrological studies should be undertaken to determine the flow of the groundwater. Boreholes should then be drilled to intercept further migration of pollution plumes that can emanate from both the coal and gold mine residues.

The residues should be covered and capped with soil material that would prevent infiltration of oxygen and rain water into the soil. Research should be undertaken to determine the best capping material and type of vegetation that should be used in order to avoid oxidation of the pyrite taking place on the coal and gold mine residues. Surface and ground water monitoring should be undertaken subsequent to the rehabilitation of the coal and gold mine residues to evaluate the success of the implemented management measures proposed.

Water quality analysis up-stream and down-stream of the gold and coal residues have indicated that possibly the underground and surface water are contaminated with constituents that leached from the residues. This study, however, was a preliminary investigation and a more comprehensive water quality study should be undertaken to quantify the extent of the problem.

CHAPTER 6

6. REFERENCES

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APPENDIX A

FORMULAE

NNP = NP – AP

NP = 50 a [x – (b/a) y]/ c

AP = Total Sulphur Analysis x 31.25 (equivalence factor)

NP = 50 a [x – (b/a) y]/ c

a = normality of HCL

b = normality of NaOH

c = sample weight in grams

x = volume (in ml) HCL added

y = volume (in ml) NaOH added to pH 7

CALCULATIONS TO OBTAIN NP, AP and NNP AT DIFFERENT LOCATIONS WITHIN THE GOLD RESIDUE

Volume of HCL added (ml)	Normality of HCL	Volume of NaOH added to pH 7	Normality of NaOH	Location of the sample	Weight of the Sample (g)
40	0.1	29	0.1	Sideway	2
40	0.1	30.1	0.1	Top	2
40	0.1	35.5	0.1	Toe	2

Note: The volumes indicated on the Table were obtained during the experimental procedure

NP = 50 (0.1) [40 – (0.1/0.1) 29]/ 2 = 27.5

NP = 50 (0.1) [40 – (0.1/0.1) 30.1)/2 = 24.75

NP = 50 (0.1) [40 – (0.1/0.1) 35.5)/2 = 11.25

AP = 0.63 x 31.25 = 19.7

AP = 0.59 x 31.25 = 18.4

AP = 0.42 x 31.25 = 13.1

NNP = 27.5 – 19.7 = 7.8

NNP = 24.75 – 18.4 = 6.4

NNP = 11.25 – 13.1 = -1.9

CALCULATIONS TO OBTAIN NP, AP and NNP AT DIFFERENT LOCATIONS WITHIN THE COAL RESIDUE

Volume of HCL added (ml)	Normality of HCL	Volume of NaOH added to pH 7	Normality of NaOH	Location of the sample	Weight of the Sample (g)
40	0.1	34.3	0.1	Sideway	2
40	0.1	29.8	0.1	Top	2
40	0.1	30.1	0.1	Toe	2

Note: The volumes indicated on the Table were obtained during the experimental procedure

NP = 50 (0.1) [40 – (0.1/0.1) 34.3]/ 2 = 14.25

NP = 50 (0.1) [40 – (0.1/0.1) 29.8)/2 = 25.5

NP = 50 (0.1) [40 – (0.1/0.1) 30.1)/2 = 24.75

AP = 1.2 x 31.25 = 37.5

AP = 0.72 x 31.25 = 22.5

AP = 1.9 x 31.25 = 59.4

NNP = 14.3 – 37.5 = -23.2

NNP = 25.2 – 22.5 = 3.0

NNP = 24.8– 59.4 = -34.6

APPENDIX B

Table 4.1: Gold Residue Acid Base Accounting Data

Sample Location Of Gold Residue	Total Sulphur Analysis	Neutralisation Potential (NP)	Acid Potential (AP)	Net Neutralisation Potential (NNP)
	%S	ppt $CaCO_3$	ppt $CaCO_3$	ppt $CaCO_3$
Sideway	0.63	27.5	19.7	7.8
Top	0.59	24.8	18.4	6.4
Toe	0.42	11.8	13.1	-1.9

Table 4.2: Sulphate concentration (ppm) of the Gold Residue

SAMPLING POINTS	CONCENTRATION (ppm)
Upstream (1)	225
Decanting Point (2)	3 490
Downstream (50m) (3)	1 601
Downstream (100m) (4)	11 577

Table 4.3: TCLP results of Gold Residue

Sampling Location	Li mg/L	Na mg/L	Mg mg/L	Al mg/L	K mg/L	Ca mg/L	Fe mg/L	Mn mg/L	Ni mg/L
Toe	0.144	0(*1 885)	117	21.85	0.143	242	28.57	13.01	87.09
Side Way	0.022	0(*1 851)	34.43	0.050	6.97	254	0.098	88.13	25.17
Top	0.053	0(*1 834)	33.69	0.892	0.105	40.21	0.158	46.88	27.21

*The high concentration of Na is due to the NaOH used in the TCLP leaching solution.

Table 4.4: ARLP Results of Gold Residue

Samples Location	Li mg/L	Na mg/L	Mg mg/L	Al mg/L	K mg/L	Ca mg/L	Fe mg/L	Mn mg/L	Ni mg/L
Toe	0.196	0.82	142	169	0.150	246	771	16.64	11.23
Side Way	0.024	33.14	39.45	0.101	6.03	210	0.100	10.03	2.80
Top	0.064	43.04	44.49	51.55	0.098	65.07	285	6.47	3.88

Table 4.5 : Concentration metals in water samples upstream and downstream of the gold residue

Samples Location	Li mg/L	Na mg/L	Mg mg/L	Al mg/L	K mg/L	Ca mg/L	Fe mg/L	Mn mg/L	Ni mg/L
Up-stream	0.007	26	16.63	0.028	1.25	40.50	0.02	3.40	0.065
Decant	0.013	289	4.13	0.11	21.15	266.04	0.20	0.01	1.76
Downstream (50m)	0.63	139.61	257.06	431.90	2.84	389.30	721.65	395.07	15.37
Downstream (100m)	0.069	236.51	106.82	0.14	19.40	461.14	31.18	24.98	0.45

APPENDIX C

Table 4.6 : Coal Residue Acid Base Accounting Results

Sample Location of Coal Residue	Total Sulphur Analysis	Neutralisation Potential (NP)	Acid Potential (AP)	Net Neutralisation Potential (NNP)
	%S	ppt $CaCO_3$	ppt $CaCO_3$	ppt $CaCO_3$
Coal residue at the side way	1.2	14.3	37.5	-23.2
Coal residue at the top	0.72	25.5	22.5	3.0
Coal residue at the toe	1.9	24.8	59.4	-34.6

Table 4.7: Sulphate concentration (ppm) of the Coal Residue

SAMPLING POINTS	CONCENTRATION (ppm)
Upstream	26
Decanting Point	3 615
Downstream (50m)	1 307
Downstream (100m)	6 509

Table 4.8: TCLP Results (Coal Residue)

Samples Location	Li mg/L	Na mg/L	Mg mg/L	Al mg/L	K mg/L	Ca mg/L	Fe mg/L	Mn mg/L	Ni mg/L
Top	0.061	0(*1 560)	1.53	0.43	0.29	34.83	0.18	0.20	0.048
Side Way	0.022	0(*1 718)	1.00	0.54	1.94	41.62	0.10	0.28	0.058
Toe	0.16	0 (*1 688)	8.35	3.32	0.11	56.40	0.21	0.99	0.082

*The high concentration of Na is due to the NaOH used in the TCLP leaching solution.

Table 4.9: ARLP Results of Coal Residue

Samples (mg/L)	Li (ppb)	Na (ppb)	Mg (ppb)	Al (ppb)	K (ppb)	Ca (ppb)	Fe (ppb)	Mn (ppb)	Ni (ppb)
Top	0.10	2.10	2.98	14.89	0.097	74.48	0.1	0.55	0.05
Side Way	0.02	0.97	0.84	2.16	0.26	28.46	0.10	0.22	0.05
Toe	0.16	2.76	7.38	7.18	0.15	136.1	0.91	1.10	0.07

Table 4.10: Concentration of metals upstream and downstream of the coal residue

Samples Location	Li mg/L	Na mg/L	Mg mg/L	Al mg/L	K mg/L	Ca mg/L	Fe mg/L	Mn mg/L	Ni mg/L
Up-stream	0.03	5.25	4.69	0.05	0.95	7.81	0.12	0.015	0.05
Decanting Point 1	0.18	189.23	270.57	15.14	9.68	337.01	68.12	12.68	0.06
Decanting Point 2	0.48	151.44	257.98	50.15	3.90	347.49	57.55	15.87	0.16
Downstream (50m)	0.21	64.80	100.41	21.48	2.19	129.43	0.48	5.17	0.06
Downstream (100m)	0.06	362.60	469.56	0.09	22.14	392.47	324.71	17.86	0.07